ANDES Manual

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ANDES MANUAL

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LTB ANDES is an open-source Python library for power system modeling, computation, analysis, and control, serving as the core simulation engine for the CURENT Large scale Testbed (LTB). It supports power flow calculation, transient stability simulation, and small-signal stability analysis for transmission systems. ANDES implements a symbolic-numeric framework for rapid prototyping of differential-algebraic equation-based models. In this framework, a comprehensive *library of models* is developed, including the full second-generation renewable models. Models in ANDES have been *verified* with commercial software.

Getting started

New to ANDES? Check out the Getting Started guides. They contain tutorials to the ANDES command-line interface, scripting usages, as well as guides to configure ANDES and work with case files.

To the getting started guides

Examples

The examples provide in-depth usage of ANDES in a Python scripting environment. Advanced usage and power system studies are shown with explanation.

To the examples

Model development guide

Looking to implement new models, algorithms, and functionalities in ANDES? The development guide provides in-depth information on the design philosophy, data structure, and implementation of the hybrid symbolic-numeric framework.

To the development guide

API reference

The API reference contains a detailed description of the ANDES package. The reference describes how the methods work and which parameters can be used. It assumes that you have an understanding of the key concepts.

To the API reference

Using ANDES for Research?

Please cite our paper [Cui2021] if ANDES is used in your research for publication.

CHAPTER

ONE

GETTING STARTED

1.1 Package Overview

ANDES is an open-source Python package for power system modeling, computation, analysis, and control. It establishes a unique **hybrid symbolic-numeric framework** for modeling differential algebraic equations (DAEs) for numerical analysis. The main features of ANDES include

- a unique hybrid symbolic-numeric approach to modeling and simulation that enables descriptive DAE modeling and automatic numerical code generation
- a rich library of transfer functions and discontinuous components (including limiters, dead-bands, and saturation) available for prototyping models, which can be readily instantiated as multiple devices for system analysis
- industry-grade second-generation renewable models (solar PV, type 3 and type 4 wind), distributed PV, and energy storage model
- comes with the Newton method for power flow calculation, the implicit trapezoidal method for time-domain simulation, and full eigenvalue calculation
- rigorously verified models with commercial software. ANDES obtains identical time-domain simulation results for IEEE 14-bus and NPCC system with GENROU and multiple controller models. See the verification link for details.
- developed with performance in mind. While written in Python, ANDES comes with a performance package and can finish a 20-second transient simulation of a 2000-bus system in a few seconds on a typical desktop computer
- out-of-the-box PSS/E raw and dyr file support for available models. Once a model is developed, inputs from a dyr file can be readily supported
- always up-to-date equation documentation of implemented models

ANDES is currently under active development. To get involved,

- Follow the tutorial at https://andes.readthedocs.io
- Checkout the Notebook examples in the examples folder
- Try ANDES in Jupyter Notebook with Binder
- Download the PDF manual at download

- Report issues in the GitHub issues page
- Learn version control with the command-line git or GitHub Desktop
- If you are looking to develop models, read the Modeling Cookbook

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ANDES is developed and actively maintained by Hantao Cui. See the GitHub repository for a full list of contributors.

1.2 Installation

1.2.1 New to Python

Setting Up Mambaforge

If you are new to Python and want to get started quickly, you can use Mambaforge, which is a conda-like package manager configured with conda-forge.

Step 1:

Downloaded the latest Mambaforge for your platform from https://github.com/conda-forge/miniforge#mambaforge. Most users will use `x86_64 (amd64)` for Intel and AMD processors. Mac users with Apple Silicon should use `arm64 (Apple Silicon)` for best performance.

Next, complete the Mambaforge installation on your system.

Note: Mambaforge is a drop-in replacement for conda. If you have an existing conda installation, you can replace all the following `mamba` commands with `conda` and achieve the same outcome.

If you are using Anaconda or Miniconda on Windows, you should open `Anaconda Prompt` instead of `Miniforge Prompt`.

Step 2:

Open Terminal (on Linux or macOS) or *Miniforge Prompt* (on Windows, **not cmd!!**). Make sure you are in a conda environment - you should see `(base)` prepended to the command-line prompt, such as `(base) C:\Users\username>`.

Create an environment for ANDES (recommended)

```
mamba create --name andes python=3.8
```

Activate the new environment with

```
mamba activate andes
```

Note: You will need to activate the `andes` environment every time in a new Miniforge Prompt or shell.

If you have completed these steps without error, you now have a working Python environment. See the commands at the top for *Getting started*.

1.2.2 Extra support package

Some ANDES features require extra support packages that are not installed by default. For example, to build the documentation, one will need to install development packages. Other packages will be required for interoperability.

The extra support packages are specified in groups. The following group names are supported, with descriptions given below:

- `dev`: packages to support development such as testing and documentation
- `interop`: packages to support interoperability of ANDES and other power systems tools.

Note: Extra support packages are not supported by conda/mamba installation. One needs to install ANDES with `pip`.

To install packages in the `dev` when installing ANDES, do:

```
pip install andes[dev]
```

To install all extra packages, do:

```
pip install andes[all]
```

One can also inspect the `requirements-extra.txt` to identify the packages for manual installation.

1.2.3 Develop Install

The development mode installation is for users who want to modify the code and, for example, develop new models or routines. The benefit of development mode installation is that changes to source code will be reflected immediately without re-installation.

Step 1: Get ANDES source code

As a developer, you are strongly encouraged to clone the source code using `git` from either your fork or the original repository. Clone the repository with

```
git clone https://github.com/cuihantao/andes
```

Note: Replace the URL with yours to use your fork. With `git`, you can later easily update the source code and perform version control.

Alternatively, you can download the ANDES source code from https://github.com/cuihantao/andes and extract all files to the path of your choice. Although works, this method is discouraged because tracking changes and pushing back code edits will require significant manual efforts.

Step 2: Install dependencies

In the Mambaforge environment, use `cd` to change directory to the ANDES root folder. The folder should contain the `setup.py` file.

Install dependencies with

```
mamba install --file requirements.txt
mamba install --file requirements-extra.txt
```

Alternatively, you can install them with `pip`:

```
pip install -r requirements.txt
pip install -r requirements-extra.txt
```

Step 3: Install ANDES in the development mode using

```
python3 -m pip install -e .
```

Note the dot at the end. Pip will take care of the rest.

Note: The ANDES version number shown in `pip list` will stuck at the version that was intalled, unless ANDES is develop-installed again. It will not update automatically with `git pull`.

To check the latest version number, check the preamble by running the `andes` command or chek the output of `python -c "import andes; print(andes.__version__)"`

Note: ANDES updates may infrequently introduce new package requirements. If you see an `ImportError` after updating ANDES, you can manually install the missing dependencies or redo *Step 2*.

Note: To install extra support packages, one can append `[NAME_OF_EXTRA]` to `pip install -e .`. For example, `pip install -e .[interop]` will install packages to support interoperability when installing ANDES in the development, editable mode.

1.2.4 Updating ANDES

Warning: If ANDES has been installed in the development mode using source code, you will need to use `git` or the manual approach to update the source code. In this case, Do not proceed with the following steps, as they will install a separate site-package installation on top of the development one.

Regular ANDES updates will be pushed to both `conda-forge` and Python package index. It is recommended to use the latest version for bug fixes and new features. We also recommended you to check the *Release notes* before updating to stay informed of changes that might break your downstream code.

Depending you how you installed ANDES, you will use one of the following ways to upgrade.

If you installed it from mamba or conda, run

```
conda install -c conda-forge --yes andes
```

If you install it from PyPI (namely, through `pip`), run

```
python3 -m pip install --yes andes
```

1.2.5 Uninstall Multiple Copies

A common mistake new users make is to have multiple copies of ANDES installed in the same environment. This can happen when one previously installed ANDES in the development mode but later ran `conda install` or `python3 -m pip install` to install the latest version. As a result, only the most recently installed version will be accessible.

In this case, we recommend that you uninstall all version and reinstall only one copy using your preferred mode. Uninstalling all copies can be done by calling `conda remove andes` and `python3 -m pip uninstall andes`. The prompted path will indicate the copy to be removed. One may need to run the two commands for a couple of time until the package managers indicate that the `andes` package can no longer be found.

1.2.6 Troubleshooting

If you get an error message on Windows, reading

```
ImportError: DLL load failed: The specified module could not be found.
```

It is a path issue of your Python. In fact, Python on Windows is so broken that many people are resorting to WSL2 just for Python. Fixes can be convoluted, but the easiest one is to install ANDES in a Conda/Mambaforge environment.

1.3 Tutorial

ANDES can be used as a command-line tool or a library. The command-line interface (CLI) comes in handy to run studies. As a library, it can be used interactively in the IPython shell or the Jupyter Notebook. This chapter describes the most common usages.

Please see the CLI cheatsheet if you are looking for quick help.

1.3.1 Command line

Basics

ANDES is invoked from the command line using the command `andes`. Running `andes` without any input is equal to `andes -h` or `andes --help`. It prints out a preamble with version and environment information, followed by and help commands

```
    _           _          | Version 1.6.0
   /_\  _ _  __| |___ ___  | Python 3.9.10 on Linux, 03/12/2022 10:30:44 AM
  / _ \| ' \/ _` / -_|_-<  |
 /_/ \_\_||_\__,_\___/__/  | This program comes with ABSOLUTELY NO WARRANTY.

usage: andes [-h] [-v {1,10,20,30,40}]
             {run,plot,doc,misc,prepare,prep,selftest,st,demo} ...

positional arguments:
{run,plot,doc,misc,prepare,prep,selftest,st,demo}
                        [run] run simulation routine; [plot] plot
                        results; [doc] quick documentation; [misc] misc.
                        functions; [prepare] prepare the numerical code;
                        [selftest] run self test;

optional arguments:
-h, --help            show this help message and exit
-v {1,10,20,30,40}, --verbose {1,10,20,30,40}
                        Verbosity level in 10-DEBUG, 20-INFO, 30-WARNING,
                        or 40-ERROR.
```

Note: If the `andes` command is not found, it could be due to

(1) missed steps in your installation process

(2) errors during installation

(3) forgot to activated the environment with ANDES

`andes` accepts an optional arugment to control verbosity level. It is done through `-v LEVEL` or `--verbose LEVEL`, where `level` is a number. Logging level by default is 20 (INFO) and can be chosen from:

- 1 (DEBUG with code location info)

- 10 (DEBUG)
- 20 (INFO)
- 30 (WARNING)
- 40 (ERROR)
- 50 (CRITICAL)

To show debugging outputs, use `andes -v 10`, followed by top-level commands. To only show warnings and errors, use `andes -v 30`.

The top-level commands are `{run,plot,doc,misc,prepare,selftest}`. Each command contains a group of subcommands, which can be looked up with `-h`. For example, use `andes run -h` to look up the subcommands for `andes run`. Frequently used commands are explained below.

Note: Some subcommands have shorthand names:

- `andes st` is equivalent to `andes selftest`
- `andes prep` is equivalent to `andes prepare`

---

andes selftest

After the installation, please run `andes selftest` from the command line to test ANDES functionality. It might take a minute to run the full self-test suite. An example output looks like

```
test_docs (test_1st_system.TestCodegen) ... ok
...
... (outputs are truncated)
...
test_pflow_mpc (test_pflow_matpower.TestMATPOWER) ... ok
----------------------------------------------------------------------
Ran 60 tests in 10.109s

OK
```

There may be more test than what is shown above. Make sure that all tests have passed.

ANDES receives frequent updates. After each update, please run `andes st` to confirm the functionality. The command also makes sure the generated code is up to date. See *andes prepare* for more details on automatic code generation.

Note: There is a quick mode to test ANDES by skipping code generation. This should only be used when you are certain that there is no modification to models between the last code generation and now.

The quick mode is invoked by `andes st -q`.

---

andes prepare

The symbolically defined models in ANDES need to be generated into numerical code for simulation. The code generation process is *automatic* the first time you use ANDES to run any case study. It takes 10 seconds to one minute to generate the code depending on your platform. When done, no code generation is needed in your future use untill you modify the models.

It is also possible to generate the code manually with `andes prepare` or `andes prep`. In addition, `andes selftest` automatically calls the code generation.

Note: Generated code files are stored in Python code in `$HOME/.andes/pycode`. While being human-readable, they are not human-friendly and should only be consulted during low-level debugging.

The default code generation mode is known as the "quick mode". It skips the generation of LaTeX-formatted equations, which are only useful in documentation and the interactive mode.

Option `-i` or `--incremental` can be used to speed up code generation during model development. `andes prepare -i` only generates code for models that are detected with changes since the last code generation.

> **Warning:** To developers:
>
> `andes prepare -i` needs to be called following model changes, such as equation modification and adding variables. Otherwise, due to mismatches in model and code, simulation results will not reflect the new changes, at best, or even lead to unexpected errors

ANDES supports precompiling the generated Python code using Numba. See *Numba compilation*. Numba needs to be installed separately. Check the version of installed numba and other dependencies with `andes misc --version`.

andes run

`andes run` is the entry point for power system analysis routines. The full list of options can be printed with `andes run -h`. `andes run` takes one positional argument, `filename`, along with other optional keyword arguments. `filename` is the path to cases, either relative or absolute.

- **Relative path**: `andes run kundur_full.xlsx`, e.g., uses a relative path. It works only if `kundur_full.xlsx` exists in the *working directory* of the command line.
- **Absolute path**: `andes run /Users/hcui7/kundur_full.xlsx` (on macOS) or `andes run C:/Users/hcui7/kundur_full.xlsx` (on Windows) use absolute paths to the case files. They do not depend on the command-line current directory.

Note: When working with the command line, use `cd` to change directory to the folder containing your test case. Spaces in folder and file names need to be escaped properly, so it's generally advised to *avoid spaces in file and folder names.*

To find out your current working directory, look for the line below the ANDES preamble that reads like

```
Working directory: "/home/hacui/repos/andes/andes/cases/kundur"
```

Input path

ANDES allows one to specify the path to look for the case file instead of the working directory. This is done by using the `-p` or `--input-path` option. For example, if `kundur_full.xlsx` is in folder `/home/hacui/cases`, one can do

```
andes run kundur_full.xlsx -p /home/hacui/cases
```

The argument passed to `-p` or `--input-path` can also be a relative path. If you need further help understanding paths, please consult other online articles.

Multiprocessing

ANDES takes multiple files inputs or wildcard. Multiprocessing will be triggered if more than one valid input files are passed to `filename`.

- Multiple files: to run the power flow for `kundur_full.xlsx` and `kundur_motor.xlsx` simultaneously, one can do

```
andes run kundur_full.xlsx kundur_motor.xlsx
```

The output will look like

```
Working directory: "/home/hacui/repos/andes/andes/cases/kundur"
-> Processing 2 jobs on 12 CPUs.
Process 0 for "kundur_full.xlsx" started.
Process 1 for "kundur_motor.xlsx" started.
Log saved to "/tmp/andes/andes-uopdutii/andes.log".
-> Multiprocessing finished in 2.4680 seconds.
```

- Wildcard: to run power flow for files with a prefix of `kundur_` and a suffix (file extension) of `.xlsx`, run

```
andes run kundur_*.xlsx
```

Case files with such name pattern, including `kundur_full.xlsx` and `kundur_motor.xlsx`, among others, will be processed.

Option `--ncpu NCPU` can be used to specify the maximum number of parallel processes. By default, all cores will be used. A small number can be specified to increase operating system responsiveness.

Routine

Option `-r` or `-routine` is used for specifying the analysis routine, followed by the routine name. Available routine names include

- `pflow` for power flow calculation
- `tds` for time domain simulation
- `eig` for eigenvalue analysis

If `-r` is not given, the power flow calculation routine will be called. There are routine specific options that can be passed to `andes run` and are discussed next.

Each routine has a list of configuration options (called "config") to control their behaviors. Config needs to be distinguished from command-line options as not all config options are available in the command-line. Refer to *Config* for details.

Power flow

Note: Examples in the following will utilize the `kundur_full.xlsx` test case. If you have cloned the ANDES repository, it can be found in `andes/cases/kundur` in the source code folder. You can also download it from here.

To run power flow, change to the directory containing `kundur_full.xlsx`, and execute the following in the command line:

```
andes run kundur_full.xlsx
```

Alternatively, the full path to the case file is also recognizable, such as

```
andes run /home/user/andes/cases/kundur/kundur_full.xlsx
```

The power flow report will be saved to the current directory where ANDES is invoked. The report contains four sections:

1) system statistics,
2) ac bus and dc node data
3) ac line data, and
4) results of other algebraic variables and state variables.

By default, the power flow routine is configured to use full Newton Raphson method, and reactive power limits are not checked. To change these config, edit the config file by referring to `andes doc PFlow` and `andes doc PV`.

Following power flow, ANDES does not initialize dynamic models to save time. When developing dynamic models, one can enable the initialization by setting in the config file

```
[PFlow]
init_tds = 1
```

Time-domain simulation

To run the time domain simulation (TDS) for `kundur_full.xlsx`, run

```
andes run kundur_full.xlsx -r tds
```

The output looks like:

```
Parsing input file "kundur_full.xlsx"...
Input file parsed in 0.1533 seconds.
System internal structure set up in 0.0174 seconds.
-> System connectivity check results:
No islanded bus detected.
System is interconnected.
Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
Sparse solver: KLU
Solution method: NR method
Numba compilation initiated with caching.
Power flow initialized in 0.1428 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745103977e-07
Converged in 5 iterations in 0.0014 seconds.
Report saved to "kundur_full_out.txt" in 0.0004 seconds.

-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
Numba compilation initiated with caching.
Initialization for dynamics completed in 0.0626 seconds.
Initialization was successful.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|########################################| 100/100 [00:00<00:00, 241.53%/
↪s]
Simulation completed in 0.4141 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0171 seconds.
-> Single process finished in 0.8890 seconds.
```

The output contains the key information for the simulation, such as solver name and step size. It prints out the disturbance information, the trip of Line `Line_8` at time `t=2.0 sec`.

There are a few places needing to be noted:

1. Make sure the power flow calculation is successful. Otherwise, there is no good starting point for dynamic simulation.
2. Make sure no suspect initialization error is found. Otherwise, the system will not be at steady state even before disturbances.

TDS writes two output files: a variable list file `kundur_full_out.lst`, and a compressed NumPy data file `kundur_full_out.npz`:

- List file: it is a plain-text file with three columns: variable indices, variable name in plain text, and variable name in the LaTeX format. The variable indices are needed to plot the needed variable.
- Data file: it is a zipped NumPy binary file. Although not directly editable, it can be used for plotting or can be converted to a CSV file. See the subsection on *andes plot*.

There are TDS-specific options that can be passed to `andes run`:

- `--tf TF`: the final time of the simulation. `TF` should be a number in seconds. By default, it is set to 20.0.
- `--addfile ADDFILE`: specify an additional data file. This is currently used to supply PSS/E dyr file in addition to a raw file.
- `--flat`: turn on "flat run" mode to ignore all disturbances. The simulation will be performed up to the end time.
- `--no-pbar`: turn off progress bar.
- `--from-csv FROM_CSV`: use data from a CSV file to perform mock simulation. The CSV file should be in the format of `andes plot --to-csv`.

Disable output

Output to files can be disabled with `--no-output` or `-n`. It is useful when computation is needed but results can be discarded. It is also useful when results are processed in memory, combined with the `--shell` option discussed next.

IPython shell

The ANDES CLI will exit to the system shell when finished running. It is sometimes useful to script in Python to quickly process the simulation results in memory, such as plotting. ANDES can exit to the IPython shell with `--shell` or `-s`. For example:

```
andes run kundur_full.xlsx -r tds -s -n
```

Note the `-n` is optional to disable file output. The terminal output will look like

```
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|########################################| 100/100 [00:00<00:00, 246.07%/
↪s]
Simulation completed in 0.4064 seconds.
```

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```
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0171 seconds.
-> Single process finished in 0.8796 seconds.
IPython: Access System object in variable `system`.
Python 3.9.10 | packaged by conda-forge | (main, Feb  1 2022, 21:24:11)
Type 'copyright', 'credits' or 'license' for more information
IPython 8.1.1 -- An enhanced Interactive Python. Type '?' for help.

In [1]:
```

A prompt will appear following `In [1]:` to indicate an IPython shell. If the test case file is parsed without error, the system object will be stored in variable `system`, i.e.

```
In [1]: system
Out[1]: <andes.system.System at 0x7fc1cd992790>
```

Python commands can be executed thereafter. To exit, type `exit` and press enter.

Format converter

ANDES uses the Excel format to store power system data in the ANDES semantics. In addition, multiple input formats are recognized and can be converted to the ANDES `xlsx` format. Converting data into the ANDES has pros and cons:

- Pros: - The data can be readily edited with an Excel-like tool - Data for models unique to ANDES can be readily added to the `xlsx` file
- Cons: - Conversion from ANDES `xlsx` back to the original format is not supported

---

Note: It is recommended to stay with the original data format to maximize compatibility when no ANDES-specific models are used.

Format conversion is done through `--convert FORMAT` or `-c FORMAT`, where `FORMAT` is the output format. For now, the following formats are supported:

- `xlsx`: an Excel spread sheet format with ANDES-specific data. It is not compatible with `xlsx` with datafrom other tools such as Pandapower.
- `json`: a JSON plain-text file with ANDES-specific data. Likewise, it is unlikely to be compatible with JSON from other power system tools. JSON is much faster to parse than `xlsx` but not as friendly to edit.

To convert `kundur_full.xlsx`, for example, to the `json` format, run

```
andes run kundur_full.xlsx --convert json
```

The output messages will look like

```
Parsing input file "kundur_full.xlsx"...
Input file parsed in 0.1576 seconds.
System internal structure set up in 0.0175 seconds.
JSON file written to "kundur_full.json"
Format conversion completed in 0.0053 seconds.
-> Single process finished in 0.2582 seconds.
```

Note that `--convert` will only create sheets for existing models.

The converter works with any input formats that are currently supported. These include:

- `.m`: MATPOWER case file
- `.raw` and `.dyr`: PSS/E raw and dyr files
- `.xlsx`: Excel spreadsheet file with ANDES data
- `.json`: JSON plain-text file with ANDES data

PSS/E inputs

To work with PSS/E input files (.raw and .dyr), one need to provide the raw file through `casefile` and pass the dyr file through `--addfile`. For example, in `andes/cases/kundur`, one can run the power flow using

```
andes run kundur.raw
```

and run a no-disturbance time-domain simulation using

```
andes run kundur.raw --addfile kundur_full.dyr -r tds
```

Note: If one wants to modify the parameters of models that are supported by both PSS/E and ANDES, one can directly edit those dynamic parameters in the `.raw` and `.dyr` files to maintain interoperability with other tools.

To create add a disturbance, there are two options. The recommended option is to convert the PSS/E data into an ANDES xlsx file, edit it and run (see the previous subsection). The alternative approach is documented in *Creating disturbances*.

Profiling

Profiling is useful for analyzing the computation time and code efficiency. Option `--profile` enables the profiling of ANDES execution. The profiling output will be written in two files in the current folder, one ending with `_prof.txt` and the other one with `_prof.prof`.

The text file can be opened with a text editor, and the `.prof` file can be visualized with `snakeviz`, which can be installed with `pip install snakeviz`.

If the output is disabled, profiling results will be printed to stdio.

andes plot

`andes plot` is the command-line tool for plotting. It currently supports time-domain simulation data. Three positional arguments are required, and a dozen of optional arguments are supported.

positional arguments:

Argument	Description
filename	simulation output file name, which should end with *out*. File extension can be omitted.
x	the X-axis variable index, typically 0 for Time
y	Y-axis variable indices. Space-separated indices or a colon-separated range is accepted

For the list of optional arguments, see the output of `andes plot -h`.

To plot the generator speed variable `omega` of GENROU_1 `omega GENROU 1` versus time, one way is to supply the variable indices found in the `.lst` output file. The index of the variable `omega GENROU 1` is found to be `5`, and Time is found to be `0`, so the plot command should be

```
andes plot kundur_full_out.lst 0 5
```

where `kundur_full_out.lst` is list file name, `0` is the index of `Time` for the x-axis, and `5` is the index of `omega GENROU 1`. Note that for the the file name, either `kundur_full_out.lst` or `kundur_full_out.npz` works as the program will automatically extract the file name.

The y-axis variable indices can also be specified as a Python range. For example, `andes plot kundur_full_out.npz 0 2:21:6` will plot the variables with indices 2, 8, 14 and 20.

It can become tedious to look up the indices of variables in the `.lst` file. `andes plot` supports `--xargs` or `-a` for searching for variable indices and passing them as arguments to `andes plot`. See Examples - "Using CLI from Notebook".

LaTeX rendering

`andes plot` will attempt to render with LaTeX if `dvipng` program is in the search path. Figures rendered by LaTeX has publication-quality aesthetics for symbols but takes considerably longer time. In case LaTeX is available but fails (frequently happens on Windows), the option `-d` can be used to disable LaTeX rendering.

andes doc

`andes doc` is a handy tool to look up model, routine and config documentation. Model documentation include the descriptions of parameters, variables, and configs. A pretty-print version is available online in *Model reference*.

The basic usage of `andes doc` is to provide a model name or a routine name as the positional argument. For a model, it will print out model parameters, variables, and equations to the stdio. For a routine, it will print out fields in the Config file.

Note: For full model documentation, visit *Model reference*.

For example, to check the parameters for model `Toggle`, run

```
$ andes doc Toggle
Model <Toggle> in Group <TimedEvent>

    Time-based connectivity status toggle.

Parameters

 Name  |         Description          | Default | Unit |    Type    |␣
↪Properties
-------+------------------------------+---------+------+------------+---------
↪--
 u     | connection status            | 1       | bool | NumParam   |
 name  | device name                  |         |      | DataParam  |
 model | Model or Group of the device |         |      | DataParam  |␣
↪mandatory
       | to control                   |         |      |            |
 dev   | idx of the device to control |         |      | IdxParam   |␣
↪mandatory
 t     | switch time for connection   | -1      |      | TimerParam |␣
↪mandatory
       | status                       |         |      |            |
```

To list all supported models, run

```
$ andes doc -l
Supported Groups and Models

     Group       |                   Models
-----------------+-------------------------------------------
 ACLine          | Line
 ACTopology      | Bus
 Collection      | Area
 DCLink          | Ground, R, L, C, RCp, RCs, RLs, RLCs, RLCp
 DCTopology      | Node
 Exciter         | EXDC2
 Experimental    | PI2
 FreqMeasurement | BusFreq, BusROCOF
```

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```
 StaticACDC       | VSCShunt
 StaticGen        | PV, Slack
 StaticLoad       | PQ
 StaticShunt      | Shunt
 SynGen           | GENCLS, GENROU
 TimedEvent       | Toggle, Fault
 TurbineGov       | TG2, TGOV1
```

To view the Config fields for a routine, run

```
$ andes doc TDS
Config Fields in [TDS]

  Option    | Value |                  Info                   | Acceptable␣
↪values
------------+-------+-----------------------------------------+-----------------
↪--
 sparselib | klu   | linear sparse solver name               | ('klu', 'umfpack
↪')
 tol        | 0.000 | convergence tolerance                   | float
 t0         | 0     | simulation starting time                | >=0
 tf         | 20    | simulation ending time                  | >t0
 fixt       | 0     | use fixed step size (1) or variable     | (0, 1)
            |       | (0)                                     |
 shrinkt    | 1     | shrink step size for fixed method if    | (0, 1)
            |       | not converged                           |
 tstep      | 0.010 | the initial step step size              | float
 max_iter   | 15    | maximum number of iterations            | >=10
```

andes misc

`andes misc` contains miscellaneous functions, such as configuration and output cleaning.

Configuration

ANDES uses a configuration file to set runtime configs for the system routines, and models. `andes misc --save-config` saves all configs to a file. By default, it saves to `$HOME/.andes/andes.conf` file, where `$HOME` is the path to your home directory.

With `andes misc --edit-config`, you can edit ANDES configuration handy. The command will automatically save the configuration to the default location if not exist. The shorter version `--edit` can be used instead as Python matches it with `--edit-config`.

You can pass an editor name to `--edit`, such as `--edit vim`. If the editor name is not provided, it will use the following defaults: - Microsoft Windows: notepad. - GNU/Linux: the `$EDITOR` environment variable, or `vim` if not exist.

For macOS users, the default is vim. If not familiar with vim, you can use nano with `--edit nano` or TextEdit with `--edit "open -a TextEdit"`.

Cleanup

`andes misc -C, --clean`

Option to remove any generated files. Removes files with any of the following suffix: `_out.txt` (power flow report), `_out.npy` (time domain data), `_out.lst` (time domain variable list), and `_eig.txt` (eigenvalue report).

Version

Check the version of ANDES and the core packages it uses, use

```
andes misc --version
```

Please include the output in your bug report.

1.3.2 Scripting

This section is a tutorial for using ANDES in an interactive/scripting environment. All scripting shells are supported, including Python shell, IPython, Jupyter Notebook, and Jupyter Lab. The examples below use Jupyter Notebook.

Jupyter Notebook

Jupyter Notebook is a convenient tool to run Python code and present results. Jupyter Notebook can be installed with

```
conda install jupyter notebook
```

After the installation, change the directory to the folder where you wish to store notebooks, then start the notebook with

```
jupyter notebook
```

A browser window should open automatically with the notebook browser loaded. To create a new notebook, use the "New" button near the upper-right corner.

Note: In the following, code blocks starting with >>> are Python code and should be executed inside Python, IPython, or Jupyter Notebook. Python code should not be entered into Anaconda Prompt or Linux shell.

Import

Like other Python libraries, ANDES needs to be imported into an interactive scripting Python environment.

```
>>> import andes
>>> andes.config_logger()
```

Verbosity

If you are debugging ANDES, you can enable debug messages with

```
>>> andes.config_logger(stream_level=10)
```

or simply

```
>>> andes.config_logger(10)
```

The `stream_level` uses the same verbosity levels as for the command line. If not explicitly enabled, the default level 20 (INFO) will apply.

To set a new logging level for the current session, call `config_logger` with the desired new levels.

Making a System

Before running studies, an *andes.system.System* object needs to be created to hold the system data. The System object can be created by passing the path to the case file to the entry-point function.

There are multiple ways to create the System object. Among them, *andes.main.run* is the most convenient way. For example, to run the file `kundur_full.xlsx` in the same directory as the notebook, use

```
>>> ss = andes.run('kundur_full.xlsx')
```

This function will parse the input file, run the power flow, and return the system as an object. Outputs will look like

```
Parsing input file </Users/user/notebooks/kundur/kundur_full.xlsx>
Input file kundur_full.xlsx parsed in 0.4172 second.
-> Power flow calculation with Newton Raphson method:
0: |F(x)| = 14.9283
1: |F(x)| = 3.60859
2: |F(x)| = 0.170093
3: |F(x)| = 0.00203827
4: |F(x)| = 3.76414e-07
Converged in 5 iterations in 0.0222 second.
Report saved to </Users/user/notebooks/kundur_full_out.txt> in 0.0015 second.
-> Single process finished in 0.4677 second.
```

In this example, `ss` is an instance of `andes.System`. It contains member attributes for models, routines, and numerical DAE.

The naming convention for the `System` attributes is as follows

- Model attributes share the same name as class names. For example, `ss.Bus` is the `Bus` instance, and `ss.GENROU` is the `GENROU` instance.
- Routine attributes share the same name as class names. For example, `ss.PFlow` and `ss.TDS` are the routine instances.
- The numerical DAE instance is in lower case `ss.dae`.

To work with PSS/E inputs, refer to *Examples* - "Working with Data".

Note: *andes.main.run* can accept multiple input files for multiprocessing. They can be passed as a list of strings to the first positional argument.

Passing options

`andes.run()` can accept options that are available to the command-line `andes run`. Options need to be passed as keyword arguments to `andes.run()` in addition to the positional argument for the test case. For example, setting `no_output` to `True` will disable all file outputs. When scripting, one can do

```
>>> ss = andes.run('kundur_full.xlsx', no_output=True)
```

which is equivalent to the following shell command:

```
andes run kundur_full.xlsx --no-output
```

Please note that the dash between `no` and `output` needs to be replaced with an underscore for scripting. This is the convention in Python's argument parser.

Another example is to specify a folder for output files. By default, outputs will be saved to the folder where Python is run (or where the notebook is run). In case you need to organize outputs, a path prefix can be passed to `andes.run()` through `output_path`:

```
>>> ss = andes.run('kundur_full.xlsx', output_path='outputs/')
```

which will put outputs into folder `outputs` relative to the current path. You can also supply an absolute path to `output_path`.

The next example is to specify the simulation time for a time-domain simulation. There are multiple ways to implement it (see *Examples*), and one way is to pass the end time (in sec) through argument `tf` and set the `routine` to `tds`:

```
>>> ss = andes.run('kundur_full.xlsx', routine='tds', tf=5)
```

which will set the simulation time to 5 seconds.

Note: While `andes run` accepts single-letter alias for the option, such as `andes run -n` for `andes run --no-output`, `andes.run()` can only work with the full option name (with hyphen replaced by

underscore)

Load Only

In many workflows, one will simulate many scenarios with largely identical system data. A base case can be loaded and modified to create scenarios in memory. See Example "Working with Data" for details

Inspecting Parameter

DataFrame

Parameters for the loaded system can be readily inspected in Jupyter Notebook using Pandas.

Parameters for a model instance can be retrieved in a DataFrame using the `as_df()` method on the model instance. For example, to view the parameters of `Bus`, use

```
>>> ss.Bus.as_df()
```

A table will be printed with the columns being parameters and the rows being Bus devices/instances. For a system that has been setup, parameters have been converted to per unit values in the system base specified by `ss.config.mva`. The per-unit values in the system base will be used in computation as all computation in ANDES uses system-base per-unit data.

To view the original input values, use the `as_df(vin=True)` method. For example, to view the system-base per unit value of `GENROU`, use

```
>>> ss.GENROU.as_df(vin=True)
```

Parameter in the table is the same as that in the input file without any conversion. Some input data, by convention, are given as per unit in the device base; see *Per Unit System* for details.

Note that `andes.core.modeldata.ModelData.as_df()` returns a *view*. Modifying the returned dataframe *will not* affect the original data used for simulation. To modify the data, see Example "Working with Data".

Running Studies

Three routines are currently supported: PFlow, TDS and EIG. Each routine provides a `run()` method to execute. The System instance contains member attributes having the same names. For example, to run the time-domain simulation for `ss`, use

```
>>> ss.TDS.run()
```

To change configuration for routines, one can set the attribute before calling run. For example, to change the end time to 5 sec, one can do

```
>>> ss.TDS.config.tf = 5
>>> ss.TDS.run()
```

Note that not all config changes are respected. Some config values are used while creating the routine instance. For config changes that does not necessarily have to be done on-the-fly, it is recommended to edit the config file.

Checking Exit Code

`andes.System` contains field `exit_code` for checking if error occurred in run time. A normal completion without error should always have `exit_code == 0`. One should read output messages carefully and check the exit code, which is particularly useful for batch simulations.

Error may occur in any phase - data parsing, power flow, or simulation. To diagnose, split the simulation steps and check the outputs from each one.

Plotting TDS Results

TDS comes with a plotting utility for scripting usage. After running the simulation, a `plotter` attributed will be created for `TDS`. To use the plotter, provide the attribute instance of the variable to plot. For example, to plot all the generator speed, use

```
>>> ss.TDS.plotter.plot(ss.GENROU.omega)
```

Note: If you see the error

> AttributeError: 'NoneType' object has no attribute 'plot'

You will need to manually load plotter with

```
>>> ss.TDS.load_plotter()
```

Optional indices is accepted to choose the specific elements to plot. It can be passed as a tuple through the `a` argument

```
>>> ss.TDS.plotter.plot(ss.GENROU.omega, a=(0, ))
```

In the above example, the speed of the "zero-th" generator will be plotted.

Scaling

A lambda function can be passed to argument `ycalc` to scale the values. This is useful to convert a per-unit variable to nominal. For example, to plot generator speed in Hertz, use

```
>>> ss.TDS.plotter.plot(ss.GENROU.omega, a=(0, ),
                        ycalc=lambda x: 60*x,
                        )
```

Formatting

A few formatting arguments are supported:

- `grid = True` to turn on grid display
- `greyscale = True` to switch to greyscale
- `ylabel` takes a string for the y-axis label

Extracting Data

One can extract data from ANDES for custom plotting. Variable names can be extracted from the following fields of `ss.dae`:

Un-formatted names (non-LaTeX):

- `x_name`: state variable names
- `y_name`: algebraic variable names
- `xy_name`: state variable names followed by algebraic ones

LaTeX-formatted names:

- `x_tex_name`: state variable names
- `y_tex_name`: algebraic variable names
- `xy_tex_name`: state variable names followed by algebraic ones

These lists only contain the variable names used in the current analysis routine. If you only ran power flow, `ss.dae.y_name` will only contain the power flow algebraic variables, and `ss.dae.x_name` will likely be empty. After initializing time-domain simulation, these lists will be extended to include all variables used by TDS.

In case you want to extract the discontinuous flags from TDS, you can set `store_z` to `1` in the config file under section `[TDS]`. When enabled, discontinuous flag names will be populated at

- `ss.dae.z_name`: discontinuous flag names
- `ss.dae.z_tex_name`: LaTeX-formatted discontinuous flag names

If not enabled, both lists will be empty.

Power flow solutions

The full power flow solutions are stored at `ss.dae.xy` after running power flow (and before initializing dynamic models). You can extract values from `ss.dae.xy`, which corresponds to the names in `ss.dae.xy_name` or `ss.dae.xy_tex_name`.

If you want to extract variables from a particular model, for example, bus voltages, you can directly access the `v` field of that variable

```
>>> import numpy as np
>>> voltages = np.array(ss.Bus.v.v)
```

which stores a **copy** of the bus voltage values. Note that the first `v` is the voltage variable of `Bus`, and the second `v` stands for *value*. It is important to make a copy by using `np.array()` to avoid accidental changes to the solutions.

If you want to extract bus voltage phase angles, do

```
>>> angle = np.array(ss.Bus.a.v)
```

where `a` is the field name for voltage angle.

To find out names of variables in a model, use command `andes doc` or refer to *Model reference*.

Time-domain data

Time-domain simulation data will be ready when simulation completes. It is stored in `ss.dae.ts`, which has the following fields:

- `txyz`: a two-dimensional array. The first column is time stamps, and the following are variables. Each row contains all variables for that time step.
- `t`: all time stamps.
- `x`: all state variables (one column per variable).
- `y`: all algebraic variables (one column per variable).
- `z`: all discontinuous flags (if enabled, one column per flag).

If you want the output in pandas DataFrame, call

```
ss.dae.ts.unpack(df=True)
```

Dataframes are stored in the following fields of `ss.dae.ts`:

- `df`: dataframe for states and algebraic variables
- `df_z`: dataframe for discontinuous flags (if enabled)

For both dataframes, time is the index column, and each column correspond to one variable.

Note: Looking to extract data for a single variable? See *Examples* - "Working with Data".

Pretty Print of Equations

Each ANDES models offers pretty print of LaTeX-formatted equations in the jupyter notebook environment.

To use this feature, symbolic equations need to be generated in the current session using

```
import andes ss = andes.System() ss.prepare()
```

Or, more concisely, one can do

```
import andes ss = andes.prepare()
```

This process may take a few minutes to complete. To save time, you can selectively generate it only for interested models. For example, to generate for the classical generator model `GENCLS`, do

```
import andes ss = andes.System() ss.GENROU.prepare()
```

Once done, equations can be viewed by accessing `ss.<ModelName>.syms.<PrintName>`, where `<ModelName>` is the model name, and `<PrintName>` is the equation or Jacobian name.

Note: Pretty print only works for the particular `System` instance whose `prepare()` method is called. In the above example, pretty print only works for `ss` after calling `prepare()`.

Supported equation names include the following:

- `xy`: variables in the order of *State*, *ExtState*, *Algeb* and *ExtAlgeb*
- `f`: the **right-hand side of** differential equations $\mathbf{M}\dot{\mathbf{x}} = \mathbf{f}$
- `g`: implicit algebraic equations $0 = \mathbf{g}$
- `df`: derivatives of `f` over all variables `xy`
- `dg`: derivatives of `g` over all variables `xy`
- `s`: the value equations for *ConstService*

For example, to print the algebraic equations of model `GENCLS`, one can use `ss.GENCLS.syms.g`.

Finding Help

docstring

To find out how a Python class, method, or function should be used, use the built-in `help()` function. This will print out the docstring of the class/method/function. For example, to check how the `get` method of `GENROU` should be called, do

```
help(ss.GENROU.get)
```

In Jupyter notebook, this can be simplified into `?ss.GENROU.get` or `ss.GENROU.get?`.

Please report issues if you find missing docstring.

Model docs

Model docs can be shown by printing the return of `doc()`. For example, to check the docs of `GENCLS`, do

```
print(ss.GENCLS.doc())
```

It is the same as calling `andes doc GENCLS` from the command line. Likewise, a pretty-print version is available online in *Model reference*.

1.3.3 Cheatsheet

A cheatsheet is available for quick lookup of supported commands.

View the PDF version at

https://www.cheatography.com//cuihantao/cheat-sheets/andes-for-power-system-simulation/pdf/

1.3.4 Documentation

The documentation you are viewing can be made locally in a variety of formats. To make HTML documentation, change directory to `docs`, and do

```
make html
```

After a few minutes, HTML documentation will be saved to `docs/build/html` with the index page being `index.html`. You can use Python to serve it locally. In the folder `docs/build/html`, run

```
python -m http.server
```

A list of supported formats is as follows. Note that some format require additional compiler or library

```
html         to make standalone HTML files
dirhtml      to make HTML files named index.html in directories
singlehtml   to make a single large HTML file
pickle       to make pickle files
json         to make JSON files
htmlhelp     to make HTML files and an HTML help project
qthelp       to make HTML files and a qthelp project
devhelp      to make HTML files and a Devhelp project
epub         to make an epub
latex        to make LaTeX files, you can set PAPER=a4 or PAPER=letter
latexpdf     to make LaTeX and PDF files (default pdflatex)
latexpdfja   to make LaTeX files and run them through platex/dvipdfmx
text         to make text files
man          to make manual pages
texinfo      to make Texinfo files
info         to make Texinfo files and run them through makeinfo
gettext      to make PO message catalogs
changes      to make an overview of all changed/added/deprecated items
xml          to make Docutils-native XML files
pseudoxml    to make pseudoxml-XML files for display purposes
linkcheck    to check all external links for integrity
doctest      to run all doctests embedded in the documentation (if enabled)
coverage     to run coverage check of the documentation (if enabled)
```

1.4 Config

ANDES uses a config file to store the various options for routines and models. As discussed in *andes misc*, the config file is at `$HOME/.andes/andes.rc`. The reference for the config fields can be found in *Config reference*.

1.4.1 Format

The ANDES config file uses the format provided by Python module `configparser`. The syntax is like the following:

```
[System]
freq = 60
mva = 100
...

[PFlow]
sparselib = klu
linsolve = 0
tol = 1e-6
...

[TGOV1]
allow_adjust = 1
```

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```
adjust_lower = 0
adjust_upper = 1
```

In the above, `System`, `PFlow` and `TGOV1` are two sections. `freq = 60`, for example, is a pair of option and value in the `[System]` section. Note the space before and after the equal sign.

The meaning of the fields in each section can be found in *Config reference*, which contains the default values and acceptable values for each option. The values for config fields can be a string or a number. Fields with acceptable values being `(0, 1)` can only accept `0` or `1` to indicate true or false. Non-binary values for such options will cause unexpected errors in the program.

Limits in models

All models have three config options:

- `allow_adjust`: allow limits of limiters in this model to be adjusted if the inputs, at steady state, is out of the limits. `allow_adjust = 0` is the global off-switch for this model.
- `adjust_lower`: allow reducing the lower limit to the input value, if the input at steady-state is below the lower limit. This is disabled by default.
- `adjust_upper`: allow increasing the upper limit to the steady-state input. This is enabled by default.

Note that setting `allow_adjust = 0` is equal to setting `adjust_lower = 0` and `adjust_upper = 0`, but the former saves some time for function calls.

The limit adjustment feature is to alleviate issues caused by the model parameters. Commercial tools have a more sophisticated mechanism for autocorrection, and the limit adjustment is part of it. However, if you see an limit adjustment warning or even initialization error, it is important not to rely on autocorrection but fix the data by yourself. Autocorrected data can yield some results but issues can remain hidden.

1.4.2 Adjusting on the fly

CLI

One can adjust config on the fly *in command line* without modifying or even storing the config file. This is useful when the config change is one-time or ANDES CLI is stored in a read-only container. The config update is done by `andes run --config-option SECTION.OPTION=VALUE`, where `SECTION` is the section name, `OPTION` is the option name, and `VALUE` is the new value. *No space is allowed* around `.` and `=`.

For example, to solve `kundur_full.json` with reactive power limit enforced, one can do:

```
andes run kundur_full.json -O PV.pv2pq=1
```

where `-O` is the shorhand command for `--config-option`, and the enabled `pv2pq` will allow PV to be converted to PQ once reactive power limit is hit.

Multiple config updates can be passed simultaneously, separated by *space*. For example, to enable reactive power limit and switch the power flow solver to UMFPACK, do:

```
andes run kundur_full.json -O PV.pv2pq=1 PFlow.sparselib=umfpack
```

Scripting

To adjust config on the fly when scripting, there are two cases:

- Update the config when creating a new System object
- Update the config for an existing System object

To update the config when creating a new System object, one can pass a list of strings to `config_option` for *andes.main.run*:

```
>>> ss = andes.run("kundur_full.json", config_option=["PV.pv2pq=1"])
```

which directly calls the backend API for the CLI. To update multiple configs, one can do

```
>>> ss = andes.run("kundur_full.json",
                   config_option=["PV.pv2pq=1", "PFlow.sparselib=umfpack"])
```

When the System object gets created, the config values will be distributed to member attributes of the System object. Therefore, the config for a System object `ss` is stored in `ss.config`, and the config for the power flow routine is stored in `ss.PFlow.config`.

To update the config for an existing system, one can directly access the `config` attribute and set the new value. To set a new simulation end time, one can overwrite the `ss.TDS.config.tf` field, such as:

```
# load system and run power flow
>>> ss = andes.run("kundur_full.json")
>>> ss.TDS.config.tf = 5.0
>>> ss.TDS.run()
```

Warning: Not all config options can be updated on the fly. Those config that are used for constructing the system object can only be updated when creating a new System object.

1.4.3 Config reference

System

Option	Value	Info	Accepted values
freq	60	base frequency [Hz]	float
mva	100	system base MVA	float
ipadd	1	use spmatrix.ipadd if available	(0, 1)
seed	None	seed (or None) for random number generator	int or None
diag_eps	0.000	small value for Jacobian diagonals	
warn_limits	1	warn variables initialized at limits	(0, 1)
warn_abnormal	1	warn initialization out of normal values	(0, 1)
dime_enabled	0		
dime_name	andes		
dime_address	ipc:///tmp/dime		
numba	0	use numba for JIT compilation	(0, 1)
numba_parallel	0	enable parallel for numba.jit	(0, 1)
numba_nopyth	1	nopython mode for numba	(0, 1)
yapf_pycode	0	format generated code with yapf	(0, 1)
save_stats	0	store statistics of function calls	(0, 1)
np_divide	warn	treatment for division by zero	{'warn', 'call', 'log', 'print', 'ignore', 'raise'}
np_invalid	warn	treatment for invalid floating-point ops.	{'warn', 'call', 'log', 'print', 'ignore', 'raise'}

PFlow

Option	Value	Info	Accepted values
sparselib	klu	linear sparse solver name	('klu', 'umfpack', 'spsolve', 'cupy')
linsolve	0	solve symbolic factorization each step (enable when KLU segfaults)	(0, 1)
tol	0.000	convergence tolerance	float
max_iter	25	max. number of iterations	>=10
method	NR	calculation method	('NR', 'dishonest', 'NK')
check_con	1	check connectivity before power flow	(0, 1)
n_factorize	4	first N iterations to factorize Jacobian in dishonest method	>0
report	1	write output report	(0, 1)
degree	0	use degree in report	(0, 1)
init_tds	0	initialize TDS after PFlow	(0, 1)

TDS

Option	Value	Info	Accepted values
sparselib	klu	linear sparse solver name	('klu', 'umfpack', 'spsolve',
linsolve	0	solve symbolic factorization each step (enable when KLU segfaults)	(0, 1)
method	trapezoid	DAE solution method	('trapezoid', 'backeuler')
tol	0.000	convergence tolerance	float
t0	0	simulation starting time	>=0
tf	20	simulation ending time	>t0
fixt	1	use fixed step size (1) or variable (0)	(0, 1)
shrinkt	1	shrink step size for fixed method if not converged	(0, 1)
honest	0	honest Newton method that updates Jac at each step	(0, 1)
tstep	0.033	integration step size	float
max_iter	15	maximum number of iterations	>=10
refresh_event	0	refresh events at each step	(0, 1)
test_init	1	test if initialization passes	(0, 1)
check_conn	1	re-check connectivity after event	(0, 1)
criteria	1	use criteria to stop simulation if unstable	(0, 1)
ddelta_limit	180	delta diff. limit to be considered unstable, in degree	
g_scale	1	scale algebraic residuals with time step size	positive
reset_tiny	1	reset tiny residuals to zero to avoid chattering	(0, 1)
qrt	0	quasi-real-time stepping	(0, 1)
kqrt	1	quasi-real-time scaling factor; kqrt > 1 means slowing down	positive
store_z	0	store limiter status in TDS output	(0, 1)
store_f	0	store RHS of diff. equations	(0, 1)
store_h	0	store RHS of external diff. equations	(0, 1)
store_i	0	store RHS of external algeb. equations	(0, 1)
limit_store	0	limit in-memory timeseries storage	(0, 1)
max_store	900	maximum steps of data stored in memory before offloading	positive integer
save_every	1	save one step to memory every N simulation steps	integer
save_mode	auto	automatically or manually save output data when done	('auto', 'manual')
no_tqdm	0	disable tqdm progressbar and outputs	(0, 1)
chatter_iter	4	minimum iterations to detect chattering	int>=4

EIG

Option	Value	Info	Accepted values
sparselib	klu	linear sparse solver name	('klu', 'umfpack', 'spsolve', 'cupy')
linsolve	0	solve symbolic factorization each step (enable when KLU segfaults)	(0, 1)
plot	0	show plot after computation	(0, 1)
tol	0.000	numerical tolerance to treat eigenvalues as zeros	

1.5 Input formats

ANDES currently supports the following input formats:

- `.xlsx`: Excel spreadsheet file with ANDES data
- `.raw` and `.dyr`: PSS/E RAW and DYR formats
- `.m`: MATPOWER format
- `.json`: JSON plain-text format with ANDES data

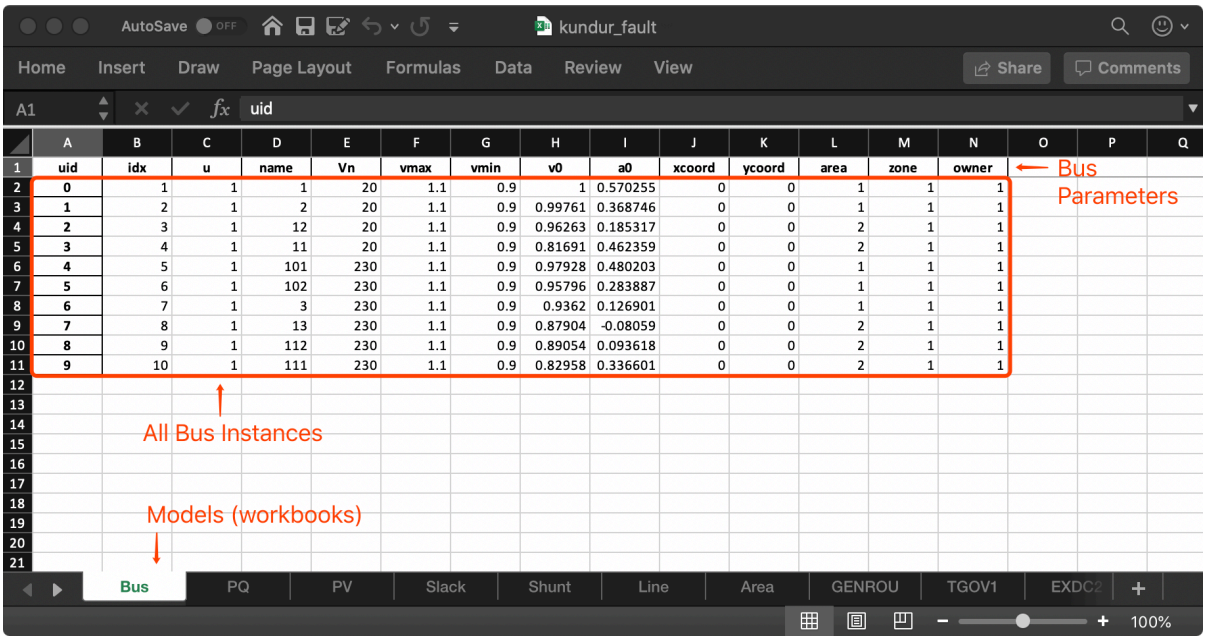
1.5.1 ANDES xlsx

The ANDES xlsx format allows one to use Excel for convenient viewing and editing. If you do not use Excel, there are alternatives such as the free and open-source LibreOffice.

Format definition

The ANDES xlsx format contains multiple workbooks (also known as "sheets") shown as tabs at the bottom. The name of a workbook is a *model* name, and each workbook contains the parameters of all *devices* that are *instances* of the model.

In each sheet, the first row contains the names of parameters of the model. Starting from the second row, each row corresponds to a *device instance* with the parameters in the corresponding columns. An example of the `Bus` sheet is shown in the following screenshot.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	uid	idx	u	name	Vn	vmax	vmin	v0	a0	xcoord	ycoord	area	zone	owner
2	0	1	1	1	20	1.1	0.9	1	0.570255	0	0	1	1	1
3	1	2	1	2	20	1.1	0.9	0.99761	0.368746	0	0	1	1	1
4	2	3	1	12	20	1.1	0.9	0.96263	0.185317	0	0	2	1	1
5	3	4	1	11	20	1.1	0.9	0.81691	0.462359	0	0	2	1	1
6	4	5	1	101	230	1.1	0.9	0.97928	0.480203	0	0	1	1	1
7	5	6	1	102	230	1.1	0.9	0.95796	0.283887	0	0	1	1	1
8	6	7	1	3	230	1.1	0.9	0.9362	0.126901	0	0	1	1	1
9	7	8	1	13	230	1.1	0.9	0.87904	-0.08059	0	0	2	1	1
10	8	9	1	112	230	1.1	0.9	0.89054	0.093618	0	0	2	1	1
11	9	10	1	111	230	1.1	0.9	0.82958	0.336601	0	0	2	1	1

Common parameters

A few columns are used across all models. That includes `uid`, `idx`, `name` and `u`:

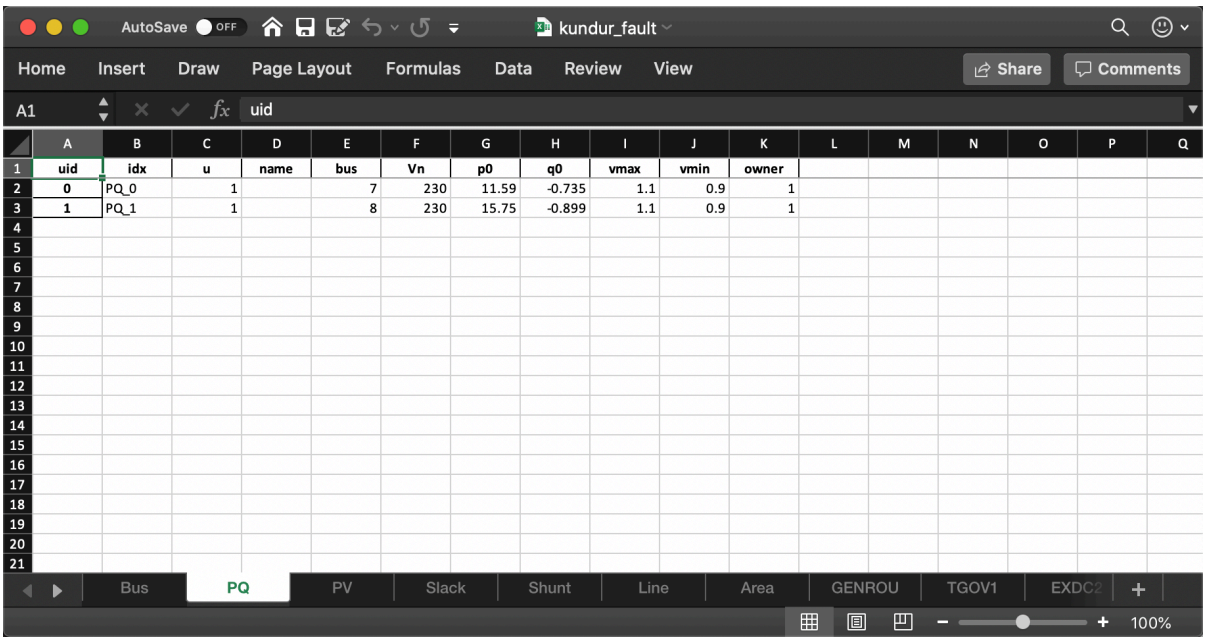
- `uid` is an unique index that is generated and used *internally*. This column can be left empty when the sheet is being created manually. Exporting systems to `xlsx` with `--convert` (see *Format converter*) will have the `uid` overwritten.
- `idx` is the *unique index to identify a device* of the model. An unique `idx` should be provided explicitly for each instance for best consistency. Accepted types for `idx` include numbers and strings without spaces.

Warning: ANDES will check the uniqueness of `idx` and assign new ones when duplication is detected. Duplicate `idx` indicates data inconsistency and will likely cause simulations to fail.

- `u` is the connectivity status of the instance. Accepted values are 0 for disconnected (turned off) and 1 for connected (turned on). Disconnected devices will still have the variables assigned in ANDES but will not interact with the simulation. Unexpected behaviors may occur if numerical values other than 0 and 1 are assigned, as `u` is often used as a multiplier in equations.
- `name` is the name for the device instance. It is used for display purposes and can be left empty.

Connecting devices

Most importantly, `idx` is the *unique* index for referencing a device, so that it can be properly connected by supported devices. In a system, a PQ (constant PQ load) device needs to connect to a Bus device to inject power. That is, the PQ device needs to indicate the Bus device to which it is connected. Such connection is done in the `PQ` sheet by setting the `bus` parameter to the `idx` of the connected bus.



	A	B	C	D	E	F	G	H	I	J	K
1	uid	idx	u	name	bus	Vn	p0	q0	vmax	vmin	owner
2	0	PQ_0	1		7	230	11.59	-0.735	1.1	0.9	1
3	1	PQ_1	1		8	230	15.75	-0.899	1.1	0.9	1

The screenshot above is from the case file `andes/cases/kundur/kundur_fault.xlsx`. In this `PQ` workbook, there are two PQ instances (also known as "devices") called `PQ_0` and `PQ_1` (referred to by `idx`). They are connected to buses `7` and `8`, respectively. The `bus` parameter of `PQ` is konwn as an indexing parameter (*`andes.core.param.IdxParam`*) through which the connections are specified. To get the connection actually work, on the `Bus` sheet, two rows must exist for two bus devices, respectively, with `idx` being `7` and `8`.

To find out the IdxParams of a device for connecting to other devices, refer to *Model reference*. For example, to find out how a device of the exciter model *EXDC2* should be connected to a synchronous generator, in the **Parameters** section, check the *Properties* column for *mandatory* parameters. Almost all IdxParams are mandatory, meaning that they must be specified to build a consistent test case. It can be seen that for *EXDC2*, `syn` is mandatory. From the description, one can tell that this is the "Synchronous generator idx", which should be the `idx` of an existing synchronous generator, i.e., *GENROU* or *GENCLS*.

Typically, models of the same group use the same IdxParams to connect to other models. Each link on the left sidebar of *Model reference* is a group, such as the *Exciter* group. With this convention, all exciters have a `syn` parameter for connecting to synchronous generators.

Creating cases

It is often easier to modify from existing cases than creating from scratch. We recommend that you get familiar with the cases available with ANDES, see *Test Cases*.

Adding devices

Adding devices to an existing workbook is straightforward. Navigate to the sheet corresponding to the model and add a new line below the existing lines.

Almost all models have so-called mandatory parameters. They are essential to describe a complete and consistent test case. For example, the `PQ` model has the `bus` parameter as mandatory to indicate the connected bus. To look up mandatory parameters, see *Model reference* or use `andes doc MODEL_NAME`. Check for "mandatory" in the last column called "Properties". This column also contains other data consistency requirements discussed in the following.

Non-mandatory parameters are optional, meaning that if not provided, ANDES will use the default parameters. The default values can also be found in *Model reference*. This does not mean that such parameters should always be left blank. For example, the `p0` (active power load) of `PQ` is optional, but likely one wants to set it to a non-zero value.

There are consistency requirements for parameters, such as `non_zero`, `non_negative` or `non_positive`. If unmet, the default values will be used. See the class reference in *`andes.core.param.NumParam`*.

Autofill data

When you finished adding devices but left some optional parameters empty, you can use ANDES to autofill them. This is useful when you want to populate a large number of devices with the same parameters that can be modified later.

The autofill is done through the data converter, namely, `--convert` or `-c`. ANDES will read in the Excel file, fill the optional parameters with default values, fix the inconsistent values, and then export the data back to Excel.

> **Warning:** Please backup the spreadsheet if it contains customized edits. Inconsistent data will be replaced during the conversion. Formatting in the spreadsheet will be lost. Unrecognized sheets will also be discarded.

To autofill `kundur_full.xlsx`, do

```
andes run kundur_full.xlsx -c
```

You will be prompted to confirm the overwrite.

Since this autofill feature utilizes the converter, the autofilled data can be exported to other formats, such as `.json`. To do so, use `-c json`.

Adding workbooks

If one wants to add workbooks for models that does not exist in an xlsx file, one can use `--add-book ADD_BOOK` (or `-b ADD_BOOK`), where `ADD_BOOK` can be a single model name or comma-separated model names (*without space*). For example,

```
andes run kundur_full.xlsx -b Fault
```

will add an empty `Fault` sheet to `kundur_full.xlsx`.

> **Warning:** With `--add-book`, the xlsx file will be overwritten with the same parameter corrections as in the autofill. Please make backups as needed.

Format conversion and workbook addition can be performed together. To convert a PSS/E raw file and a dyr file into an xlsx file and add a workbook for `Fault`, do

```
andes run kundur.raw -addfile kundur_full.dyr -c -b Fault
```

The output will have the same name as the raw file.

Data Consistency

Input data needs to have consistent types for `idx`. Both string and numerical types are allowed for `idx`, but the original type and the referencing type must be the same. Suppose we have a bus and a connected PQ. The Bus device may use `1` or `'1'` as its `idx`, as long as the PQ device uses the same value for its `bus` parameter.

The ANDES xlsx reader will try to convert data into numerical types when possible. This is especially relevant when the input `idx` is string literal of numbers, the exported file will have them converted to numbers. The conversion does not affect the consistency of data.

Parameter Check

The following parameter checks are applied after converting input values to array:

- Any `NaN` values will raise a `ValueError`
- Any `inf` will be replaced with 10^8, and `-inf` will be replaced with -10^8.

1.5.2 PSS/E RAW and DYR

The Siemens PSS/E data format is a widely used for power system simulation. PSS/E uses a variety of plain-text files to store data for different actions. The RAW format (with file extension `.raw`) is used to store the steady-state data for power flow analysis, and the DYR format (with extension `.dyr`) is used to store the parameters of dynamic devices for transient simulation.

RAW Compatibility

ANDES supports PSS/E RAW in versions 32 and 33. Newer versions of `raw` files can store PSS/E settings along with the system data, but such feature is not yet supported in ANDES. Also, manually edited `raw` files can confuse the parser in ANDES. Following manual edits, it is strongly recommended to load the data into PSS/E and save the case as a v33 RAW file.

ANDES supports most power flow models in PSS/E. It needs to be recognized that the power flow models in PSS/E is is a larger set compared with those in ANDES. For example, switched shunts in PSS/E are converted to fixed ones, not all three-winding transformer flags are supported, and HVDC devices are not yet converted. This is not an exhaustive list, but all of them are advanced models.

We welcome contributions but please also reach out to us if you need to arrange the development of such models.

DYR Compatibility

Fortunately, the DYR format does not have different versions yet. ANDES support reading parameters from DYR files for models that have been implemented in ANDES. Owing to the descriptive modeling framework, we implement the identical model so that parameters can be without conversion. If a dyr file contains models that are not recognized by ANDES, an error will be thrown. One needs to manually remove those unsupported models to load.

Like RAW files, manually edited DYR files can often be understood by PSS/E but may confuse the ANDES parser. We also recommend to load and re-save the file using PSS/E.

Loading files

In the command line, PSS/E files can be loaded with

```
andes run kundur.raw --addfile kundur.dyr
```

where `--addfile` or `-a` is used to specify the optional DYR file. For now, DYR files can only be added to a RAW file. We will allow different formats to be mixed in the future.

Likewise, one can convert PSS/E files to ANDES xlsx:

```
andes run kundur.raw --addfile kundur.dyr -c
```

This will convert all models in the RAW and DYR files. If only the RAW file is provided, only power flow models will be converted. One cannot easily append those in a DYR file to an existing xlx file yet.

To load PSS/E files into a scripting environment, see Example - "Working with Data".

Creating disturbances

Instead of converting `raw` and `dyr` to `xlsx` before adding disturbances, one can edit the `.dyr` file with a planin-text editor (such as Notepad) and append lines customized for ANDES models. This is for advanced users after referring to `andes/io/psse-dyr.yaml`, at the end of which one can find the format of `Toggle`:

```
# === Custom Models ===
Toggle:
    inputs:
        - model
        - dev
        - t
```

To define two Toggles in the `.dyr` file, one can append lines to the end of the file using, for example,

```
Line    'Toggle'  Line_2  1 /
Line    'Toggle'  Line_2  1.1 /
```

which is separated by spaces and ended with a slash. The second parameter is fixed to the model name quoted by a pair of single quotation marks, and the others correspond to the fields defined in the above `inputs`. Each entry is properly terminated with a forward slash.

Mapping dyr to ANDES models

ANDES supporting parsing PSS/E dynamic files in the format of `.dyr`. Support new dynamic models can be added by editing the input and output conversion definition file in `andes/io/psse-dyr.yaml`, which is in the standard YAML format. To add support for a new dynamic model, it is recommended to start with an existing model of similar functionality.

Consider a `GENCLS` entry in a dyr file. The entry looks like

```
1 'GENCLS' 1    13.0000  0.000000  /
```

where the fields are in the order of bus index, model name, generator index on the bus, inertia (H) and damping coefficient (D).

The input-output conversion definition for GENCLS is as follows

```
GENCLS:
    destination: GENCLS
    inputs:
        - BUS
        - ID
        - H
        - D
    find:
        gen:
            StaticGen:
                bus: BUS
                subidx: ID
    get:
        u:
            StaticGen:
                src: u
                idx: gen
        Sn:
            StaticGen:
                src: Sn
                idx: gen
        Vn:
            Bus:
                src: Vn
                idx: BUS
        ra:
            StaticGen:
                src: ra
                idx: gen
        xs:
            StaticGen:
```

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```
                src: xs
                idx: gen
    outputs:
        u: u
        bus: BUS
        gen: gen
        Sn: Sn
        Vn: Vn
        D: D
        M: "GENCLS.H; lambda x: 2 * x"
        ra: ra
        xd1: xs
```

It begins with a base-level definition of the model name to be parsed from the dyr file, namely, `GENCLS`. Five directives can be defined for each model: `destination`, `inputs`, `outputs`, `find` and `get`. Note that `find` and `get` are optional, but the other three are mandatory.

- `destination` is ANDES model to which the original PSS/E model will be converted. In this case, the ANDES model have the same name `GENCLS`.
- `inputs` is a list of the parameter names for the PSS/E data. Arbitrary names can be used, but it is recommended to use the same notation following the PSS/E manual.
- `outputs` is a dictionary where the keys are the ANDES model parameter and the values are the input parameter or lambda functions that processes the inputs (see notes below).
- `find` is a dictionary with the keys being the temporary parameter name to store the `idx` of external devices and the values being the criteria to locate the devices. In the example above, `GENCLS` will try to find the `idx` of `StaticGen` with `bus == BUS` and the `subidx == ID`, where `BUS` and `ID` are from the dyr file.
- `get` is a dictionary with each key being a temporary parameter name for storing an external parameter and each value being the criteria to find the external parameter. In the example above, a temporary parameter `u` is the `u` parameter of `StaticGen` whose `idx == gen`. Note that `gen` is the `idx` of `StaticGen` retrieved in the above `find` section.

For the `inputs` section, one will need to skip the model name because for any model, the second field is always the model name. That is why for `GENCLS` below, we only list four input parameters.

```
1 'GENCLS' 1    13.0000  0.000000  /
```

For the `outputs` section, the order can be arbitrary, but it is recommended to follow the input order as much as possible for maintainability. In particular, the right-hand-side of the outputs can be either an input parameter name or an anonymous expression that processes the input parameters. For the example of GENCLS, since ANDES internally uses the parameter of `M = 2H`, the input `H` needs to be multiplied by 2. It is done by the following

```
M: "GENCLS.H; lambda x: 2 * x"
```

where the left-hand-side is the output parameter name (destination ANDES model parameter name), and the right-hand-side is arguments and the lambda function separated by semi-colon, all in a pair of double quotation

marks. Multiple arguments are accepted and should be separated by comma. Arguments can come from the same model or another model. In the case of the same model, the model name can be neglected, namely, by writing `M: "H; lambda x: 2 * x"`.

1.5.3 MATPOWER

ANDES supports MATPOWER data in version 2 in part for power flow calculation. The following fields are supported:

- `mpc.busMVA`
- `mpc.bus`
- `mpc.gen`
- `mpc.branch`
- `mpc.area`
- `mpc.bus_name`

Other fields are not supported, most notably, `mpc.gencost`.

Power flow calculation results for MATPOWER cases are typically identical to that from MATPOWER using default settings. These settings include no reactive power limits and following all generator connectivity status. Discrepencies in the power flow solution between ANDES and MATPOWER are typically due to configuration issues or different interpretation of the data, rather than in the power flow models.

1.5.4 ANDES JSON

Overview

JSON is a portable format for storing data. It has been used in several other power system tools, including PowerModels, Pandapower, NREL-SIIP, and GridCal. It must be noted that JSON files from these tools are not interoperable because JSON only defines the data structure, not the meaning of data.

Compared with the *xlsx* file which is a zipped package, the ANDES JSON file is much faster to parse. We recommend that you use JSON in the following scenarios:

- Your test case is stable and require no manual editing, or
- You will read/write a large number of cases

To convert `kundur_full.xlsx` to the ANDES JSON format, do

```
andes run kundur_full.xlsx -c json
```

The output file will be named `kundur_full.json`.

Data storage

The ANDES JSON format uses one large dictionary for all devices in the system. The keys of the dictionary are the model names, and the values are lists of dictionaries. In each dictionary, the keys are the parameter names and the values are the parameter values.

The following shows the structure of a JSON file:

```
{
"Toggle": [
    {
    "idx": 1,
    "u": 1.0,
    "name": "Toggle_1",
    "model": "Line",
    "dev": "Line_8",
    "t": 2.0
    }  //      <- Toggle_1 ends
],     //      <- Toggle model ends
"Bus": [
    {
    "idx": 1,
    "u": 1.0,
    "name": 1,
    "Vn": 20.0,
    "vmax": 1.1,
    "vmin": 0.9,
    ...  //    <- other parameters are omitted
    },
    {
    "idx": 2,
    "u": 1.0,
    "name": 2,
    "Vn": 20.0,
    "vmax": 1.1,
    "vmin": 0.9,
    ...  //    <- other parameters are omitted
    },
    ...  //    <- other buses

],   //        <- Bus model ends
...  //        <- other models
}    //        <- whole system ends
```

There are thirdparty tools for editing JSON files, but we still recommend to convert files to `xlsx` for editing. The conversion can be readily done with

```
andes run kundur_full.json -c xlsx
```

1.5.5 Disturbances

Disturbance Devices

Predefined disturbances at specified time can be created by adding the corresponding devices. Three types of predefined disturbances are supported:

1. Three-phase-to-ground fault on buses. See *Fault* for details.
2. Connectivity status toggling. Disconnecting, connecting, or reconnecting any device, including lines, generators and motors can be implemented by *Toggle*.
3. Alteration of values. See *Alter* for details.

To use these devices, the time of disturbance needs to be known ahead of the simulation. The simulation program by default checks the network connectivity status after any disturbance.

Perturbation File

One can implement any custom disturbance using a perturbation file as discussed in [Milano2010]. The perturbation file is a Python script with a function named `pert`. The example for the perturbation file can be found in `andes/cases/ieee14/pert.py`.

`andes.cases.ieee14.pert.`**`pert`**(*t*, *system*)

Perturbation function called at each step.

The function needs to be named `pert` and takes two positional arguments: `t` for the simulation time, and `system` for the system object. Arbitrary logic and calculations can be applied in this function to `system`.

If the perturbation event involves switching, such as disconnecting a line, one will need to set the `system.TDS.custom_event` flag to `True` to trigger a system connectivity checking, and Jacobian rebuilding and refactorization. To implement, add the following line to the scope where the event is triggered:

```
system.TDS.custom_event = True
```

In other scopes of the code where events are not triggered, do not add the above line as it may cause significant slow-down.

The perturbation file can be supplied to the CLI using the `--pert` argument or supplied to *`andes.main.run()`* using the `pert` keyword.

Parameters

t
[float] Simulation time.

system
[andes.system.System] System object supplied by the simulator.

1.6 Test Cases

ANDES ships with with test cases in the `andes/cases` folder. The cases can be found in the online repository.

1.6.1 Summary

Below is a summary of the folders and the corresponding test cases. Some folders contain a README file with notes. When viewing the case folder on GitHub, one can conveniently read the README file below the file listing.

- `smib`: single machine infinite bus (SMIB) system [Sauer].
- `5bus`: a small PJM 5-bus test case for power flow study [PJM5].
- `GBnetwork`: a 2,000-bus system for the Great Britain network [GB]. Dynamic data is randomly generated.
- `EI`: the CURENT Eastern Interconnection network [EI].
- `ieee14` and `ieee39`: the IEEE 14-bus and 39-bus test cases [IEEE].
- `kundur`: a modified Kundur's two area system from [RLGC]. The modified system is different in the number of buses and lines from the textbook.
- `matpower`: a subset of test cases from [MATPOWER].
- `nordic44`: Nordpool 44-bus test case [Nordic]. Not all dynamic models are supported.
- `npcc`: the 140-bus Northeast Power Coordinating Council (NPCC) test case originated from Power System Toolbox [PST].
- `wecc`: the 179-bus Western Electric Coordinating Council (WECC) test case [WECC].
- `wscc`: the 9-bus WSCC (succeeded by WECC) power flow data converted from [PSAT].

Note: Different systems exhibit different dynamics, thus the appropriate systems should be used to study power system stability. For example:

- The Kundur's two-area system has under-damped modes and two coherent groups of generators. It is suitable for oscillation study and transient stability studies.
- The WECC system is known for the inter-area oscillation.
- The IEEE 14-bus system and the 140-bus NPCC system is are frequently used for frequency control studies. So is the Eastern Interconnection system.

Currently, the Kundur's 2-area system, IEEE 14-bus system, NPCC 140-bus system, and the WECC 179-bus system has been verified against DSATools TSAT.

1.6.2 Example data

When developing models, we manually create cases with example data to verify the models. The Kundur's system and the IEEE 14-bus system are used as the bases for adding specific models. One can find many cases in the folder `andes/cases/kundur`. The case file names typically indicate the specific model added to the file. These example cases with specific models are useful when one needs to find example parameters for the model. For example:

- `kundur_ieeeg1` indicates the use of `IEEEG1` model in a Kundur's sytem
- `ieee14_solar.xlsx` contains the solar PV models (REGCA1, REECA1, and REPCA1)
- `ieee14_plbvfu1.xlsx` is the case for `PLBVFU1` (playback of voltage and frequency). The case provides an example of specifying `plbvf.xlsx`
- `ieee14_timeseries.xlsx` is an example for specifying timeseries for load data, which is provided in `pqts.xlsx`

1.6.3 MATPOWER cases

MATPOWER cases has been tested in ANDES for power flow calculation. All following cases are calculated with the provided initial values using the full Newton-Raphson iterative approach.

Benchmark

See *MATPOWER cases* for the benchmark of MATPOWER cases.

Synthetic systems

The 70K and the USA synthetic systems have difficulties to converge using the provided initial values. One can solve the case in MATPOWER and save it as a new case for ANDES. For example, the SyntheticUSA case can be converted in MATLAB with

```
mpc = runpf(case_SyntheticUSA)
savecase('USA.m', mpc)
```

And then solve it with ANDES from command line:

```
andes run USA.m
```

The output should look like

```
-> Power flow calculation
Sparse solver: KLU
Solution method: NR method
Power flow initialized.
0: |F(x)| = 140.5782767
1: |F(x)| = 29.61673314
```

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```
2: |F(x)| = 4.161452394
3: |F(x)| = 0.2337870537
4: |F(x)| = 0.001149488448
5: |F(x)| = 3.646516689e-08
Converged in 6 iterations in 1.6082 seconds.
```

1.6.4 How to contribute

We welcome the contribution of test cases! You can make a pull request to contribute new test cases. Please follow the structure in the `cases` folder and provide an example Jupyter notebook (see `examples/demonstration`) to showcase the results of your system.

1.7 Performance

We discuss methods to improve the compuattional performance in ANDES using Numba. Performance benchmarks are also presented.

1.7.1 Numba compilation

In nearly all numerical simulation software, time is mostly spent on *constructing* the numerical system and *solving* it. The construction of the DAE in ANDES involves the evaluation of functions from models that implement the residuals and Jacobians.

Numba is a just-in-time compiler in Python that can turn numerical functions into compiled machine code. In ANDES, it can speed up simulations by as much as 30%. The speedup is most effective in medium-sized systems with multiple models. Such systems involve heavy function calls but rather moderate load for linear equation solvers. It is is less significant in large-scale systems where solving equations is the major time consumer.

Note: Numba is supported since ANDES 1.5.0. One needs to manually install it with `python -m pip install numba` from the Anaconda Prompt.

Enabling Numba JIT

Numba needs to be enabled *manually*. In the ANDES config file: in section `[System]`, set `numba = 1`, so that it looks like

```
[System]
   ...
   numba = 1
   ...
```

where the `...` are other options that are omitted here.

Just-in-time compilation will compile the code upon the *first execution* based on the input types. This is the default mode of Numba. When compilation is triggered, ANDES may appear frozen due to the compilation lag. To reuse the compiled code and save compilation time for future runs, the compiled binary code will be automatically cached. The default cache folder is in `$HOME/.andes/pydata/__pycache__` with file extensions `nbc` and `nbi`

Numba compilation needs to be distinguished from the ANDES code generation by *andes prepare*. The ANDES code generation is to generate Python code from symbolically defined models and is relatively fast. The Numba compilation further compiles the generated Python code to machine code. Whenever the ANDES code generation produces new Python code, the cached Numba binary code will be invalidated.

When not to compile

when developing models, we recommend disabling numba to avoid spending time on compilation.

Ahead-of-time compilation

Just-in-time compilation can feel laggy. When ANDES is not being developed, one can compile the generated Python code ahead of time to avoid just-in-time delays. We call it "precompilation".

Precompilation is invoked by

```
andes prep -c
```

It may take a minute for the first time. Owing to caching, future compilations will be incremental and much faster.

1.7.2 MATPOWER cases

The hardware platform is an AMD Ryzen 9 5950X with 64GB of 3200 MHz DDR4 RAM. The operating system is WSL2 Ubunbu 20.04 on Windows 10. Software packages are:

- ANDES 1.5.3
- KVXOPT 1.2.7.1
- NumPy 1.20.3
- numba 0.54.1
- OpenBLAS 0.3.18.

Numba is enabled, and all generated code are precompiled. Network connectivity checking is turned off (`[PFlow] check_conn=0`). Time to read numba cache (~0.3s) is not included.

The table below shows the power flow time in ANDES. All the cases are original in MATPOWER 7.0, and cases not listed below will not solve with ANDES 1.5.3. The computation time may vary depending on hardware, operating system, and software.

File Name	Converged?	# of Iterations	ANDES Time [s]
case1354pegase.m	1	4	0.034
case13659pegase.m	1	5	0.276
case14.m	1	2	0.009
case145.m	1	3	0.014
case15nbr.m	1	17	0.024
case17me.m	1	3	0.010
case18.m	1	3	0.011
case1888rte.m	1	2	0.025
case18nbr.m	1	18	0.026
case1951rte.m	1	3	0.031
case2383wp.m	1	6	0.059
case24_ieee_rts.m	1	4	0.012
case2736sp.m	1	4	0.053
case2737sop.m	1	5	0.060
case2746wop.m	1	4	0.053
case2746wp.m	1	4	0.054
case2848rte.m	1	3	0.043
case2868rte.m	1	4	0.056
case2869pegase.m	1	6	0.084
case30.m	1	3	0.010
case300.m	1	5	0.019
case30Q.m	1	3	0.009
case30pwl.m	1	3	0.010
case39.m	1	1	0.008
case4_dist.m	1	3	0.010
case4gs.m	1	3	0.011
case5.m	1	3	0.011
case57.m	1	3	0.010
case60nordic.m	1	1	0.008
case6468rte.m	1	6	0.144
case6470rte.m	1	4	0.111
case6495rte.m	1	5	0.130
case6515rte.m	1	4	0.116
case6ww.m	1	3	0.010
case8387pegase.m	1	3	0.143
case89pegase.m	1	5	0.015
case9.m	1	3	0.011
case9241pegase.m	1	6	0.243
case9Q.m	1	3	0.011
case9target.m	1	4	0.010
case_ACTIVSg10k.m	1	4	0.157
case_ACTIVSg200.m	1	2	0.010
case_ACTIVSg2000.m	1	3	0.042
case_ACTIVSg25k.m	1	7	0.549

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Table 2 – continued from previous page

File Name	Converged?	# of Iterations	ANDES Time [s]
case_ACTIVSg500.m	1	3	0.015
case_ACTIVSg70k.m	1	5	1.398
case_RTS_GMLC.m	1	3	0.013
case_SyntheticUSA.m	1	5	1.727
case_ieee30.m	1	2	0.008

1.8 Verification

This section presents the verification of the models and algorithms implemented in ANDES by comparing the time-domain simulation results with commercial tools.

ANDES produces identical results for the IEEE 14-bus and the NPCC systems with several models. For the CURENT WECC system, ANDES, TSAT, and PSS/E produce slightly different results. In fact, results from different tools can hardly match for large systems with a variety of dynamic models.

1.8.1 IEEE 14-Bus Verification

Prepared by Hantao Cui. Last revised 23 May 2020.

Background

Two line trip scenarios are used to verify ANDES simulation results with DSATools TSAT.

Dynamic data is created to utilize the available models, including GENROU, TGOV1, IEEEG1, EXST2, EXDC2, ESST3A, IEEEST and ST2CUT. Test case data can be found at the end of the notebook.

Simulation Parameters

Integretion method: Trapezidal Rule (ANDES and TSAT).

Time step size: `1/120` sec. (Note: step size between `1/30` to `1/120` has little impact on the ANDES results. One can use `tstep=1/30` to obtain almost the same results.)

Load conversion: static loads are converted to 100% constant impedances for both P and Q.

TSAT automatic parameter correction is disabled.

Initialization

Power flow solutions are identical across all the two software.

GENROU initialization (E_{FD}, E_{TERM}, P, Q, δ, I_d and I_q) is identical to that from **PSS/E** for all cases (with and without generator saturation). Note that I_d and I_q are in machine base in PSS/E but in system base in ANDES.

GENROU initialization (including all the internal variables $E'*d$, $E'*q$, $\psi*{kd}$, ψ_{kq}, ψ''_d, and ψ''_q) is identical to that from **OpenIPSL**.

No controller limit violation occurs during initialization.

Conclusion

IEEE 14-bus system simulation results from ANDES are identical to that from TSAT.

```
import andes
import numpy as np
from andes.utils.tsat import tsat_to_df, plot_comparison, run_cmp

andes.config_logger(stream_level=30)
```

```
# load scenario 1 data
omega_lt2 = tsat_to_df('omega_lt2s.xls')
v_lt2 = tsat_to_df('v_lt2s.xls')

# load scenario 2 data
omega_gt = tsat_to_df('omega_gt.xls')
v_gt = tsat_to_df('v_gt.xls')
```

Scenario 1

Line 1-2 trips at 1 sec. and reconnects after 2.0 sec. The reconnection delay is set to 2 seconds to trigger a large disturbance to the system to verify nonlinear models.

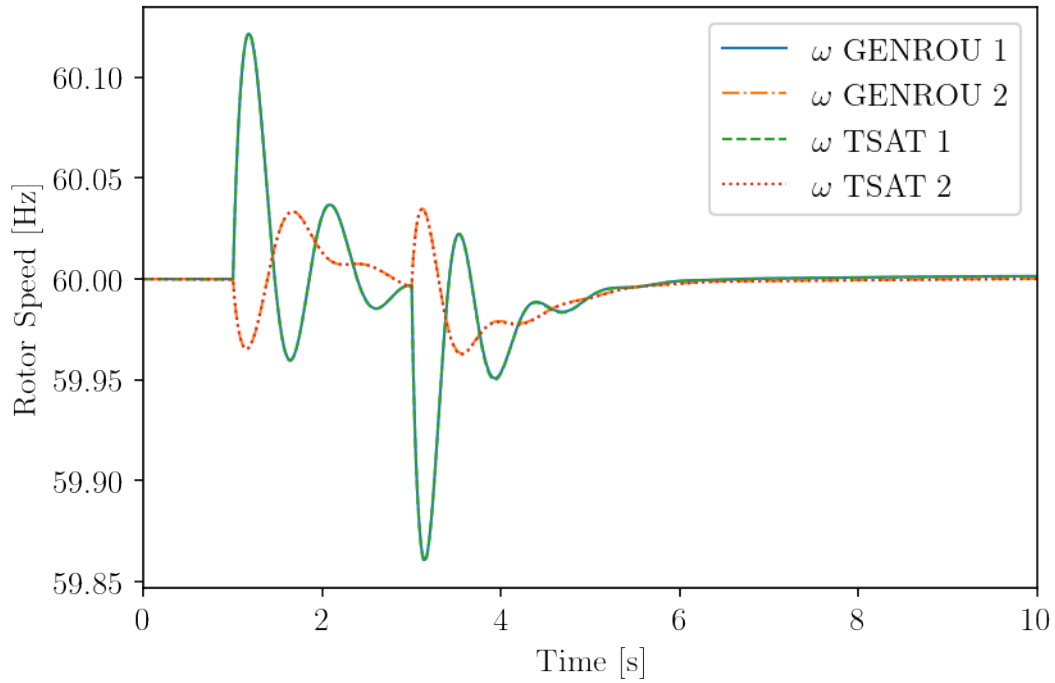
Simulation Setup

```
ss = run_cmp('ieee14.raw', dyr='ieee14.dyr', fault_line='Line_1',
             t1=1.0, t2=3.0, tstep=1/120)
```

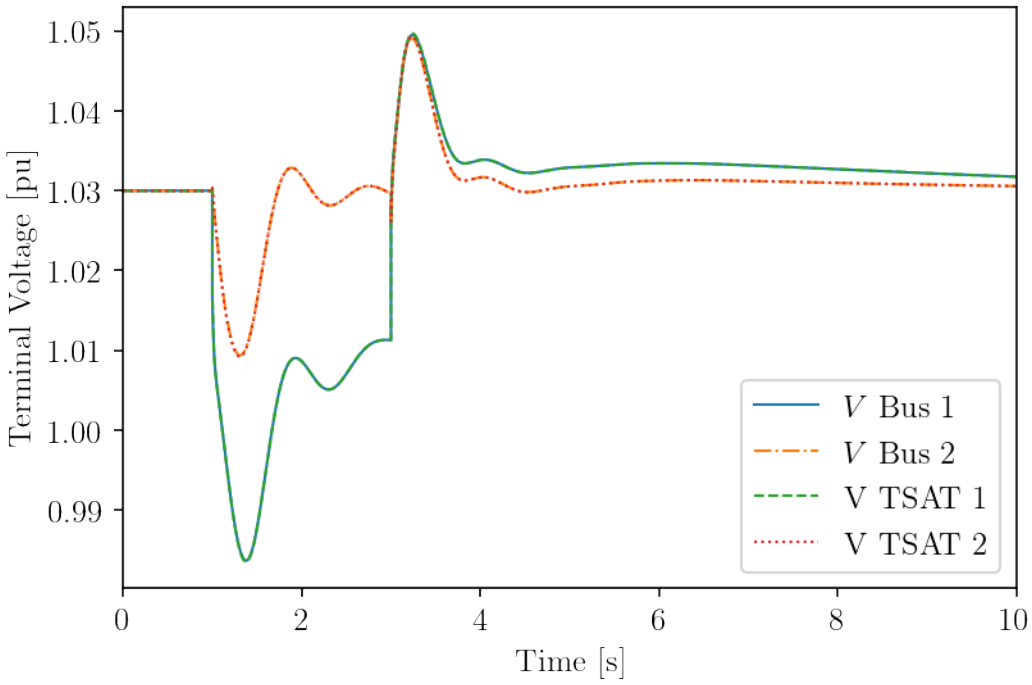
```
<Toggle Toggle_1>: Line.Line_1 status changed to 0.0 at t=1.0 sec.
<Toggle Toggle_2>: Line.Line_1 status changed to 1.0 at t=3.0 sec.
100%|████████████████████████████████████| 100/100 [00:16<00:00,  6.15%/s]
```

Scenario 1 Plots

```
fig, ax = plot_comparison(ss, ss.GENROU.omega,
                omega_lt2, a=[0, 1],
                ylabel="Rotor Speed [Hz]",
                tsat_header=[r'$\omega$ TSAT 1', r'$\omega$ TSAT 2'],
                scale=60, left=0, right=10)
```




```
fig, ax = plot_comparison(ss, ss.GENROU.v,
                v_lt2, a=[0, 1],
                ylabel="Terminal Voltage [pu]",
                tsat_header=['V TSAT 1', 'V TSAT 2'],
                left=0, right=10)
```



Scenario 2

Line 7-8 trips at 1 sec. and reconnects after 0.1 sec. The line is an equivalent branch of the three-winding transformer. Tripping 7-8 will isolate Bus 8.

Simulation Setup

```
ss2 = run_cmp('ieee14.raw', dyr='ieee14.dyr', fault_line='Line_20',
              t1=1.0, t2=1.1, tstep=1/120)
```

```
<Toggle Toggle_1>: Line.Line_20 status changed to 0.0 at t=1.0 sec.
<Toggle Toggle_2>: Line.Line_20 status changed to 1.0 at t=1.1 sec.
100%|████████████████████████████████| 100/100 [00:12<00:00,  8.10%/s]
```

```
# line data
ss2.Line.cache.df.iloc[19]
```

```
idx        Line_20
u                1
name       Line_20
bus1             8
bus2             7
Sn             100
fn              60
Vn1             69
```

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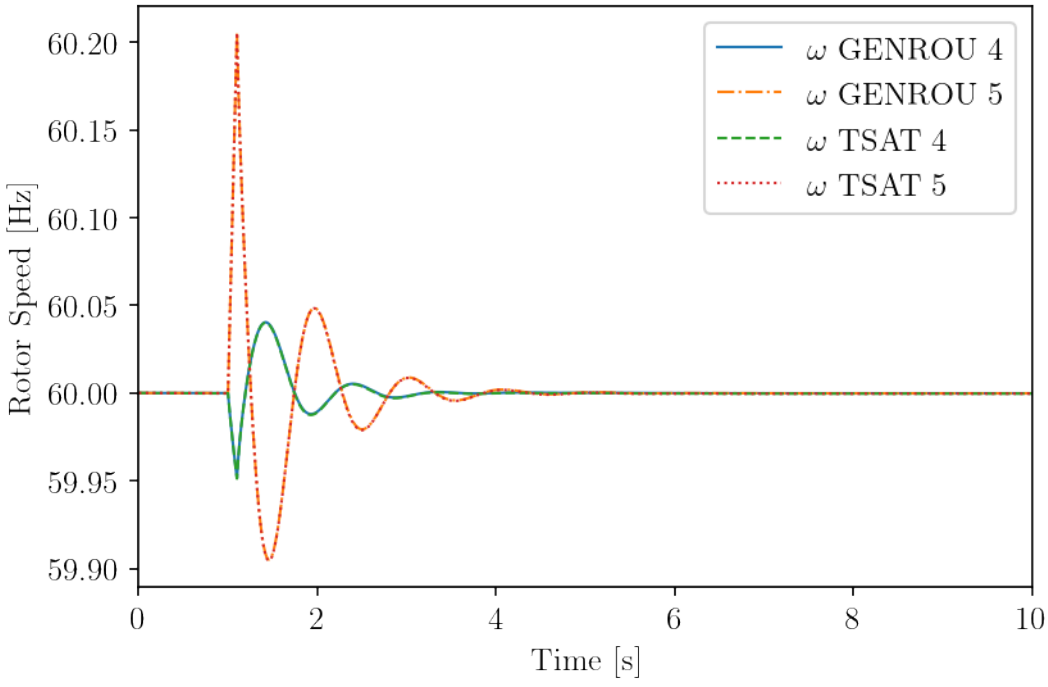
```
Vn2            138
r                0
x          0.17615
b                0
g                0
b1               0
g1               0
b2               0
g2               0
trans            1
tap          0.99677
phi              0
owner         None
xcoord        None
ycoord        None
Name: 19, dtype: object
```

Scenario 2 Plots

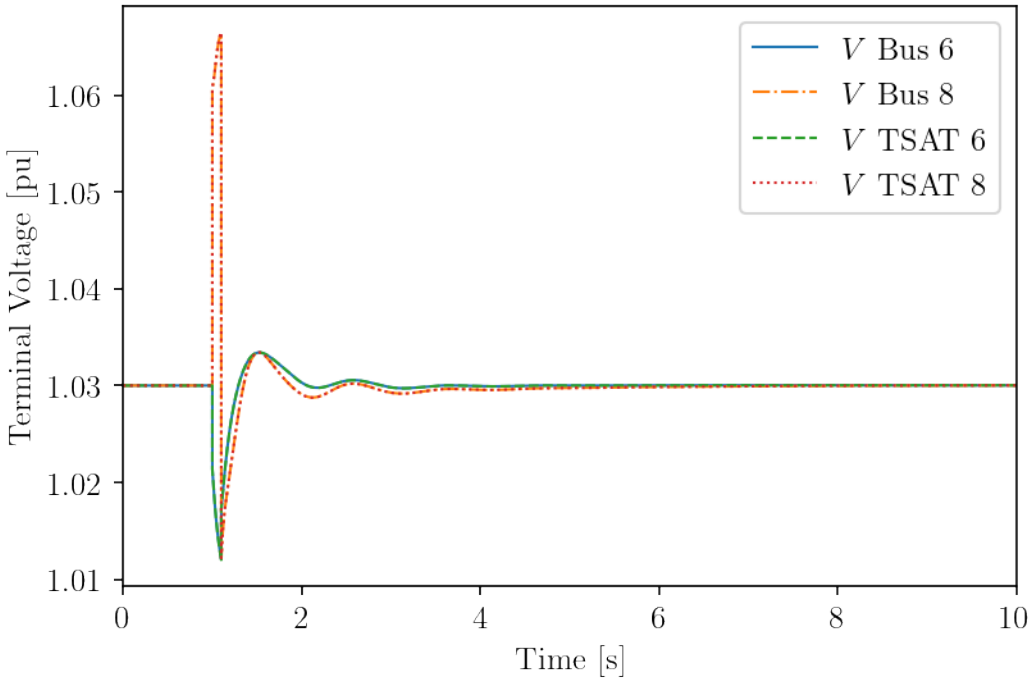
```
tsat_omega_headers = [ss.TDS.plt._fname[i + 1] for i in ss.GENROU.omega.a]
tsat_omega_headers = [i.replace('GENROU', 'TSAT') for i in tsat_omega_headers]

fig2, ax2 = plot_comparison(ss2, ss2.GENROU.omega,
                omega_gt, a=[3, 4],
                ylabel="Rotor Speed [Hz]",
                tsat_header=tsat_omega_headers,
                scale=60, left=0, right=10)
```



```
tsat_v_headers = [ss.TDS.plt._fname[i + 1 + ss.dae.n] for i in ss.GENROU.v.a]
tsat_v_headers = [i.replace('Bus', 'TSAT') for i in tsat_v_headers]

fig2, ax2 = plot_comparison(ss2, ss2.GENROU.v,
                v_gt, a=[3, 4],
                ylabel="Terminal Voltage [pu]",
                tsat_header=tsat_v_headers,
                left=0, right=10)
```



Appendix

IEEE 14-Bus System Data

Power Flow Data (PSS/E RAW format)

```
# !cat results won't save to PDF

data = !cat ieee14.raw
print('\n'.join(data))
```

```
0,   100.00,  32, 0, 1, 60.00     / PSS(R)E 32 RAW created by rawd32  SUN,␣
↪MAY 17 2020  20:38
 IEEE 14 BUS TEST CASE
DISTRIBUTED WITH ANDES (HTTPS://GITHUB.COM/CURENT/ANDES)
     1,'BUS1        ',  69.0000,3,   1,   1,   1,1.03000,   0.0000
```

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```
     2,'BUS2        ',  69.0000,2,    1,    1,    1,1.01970,  -1.6032
     3,'BUS3        ',  69.0000,2,    1,    1,    1,1.00042,  -3.4433
     4,'BUS4        ',  69.0000,1,    1,    1,    1,0.99858,  -4.2812
     5,'BUS5        ',  69.0000,1,    1,    1,    1,1.00443,  -3.6850
     6,'BUS6        ', 138.0000,2,    2,    2,    2,0.99871,  -6.3024
     7,'BUS7        ', 138.0000,1,    2,    2,    2,1.00682,  -4.8292
     8,'BUS8        ',  69.0000,2,    2,    2,    2,1.01895,  -1.3945
     9,'BUS9        ', 138.0000,1,    2,    2,    2,1.00193,  -7.3053
    10,'BUS10       ', 138.0000,1,    2,    2,    2,0.99351,  -7.4600
    11,'BUS11       ', 138.0000,1,    2,    2,    2,0.99245,  -7.0444
    12,'BUS12       ', 138.0000,1,    2,    2,    2,0.98639,  -7.3874
    13,'BUS13       ', 138.0000,1,    2,    2,    2,0.98403,  -7.6654
    14,'BUS14       ', 138.0000,1,    2,    2,    2,0.99063,  -9.5636
 0 /End of Bus data, Begin Load data
     2,'1 ',1,    1,    1,    21.700,    12.700,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     3,'1 ',1,    1,    1,    50.000,    25.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     4,'1 ',1,    1,    1,    47.800,    10.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     5,'1 ',1,    1,    1,     7.600,     1.600,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     6,'1 ',1,    2,    2,    15.000,     7.500,     0.000,     0.000,     0.
↪000,     0.000,   2,1
     9,'1 ',1,    2,    2,    29.500,    16.600,     0.000,     0.000,     0.
↪000,     0.000,   2,1
    10,'1 ',1,    2,    2,     9.000,     5.800,     0.000,     0.000,     0.
↪000,     0.000,   2,1
    11,'1 ',1,    2,    2,     3.500,     1.800,     0.000,     0.000,     0.
↪000,     0.000,   2,1
    12,'1 ',1,    2,    2,     6.100,     1.600,     0.000,     0.000,     0.
↪000,     0.000,   2,1
    13,'1 ',1,    2,    2,    13.500,     5.800,     0.000,     0.000,     0.
↪000,     0.000,   2,1
    14,'1 ',1,    2,    2,    20.000,     7.000,     0.000,     0.000,     0.
↪000,     0.000,   2,1
 0 /End of Load data, Begin Fixed shunt data
 0 /End of Fixed shunt data, Begin Generator data
     1,'1 ',    81.442,     1.962,   100.000,   -50.000,1.03000,     0,   100.
↪000, 0.00000E+0, 2.30000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,  ␣
↪200.000,    50.000,   1,1.0000
     2,'1 ',    40.000,    15.000,    15.000,   -40.000,1.03000,     0,   100.
↪000, 0.00000E+0, 1.30000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,   ␣
↪50.000,    10.000,   1,1.0000
     3,'1 ',    40.000,    15.000,    15.000,   -10.000,1.01000,     0,   100.
↪000, 0.00000E+0, 1.30000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,   ␣
↪50.000,    10.000,   1,1.0000
     6,'1 ',    30.000,    10.000,    10.000,    -6.000,1.03000,     0,   100.
↪000, 0.00000E+0, 1.20000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,   ␣
↪50.000,    10.000,   1,1.0000
     8,'1 ',    35.000,    10.000,    10.000,    -6.000,1.03000,     0,   100.
↪000, 0.00000E+0, 1.20000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0,   ␣
```

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```
↪50.000,    10.000,   1,1.0000
 0 /End of Generator data, Begin Branch data
     1,      2,'1 ', 1.93800E-2, 5.91700E-2,   0.05280,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     1,      5,'1 ', 5.40300E-2, 2.23040E-1,   0.04920,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     2,      3,'1 ', 4.69900E-2, 1.97970E-1,   0.04380,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     2,      4,'1 ', 5.81100E-2, 1.76320E-1,   0.03400,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     2,      5,'1 ', 5.69500E-2, 1.73880E-1,   0.03460,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     3,      4,'1 ', 6.70100E-2, 1.71030E-1,   0.01280,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     4,      5,'1 ', 1.33500E-2, 4.21100E-2,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     6,     11,'1 ', 9.49800E-2, 1.98900E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     6,     12,'1 ', 1.22910E-1, 2.55810E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     6,     13,'1 ', 6.61500E-2, 1.30270E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     7,      9,'1 ',-0.00000E+0, 1.10010E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     9,     10,'1 ', 3.18100E-2, 8.45000E-2,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     9,     14,'1 ', 1.27110E-1, 2.70380E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    10,     11,'1 ', 8.20500E-2, 1.92070E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    12,     13,'1 ', 2.20920E-1, 1.99880E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    13,     14,'1 ', 1.70930E-1, 3.48020E-1,   0.00000,  100.00,  100.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
 0 /End of Branch data, Begin Transformer data
     4,      7,      0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 2.09120E-1,   100.00
0.99677,   0.000,   0.000,    20.00,    20.00,     0.00,-1,       0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  32, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     4,      9,      0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 5.56180E-1,   100.00
0.99677,   0.000,   0.000,    20.00,    20.00,     0.00,-1,       0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  32, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     6,      5,      0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,1,'                  ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 2.52020E-1,   100.00
0.99677,   0.000,   0.000,    50.00,    50.00,     0.00,-1,       0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  32, 0, 0.00000, 0.00000,  0.000
```

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```
1.00000,   0.000
     8,     7,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,1,'                    ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.76150E-1,   100.00
0.99677,   0.000,   0.000,    50.00,    50.00,     0.00,-1,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  32, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
 0 /End of Transformer data, Begin Area interchange data
   1,     2,     0.000,   999.990,'AREA1       '
   2,     0,     0.000,    10.000,'AREA2       '
 0 /End of Area interchange data, Begin Two-terminal dc line data
 0 /End of Two-terminal dc line data, Begin VSC dc line data
 0 /End of VSC dc line data, Begin Impedance correction table data
 0 /End of Impedance correction table data, Begin Multi-terminal dc line data
 0 /End of Multi-terminal dc line data, Begin Multi-section line data
 0 /End of Multi-section line data, Begin Zone data
   1,'ZONE1       '
   2,'ZONE2       '
 0 /End of Zone data, Begin Inter-area transfer data
 0 /End of Inter-area transfer data, Begin Owner data
   1,'OWNER1      '
   2,'OWNER2      '
 0 /End of Owner data, Begin FACTS device data
 0 /End of FACTS device data, Begin Switched shunt data
     9,1,0,1,1.02500,0.96000,     0,  100.0,'            ',   19.00, 3,   5.
↪00, 1,   4.00
    14,1,0,1,1.02500,0.96000,     0,  100.0,'            ',   15.00, 3,   5.00
 0 /End of Switched shunt data, Begin GNE device data
 0 /End of GNE device data
Q
```

Dynamic Data (PSS/E DYR format)

```
data = !cat ieee14.dyr
print('\n'.join(data))
```

```
      1 'GENROU' 1     6.5000      0.60000E-01  0.20000      0.50000E-01
          4.0000       0.0000       1.8000       1.7500      0.60000
         0.80000      0.23000      0.15000      0.90000E-01  0.38000      /
      1 'ST2CUT' 1          1            0            0            0
          0.0000       0.0000       0.0000       0.0000       30.000
          30.000      0.23000      0.25000E-01  0.23000      0.25000E-01
          0.0000       0.0000      0.60000E-01 -0.60000E-01   0.0000
          0.0000      /
      1 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       8.0000
          1.0000       5.0000       20.000       0.0000       99.000
         -99.000       1.0000       3.6700      0.43500       5.4800
         0.10000E-01  0.98000E-02   3.8600       3.3300      0.40000
          99.000       0.0000    /
```

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```
     1 'TGOV1'  1    0.50000E-01  0.50000E-01   1.0500      0.30000
        1.0000       2.1000       0.0000      /
     2 'GENROU' 1     6.5000      0.60000E-01  0.20000      0.50000E-01
        6.5000       0.0000       1.8000       1.7500      0.60000
       0.80000      0.28000      0.15000      0.90000E-01  0.38000      /
     2 'ST2CUT' 1          1            0            0           0
        10.000       0.0000       0.0000       0.0000       3.0000
        3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
       0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
        0.0000      /
     2 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
       0.20000E-01   50.000      0.20000E-01   9999.0      -9999.0
        0.0000      0.10000E-01   1.0000    /
     2 'IEEEG1' 1          0           0        20.000      0.10000
        0.0000      0.20000       1.0000      -1.0000      0.95000
        0.0000      0.10000       0.0000       0.0000       0.0000
        0.0000       0.0000       0.0000      0.30000       0.0000
        8.7200      0.70000       0.0000    /
     3 'GENROU' 1     6.5000      0.60000E-01  0.20000      0.50000E-01
        5.0000       0.0000       1.8000       1.7500      0.60000
       0.80000      0.34000      0.15000      0.90000E-01  0.38000      /
     3 'IEEEST' 1          3            0       0.0000       0.0000
        0.0000       0.0000       0.0000       0.0000       0.0000
        0.0000       0.0000      0.75000       1.0000       4.2000
       -2.0000      0.10000     -0.10000       0.0000       0.0000      /
     3 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       8.0000
        1.0000       5.0000       20.000       0.0000       99.000
       -99.000       1.0000       3.6700      0.43500       5.4800
       0.10000E-01  0.98000E-02   3.8600       3.3300      0.40000
        99.000       0.0000    /
     3 'IEEEG1' 1          0           0        20.000      0.10000
        0.0000      0.20000       1.0000      -1.0000      0.95000
        0.0000      0.10000       0.0000       0.0000       0.0000
        0.0000       0.0000       0.0000      0.30000       0.0000
        8.7200      0.70000       0.0000    /
     6 'GENROU' 1     6.5000      0.60000E-01  0.20000      0.50000E-01
        5.0000       0.0000       1.8000       1.7500      0.60000
       0.80000      0.28000      0.15000      0.90000E-01  0.38000      /
     6 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       8.0000
        1.0000       5.0000       20.000       0.0000       99.000
       -99.000       1.0000       3.6700      0.43500       5.4800
       0.10000E-01  0.98000E-02   3.8600       3.3300      0.40000
        99.000       0.0000    /
     6 'TGOV1'  1    0.50000E-01  0.50000E-01   1.0500      0.30000
        1.0000       2.1000       0.0000      /
     8 'GENROU' 1     6.5000      0.60000E-01  0.20000      0.50000E-01
        5.0000       0.0000       1.8000       1.7500      0.60000
       0.80000      0.34000      0.15000      0.90000E-01  0.38000      /
     8 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       8.0000
        1.0000       5.0000       20.000       0.0000       99.000
       -99.000       1.0000       3.6700      0.43500       5.4800
       0.10000E-01  0.98000E-02   3.8600       3.3300      0.40000
```

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```
      99.000       0.0000    /
  8 'TGOV1'  1    0.50000E-01  0.50000E-01   1.0500      0.30000
      1.0000       2.1000       0.0000      /
```

1.8.2 CURENT NPCC Verification

Prepared by Hantao Cui. Last revised 23 May 2020.

Background

The CURENT NPCC test system contains 140 buses, 233 branches, and 48 generators. Dynamic data uses models GENROU, GENCLS, TGOV1 and IEEEX1.

One line trip scenario is used to verify ANDES simulation results with DSATools TSAT.

Simulation Parameters

Integretion method: Trapezidal Rule (ANDES and TSAT).

Time step size: `1/120` sec. (Note: step size between `1/30` to `1/120` has little impact on the ANDES results. One can use `tstep=1/30` to obtain almost the same results.)

Load conversion: static loads are converted to 100% constant impedances for both P and Q.

TSAT automatic parameter correction is disabled.

Initialization

Power flow solutions are identical across all the two software.

GENROU initialization (E_{FD}, E_{TERM}, P, Q, δ, I_d and I_q) is identical to that from **PSS/E** for all cases (with and without generator saturation). Note that I_d and I_q are in machine base in PSS/E but in system base in ANDES.

GENROU initialization (including all the internal variables $E'*d$, $E'*q$, $\psi*{kd}$, ψ_{kq}, ψ''_d, and ψ''_q) is identical to that from **OpenIPSL**.

No controller limit violation occurs during initialization.

Conclusion

NPCC simulation results from ANDES are identical to that from TSAT.

```
import andes
import numpy as np
from andes.utils.tsat import tsat_to_df, plot_comparison, run_cmp

andes.config_logger(stream_level=30)
```

```
omega_lt2s = tsat_to_df('omega_lt2s.xls')
v_lt2s = tsat_to_df('v_lt2s.xls')
```

Scenario 1

Line 1-2 trips at 1 sec. and reconnects after 2.0 sec. The reconnection delay is set to 2 seconds to trigger a large disturbance to the system to verify nonlinear models.

Simulation Setup

```
ss = run_cmp('npcc.raw', dyr='npcc.dyr', fault_line='Line_1',
             t1=1.0, t2=3.0, tstep=1/120)
```

```
<Toggle Toggle_1>: Line.Line_1 status changed to 0.0 at t=1.0 sec.
<Toggle Toggle_2>: Line.Line_1 status changed to 1.0 at t=3.0 sec.
100%|████████████████████████████████| 100/100 [00:10<00:00,  9.87%/s]
```

```
# line information
ss.Line.cache.df_in.iloc[0]
```

```
idx       Line_1
u              1
name      Line_1
bus1           1
bus2           2
Sn           100
fn            60
Vn1          345
Vn2          345
r         0.0004
x         0.0043
b           0.07
g              0
b1             0
g1             0
b2             0
g2             0
```

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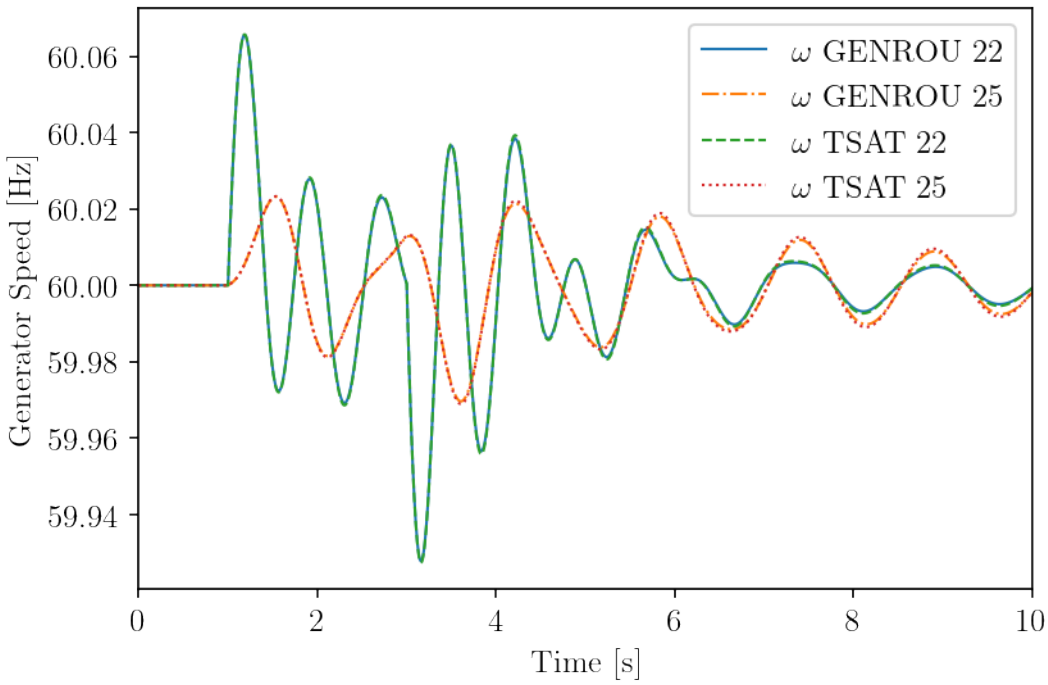
```
trans          0
tap            1
phi            0
owner       None
xcoord      None
ycoord      None
Name: 0, dtype: object
```

Scenario 1 Plots

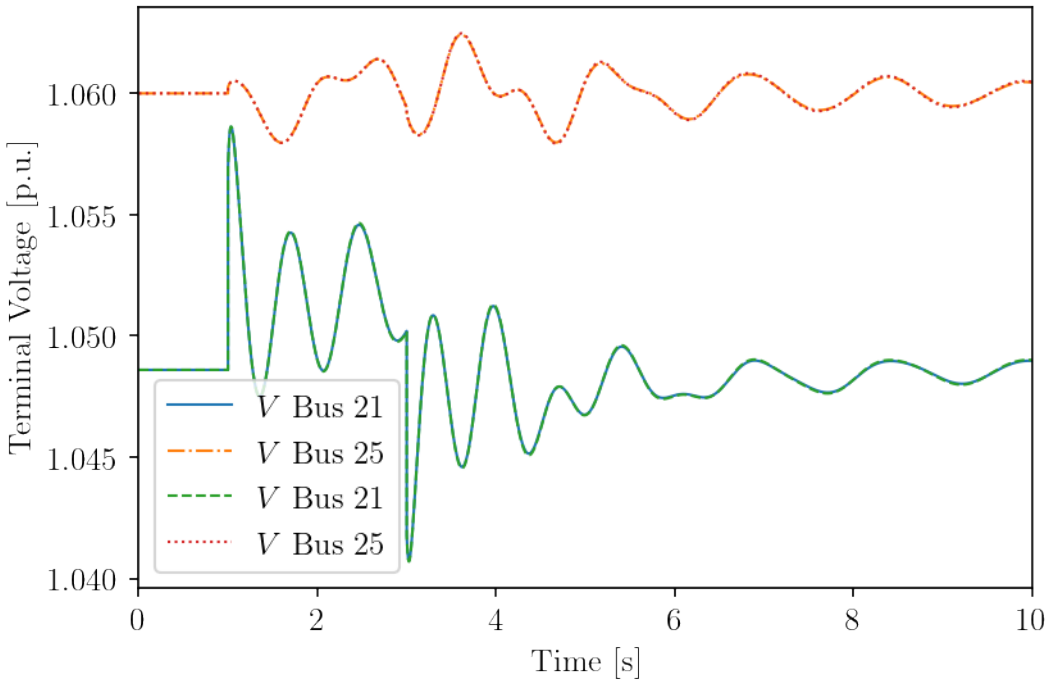
```
tsat_omega_headers = [ss.TDS.plt._fname[i + 1] for i in ss.GENROU.omega.a]
tsat_omega_headers = [i.replace('GENROU', 'TSAT') for i in tsat_omega_headers]

fig, ax = plot_comparison(ss, ss.GENROU.omega, omega_lt2s,
                a=[0, 3], ylabel="Generator Speed [Hz]",
                tsat_header=tsat_omega_headers,
                scale=60, right=10)
```




```
tsat_v_headers = [ss.TDS.plt._fname[i + 1 + ss.dae.n] for i in ss.GENROU.v.a]
tsat_v_headers = [i.replace('GENROU', 'TSAT') for i in tsat_v_headers]

fig, ax = plot_comparison(ss, ss.GENROU.v,
                          v_lt2s, a=[0, 5],
                          ylabel="Terminal Voltage [p.u.]",
                          tsat_header=tsat_v_headers, right=10)
```



Appendix

CURENT NPCC 140-Bus System Data

Power Flow Data (PSS/E RAW format)

```
data = !cat npcc.raw
print('\n'.join(data))
```

```
0,   100.00,  32, 0, 1, 60.00     / PSS(R)E 32 RAW created by rawd32  MON,␣
↪JUN 22 2015   8:32
CURENT NPCC 48-MACHINE TESTBED, CONVERTED FROM PST BY BIN WANG
REVISED BY YIN LEI, 11/18/2013
     1,'MILLSTONE PT', 345.0000,1,   1,   1,   1,1.01517,   4.8434
     2,'MONTVILLE   ', 345.0000,1,   1,   1,   1,1.01090,   4.0566
     3,'MONTVILLE   ', 115.0000,1,   1,   1,   1,0.99170,   4.0069
     4,'MONTVILLE   ', 345.0000,1,   1,   1,   1,1.01125,   4.1005
     5,'CARD ST     ', 345.0000,1,   1,   1,   1,1.00618,   2.3527
     6,'SHERMAN RD  ', 345.0000,1,   1,   1,   1,1.00594,   1.8603
     7,'MEDWAY      ', 345.0000,1,   1,   1,   1,1.02071,   3.2654
     8,'MILLBURY    ', 115.0000,1,   1,   1,   1,1.02151,   1.9975
     9,'CARPENTER HL', 115.0000,1,   1,   1,   1,1.01811,   1.0727
    10,'BRAYTON PT  ', 115.0000,1,   1,   1,   1,1.03060,   8.0176
    11,'BRAYTON PT  ', 115.0000,1,   1,   1,   1,1.01169,   6.7075
    12,'BRIDGEWATER ', 115.0000,1,   1,   1,   1,1.02371,   5.9431
    13,'PILGRIM     ', 345.0000,1,   1,   1,   1,1.04565,  10.6737
```

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```
   14,'CANAL       ', 345.0000,1,   1,   1,   1,1.03950,  10.3866
   15,'WALPOLA     ', 345.0000,1,   1,   1,   1,1.02697,   3.4395
   16,'VERMONT YNK ', 345.0000,1,   1,   1,   1,1.04108,   4.4713
   17,'SCOBIE      ', 345.0000,1,   1,   1,   1,1.04016,   3.2759
   18,'SANDY POND  ', 115.0000,1,   1,   1,   1,1.02570,   1.5065
   19,'POWNAL      ', 345.0000,1,   1,   1,   1,1.04132,   6.4689
   20,'MAINE YANKEE', 345.0000,1,   1,   1,   1,1.04211,   9.1477
   21,'MILLSTONE PT',  24.0000,2,   1,   1,   1,1.04860,  11.8582
   22,'BRAYTON PT  ',  18.0000,2,   1,   1,   1,1.05930,  12.6562
   23,'BRAYTON PT  ',  20.0000,2,   1,   1,   1,1.01570,  11.7526
   24,'PILGRIM     ',  22.8000,2,   1,   1,   1,1.07625,  15.7768
   25,'CANAL       ',  20.0000,2,   1,   1,   1,1.06000,  18.3042
   26,'MAINE YANKEE',  20.0000,2,   1,   1,   1,1.04550,  15.7134
   27,'VERMONT YNK ',  22.0000,2,   1,   1,   1,1.04550,  11.0690
   28,'NORTHFIELD  ',  13.8000,1,   1,   1,   1,1.02751,   3.2234
   29,'NORTHFIELD  ', 345.0000,1,   1,   1,   1,1.02751,   3.2234
   30,'LUDLOW      ', 345.0000,1,   1,   1,   1,1.01622,   0.7209
   31,'MANCHESTER  ', 345.0000,1,   1,   1,   1,0.99761,   0.3966
   32,'SCOVILL ROCK', 345.0000,1,   1,   1,   1,1.00329,   1.8450
   33,'HADDAM NECK ', 345.0000,1,   1,   1,   1,1.00627,   2.5437
   34,'BLACK POND  ', 345.0000,1,   1,   1,   1,0.99603,   0.4986
   35,'SOUTHINGTEN ', 345.0000,1,   1,   1,   1,0.99524,   0.0743
   36,'CONN YANKEE ', 345.0000,2,   1,   1,   1,1.04860,   9.9630
   37,'NEW SEATHED ', 345.0000,1,   2,   1,   1,1.04419,   4.6062
   38,'GILBOA      ', 345.0000,1,   2,   1,   1,1.04210,   6.9752
   39,'LEEDS       ', 345.0000,1,   2,   1,   1,1.04100,   3.2739
   40,'NEW SEATHED ', 230.0000,1,   2,   1,   1,1.03072,   0.5762
   41,'ROTTERDAM   ', 115.0000,1,   2,   1,   1,1.02634,  -3.3709
   42,'ALBANY      ', 115.0000,2,   2,   1,   1,1.04000,  -2.5665
   43,'EDIC        ', 345.0000,1,   2,   1,   1,1.04908,   8.3430
   44,'PORTER      ', 230.0000,1,   2,   1,   1,1.04792,   6.5696
   45,'PORTER      ', 115.0000,1,   2,   1,   1,1.04349,   3.9472
   46,'COLTON      ', 115.0000,1,   2,   1,   1,1.04781,   6.1850
   47,'MOSES W     ', 230.0000,2,   2,   1,   1,1.03000,  11.6793
   48,'MOSES E     ', 230.0000,2,   2,   1,   1,1.05000,  15.0127
   49,'PLATTSBURGH ', 115.0000,1,   2,   1,   1,0.96523,  -1.1162
   50,'CLAY        ', 345.0000,2,   2,   1,   1,1.05000,  13.2144
   51,'CLAY        ', 115.0000,2,   2,   1,   1,1.04000,   8.5283
   52,'ROCHESTER   ', 345.0000,1,   2,   1,   1,1.04193,  19.4130
   53,'ROCHESTER   ', 115.0000,2,   2,   1,   1,1.03000,  18.0053
   54,'NIAGARA W   ', 230.0000,2,   2,   1,   1,1.04080,  26.9321
   55,'NIAGARA E   ', 230.0000,2,   2,   1,   1,1.04000,  26.2095
   56,'HUNTLEY     ', 230.0000,2,   2,   1,   1,1.03000,  26.8995
   57,'HUNTLEY     ', 115.0000,2,   2,   1,   1,1.03000,  25.7233
   58,'GARDENVILLE ', 230.0000,1,   2,   1,   1,1.01010,  24.5883
   59,'GARDENVILLE ', 115.0000,1,   2,   1,   1,0.99669,  22.1857
   60,'DUNKIRK     ', 230.0000,2,   2,   1,   1,1.04000,  30.2181
   61,'DUNKIRK     ', 115.0000,2,   2,   1,   1,1.04000,  26.7270
   62,'STOLLE RD   ', 230.0000,1,   2,   1,   1,1.01628,  23.9633
   63,'MEYER       ', 230.0000,1,   2,   1,   1,1.00548,  17.6467
   64,'MEYER       ', 115.0000,1,   2,   1,   1,1.00715,  14.5476
   65,'GESONIDGE   ', 115.0000,2,   2,   1,   1,1.04000,  15.7558
```

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```
   66,'WATERCURE   ', 345.0000,1,   2,   1,   1,1.01975,  20.8736
   67,'WRHL        ', 230.0000,1,   2,   1,   1,1.00265,  16.6813
   68,'HILLSIDE    ', 115.0000,2,   2,   1,   1,0.99000,  12.7432
   69,'BINGHAMTON  ', 345.0000,1,   2,   1,   1,1.01948,  14.3356
   70,'BINGHAMTON  ', 230.0000,1,   2,   1,   1,0.99894,  13.5662
   71,'BINGHAMTON  ', 115.0000,2,   2,   1,   1,1.00000,  11.1142
   72,'LAPEER      ', 115.0000,2,   2,   1,   1,1.05000,  10.1183
   73,'PLEASANT VLY', 345.0000,1,   3,   1,   1,1.03292,   1.6376
   74,'MILLWOOD    ', 345.0000,1,   3,   1,   1,1.02708,   0.2979
   75,'RAMAPO      ', 138.0000,1,   3,   1,   1,1.04944,   1.2631
   76,'RAMAPO      ', 345.0000,1,   3,   1,   1,1.04639,   0.7974
   77,'BUCHANAN    ', 345.0000,1,   3,   1,   1,1.03539,   0.5458
   78,'CE UG       ', 345.0000,3,   3,   1,   1,1.02000,   0.0000
   79,'RAV A-3     ',  22.0000,2,   3,   1,   1,1.05000,   8.1715
   80,'NORTHPORT   ', 138.0000,2,   3,   1,   1,1.02320,   0.6309
   81,'GOETHALS    ', 345.0000,1,   3,   1,   1,1.02198,  -3.2846
   82,'AK-3        ',  22.0000,2,   3,   1,   1,1.05000,   7.5680
   83,'KEITH       ', 220.0000,1,   4,   1,   1,0.95576,  22.9842
   84,'KEITH JCT   ', 118.1000,1,   4,   1,   1,0.96323,  23.4874
   85,'LAMBTON     ', 220.0000,1,   4,   1,   1,0.99128,  36.4486
   86,'LAMBTON     ',  24.0000,2,   4,   1,   1,1.00000,  41.7274
   87,'LAMBTON     ', 220.0000,1,   4,   1,   1,1.01813,  33.6520
   88,'SCOTT       ', 220.0000,1,   4,   1,   1,0.97335,  32.8563
   89,'SCOTT       ', 220.0000,1,   4,   1,   1,0.95584,  30.2514
   90,'VIDA        ', 220.0000,1,   4,   1,   1,0.95411,  30.1020
   91,'RICHVIEW    ', 220.0000,2,   4,   1,   1,1.04000,  11.2134
   92,'HANMER      ', 500.0000,2,   4,   1,   1,1.04000,  18.6819
   93,'ESSA        ', 220.0000,1,   4,   1,   1,0.96211,   7.5454
   94,'ORANGEVILLE ', 220.0000,1,   4,   1,   1,0.95948,   7.7792
   95,'DES JOAC    ', 220.0000,1,   4,   1,   1,0.97264,  14.6338
   96,'HOLDEN      ',  13.8000,1,   4,   1,   1,1.02323,  15.2006
   97,'MARTINDELE  ', 220.0000,2,   4,   1,   1,1.04000,  14.0482
   98,'STLA        ', 220.0000,2,   4,   1,   1,1.04000,  31.9721
   99,'PVR         ', 220.0000,1,   4,   1,   1,1.03842,  31.3229
  100,'PHAS        ', 220.0000,1,   4,   1,   1,1.03248,  26.3181
  101,'SAB 2       ', 220.0000,2,   4,   1,   1,1.05000,  24.3484
  102,'BP 76       ', 220.0000,1,   4,   1,   1,1.04550,  25.5246
  103,'PA 27       ', 220.0000,1,   4,   1,   1,1.04629,  25.3162
  104,'BEACH       ', 220.0000,1,   4,   1,   1,0.99699,  13.1740
  105,'BUCHANAN    ', 220.0000,1,   4,   1,   1,0.97457,  24.1225
  106,'NEALE       ', 220.0000,1,   4,   1,   1,0.99289,  14.5859
  107,'NEALE       ', 220.0000,1,   4,   1,   1,1.00616,  15.9332
  108,'S CT        ', 220.0000,1,   4,   1,   1,1.00033,  13.9155
  109,'SLT         ', 220.0000,1,   4,   1,   1,1.00029,  13.8910
  110,'BURLINGTON  ', 220.0000,1,   4,   1,   1,1.00281,  12.4399
  111,'DETWIERER   ', 220.0000,1,   4,   1,   1,0.96194,  10.0383
  112,'CHATHAM     ', 220.0000,1,   4,   1,   1,0.97541,  29.6056
  113,'LAUZON      ', 118.1000,1,   4,   1,   1,0.95230,  22.4473
  114,'MARYSVILLE  ', 220.0000,1,   5,   1,   1,0.95972,  30.6392
  115,'ST CLAIR    ', 500.0000,2,   5,   1,   1,1.02000,  33.4478
  116,'WATERMAN    ', 220.0000,1,   5,   1,   1,0.99338,  26.8500
  117,'PONTIAC     ', 230.0000,1,   5,   1,   1,1.00506,  30.8651
```

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```
   118,'WAYNE       ', 115.0000,1,    5,    1,    1,0.99857,   31.7891
   119,'THETFORD    ', 220.0000,2,    5,    1,    1,1.00000,   30.2408
   120,'ARGENTA     ', 220.0000,2,    5,    1,    1,1.02000,   26.6696
   121,'SC415       ', 220.0000,2,    5,    1,    1,1.04000,   32.8926
   122,'WATERMAN    ', 220.0000,2,    5,    1,    1,1.05000,   32.3212
   123,'MONROE      ', 230.0000,2,    5,    1,    1,1.01000,   37.6123
   124,'BRANCHBURG  ', 230.0000,1,    6,    1,    1,1.04471,    2.3841
   125,'LINDON      ', 230.0000,1,    6,    1,    1,1.02196,   -3.4160
   126,'HUDSON      ', 230.0000,1,    6,    1,    1,1.02261,   -5.3945
   127,'ALBURTIS    ', 500.0000,1,    6,    1,    1,1.04853,    6.5520
   128,'WHITPAIN    ', 500.0000,1,    6,    1,    1,1.03926,    2.7377
   129,'KEENEY      ', 500.0000,1,    6,    1,    1,1.02303,    8.9401
   130,'PEACH BOTTOM', 500.0000,2,    6,    1,    1,1.02000,   12.1966
   131,'CONASTONE   ', 500.0000,1,    6,    1,    1,1.02604,   13.4125
   132,'JUNIATA     ', 500.0000,1,    6,    1,    1,1.03978,   19.5565
   133,'CONEMAUGH   ', 500.0000,2,    6,    1,    1,1.02000,   34.3480
   134,'HOMER CITY  ', 230.0000,2,    6,    1,    1,1.03000,   25.5764
   135,'KEYSTONE    ', 500.0000,2,    6,    1,    1,1.02000,   35.0063
   136,'ERIE W      ', 345.0000,1,    6,    1,    1,1.00058,   19.7176
   137,'ERIE S      ', 230.0000,2,    6,    1,    1,1.04000,   20.3245
   138,'E TOMANO    ', 230.0000,1,    6,    1,    1,0.97073,   13.5527
   139,'KYGER       ', 345.0000,2,    6,    1,    1,1.01000,   29.3780
   140,'TE          ', 230.0000,1,    6,    1,    1,1.04132,   30.2102
 0 /End of Bus data, Begin Load data
     3,'1 ',1,   1,   1,     9.000,    88.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     6,'1 ',1,   1,   1,   320.000,   153.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     7,'1 ',1,   1,   1,   329.000,    32.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
     9,'1 ',1,   1,   1,   158.000,    30.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    11,'1 ',1,   1,   1,   680.000,   103.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    12,'1 ',1,   1,   1,   274.000,   115.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    14,'1 ',1,   1,   1,   248.000,    85.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    15,'1 ',1,   1,   1,   309.000,   -92.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    16,'1 ',1,   1,   1,   224.000,    47.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    17,'1 ',1,   1,   1,   139.000,    17.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    18,'1 ',1,   1,   1,   281.000,    76.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    19,'1 ',1,   1,   1,   206.000,    28.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    20,'1 ',1,   1,   1,   284.000,    27.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    30,'1 ',1,   1,   1,   322.000,     2.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
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    31,'1 ',1,   1,   1,   500.000,   184.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    34,'1 ',1,   1,   1,   234.000,    84.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    35,'1 ',1,   1,   1,   522.000,   177.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    36,'1 ',1,   1,   1,     9.000,     5.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    41,'1 ',1,   2,   1,   700.000,   125.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    42,'1 ',1,   2,   1,   177.000,    17.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    45,'1 ',1,   2,   1,   256.000,    17.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    46,'1 ',1,   2,   1,   177.000,    25.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    46,'2 ',1,   2,   1,  -154.000,   -67.500,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    47,'1 ',1,   2,   1,   528.000,   100.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    49,'1 ',1,   2,   1,   208.000,    17.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    51,'1 ',1,   2,   1,   731.000,    75.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    53,'1 ',1,   2,   1,   923.000,   250.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    54,'1 ',1,   2,   1,    20.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    55,'1 ',1,   2,   1,   939.000,   132.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    56,'1 ',1,   2,   1,   172.000,    44.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    57,'1 ',1,   2,   1,   240.000,    -6.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    58,'1 ',1,   2,   1,    84.000,    38.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    59,'1 ',1,   2,   1,   705.000,   198.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    61,'1 ',1,   2,   1,   237.000,     8.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    64,'1 ',1,   2,   1,   143.000,    25.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    65,'1 ',1,   2,   1,    91.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    68,'1 ',1,   2,   1,   211.000,    41.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    71,'1 ',1,   2,   1,   371.000,    53.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    74,'1 ',1,   3,   1,   102.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    78,'1 ',1,   3,   1,  2000.000,   600.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
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    80,'1 ',1,   3,   1,   700.000,    25.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    83,'1 ',1,   4,   1,    80.000,    16.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    85,'1 ',1,   4,   1,    18.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    86,'1 ',1,   4,   1,    50.000,    25.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    88,'1 ',1,   4,   1,   110.000,    55.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    89,'1 ',1,   4,   1,   100.000,    70.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    90,'1 ',1,   4,   1,   115.000,    45.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    91,'1 ',1,   4,   1,  1650.000,   500.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    92,'1 ',1,   4,   1,    10.000,   320.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    93,'1 ',1,   4,   1,   125.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    94,'1 ',1,   4,   1,    95.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    95,'1 ',1,   4,   1,    25.000,   100.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    95,'2 ',1,   4,   1,  -125.000,   -13.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    96,'1 ',1,   4,   1,    20.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    96,'2 ',1,   4,   1,   -60.000,   -25.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    97,'1 ',1,   4,   1,   910.000,    50.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   101,'1 ',1,   4,   1,   350.000,   130.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   104,'1 ',1,   4,   1,   200.000,    90.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   105,'1 ',1,   4,   1,   325.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   106,'1 ',1,   4,   1,     0.000,   -12.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   107,'1 ',1,   4,   1,     0.000,   -19.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   108,'1 ',1,   4,   1,     0.000,   -13.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   109,'1 ',1,   4,   1,     0.000,   -13.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   110,'1 ',1,   4,   1,   718.000,   125.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   111,'1 ',1,   4,   1,   399.000,    45.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   113,'1 ',1,   4,   1,   206.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
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   114,'1 ',1,    5,    1,      0.000,     90.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   115,'1 ',1,    5,    1,    100.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   116,'1 ',1,    5,    1,    200.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   117,'1 ',1,    5,    1,    400.000,     97.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   118,'1 ',1,    5,    1,    280.000,     86.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   119,'1 ',1,    5,    1,    750.000,    200.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   120,'1 ',1,    5,    1,    946.000,    -40.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   123,'1 ',1,    5,    1,     63.000,     10.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   124,'1 ',1,    6,    1,    370.000,     71.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   124,'2 ',1,    6,    1,      0.000,    -22.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   125,'1 ',1,    6,    1,    320.000,      5.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   126,'1 ',1,    6,    1,    450.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   127,'1 ',1,    6,    1,    200.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   127,'2 ',1,    6,    1,      0.000,   -150.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   128,'1 ',1,    6,    1,    970.000,     60.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   128,'2 ',1,    6,    1,      0.000,   -162.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   129,'1 ',1,    6,    1,    610.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   129,'2 ',1,    6,    1,      0.000,    -50.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   130,'1 ',1,    6,    1,    180.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   131,'1 ',1,    6,    1,   1160.000,    468.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   131,'2 ',1,    6,    1,      0.000,   -900.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   132,'1 ',1,    6,    1,    210.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   132,'2 ',1,    6,    1,      0.000,   -337.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   135,'1 ',1,    6,    1,    170.000,      0.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   136,'1 ',1,    6,    1,    270.000,    223.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
   138,'1 ',1,    6,    1,    110.000,     64.000,      0.000,      0.000,      0.
↪000,      0.000,    1,1
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0 /End of Load data, Begin Fixed shunt data
0 /End of Fixed shunt data, Begin Generator data
   21,'1 ',   650.000,   215.117,   999.000,  -999.000,1.04860,     0,   750.
↪000, 0.00000E+0, 2.17500E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   22,'1 ',   632.000,   208.118,   999.000,  -999.000,1.05930,     0,   700.
↪000, 0.00000E+0, 2.06500E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   23,'1 ',   276.650,    10.788,   999.000,  -999.000,1.01570,     0,   300.
↪000, 0.00000E+0, 9.99000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   23,'2 ',   226.350,     8.827,  9999.000, -9999.000,1.01570,     0,   300.
↪000, 0.00000E+0, 2.23500E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   24,'1 ',   700.000,   261.533,   999.000,  -999.000,1.07625,     0,   800.
↪000, 0.00000E+0, 2.32000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   25,'1 ',   560.000,   108.222,   999.000,  -999.000,1.06000,     0,   650.
↪000, 0.00000E+0, 2.09300E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   26,'1 ',   800.000,    27.488,   999.000,  -999.000,1.04550,     0,   900.
↪000, 0.00000E+0, 2.81700E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   27,'1 ',   540.000,    37.044,   999.000,  -999.000,1.04550,     0,   600.
↪000, 0.00000E+0, 1.80000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   36,'1 ',   554.000,   217.901,   999.000,  -999.000,1.04860,     0,   650.
↪000, 0.00000E+0, 2.99000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   42,'1 ',   370.000,   134.949,   999.000,  -999.000,1.04000,     0,   400.
↪000, 0.00000E+0, 1.78000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   47,'1 ',   400.000,    -3.268,   999.000,  -999.000,1.03000,     0,   450.
↪000, 0.00000E+0, 3.51900E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   48,'1 ',   400.000,   107.452,   999.000,  -999.000,1.05000,     0,   500.
↪000, 0.00000E+0, 3.91000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   50,'1 ',   600.000,    41.180,   999.000,  -999.000,1.05000,     0,   700.
↪000, 0.00000E+0, 2.95000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   51,'1 ',   141.000,    20.685,   999.000,  -999.000,1.04000,     0,   150.
↪000, 0.00000E+0, 6.19500E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   53,'1 ',   833.000,   173.977,   999.000,  -999.000,1.03000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   54,'1 ',   557.500,    -0.649,   999.000,  -999.000,1.04080,     0,   650.
↪000, 0.00000E+0, 3.25000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   54,'2 ',   557.500,    -0.649,  9999.000, -9999.000,1.04080,     0,   650.
↪000, 0.00000E+0, 3.25000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
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↪9999.000, -9999.000,   1,1.0000
   55,'1 ',  1095.000,   148.655,   999.000,  -999.000,1.04000,     0,  1200.
↪000, 0.00000E+0, 3.62400E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   56,'1 ',   410.000,    87.207,   999.000,  -999.000,1.03000,     0,   500.
↪000, 0.00000E+0, 2.57500E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   57,'1 ',   298.000,     3.534,   999.000,  -999.000,1.03000,     0,   350.
↪000, 0.00000E+0, 1.62400E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   60,'1 ',   410.000,    54.828,   999.000,  -999.000,1.04000,     0,   450.
↪000, 0.00000E+0, 2.35350E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   61,'1 ',   194.000,    13.180,   999.000,  -999.000,1.04000,     0,   200.
↪000, 0.00000E+0, 1.89400E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   65,'1 ',    91.000,    51.625,   999.000,  -999.000,1.04000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   68,'1 ',    66.000,    -0.140,   999.000,  -999.000,0.99000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   71,'1 ',   134.000,  -373.660,   999.000,  -999.000,1.00000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   72,'1 ',   150.000,   379.422,   999.000,  -999.000,1.05000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   78,'1 ',   466.019,    74.010,   999.000,  -999.000,1.02000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   79,'1 ',  1000.000,   257.345,   999.000,  -999.000,1.05000,     0,  1150.
↪000, 0.00000E+0, 3.22000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   80,'1 ',   720.000,    -0.078,   999.000,  -999.000,1.02320,     0,   800.
↪000, 0.00000E+0, 2.00000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   82,'1 ',   460.000,   125.095,   999.000,  -999.000,1.05000,     0,   500.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   86,'1 ',  1650.000,   251.799,   999.000,  -999.000,1.00000,     0,  1900.
↪000, 0.00000E+0, 1.90000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   91,'1 ',   930.000,  1082.086,  9999.000, -9999.000,1.04000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   92,'1 ',   450.000,   324.468,   999.000,  -999.000,1.04000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   97,'1 ',   600.000,    96.902,   999.000,  -999.000,1.04000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
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    98,'1 ',   585.000,    33.013,   999.000,  -999.000,1.04000,     0,   650.
↪000, 0.00000E+0, 9.75000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   101,'1 ',  1200.000,   506.878,   999.000,  -999.000,1.05000,     0,  1350.
↪000, 0.00000E+0, 2.29500E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   115,'1 ',   550.000,   269.536,   999.000,  -999.000,1.02000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   119,'1 ',   550.000,   145.624,   999.000,  -999.000,1.00000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   120,'1 ',   700.000,    57.157,   999.000,  -999.000,1.02000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   121,'1 ',   145.000,   157.850,   999.000,  -999.000,1.04000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   122,'1 ',   155.000,   127.774,   999.000,  -999.000,1.05000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   123,'1 ',   655.000,    58.623,   999.000,  -999.000,1.01000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   130,'1 ',   490.000,  -467.860,   999.000,  -999.000,1.02000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   133,'1 ',  1700.000,  -141.013,   999.000,  -999.000,1.02000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   134,'1 ',   880.000,    43.093,   999.000,  -999.000,1.03000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   135,'1 ',  2330.000,  -100.279,   999.000,  -999.000,1.02000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   137,'1 ',    70.000,   174.600,   999.000,  -999.000,1.04000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
   139,'1 ',   115.000,    18.439,   999.000,  -999.000,1.01000,     0,   100.
↪000, 0.00000E+0, 2.00000E-2, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000, -9999.000,   1,1.0000
 0 /End of Generator data, Begin Branch data
    1,      2,'1 ', 4.00000E-4, 4.30000E-3,   0.07000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    1,      4,'1 ', 4.00000E-4, 4.30000E-3,   0.07000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    2,     33,'1 ', 7.00000E-4, 8.20000E-3,   0.14000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    4,      5,'1 ', 9.00000E-4, 1.01000E-2,   0.17000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    5,      6,'1 ', 1.80000E-3, 2.17000E-2,   0.37000,    0.00,    0.00,   ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     5,     31,'1 ', 8.00000E-4, 1.29000E-2,   0.14000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
     6,      7,'1 ', 9.00000E-4, 9.40000E-3,   0.17000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     7,      8,'1 ', 7.00000E-4, 8.90000E-3,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     7,     10,'1 ', 1.60000E-3, 1.95000E-2,   0.30000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     7,     12,'1 ', 8.00000E-4, 1.35000E-2,   0.25000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     7,     15,'1 ', 3.00000E-4, 5.90000E-3,   0.07000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     8,      9,'1 ', 7.00000E-4, 8.20000E-3,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     8,     18,'1 ', 1.30000E-3, 1.73000E-2,   0.32000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
     9,     30,'1 ', 1.10000E-3, 1.33000E-2,   0.21000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    12,     13,'1 ', 8.00000E-4, 1.40000E-2,   0.26000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    13,     14,'1 ', 6.00000E-4, 9.60000E-3,   0.18000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    14,     15,'1 ', 2.20000E-3, 3.50000E-2,   0.36000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    16,     17,'1 ', 3.20000E-3, 3.23000E-2,   0.53000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    16,     29,'1 ', 7.00000E-3, 8.60000E-3,   0.15000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    17,     18,'1 ', 1.40000E-3, 1.47000E-2,   0.24000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    17,     19,'1 ', 4.30000E-3, 4.74000E-2,   0.78000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    17,     20,'1 ', 5.70000E-3, 6.25000E-2,   1.03000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    19,     20,'1 ', 1.40000E-3, 1.51000E-2,   0.25000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    29,     30,'1 ', 1.30000E-3, 1.51000E-2,   0.26000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    29,     37,'1 ', 3.50000E-3, 4.11000E-2,   0.70000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    30,     31,'1 ', 1.30000E-3, 2.13000E-2,   0.22000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    31,     32,'1 ', 8.00000E-4, 1.28000E-2,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    32,     33,'1 ', 2.00000E-4, 2.60000E-3,   0.04000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    32,     35,'1 ', 8.00000E-4, 1.12000E-2,   0.15000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    33,     34,'1 ', 6.00000E-4, 9.20000E-3,   0.11000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    34,     35,'1 ', 4.00000E-4, 4.60000E-3,   0.08000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   35,     73,'1 ', 2.30000E-3, 3.63000E-2,   0.38000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   37,     38,'1 ', 1.60000E-3, 1.63000E-2,   0.25000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   37,     39,'1 ', 8.00000E-4, 7.40000E-3,   0.48000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   37,     40,'1 ', 9.00000E-4, 3.15000E-2,   0.06000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   37,     43,'1 ', 1.30000E-3, 1.88000E-2,   1.31000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   38,     69,'1 ', 4.30000E-3, 4.85000E-2,   0.79000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   39,     73,'1 ', 1.90000E-3, 1.83000E-2,   0.29000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   39,     73,'2 ', 1.90000E-3, 1.83000E-2,   0.29000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   40,     44,'1 ', 8.00000E-3, 5.30000E-2,   0.40000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   41,     42,'1 ', 1.80000E-3, 8.90000E-3,   0.07000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   41,     45,'1 ', 7.76000E-2, 2.24100E-1,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   43,     44,'1 ', 0.00000E+0, 1.10000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   43,     50,'1 ', 2.50000E-3, 2.68000E-2,   0.40000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   43,     50,'2 ', 2.50000E-3, 2.68000E-2,   0.40000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   44,     45,'1 ', 0.00000E+0, 2.05000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   44,     48,'1 ', 1.50000E-2, 1.05000E-1,   0.79000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   45,     46,'1 ', 1.23500E-1, 3.54800E-1,   0.16000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   45,     51,'1 ', 6.05000E-2, 1.89600E-1,   0.08000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   45,     71,'1 ', 1.75100E-1, 5.57500E-1,   0.12000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   46,     47,'1 ', 6.32000E-2, 1.21000E-1,   0.05000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   46,     49,'1 ', 1.64000E-1, 5.78000E-1,   0.06000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   47,     48,'1 ', 0.00000E+0, 3.30000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   50,     51,'1 ', 0.00000E+0, 2.07000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   50,     52,'1 ', 2.00000E-3, 2.20000E-2,   1.28000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   51,     53,'1 ', 8.44000E-2, 2.16100E-1,   0.22000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   51,     72,'1 ', 5.10000E-3, 2.32000E-2,   0.30000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    52,     53,'1 ', 1.40000E-3, 3.88000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    53,     55,'1 ', 3.00000E-2, 1.07000E-1,   0.30000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    53,     65,'1 ', 3.50000E-2, 8.00000E-2,   0.05000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    54,     56,'1 ', 1.00000E-2, 8.00000E-3,   0.07000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    54,     62,'1 ', 8.00000E-3, 6.90000E-2,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    54,    102,'1 ', 1.60000E-3, 2.48000E-2,   0.06000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    54,    103,'1 ', 1.60000E-3, 2.48000E-2,   0.06000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    55,     57,'1 ', 7.40000E-3, 4.00000E-2,   0.02000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    55,     59,'1 ', 1.60000E-2, 8.17000E-2,   0.04000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    56,     58,'1 ', 2.00000E-3, 1.50000E-2,   0.11000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    57,     59,'1 ', 1.40000E-2, 6.80000E-2,   0.03000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    58,     60,'1 ', 3.50000E-3, 3.44000E-2,   0.27000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    58,     62,'1 ', 2.00000E-3, 1.80000E-2,   0.03000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    59,     61,'1 ', 6.80000E-2, 1.43000E-1,   0.06000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    60,    140,'1 ', 3.90000E-3, 3.63000E-2,   0.07000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    62,     63,'1 ', 1.29000E-2, 8.03000E-2,   0.15000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    63,     64,'1 ', 0.00000E+0, 4.60000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    63,     67,'1 ', 1.20000E-2, 9.30000E-2,   0.18000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    64,     65,'1 ', 3.50000E-2, 8.00000E-2,   0.05000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    64,     68,'1 ', 9.88000E-2, 2.31000E-1,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    66,     67,'1 ', 0.00000E+0, 2.31000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    66,     69,'1 ', 1.80000E-3, 2.74000E-2,   0.27000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    66,    134,'1 ', 7.60000E-4, 1.14100E-2,   1.16000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    67,     68,'1 ', 0.00000E+0, 4.90000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    67,     70,'1 ', 7.00000E-3, 6.19000E-2,   0.12000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    67,    138,'1 ', 6.30000E-3, 4.91000E-2,   0.09000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    68,     71,'1 ', 1.20300E-1, 2.04800E-1,   0.07000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    69,     71,'1 ', 0.00000E+0, 3.75000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    70,     71,'1 ', 0.00000E+0, 4.90000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    71,     72,'1 ', 5.30000E-3, 1.35000E-2,   0.10000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    73,     74,'1 ', 2.20000E-3, 1.96000E-2,   0.34000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    73,     74,'2 ', 2.20000E-3, 1.96000E-2,   0.34000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    74,     77,'1 ', 3.00000E-4, 4.30000E-3,   0.08000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    74,     78,'1 ', 5.00000E-4, 4.50000E-3,   0.32000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    74,     78,'2 ', 5.00000E-4, 4.50000E-3,   0.32000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    75,    124,'1 ', 7.00000E-4, 1.75000E-2,   1.39000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    76,     77,'1 ', 3.00000E-3, 6.80000E-3,   1.37000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    78,     79,'1 ', 3.00000E-4, 1.53000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    78,     80,'1 ', 1.35000E-2, 5.82000E-2,   0.50000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    78,     81,'1 ', 5.00000E-4, 2.76000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    78,     82,'1 ', 5.00000E-4, 3.08000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    81,    125,'1 ', 1.00000E-4, 1.10000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    83,    112,'1 ', 1.85000E-2, 1.53700E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    83,    113,'1 ', 3.70000E-3, 2.02000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    84,    116,'1 ', 1.50000E-3, 1.04500E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    85,     88,'1 ', 1.60000E-3, 2.02000E-2,   0.03000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    85,     88,'2 ', 1.60000E-3, 2.02000E-2,   0.03000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    85,    105,'1 ', 1.00000E-2, 1.09000E-1,   0.18000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    85,    105,'2 ', 1.00000E-2, 1.09000E-1,   0.18000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    85,    112,'1 ', 6.90000E-3, 5.95000E-2,   0.10000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    85,    112,'2 ', 6.90000E-3, 5.95000E-2,   0.10000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    87,    115,'1 ', 1.00000E-4, 1.80000E-3,   0.02000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   88,     89,'1 ', 5.00000E-4, 2.05000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   88,    105,'1 ', 1.12000E-2, 9.93000E-2,   0.17000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   88,    105,'2 ', 1.12000E-2, 9.93000E-2,   0.17000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   89,     90,'1 ', 1.30000E-3, 4.90000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   89,    105,'1 ', 8.94000E-2, 3.36300E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   89,    113,'1 ', 1.45600E-1, 4.11500E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   90,    114,'1 ', 2.40000E-3, 1.50000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   91,     92,'1 ', 5.80000E-3, 9.28000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   91,     93,'1 ', 4.21000E-2, 2.93200E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   91,     95,'1 ', 2.61000E-2, 1.84400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   91,     98,'1 ', 1.20000E-2, 8.54000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   91,    110,'1 ', 1.70000E-3, 1.17000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   92,     97,'1 ', 8.00000E-4, 3.03000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   93,     94,'1 ', 4.20000E-3, 2.83000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   93,     95,'1 ', 1.87000E-2, 1.28400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   94,    111,'1 ', 4.90000E-3, 3.36000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   95,     96,'1 ', 1.36000E-2, 9.55000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   96,     97,'1 ', 1.60000E-2, 7.67000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   98,     99,'1 ', 3.00000E-4, 9.20000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   99,    100,'1 ', 1.00000E-3, 7.02000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    104,'1 ', 7.70000E-3, 7.73000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    105,'1 ', 1.88000E-2, 1.49300E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    107,'1 ', 7.60000E-3, 7.51000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    108,'1 ', 7.80000E-3, 7.72000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    109,'1 ', 7.80000E-3, 7.83000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    110,'1 ', 4.82000E-2, 2.63600E-1,   0.00000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  104,    106,'1 ', 1.80000E-3, 1.80000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  104,    110,'1 ', 6.00000E-4, 6.20000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  105,    106,'1 ', 1.65000E-2, 1.15600E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  105,    107,'1 ', 1.15000E-2, 1.10300E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  105,    111,'1 ', 1.31000E-2, 8.09000E-2,   0.13000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  105,    112,'1 ', 8.00000E-3, 4.97000E-2,   0.30000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  105,    113,'1 ', 3.82400E-1, 9.47900E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  107,    110,'1 ', 2.10000E-3, 1.86000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  108,    110,'1 ', 2.60000E-3, 1.94000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  108,    111,'1 ', 5.90000E-3, 5.77000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  109,    110,'1 ', 2.60000E-3, 1.94000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  109,    111,'1 ', 5.90000E-3, 5.77000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  112,    113,'1 ', 1.01000E-2, 8.73000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  114,    117,'1 ', 6.63000E-2, 3.69600E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  114,    119,'1 ', 8.76000E-2, 2.54000E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  114,    121,'1 ', 6.30000E-3, 8.02000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    116,'1 ', 7.33000E-2, 9.79900E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    117,'1 ', 1.00000E-3, 1.14000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    118,'1 ', 1.65700E-1, 1.55100E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    119,'1 ', 3.30000E-3, 3.92000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    121,'1 ', 2.20000E-2, 2.98400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    135,'1 ', 0.00000E+0, 6.30900E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  115,    139,'1 ', 0.00000E+0, 1.24300E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  116,    117,'1 ', 4.74000E-2, 2.63100E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  116,    118,'1 ', 1.17000E-2, 7.44000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  116,    120,'1 ', 2.30700E-1, 7.04100E-1,   0.00000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  116,    121,'1 ', 9.51000E-2, 4.57600E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  116,    122,'1 ', 3.30000E-3, 1.28700E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  117,    118,'1 ', 2.00000E-3, 1.99000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  117,    119,'1 ', 1.70000E-3, 1.89000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  117,    120,'1 ', 6.70000E-3, 7.97000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  117,    121,'1 ', 1.50000E-2, 8.69000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  117,    122,'1 ', 3.83000E-2, 8.86000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    120,'1 ', 5.00000E-3, 6.29000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    121,'1 ', 1.39100E-1, 4.79800E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    122,'1 ', 9.50000E-2, 5.07100E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    123,'1 ', 1.40000E-3, 1.74000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  119,    120,'1 ', 1.06500E-1, 3.49800E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  119,    121,'1 ', 1.63600E-1, 5.80400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  121,    122,'1 ', 1.25000E-1, 4.69900E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  122,    135,'1 ', 5.73000E-2, 7.58100E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  122,    139,'1 ', 0.00000E+0, 1.53200E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  124,    125,'1 ', 2.50000E-3, 7.30000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  124,    126,'1 ', 0.00000E+0, 8.39000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  124,    127,'1 ', 4.00000E-4, 1.05000E-2,   0.72000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  124,    128,'1 ', 5.00000E-4, 1.17000E-2,   0.84000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  125,    126,'1 ', 0.00000E+0, 4.11000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  125,    128,'1 ', 4.90000E-3, 2.63400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  126,    127,'1 ', 0.00000E+0, 2.53200E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  126,    128,'1 ', 0.00000E+0, 2.74100E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  126,    138,'1 ', 0.00000E+0, 6.80500E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  127,    128,'1 ', 0.00000E+0, 1.33900E-1,   0.00000,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   127,    132,'1 ', 9.00000E-4, 2.21000E-2,   1.62000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   128,    129,'1 ', 0.00000E+0, 1.38100E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   128,    130,'1 ', 7.00000E-4, 1.75000E-2,   1.26000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   129,    130,'1 ', 4.00000E-4, 8.50000E-3,   0.60000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   130,    131,'1 ', 2.00000E-4, 3.80000E-3,   0.54000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   130,    132,'1 ', 7.00000E-4, 1.73000E-2,   1.25000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   131,    133,'1 ', 2.00000E-3, 3.90000E-2,   2.77000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   131,    135,'1 ', 5.70000E-3, 6.99000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   131,    139,'1 ', 5.90000E-3, 1.05200E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   132,    133,'1 ', 1.20000E-3, 2.93000E-2,   2.09000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   132,    134,'1 ', 2.35000E-3, 4.38800E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   132,    135,'1 ', 1.20000E-3, 2.88000E-2,   2.06000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   132,    138,'1 ', 3.31000E-2, 4.22400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   133,    135,'1 ', 3.00000E-4, 6.30000E-3,   0.45000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   134,    135,'1 ', 4.60000E-3, 6.25000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   134,    136,'1 ', 4.60000E-3, 7.82000E-2,   0.79000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   135,    139,'1 ', 1.77000E-2, 6.61000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   136,    139,'1 ', 0.00000E+0, 2.05400E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   137,    138,'1 ', 2.55300E-1, 7.18000E-1,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
 0 /End of Branch data, Begin Transformer data
     1,    21,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 2.00000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     3,     2,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 1.60000E-3, 4.35000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
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     3,     4,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 1.60000E-3, 4.35000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    10,    11,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 7.00000E-4, 1.38000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    10,    22,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 7.00000E-4, 1.42000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    11,    23,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 9.00000E-4, 1.80000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    13,    24,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 0.00000E+0, 1.43000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    14,    25,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 5.00000E-4, 2.72000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    16,    27,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 6.00000E-4, 2.32000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    20,    26,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 8.00000E-4, 1.56000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    28,    29,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,␣
↪1,1.0000
 0.00000E+0, 1.81000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
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↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    33,    36,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 2.50000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    40,    41,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 1.61000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    49,    48,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 1.56000E-2, 1.53600E-1,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    48,   100,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 1.00000E-3, 1.59500E-1,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    54,    52,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 2.00000E-3, 2.33000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    54,    55,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 1.30000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    56,    57,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 1.42000E-1,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    58,    59,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 9.30000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    60,    61,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
```

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```
 0.00000E+0, 6.40000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    75,    76,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 1.00000E-4, 7.40000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    84,    83,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 5.20000E-3, 1.74000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    85,    86,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 0.00000E+0, 5.70000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    87,    85,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 2.00000E-4, 2.46000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   101,   102,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 7.00000E-4, 2.11000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   101,   103,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 6.00000E-4, 1.51000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   137,   136,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'TWO-WINDINGS',1,  ␣
↪1,1.0000
 8.00000E-4, 2.39000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.10000,␣
↪0.90000, 1.10000, 0.90000,  33, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
 0 /End of Transformer data, Begin Area interchange data
   1,     0,     0.000,    10.000,'NEPOOL      '
   2,     0,     0.000,    10.000,'NYISO       '
   3,     0,     0.000,    10.000,'NYISO2      '
   4,     0,     0.000,    10.000,'IESO        '
   5,     0,     0.000,    10.000,'MISO        '
```

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```
   6,     0,     0.000,    10.000,'PJM         '
 0 /End of Area interchange data, Begin Two-terminal dc line data
 0 /End of Two-terminal dc line data, Begin VSC dc line data
 0 /End of VSC dc line data, Begin Impedance correction table data
 0 /End of Impedance correction table data, Begin Multi-terminal dc line data
 0 /End of Multi-terminal dc line data, Begin Multi-section line data
 0 /End of Multi-section line data, Begin Zone data
 0 /End of Zone data, Begin Inter-area transfer data
 0 /End of Inter-area transfer data, Begin Owner data
 0 /End of Owner data, Begin FACTS device data
 0 /End of FACTS device data, Begin Switched shunt data
 0 /End of Switched shunt data, Begin GNE device data
 0 /End of GNE device data
Q
```

Dynamic Data (PSS/E DYR format)

```
data = !cat npcc.dyr
print('\n'.join(data))
```

```
     21 'GENROU' 1     5.7000      0.30000E-01  0.35000      0.50000E-01
          4.6400       0.0000       1.9050       1.8075      0.36000
         0.36000      0.23270      0.20270       0.0000       0.0000    /
     22 'GENROU' 1     5.6900      0.30000E-01  0.35000      0.50000E-01
          4.0857       0.0000       1.8340       1.8060      0.30520
         0.30520      0.220955      0.200955       0.0000       0.0000    /
     23 'GENROU' 1     5.6000      0.30000E-01  0.35000      0.50000E-01
          2.4467       0.0000       1.7400       1.6800      0.24450
         0.24450      0.100799     0.090799   0.0000       0.0000    /
     23 'GENROU' 2     5.2000      0.30000E-01  0.35000      0.50000E-01
          6.2000       0.0000       2.1150       2.0400      0.54600
         0.54600      0.225511      0.205511       0.0000       0.0000    /
     24 'GENROU' 1     7.3000      0.30000E-01  0.35000      0.50000E-01
          4.3500       0.0000       2.0320       1.9280      0.38400
         0.38400      0.23780      0.20780       0.0000       0.0000    /
     25 'GENROU' 1     5.7000      0.30000E-01  0.35000      0.50000E-01
          4.0615       0.0000       1.9175       1.8980      0.31200
         0.31200      0.20930      0.19930       0.0000       0.0000    /
     26 'GENROU' 1     4.7900      0.30000E-01  0.35000      0.50000E-01
          3.8000       0.0000       1.8900       1.8450      0.52200
         0.52200      0.28874      0.20874       0.0000       0.0000    /
     27 'GENROU' 1     6.7000      0.30000E-01  0.35000      0.50000E-01
          4.0500       0.0000       1.7400       1.6800      0.33000
         0.33000      0.18450      0.10450       0.0000       0.0000    /
     36 'GENROU' 1     5.7000      0.30000E-01  0.35000      0.50000E-01
          4.6615       0.0000       1.9175       1.8590      0.52650
         0.52650      0.319930      0.30993       0.0000       0.0000    /
     42 'GENROU' 1     5.0000      0.30000E-01  0.35000      0.50000E-01
          4.7150       0.0000       1.2648       1.2108      0.23800
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     0.23800      0.17800      0.10800       0.0000       0.0000    /
47 'GENROU' 1     5.0000      0.30000E-01  0.35000      0.50000E-01
     3.3711       0.0000       1.3410      0.76950      0.49500
     0.49500      0.35190      0.30190       0.0000       0.0000    /
48 'GENROU' 1     5.0000      0.30000E-01  0.35000      0.50000E-01
     3.0340       0.0000       1.4900      0.85500      0.55000
     0.55000      0.39100      0.30100       0.0000       0.0000    /
50 'GENROU' 1     6.7000      0.30000E-01  0.35000      0.50000E-01
     4.9200       0.0000       1.3750       1.3050      0.39000
     0.39000      0.29500      0.20500       0.0000       0.0000    /
51 'GENROU' 1     5.5000      0.30000E-01  0.35000      0.50000E-01
     14.307       0.0000       0.46545      0.44115      0.93750E-01
     0.93750E-01  0.61950E-01  0.60950E-01   0.0000       0.0000    /
53 'GENCLS' 1     37.000       37.000    /
54 'GENROU' 1     7.0000      0.30000E-01  0.35000      0.50000E-01
     7.8831       0.0000       0.85930      0.58500      0.36790
     0.36790      0.32500      0.30500       0.0000       0.0000    /
54 'GENROU' 2     7.0000      0.30000E-01  0.35000      0.50000E-01
     7.8831       0.0000       0.85930      0.58500      0.36790
     0.36790      0.32500      0.30500       0.0000       0.0000    /
55 'GENROU' 1     7.0000      0.30000E-01  0.35000      0.50000E-01
     4.9817       0.0000       1.2192      0.77160      0.43680
     0.43680      0.36240      0.30240       0.0000       0.0000    /
56 'GENROU' 1     5.5000      0.30000E-01  0.35000      0.50000E-01
     4.3880       0.0000       1.9235       1.8485      0.35750
     0.35750      0.25750      0.20750       0.0000       0.0000    /
57 'GENROU' 1     5.6000      0.30000E-01  0.35000      0.50000E-01
     5.0600       0.0000       1.1805       1.1294      0.24465
     0.24465      0.16240      0.10240       0.0000       0.0000    /
60 'GENROU' 1     5.5000      0.30000E-01  0.35000      0.50000E-01
     4.8311       0.0000       1.7334       1.6673      0.32490
     0.32490      0.23535      0.20535       0.0000       0.0000    /
61 'GENROU' 1     5.0000      0.30000E-01  0.35000      0.50000E-01
     4.1600       0.0000       1.2768       1.2228      0.24960
     0.24960      0.18940      0.10940       0.0000       0.0000    /
65 'GENCLS' 1     10.710       10.710    /
68 'GENCLS' 1     3.7700       3.7700    /
71 'GENCLS' 1     8.5000       8.5000    /
72 'GENCLS' 1     11.770       11.770    /
78 'GENCLS' 1     1000.0       1000.0    /
79 'GENROU' 1     8.0000      0.30000E-01  0.35000      0.50000E-01
     4.1739       0.0000       2.0010       1.9550      0.36800
     0.36800      0.32200      0.30200       0.0000       0.0000    /
80 'GENROU' 1     4.0000      0.30000E-01  0.35000      0.50000E-01
     2.9750       0.0000       1.7040       1.5440      0.37600
     0.37600      0.20000      0.19000       0.0000       0.0000    /
82 'GENROU' 1     5.9000      0.30000E-01  0.35000      0.50000E-01
     3.9200       0.0000       1.5450       1.5100      0.31000
     0.31000      0.25000      0.20000       0.0000       0.0000    /
86 'GENROU' 1     6.0000      0.30000E-01  0.35000      0.50000E-01
     4.1579       0.0000       1.9000       1.5060      0.38000
     0.38000       0.2109      0.20090       0.0000       0.0000    /
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 98 'GENROU' 1     4.6000      0.30000E-01  0.35000      0.50000E-01
      11.077       0.0000       0.4550      0.32500      0.143
      0.143        0.0975       0.0775       0.0000       0.0000    /
101 'GENROU' 1     5.5000      0.30000E-01  0.35000      0.50000E-01
      4.0740       0.0000       1.0125       0.648       0.351
     0.35100       0.2295       0.2095       0.0000       0.0000    /
 91 'GENCLS' 1     98.700       98.700    /
 92 'GENCLS' 1     27.000       27.000    /
 97 'GENCLS' 1     36.000       36.000    /
115 'GENCLS' 1     46.000       46.000    /
119 'GENCLS' 1     30.000       30.000    /
120 'GENCLS' 1     1000.0       1000.0    /
121 'GENCLS' 1     66.000       66.000    /
122 'GENCLS' 1     190.00       190.00    /
123 'GENCLS' 1     33.000       33.000    /
130 'GENCLS' 1     24.000       24.000    /
133 'GENCLS' 1     1000.0       1000.0    /
134 'GENCLS' 1     44.000       44.000    /
135 'GENCLS' 1     115.00       115.00    /
137 'GENCLS' 1     3.5000       3.5000    /
139 'GENCLS' 1     1000.0       1000.0    /

 21 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 22 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 23 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 23 'TGOV1'  2    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 24 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 25 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 26 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 27 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 36 'TGOV1'  1    0.50000E-01  10.0000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 42 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 47 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 48 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 50 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 51 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
 54 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
      6.0000       6.0000       0.0000    /
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```
    54 'TGOV1'  2    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    55 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    56 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    57 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    60 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    61 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    79 'TGOV1'  1    0.50000E-01  10.0000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    80 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    82 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    86 'TGOV1'  1    0.50000E-01  10.0000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    98 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    101 'TGOV1'  1    0.30000E-01  0.50000       1.0000      0.30000
         6.0000       6.0000       0.0000    /
    119 'TGOV1'  1    0.50000E-01  10.0000       100.0000      0.30000
         6.0000       6.0000       0.0000    /
    133 'TGOV1'  1    0.50000E-01  10.0000       100.0000      0.30000
         6.0000       6.0000       0.0000    /

    21 'IEEEX1' 1     0.0000       50.000      0.60000E-01   0.0000
         0.0000       1.0000      -1.0000     -0.20000E-01  0.50000
        0.80000E-01   1.0000       0.0000       2.0000      0.16000E-02
         3.0000       1.7300    /
    22 'IEEEX1' 1     0.0000       400.00      0.20000E-01   0.0000
         0.0000       7.3000      -7.3000       1.0000      0.79000
        0.30000E-01   1.0000       0.0000       2.0000      0.16000E-02
         3.0000       1.4500    /
    23 'IEEEX1' 1     0.0000       50.000      0.60000E-01   0.0000
         0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
        0.80000E-01   1.0000       0.0000       2.0000      0.16000E-02
         3.0000       1.7300    /
    23 'IEEEX1' 2     0.0000       50.000      0.60000E-01   0.0000
         0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
        0.80000E-01   1.0000       0.0000       2.0000      0.16000E-02
         3.0000       1.7300    /
    24 'IEEEX1' 1     0.0000       50.000      0.20000E-01   0.0000
         0.0000       1.0000      -1.0000     -0.40000E-01  0.47000
        0.60000E-01   1.2500       0.0000       2.0000      0.16000E-02
         3.0000       1.7300    /
    25 'IEEEX1' 1     0.0000       400.00      0.20000E-01   0.0000
         0.0000       6.5000      -6.5000       1.0000      0.73000
        0.30000E-01   1.0000       0.0000       2.0000      0.39000E-02
```

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```
      3.0000       1.5550    /
26 'IEEEX1' 1     0.0000       200.00      0.20000E-01   0.0000
      0.0000       4.2600      -4.2600       1.0000       1.4000
     0.30000E-01   1.0000       0.0000       2.0000      0.16000E-02
      3.0000       1.4650    /
27 'IEEEX1' 1     0.0000       50.000      0.20000E-01   0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.53000
     0.33200E-01   1.2600       0.0000       2.0000      0.16000E-02
      3.0000       1.4650    /
36 'IEEEX1' 1     0.0000       62.000      0.50000E-01   0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.40500
     0.11400      0.50000       0.0000       2.0000      0.16000E-02
      3.0000       1.7300    /
42 'IEEEX1' 1     0.0000       25.000      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.62000E-01  0.50000
     0.65710      0.35000       0.0000       2.0000      0.16000E-02
      3.0000       2.0250    /
47 'IEEEX1' 1     0.0000       16.500      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.37000E-01  0.27000
     0.60000E-01   1.0000       0.0000       2.0000      0.58000E-02
      3.0000       1.1500    /
48 'IEEEX1' 1     0.0000       16.500      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.37000E-01  0.27000
     0.60000E-01   1.0000       0.0000       2.0000      0.58000E-02
      3.0000       1.1500    /
50 'IEEEX1' 1     0.0000       50.000      0.60000E-01   0.0000
      0.0000       1.0000      -1.0000     -0.46000E-01  0.50000
     0.80000E-01   1.0000       0.0000       2.0000      0.16000E-02
      3.0000       1.5250    /
51 'IEEEX1' 1     0.0000       23.100      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.44000E-01  0.50000
     0.71430E-01  0.35000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
54 'IEEEX1' 1     0.0000       50.000      0.50000E-01   0.0000
      0.0000       5.0000      -5.0000       1.0000      0.40000
     0.80000E-01   1.0000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
54 'IEEEX1' 2     0.0000       50.000      0.50000E-01   0.0000
      0.0000       5.0000      -5.0000       1.0000      0.40000
     0.80000E-01   1.0000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
55 'IEEEX1' 1     0.0000       23.100      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
     0.71430E-01  0.35000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
56 'IEEEX1' 1     0.0000       25.000      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
     0.65710E-01  0.35000       0.0000       2.0000      0.16000E-02
      3.0000       1.6670    /
57 'IEEEX1' 1     0.0000       25.000      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
     0.65710E-01  0.35000       0.0000       2.0000      0.16000E-02
```

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```
      3.0000       2.0600    /
60 'IEEEX1' 1     0.0000       25.000      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
     0.65710      0.35000       0.0000       2.0000      0.16000E-02
      3.0000       1.6670    /
61 'IEEEX1' 1     0.0000       25.000      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.62000E-01  0.50000
     0.65710      0.35000       0.0000       2.0000      0.16000E-02
      3.0000       2.0250    /
79 'IEEEX1' 1     0.0000       50.000      0.60000E-01   0.0000
      0.0000       1.0000      -1.0000     -0.40000E-01  0.50000
     0.80000E-01  1.0000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
80 'IEEEX1' 1     0.0000       25.000      0.20000       0.0000
      0.0000       1.0000      -1.0000     -0.50000E-01  0.50000
     0.65140      0.35000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
82 'IEEEX1' 1     0.0000       50.000      0.60000E-01   0.0000
      0.0000       1.0000      -1.0000     -0.40000E-01  0.50000
     0.80000E-01  1.0000       0.0000       2.0000      0.16000E-02
      3.0000       1.4500    /
```

1.8.3 CURENT WECC Verification

Prepared by Hantao Cui. Last revised 23 May 2020.

Background

The CURENT WECC system contains 179 buses and 263 branches. Two line trip scenarios are created to verify ANDES simulation results with DSATools TSAT and Siemens PTI PSS/E.

Dynamic data is based on the CURENT WECC 179-Bus test system, which uses models GENROU, TGOV1, IEEEG1, EXST2, EXDC2, ESST3A, IEEEST, ST2CUT and ESDC2A, the saturation of which could be implemented differently across software.

Simulation Parameters

Integretion method: Trapezidal Rule (ANDES and TSAT), the default second order Adams-Bashforth method (AB-2) (PSS/E)

Time step size: `1/120` sec. (Note: step size between `1/30` to `1/120` has little impact on the ANDES results. One can use `tstep=1/30` to obtain almost the same results.)

Load conversion: static loads are converted to 100% constant impedances for both P and Q.

TSAT automatic parameter correction is disabled.

Initialization

Power flow solutions are identical across all the three software.

GENROU initialization (E_{FD}, E_{TERM}, P, Q, δ, I_d and I_q) is identical to that from **PSS/E** for all cases (with and without generator saturation). Note that I_d and I_q are in machine base in PSS/E but in system base in ANDES.

GENROU initialization (including all the internal variables $E'*d$, $E'*q$, $\psi*{kd}$, ψ_{kq}, ψ''_d, and ψ''_q) is identical to that from **OpenIPSL**.

No controller limit violation occurs during initialization.

Conclusion

The finding is that, **for particular disturbances in large systems, neither two of ANDES, TSAT and PSS/E could match**. Implementation details in commercial software are lacking. Thus, it could be futile to insist on obtaining the same results for large systems, especially with several complex models.

Nevertheless, Scenario 2 shows that ANDES results are trustworthy. **In fact, ANDES is open-source with all the implemented equations clearly documented, which makes the results highly credible for research and education purposes.**

```
import andes
import numpy as np
from andes.utils.tsat import tsat_to_df, psse_to_df, plot_comparison, run_cmp

andes.config_logger(stream_level=30)
```

Scenario 1

Line 38-39 trips and reconnects after 0.1 sec. This branch is a transformer branch that connects generator #11 on Bus 39 to Bus 38. It is the only link to Bus 39.

```
ss = run_cmp('wecc.raw', dyr='wecc.dyr', fault_line='Line_221',
             t1=1.0, t2=1.1, tstep=1/120)
```

```
<Toggle Toggle_1>: Line.Line_221 status changed to 0.0 at t=1.0 sec.
<Toggle Toggle_2>: Line.Line_221 status changed to 1.0 at t=1.1 sec.
100%|████████████████████████████████████| 100/100 [00:16<00:00,  5.89%/s]
```

```
# Line_221 information
ss.Line.cache.df_in.iloc[220]
```

```
idx       Line_221
u                1
name      Line_221
bus1            38
```

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```
bus2            39
Sn             100
fn              60
Vn1            230
Vn2             18
r           0.0005
x           0.0238
b                0
g                0
b1               0
g1               0
b2               0
g2               0
trans            1
tap              1
phi              0
owner         None
xcoord        None
ycoord        None
Name: 220, dtype: object
```

```
# Load TSAT and PSSE Outputs
omega2 = tsat_to_df('omega2.xls')
v2 = tsat_to_df('v2.xls')

omega2_psse = psse_to_df('omega2_psse.xlsx')
v2_psse = psse_to_df('v2_psse.xlsx')
omega2_psse.iloc[:, 1:] += 1
omega2_psse.iloc[:, 1:] *= 60

# prepare variable headers for TSAT and PSSE
def header_replace(fname, idx, offset, old_str, new_str):
    """
    Utility function for replacing strings in variable header
    """
    old_headers = [fname[i + offset] for i in idx]
    return [i.replace(old_str, new_str) for i in old_headers]

fname = ss.TDS.plt._fname
tsat_omega_headers = header_replace(fname, ss.GENROU.omega.a, 1, "GENROU",
↪"TSAT")
tsat_v_headers = header_replace(fname, ss.GENROU.v.a, 1 + ss.dae.n, "Bus",
↪"TSAT")

psse_omega_headers = header_replace(fname, ss.GENROU.omega.a, 1, "GENROU",
↪"PSSE")
psse_v_headers = header_replace(fname, ss.GENROU.v.a, 1 + ss.dae.n, "Bus",
↪"PSSE")
```

```
fig, ax = plot_comparison(ss, ss.GENROU.omega, omega2,
                          a=(10,), a_tsat=[10], a_psse=[10],
```

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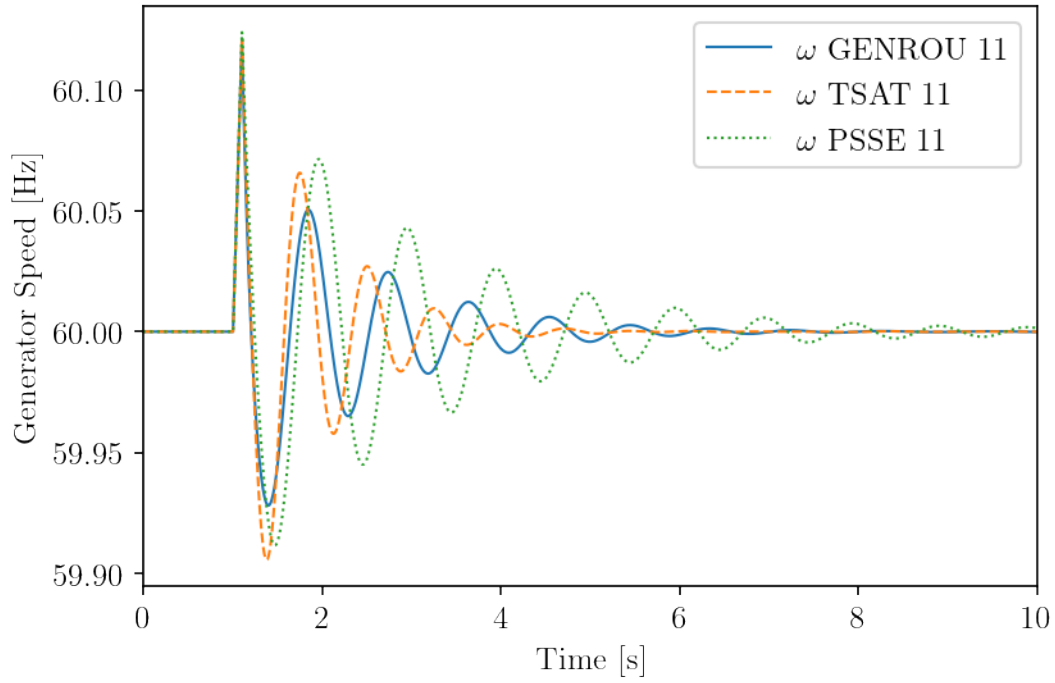
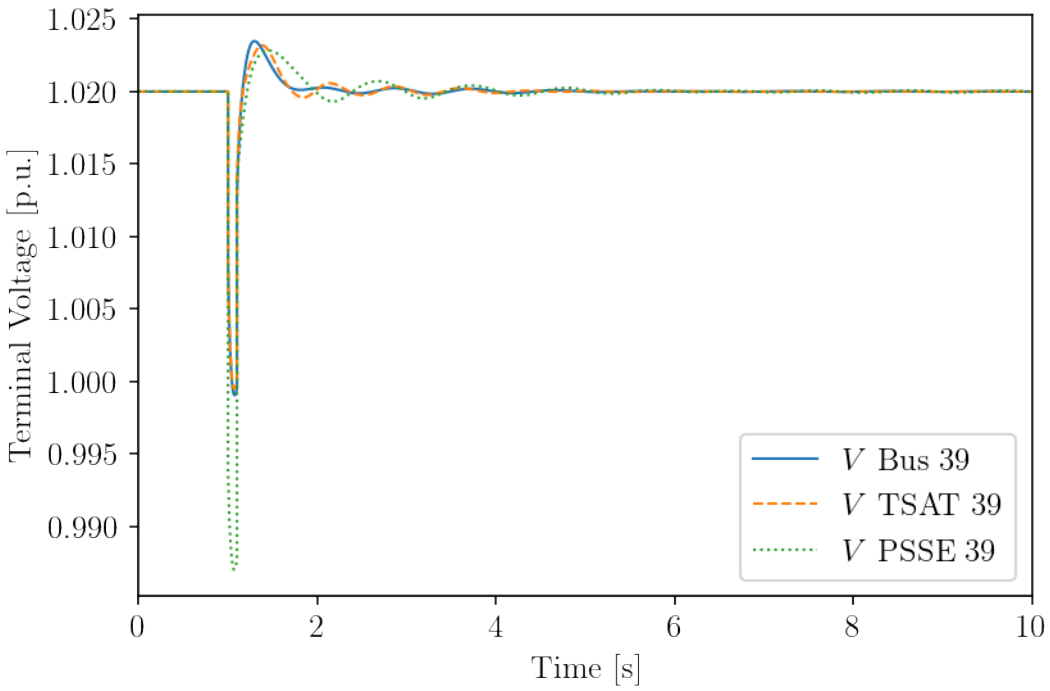
```
                          ylabel="Generator Speed [Hz]",
                          tsat_header=tsat_omega_headers,
                          psse_data = omega2_psse,
                          psse_header = psse_omega_headers,
                          scale=60, right=10,
                          legend=True,
                          show=False,
                         )
```




```
fig, ax = plot_comparison(ss, ss.GENROU.v, v2,
                          a=(10,), a_tsat=[10], a_psse=[10],
                          ylabel="Terminal Voltage [p.u.]",
                          tsat_header=tsat_v_headers,
                          psse_data = v2_psse,
                          psse_header = psse_v_headers,
                          scale=1, right=10,
                          legend=True,
                          show=False
                         )
```



Scenario 2

In this scenario, Line 4-16 trips and reconnects after 0.1 sec. This line in the eastern zone that connects two generator buses (CRAIG and SAN JUAN).

```
ss2 = run_cmp('wecc.raw', dyr='wecc.dyr', fault_line='Line_2',
              t1=1.0, t2=1.1, tstep=1/120)
```

```
<Toggle Toggle_1>: Line.Line_2 status changed to 0.0 at t=1.0 sec.
<Toggle Toggle_2>: Line.Line_2 status changed to 1.0 at t=1.1 sec.
100%|████████████████████████████████████| 100/100 [00:18<00:00,  5.45%/s]
```

```
# Line 2 information
ss2.Line.cache.df_in.iloc[1]
```

```
idx         Line_2
u                1
name        Line_2
bus1             4
bus2            16
Sn             100
fn              60
Vn1            345
Vn2            345
r          0.00977
x             0.11
b                2
```

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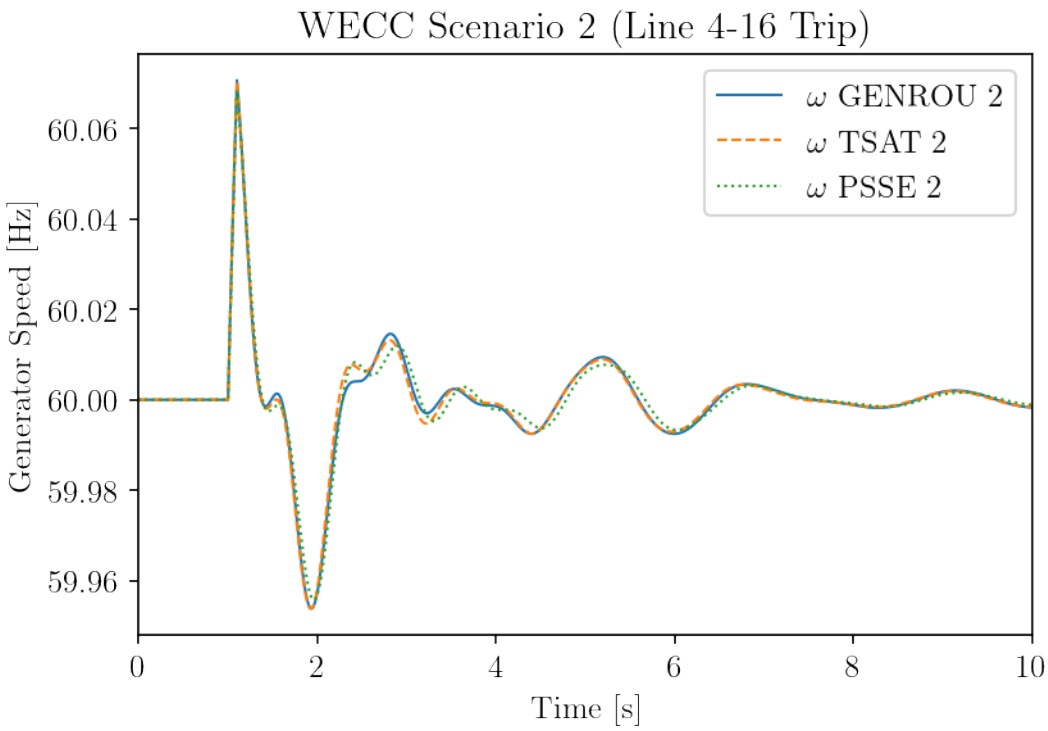
```
g               0
b1              0
g1              0
b2              0
g2              0
trans           0
tap             1
phi             0
owner        None
xcoord       None
ycoord       None
Name: 1, dtype: object
```

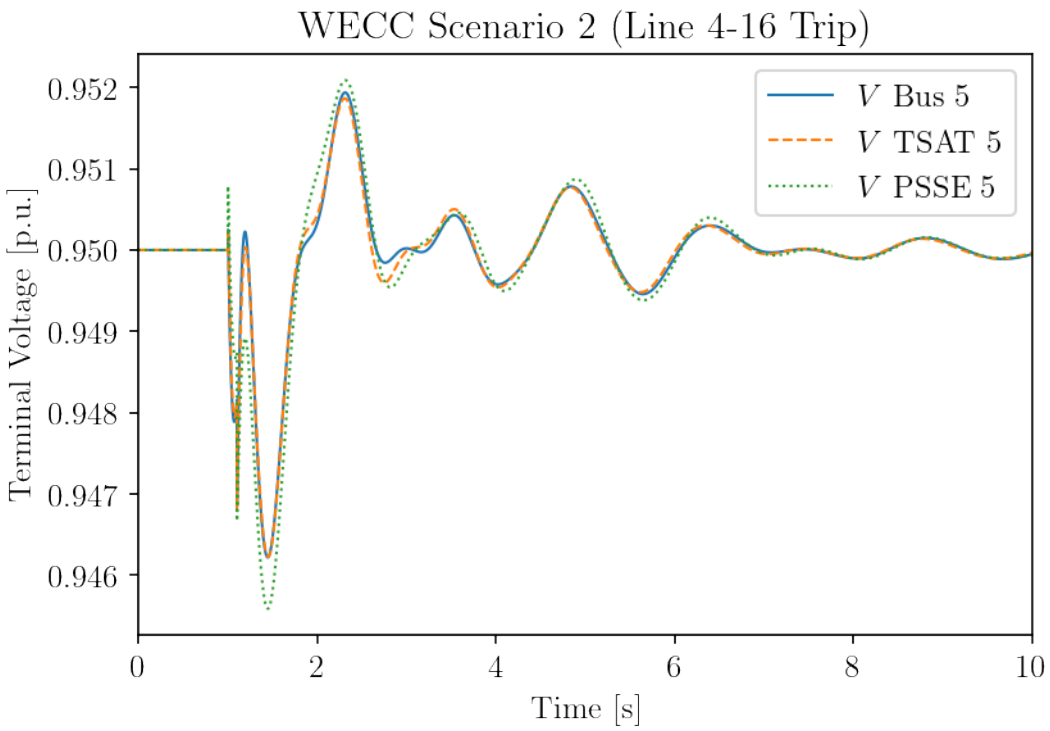
```
# load data
omega = tsat_to_df('omega.xls')
v = tsat_to_df('v.xls')

omega_psse = psse_to_df('omega_psse.xlsx')
v_psse = psse_to_df('v_psse.xlsx')
omega_psse.iloc[:, 1:] += 1
omega_psse.iloc[:, 1:] *= 60

fig, ax = plot_comparison(ss2, ss2.GENROU.omega, omega,
                          a=(1,), a_tsat=[1], a_psse=[1],
                          ylabel="Generator Speed [Hz]",
                          title="WECC Scenario 2 (Line 4-16 Trip)",
                          tsat_header=tsat_omega_headers,
                          psse_data = omega_psse,
                          psse_header = psse_omega_headers,
                          scale=60, right=10,
                          legend=True,
                          show=False
                         )
```




```
fig, ax = plot_comparison(ss2, ss2.GENROU.v, v,
                          a=(1,), a_tsat=[1], a_psse=[1],
                          ylabel="Terminal Voltage [p.u.]",
                          title="WECC Scenario 2 (Line 4-16 Trip)",
                          tsat_header=tsat_v_headers,
                          psse_data = v_psse,
                          psse_header = psse_v_headers,
                          scale=1, right=10,
                          legend=True,
                          show=False
                         )
```



Appendix: CURENT WECC 179-Bus System Data

Power Flow Data (PSS/E RAW format)

```
data = !cat wecc.raw
print('\n'.join(data))
```

```
0,   100.00,  32, 0, 1, 60.00     / PSS(R)E 32 RAW created by rawd32  THU,␣
↪MAY 21 2020  10:24
WESTERN ELECTRICITY COORDINATING COUNCIL 179-BUS SYSTEM (MOD
DISTRIBUTED WITH ANDES (HTTPS://GITHUB.COM/CUIHANTAO/ANDES)
     1,'CORONADO    ', 500.0000,1,   1,   1,   1,0.97947, -26.1745
     2,'CHOLLA      ', 345.0000,1,   1,   1,   1,0.97744, -16.9603
     3,'CORONADO    ',  20.0000,2,   1,   1,   1,1.04000, -19.6589
     4,'CRAIG       ', 345.0000,1,   1,   1,   1,0.97518,  16.2755
     5,'CRAIG       ',  22.0000,2,   1,   1,   1,0.95000,  23.5536
     6,'FOURCORN    ', 500.0000,1,   1,   1,   1,1.06814,  -7.9038
     7,'FOURCORN    ', 345.0000,1,   1,   1,   1,1.00914,  -4.6874
     8,'FCNGN4CC    ',  22.0000,2,   1,   1,   1,1.00000,   2.2301
     9,'FOURCORN    ', 230.0000,1,   1,   1,   1,1.00726,  -5.2308
    10,'HAYDEN      ',  20.0000,2,   1,   1,   1,1.00000,  33.7299
    11,'NAVAJO      ', 500.0000,1,   2,   1,   1,1.07205, -23.9351
    12,'NAVAJO 2    ',  26.0000,2,   2,   1,   1,1.00000, -17.8112
    13,'MOENKOPI    ', 500.0000,1,   2,   1,   1,1.06735, -24.8548
    14,'PALOVRD2    ',  24.0000,2,   2,   1,   1,0.96000, -21.7139
    15,'PALOVRDE    ', 500.0000,1,   2,   1,   1,1.04856, -29.6406
```

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```
 16,'SAN JUAN    ', 345.0000,1,   1,   1,   1,1.03559,  -3.8744
 17,'SJUAN G4    ',  22.0000,2,   1,   1,   1,1.00000,  -0.8871
 18,'WESTWING    ', 500.0000,1,   2,   1,   1,1.05593, -29.5910
 19,'NAVAJO1     ', 500.0000,1,   2,   1,   1,1.07025, -22.8500
 20,'NAVAJO2     ', 500.0000,1,   2,   1,   1,1.06042, -25.9522
 21,'NAVAJO3     ', 500.0000,1,   2,   1,   1,1.04693, -22.1208
 22,'NAVAJO4     ', 500.0000,1,   2,   1,   1,1.02564, -31.4586
 23,'MOENKOP1    ', 500.0000,1,   2,   1,   1,1.05571, -23.3906
 24,'MOENKOP2    ', 500.0000,1,   2,   1,   1,1.04116, -31.0832
 25,'MOENKOP3    ', 500.0000,1,   2,   1,   1,1.05132, -15.5499
 26,'MOENKOP4    ', 500.0000,1,   2,   1,   1,1.04671, -42.3967
 27,'FOURCOR1    ', 500.0000,1,   1,   1,   1,1.06585,  -5.7792
 28,'FOURCOR2    ', 500.0000,1,   1,   1,   1,1.06933, -27.9822
 29,'CANAD G1    ',  20.0000,2,   1,   1,   1,1.00000,  24.7380
 30,'CANADA      ', 500.0000,1,   1,   1,   1,1.03634,  20.9474
 31,'CANALB      ', 500.0000,1,   1,   1,   1,1.07861,  49.2370
 32,'CA230TO     ', 230.0000,1,   1,   1,   1,0.97855,  53.8260
 33,'CA230       ', 230.0000,1,   1,   1,   1,1.00114,  62.8749
 34,'CMAIN GM    ',  20.0000,2,   1,   1,   1,1.02000,  67.7961
 35,'BRIDGER2    ',  22.0000,2,   1,   1,   1,1.00900,   2.4615
 36,'ADELANTO    ', 500.0000,1,   2,   1,   1,1.06032, -42.1554
 37,'ADELAN&1    ', 500.0000,1,   2,   1,   1,1.08090, -46.2256
 38,'CASTAIC     ', 230.0000,1,   2,   1,   1,1.03195, -47.2901
 39,'CASTAI4G    ',  18.0000,2,   2,   1,   1,1.02000, -45.9803
 40,'GLENDAL     ', 230.0000,1,   2,   1,   1,1.02337, -50.9223
 41,'HAYNES      ', 230.0000,1,   2,   1,   1,1.03129, -50.6520
 42,'HAYNES3G    ',  18.0000,2,   2,   1,   1,1.00000, -47.3488
 43,'INTERMT     ', 345.0000,1,   1,   1,   1,1.05257,  -4.3661
 44,'INTERM1G    ',  26.0000,2,   1,   1,   1,1.05000,   0.2811
 45,'OLIVE       ', 230.0000,1,   2,   1,   1,1.03475, -47.6289
 46,'OWENS G     ',  11.5000,2,   2,   1,   1,1.02000, -47.2682
 47,'RINALDI     ', 230.0000,1,   2,   1,   1,1.03402, -47.8387
 48,'RINALDI     ', 500.0000,1,   2,   1,   1,1.07212, -45.4811
 49,'RIVER       ', 230.0000,1,   2,   1,   1,1.02362, -51.8438
 50,'STA B       ', 138.0000,1,   2,   1,   1,1.03256, -51.9003
 51,'STA B1      ', 287.0000,1,   2,   1,   1,1.03663, -50.7167
 52,'STA B2      ', 287.0000,1,   2,   1,   1,1.03663, -50.7167
 53,'STA BLD     ', 230.0000,1,   2,   1,   1,1.02728, -52.1086
 54,'STA E       ', 230.0000,1,   2,   1,   1,1.02516, -50.0567
 55,'STA E       ', 500.0000,1,   2,   1,   1,1.04304, -47.6632
 56,'STA F       ', 230.0000,1,   2,   1,   1,1.02484, -51.8789
 57,'STA G       ', 230.0000,1,   2,   1,   1,1.02394, -51.1740
 58,'STA J       ', 230.0000,1,   2,   1,   1,1.03112, -48.9133
 59,'SYLMARLA    ', 230.0000,1,   2,   1,   1,1.03832, -47.1488
 60,'SYLMAR S    ', 230.0000,1,   2,   1,   1,1.02073, -48.2552
 61,'VALLEY      ', 230.0000,1,   2,   1,   1,1.02930, -49.0304
 62,'VICTORVL    ', 287.0000,1,   2,   1,   1,1.05209, -44.4925
 63,'VICTORVL    ', 500.0000,1,   2,   1,   1,1.05866, -42.4751
 64,'MONTA G1    ',  20.0000,2,   1,   1,   1,1.00000,  56.5947
 65,'MONTANA     ', 500.0000,1,   1,   1,   1,1.04928,  48.2022
 66,'BIG EDDY    ', 115.0000,1,   1,   1,   1,1.06863, -16.9326
 67,'BIG EDDY    ', 230.0000,1,   1,   1,   1,1.06592, -14.5699
```

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```
   68,'BIG EDDY    ', 500.0000,1,   1,   1,   1,1.08919, -13.3098
   69,'DALLES21    ',  13.8000,2,   1,   1,   1,1.05500,  -7.9400
   70,'CELILO      ', 230.0000,1,   1,   1,   1,1.06159, -15.0760
   71,'CELILOCA    ', 500.0000,1,   1,   1,   1,1.08964, -13.4178
   72,'COLSTRP     ', 500.0000,1,   1,   1,   1,1.07839,  -1.3595
   73,'COULEE      ', 500.0000,1,   1,   1,   1,1.07000,   0.1645
   74,'GARRISON    ', 500.0000,1,   1,   1,   1,1.03705, -12.1586
   75,'JOHN DAY    ', 500.0000,1,   1,   1,   1,1.08283, -11.1230
   76,'JOHN DAY    ',  13.8000,3,   1,   1,   1,1.00000,   0.0000
   77,'HANFORD     ', 500.0000,1,   1,   1,   1,1.04947,   0.2258
   78,'NORTH G3    ',  20.0000,2,   1,   1,   1,1.00000,  26.5872
   79,'NORTH       ', 500.0000,1,   1,   1,   1,1.04993,  12.1085
   80,'BURNS       ', 500.0000,1,   1,   1,   1,1.05295, -19.5513
   81,'GRIZZLY     ', 500.0000,1,   1,   1,   1,1.06740, -17.1477
   82,'MALIN       ', 500.0000,1,   1,   1,   1,1.05433, -23.3455
   83,'MIDPOINT    ', 500.0000,1,   1,   1,   1,1.06195,  -5.1981
   84,'MIDPOINT    ', 345.0000,1,   1,   1,   1,0.99845,  -1.5707
   85,'SUMMER L    ', 500.0000,1,   1,   1,   1,1.05818, -18.2347
   86,'GRIZZLY1    ', 500.0000,1,   1,   1,   1,1.06533, -18.7474
   87,'GRIZZLY2    ', 500.0000,1,   1,   1,   1,1.07143, -16.0156
   88,'MALIN1      ', 500.0000,1,   1,   1,   1,1.05062, -14.1380
   89,'MALIN2      ', 500.0000,1,   1,   1,   1,1.06088, -19.8058
   90,'GRIZZLY3    ', 500.0000,1,   1,   1,   1,1.07997, -21.7956
   91,'GRIZZLY4    ', 500.0000,1,   1,   1,   1,1.06943, -17.2249
   92,'GRIZZLY5    ', 500.0000,1,   1,   1,   1,1.06860, -22.4488
   93,'GRIZZLY6    ', 500.0000,1,   1,   1,   1,1.07170, -17.8609
   94,'GRIZZLY7    ', 500.0000,1,   1,   1,   1,1.07926, -22.0559
   95,'GRIZZLY8    ', 500.0000,1,   1,   1,   1,1.06917, -17.2247
   96,'GRIZZLY9    ', 500.0000,1,   1,   1,   1,1.06761, -22.7454
   97,'GRIZZLYA    ', 500.0000,1,   1,   1,   1,1.07104, -17.8942
   98,'BURNS1      ', 500.0000,1,   1,   1,   1,0.97284,   8.0442
   99,'CORTINA     ', 200.0000,1,   3,   1,   1,1.13097, -34.9741
  100,'COTWDPGE    ', 200.0000,1,   3,   1,   1,1.13613, -30.4883
  101,'DIABLO      ', 500.0000,1,   2,   1,   1,1.05298, -46.1260
  102,'DIABLO1     ',  25.0000,2,   2,   1,   1,0.98000, -42.3238
  103,'GATES       ', 500.0000,1,   2,   1,   1,1.04707, -47.6820
  104,'GLENN       ', 200.0000,1,   3,   1,   1,1.14090, -34.1986
  105,'LOGAN CR    ', 200.0000,1,   3,   1,   1,1.14016, -34.5836
  106,'LOSBANOS    ', 500.0000,1,   2,   1,   1,1.04927, -49.5273
  107,'MIDWAY      ', 500.0000,1,   2,   1,   1,1.05934, -48.6051
  108,'MIDWAY      ', 200.0000,1,   2,   1,   1,1.16705, -51.4430
  109,'MOSSLAND    ', 500.0000,1,   2,   1,   1,1.04639, -49.7921
  110,'OLINDA      ', 500.0000,1,   3,   1,   1,1.03727, -31.0686
  111,'ROUND MT    ',  20.0000,2,   3,   1,   1,1.02000, -15.0791
  112,'ROUND MT    ', 200.0000,1,   3,   1,   1,1.12385, -25.1402
  113,'ROUND MT    ', 500.0000,1,   3,   1,   1,1.03454, -27.9316
  114,'TABLE MT    ', 500.0000,1,   3,   1,   1,1.01342, -32.0699
  115,'TEVATR      ',  20.0000,2,   3,   1,   1,1.05000, -35.6850
  116,'TEVATR      ', 200.0000,1,   3,   1,   1,1.12744, -39.6332
  117,'TEVATR2     ',  20.0000,2,   3,   1,   1,1.00000, -30.7816
  118,'TEVATR      ', 500.0000,1,   3,   1,   1,0.99816, -38.9938
  119,'OLINDA1     ', 500.0000,1,   3,   1,   1,1.05026, -24.0934
```

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```
 120,'OLINDA2     ', 500.0000,1,   3,   1,   1,1.01142, -38.0294
 121,'OLINDA3     ', 500.0000,1,   3,   1,   1,1.02786, -30.7891
 122,'OLINDA4     ', 500.0000,1,   3,   1,   1,0.98098, -46.5990
 123,'ROUND1      ', 500.0000,1,   3,   1,   1,1.04054, -22.0273
 124,'ROUND2      ', 500.0000,1,   3,   1,   1,1.01079, -36.1445
 125,'ROUND3      ', 500.0000,1,   3,   1,   1,1.04054, -22.0273
 126,'ROUND4      ', 500.0000,1,   3,   1,   1,1.01079, -36.1445
 127,'TABLE1      ', 500.0000,1,   3,   1,   1,1.01257, -25.8067
 128,'TABLE2      ', 500.0000,1,   3,   1,   1,0.99882, -45.3405
 129,'TABLE3      ', 500.0000,1,   3,   1,   1,1.01755, -27.3173
 130,'TABLE4      ', 500.0000,1,   3,   1,   1,0.99876, -41.4218
 131,'TEVATR1     ', 500.0000,1,   2,   1,   1,0.97999, -36.9419
 132,'TEVATR2     ', 500.0000,1,   2,   1,   1,1.07047, -51.7010
 133,'TEVATR3     ', 500.0000,1,   2,   1,   1,0.97141, -35.0590
 134,'GATES1      ', 500.0000,1,   2,   1,   1,1.06807, -49.9922
 135,'DEVERS      ', 500.0000,1,   2,   1,   1,1.03539, -43.5212
 136,'EAGLROCK    ', 230.0000,1,   2,   1,   1,1.01010, -52.7598
 137,'ELDORADO    ',  20.0000,2,   2,   1,   1,1.02000, -25.9732
 138,'ELDORADO    ', 500.0000,1,   2,   1,   1,1.05122, -33.0947
 139,'LITEHIPE    ',  20.0000,2,   2,   1,   1,1.02000, -49.6246
 140,'LITEHIPE    ', 230.0000,1,   2,   1,   1,1.01186, -55.7741
 141,'LUGO        ', 500.0000,1,   2,   1,   1,1.05498, -46.0893
 142,'MESA CAL    ', 230.0000,1,   2,   1,   1,1.00705, -55.0594
 143,'MIRALOMA    ',  20.0000,2,   2,   1,   1,1.05000, -45.4414
 144,'MIRALOMA    ', 500.0000,1,   2,   1,   1,1.04087, -49.6789
 145,'MIRALOMA    ', 230.0000,1,   2,   1,   1,1.03821, -50.1247
 146,'MOHAVE      ', 500.0000,1,   2,   1,   1,1.06999, -29.3603
 147,'MOHAV1CC    ',  22.0000,2,   2,   1,   1,1.05000, -21.0397
 148,'PARDEE      ',  20.0000,2,   2,   1,   1,1.01000, -39.5994
 149,'PARDEE      ', 230.0000,1,   2,   1,   1,1.00600, -51.6818
 150,'SERRANO     ', 500.0000,1,   2,   1,   1,1.04129, -50.0775
 151,'VALLEY      ', 500.0000,1,   2,   1,   1,1.03694, -47.7607
 152,'VINCENT     ', 500.0000,1,   2,   1,   1,1.06119, -48.9450
 153,'VINCENT     ', 230.0000,1,   2,   1,   1,0.99489, -51.6324
 154,'CAMP WIL    ', 345.0000,1,   1,   1,   1,1.04289,  -2.4160
 155,'BENLOMND    ', 345.0000,1,   1,   1,   1,1.04464,  -3.3929
 156,'BENLOMND    ', 230.0000,1,   1,   1,   1,1.04624,  -3.9585
 157,'EMERY       ', 345.0000,1,   1,   1,   1,1.03705,   4.8898
 158,'EMERY       ',  20.0000,2,   1,   1,   1,1.05000,   9.6052
 159,'MONA        ', 345.0000,1,   1,   1,   1,1.05596,  -2.0072
 160,'NAUGHTON    ', 230.0000,1,   1,   1,   1,1.04453,   0.6143
 161,'NAUGHT      ',  20.0000,2,   1,   1,   1,1.00000,   3.4140
 162,'PINTO PS    ', 345.0000,1,   1,   1,   1,1.03679,  -2.4413
 163,'PINTO       ', 345.0000,1,   1,   1,   1,1.04044,  -1.4027
 164,'SPAN FRK    ', 345.0000,1,   1,   1,   1,1.03514,  -1.0920
 165,'SIGURD      ', 345.0000,1,   1,   1,   1,1.05190,  -0.5455
 166,'TERMINAL    ', 345.0000,1,   1,   1,   1,1.03911,  -3.4207
 167,'MALIN3      ', 500.0000,1,   3,   1,   1,1.06106, -19.7689
 168,'MALIN4      ', 500.0000,1,   3,   1,   1,1.02557, -31.6678
 169,'MALIN5      ', 500.0000,1,   3,   1,   1,1.06179, -19.0138
 170,'MALIN6      ', 500.0000,1,   3,   1,   1,1.02702, -31.6971
 171,'MALIN7      ', 500.0000,1,   3,   1,   1,1.05696, -17.4396
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  172,'MALIN8      ', 500.0000,1,   3,   1,   1,1.03194, -37.1499
  173,'MIDWAY1     ', 500.0000,1,   2,   1,   1,1.04651, -48.2385
  174,'MIDWAY2     ', 500.0000,1,   2,   1,   1,1.05458, -49.3078
  175,'MIDWAY3     ', 500.0000,1,   2,   1,   1,1.04625, -48.2334
  176,'MIDWAY4     ', 500.0000,1,   2,   1,   1,1.05470, -49.3092
  177,'MIDWAY5     ', 500.0000,1,   2,   1,   1,1.04598, -48.2211
  178,'MIDWAY6     ', 500.0000,1,   2,   1,   1,1.05705, -49.2854
  179,'BURNS2      ', 500.0000,1,   1,   1,   1,0.98437,  -6.6858
0 /End of Bus data, Begin Load data
    1,'BL',1,   1,   1,  1750.000,   -56.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    3,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    4,'BL',1,   1,   1,  2350.000,  -127.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    5,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    7,'BL',1,   1,   1,   239.000,   -56.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    8,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
    9,'BL',1,   1,   1,   139.700,    23.800,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   10,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   11,'BL',1,   2,   1,    90.000,    70.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   12,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   14,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   15,'BL',1,   2,   1,   793.400,   207.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   16,'BL',1,   1,   1,   840.000,     5.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   17,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   18,'BL',1,   2,   1,   617.000,   -69.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   29,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   30,'BL',1,   1,   1,  4400.000,  1000.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   33,'BL',1,   1,   1,  3600.000,   700.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   34,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   35,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   36,'BL',1,   2,   1, -1862.000,   971.000,     0.000,     0.000,     0.
↪000,     0.000,   1,1
   39,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
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↪000,      0.000,   1,1
    40,'BL',1,   2,   1,   135.000,    27.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    42,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    43,'BL',1,   1,   1,  2053.000,   907.100,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    44,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    45,'BL',1,   2,   1,   -72.800,   -17.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    46,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    47,'BL',1,   2,   1,   121.000,    25.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    49,'BL',1,   2,   1,   320.000,    65.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    50,'BL',1,   2,   1,   237.200,   -63.200,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    53,'BL',1,   2,   1,   138.000,    28.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    54,'BL',1,   2,   1,   807.800,   132.100,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    56,'BL',1,   2,   1,   117.000,    24.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    57,'BL',1,   2,   1,   121.000,    25.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    58,'BL',1,   2,   1,   887.700,    -6.200,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    59,'BL',1,   2,   1, -2771.000,  1654.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    60,'BL',1,   2,   1,   401.000,    80.600,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    61,'BL',1,   2,   1,   205.200,    17.600,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    62,'BL',1,   2,   1,  -129.000,    32.200,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    64,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    65,'BL',1,   1,   1,  1700.000,   300.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    66,'BL',1,   1,   1,   160.000,    31.250,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    67,'BL',1,   1,   1,   -67.500,   160.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    68,'BL',1,   1,   1,   -44.200,    22.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    69,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    70,'BL',1,   1,   1,  3137.000,  1681.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    72,'BL',1,   1,   1, -1525.000,   -50.000,     0.000,     0.000,     0.
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↪000,      0.000,   1,1
    74,'BL',1,   1,   1,  2584.000,   394.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    75,'BL',1,   1,   1,  3200.000,  1100.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    76,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    77,'BL',1,   1,   1,  3500.000,   500.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    78,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    79,'BL',1,   1,   1,  5000.000,   400.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    81,'BL',1,   1,   1,   -66.600,   -97.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    82,'BL',1,   1,   1,  -339.000,  -119.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    84,'BL',1,   1,   1,   610.000,  -414.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
    99,'BL',1,   3,   1,   -43.300,    20.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   100,'BL',1,   3,   1,   210.400,   -77.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   101,'BL',1,   2,   1,    50.000,    25.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   102,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   103,'BL',1,   2,   1,   305.000,    -7.600,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   104,'BL',1,   3,   1,    27.500,    -0.100,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   105,'BL',1,   3,   1,     8.010,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   106,'BL',1,   2,   1,   265.000,    14.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   107,'BL',1,   2,   1,    55.600,  -329.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   108,'BL',1,   2,   1,   777.600,    32.600,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   109,'BL',1,   2,   1,    40.000,    21.500,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   110,'BL',1,   3,   1,  -189.000,    61.500,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   111,'BL',1,   3,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   112,'BL',1,   3,   1,   148.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   114,'BL',1,   3,   1,    -0.700,   118.500,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   115,'BL',1,   3,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   116,'BL',1,   3,   1,   884.000,    54.800,     0.000,     0.000,     0.
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↪000,      0.000,   1,1
   117,'BL',1,   3,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   118,'BL',1,   3,   1,  5661.000,  3491.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   135,'BL',1,   2,   1,   856.000,    19.600,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   136,'BL',1,   2,   1,   175.000,    18.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   137,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   138,'BL',1,   2,   1,   902.300,   -11.400,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   139,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   140,'BL',1,   2,   1,  3191.000,   630.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   141,'BL',1,   2,   1,   204.200,   -28.200,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   142,'BL',1,   2,   1,   377.400,    64.500,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   143,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   144,'BL',1,   2,   1,  3098.000,  1189.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   147,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   148,'BL',1,   2,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   149,'BL',1,   2,   1,  3118.000,    78.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   150,'BL',1,   2,   1,  1230.000,    72.800,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   151,'BL',1,   2,   1,   406.000,    41.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   153,'BL',1,   2,   1,  1066.000,   -10.800,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   154,'BL',1,   1,   1,   457.700,    81.700,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   155,'BL',1,   1,   1,    33.900,    11.900,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   156,'BL',1,   1,   1,   148.000,    -7.900,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   157,'BL',1,   1,   1,   116.100,    38.400,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   158,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   159,'BL',1,   1,   1,   -62.000,    12.800,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   160,'BL',1,   1,   1,   255.000,   100.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   161,'BL',1,   1,   1,   100.000,     0.000,     0.000,     0.000,     0.
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↪000,      0.000,   1,1
   163,'BL',1,   1,   1,    31.600,    11.500,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   164,'BL',1,   1,   1,   141.200,    71.400,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   165,'BL',1,   1,   1,   379.000,   -43.000,     0.000,     0.000,     0.
↪000,      0.000,   1,1
   166,'BL',1,   1,   1,   185.000,    78.500,     0.000,     0.000,     0.
↪000,      0.000,   1,1
 0 /End of Load data, Begin Fixed shunt data
     6,'1 ',1,     0.000,  -113.000
     7,'1 ',1,     0.000,  -155.000
    11,'1 ',1,     0.000,  -190.000
    13,'1 ',1,     0.000,  -391.000
    15,'1 ',1,     0.000,  -146.000
    16,'1 ',1,     0.000,   390.000
    18,'1 ',1,     0.000,  -427.000
    36,'1 ',1,     0.000,   912.000
    43,'1 ',1,     0.000,   430.000
    48,'1 ',1,     0.000,   -80.000
    59,'1 ',1,     0.000,  2146.000
    62,'1 ',1,     0.000,  -108.000
    67,'1 ',1,     0.000,   576.850
    70,'1 ',1,     0.000,   792.000
    71,'1 ',1,     0.000,   462.000
    75,'1 ',1,     0.000,  1019.350
    77,'1 ',1,     0.000,   550.000
    79,'1 ',1,     0.000,  1200.000
    80,'1 ',1,     0.000,  -220.000
    81,'1 ',1,     0.000,  -674.000
    82,'1 ',1,     0.000,  -110.000
    83,'1 ',1,     0.000,  -220.000
    84,'1 ',1,     0.000,  -870.000
   103,'1 ',1,     0.000,   -91.000
   107,'1 ',1,     0.000,  -327.000
   108,'1 ',1,     0.000,  -130.000
   112,'1 ',1,     0.000,  -128.000
   113,'1 ',1,     0.000,   -91.000
   114,'1 ',1,     0.000,   -91.000
   116,'1 ',1,     0.000,   -32.000
   118,'1 ',1,     0.000,  1500.000
   138,'1 ',1,     0.000,  -319.000
   144,'1 ',1,     0.000,   400.000
   146,'1 ',1,     0.000,  -196.000
   153,'1 ',1,     0.000,  -190.000
   154,'1 ',1,     0.000,   -60.000
   157,'1 ',1,     0.000,  -220.000
   163,'1 ',1,     0.000,   -18.000
   165,'1 ',1,     0.000,   -50.000
   179,'1 ',1,     0.000,  -220.000
 0 /End of Fixed shunt data, Begin Generator data
     3,'1 ',   800.000,   123.043,   300.000,  -300.000,1.04000,     0,  1600.
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↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
    5,'1 ',  1048.000,  -132.905,   400.000,  -400.000,0.95000,     0,  2100.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
    8,'1 ',  2160.000,   -30.469,   700.000,  -500.000,1.00000,     0,  4300.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   10,'1 ',  2050.000,   464.829,   900.000,  -900.000,1.00000,     0,  4100.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   12,'1 ',  1690.000,   195.571,   700.000,  -280.000,1.00000,     0,  3400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   14,'1 ',  2640.000,   378.080,  1300.000,  -900.000,0.96000,     0,  5300.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   17,'1 ',   962.000,   148.778,   300.000,  -300.000,1.00000,     0,  2000.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   29,'1 ',  4450.000,  1011.075,  4000.000, -4000.000,1.00000,     0,  8900.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   34,'1 ',  4480.000,  1150.177,  5320.000, -3500.000,1.02000,     0,  9000.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   35,'1 ',  1640.000,   285.666,   600.000,  -525.000,1.00900,     0,  3300.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   39,'1 ',   200.000,   -52.159,   268.000,  -134.000,1.02000,     0,   400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   42,'1 ',   325.000,    68.266,   300.000,  -220.000,1.00000,     0,   650.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   44,'1 ',  1780.000,   534.593,   850.000,  -440.000,1.05000,     0,  3600.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   46,'1 ',   110.000,    29.078,   100.000,  -100.000,1.02000,     0,   220.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   64,'1 ',  2910.000,   953.299,  1500.000, -1000.000,1.00000,     0,  5800.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   69,'1 ',  1301.000,   431.493,   692.000,  -711.000,1.05500,     0,  2600.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   76,'1 ',  5174.765,   855.276,  2649.000, -1850.000,1.00000,     0, 10400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
   78,'1 ',  9950.000,  1854.073,  5780.000, -2000.000,1.00000,     0, 20000.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
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↪9999.000,     0.000,   1,1.0000
  102,'1 ',   765.000,  -206.264,   330.000,  -310.000,0.98000,     0,  1500.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  111,'1 ',  1057.000,    25.675,   400.000,  -400.000,1.02000,     0,  2100.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  115,'1 ',   594.000,   192.348,   300.000,  -300.000,1.05000,     0,  1200.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  117,'1 ',  3467.000,  1654.420,  2500.000, -1000.000,1.00000,     0,  6900.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  137,'1 ',   982.700,  -128.764,   300.000,  -300.000,1.02000,     0,  2000.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  139,'1 ',  3195.000,  1032.512,  2000.000,  -900.000,1.02000,     0,  6400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  143,'1 ',  1690.000,   593.821,   900.000,  -400.000,1.05000,     0,  3400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  147,'1 ',  1680.000,   446.627,   700.000,  -300.000,1.05000,     0,  3400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  148,'1 ',  2200.000,   393.721,   600.000,  -600.000,1.01000,     0,  4400.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  158,'1 ',  1665.000,   -31.368,  9999.000, -9999.000,1.05000,     0,  3300.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
  161,'1 ',   445.000,    91.733,  9999.000, -9999.000,1.00000,     0,   900.
↪000, 0.00000E+0, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1,  100.0, ␣
↪9999.000,     0.000,   1,1.0000
 0 /End of Generator data, Begin Branch data
    2,      7,'1 ', 1.79000E-3, 1.98800E-2,   2.57600,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    4,     16,'1 ', 9.77000E-3, 1.10000E-1,   2.00000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    4,    159,'1 ', 8.11000E-3, 1.36900E-1,   2.43480,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    6,     27,'1 ',-0.00000E+0,-4.08000E-3,   0.00000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    7,     16,'1 ', 5.00000E-4, 5.30000E-3,   0.08820,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    7,    162,'1 ', 4.80000E-3, 4.36000E-2,   0.70780,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   11,     19,'1 ',-0.00000E+0,-6.34000E-3,   0.00000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   11,     21,'1 ',-0.00000E+0,-1.18800E-2,   0.00000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   11,    138,'1 ', 2.80000E-3, 2.11000E-2,   1.01940,    0.00,    0.00,␣
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↪1630.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    13,     20,'1 ',-0.00000E+0,-6.34000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    13,     23,'1 ',-0.00000E+0,-8.26000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    13,     25,'1 ',-0.00000E+0,-1.79500E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    13,     28,'1 ',-0.00000E+0,-6.12000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    15,     18,'1 ', 4.00000E-4, 9.60000E-3,   0.90380,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    15,     18,'2 ', 4.00000E-4, 9.60000E-3,   0.90380,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    15,    135,'1 ', 2.59000E-3, 2.96700E-2,   2.15300,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    15,    135,'2 ', 2.59000E-3, 2.96700E-2,   2.15300,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    18,     22,'1 ',-0.00000E+0,-1.18800E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    18,     24,'1 ',-0.00000E+0,-8.26000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    19,     20,'1 ', 7.70000E-4, 1.80400E-2,   1.39842,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    21,     22,'1 ', 2.41000E-3, 5.86500E-2,   4.86560,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    23,     24,'1 ', 1.79000E-3, 4.24400E-2,   3.39220,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    25,     26,'1 ', 2.07000E-3, 4.95900E-2,   3.95160,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    26,    138,'1 ',-0.00000E+0,-1.79500E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    27,     28,'1 ', 1.77000E-3, 4.18900E-2,   3.34460,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    30,     31,'1 ', 3.50000E-3, 7.00000E-2,   4.60600,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    30,     79,'1 ', 8.30000E-4, 2.39000E-2,   3.30000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    32,     33,'1 ', 2.00000E-3, 2.00000E-2,   0.80000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    36,     37,'1 ', 7.40000E-4, 1.86100E-2,   1.40264,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    36,     55,'1 ', 8.20000E-4, 1.66800E-2,   1.18802,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    36,     63,'1 ',-0.00000E+0, 1.59000E-3,   0.12002,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    36,     63,'2 ',-0.00000E+0, 1.59000E-3,   0.12002,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    38,     45,'1 ', 2.21000E-3, 3.34600E-2,   0.07338,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    38,     47,'1 ', 2.90000E-3, 3.80000E-2,   0.08240,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    38,     58,'1 ', 3.09000E-3, 4.67700E-2,   0.10080,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    38,     59,'1 ', 2.26000E-3, 3.42200E-2,   0.07506,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    40,     54,'1 ', 4.70000E-4, 7.23000E-3,   0.01624,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    40,     57,'1 ', 3.50000E-4, 5.36000E-3,   0.01204,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    41,     49,'1 ', 2.20000E-3, 3.42200E-2,   0.07716,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    41,     49,'2 ', 2.38000E-3, 3.66900E-2,   0.08284,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    41,     56,'1 ', 2.01000E-3, 3.07400E-2,   0.06886,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    41,     57,'1 ', 2.81000E-3, 4.29600E-2,   0.09648,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    43,    159,'1 ', 1.80000E-3, 2.45000E-2,   0.43920,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    43,    159,'2 ', 1.80000E-3, 2.45000E-2,   0.43920,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    45,     47,'1 ', 2.90000E-4, 4.34000E-3,   0.00950,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    47,     54,'1 ', 2.29000E-3, 1.58300E-2,   0.03060,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     54,'2 ', 2.29000E-3, 1.58300E-2,   0.03060,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     58,'1 ', 1.41000E-3, 9.67000E-3,   0.01940,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     58,'2 ', 1.41000E-3, 9.67000E-3,   0.01940,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     58,'3 ', 1.61000E-3, 9.71000E-3,   0.01928,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     58,'4 ', 1.61000E-3, 9.71000E-3,   0.01928,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     59,'1 ', 2.70000E-4, 3.93000E-3,   0.00918,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     59,'2 ', 2.70000E-4, 3.93000E-3,   0.00918,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     59,'3 ', 2.70000E-4, 3.93000E-3,   0.00918,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     61,'1 ', 1.38000E-3, 1.11600E-2,   0.02470,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    47,     61,'2 ', 1.38000E-3, 1.11600E-2,   0.02470,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    48,     63,'1 ', 8.30000E-4, 1.88400E-2,   1.66668,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
    49,     56,'1 ', 3.70000E-4, 3.66000E-3,   0.00830,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    49,     57,'1 ', 5.50000E-4, 5.86000E-3,   0.01246,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    51,     62,'1 ', 1.07000E-2, 7.90500E-2,   0.36670,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
    52,     62,'1 ', 1.07000E-2, 7.90500E-2,   0.36670,    0.00,    0.00,  ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   53,     56,'1 ', 7.30000E-4, 1.02500E-2,   0.02558,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   53,     56,'2 ', 7.30000E-4, 1.02500E-2,   0.02558,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   54,     57,'1 ', 1.19000E-3, 1.24400E-2,   0.02798,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   54,     57,'2 ', 1.19000E-3, 1.24400E-2,   0.02798,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   54,     61,'1 ', 1.28000E-3, 9.79000E-3,   0.02120,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   56,     57,'1 ', 1.10000E-3, 1.18900E-2,   0.02514,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   60,    136,'1 ', 1.40000E-3, 2.64000E-2,   0.10200,    0.00,    0.00,␣
↪3070.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   60,    149,'1 ', 6.50000E-4, 1.18700E-2,   0.04672,    0.00,    0.00,␣
↪3070.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   60,    149,'2 ', 6.50000E-4, 1.18700E-2,   0.04672,    0.00,    0.00,␣
↪3070.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   63,    138,'1 ', 1.79000E-3, 2.52400E-2,   0.53546,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   63,    138,'2 ', 1.79000E-3, 2.52400E-2,   0.53546,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   63,    141,'1 ', 2.00000E-4, 4.10000E-3,   0.29620,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   65,     77,'1 ', 7.00000E-4, 7.40000E-2,   4.87000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   67,     70,'1 ', 6.00000E-5, 1.31000E-3,   0.00378,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   67,     70,'2 ', 6.00000E-5, 1.16000E-3,   0.00332,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   68,     71,'1 ', 1.00000E-5, 3.00000E-4,   0.01434,    0.00,    0.00,␣
↪3450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   68,     71,'2 ', 1.00000E-5, 3.00000E-4,   0.01844,    0.00,    0.00,␣
↪3450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   68,     75,'1 ', 2.30000E-4, 4.51000E-3,   0.33320,    0.00,    0.00,␣
↪2175.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   68,     75,'2 ', 2.00000E-4, 4.46000E-3,   0.30500,    0.00,    0.00,␣
↪2175.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   72,     74,'1 ', 1.79000E-3, 1.40500E-2,   3.68000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   73,     77,'1 ', 1.13000E-3, 2.06900E-2,   1.85526,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   74,     75,'1 ', 1.96000E-3, 3.30400E-2,   1.88000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   74,     77,'1 ', 1.42000E-3, 2.25800E-2,   1.88000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   75,     77,'1 ', 1.20000E-3, 2.31600E-2,   1.71520,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   75,     77,'2 ', 3.00000E-4, 2.00000E-2,   3.60000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   75,     81,'1 ', 6.30000E-4, 1.41200E-2,   1.09756,    0.00,    0.00,␣
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↪3450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   75,     81,'2 ', 1.09000E-3, 2.40800E-2,   1.55542,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   75,     81,'3 ', 1.08000E-3, 2.40900E-2,   1.55348,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   77,     79,'1 ', 2.00000E-4, 8.20000E-3,   1.30000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   77,     79,'2 ', 2.00000E-4, 8.20000E-3,   1.30000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   80,     98,'1 ', 2.64000E-3, 5.35600E-2,   5.29066,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   80,    179,'1 ',-0.00000E+0,-2.66700E-2,   0.00000,    0.00,    0.00,␣
↪1732.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   81,     86,'1 ', 4.10000E-4, 7.37000E-3,   0.72694,    0.00,    0.00,␣
↪3450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   81,     90,'1 ', 6.60000E-4, 1.26600E-2,   0.95976,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   81,     94,'1 ', 6.60000E-4, 1.26600E-2,   0.95976,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   82,     88,'1 ', 7.20000E-4, 1.38200E-2,   1.27572,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   82,     93,'1 ', 7.80000E-4, 1.50200E-2,   1.13810,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   82,     97,'1 ', 7.40000E-4, 1.41300E-2,   1.06634,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   82,    167,'1 ',-0.00000E+0,-7.20000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   82,    169,'1 ',-0.00000E+0,-8.64000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   82,    171,'1 ',-0.00000E+0,-1.00000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   83,     98,'1 ',-0.00000E+0,-2.66700E-2,   0.00000,    0.00,    0.00,␣
↪1732.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   84,    155,'1 ', 6.20000E-3, 6.73000E-2,   1.11560,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   85,     87,'1 ', 6.00000E-4, 1.03600E-2,   1.01456,    0.00,    0.00,␣
↪3450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   85,     89,'1 ', 1.20000E-4, 2.38000E-3,   0.21926,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   85,    179,'1 ', 1.22000E-3, 2.37300E-2,   2.20710,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   86,     87,'1 ',-0.00000E+0,-1.26300E-2,   0.00000,    0.00,    0.00,␣
↪2000.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   88,     89,'1 ',-0.00000E+0,-8.58000E-3,   0.00000,    0.00,    0.00,␣
↪2000.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   90,     91,'1 ',-0.00000E+0,-1.26300E-2,   0.00000,    0.00,    0.00,␣
↪2400.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   91,     92,'1 ', 7.40000E-4, 1.42800E-2,   1.08220,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   92,     93,'1 ',-0.00000E+0,-1.26300E-2,   0.00000,    0.00,    0.00,␣
↪2400.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   94,     95,'1 ',-0.00000E+0,-1.26300E-2,   0.00000,    0.00,    0.00,␣
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↪2000.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   95,     96,'1 ', 7.40000E-4, 1.42800E-2,   1.08220,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   96,     97,'1 ',-0.00000E+0,-1.26300E-2,   0.00000,    0.00,    0.00,␣
↪2000.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   99,    100,'1 ', 2.48200E-2, 1.69380E-1,   0.20232,    0.00,    0.00, ␣
↪838.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
   99,    116,'1 ', 1.48000E-2, 1.01010E-1,   0.12066,    0.00,    0.00, ␣
↪838.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  100,    104,'1 ', 1.38200E-2, 9.26800E-2,   0.11060,    0.00,    0.00, ␣
↪747.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  100,    105,'1 ', 1.66800E-2, 1.13810E-1,   0.13608,    0.00,    0.00, ␣
↪838.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  100,    112,'1 ', 1.11300E-2, 6.67800E-2,   0.07286,    0.00,    0.00, ␣
↪752.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  100,    112,'2 ', 1.05000E-2, 6.54000E-2,   0.06860,    0.00,    0.00, ␣
↪602.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  100,    112,'3 ', 1.10500E-2, 6.64200E-2,   0.07160,    0.00,    0.00, ␣
↪752.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  100,    116,'1 ', 3.90300E-2, 2.74030E-1,   0.31072,    0.00,    0.00, ␣
↪747.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  101,    103,'1 ', 7.90000E-4, 1.93700E-2,   1.32850,    0.00,    0.00,    ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  101,    107,'1 ', 8.70000E-4, 2.08700E-2,   1.45710,    0.00,    0.00,    ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  101,    107,'2 ', 8.70000E-4, 2.08700E-2,   1.45710,    0.00,    0.00,    ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  103,    106,'1 ', 8.30000E-4, 1.98500E-2,   0.00000,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  103,    133,'1 ', 9.30000E-4, 3.64400E-2,   1.38950,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  103,    134,'1 ', 7.20000E-4, 1.60000E-2,   1.08790,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  104,    116,'1 ', 3.05800E-2, 2.04600E-1,   0.24472,    0.00,    0.00, ␣
↪747.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  105,    116,'1 ', 2.23500E-2, 1.61060E-1,   0.18342,    0.00,    0.00, ␣
↪838.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  106,    107,'1 ', 1.53000E-3, 1.47000E-2,   0.00000,    0.00,    0.00,␣
↪1560.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  106,    109,'1 ', 5.30000E-4, 1.29700E-2,   0.00000,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  107,    132,'1 ', 2.00000E-5,-1.33100E-2,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  107,    134,'1 ', 2.00000E-5,-9.98000E-3,   0.00000,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  107,    173,'1 ',-0.00000E+0,-9.35000E-3,   0.00000,    0.00,    0.00,␣
↪2134.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  107,    175,'1 ',-0.00000E+0,-9.44000E-3,   0.00000,    0.00,    0.00,␣
↪2134.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  107,    177,'1 ',-0.00000E+0,-9.35000E-3,   0.00000,    0.00,    0.00,␣
↪2134.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  110,    119,'1 ',-0.00000E+0,-1.00000E-2,   0.00000,    0.00,    0.00,␣
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↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  110,    172,'1 ',-0.00000E+0,-1.00000E-2,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  113,    123,'1 ', 2.00000E-5,-9.98000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  113,    125,'1 ', 2.00000E-5,-9.98000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  113,    168,'1 ',-0.00000E+0,-7.20000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  113,    170,'1 ',-0.00000E+0,-7.20000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  114,    124,'1 ', 1.00000E-5,-6.66000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  114,    126,'1 ', 1.00000E-5,-6.66000E-3,   0.00000,    0.00,    0.00,␣
↪1800.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  114,    127,'1 ', 1.00000E-5,-1.12000E-2,   0.00000,    0.00,    0.00,␣
↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  114,    129,'1 ', 1.00000E-5,-7.20000E-3,   0.00000,    0.00,    0.00,␣
↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  118,    122,'1 ',-0.00000E+0,-1.00000E-2,   0.00000,    0.00,    0.00,␣
↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    128,'1 ', 1.00000E-5,-1.12000E-2,   0.00000,    0.00,    0.00,␣
↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    130,'1 ', 1.00000E-5,-3.60000E-3,   0.00000,    0.00,    0.00,␣
↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  118,    131,'1 ', 1.00000E-5,-7.55000E-3,   0.00000,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  118,    133,'1 ', 1.00000E-5,-1.09800E-2,   0.00000,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  119,    120,'1 ', 7.60000E-4, 1.95200E-2,   1.82450,    0.00,    0.00,␣
↪2894.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  120,    121,'1 ',-0.00000E+0,-1.00000E-2,   0.00000,    0.00,    0.00,␣
↪2667.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  121,    122,'1 ', 8.20000E-4, 2.11900E-2,   1.98420,    0.00,    0.00,␣
↪2894.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  123,    124,'1 ', 1.40000E-3, 2.33800E-2,   1.47500,    0.00,    0.00,␣
↪2396.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  125,    126,'1 ', 1.40000E-3, 2.33800E-2,   1.47500,    0.00,    0.00,␣
↪2396.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  127,    128,'1 ', 1.54000E-3, 3.40900E-2,   2.31140,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  129,    130,'1 ', 9.50000E-4, 2.10200E-2,   1.42520,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  131,    132,'1 ', 1.65000E-3, 5.71900E-2,   2.47740,    0.00,    0.00,␣
↪2450.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  135,    151,'1 ', 4.20000E-4, 9.05000E-3,   0.66794,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  136,    142,'1 ', 1.90000E-3, 2.58000E-2,   0.09840,    0.00,    0.00,␣
↪2320.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  136,    149,'1 ', 8.45000E-3, 7.03400E-2,   0.15954,    0.00,    0.00,␣
↪1160.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  138,    141,'1 ', 1.93000E-3, 2.77900E-2,   4.67120,    0.00,    0.00,␣
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↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  138,    146,'1 ', 5.60000E-4, 1.41500E-2,   1.04290,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  140,    142,'1 ', 1.10000E-3, 1.27000E-2,   0.04800,    0.00,    0.00,␣
↪2320.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  141,    144,'1 ', 2.80000E-4, 7.53000E-3,   0.51736,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  141,    144,'2 ', 3.50000E-4, 7.50000E-3,   0.55360,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  141,    146,'1 ', 1.90000E-3, 3.10000E-2,   4.14020,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  141,    150,'1 ', 6.00000E-4, 1.28000E-2,   0.94620,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  141,    152,'1 ', 4.40000E-4, 1.12500E-2,   0.82920,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  141,    152,'2 ', 4.40000E-4, 1.12500E-2,   0.82920,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  142,    145,'1 ', 1.38000E-3, 5.39900E-2,   0.15252,    0.00,    0.00,␣
↪2320.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  142,    153,'1 ', 3.20000E-3, 3.95000E-2,   0.14400,    0.00,    0.00,␣
↪2320.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  144,    150,'1 ', 2.10000E-4, 4.57000E-3,   0.32336,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  149,    153,'1 ', 2.85000E-3, 3.64900E-2,   0.12656,    0.00,    0.00,␣
↪2320.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  149,    153,'2 ', 1.38000E-3, 3.39900E-2,   0.11252,    0.00,    0.00,␣
↪2320.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  150,    151,'1 ', 4.00000E-4, 9.30000E-3,   0.68560,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  152,    174,'1 ',-0.00000E+0,-9.35000E-3,   0.00000,    0.00,    0.00,␣
↪2134.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  152,    176,'1 ',-0.00000E+0,-9.35000E-3,   0.00000,    0.00,    0.00,␣
↪2134.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  152,    178,'1 ',-0.00000E+0,-8.40000E-3,   0.00000,    0.00,    0.00,␣
↪2100.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  154,    155,'1 ', 2.40000E-3, 3.32000E-2,   0.58490,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,2,   0.00,   1,1.0000
  154,    157,'1 ', 5.20000E-3, 6.02000E-2,   1.01000,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  154,    157,'2 ', 4.90000E-3, 5.37000E-2,   0.88430,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  154,    159,'1 ', 1.70000E-3, 2.25000E-2,   0.39920,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  154,    159,'2 ', 2.10000E-3, 2.38000E-2,   0.38450,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  154,    164,'1 ', 1.20000E-3, 1.72000E-2,   0.29870,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  154,    166,'1 ', 8.00000E-4, 1.06000E-2,   0.20390,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  155,    166,'1 ', 1.60000E-3, 2.26000E-2,   0.38100,    0.00,    0.00,   ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
  156,    160,'1 ', 1.08000E-2, 9.65000E-2,   0.32960,    0.00,    0.00,   ␣
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↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   157,    163,'1 ', 9.60000E-3, 8.78000E-2,   1.42650,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   157,    164,'1 ', 3.40000E-3, 3.92000E-2,   0.65240,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   157,    165,'1 ', 3.40000E-3, 3.74000E-2,   0.62080,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   157,    165,'2 ', 3.40000E-3, 3.72000E-2,   0.61820,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   159,    165,'1 ', 3.80000E-3, 3.40000E-2,   0.58240,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   159,    165,'2 ', 3.20000E-3, 3.49000E-2,   0.57220,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   167,    168,'1 ', 1.03000E-3, 2.33800E-2,   1.58040,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   169,    170,'1 ', 1.07000E-3, 2.47000E-2,   1.52700,    0.00,    0.00,␣
↪3020.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   171,    172,'1 ', 1.03000E-3, 3.23000E-2,   2.79600,    0.00,    0.00,  ␣
↪0.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   173,    174,'1 ', 1.23000E-3, 2.65900E-2,   1.98702,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   175,    176,'1 ', 1.23000E-3, 2.66200E-2,   1.98880,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
   177,    178,'1 ', 1.12000E-3, 2.51700E-2,   1.83586,    0.00,    0.00,␣
↪3600.00,  0.00000,  0.00000,  0.00000,  0.00000,1,1,   0.00,   1,1.0000
 0 /End of Branch data, Begin Transformer data
     1,     2,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.46000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,       0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     1,     3,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.73000E-2,   100.00
0.95450,   0.000,   0.000,     0.00,     0.00,     0.00, 0,       0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     4,     5,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.23800E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,       0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     4,    10,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.50000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,       0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     6,     7,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
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 0.00000E+0, 1.10000E-2,   100.00
1.06300,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     6,     7,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.10000E-2,   100.00
1.06300,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     7,     8,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 5.90000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,  3000.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     7,     9,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 2.80000E-4, 1.38000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,   430.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
     7,     9,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 2.90000E-4, 1.39000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,   430.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    11,    12,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 6.66000E-3,   100.00
1.08000,   0.000,   0.000,     0.00,     0.00,  2000.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    15,    14,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 6.00000E-5, 4.95000E-3,   100.00
1.10610,   0.000,   0.000,     0.00,     0.00,  3066.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    16,    17,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 6.00000E-3,   100.00
1.04350,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    30,    29,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.50000E-3,   100.00
1.05000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
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    31,    32,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.00000E-2,   100.00
1.10000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    33,    34,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 2.00000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    84,    35,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 4.60000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,  2000.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    37,    47,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 1.30000E-4, 6.93000E-3,   100.00
1.05000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    38,    39,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 5.00000E-4, 2.38000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    41,    42,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 5.80000E-4, 2.53500E-2,   100.00
1.04910,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    43,    44,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 5.20000E-3,   100.00
1.02500,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    47,    46,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 4.99000E-3, 1.14730E-1,   100.00
1.04780,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    48,    47,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                     ',1,   1,1.0000
 2.60000E-4, 1.38600E-2,   100.00
1.05000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
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↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    51,    50,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 5.90000E-4, 1.49100E-2,   100.00
1.00170,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    52,    50,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 5.90000E-4, 1.49100E-2,   100.00
1.00170,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    53,    50,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 3.00000E-4, 1.33000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    53,    50,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 3.00000E-4, 1.34000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    55,    54,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 1.30000E-4, 1.38600E-2,   100.00
1.01060,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    55,    54,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 1.30000E-4, 1.38600E-2,   100.00
1.01060,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    59,    60,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 1.15000E-3,   100.00
1.01330,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    63,    62,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 2.00000E-4, 2.33800E-2,   100.00
0.97890,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    65,    64,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
```

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 0.00000E+0, 5.00000E-3,   100.00
1.09000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    67,    66,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 8.90000E-4, 2.99000E-2,   100.00
0.98730,   0.000,   0.000,     0.00,     0.00,   250.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    68,    67,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 2.00000E-4, 1.18100E-2,   100.00
1.02380,   0.000,   0.000,     0.00,     0.00,  1008.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    68,    67,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 9.00000E-5, 7.35000E-3,   100.00
1.02380,   0.000,   0.000,     0.00,     0.00,  1300.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    67,    69,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.03400E-2,   100.00
1.04550,   0.000,   0.000,     0.00,     0.00,  2000.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    71,    70,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 2.21000E-3,   100.00
1.02340,   0.000,   0.000,     0.00,     0.00,  2500.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    75,    76,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 3.75000E-3,   100.00
1.09770,   0.000,   0.000,     0.00,     0.00,  5000.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    79,    78,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 2.50000E-3,   100.00
1.06600,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
    83,    84,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 7.20000E-3,   100.00
1.05000,   0.000,   0.000,     0.00,     0.00,  1500.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
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   101,   102,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 9.80000E-3,   100.00
1.05000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   108,   107,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 3.00000E-4, 1.74000E-2,   100.00
1.11900,   0.000,   0.000,     0.00,     0.00,   840.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   108,   107,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 2.00000E-4, 1.19000E-2,   100.00
1.11900,   0.000,   0.000,     0.00,     0.00,  1120.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   111,   112,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 2.28100E-2,   100.00
0.91740,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   112,   113,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 1.00000E-4, 1.74000E-2,   100.00
1.11900,   0.000,   0.000,     0.00,     0.00,   840.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   115,   116,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 1.81500E-2,   100.00
0.90910,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   116,   118,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 2.00000E-4, 1.25000E-2,   100.00
1.11900,   0.000,   0.000,     0.00,     0.00,  1120.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   117,   118,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 4.48000E-3,   100.00
0.94520,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   137,   138,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                    ␣
↪                    ',1,   1,1.0000
 0.00000E+0, 1.51200E-2,   100.00
0.99600,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
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↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   139,   140,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 3.65000E-3,   100.00
0.97870,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   143,   144,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 5.16000E-3,   100.00
0.98430,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   144,   145,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 5.00000E-3,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   146,   147,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 9.80000E-3,   100.00
1.05000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   148,   149,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 1.02600E-2,   100.00
0.98710,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   152,   153,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 1.14900E-2,   100.00
1.06310,   0.000,   0.000,     0.00,     0.00,  1120.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   152,   153,     0,'2 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 1.14900E-2,   100.00
1.06310,   0.000,   0.000,     0.00,     0.00,  1120.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   152,   153,     0,'3 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
 0.00000E+0, 1.14900E-2,   100.00
1.06310,   0.000,   0.000,     0.00,     0.00,  1120.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   155,   156,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                      ',1,   1,1.0000
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 3.00000E-4, 1.81000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   157,   158,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 2.00000E-4, 5.80000E-3,   100.00
0.98550,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   160,   161,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 5.00000E-4, 1.41000E-2,   100.00
1.05880,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
   163,   162,     0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,'                  ␣
↪                     ',1,   1,1.0000
 0.00000E+0, 1.95000E-2,   100.00
1.00000,   0.000,   0.000,     0.00,     0.00,     0.00, 0,      0, 1.50000,␣
↪0.51000, 1.50000, 0.51000, 159, 0, 0.00000, 0.00000,  0.000
1.00000,   0.000
 0 /End of Transformer data, Begin Area interchange data
 0 /End of Area interchange data, Begin Two-terminal dc line data
 0 /End of Two-terminal dc line data, Begin VSC dc line data
 0 /End of VSC dc line data, Begin Impedance correction table data
 0 /End of Impedance correction table data, Begin Multi-terminal dc line data
 0 /End of Multi-terminal dc line data, Begin Multi-section line data
 0 /End of Multi-section line data, Begin Zone data
   1,'1           '
 0 /End of Zone data, Begin Inter-area transfer data
 0 /End of Inter-area transfer data, Begin Owner data
   1,'1           '
 0 /End of Owner data, Begin FACTS device data
 0 /End of FACTS device data, Begin Switched shunt data
 0 /End of Switched shunt data, Begin GNE device data
 0 /End of GNE device data
Q
```

Dynamic Data (PSS/E DYR format)

```
data = !cat wecc.dyr
print('\n'.join(data))
```

```
     3 'GENROU' 1     3.9000      0.32000E-01  0.54000      0.62000E-01
         2.6400       5.0000       1.8600       1.7800      0.25000
        0.45300      0.19500      0.14500       1.9714       6.9000      /
     3 'IEEEST' 1           3            0       0.0000       0.0000
         0.0000       0.0000       0.0000       0.0000       0.0000
```

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```
      0.0000       0.0000      0.75000       1.0000       4.2000
     -2.0000      0.10000     -0.10000       0.0000       0.0000      /
  3 'ESST3A' 1    0.20000E-01  0.30000     -0.20000       8.0000
      1.0000       5.0000       20.000       0.0000       99.000
     -99.000       1.0000       3.6700      0.43500       6.4800
     0.10000E-01  0.98000E-02   4.8600       3.3300      0.40000
      99.000       0.0000    /
  3 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
  5 'GENROU' 1     4.0000      0.32000E-01  0.52000      0.63000E-01
      2.6100       0.0000       1.8100       1.7300      0.24500
     0.51000      0.19000      0.14000       1.7850       7.1400      /
  5 'ST2CUT' 1          1           0            0            0
      5.5000       0.0000      0.30000E-01   0.0000       10.000
      10.000      0.40000      0.40000E-01   0.0000       0.0000
      0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
  5 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       8.2000
      1.0000       5.0000       50.000       0.0000       99.000
     -99.000       1.0000       3.5600      0.33500       5.8100
     0.10000E-01  0.77000E-02   5.6000       3.7500      0.40000
      99.000       0.0000    /
  5 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
  8 'GENROU' 1     8.4000      0.35000E-01  0.46000      0.70000E-01
      3.4200       0.0000       1.7600       1.5800      0.28500
     0.48500      0.20500      0.15500       1.8429       6.4500      /
  8 'ST2CUT' 1          1           0            0            0
      10.000       0.0000       0.0000       0.0000       3.0000
      3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
     0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
  8 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   50.000      0.20000E-01   9999.0      -9999.0
      0.0000      0.10000E-01   1.0000    /
  8 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
 10 'GENROU' 1     4.5000      0.40000E-01  0.50000      0.60000E-01
      2.4500       0.0000       1.7000       1.6500      0.25000
     0.50000      0.19000      0.14000       1.7850       7.1400      /
 10 'ST2CUT' 1          1           0            0            0
      0.0000       0.0000      0.25000E-01   0.0000      0.16000E-01
     0.16000E-01  0.26000      0.26000E-01  0.26000      0.26000E-01
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      0.0000       0.0000      0.10000     -0.10000       0.0000
      0.0000      /
   10 'ESDC2A' 1    0.20000E-01   50.000      0.50000E-01  0.20000E-01
      0.0000       3.0000      -3.0000       0.0000      0.51200
     0.70000E-01   1.3000       0.0000       3.9825      0.50000
      5.3100       1.0490    /
   10 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
   12 'GENROU' 1     4.2000      0.32000E-01  0.60000      0.66000E-01
      3.5900       0.0000       1.7600       1.6800      0.22000
     0.40000      0.17500      0.13000       1.9225       7.6900      /
   12 'ST2CUT' 1          1           0           0           0
      10.000       0.0000       0.0000       0.0000       3.0000
      3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
     0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
   12 'EXST1'  1    0.20000E-01   99.000      -99.000       1.0000
      10.000       75.000      0.20000E-01   9999.0      -9999.0
      0.0000      0.10000E-01   1.0000    /
   12 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
   14 'GENROU' 1     8.2000      0.33000E-01  0.48000      0.55000E-01
      3.8300       0.0000       1.9800       1.8500      0.37500
     0.56700      0.28500      0.22500       1.4800       4.4400      /
   14 'ST2CUT' 1          1           0           0           0
      10.000       0.0000       0.0000       0.0000       3.0000
      3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
     0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
   14 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       6.8000
      1.0000       5.0000       50.000       0.0000       99.000
     -99.000       1.0000       3.7700      0.12400       6.5200
     0.10000E-01  0.50000E-02   6.7700       0.0000      0.40000
      99.000       0.0000    /
   14 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
   17 'GENROU' 1     3.8000      0.31000E-01  0.49000      0.58000E-01
      2.6300       0.0000       1.6700      0.61000      0.26000
     0.45300      0.20500      0.14500       1.9714       6.9000      /
   17 'ST2CUT' 1          1           0           0           0
      0.0000       0.0000       0.0000       0.0000       30.000
      30.000      0.23000      0.25000E-01  0.23000      0.25000E-01
      0.0000       0.0000      0.60000E-01 -0.60000E-01   0.0000
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      0.0000      /
17 'ESDC2A' 1    0.20000E-01   25.000      0.20000E-01  0.20000E-01
      0.0000       3.0000      -3.0000       0.0000      0.64200
     0.10300      0.99400       0.0000       2.5950      0.35600
      3.4600       1.0000    /
17 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
29 'GENROU' 1     8.0000      0.50000E-01  0.20000      0.80000E-01
      4.3400       0.0000      0.90000      0.60000      0.25000
     0.60000      0.15000      0.90000E-01   2.2000       11.000      /
29 'ST2CUT' 1          3           0            0            0
     -3.5000       0.0000       0.0000       0.0000       1.0000
      1.0000       0.0000       3.0000      0.80000E-01  0.27000E-01
     0.80000E-01  0.27000E-01  0.10000     -0.10000       0.0000
      0.0000      /
29 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   72.500      0.20000E-01   9999.0      -9999.0
      0.0000      0.10000E-01   1.5000    /
29 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
34 'GENROU' 1     4.6000      0.40000E-01  0.37000      0.10000
      2.9500       0.0000       1.8250       1.7800      0.29100
     0.44000      0.25000      0.23900       1.3933       4.1800      /
34 'ST2CUT' 1          1           0            0            0
      10.000       0.0000      0.10000       0.0000       1.0000
      1.0000      0.20000      0.10000E-01   0.0000       0.0000
      0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
34 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   50.000      0.80000E-01   9999.0      -9999.0
      0.0000      0.15000E-01   1.0000    /
34 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
35 'GENROU' 1     4.1000      0.33000E-01  0.56000      0.62000E-01
      2.3200       0.0000       2.0700       1.9900      0.28000
     0.49000      0.21500      0.15500       1.8429       6.4500      /
35 'ST2CUT' 1          1           0            0            0
      10.000       0.0000       0.0000       0.0000       3.0000
      3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
     0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
35 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   50.000      0.36000       9999.0      -9999.0
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     0.0000      0.30000E-01   1.0000    /
35 'IEEEG1' 1          0           0        20.000      0.10000
     0.0000      0.20000       1.0000      -1.0000      0.95000
     0.0000      0.10000       0.0000       0.0000       0.0000
     0.0000       0.0000       0.0000      0.30000       0.0000
     8.7200      0.70000       0.0000    /
39 'GENROU' 1     9.8000      0.28000E-01  0.20000      0.16000
     6.4100       0.0000      0.99500      0.56800      0.19500
    0.56800      0.10000      0.89000E-01   2.2400       11.200      /
39 'ST2CUT' 1          1           0           0           0
     0.0000       0.0000       0.0000       0.0000       15.000
     15.000       0.0000      0.53000E-01   0.0000      0.53000E-01
     0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
     0.0000      /
39 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
    0.20000E-01   75.000      0.16000       9999.0      -9999.0
     0.0000      0.10000E-01   1.0000    /
39 'IEEEG1' 1          0           0        20.000      0.10000
     0.0000      0.30000       1.0000      -1.0000      0.95000
     0.0000      0.10000       0.0000       0.0000       0.0000
     0.0000       0.0000       0.0000      0.30000       0.0000
     10.000      0.70000       0.0000    /
42 'GENROU' 1     4.8000      0.37000E-01  0.50000      0.75000E-01
     4.1300       0.0000       1.7000       1.6200      0.25600
    0.41000      0.10000      0.85000E-01   1.8429       6.4500      /
42 'ST2CUT' 1          3           0           0           0
     0.0000       0.0000      0.30000E-01   0.0000       1.5000
     1.5000      0.37500       12.000       0.0000       0.0000
     0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
     0.0000      /
42 'ESDC2A' 1    0.20000E-01   20.000      0.20000      0.20000E-01
     0.0000       2.0000      -2.0000       0.0000      0.54500
    0.90000E-01   1.0000       0.0000       3.0975      0.41000
     4.1300       1.0000    /
42 'IEEEG1' 1          0           0        20.000      0.80000E-01
     0.0000      0.15000       1.0000      -1.0000      0.95000
     0.0000      0.50000E-01   0.0000       0.0000       0.0000
     0.0000       0.0000       0.0000      0.28000       0.0000
     10.000      0.72000       0.0000    /
44 'GENROU' 1     4.7000      0.31000E-01  0.67000      0.61000E-01
     2.8800       0.0000       1.9900       1.9000      0.24500
    0.42000      0.10000      0.85000E-01   1.9057       6.6700      /
44 'ST2CUT' 1          1           0           0           0
     3.0000       0.0000       0.0000       0.0000       10.000
     10.000      0.30000      0.30000E-01  0.30000      0.30000E-01
     0.0000       0.0000      0.10000     -0.10000       0.0000
     0.0000      /
44 'ESST3A' 1    0.20000E-01  0.20000     -0.20000       7.2000
     1.0000       4.0000       50.000       0.0000       99.000
    -99.000       1.0000       4.3500      0.24300       8.4000
    0.10000E-01  0.50000E-02   6.3600       20.000      0.60000
     99.000       0.0000    /
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    44 'IEEEG1' 1          0          0        20.000      0.10000
         0.0000      0.20000       1.0000      -1.0000      0.95000
         0.0000      0.10000       0.0000       0.0000       0.0000
         0.0000       0.0000       0.0000      0.30000       0.0000
         8.7200      0.70000       0.0000    /
    46 'GENROU' 1     7.4000      0.30000E-01  0.20000      0.16000
         3.8000       0.0000      0.61900      0.36500      0.23800
        0.36500      0.10000      0.85000E-01   1.7850       7.1400      /
    46 'ST2CUT' 1          1           0           0           0
         10.000       0.0000       0.0000       0.0000       3.0000
         3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
        0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
         0.0000      /
    46 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
        0.20000E-01   50.000      0.16000       9999.0      -9999.0
         0.0000      0.15000E-01   1.0000    /
    46 'IEEEG1' 1          0          0        20.000      0.90000E-01
         0.0000      0.20000       1.0000      -1.0000      0.98000
         0.0000      0.30000      0.10000       0.0000       0.0000
         0.0000       0.0000       0.0000       0.0000       0.0000
         0.0000      0.90000       0.0000    /
    64 'GENROU' 1     4.7800      0.41000E-01  0.53000      0.67000E-01
         3.3800       0.0000       1.6026       1.5818      0.28525
        0.45122      0.23079      0.16596       1.9475       7.7900      /
    64 'ST2CUT' 1          1           0           0           0
         3.0000       0.0000      0.30000E-01   0.0000       20.000
         20.000       6.7200      0.67200       0.0000       0.0000
         0.0000       0.0000      0.10000     -0.10000       0.0000
         0.0000      /
    64 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
        0.20000E-01   47.500      0.13000       9999.0      -9999.0
         0.0000      0.20000E-01   1.0000    /
    64 'IEEEG1' 1          0          0        20.000      0.10000
         0.0000      0.20000       1.0000      -1.0000      0.95000
         0.0000      0.50000       0.0000       0.0000       0.0000
         0.0000       0.0000       0.0000      0.30000       0.0000
         8.7200      0.70000       0.0000    /
    69 'GENROU' 1     4.0000      0.20000E-01  0.20000      0.50000E-01
         3.0000       0.0000       1.4846      0.83403      0.61720
        0.83403      0.47870      0.40033       1.3900       4.1700      /
    69 'ST2CUT' 1          1           0           0           0
         10.000       0.0000       0.0000       0.0000       3.0000
         3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
        0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
         0.0000      /
    69 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
        0.20000E-01   50.000      0.16000       9999.0      -9999.0
         0.0000      0.26000E-01   1.0000    /
    69 'IEEEG1' 1          0          0        20.000      0.10000
         0.0000      0.20000       1.0000      -1.0000      0.95000
         0.0000      0.10000      0.30000       0.0000       0.0000
         0.0000       0.0000       0.0000      0.30000       0.0000
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      8.7200      0.40000       0.0000    /
 76 'GENROU' 1     8.0000      0.30000E-01  0.20000      0.60000E-01
      3.6700       0.0000       1.2009      0.84062      0.46099
     0.84062      0.32024      0.30991       1.3900       4.1700      /
 76 'ST2CUT' 1          3            0            0            0
   -0.40000E-01   0.0000       0.0000       0.0000       29.500
      29.500       1.5000      0.15000       1.5000      0.15000
      0.0000       0.0000      0.90000E-01 -0.90000E-01   0.0000
      0.0000      /
 76 'ESDC2A' 1    0.20000E-01   20.000      0.60000E-01  0.20000E-01
      0.0000       3.0000      -3.0000       0.0000      0.13000
     0.50000E-01   1.3000       0.0000       3.3750      0.30000
      4.5000       1.0000    /
 76 'IEEEG1' 1          0            0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000       1.0500
      0.0000      0.80000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
 78 'GENROU' 1     7.2000      0.43000E-01  0.20000      0.79000E-01
      3.4600       0.0000      0.63800      0.42400      0.22800
     0.42400      0.16100      0.12700       1.9675       7.8700      /
 78 'ST2CUT' 1          3            0            0            0
   -0.60000E-01   0.0000       0.0000       0.0000       29.500
      29.500       1.5000      0.15000       1.5000      0.15000
      0.0000       0.0000      0.90000E-01 -0.90000E-01   0.0000
      0.0000      /
 78 'ESDC2A' 1    0.20000E-01   20.000      0.10000      0.20000E-01
      0.0000       3.0000      -3.0000       0.0000      0.57000
     0.50000E-01   1.2000       0.0000       3.3750      0.30000
      4.5000       1.0000    /
 78 'IEEEG1' 1          0            0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
102 'GENROU' 1     6.1200      0.52000E-01   1.5000      0.14400
      3.4600       0.0000       2.1290       2.0740      0.46700
      1.2700      0.31100      0.25000       1.3333       4.0000      /
102 'ST2CUT' 1          1            0            0            0
      10.000       0.0000       0.0000       0.0000       3.0000
      3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
     0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
102 'EXST1'  1    0.20000E-01   99.000      -99.000      0.20000E-01
     0.20000E-01   40.000      0.20000E-01   9999.0      -9999.0
      0.0000      0.10000E-01   1.0000    /
102 'IEEEG1' 1          0            0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
111 'GENROU' 1     4.0000      0.51000E-01  0.20000      0.33000E-01
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      4.3900       5.0000       2.0548       1.3111      0.62622
      1.3111      0.51468      0.27397       1.7850       7.1400      /
111 'IEEEST' 1          3            0       0.0000       0.0000
      0.0000       0.0000       0.0000       0.0000       0.0000
      0.0000       0.0000      0.75000       1.0000       4.2000
     -2.0000      0.10000     -0.10000       0.0000       0.0000      /
111 'ESDC2A' 1    0.20000E-01   40.500      0.60000E-01  0.20000E-01
      0.0000       2.0000      -2.0000       0.0000      0.50000
     0.50000E-01   1.0000       0.0000       2.6250      0.54000
      20.000       1.0000    /
111 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000      0.10000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.60000       0.0000    /
115 'GENROU' 1     7.8000      0.60000E-01  0.20000      0.11000
      4.1600       0.0000      0.75000      0.53000      0.32000
     0.53000      0.30000      0.21500       1.5500       4.6500      /
115 'IEEEST' 1          3            0       0.0000       0.0000
      0.0000       0.0000       0.0000       0.0000       0.0000
      0.0000       0.0000      0.75000       1.0000       4.2000
     -2.0000      0.10000     -0.10000       0.0000       0.0000      /
115 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   40.000      0.20000E-01   9999.0      -9999.0
      0.0000      0.10000E-01   1.2000    /
115 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
117 'GENROU' 1     4.5000      0.40000E-01  0.50000      0.60000E-01
      3.8200       0.0000       1.7000       1.6500      0.25000
     0.50000      0.19000      0.14000       1.7850       7.1400      /
117 'IEEEST' 1          3            0       0.0000       0.0000
      0.0000       0.0000       0.0000       0.0000       0.0000
      0.0000       0.0000      0.75000       1.0000       4.2000
     -2.0000      0.10000     -0.10000       0.0000       0.0000      /
117 'ESDC2A' 1    0.20000E-01   40.000      0.50000E-01  0.20000E-01
      0.0000       3.0000      -3.0000       0.0000      0.51200
     0.70000E-01   1.3000       0.0000       3.9825      0.50000
      5.3100       1.0490    /
117 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
137 'GENROU' 1     7.8000      0.60000E-01  0.20000      0.11000
      6.0700       0.0000      0.75000      0.53000      0.32000
     0.53000      0.30000      0.21500       1.5500       4.6500      /
137 'ST2CUT' 1          1            0            0            0
      10.000       0.0000       0.0000       0.0000       3.0000
      3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
```

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```
     0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
137 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   50.000      0.20000E-01   9999.0      -9999.0
      0.0000      0.10000E-01   1.2000    /
137 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
139 'GENROU' 1     5.3000      0.35000E-01  0.50000      0.77000E-01
      2.8200       0.0000       1.6200       1.5700      0.24500
     0.37600      0.10000      0.95000E-01   2.1060       10.530      /
139 'ST2CUT' 1          3           0           0           0
      0.0000       0.0000       0.0000       0.0000       29.500
      29.500       1.5000      0.15000       1.5000      0.15000
      0.0000       0.0000      0.90000E-01 -0.90000E-01   0.0000
      0.0000      /
139 'ESDC2A' 1    0.20000E-01   20.000      0.50000E-01  0.20000E-01
      0.0000       3.0000      -3.0000       0.0000      0.60000
     0.70000E-01   1.3000       0.0000       2.8200      0.32000
      3.7600       1.0000    /
139 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
143 'GENROU' 1     8.0000      0.50000E-01   1.5000      0.60000E-01
      2.7500       0.0000       1.9500       1.8700      0.34000
      1.0000      0.29000      0.24000       1.3900       4.1700      /
143 'ST2CUT' 1          1           0           0           0
     0.50000       0.0000      0.42000E-01   0.0000       10.000
      10.000       1.0000      0.80000E-01   1.7000      0.80000E-01
      0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
143 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
     0.20000E-01   50.000      0.19000       9999.0      -9999.0
      0.0000      0.15000E-01   1.0000    /
143 'IEEEG1' 1          0           0        20.000      0.10000
      0.0000      0.20000       1.0000      -1.0000      0.95000
      0.0000      0.10000       0.0000       0.0000       0.0000
      0.0000       0.0000       0.0000      0.30000       0.0000
      8.7200      0.70000       0.0000    /
147 'GENROU' 1     8.4000      0.35000E-01  0.46000      0.70000E-01
      3.4900       0.0000       1.7600       1.5800      0.28500
     0.48500      0.20500      0.15500       1.8429       6.4500      /
147 'ST2CUT' 1          1           0           0           0
      5.0000       0.0000      0.29000E-01   0.0000       2.4000
      2.4000      0.14400      0.40000E-01  0.37700      0.10500
      0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
      0.0000      /
147 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
```

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```
      0.20000E-01   40.000      0.20000E-01   9999.0      -9999.0
       0.0000      0.10000E-01   1.0000    /
147 'IEEEG1' 1          0          0        20.000      0.10000
       0.0000      0.20000       1.0000     -1.0000      0.95000
       0.0000      0.10000       0.0000      0.0000       0.0000
       0.0000       0.0000       0.0000     0.30000       0.0000
       8.7200      0.70000       0.0000    /
148 'GENROU' 1     4.3000      0.32000E-01  0.43000      0.66000E-01
       3.0300       0.0000       1.7900      1.7150      0.22000
      0.44000      0.10000      0.85000E-01   1.8525       7.4100      /
148 'ST2CUT' 1          1           0           0           0
       10.000       0.0000       0.0000      0.0000       3.0000
       3.0000      0.15000      0.50000E-01  0.15000      0.50000E-01
      0.15000      0.50000E-01  0.50000E-01 -0.50000E-01   0.0000
       0.0000      /
148 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
      0.20000E-01   40.000      0.20000       9999.0      -9999.0
       0.0000      0.35000E-01   1.7500    /
148 'IEEEG1' 1          0          0        20.000      0.10000
       0.0000      0.20000       1.0000     -1.0000      0.95000
       0.0000      0.10000       0.0000      0.0000       0.0000
       0.0000       0.0000       0.0000     0.30000       0.0000
       8.7200      0.70000       0.0000    /
158 'GENROU' 1     3.9000      0.32000E-01  0.49000      0.62000E-01
       2.8200       0.0000       1.6400      1.5700      0.24000
      0.43000      0.18500      0.13000       1.9225       7.6900      /
158 'ST2CUT' 1          1           0           0           0
       8.0800       0.0000      0.30000E-01   0.0000       10.000
       10.000      0.15000      0.50000E-01  0.15000      0.50000E-01
       0.0000       0.0000      0.50000E-01 -0.50000E-01   0.0000
       0.0000      /
158 'EXST1'  1    0.20000E-01   99.000      -99.000       1.0000
       10.000       40.000      0.20000E-01   9999.0      -9999.0
       0.0000      0.10000E-01   1.0000    /
158 'IEEEG1' 1          0          0        20.000      0.10000
       0.0000      0.20000       1.0000     -1.0000      0.95000
       0.0000      0.10000       0.0000      0.0000       0.0000
       0.0000       0.0000       0.0000     0.30000       0.0000
       8.7200      0.70000       0.0000    /
161 'GENROU' 1     5.2100      0.42000E-01   1.5000      0.42000E-01
       3.0100       0.0000       1.7980      1.7780      0.32400
      0.45000      0.26000      0.19300       1.4800       5.1800      /
161 'ST2CUT' 1          1           0           0           0
       10.000       0.0000      0.30000E-01   0.0000       30.000
       30.000      0.40000      0.50000E-01  0.40000      0.50000E-01
       0.0000       0.0000      0.40000E-01 -0.40000E-01   0.0000
       0.0000      /
161 'EXST1'  1    0.20000E-01   99.000      -99.000       0.0000
      0.20000E-01   50.000      0.10000       9999.0      -9999.0
       0.0000      0.12000E-01   1.0000    /
161 'IEEEG1' 1          0          0        20.000      0.10000
       0.0000      0.20000       1.0000     -1.0000      0.95000
```

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```
        0.0000      0.10000      0.0000       0.0000       0.0000
        0.0000       0.0000      0.0000      0.30000       0.0000
        8.7200      0.70000      0.0000    /
```

1.9 Miscellaneous

1.9.1 Per Unit System

The bases for AC system are

- S_b^{ac}: three-phase power in MVA. By default, $S_b^{ac} = 100MVA$ (set by `System.config.mva`).
- V_b^{ac}: phase-to-phase voltage in kV.
- I_b^{ac}: current base $I_b^{ac} = \frac{S_b^{ac}}{\sqrt{3}V_b^{ac}}$

The bases for DC system are

- S_b^{dc}: power in MVA. It is assumed to be the same as S_b^{ac}.
- V_b^{dc}: voltage in kV.

Some device parameters are given as per unit values under the device base power and voltage (if applicable). For example, the Line model `andes.models.line.Line` has parameters `r`, `x` and `b` as per unit values in the device bases `Sn`, `Vn1`, and `Vn2`. It is up to the user to check data consistency. For example, line voltage bases are typically the same as bus nominal values. If the `r`, `x`, and `b` are meant to be per unit values under the system base, each Line device should use an `Sn` equal to the system base mva.

Parameters in the device base will have a property value in the Model References page. For example, `Line.r` has a property `z`, which means it is a per unit impedance in the device base. To find out all applicable properties, refer to the "Other Parameters" section of *`andes.core.param.NumParam`*.

After setting up the system, these parameters will be converted to per-units in the bases of system base MVA and bus nominal voltages. The parameter values in the system base will be stored to the `v` attribute of the `NumParam`. The original inputs in the device base will be moved to the `vin` attribute. For example, after setting up the system, `Line.x.v` is the line reactances in per unit under the system base.

Values in the `v` attribute is what get utilized in computation. Writing new values directly to `vin` will not affect the values in `v` afterward. To alter parameters after setting up, refer to example notebook 2.

1.9.2 Notes

Modeling Blocks

State Freeze

State freeze is used by converter controllers during fault transients to fix a variable at the pre-fault values. The concept of state freeze applies to both state and algebraic variables. For example, in the renewable energy electric control model (REECA), the proportional-integral controllers for reactive power error and voltage error are subject to state freeze when voltage dip is observed. The internal and output states should be frozen when the freeze signal turns one and frees when the signal turns back to zero.

Freezing a state variable can be easily implemented by multiplying the freeze signal with the right-hand side (RHS) of the differential equation:

$$T\dot{x} = (1 - z_f) \times f(x)$$

where $f(x)$ is the original RHS of the differential equation, and z_f is the freeze signal. When z_f becomes zero the differential equation will evaluate to zero, making the increment zero.

Freezing an algebraic variable is more difficult to implement. One might consider a similar solution to freezing a differential variable by constructing a piecewise equation, for example,

$$0 = (1 - z_f) \times g(y)$$

where $g(y)$ is the original RHS of the algebraic equation. One might also need to add a small value to the diagonals of `dae.gy` associated with the algebraic variable to avoid singularity. The rationale behind this implementation is to zero out the algebraic equation mismatch and thus stop incremental correction: in the frozen state, since z_f switches to zero, the algebraic increment should be forced to zero. This method, however, would not work when a dishonest Newton method is used.

If the Jacobian matrix is not updated after z_f switches to one, in the row associated with the equation, the derivatives will remain the same. For the algebraic equation of the PI controller given by

$$0 = (K_p u + x_i) - y$$

where K_p is the proportional gain, u is the input, x_I is the integrator output, and y is the PI controller output, the derivatives w.r.t u, x_i and y are nonzero in the pre-frozen state. These derivative corrects y following the changes of u and x. Although x has been frozen, if the Jacobian is not rebuilt, the correction will still be made due to the change of u. Since this equation is linear, only one iteration is needed to let y track the changes of u. For nonlinear algebraic variables, this approach will likely give the wrong results, since the residual is pegged at zero.

To correctly freeze an algebraic variable, the freezing signal needs to be passed to an `EventFlag`, which will set an `custom_event` flag if any input changes. `EventFlag` is a `VarService` that will be evaluated at each iteration after discrete components and before equations.

1.9.3 Profiling Import

To speed up the command-line program, import profiling is used to break down the program loading time.

With tool `profimp`, `andes` can be profiled with `profimp "import andes" --html > andes_import.htm`. The report can be viewed in any web browser.

1.9.4 What won't work

You might have heard that PyPy is faster than CPython due to a built-in JIT compiler. Before you spend an hour compiling the dependencies, here is the fact: PyPy won't work for speeding up ANDES.

PyPy is often much slower than CPython when using CPython extension modules (see the PyPy_FAQ). Unfortunately, NumPy is one of the highly optimized libraries that heavily use CPython extension modules.

1.10 Frequently Asked Questions

1.10.1 Program Startup

1.10.2 General

Q: What is the Hybrid Symbolic-Numeric Framework in ANDES?

A: It is a modeling and simulation framework that uses symbolic computation for descriptive modeling and code generation for fast numerical simulation. The goal of the framework is to reduce the programming efforts associated with implementing complex models and automate the research workflow of modeling, simulation, and documentation.

The framework reduces the modeling efforts from two aspects: (1) allowing modeling by typing in equations, and (2) allowing modeling using modularized control blocks and discontinuous components. One only needs to describe the model using equations and blocks without having to write the numerical code to implement the computation. The framework automatically generate symbolic expressions, computes partial derivatives, and generates vectorized numerical code.

1.10.3 Modeling

Admittance matrix

Q: Where to find the line admittance matrix?

A: ANDES does not build line admittance matrix for computing line power injections. Instead, line power injections are computed as vectors on the two line terminal. This approach generalizes line as a power injection model.

Q: Without admittance matrix, how to switch out lines?

A: Lines can be switched out and in by using `Toggle`. See the example in `cases/kundur/kundur_full.xlsx`. One does not need to manually trigger a Jacobian matrix rebuild because `Toggle` automatically triggers it using the new connectivity status.

Reference of the existing model

Q: Is there any further reference of the existing model?

A: Most of them can be found online, such as ESIG and PowerWorld.

1.11 License

1.11.1 GNU Public License v3

1.12 Quick install

Working with Conda?

ANDES is available on conda-forge and can be installed with Anaconda, Miniconda, and Mambaforge:

```
conda install -c conda-forge andes
```

Prefer pip?

ANDES can be installed via pip from PyPI.

```
pip install andes
```

New to Python?

Set up a Mambaforge environment by following *Setting Up Mambaforge*. We recommend Mambaforge on Windows and Apple Silicon for new users.

Are you a developer?

Installing from source? Looking to develop models? Check the guide in *Develop Install*.

CHAPTER

TWO

EXAMPLES

A collection of examples are presented to supplement the tutorial. The examples below are identical to the Jupyter Notebook in the `examples` folder of the repository here. You can run the examples in a live Jupyter Notebook online using Binder.

2.1 Simulate and Plot

2.1.1 Import and Setting the Verbosity Level

We first import the `andes` library and the `get_case` function that for loading test cases shipped with ANDES.

```
import andes

from andes.utils.paths import get_case
```

We can configure the verbosity level for logging (output messages) by passing a verbosity level (10-DEBUG, 20-INFO, 30-WARNING, 40-ERROR, 50-CRITICAL) to the `stream_level` argument of `andes.main.config_logger()`. Verbose level 10 is useful for getting debug output.

The logging level can be altered (as of v1.4.3) by calling `config_logger` again with new `stream_level` and `file_level`.

```
andes.config_logger(stream_level=20)
```

Note that the above `andes.config_logger()` is a shorthand to `andes.main.config_logger()`.

If this step is omitted, the default `INFO` level (`stream_level=20`) will be used.

2.1.2 Run Time-Domain Simulation

Run power flow by default

`get_case` takes a relative path to `ANDES_ROOT/andes/cases` and returns the full path, where `ANDES_ROOT` is the root folder of ANDES.

`andes.run` is the entrypoint function for loading files and running routines. It runs power flow by default and returns a `System` object.

Note: if `default_config=True`, the default concif will be used. To use your own config, remove `default_config=True`.

See the tutorial for saving and editing ANDES config.

```
ss = andes.run(get_case('kundur/kundur_full.xlsx'), default_config=True)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.2775 seconds.
System internal structure set up in 0.0322 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0039 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745104027e-07
Converged in 5 iterations in 0.0084 seconds.
Report saved to "kundur_full_out.txt" in 0.0020 seconds.
```

```
-> Single process finished in 0.5018 seconds.
```

Run time-domain simulation

Run TDS by calling `TDS.run()` on the system. Note that the call must follow the power flow immediately.

The default simulation is for 20 seconds. To change if, change `config.tf` to the desired value.

```
ss.TDS.config.tf = 10  # simulate for 10 seconds
```

```
ss.TDS.run()
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-10 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
Initialization for dynamics completed in 0.0490 seconds.
Initialization was successful.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
```

```
Simulation completed in 0.5985 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0104 seconds.
```

```
True
```

To check if all operations completed successfully, check `ss.exit_code`. `exit_code == 0` means that all operations were successful.

If not zero, `exit_code` indicates the number of errors caught. One will need to check output messages for errors.

```
ss.exit_code
```

```
0
```

2.1.3 Export and Plot Results

If you are using ANDES interactively from Jupyter Notebook or IPython, at the end of a time-domain simulation. a plotter object `ss.TDS.plt` will automatically be created.

To check if that has been created successfully (in case the detection of an interactive environment fails), check the type of `ss.TDS.plt`.

```
ss.TDS.plt
```

```
<andes.plot.TDSData at 0x7fb229d9ff70>
```

If `ss.TDS.plt` is None, it can be manually loaded with `ss.TDS.load_plotter()`. Otherwise, `load_plotter()` can be safely skipped.

```
ss.TDS.load_plotter()
```

Exporting simulation data to csv

To export simulation results to a CSV file, one can use `ss.TDS.plt.export_csv()`, which takes an optional argument of the file name.

If not provided, a default file name will be assigned.

```
ss.TDS.plt.export_csv()
```

```
CSV data saved to "/home/hacui/repos/andes/examples/kundur_full_out.csv".
```

Index-based Plotting

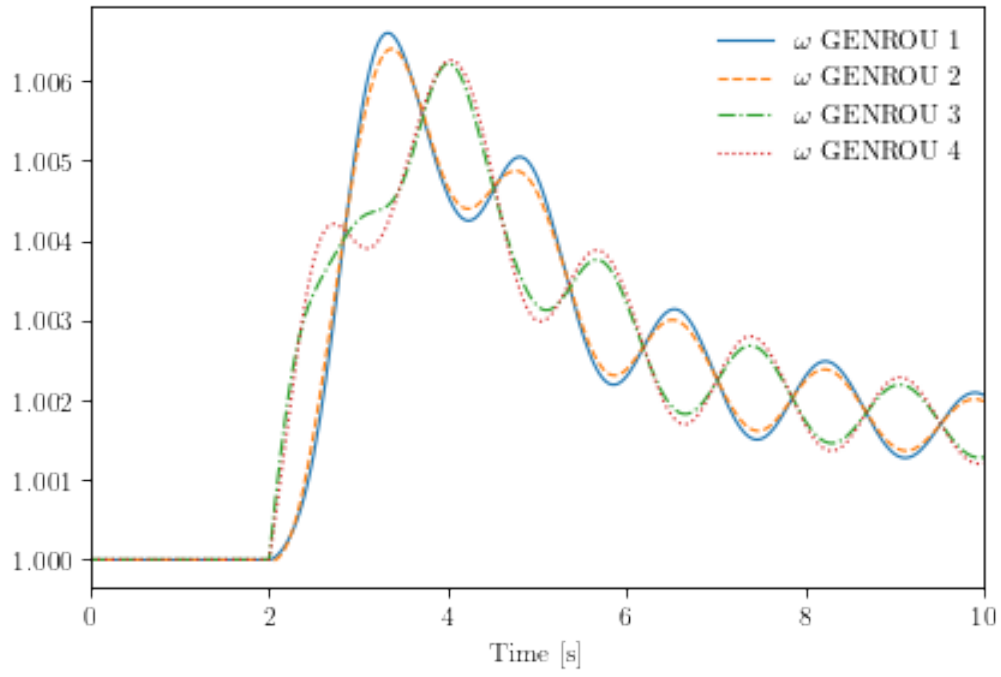
`plotter.plot()` is the entry point for plotting. It is the backend of the command-line `andes plot`.

Before plotting, open the `kundur_full_out.lst` to find the indices (first column) for the variables to plot.

For example, if we want to plot all generator speed, which is the `omega` variable of `GENROU`. By inspect, we found the indices as `5, 6, 7, 8`.

Pass them in a tuple or a list to `ss.TDS.plt.plot`.

```
fig, ax = ss.TDS.plt.plot((5, 6, 7, 8))
```



`plot()` returns a figure object and an axis object.

Find index by variable name

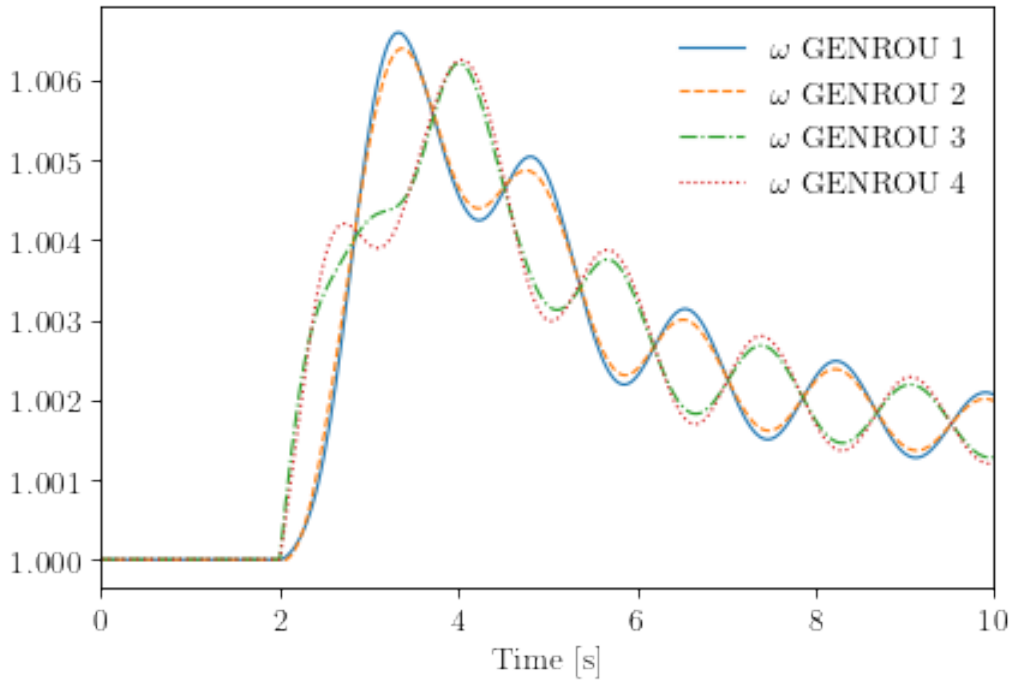
`plotter.find()` is a method for finding indices based on variable name.

The first argument is the pattern to find. An optional argument `exclude` is the pattern to exclude. Regular expression is supported for both.

```
ss.TDS.plt.find('omega')
```

```
([5, 6, 7, 8],
 ['omega GENROU 1', 'omega GENROU 2', 'omega GENROU 3', 'omega GENROU 4'])
```

```
fig, ax = ss.TDS.plotter.plot(ss.TDS.plotter.find('omega')[0])
```

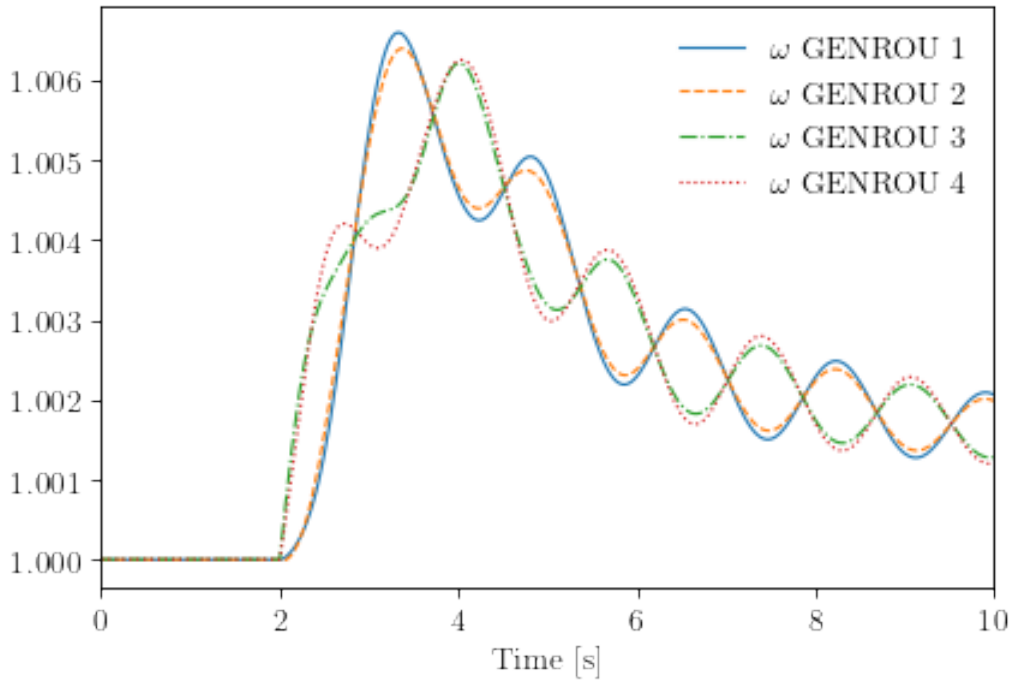


Plotting by variable

Looking up indices from the `lst` file can be tedious.

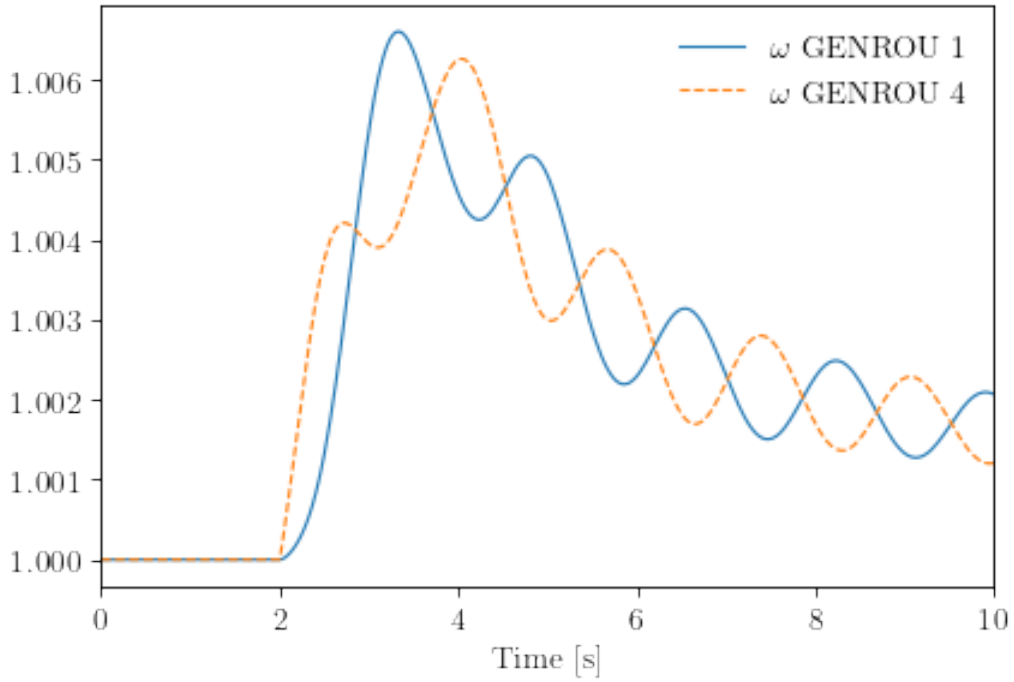
Instead, one can pass a a variable in a model to `ss.TDS.plt.plot`. For example, to plot `ss.GENROU.omega`, do

```
fig, ax = ss.TDS.plt.plot(ss.GENROU.omega)
```



To plot a subset of the variables, pass the 0-indexed selection indices in a tuple through argument `a` of `ss.TDS.plt.plot`. For example, to plot the 0-th and the 3-th `GENROU.omega`, do

```
fig, ax = ss.TDS.plt.plot(ss.GENROU.omega, a=(0, 3))
```



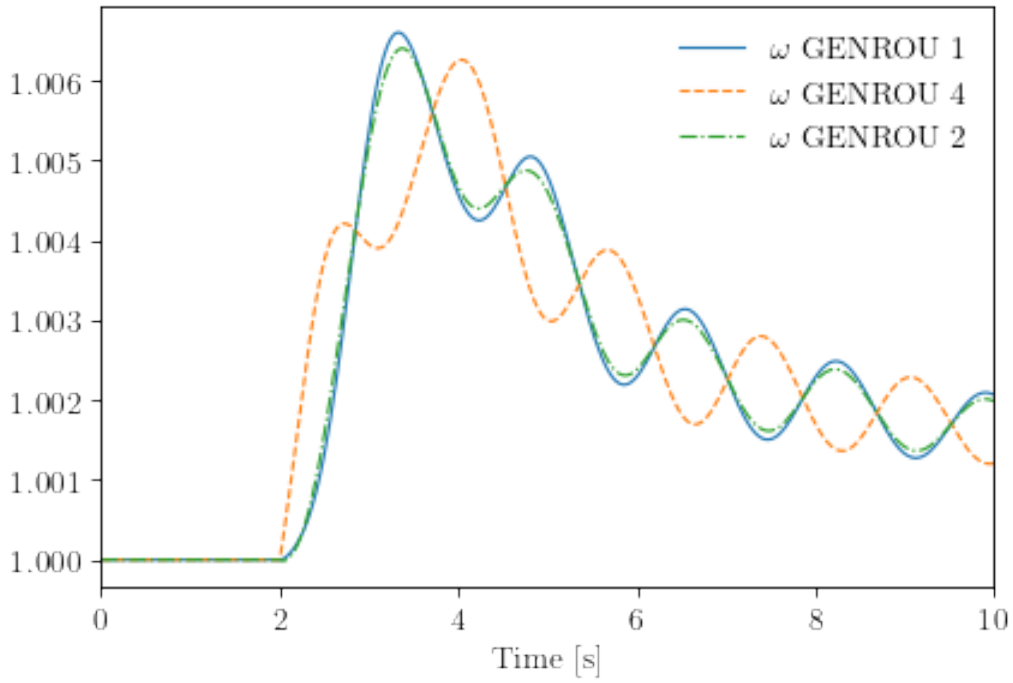
Adding curves to an existing figure

Plotting curves into an existing figure allows easy comparison of results. It can be done by passing a figure and an axis object of `plot()`.

For example, to plot the speed of the second generator (a=1) on the figure above, do

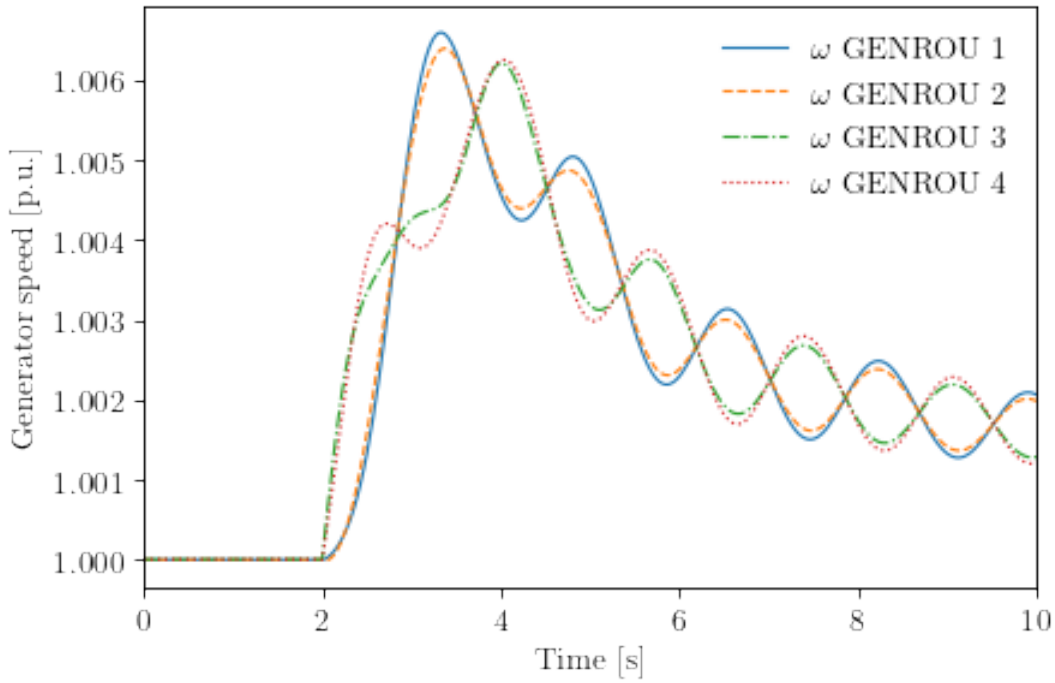
```
fig, ax = ss.TDS.plt.plot(ss.GENROU.omega, a=(1, ), fig=fig, ax=ax,␣
↪linestyles=['-.'])
fig
```

```
<Figure size 432x288 with 0 Axes>
```



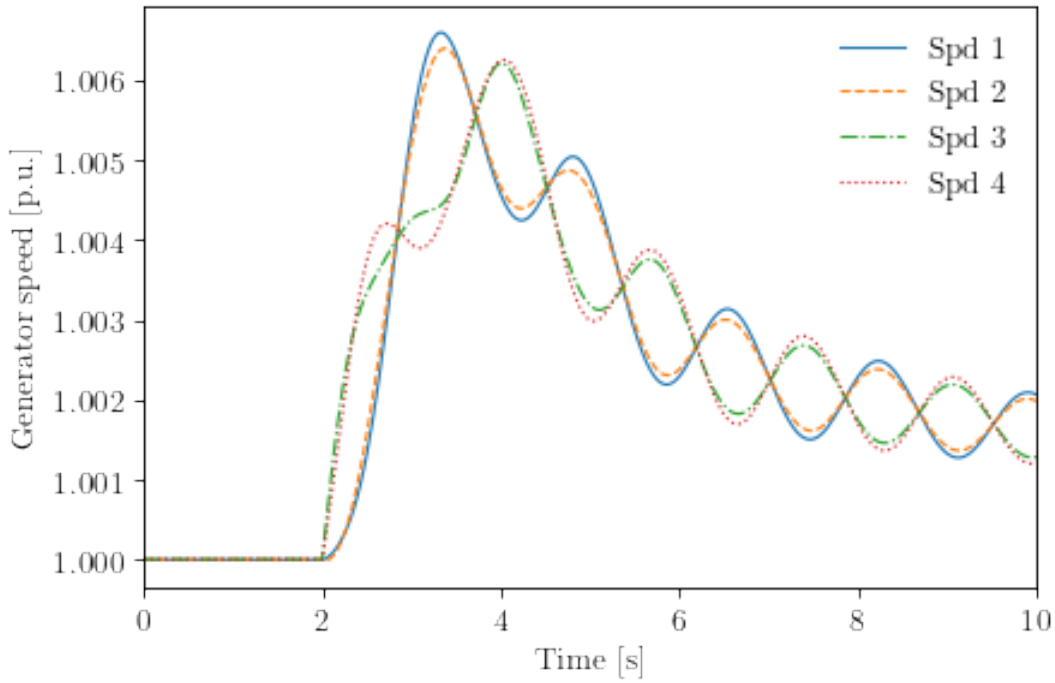
Y-axis label

```
fig, ax = ss.TDS.plotter.plot((5, 6, 7, 8), ylabel='Generator speed [p.u.]')
```



Legend names (yheader)

```
fig, ax = ss.TDS.plotter.plot((5, 6, 7, 8), ylabel='Generator speed [p.u.]',
                              yheader=['Spd 1', 'Spd 2', 'Spd 3', 'Spd 4'])
```



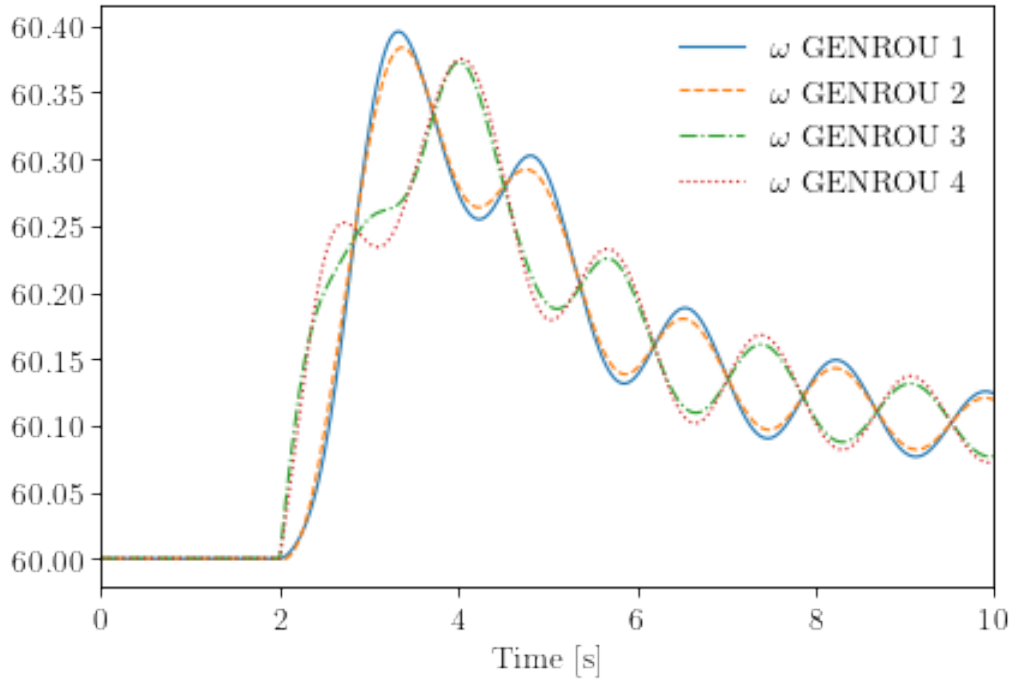
Note that the number of elements passed to `yheader` should match the number of variables. `yheader` only

applies to new curves and cannot be used to modify existing legends.

Scaling

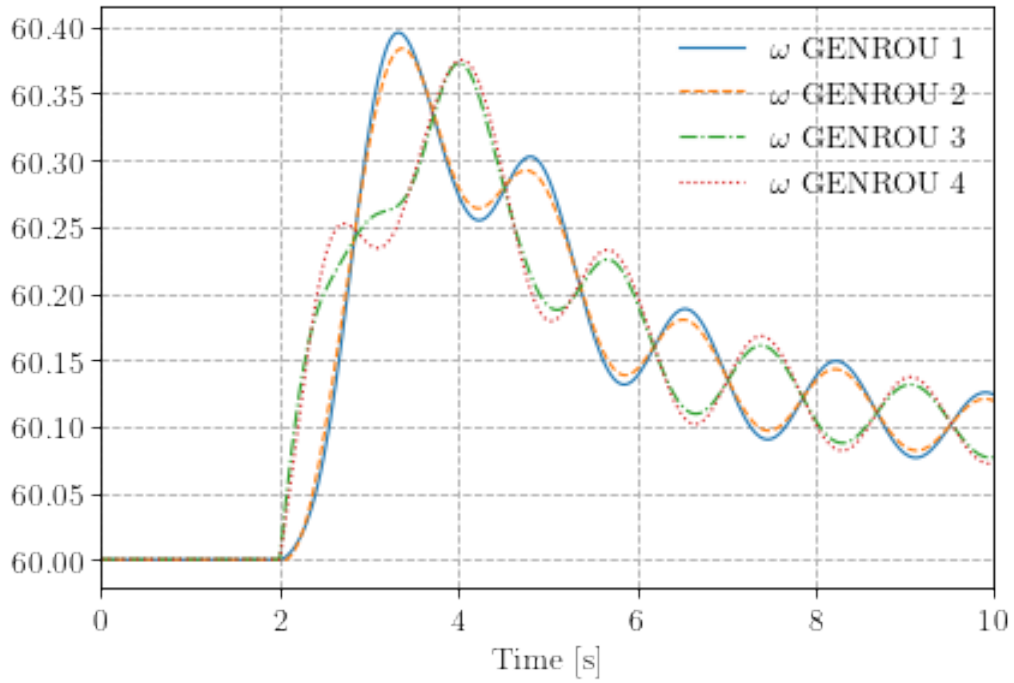
A lambda functino can be passed to `ycalc` to scale the value. To scale the frequency from per unit to 60 Hz nominal values, use

```
fig, ax = ss.TDS.plotter.plot((5, 6, 7, 8), ycalc=lambda x: 60 * x)
```



Greyscale and Grid

```
fig, ax = ss.TDS.plotter.plot((5, 6, 7, 8),
                              ycalc=lambda x: 60 * x,
                              greyscale=True,
                              grid=True)
```

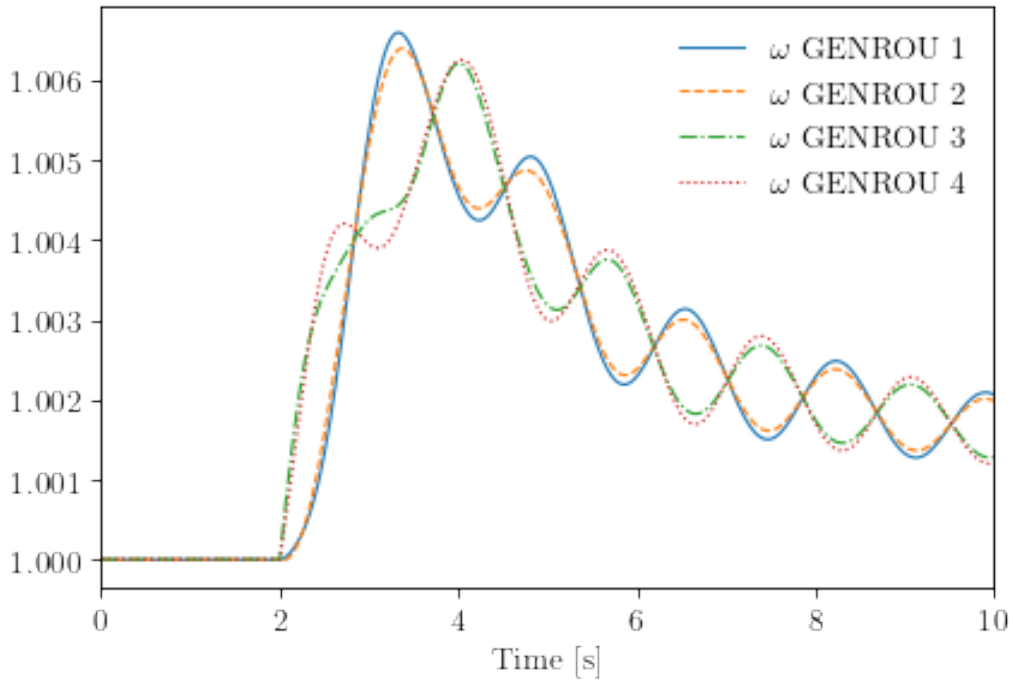


Save figure

Pass `savefig = True` to save the figure to a `png` file.

```
fig, ax = ss.TDS.plotter.plot((5, 6, 7, 8), savefig=True)
```

```
Figure saved to "kundur_full_out_1.png".
```



Additional arguments

`plotter.plot` takes addition arguments. To check additional arguments, please use `help` or refer to the source code.

```
help(ss.TDS.plotter.plot)
```

```
Help on method plot in module andes.plot:

plot(yidx, xidx=(0,), *, a=None, ytimes=None, ycalc=None, left=None,␣
↪right=None, ymin=None, ymax=None, xlabel=None, ylabel=None, xheader=None,␣
↪yheader=None, legend=None, grid=False, greyscale=False, latex=True, dpi=80,␣
↪line_width=1.0, font_size=12, savefig=None, save_format=None, show=True,␣
↪title=None, linestyles=None, use_bqplot=False, hline1=None, hline2=None,␣
↪vline1=None, vline2=None, hline=None, vline=None, fig=None, ax=None,␣
↪backend=None, set_xlim=True, set_ylim=True, autoscale=False, legend_
↪bbox=None, legend_loc=None, legend_ncol=1, figsize=None, color=None,␣
↪**kwargs) method of andes.plot.TDSData instance
    Entry function for plotting.

    This function retrieves the x and y values based on the `xidx` and
    `yidx` inputs, applies scaling functions `ytimes` and `ycalc`␣
↪sequentially,
    and delegates the plotting to the backend.

    Parameters
    ----------
    yidx : list or int
```

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```
        The indices for the y-axis variables
    xidx : tuple or int, optional
        The index for the x-axis variable
    a : tuple or list, optional
        The 0-indexed sub-indices into `yidx` to plot.
    ytimes : float, optional
        A scaling factor to apply to all y values.
    left : float
        The starting value of the x axis
    right : float
        The ending value of the x axis
    ymin : float
        The minimum value of the y axis
    ymax : float
        The maximum value of the y axis
    ylabel : str
        Text label for the y axis
    yheader : list
        A list containing the variable names for the y-axis variable
    title : str
        Title string to be shown at the top
    fig
        Existing figure object to draw the axis on.
    ax
        Existing axis object to draw the lines on.

    Other Parameters
    ----------------
    ycalc: callable, optional
        A callable to apply to all y values after scaling with `ytimes`.
    xlabel : str
        Text label for the x axis
    xheader : list
        A list containing the variable names for the x-axis variable
    legend : bool
        True to show legend and False otherwise
    legend_ncol : int
        Number of columns in legend
    legend_bbox : tuple of two floats
        legend box to anchor
    grid : bool
        True to show grid and False otherwise
    latex : bool
        True to enable latex and False to disable
    greyscale : bool
        True to use greyscale, False otherwise
    savefig : bool or str
        True to save to png figure file.
        str is treated as the output file name.
    save_format : str
        File extension string (pdf, png or jpg) for the savefig format
    dpi : int
```

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```
        Dots per inch for screen print or save.
        `savefig` uses a minimum of 200 dpi
    line_width : float
        Plot line width
    font_size : float
        Text font size (labels and legends)
    figsize : tuple
        Figure size passed when creating new figure
    show : bool
        True to show the image
    backend : str or None
        `bqplot` to use the bqplot backend in notebook.
        None for matplotlib.
    hline1: float, optional
        Dashed horizontal line 1
    hline2: float, optional
        Dashed horizontal line 2
    vline1: float, optional
        Dashed horizontal line 1
    vline2: float, optional
        Dashed vertical line 2
    hline: float or Iterable
        y-axis location of horizontal line(s)
    vline: float or Iterable
        x-axis location of vertical line(s)

    Returns
    -------
    (fig, ax)
        Figure and axis handles for matplotlib backend.
    fig
        Figure object for bqplot backend.
```

2.1.4 Cleanup

```
! andes misc -C
```

```
"/home/hacui/repos/andes/examples/kundur_full_out.npz" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.txt" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.lst" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.csv" removed.
```

```
!rm kundur_full_out_1.png
```

2.2 Working with Data

This example shows how to work with the data of a loaded test system, including parameters and variables.

```
import andes
from andes.utils.paths import get_case

andes.config_logger()
```

To show all the rows and columns, change the pandas configuration with

```
import pandas as pd

pd.options.display.max_columns = None
pd.options.display.max_rows = None
```

Let's load the Kundur's system.

2.2.1 Load System from an ANDES XLSX File

The ANDES xlsx file is the best supported format. Other formats can be converted to the xlsx format.

See the link below for more about format conversion. https://github.com/cuihantao/andes/blob/master/README.md#format-converter

As previously shown, test cases can be loaded with `andes.run()`:

```
ss = andes.run(get_case('kundur/kundur_full.xlsx'),
               default_config=True)  # one can remove `default_config=True`␣
↪to use custom config file
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.1394 seconds.
System internal structure set up in 0.0319 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0036 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
```

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```
4: |F(x)| = 3.745104027e-07
Converged in 5 iterations in 0.0074 seconds.
Report saved to "kundur_full_out.txt" in 0.0010 seconds.
```

```
-> Single process finished in 0.3582 seconds.
```

Alternatively, one can load a test case *without setting up* using `andes.load(..., setup=False)`. Note that `setup=False` option. It is useful to apply parameter changes to an existing test case.

```
ss = andes.load(get_case('kundur/kundur_full.xlsx'),
                default_config=True,
                setup=False)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.1263 seconds.
```

For example, we can toggle the connectivity status `u` of `Line_3` to `0` using

```
ss.Line.alter('u', 'Line_3', 0)
```

When done, remember to set up the system before running calculation routines:

```
ss.setup()

ss.PFlow.run()
```

```
System internal structure set up in 0.0366 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0049 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.579044433
2: |F(x)| = 0.119268955
3: |F(x)| = 0.03278820195
4: |F(x)| = 2.880943096e-05
5: |F(x)| = 3.93747257e-11
Converged in 6 iterations in 0.0122 seconds.
Report saved to "kundur_full_out.txt" in 0.0016 seconds.
```

```
True
```

After setting up the system, adding or removing devices are not yet allowed.

2.2.2 Load System from PSS/E RAW and DYR Files

ANDES supports loading systems from PSS/E RAW and DYR files.

The PSS/E v32 raw format is best supported.

Note that this feature is experimental. We try out best to support this format, but the compatibility is not guaranteed.

```
raw_path = get_case('kundur/kundur.raw')
dyr_path = get_case('kundur/kundur_full.dyr')
```

The raw file is passed to the positional argument, whereas the dyr file is passed to `addfile`.

```
ss = andes.run(raw_path, addfile=dyr_path, default_config=True)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur.raw"...
  MODIFIED KUNDUR'S TWO-AREA TEST SYSTEM, DISTRIBUTED WITH ANDES
  SEE THE BOOK "POWER SYSTEM STABILITY AND CONTROL" FOR ORIGINAL DATA
Input file parsed in 0.0047 seconds.
Parsing additional file "/home/hacui/repos/andes/andes/cases/kundur/kundur_
↪full.dyr"...
Addfile parsed in 0.0912 seconds.
System internal structure set up in 0.0310 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0037 seconds.
0: |F(x)| = 3.175850023
1: |F(x)| = 3.176155228e-08
Converged in 2 iterations in 0.0044 seconds.
Report saved to "kundur_out.txt" in 0.0006 seconds.
```

```
-> Single process finished in 0.2371 seconds.
```

Attributes for storing values

Parameters are stored as attributes of the model. For example, `ss.GENROU.M`, the machine starting time constant (`2H`), is stored in `ss.GENROU.M`.

```
ss.GENROU.M
```

```
NumParam: GENROU.M, v=[117.   117.   111.15 111.15], vin=[13.   13.   12.35␣
↪12.35]
```

It is an instance of `NumParam`, which contains fields `v` for the values after converting to system-base per unit values.

```
ss.GENROU.M.v
```

```
array([117.  , 117.  , 111.15, 111.15])
```

And field `vin` is for the original input data.

```
ss.GENROU.M.vin
```

```
array([13.  , 13.  , 12.35, 12.35])
```

Tabulated view

ANDES provides tabulated **view** of model parameters by using DataFrame. Each model object has an attribute called `cache` for caching the parameter dataframes.

The original parameters from the input file are stored in `cache.df_in` of the model object. For `GENROU`, do

```
ss.GENROU.cache.df_in
```

```
          idx    u      name  bus  gen   coi  coi2     Sn    Vn    fn    D  \
uid
0    GENROU_1  1.0  GENROU_1    1    1  None  None  900.0  20.0  60.0  0.0
1    GENROU_2  1.0  GENROU_2    2    2  None  None  900.0  20.0  60.0  0.0
2    GENROU_3  1.0  GENROU_3    3    3  None  None  900.0  20.0  60.0  0.0
3    GENROU_4  1.0  GENROU_4    4    4  None  None  900.0  20.0  60.0  0.0

         M   ra    xl  xd1   kp   kw  S10  S12  gammap  gammaq   xd   xq  \
uid
0    13.00  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7
1    13.00  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7
2    12.35  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7
3    12.35  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7

      xd2   xq1   xq2  Td10  Td20  Tq10  Tq20
uid
```

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```
0    0.25  0.55  0.25   8.0  0.03   0.4  0.05
1    0.25  0.55  0.25   8.0  0.03   0.4  0.05
2    0.25  0.55  0.25   8.0  0.03   0.4  0.05
3    0.25  0.55  0.25   8.0  0.03   0.4  0.05
```

Parameters will be **converted** to per-unit in the system base after loading. This process have been done if `andes.run` is used for loading the data file.

To inspect the converted parameters, check the `cache.df` parameter.

```
ss.GENROU.cache.df
```

```
          idx    u      name  bus  gen   coi  coi2     Sn    Vn    fn    D  \
uid
0    GENROU_1  1.0  GENROU_1    1    1  None  None  900.0  20.0  60.0  0.0
1    GENROU_2  1.0  GENROU_2    2    2  None  None  900.0  20.0  60.0  0.0
2    GENROU_3  1.0  GENROU_3    3    3  None  None  900.0  20.0  60.0  0.0
3    GENROU_4  1.0  GENROU_4    4    4  None  None  900.0  20.0  60.0  0.0

          M   ra        xl       xd1   kp   kw  S10  S12  gammap  gammaq   xd␣
↪ \
uid
0    117.00  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2
1    117.00  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2
2    111.15  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2
3    111.15  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2

           xq       xd2       xq1       xq2  Td10  Td20  Tq10  Tq20
uid
0    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
1    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
2    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
3    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
```

One will notice the converted parameters such as `M`, `xl`, and all other impedances.

It is very important to notice that `cache.df` and `cache.df_in` are both views. Altering data in these views will NOT alter the underlying parameter values.

To alter values, see the example below.

One may have noticed that `ss.GENROU.cache.df` and `ss.GENROU.as_df()` returns the same dataframe. The difference is that the latter creates a new dataframe everytime it is called, but the former caches the dataframe when it is initally accessed.

Altering parameters

Parameters can be altered by calling the `alter` method on a model instance.

We first look up the original value through `get`.

Either `v` or `vin` can be passed to argument `attr` to retrieve the converted or the original data. Here we are retrieving the original input data. If `attr` is not provided, `get` returns the value after per-unit conversion, which is the value used for calculation, by default.

```
ss.GENROU.get("M", "GENROU_1", attr='vin')
```

```
13.0
```

To change the `M` of `GENROU_1` to `10`, do

```
ss.GENROU.alter("M", "GENROU_1", 10)
```

The value set through `alter` is always the data before per-unit conversion - just like it should have been in an input file. ANDES will perform the conversion and set `vin` and `v` correctly.

Parameters altered through `Model.alter()` can be saved as a new system using

```
andes.io.xlsx.write(ss, 'new_system.xlsx', overwrite=True)
```

```
xlsx file written to "new_system.xlsx"
```

```
True
```

In-place update

`alter()` can be used to change the value of `ConstService` to modify the equation that depend on such `ConstService`. For example, the distributed PV model `PVD1` implements a `ConstService` called `pref0` to store the initial value of the power reference. An equation associated with variable `Pref` enforces that `0 = Pref - pref0`.

If one needs to modify `Pref`, it has to be done through modifying `pref0`. Modifying `Pref` directly will not take any effect since the variable will be overwritten by the solution of equations.

To update `pref0` for a `PVD1` device with `idx = "PVD_1"`, one can do

`ss.PVD1.alter('pref0', 'PVD_1', 0.005)`

or, using keyword arguments in any order,

`ss.PVD1.alter(src='pref0', idx='PVD_1', value=0.005)`

If `PVD_1` is the first (i.e., 0-th in the Python indexing) in the idx list, this modification is equivalent to setting

`ss.PVD1.pref0.v[0] = 0.005`.

Since index `0` is given, the array `ss.PVD1.pref0.v` is updated in-place.

When one needs to modify the `pref0` of all `PVD1` devices to 0.005, one can do

```
ss.PVD1.alter('pref0', ss.PVD1.idx.v, 0.005)
```

This is equivalent to

```
ss.PVD1.pref0.v[:] = 0.005
```

Note the `[:]` in the above line. This is a slice operation so that the assignment happens in-place.

One must never do out-of-place assignment, i.e.,

```
ss.PVD1.pref0.v = 0.005
```

or

```
ss.PVD1.pref0.v = 0.005 * np.ones_line(ss.PVD1.pref0.v)
```

because the assignment will point `ss.PVD1.pref0.v` to a new array. Internally, ANDES reuses the memory for all arrays, meaning that their addresses are assumed to be constant. If one modifies `ss.PVD1.pref0.v` out of place, the previous memory will no longer be accessible through `ss.PVD1.pref0.v`.

On the safe side, one should modify variables using `alter()` or, at least, always use in-place assignment to internal arrays.

Refreshing the view

As mentioned, `cache.df` and `cache.df_in` are *cached* views and will not be automatically updated for inspection.

This is generally not an issue if one performs the simulation after altering data. However, if one needs to inspect the data again, `cache.refresh()` needs to be called manually.

```
ss.GENROU.cache.refresh()
```

```
ss.GENROU.cache.df_in
```

```
          idx    u      name  bus  gen   coi  coi2     Sn    Vn    fn    D  \
uid
0    GENROU_1  1.0  GENROU_1    1    1  None  None  900.0  20.0  60.0  0.0
1    GENROU_2  1.0  GENROU_2    2    2  None  None  900.0  20.0  60.0  0.0
2    GENROU_3  1.0  GENROU_3    3    3  None  None  900.0  20.0  60.0  0.0
3    GENROU_4  1.0  GENROU_4    4    4  None  None  900.0  20.0  60.0  0.0

         M   ra    xl  xd1   kp   kw  S10  S12  gammap  gammaq   xd   xq  \
uid
0    10.00  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7
1    13.00  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7
2    12.35  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7
3    12.35  0.0  0.06  0.3  0.0  0.0  0.0  0.0     1.0     1.0  1.8  1.7

      xd2   xq1   xq2  Td10  Td20  Tq10  Tq20
uid
```

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```
0    0.25  0.55  0.25   8.0  0.03   0.4  0.05
1    0.25  0.55  0.25   8.0  0.03   0.4  0.05
2    0.25  0.55  0.25   8.0  0.03   0.4  0.05
3    0.25  0.55  0.25   8.0  0.03   0.4  0.05
```

Alternatively, one can call the `as_df()` function to build a new dataframe *without overwriting* the cache:

```
ss.GENROU.as_df()
```

```
          idx    u      name  bus  gen   coi  coi2     Sn    Vn    fn    D  \
uid
0    GENROU_1  1.0  GENROU_1    1    1  None  None  900.0  20.0  60.0  0.0
1    GENROU_2  1.0  GENROU_2    2    2  None  None  900.0  20.0  60.0  0.0
2    GENROU_3  1.0  GENROU_3    3    3  None  None  900.0  20.0  60.0  0.0
3    GENROU_4  1.0  GENROU_4    4    4  None  None  900.0  20.0  60.0  0.0

          M   ra        xl       xd1   kp   kw  S10  S12  gammap  gammaq   xd␣
↪ \
uid
0     90.00  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2
1    117.00  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2
2    111.15  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2
3    111.15  0.0  0.006667  0.033333  0.0  0.0  0.0  0.0     1.0     1.0  0.2

           xq       xd2       xq1       xq2  Td10  Td20  Tq10  Tq20
uid
0    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
1    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
2    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
3    0.188889  0.027778  0.061111  0.027778   8.0  0.03   0.4  0.05
```

2.2.3 Variables

Snapshots

One might also want to check the variable values in a similar way to that for a parameter. Certainly, a variable has a `v` attribute which stores values.

It is important to note that `v` only holds the values at the last program state. Such program state could be the solution of power flow, the initialization of time-domain simulation, or the end of a simulation disturbances.

Since we have only ran power flow for `ss`, `ss.Bus.v.v` are the voltage magnitude solutions, where the first `v` is for "voltage", and the second `v` is the first `v`'s value attribute.

```
ss.Bus.v.v
```

```
array([1.        , 1.        , 1.        , 1.        , 0.98337472,
       0.96908585, 0.9562181 , 0.95400018, 0.96856366, 0.98377143])
```

Variables hold more than values. They have an attribute `a` for the addresses indexing into the corresponding type of array.

There are two system-level arrays, `ss.dae.x` and `ss.dae.y` for the right-hand-side of the differential and algebraic equations, respectively.

```
type(ss.Bus.v)
```

```
andes.core.var.Algeb
```

`ss.Bus.v` is an algebraic variable, thus `ss.Bus.v.a` holds the indices into `ss.dae.g`.

```
ss.dae.y[ss.Bus.v.a]
```

```
array([1.        , 1.        , 1.        , 1.        , 0.98337472,
       0.96908585, 0.9562181 , 0.95400018, 0.96856366, 0.98377143])
```

We can see that these two values are the same.

Time series

After a time-domain simulation, the time series of the variables can be retrieved through `ss.dae.ts`. Let's first run a simulation.

```
ss.TDS.run()
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
Initialization for dynamics completed in 0.0489 seconds.
Initialization was successful.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Toggle Toggle_1>: Line.Line_8 status changed to 0 at t=2.0 sec.
```

```
Simulation completed in 1.1192 seconds.
Outputs to "kundur_out.lst" and "kundur_out.npz".
Outputs written in 0.0226 seconds.
```

```
True
```

```
ss.dae.ts
```

```
<andes.variables.dae.DAETimeSeries at 0x7f7bc75c1b50>
```

`ss.dae.ts` has four commonly used attributes: `t` for time stamps, `xy` for variables (differential and then algebraic), `z` for discontinuous states, and `df` for the dataframe of all.

- Each point in `ss.dae.ts.t` correspond to a row in `ss.dae.ts.xy`.
- Each column in `ss.dae.ts.xy` correspond to a variable, whose name can be located in `ss.dae.xy_name`, for all timestamps.
- `z` is not stored by default unless one enables it before simulation by setting `ss.TDS.config.store_z = 1`.
- `df` is not built by default but can be manually triggered after simulation by calling `ss.dae.ts.unpack(df=True)`

The following are some statistics of the shapes of arrays:

```
ss.dae.ts.t.shape
```

```
(603,)
```

```
ss.dae.ts.xy.shape  # x-axis is for time stamps, and y-axis is for variables
```

```
(603, 201)
```

```
len(ss.dae.xy_name)
```

```
201
```

Extracting Variable Data

Let's extract the data for rotor speed (variable `omega`) of `GENROU` generators. The first step to extract variable data is to determine the type of the variable: differential or algebraic. One can print the variable to see the type:

```
ss.GENROU.omega
```

```
State: GENROU.omega, a=[4 5 6 7], v=[1.00165687 1.00166417 1.00182915 1.
↪00184744], e=[-0.00251535 -0.00375723  0.00131868  0.00182826]
```

The output shows that `omega` is a state (differential variable), which should be looked up in `ss.dae.x`. For algebraic variables such as `ss.Bus.v`, they should be looked up in `ss.dae.y`.

Therefore, all `omega` variables can be extracted as follows:

```
omega = ss.dae.ts.x[:, ss.GENROU.omega.a]
```

where the `:` in the first axis will access such data for all time stamps, and `ss.GENROU.omega.a` stores the addresses of all `omega` into `ss.dae.x`.

To access all bus voltages (algebraic variable `v`) of the generators, one can use:

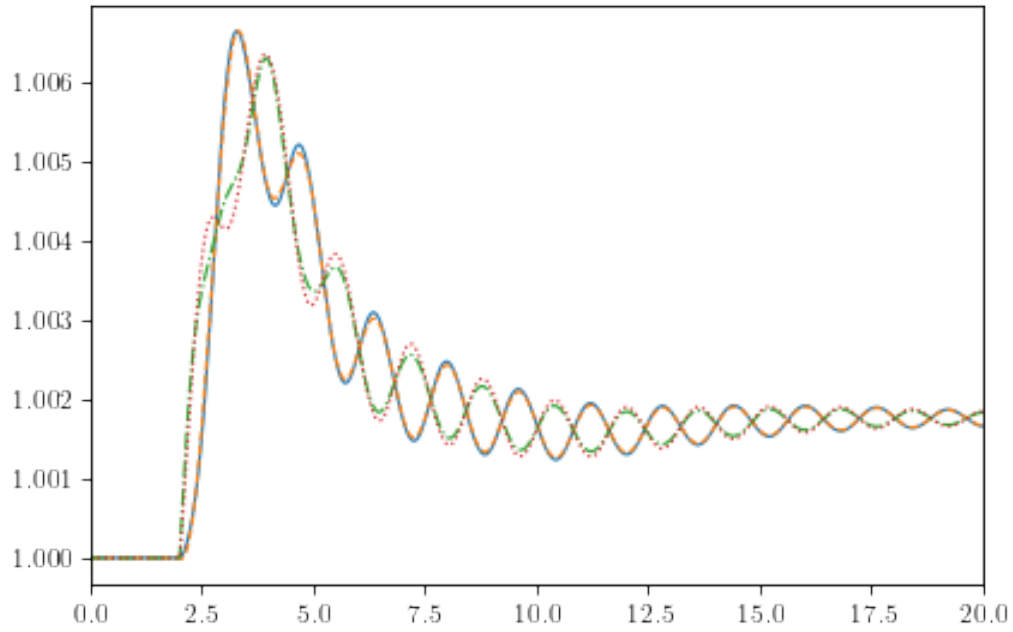
```
ss.dae.ts.y[:, ss.GENROU.v.a]
```

```
array([[1.        , 1.        , 1.        , 1.        ],
       [1.        , 1.        , 1.        , 1.        ],
       [1.        , 1.        , 1.        , 1.        ],
       ...,
       [1.00240968, 1.00148908, 0.99526693, 1.00007159],
       [1.00249935, 1.00159007, 0.99515528, 0.99997846],
       [1.00259067, 1.0016924 , 0.99504062, 0.999883  ]])
```

These data correspond to the timestamps stored in `ss.dae.ts.t`. One can process such data as necessary.

To show verify the extracted data, we plot them with `ss.TDS.plt.plot_data`.

```
ss.TDS.plt.plot_data(ss.dae.ts.t, omega )
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:>)
```

2.2.4 Altering Fault duration

`Alter` can be used for updating any model parameter. We show another example of updating the duration of a fault. Using the `ieee14_fault.xlsx` test case, we have

```
ss = andes.run(get_case("ieee14/ieee14_fault.xlsx"))
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/ieee14/ieee14_fault.
↪xlsx"...
```

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```
Input file parsed in 0.0546 seconds.
System internal structure set up in 0.0348 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0037 seconds.
0: |F(x)| = 0.5605182134
1: |F(x)| = 0.006202200332
2: |F(x)| = 5.819382824e-06
3: |F(x)| = 6.96508129e-12
Converged in 4 iterations in 0.0047 seconds.
Initialization for dynamics completed in 0.0353 seconds.
Initialization was successful.
Report saved to "ieee14_fault_out.txt" in 0.0021 seconds.
```

```
-> Single process finished in 0.3141 seconds.
```

Again, if you need to add devices, you should use `ss = andes.load(.., setup=False)` and `ss.setup()` instead of `andes.run()`.

List the existing `Fault` devices:

```
ss.Fault.as_df()
```

```
     idx    u     name  bus   tf   tc      xf   rf
uid
0      1  1.0  Fault_1    9  1.0  1.1  0.0001  0.0
```

One fault on Bus 9 is applied at t=1.0 sec and cleared at t=1.1 sec. Suppose that we want to clear the fault at t = 1.05 sec, we can do

```
ss.Fault.alter('tc', 1, 1.05)  # arguments are `src`, `idx`, `value`
```

where `tc` is the parameter to alter, `1` is the idx of the Fault to find, and `1.05` is the new value. Inspect the Fault devices to see the updated value. The simulation for the new system can be performed next.

```
ss.Fault.as_df()
```

```
     idx    u     name  bus   tf    tc      xf   rf
uid
0      1  1.0  Fault_1    9  1.0  1.05  0.0001  0.0
```

2.2.5 Cleanup

```
!andes misc -C
```

```
"/home/hacui/repos/andes/examples/kundur_full_out.txt" removed.
"/home/hacui/repos/andes/examples/kundur_out.lst" removed.
"/home/hacui/repos/andes/examples/kundur_out.npz" removed.
"/home/hacui/repos/andes/examples/ieee14_fault_out.txt" removed.
"/home/hacui/repos/andes/examples/kundur_out.txt" removed.
```

```
!rm new_system.xlsx
```

2.3 Inspecting Models

First of all, import `andes` and configure the logger to the WARNING level (30).

```
import andes

andes.config_logger(30)
```

2.3.1 Inspect Model Equations

Create an empty `andes.System` object and call `prepare(nomp=True)` to generate equations and pretty print, where `nomp` disables multiprocessing so that equations can be properly returned. This operation may take a moment.

To only generate equations for a specific model, such as `GENCLS`, do:

```
ss = andes.System()
ss.GENCLS.prepare()
```

List all models

```
print(ss.supported_models())
```

```
Supported Groups and Models

      Group         |                              Models
--------------------+-------------------------------------------------------------
 ACLine             | Line
 ACShort            | Jumper
 ACTopology         | Bus
 Calculation        | ACE, ACEc, COI
 Collection         | Area
 DCLink             | Ground, R, L, C, RCp, RCs, RLs, RLCs, RLCp
```

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```
 DCTopology         | Node
 DG                 | PVD1, ESD1, EV1, EV2
 DGProtection       | DGPRCT1, DGPRCTExt
 DynLoad            | ZIP, FLoad
 Exciter            | EXDC2, IEEEX1, ESDC2A, EXST1, ESST3A, SEXS, IEEET1,
                    | EXAC1, EXAC4, ESST4B, AC8B, IEEET3, ESAC1A, ESST1A
 FreqMeasurement    | BusFreq, BusROCOF
 Information        | Summary
 Motor              | Motor3, Motor5
 PLL                | PLL1
 PSS                | IEEEST, ST2CUT
 PhasorMeasurement  | PMU
 RenAerodynamics    | WTARA1, WTARV1
 RenExciter         | REECA1, REECA1E, REECA1G
 RenGen             | REGCA1, REGCP1, REGCV1, REGCV2
 RenGovernor        | WTDTA1, WTDS
 RenPitch           | WTPTA1
 RenPlant           | REPCA1
 RenTorque          | WTTQA1
 StaticACDC         | VSCShunt
 StaticGen          | PV, Slack
 StaticLoad         | PQ
 StaticShunt        | Shunt, ShuntTD, ShuntSw
 SynGen             | GENCLS, GENROU, PLBVFU1, GENROUOS
 TimedEvent         | Toggle, Fault, Alter
 TurbineGov         | TG2, TGOV1, TGOV1DB, TGOV1N, TGOV1NDB, IEEEG1, IEESGO,
                    | GAST, HYGOV, HYGOVDB
 Undefined          | TimeSeries
 VoltComp           | IEEEVC
```

2.3.2 Check model documentation

To check the documentation for the model, print the return of `doc()` for the model instance.

For example, the documentation for `GENCLS` can be printed with

```
print(ss.GENCLS.doc())
```

```
Model <GENCLS> in Group <SynGen>
Classical generator model.

Parameters

 Name   |       Description         | Default | Unit |        Properties
--------+---------------------------+---------+------+--------------------------
 idx    | unique device idx         |         |      |
 u      | connection status         | 1       | bool |
 name   | device name               |         |      |
 bus    | interface bus id          |         |      | mandatory
 gen    | static generator index    |         |      | mandatory
```

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```
 coi     | center of inertia index  |         |       |
 coi2    | center of inertia index  |         |       |
 Sn      | Power rating             | 100     | MVA   |
 Vn      | AC voltage rating        | 110     |       |
 fn      | rated frequency          | 60      |       |
 D       | Damping coefficient      | 0       |       | power
 M       | machine start up time    | 6       |       | non_zero,non_negative,po
         | (2H)                     |         |       | wer
 ra      | armature resistance      | 0       |       | z
 xl      | leakage reactance        | 0       |       | z
 xd1     | d-axis transient         | 0.302   |       | z
         | reactance                |         |       |
 kp      | active power feedback    | 0       |       |
         | gain                     |         |       |
 kw      | speed feedback gain      | 0       |       |
 S10     | first saturation factor  | 0       |       |
 S12     | second saturation factor | 1       |       |
 gammap  | P ratio of linked static | 1       |       |
         | gen                      |         |       |
 gammaq  | Q ratio of linked static | 1       |       |
         | gen                      |         |       |
 subidx  | Generator idx in plant;  | 0       |       |
         | only used by PSS/E data  |         |       |

Variables

 Name    |   Type    |            Description             |   Unit    | Properties
---------+-----------+------------------------------------+-----------+-----------
 delta   | State     | rotor angle                        | rad       | v_str
 omega   | State     | rotor speed                        | pu (Hz)   | v_str
 Id      | Algeb     | d-axis current                     |           | v_str
 Iq      | Algeb     | q-axis current                     |           | v_str
 vd      | Algeb     | d-axis voltage                     |           | v_str
 vq      | Algeb     | q-axis voltage                     |           | v_str
 tm      | Algeb     | mechanical torque                  |           | v_str
 te      | Algeb     | electric torque                    |           | v_str
 vf      | Algeb     | excitation voltage                 | pu        | v_str
 XadIfd  | Algeb     | d-axis armature excitation         | p.u (kV)  | v_str
         |           | current                            |           |
 Pe      | Algeb     | active power injection             |           | v_str
 Qe      | Algeb     | reactive power injection           |           | v_str
 psid    | Algeb     | d-axis flux                        |           | v_str
 psiq    | Algeb     | q-axis flux                        |           | v_str
 a       | ExtAlgeb  | Bus voltage phase angle            |           |
 v       | ExtAlgeb  | Bus voltage magnitude              |           |

Initialization Equations

 Name    |   Type    |        Initial Value
---------+-----------+----------------------------
 delta   | State     | delta0
 omega   | State     | u
```

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```
 Id     | Algeb    | u * Id0
 Iq     | Algeb    | u * Iq0
 vd     | Algeb    | u * vd0
 vq     | Algeb    | u * vq0
 tm     | Algeb    | tm0
 te     | Algeb    | u * tm0
 vf     | Algeb    | u * vf0
 XadIfd | Algeb    | u * vf0
 Pe     | Algeb    | u * (vd0 * Id0 + vq0 * Iq0)
 Qe     | Algeb    | u * (vq0 * Id0 - vd0 * Iq0)
 psid   | Algeb    | u * psid0
 psiq   | Algeb    | u * psiq0
 a      | ExtAlgeb |
 v      | ExtAlgeb |

Differential Equations

 Name  | Type  | RHS of Equation "T x' = f(x, y)" | T (LHS)
-------+-------+----------------------------------+--------
 delta | State | u * (2 * pi * fn) * (omega - 1)  |
 omega | State | u * (tm - te - D * (omega - 1))  | M

Algebraic Equations

 Name   |   Type   |  RHS of Equation "0 = g(x, y)"
--------+----------+--------------------------------
 Id     | Algeb    | + xq * Id - vf+ psid
 Iq     | Algeb    | + xq * Iq+ psiq
 vd     | Algeb    | u * v * sin(delta - a) - vd
 vq     | Algeb    | u * v * cos(delta - a) - vq
 tm     | Algeb    | tm0 - tm
 te     | Algeb    | u * (psid * Iq - psiq * Id) - te
 vf     | Algeb    | u * vf0 - vf
 XadIfd | Algeb    | u * vf0 - XadIfd
 Pe     | Algeb    | u * (vd * Id + vq * Iq) - Pe
 Qe     | Algeb    | u * (vq * Id - vd * Iq) - Qe
 psid   | Algeb    | u * (ra*Iq + vq) - psid
 psiq   | Algeb    | u * (ra*Id + vd) + psiq
 a      | ExtAlgeb | -u * (vd * Id + vq * Iq)
 v      | ExtAlgeb | -u * (vq * Id - vd * Iq)

Services

  Name   |                        Equation                        |     Type
---------+--------------------------------------------------------+-------------
 p0      | p0s * gammap                                           | ConstService
 q0      | q0s * gammaq                                           | ConstService
 _V      | v * exp(1j * a)                                        | ConstService
 _S      | p0 - 1j * q0                                           | ConstService
 _I      | _S / conj(_V)                                          | ConstService
 _E      | _V + _I * (ra + 1j * xq)                               | ConstService
 _deltac | log(_E / abs(_E))                                      | ConstService
```

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```
 delta0  | u * im(_deltac)                                              | ConstService
 vdq     | u * (_V * exp(1j * 0.5 * pi - _deltac))                      | ConstService
 Idq     | u * (_I * exp(1j * 0.5 * pi - _deltac))                      | ConstService
 Id0     | re(Idq)                                                      | ConstService
 Iq0     | im(Idq)                                                      | ConstService
 vd0     | re(vdq)                                                      | ConstService
 vq0     | im(vdq)                                                      | ConstService
 tm0     | u * ((vq0 + ra * Iq0) * Iq0 + (vd0 + ra * Id0) *             | ConstService
         | Id0)                                                        |
 psid0   | u * (ra * Iq0) + vq0                                         | ConstService
 psiq0   | -u * (ra * Id0) - vd0                                        | ConstService
 vf0     | (vq0 + ra * Iq0) + xq * Id0                                  | ConstService


Config Fields in [GENCLS]

   Option     | Value |                Info                 | Acceptable values
--------------+-------+-------------------------------------+-------------------
 allow_adjust | 1     | allow adjusting upper or lower      | (0, 1)
              |       | limits                              |
 adjust_lower | 0     | adjust lower limit                  | (0, 1)
 adjust_upper | 1     | adjust upper limit                  | (0, 1)
 vf_lower     | 1     | lower limit for vf warning          |
 vf_upper     | 5     | upper limit for vf warning          |
```

Pretty print of variables

All symbols are stored in the attributes of `Model.syms`. For example,

```
ss.GENCLS.syms.xy
```

$$
\begin{bmatrix}
\delta \\
\omega \\
I_d \\
I_q \\
V_d \\
V_q \\
\tau_m \\
\tau_e \\
v_f \\
X_{ad} I_{fd} \\
P_e \\
Q_e \\
\psi_d \\
\psi_q \\
\theta \\
V
\end{bmatrix}
$$

Differential variables comes before algebraic variables.

```
ss.GENCLS.states
```

```
OrderedDict([('delta', State: GENCLS.delta, []),
             ('omega', State: GENCLS.omega, [])])
```

```
ss.GENCLS.algebs
```

```
OrderedDict([('Id', Algeb: GENCLS.Id, []),
             ('Iq', Algeb: GENCLS.Iq, []),
             ('vd', Algeb: GENCLS.vd, []),
             ('vq', Algeb: GENCLS.vq, []),
             ('tm', Algeb: GENCLS.tm, []),
             ('te', Algeb: GENCLS.te, []),
             ('vf', Algeb: GENCLS.vf, []),
             ('XadIfd', Algeb: GENCLS.XadIfd, []),
             ('Pe', Algeb: GENCLS.Pe, []),
             ('Qe', Algeb: GENCLS.Qe, []),
             ('psid', Algeb: GENCLS.psid, []),
             ('psiq', Algeb: GENCLS.psiq, [])])
```

Pretty print of equations

Formatted equations are stored in each model. The following attributes of `Model.syms` are available for equation printing.

- f: differential equations
- g: algebraic equations
- df: df/dxy
- dg: dg/dxy

```
ss.GENCLS.syms.f
```

$$\begin{bmatrix} 2\pi f u \left(\omega - 1\right) \\ u \left(-D \left(\omega - 1\right) - \tau_{e} + \tau_{m}\right) \end{bmatrix}$$

```
ss.GENCLS.syms.g
```

$$\begin{bmatrix} I_d xq + \psi_d - v_f \\ I_q xq + \psi_q \\ Vu\sin(\delta-\theta) - V_d \\ Vu\cos(\delta-\theta) - V_q \\ -\tau_m + \tau_{m0} \\ -\tau_e + u\left(-I_d\psi_q + I_q\psi_d\right) \\ uv_{f0} - v_f \\ -X_{ad}I_{fd} + uv_{f0} \\ -P_e + u\left(I_dV_d + I_qV_q\right) \\ -Q_e + u\left(I_dV_q - I_qV_d\right) \\ -\psi_d + u\left(I_q r_a + V_q\right) \\ \psi_q + u\left(I_d r_a + V_d\right) \\ -u\left(I_dV_d + I_qV_q\right) \\ -u\left(I_dV_q - I_qV_d\right) \end{bmatrix}$$

```
ss.GENCLS.syms.df
```

$$\begin{bmatrix} 0 & 2\pi fu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -Du & 0 & 0 & 0 & 0 & u & -u & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

```
ss.GENCLS.syms.dg
```

$$\begin{bmatrix} 0 & 0 & xq & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & xq & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ Vu\cos(\delta-\theta) & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -Vu\cos(\delta-\theta) \\ -Vu\sin(\delta-\theta) & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Vu\sin(\delta-\theta) \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\psi_q u & \psi_d u & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & I_q u & -I_d u & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & V_d u & V_q u & I_d u & I_q u & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & V_q u & -V_d u & -I_q u & I_d u & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & r_a u & 0 & u & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & r_a u & 0 & u & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -V_d u & -V_q u & -I_d u & -I_q u & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -V_q u & V_d u & I_q u & -I_d u & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Pretty print of services

The list of services is in `services`.

```
ss.GENCLS.services
```

```
OrderedDict([('p0', ConstService: GENCLS.p0, v=0.0),
             ('q0', ConstService: GENCLS.q0, v=0.0),
             ('_V', ConstService: GENCLS._V, v=0.0),
             ('_S', ConstService: GENCLS._S, v=0.0),
             ('_I', ConstService: GENCLS._I, v=0.0),
             ('_E', ConstService: GENCLS._E, v=0.0),
             ('_deltac', ConstService: GENCLS._deltac, v=0.0),
             ('delta0', ConstService: GENCLS.delta0, v=0.0),
             ('vdq', ConstService: GENCLS.vdq, v=0.0),
             ('Idq', ConstService: GENCLS.Idq, v=0.0),
             ('Id0', ConstService: GENCLS.Id0, v=0.0),
             ('Iq0', ConstService: GENCLS.Iq0, v=0.0),
             ('vd0', ConstService: GENCLS.vd0, v=0.0),
             ('vq0', ConstService: GENCLS.vq0, v=0.0),
             ('tm0', ConstService: GENCLS.tm0, v=0.0),
             ('psid0', ConstService: GENCLS.psid0, v=0.0),
             ('psiq0', ConstService: GENCLS.psiq0, v=0.0),
             ('vf0', ConstService: GENCLS.vf0, v=0.0)])
```

Service equations are in `Model.syms.s` For example, services of `GENCLS` is in

```
ss.GENCLS.syms.s
```

```
[P_{0s}*\gamma_P,
 Q_{0s}*\gamma_Q,
 V*exp(I*\theta),
 P_0 - I*Q_0,
 S/conj(V_c),
 I_c*(r_a + I*xq) + V_c,
 log(E/Abs(E)),
 u*im(\delta_c),
 V_c*u*exp(-\delta_c + 0.5*I*pi),
 I_c*u*exp(-\delta_c + 0.5*I*pi),
 re(I_{dq}),
 im(I_{dq}),
 re(V_{dq}),
 im(V_{dq}),
 u*(I_{d0}*(I_{d0}*r_a + V_{d0}) + I_{q0}*(I_{q0}*r_a + V_{q0})),
 I_{q0}*r_a*u + V_{q0},
 -I_{d0}*r_a*u - V_{d0},
 I_{d0}*xq + I_{q0}*r_a + V_{q0}]
```

2.4 Eigenvalue Analysis

2.4.1 Run Eigenvalue Analysis

```
import numpy as np

import andes
from andes.utils.paths import list_cases, get_case
```

```
case_path = get_case('kundur/kundur_full.xlsx')
```

Pass the routine name `EIG` or `eig` to `andes.run`.

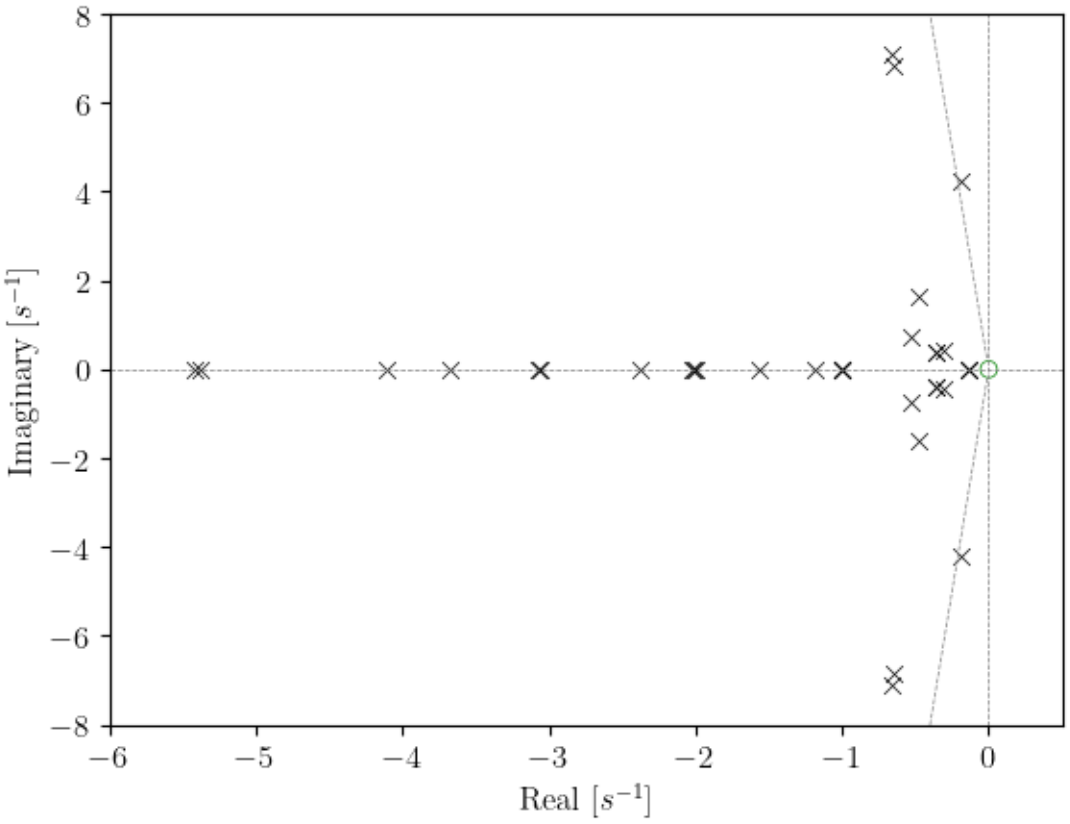
```
ss = andes.run(case_path, routine='eig')
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.1985 seconds.
System internal structure set up in 0.0309 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0042 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745104027e-07
Converged in 5 iterations in 0.0070 seconds.
Report saved to "kundur_full_out.txt" in 0.0010 seconds.
Initialization for dynamics completed in 0.0301 seconds.
Initialization was successful.

-> Eigenvalue Analysis:
  Positive       0
  Zeros          1
  Negative      52
Eigenvalue analysis finished in 0.0051 seconds.
Report saved to "kundur_full_eig.txt".
```

```
-> Single process finished in 0.5363 seconds.
```

2.4.2 Plotting in S-Domain

```
ss.EIG.plot()
```




```
(<Figure size 640x480 with 1 Axes>,
 <AxesSubplot:xlabel='Real [$s^{-1}$]', ylabel='Imaginary [$s^{-1}$]'>)
```

2.4.3 Report

Report is saved to the file and can be loaded into the notebook.

```
with open('kundur_full_eig.txt', 'r') as f:
    print(f.read())
```

```
ANDES 1.7.5.post2.dev0+ga53a31fa
Copyright (C) 2015-2022 Hantao Cui

ANDES comes with ABSOLUTELY NO WARRANTY
Case file: /home/hacui/repos/andes/andes/cases/kundur/kundur_full.xlsx
Report time: 07/05/2022 08:57:50 PM

Power flow converged in 5 iterations.
Flat-start: No
```

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```
EIGENVALUE ANALYSIS REPORT

Positives                          0
Zeros                              1
Negatives                         52

STATISTICS
                    Most Associated              Real              Imag.      ␣
↪Damped Freq.         Frequency       Damping [%]

#1                     LL_x EXDC2 1               -1                 0      ␣
↪           0                 0                0
#2                     LL_x EXDC2 2               -1                 0      ␣
↪           0                 0                0
#3                     LL_x EXDC2 3               -1                 0      ␣
↪           0                 0                0
#4                     LL_x EXDC2 4               -1                 0      ␣
↪           0                 0                0
#5                     LS_y EXDC2 3           -49.191           0.64233      ␣
↪     0.10223             7.8296           99.991
#6                     LS_y EXDC2 3           -49.191          -0.64233      ␣
↪     0.10223             7.8296           99.991
#7                     LS_y EXDC2 1           -49.535                 0      ␣
↪           0                 0                0
#8                     LS_y EXDC2 4           -49.515                 0      ␣
↪           0                 0                0
#9                     LA_y EXDC2 2           -49.202           0.39349      ␣
↪    0.062627             7.831           99.997
#10                    LA_y EXDC2 2           -49.202          -0.39349      ␣
↪    0.062627             7.831           99.997
#11                    LA_y EXDC2 1           -48.885                 0      ␣
↪           0                 0                0
#12                    LA_y EXDC2 4           -48.905                 0      ␣
↪           0                 0                0
#13                    e2d GENROU 2           -36.896                 0      ␣
↪           0                 0                0
#14                    e2d GENROU 4            -36.75                 0      ␣
↪           0                 0                0
#15                    e2d GENROU 1           -34.732                 0      ␣
↪           0                 0                0
#16                    e2q GENROU 3            -33.89                 0      ␣
↪           0                 0                0
#17                    e2q GENROU 2           -33.526                 0      ␣
↪           0                 0                0
#18                    e2d GENROU 3           -31.242                 0      ␣
↪           0                 0                0
#19                    e2q GENROU 4           -27.613                 0      ␣
↪           0                 0                0
#20                    e2q GENROU 1           -24.954                 0      ␣
↪           0                 0                0
```

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```
#21                  delta GENROU 3          -0.6564             7.086      ␣
↪      1.1278            1.1326            9.224
#22                  delta GENROU 3          -0.6564            -7.086      ␣
↪      1.1278            1.1326            9.224
#23                  delta GENROU 2          -0.65252            6.8343     ␣
↪      1.0877            1.0927            9.5046
#24                  delta GENROU 2          -0.65252           -6.8343     ␣
↪      1.0877            1.0927            9.5046
#25                  delta GENROU 1          -0.19177            4.2247     ␣
↪     0.67239           0.67308            4.5346
#26                  delta GENROU 1          -0.19177           -4.2247     ␣
↪     0.67239           0.67308            4.5346
#27                    e1d GENROU 2            -5.4189                0      ␣
↪           0                 0                 0
#28                    e1d GENROU 3            -5.3729                0      ␣
↪           0                 0                 0
#29                    e1d GENROU 4            -4.1119                0      ␣
↪           0                 0                 0
#30                    e1d GENROU 2            -3.6722                0      ␣
↪           0                 0                 0
#31                     vp EXDC2 2            -0.48245              1.628     ␣
↪     0.25911           0.27025            28.413
#32                     vp EXDC2 2            -0.48245             -1.628     ␣
↪     0.25911           0.27025            28.413
#33                     vp EXDC2 4            -3.0736                0      ␣
↪           0                 0                 0
#34                     vp EXDC2 1            -3.0635                0      ␣
↪           0                 0                 0
#35                     vp EXDC2 1            -2.3787                0      ␣
↪           0                 0                 0
#36                   LAG_y TGOV1 1           -1.5702                0      ␣
↪           0                 0                 0
#37                   LAG_y TGOV1 4           -1.9922                0      ␣
↪           0                 0                 0
#38                   LAG_y TGOV1 2           -2.0109                0      ␣
↪           0                 0                 0
#39                   LAG_y TGOV1 3           -2.0194                0      ␣
↪           0                 0                 0
#40                     W_x EXDC2 2           -1.1816                0      ␣
↪           0                 0                 0
#41                     W_x EXDC2 4           -0.53573             0.73459     ␣
↪     0.11691            0.1447            58.924
#42                     W_x EXDC2 4           -0.53573            -0.73459     ␣
↪     0.11691            0.1447            58.924
#43*                 delta GENROU 3        -1.1783e-14                0      ␣
↪           0                 0                 0
#44                    LL_x TGOV1 2           -0.30739             0.44664     ␣
↪    0.071085           0.086293            56.693
#45                    LL_x TGOV1 2           -0.30739            -0.44664     ␣
↪    0.071085           0.086293            56.693
#46                     W_x EXDC2 1           -0.36003             0.38874     ␣
↪    0.061869           0.084328             67.95
```

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```
#47                    W_x EXDC2 1          -0.36003          -0.38874      ␣
↪    0.061869          0.084328             67.95
#48                    W_x EXDC2 3          -0.35993           0.37956      ␣
↪    0.060409          0.083251             68.81
#49                    W_x EXDC2 3          -0.35993          -0.37956      ␣
↪    0.060409          0.083251             68.81
#50                   LL_x TGOV1 1          -0.14157                 0      ␣
↪           0                 0                0
#51                   LL_x TGOV1 2          -0.14203                 0      ␣
↪           0                 0                0
#52                   LL_x TGOV1 3          -0.14202                 0      ␣
↪           0                 0                0

EIGENVALUE DATA
                                  #1               #2               #3      ␣
↪          #4                #5               #6               #7

delta GENROU 1                     0                0                0      ␣
↪           0                 0                0           4e-05
delta GENROU 2                     0                0                0      ␣
↪           0                 0                0           6e-05
delta GENROU 3                     0                0                0      ␣
↪           0                 0                0           2e-05
delta GENROU 4                     0                0                0      ␣
↪           0                 0                0           1e-05
omega GENROU 1                     0                0                0      ␣
↪           0                 0                0           2e-05
omega GENROU 2                     0                0                0      ␣
↪           0                 0                0           3e-05
omega GENROU 3                     0                0                0      ␣
↪           0                 0                0           1e-05
omega GENROU 4                     0                0                0      ␣
↪           0                 0                0                0
e1q GENROU 1                       0                0                0      ␣
↪           0           0.00084          0.00084          0.00306
e1q GENROU 2                       0                0                0      ␣
↪           0            0.0019           0.0019          0.00224
e1q GENROU 3                       0                0                0      ␣
↪           0            0.0026           0.0026          0.00069
e1q GENROU 4                       0                0                0      ␣
↪           0           0.00118          0.00118          0.00063
e1d GENROU 1                       0                0                0      ␣
↪           0                 0                0                0
e1d GENROU 2                       0                0                0      ␣
↪           0                 0                0                0
e1d GENROU 3                       0                0                0      ␣
↪           0                 0                0                0
e1d GENROU 4                       0                0                0      ␣
↪           0                 0                0                0
e2d GENROU 1                       0                0                0      ␣
↪           0           0.00839          0.00839          0.02012
e2d GENROU 2                       0                0                0      ␣
```

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```
↪            0            0.01824            0.01824            0.01364
e2d GENROU 3                      0                  0                  0      ␣
↪            0            0.02784            0.02784            0.00467
e2d GENROU 4                      0                  0                  0      ␣
↪            0            0.01361            0.01361            0.00474
e2q GENROU 1                      0                  0                  0      ␣
↪            0            0.00096            0.00096            0.00036
e2q GENROU 2                      0                  0                  0      ␣
↪            0            0.00026            0.00026            0.00114
e2q GENROU 3                      0                  0                  0      ␣
↪            0              3e-05              3e-05            0.00031
e2q GENROU 4                      0                  0                  0      ␣
↪            0            0.00118            0.00118              9e-05
LAG_y TGOV1 1                     0                  0                  0      ␣
↪            0                  0                  0                  0
LAG_y TGOV1 2                     0                  0                  0      ␣
↪            0                  0                  0                  0
LAG_y TGOV1 3                     0                  0                  0      ␣
↪            0                  0                  0                  0
LAG_y TGOV1 4                     0                  0                  0      ␣
↪            0                  0                  0                  0
LL_x TGOV1 1                      0                  0                  0      ␣
↪            0                  0                  0                  0
LL_x TGOV1 2                      0                  0                  0      ␣
↪            0                  0                  0                  0
LL_x TGOV1 3                      0                  0                  0      ␣
↪            0                  0                  0                  0
LL_x TGOV1 4                      0                  0                  0      ␣
↪            0                  0                  0                  0
vp EXDC2 1                        0                  0                  0      ␣
↪            0            0.00157            0.00157            0.00231
vp EXDC2 2                        0                  0                  0      ␣
↪            0            0.00352            0.00352            0.00168
vp EXDC2 3                        0                  0                  0      ␣
↪            0            0.00346            0.00346            0.00037
vp EXDC2 4                        0                  0                  0      ␣
↪            0            0.00202            0.00202            0.00043
LS_y EXDC2 1                      0                  0                  0      ␣
↪            0            0.06526            0.06526            0.53032
LS_y EXDC2 2                      0                  0                  0      ␣
↪            0            0.14386            0.14386            0.37893
LS_y EXDC2 3                      0                  0                  0      ␣
↪            0            0.30715            0.30715            0.18162
LS_y EXDC2 4                      0                  0                  0      ␣
↪            0            0.08575            0.08575            0.10168
LL_x EXDC2 1                  0.66046                  0                  0      ␣
↪            0                  0                  0                  0
LL_x EXDC2 2                      0            0.66046                  0      ␣
↪            0                  0                  0                  0
LL_x EXDC2 3                      0                  0                  1      ␣
↪            0                  0                  0                  0
LL_x EXDC2 4                      0                  0                  0      ␣
```

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```
↪     0.65832                  0                  0                  0
LA_y EXDC2 1                          0                  0                  0      ␣
↪           0            0.06704            0.06704            0.22072
LA_y EXDC2 2                          0                  0                  0      ␣
↪           0            0.20271            0.20271            0.21636
LA_y EXDC2 3                          0                  0                  0      ␣
↪           0            0.30051            0.30051              0.072
LA_y EXDC2 4                          0                  0                  0      ␣
↪           0             0.1453             0.1453            0.06982
W_x EXDC2 1                           0                  0                  0      ␣
↪           0              5e-05              5e-05            0.00015
W_x EXDC2 2                           0                  0                  0      ␣
↪           0            0.00012            0.00012            0.00013
W_x EXDC2 3                           0                  0                  0      ␣
↪           0            0.00017            0.00017              4e-05
W_x EXDC2 4                           0                  0                  0      ␣
↪           0              8e-05              8e-05              4e-05

PARTICIPATION FACTORS [1/8]
                                     #8                 #9                #10      ␣
↪          #11                #12                #13                #14

delta GENROU 1                    2e-05              1e-05              1e-05      ␣
↪        5e-05              2e-05            0.00044            0.00047
delta GENROU 2                    1e-05                  0                  0      ␣
↪        6e-05              1e-05            0.00078            0.00049
delta GENROU 3                    5e-05                  0                  0      ␣
↪        2e-05              6e-05            0.00062            0.00061
delta GENROU 4                    5e-05              1e-05              1e-05      ␣
↪        1e-05              6e-05            0.00032            0.00067
omega GENROU 1                    1e-05              1e-05              1e-05      ␣
↪        3e-05              1e-05            0.00025            0.00027
omega GENROU 2                    1e-05                  0                  0      ␣
↪        4e-05              1e-05            0.00045            0.00028
omega GENROU 3                    2e-05                  0                  0      ␣
↪        1e-05              2e-05            0.00025            0.00024
omega GENROU 4                    2e-05                  0                  0      ␣
↪           0               2e-05            0.00012            0.00025
e1q GENROU 1                    0.00117            0.00225            0.00225      ␣
↪       0.0031             0.00115             0.0003            0.00033
e1q GENROU 2                    0.00043            0.00285            0.00285      ␣
↪      0.00224             0.00041            0.00042            0.00021
e1q GENROU 3                    0.00184            0.00167            0.00167      ␣
↪      0.00067             0.00185            0.00028            0.00027
e1q GENROU 4                    0.00329            0.00134            0.00134      ␣
↪      0.00061             0.00333            0.00019            0.00041
e1d GENROU 1                          0                  0                  0      ␣
↪           0                  0              2e-05              1e-05
e1d GENROU 2                          0                  0                  0      ␣
↪           0                  0              7e-05              2e-05
e1d GENROU 3                          0                  0                  0      ␣
↪           0                  0              5e-05              5e-05
```

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```
e1d GENROU 4                      0                 0                 0      ␣
↪           0                   0             2e-05             1e-05
e2d GENROU 1                  0.00784           0.01923           0.01923      ␣
↪     0.02323           0.00867           0.23812           0.24595
e2d GENROU 2                  0.00261           0.02337           0.02337      ␣
↪     0.01559           0.00284           0.33371           0.16432
e2d GENROU 3                  0.01258           0.01507           0.01507      ␣
↪     0.00518           0.01432            0.2465           0.23261
e2d GENROU 4                  0.02533           0.01309           0.01309      ␣
↪     0.00526           0.02886           0.17228           0.34779
e2q GENROU 1                  0.00015            0.0011            0.0011      ␣
↪     0.00039           0.00016           0.00111           0.00037
e2q GENROU 2                  0.00038           0.00045           0.00045      ␣
↪     0.00121           0.00039            0.0033           0.00106
e2q GENROU 3                  0.00116             7e-05             7e-05      ␣
↪     0.00032           0.00123           0.00241           0.00234
e2q GENROU 4                  0.00041           0.00079           0.00079      ␣
↪       9e-05           0.00044           0.00069           0.00043
LAG_y TGOV1 1                     0                 0                 0      ␣
↪           0                   0                 0                 0
LAG_y TGOV1 2                     0                 0                 0      ␣
↪           0                   0                 0                 0
LAG_y TGOV1 3                     0                 0                 0      ␣
↪           0                   0                 0                 0
LAG_y TGOV1 4                     0                 0                 0      ␣
↪           0                   0                 0                 0
LL_x TGOV1 1                      0                 0                 0      ␣
↪           0                   0                 0                 0
LL_x TGOV1 2                      0                 0                 0      ␣
↪           0                   0                 0                 0
LL_x TGOV1 3                      0                 0                 0      ␣
↪           0                   0                 0                 0
LL_x TGOV1 4                      0                 0                 0      ␣
↪           0                   0                 0                 0
vp EXDC2 1                    0.00094           0.00415           0.00415      ␣
↪     0.01364           0.00476           0.00032           0.00034
vp EXDC2 2                    0.00034           0.00522           0.00522      ␣
↪     0.00979           0.00169           0.00042            0.0002
vp EXDC2 3                    0.00105            0.0022            0.0022      ␣
↪      0.0021           0.00546            0.0002           0.00019
vp EXDC2 4                    0.00242           0.00226           0.00226      ␣
↪     0.00246           0.01263           0.00018           0.00038
LS_y EXDC2 1                  0.19482             0.203             0.203      ␣
↪     0.22143           0.08347           0.00069           0.00074
LS_y EXDC2 2                  0.06924           0.25052           0.25052      ␣
↪     0.15607           0.02909            0.0009           0.00042
LS_y EXDC2 3                  0.46474           0.22878           0.22878      ␣
↪     0.07262            0.2043           0.00092           0.00088
LS_y EXDC2 4                  0.51255           0.11281           0.11281      ␣
↪     0.04075           0.22639           0.00041           0.00085
LL_x EXDC2 1                      0                 0                 0      ␣
↪           0                   0                 0                 0
```

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```
LL_x EXDC2 2                      0                0                0 ␣
↪           0                0                0                0
LL_x EXDC2 3                      0                0                0 ␣
↪           0                0                0                0
LL_x EXDC2 4                      0                0                0 ␣
↪           0                0                0                0
LA_y EXDC2 1                0.08621           0.2062           0.2062 ␣
↪     0.53692          0.19058          0.00079          0.00084
LA_y EXDC2 2                0.04203          0.34908          0.34908 ␣
↪     0.51915          0.09112          0.00141          0.00066
LA_y EXDC2 3                0.19588          0.22134          0.22134 ␣
↪     0.16772          0.44428            0.001          0.00095
LA_y EXDC2 4                0.37416          0.18904          0.18904 ␣
↪     0.16302          0.85269          0.00077           0.0016
W_x EXDC2 1                   6e-05          0.00014          0.00014 ␣
↪     0.00038          0.00014                0                0
W_x EXDC2 2                   2e-05          0.00021          0.00021 ␣
↪     0.00031            5e-05                0                0
W_x EXDC2 3                 0.00011          0.00013          0.00013 ␣
↪      0.0001          0.00026                0                0
W_x EXDC2 4                 0.00021          0.00011          0.00011 ␣
↪      0.0001           0.0005                0                0

PARTICIPATION FACTORS [2/8]
                                 #15              #16              #17 ␣
↪         #18              #19              #20              #21

delta GENROU 1               0.0013          0.00058          0.00086 ␣
↪       4e-05            1e-05          0.00014          0.04024
delta GENROU 2              0.00034          0.00024          0.00268 ␣
↪       6e-05            7e-05            2e-05          0.08541
delta GENROU 3              0.00011          0.00276          0.00076 ␣
↪       5e-05            5e-05           0.0002          0.23816
delta GENROU 4              0.00079          0.00199           1e-05 ␣
↪     0.00011            1e-05            1e-05          0.16086
omega GENROU 1              0.00075          0.00034           0.0005 ␣
↪       3e-05                0            8e-05          0.02377
omega GENROU 2               0.0002          0.00014          0.00155 ␣
↪       3e-05            4e-05            1e-05          0.05045
omega GENROU 3                4e-05          0.00109           0.0003 ␣
↪       2e-05            2e-05            8e-05           0.0965
omega GENROU 4              0.00029          0.00074           1e-05 ␣
↪       4e-05                0                0          0.06107
e1q GENROU 1                0.00054            6e-05          0.00042 ␣
↪     0.00094            4e-05           0.0003          0.00067
e1q GENROU 2                0.00065          0.00022           2e-05 ␣
↪     0.00115          0.00016          0.00097          0.00141
e1q GENROU 3                0.00038          0.00019          0.00019 ␣
↪     0.00144          0.00011          0.00123          0.00194
e1q GENROU 4                0.00034           1e-05           0.0003 ␣
↪     0.00112            2e-05          0.00045           0.0034
e1d GENROU 1                0.00197          0.00266          0.00808 ␣
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↪       1e-05           0.02906           0.04674           0.00263
e1d GENROU 2                0.0033           0.00186           0.01412  ␣
↪     0.00441           0.01327           0.03129           0.00637
e1d GENROU 3               0.00138           0.01461           0.00314  ␣
↪     0.00479            0.0177           0.02276           0.02746
e1d GENROU 4               0.00094           0.01041           0.00046  ␣
↪       5e-05           0.03673           0.03898           0.00549
e2d GENROU 1               0.25874           0.03867           0.05142  ␣
↪     0.14321           0.00031            0.0033           0.00066
e2d GENROU 2               0.16397           0.03747            0.0468  ␣
↪     0.20085           0.00352           0.02285           0.00139
e2d GENROU 3               0.11321            0.0137           0.07851  ␣
↪     0.27348           0.00187           0.03733           0.00213
e2d GENROU 4               0.18053           0.00845           0.08023  ␣
↪     0.18763           0.00026           0.00906           0.00371
e2q GENROU 1               0.05939           0.06822           0.19355  ␣
↪     0.00017           0.23112           0.22378           0.00134
e2q GENROU 2               0.09922           0.04763            0.3366  ␣
↪     0.06848           0.10503            0.1491           0.00325
e2q GENROU 3               0.04116           0.36911           0.07409  ␣
↪     0.07356           0.13858           0.10724           0.01383
e2q GENROU 4                 0.028           0.26219            0.0109  ␣
↪     0.00082           0.28669           0.18311           0.00276
LAG_y TGOV1 1                     0                 0                 0  ␣
↪           0                 0                 0           0.00067
LAG_y TGOV1 2                     0                 0                 0  ␣
↪           0                 0                 0           0.00142
LAG_y TGOV1 3                     0                 0                 0  ␣
↪           0                 0                 0           0.00355
LAG_y TGOV1 4                     0                 0                 0  ␣
↪           0                 0                 0           0.00239
LL_x TGOV1 1                      0                 0                 0  ␣
↪           0                 0                 0             3e-05
LL_x TGOV1 2                      0                 0                 0  ␣
↪           0                 0                 0             7e-05
LL_x TGOV1 3                      0                 0                 0  ␣
↪           0                 0                 0           0.00014
LL_x TGOV1 4                      0                 0                 0  ␣
↪           0                 0                 0             9e-05
vp EXDC2 1                  0.00033             3e-05           0.00062  ␣
↪     0.00077             9e-05           0.00049             6e-05
vp EXDC2 2                  0.00084            0.0003           0.00017  ␣
↪     0.00073           0.00025           0.00122           0.00018
vp EXDC2 3                  0.00034           0.00023              6e-05  ␣
↪     0.00069           0.00014           0.00101           0.00069
vp EXDC2 4                  0.00022              4e-05           0.00029  ␣
↪      0.0009             3e-05           0.00061           0.00083
LS_y EXDC2 1                 0.0006              5e-05           0.00101  ␣
↪     0.00103             9e-05           0.00039             1e-05
LS_y EXDC2 2                0.00149           0.00049           0.00026  ␣
↪     0.00095           0.00024           0.00095             3e-05
LS_y EXDC2 3                0.00129           0.00084            0.0002  ␣
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↪     0.00197            0.0003           0.00172           0.00021
LS_y EXDC2 4                0.00041             6e-05           0.00048 ␣
↪     0.00123             3e-05           0.00049           0.00012
LL_x EXDC2 1                    0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 2                    0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 3                    0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 4                    0                 0                 0 ␣
↪           0                 0                 0                 0
LA_y EXDC2 1                0.00067             6e-05           0.00113 ␣
↪     0.00114            0.0001           0.00042             1e-05
LA_y EXDC2 2                0.00229           0.00074            0.0004 ␣
↪     0.00144           0.00037           0.00143             3e-05
LA_y EXDC2 3                0.00137           0.00089           0.00021 ␣
↪     0.00207           0.00031           0.00179           0.00018
LA_y EXDC2 4                0.00076           0.00011           0.00089 ␣
↪     0.00224             6e-05           0.00089           0.00018
W_x EXDC2 1                     0                 0                 0 ␣
↪           0                 0                 0                 0
W_x EXDC2 2                     0                 0                 0 ␣
↪           0                 0             1e-05             1e-05
W_x EXDC2 3                     0                 0                 0 ␣
↪           0                 0             1e-05             3e-05
W_x EXDC2 4                     0                 0                 0 ␣
↪       1e-05                 0                 0             3e-05

PARTICIPATION FACTORS [3/8]
                                 #22               #23               #24 ␣
↪          #25               #26               #27               #28

delta GENROU 1              0.04024           0.17926           0.17926 ␣
↪     0.17245           0.17245           0.01877           0.00547
delta GENROU 2              0.08541           0.21636           0.21636 ␣
↪     0.08005           0.08005           0.02617           0.00332
delta GENROU 3              0.23816           0.04918           0.04918 ␣
↪     0.09817           0.09817           0.00681           0.02482
delta GENROU 4              0.16086           0.08069           0.08069 ␣
↪     0.14333           0.14333           0.00315           0.02115
omega GENROU 1              0.02377           0.10604           0.10604 ␣
↪     0.10491           0.10491           0.01037           0.00302
omega GENROU 2              0.05045           0.12794           0.12794 ␣
↪     0.04872           0.04872           0.01445           0.00183
omega GENROU 3               0.0965           0.01995           0.01995 ␣
↪     0.04102           0.04102           0.00257           0.00936
omega GENROU 4              0.06107           0.03068           0.03068 ␣
↪     0.05611           0.05611           0.00111           0.00747
e1q GENROU 1                0.00067           0.00511           0.00511 ␣
↪     0.00596           0.00596           0.00153           0.00043
e1q GENROU 2                0.00141           0.00145           0.00145 ␣
↪     0.00491           0.00491           0.00172           0.00027
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e1q GENROU 3                0.00194          0.00018          0.00018  ␣
↪     0.00041          0.00041          0.00039           0.0016
e1q GENROU 4                 0.0034          0.00215          0.00215  ␣
↪     0.00091          0.00091          0.00022          0.00155
e1d GENROU 1                0.00263          0.00462          0.00462  ␣
↪     0.00044          0.00044          0.36152          0.09703
e1d GENROU 2                0.00637          0.02796          0.02796  ␣
↪     0.00049          0.00049          0.49924          0.07963
e1d GENROU 3                0.02746          0.00894          0.00894  ␣
↪     0.00335          0.00335          0.12193          0.48105
e1d GENROU 4                0.00549          0.00157          0.00157  ␣
↪     0.00281          0.00281          0.05818          0.38742
e2d GENROU 1                0.00066           0.0043           0.0043  ␣
↪     0.00204          0.00204          0.00033            8e-05
e2d GENROU 2                0.00139          0.00146          0.00146  ␣
↪     0.00158          0.00158          0.00074          0.00013
e2d GENROU 3                0.00213          0.00012          0.00012  ␣
↪     0.00027          0.00027          0.00018          0.00073
e2d GENROU 4                0.00371          0.00209          0.00209  ␣
↪     0.00056          0.00056            6e-05           0.0004
e2q GENROU 1                0.00134          0.00229          0.00229  ␣
↪     0.00017          0.00017          0.01819          0.00503
e2q GENROU 2                0.00325          0.01381          0.01381  ␣
↪     0.00019          0.00019          0.02501          0.00411
e2q GENROU 3                0.01383          0.00437          0.00437  ␣
↪     0.00129          0.00129          0.00604          0.02453
e2q GENROU 4                0.00276          0.00076          0.00076  ␣
↪     0.00109          0.00109          0.00287          0.01969
LAG_y TGOV1 1               0.00067           0.0032           0.0032  ␣
↪     0.00728          0.00728          0.00125          0.00038
LAG_y TGOV1 2               0.00142          0.00386          0.00386  ␣
↪     0.00338          0.00338          0.00175          0.00023
LAG_y TGOV1 3               0.00355          0.00079          0.00079  ␣
↪     0.00371          0.00371          0.00041          0.00152
LAG_y TGOV1 4               0.00239          0.00129          0.00129  ␣
↪      0.0054           0.0054          0.00019          0.00129
LL_x TGOV1 1                  3e-05          0.00016          0.00016  ␣
↪     0.00064          0.00064            6e-05            2e-05
LL_x TGOV1 2                  7e-05           0.0002           0.0002  ␣
↪     0.00031          0.00031            8e-05            1e-05
LL_x TGOV1 3                0.00014           3e-05            3e-05  ␣
↪     0.00026          0.00026            1e-05            5e-05
LL_x TGOV1 4                  9e-05           5e-05            5e-05  ␣
↪     0.00038          0.00038            1e-05            5e-05
vp EXDC2 1                    6e-05          0.00162          0.00162  ␣
↪     0.00482          0.00482          0.00739            0.002
vp EXDC2 2                  0.00018          0.00133          0.00133  ␣
↪     0.00482          0.00482          0.01079          0.00183
vp EXDC2 3                  0.00069          0.00024          0.00024  ␣
↪     0.00056          0.00056          0.00174          0.00719
vp EXDC2 4                  0.00083          0.00076          0.00076  ␣
↪     0.00082          0.00082          0.00101          0.00706
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LS_y EXDC2 1                  1e-05           0.00022           0.00022 ␣
↪     0.00047           0.00047           0.00037            0.0001
LS_y EXDC2 2                  3e-05           0.00018           0.00018 ␣
↪     0.00046           0.00046           0.00052             9e-05
LS_y EXDC2 3                0.00021             7e-05             7e-05 ␣
↪     0.00012           0.00012           0.00018           0.00074
LS_y EXDC2 4                0.00012           0.00011           0.00011 ␣
↪       8e-05             8e-05             5e-05           0.00035
LL_x EXDC2 1                      0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 2                      0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 3                      0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 4                      0                 0                 0 ␣
↪           0                 0                 0                 0
LA_y EXDC2 1                  1e-05           0.00021           0.00021 ␣
↪     0.00039           0.00039           0.00064           0.00017
LA_y EXDC2 2                  3e-05           0.00023           0.00023 ␣
↪     0.00052           0.00052           0.00126           0.00021
LA_y EXDC2 3                0.00018             6e-05             6e-05 ␣
↪       9e-05             9e-05           0.00031           0.00125
LA_y EXDC2 4                0.00018           0.00016           0.00016 ␣
↪     0.00011           0.00011           0.00015           0.00102
W_x EXDC2 1                       0             5e-05             5e-05 ␣
↪     0.00038           0.00038           0.00056           0.00015
W_x EXDC2 2                   1e-05             5e-05             5e-05 ␣
↪     0.00044           0.00044           0.00093           0.00016
W_x EXDC2 3                   3e-05             1e-05             1e-05 ␣
↪       7e-05             7e-05           0.00022           0.00094
W_x EXDC2 4                   3e-05             3e-05             3e-05 ␣
↪       9e-05             9e-05           0.00011           0.00076

PARTICIPATION FACTORS [4/8]
                                 #29               #30               #31 ␣
↪         #32               #33               #34               #35

delta GENROU 1              0.00184           0.00076            0.0105 ␣
↪      0.0105           0.00211           0.00572           0.00175
delta GENROU 2              0.00619           0.00021             8e-05 ␣
↪       8e-05            0.0019           0.00509           0.00601
delta GENROU 3              0.00524           0.00086           0.00348 ␣
↪     0.00348           0.00522           0.00212           0.00608
delta GENROU 4              0.00254                 0           0.00062 ␣
↪     0.00062           0.00562           0.00191           0.00119
omega GENROU 1              0.00097           0.00039           0.00811 ␣
↪     0.00811           0.00097           0.00262           0.00049
omega GENROU 2              0.00326           0.00011           0.00024 ␣
↪     0.00024           0.00087           0.00234           0.00176
omega GENROU 3              0.00188            0.0003           0.00176 ␣
↪     0.00176           0.00163           0.00066           0.00119
omega GENROU 4              0.00086                 0           0.00023 ␣
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↪     0.00023           0.00164           0.00056            0.0002
e1q GENROU 1                0.00024           0.00202           0.07076  ␣
↪     0.07076           0.00382           0.01402           0.05544
e1q GENROU 2                 0.0016            0.0052            0.0874  ␣
↪      0.0874           0.00481           0.01018           0.04937
e1q GENROU 3                0.00126           0.00534           0.07194  ␣
↪     0.07194           0.01035           0.00282           0.04397
e1q GENROU 4                0.00048           0.00212            0.0524  ␣
↪      0.0524           0.01026           0.00535           0.04396
e1d GENROU 1                0.22346           0.14687           0.02655  ␣
↪     0.02655            0.0065           0.02563           0.01032
e1d GENROU 2                0.16265           0.15839           0.02676  ␣
↪     0.02676           0.00999           0.01879           0.00058
e1d GENROU 3                 0.1893           0.12278           0.02515  ␣
↪     0.02515           0.02218           0.00485           0.00021
e1d GENROU 4                0.28887           0.12266           0.02446  ␣
↪     0.02446           0.02447            0.0144           0.00922
e2d GENROU 1                  1e-05           0.00011           0.00296  ␣
↪     0.00296           0.00013            0.0005           0.00144
e2d GENROU 2                  9e-05           0.00027           0.00367  ␣
↪     0.00367           0.00016           0.00032           0.00127
e2d GENROU 3                  8e-05            0.0003           0.00331  ␣
↪     0.00331           0.00037            0.0001           0.00124
e2d GENROU 4                  4e-05           0.00013            0.0025  ␣
↪      0.0025           0.00042           0.00022           0.00131
e2q GENROU 1                0.02215            0.0174           0.00812  ␣
↪     0.00812           0.00095           0.00378           0.00189
e2q GENROU 2                0.01605           0.01868           0.00815  ␣
↪     0.00815           0.00146           0.00276           0.00011
e2q GENROU 3                0.01847           0.01432           0.00757  ␣
↪     0.00757           0.00321            0.0007             4e-05
e2q GENROU 4                 0.0281           0.01426           0.00734  ␣
↪     0.00734           0.00353           0.00208           0.00165
LAG_y TGOV1 1                0.0003           0.00019            0.0023  ␣
↪      0.0023           0.00118           0.00327           0.00534
LAG_y TGOV1 2               0.00103             5e-05             7e-05  ␣
↪       7e-05           0.00107           0.00292            0.0193
LAG_y TGOV1 3               0.00077            0.0002           0.00065  ␣
↪     0.00065            0.0026           0.00108           0.01706
LAG_y TGOV1 4               0.00037                 0             9e-05  ␣
↪       9e-05           0.00279           0.00096           0.00309
LL_x TGOV1 1                  1e-05             1e-05           0.00065  ␣
↪     0.00065             5e-05           0.00015           0.00014
LL_x TGOV1 2                  5e-05                 0             2e-05  ␣
↪       2e-05             5e-05           0.00014           0.00054
LL_x TGOV1 3                  3e-05             1e-05           0.00015  ␣
↪     0.00015            0.0001              4e-05           0.00037
LL_x TGOV1 4                  1e-05                 0             2e-05  ␣
↪       2e-05            0.0001              4e-05             7e-05
vp EXDC2 1                   0.0018           0.02792            0.0755  ␣
↪      0.0755           0.08166           0.28549           0.19372
vp EXDC2 2                   0.01151           0.07037           0.09369  ␣
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↪     0.09369           0.10072           0.20041           0.17109
vp EXDC2 3                  0.00659           0.05154           0.05539     ␣
↪     0.05539           0.15513           0.03978           0.10881
vp EXDC2 4                  0.00328           0.02678           0.05123     ␣
↪     0.05123           0.20162           0.10006            0.1402
LS_y EXDC2 1                  4e-05           0.00026           0.00452     ␣
↪     0.00452           0.00039           0.00144           0.00445
LS_y EXDC2 2                0.00022           0.00065           0.00551     ␣
↪     0.00551           0.00047           0.00099           0.00386
LS_y EXDC2 3                0.00027           0.00103           0.00707     ␣
↪     0.00707           0.00158           0.00043           0.00532
LS_y EXDC2 4                  7e-05           0.00026           0.00313     ␣
↪     0.00313           0.00099           0.00052           0.00329
LL_x EXDC2 1                     0                 0                 0     ␣
↪           0                 0                 0                 0
LL_x EXDC2 2                     0                 0                 0     ␣
↪           0                 0                 0                 0
LL_x EXDC2 3                     0                 0                 0     ␣
↪           0                 0                 0                 0
LL_x EXDC2 4                     0                 0                 0     ␣
↪           0                 0                 0                 0
LA_y EXDC2 1                0.0001           0.00137            0.0025     ␣
↪      0.0025           0.00299            0.0104           0.00439
LA_y EXDC2 2                 0.0009           0.00465           0.00418     ␣
↪     0.00418           0.00497           0.00984           0.00523
LA_y EXDC2 3                0.00078           0.00513           0.00372     ␣
↪     0.00372           0.01154           0.00294           0.00501
LA_y EXDC2 4                0.00032           0.00221           0.00285     ␣
↪     0.00285           0.01245           0.00614           0.00536
W_x EXDC2 1                 0.00026           0.00528           0.03995     ␣
↪     0.03995           0.02435           0.08588           0.11819
W_x EXDC2 2                 0.00188           0.01518           0.05653     ␣
↪     0.05653           0.03424           0.06873             0.119
W_x EXDC2 3                 0.00159           0.01641           0.04933     ␣
↪     0.04933           0.07785           0.02014           0.11172
W_x EXDC2 4                 0.00065           0.00702           0.03754     ␣
↪     0.03754           0.08326           0.04168           0.11845

PARTICIPATION FACTORS [5/8]
                                 #36               #37               #38     ␣
↪          #39               #40               #41               #42

delta GENROU 1              0.00239           0.01045           0.00051     ␣
↪     0.00201           0.00333           0.00065           0.00065
delta GENROU 2              0.00236           0.00093           0.00922     ␣
↪     0.00128           0.00055           0.00047           0.00047
delta GENROU 3              0.00232           0.00157           0.00622     ␣
↪     0.00373           0.00374           0.00048           0.00048
delta GENROU 4              0.00245            0.0139           0.00281     ␣
↪     0.00283             8e-05           0.00065           0.00065
omega GENROU 1              0.05646           0.00087             2e-05     ␣
↪       7e-05           0.00453           0.00107           0.00107
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omega GENROU 2              0.05461             8e-05            0.00045 ␣
↪       4e-05           0.00192           0.00065           0.00065
omega GENROU 3              0.03522             8e-05             0.0002 ␣
↪       8e-05           0.00528            0.0005            0.0005
omega GENROU 4              0.03404              0.0007              8e-05 ␣
↪       6e-05           0.00043           0.00073           0.00073
e1q GENROU 1                0.00021             0.01108            0.00476 ␣
↪     0.00142           0.03388           0.08211           0.08211
e1q GENROU 2                0.00026             0.00532            0.00231 ␣
↪     0.00021           0.04408           0.06594           0.06594
e1q GENROU 3                 0.0001             0.00154            0.00122 ␣
↪      0.0004           0.03867           0.06805           0.06805
e1q GENROU 4                  7e-05             0.00458            0.00375 ␣
↪      0.0018           0.02724           0.07576           0.07576
e1d GENROU 1                0.00019             0.00414            0.00056 ␣
↪     0.00018           0.02258           0.00026           0.00026
e1d GENROU 2                 0.0002             0.00398             0.0024 ␣
↪     0.00016           0.02473           0.00126           0.00126
e1d GENROU 3                 0.0001             0.00324            0.00173 ␣
↪     0.00029           0.02321           0.00142           0.00142
e1d GENROU 4                 0.0001              0.0042            0.00103 ␣
↪     0.00044           0.02112           0.00043           0.00043
e2d GENROU 1                      0             0.00015            0.00011 ␣
↪       2e-05           0.00025           0.00119           0.00119
e2d GENROU 2                      0              6e-05              2e-05 ␣
↪       2e-05           0.00035           0.00092           0.00092
e2d GENROU 3                      0              2e-05              1e-05 ␣
↪       6e-05           0.00034           0.00105           0.00105
e2d GENROU 4                      0              2e-05              7e-05 ␣
↪       2e-05           0.00024           0.00127           0.00127
e2q GENROU 1                 4e-05             0.00084            0.00011 ␣
↪       4e-05           0.00566             8e-05              8e-05
e2q GENROU 2                 4e-05             0.00081            0.00049 ␣
↪       3e-05           0.00617           0.00037           0.00037
e2q GENROU 3                 2e-05             0.00065            0.00034 ␣
↪       6e-05           0.00573           0.00041           0.00041
e2q GENROU 4                 2e-05             0.00084            0.00021 ␣
↪       9e-05            0.0052           0.00012           0.00012
LAG_y TGOV1 1               0.28771             0.44443            0.03358 ␣
↪     0.18229           0.00614            0.0005            0.0005
LAG_y TGOV1 2               0.27828             0.03862            0.60969 ␣
↪     0.11639            0.0026            0.0003            0.0003
LAG_y TGOV1 3               0.23415             0.05545            0.34788 ␣
↪     0.28645           0.00933            0.0003            0.0003
LAG_y TGOV1 4               0.24068             0.49682            0.15655 ␣
↪     0.21672            0.0008           0.00047           0.00047
LL_x TGOV1 1                0.02949             0.00262            0.00012 ␣
↪     0.00046           0.00245           0.00046           0.00046
LL_x TGOV1 2                0.02951             0.00024            0.00224 ␣
↪      0.0003           0.00107           0.00029           0.00029
LL_x TGOV1 3                0.01928             0.00026            0.00099 ␣
↪     0.00058           0.00299           0.00022           0.00022
```

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```
LL_x TGOV1 4                 0.0199           0.00236           0.00045 ␣
↪     0.00044           0.00026           0.00035           0.00035
vp EXDC2 1                  0.00028           0.01851           0.01021 ␣
↪     0.00225           0.02054           0.04771           0.04771
vp EXDC2 2                  0.00034           0.00805           0.00341 ␣
↪     0.00124           0.02771           0.03765           0.03765
vp EXDC2 3                  0.00019            0.0005           0.00126 ␣
↪     0.00202           0.01745           0.02788           0.02788
vp EXDC2 4                  0.00016           0.00385           0.00608 ␣
↪     0.00268           0.01504            0.0403            0.0403
LS_y EXDC2 1                  2e-05           0.00065           0.00035 ␣
↪        8e-05           0.00189           0.00251           0.00251
LS_y EXDC2 2                  2e-05           0.00028           0.00012 ␣
↪        4e-05           0.00251           0.00194           0.00194
LS_y EXDC2 3                  2e-05             4e-05             9e-05 ␣
↪     0.00015           0.00343           0.00312           0.00312
LS_y EXDC2 4                  1e-05           0.00014           0.00021 ␣
↪        9e-05           0.00142           0.00216           0.00216
LL_x EXDC2 1                      0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 2                      0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 3                      0                 0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 4                      0                 0                 0 ␣
↪           0                 0                 0                 0
LA_y EXDC2 1                      0           0.00028           0.00016 ␣
↪        4e-05             1e-05           0.00088           0.00088
LA_y EXDC2 2                      0           0.00016             7e-05 ␣
↪        3e-05             2e-05           0.00094           0.00094
LA_y EXDC2 3                      0             2e-05             4e-05 ␣
↪        6e-05             2e-05           0.00105           0.00105
LA_y EXDC2 4                      0              0.0001           0.00016 ␣
↪        7e-05             1e-05           0.00125           0.00125
W_x EXDC2 1                  0.0007           0.01967           0.01051 ␣
↪     0.00229             0.2114           0.11396           0.11396
W_x EXDC2 2                 0.00099           0.00975             0.004 ␣
↪     0.00144           0.32512           0.10252           0.10252
W_x EXDC2 3                  0.0008           0.00089           0.00219 ␣
↪     0.00345           0.30227           0.11206           0.11206
W_x EXDC2 4                 0.00057           0.00566           0.00867 ␣
↪     0.00377           0.21431           0.13329           0.13329

PARTICIPATION FACTORS [6/8]
                                #43*              #44               #45 ␣
↪         #46               #47               #48               #49

delta GENROU 1               0.23884           0.00446           0.00446 ␣
↪        5e-05             5e-05             4e-05             4e-05
delta GENROU 2               0.24952           0.00469           0.00469 ␣
↪        2e-05             2e-05             3e-05             3e-05
delta GENROU 3               0.26107           0.00465           0.00465 ␣
```

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```
↪       2e-05             2e-05             7e-05             7e-05
delta GENROU 4              0.25057           0.00449           0.00449     ␣
↪       7e-05             7e-05             5e-05             5e-05
omega GENROU 1                    0           0.10227           0.10227     ␣
↪     0.00063           0.00063           0.00032           0.00032
omega GENROU 2                    0           0.10619           0.10619     ␣
↪     0.00022           0.00022           0.00028           0.00028
omega GENROU 3                    0           0.07177           0.07177     ␣
↪     0.00013           0.00013           0.00029           0.00029
omega GENROU 4                    0           0.06484           0.06484     ␣
↪     0.00031           0.00031            0.0002            0.0002
e1q GENROU 1                      0             2e-05             2e-05     ␣
↪     0.07049           0.07049           0.04381           0.04381
e1q GENROU 2                      0             2e-05             2e-05     ␣
↪     0.05619           0.05619           0.05594           0.05594
e1q GENROU 3                      0             3e-05             3e-05     ␣
↪      0.0392            0.0392           0.06379           0.06379
e1q GENROU 4                      0             4e-05             4e-05     ␣
↪     0.04984           0.04984           0.04973           0.04973
e1d GENROU 1                      0                 0                 0     ␣
↪     0.00451           0.00451           0.00282           0.00282
e1d GENROU 2                      0                 0                 0     ␣
↪     0.00354           0.00354           0.00354           0.00354
e1d GENROU 3                      0                 0                 0     ␣
↪     0.00267           0.00267           0.00435           0.00435
e1d GENROU 4                      0             1e-05             1e-05     ␣
↪     0.00388           0.00388            0.0039            0.0039
e2d GENROU 1                      0                 0                 0     ␣
↪     0.00069           0.00069           0.00042           0.00042
e2d GENROU 2                      0                 0                 0     ␣
↪     0.00051           0.00051            0.0005            0.0005
e2d GENROU 3                      0                 0                 0     ␣
↪     0.00039           0.00039           0.00063           0.00063
e2d GENROU 4                      0                 0                 0     ␣
↪     0.00056           0.00056           0.00055           0.00055
e2q GENROU 1                      0                 0                 0     ␣
↪     0.00136           0.00136           0.00085           0.00085
e2q GENROU 2                      0                 0                 0     ␣
↪     0.00106           0.00106           0.00106           0.00106
e2q GENROU 3                      0                 0                 0     ␣
↪     0.00079           0.00079           0.00129           0.00129
e2q GENROU 4                      0                 0                 0     ␣
↪     0.00115           0.00115           0.00116           0.00116
LAG_y TGOV1 1                     0           0.04715           0.04715     ␣
↪     0.00028           0.00028           0.00015           0.00015
LAG_y TGOV1 2                     0           0.04895           0.04895     ␣
↪      0.0001            0.0001           0.00013           0.00013
LAG_y TGOV1 3                     0           0.04317           0.04317     ␣
↪       7e-05             7e-05           0.00017           0.00017
LAG_y TGOV1 4                     0           0.04147           0.04147     ␣
↪      0.0002            0.0002           0.00012           0.00012
LL_x TGOV1 1                      0           0.12629           0.12629     ␣
```

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```
↪     0.00092           0.00092           0.00049           0.00049
LL_x TGOV1 2                    0            0.13567           0.13567 ␣
↪     0.00033           0.00033           0.00045           0.00045
LL_x TGOV1 3                    0             0.0929            0.0929 ␣
↪     0.00019           0.00019           0.00047           0.00047
LL_x TGOV1 4                    0            0.08958           0.08958 ␣
↪     0.00052           0.00052           0.00034           0.00034
vp EXDC2 1                      0              8e-05             8e-05 ␣
↪     0.02856           0.02856           0.01757           0.01757
vp EXDC2 2                      0              7e-05             7e-05 ␣
↪     0.02194           0.02194           0.02157           0.02157
vp EXDC2 3                      0              6e-05             6e-05 ␣
↪     0.01098           0.01098           0.01765           0.01765
vp EXDC2 4                      0              8e-05             8e-05 ␣
↪     0.01848           0.01848           0.01825           0.01825
LS_y EXDC2 1                    0                   0                 0 ␣
↪     0.00105           0.00105           0.00064           0.00064
LS_y EXDC2 2                    0                   0                 0 ␣
↪     0.00079           0.00079           0.00077           0.00077
LS_y EXDC2 3                    0                   0                 0 ␣
↪     0.00086           0.00086           0.00136           0.00136
LS_y EXDC2 4                    0                   0                 0 ␣
↪     0.00069           0.00069           0.00068           0.00068
LL_x EXDC2 1                    0                   0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 2                    0                   0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 3                    0                   0                 0 ␣
↪           0                 0                 0                 0
LL_x EXDC2 4                    0                   0                 0 ␣
↪           0                 0                 0                 0
LA_y EXDC2 1                    0                   0                 0 ␣
↪     0.00049           0.00049            0.0003            0.0003
LA_y EXDC2 2                    0                   0                 0 ␣
↪     0.00051           0.00051            0.0005            0.0005
LA_y EXDC2 3                    0                   0                 0 ␣
↪     0.00038           0.00038           0.00061           0.00061
LA_y EXDC2 4                    0                   0                 0 ␣
↪     0.00054           0.00054           0.00053           0.00053
W_x EXDC2 1                     0            0.00025           0.00025 ␣
↪     0.11968           0.11968           0.07515           0.07515
W_x EXDC2 2                     0            0.00028           0.00028 ␣
↪     0.10481           0.10481           0.10518           0.10518
W_x EXDC2 3                     0            0.00032           0.00032 ␣
↪     0.07742           0.07742           0.12701           0.12701
W_x EXDC2 4                     0            0.00035           0.00035 ␣
↪     0.10724           0.10724            0.1081            0.1081

PARTICIPATION FACTORS [7/8]
                                #50               #51               #52

delta GENROU 1               0.00304           0.00244             4e-05
```

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```
delta GENROU 2              0.00157           0.00344             8e-05
delta GENROU 3              0.00179             6e-05           0.00325
delta GENROU 4              0.00266                 0           0.00268
omega GENROU 1                    0                 0                 0
omega GENROU 2                    0                 0                 0
omega GENROU 3                    0                 0                 0
omega GENROU 4                    0                 0                 0
e1q GENROU 1                      0             3e-05                 0
e1q GENROU 2                  2e-05             7e-05                 0
e1q GENROU 3                      0                 0             6e-05
e1q GENROU 4                      0                 0             3e-05
e1d GENROU 1                  1e-05             2e-05                 0
e1d GENROU 2                      0             5e-05                 0
e1d GENROU 3                  1e-05                 0             4e-05
e1d GENROU 4                  1e-05                 0             3e-05
e2d GENROU 1                      0                 0                 0
e2d GENROU 2                      0                 0                 0
e2d GENROU 3                      0                 0                 0
e2d GENROU 4                      0                 0                 0
e2q GENROU 1                      0             1e-05                 0
e2q GENROU 2                      0             1e-05                 0
e2q GENROU 3                      0                 0             1e-05
e2q GENROU 4                      0                 0             1e-05
LAG_y TGOV1 1               0.00021           0.00017                 0
LAG_y TGOV1 2               0.00011           0.00023             1e-05
LAG_y TGOV1 3                0.0001                 0           0.00019
LAG_y TGOV1 4               0.00015                 0           0.00015
LL_x TGOV1 1                0.30765           0.38484            0.0055
LL_x TGOV1 2                0.16372           0.56187           0.01273
LL_x TGOV1 3                0.12342           0.00631           0.34609
LL_x TGOV1 4                 0.1836           0.00014           0.28568
vp EXDC2 1                    3e-05             8e-05                 0
vp EXDC2 2                    2e-05             6e-05                 0
vp EXDC2 3                    1e-05                 0             4e-05
vp EXDC2 4                    2e-05                 0             6e-05
LS_y EXDC2 1                      0                 0                 0
LS_y EXDC2 2                      0                 0                 0
LS_y EXDC2 3                      0                 0                 0
LS_y EXDC2 4                      0                 0                 0
LL_x EXDC2 1                      0                 0                 0
LL_x EXDC2 2                      0                 0                 0
LL_x EXDC2 3                      0                 0                 0
LL_x EXDC2 4                      0                 0                 0
LA_y EXDC2 1                      0                 0                 0
LA_y EXDC2 2                      0                 0                 0
LA_y EXDC2 3                      0                 0                 0
LA_y EXDC2 4                      0                 0                 0
W_x EXDC2 1                   9e-05           0.00026                 0
W_x EXDC2 2                   9e-05           0.00023             1e-05
W_x EXDC2 3                   5e-05                 0           0.00021
W_x EXDC2 4                   7e-05                 0           0.00029
```

2.4.4 Parameter Sweep and Root Loci Plot

Parameter sweep allows automatically applying a set of parameters to compute the eigenvalues. It is useful to plot the root loci of the system.

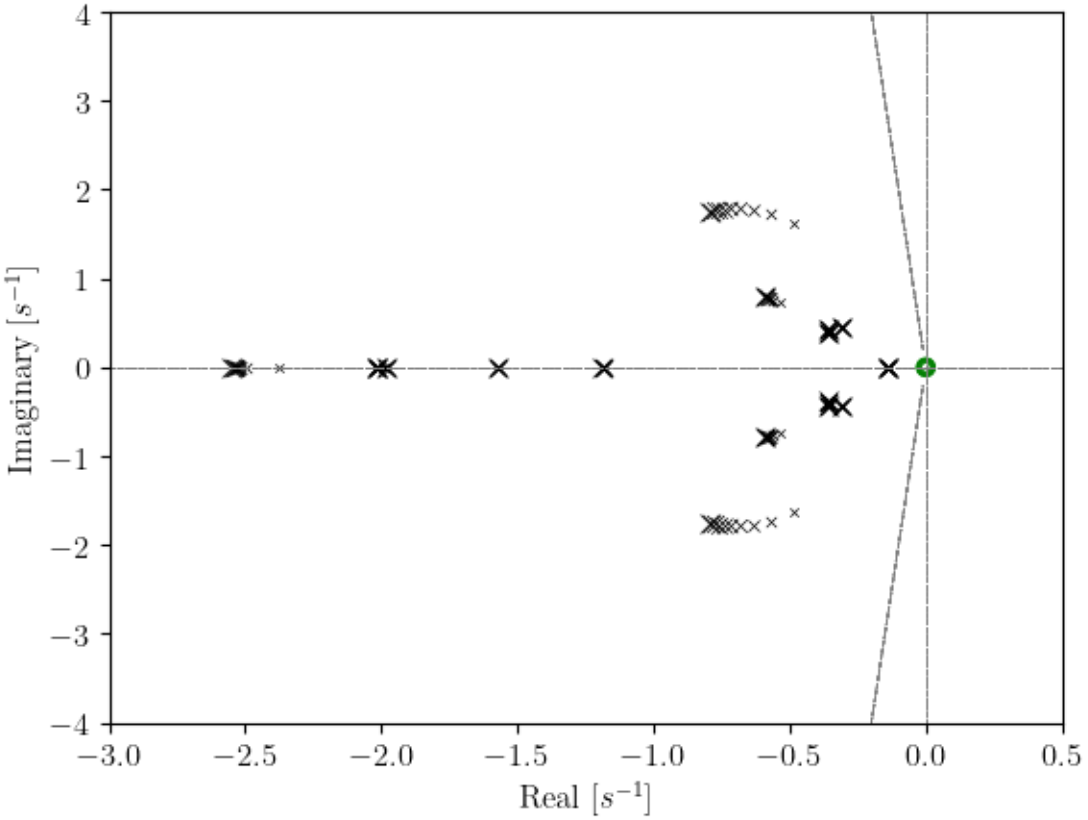
In this example, we will study the impact of `EXDC2.KA` of the device `1` on the system stability. Let its `KA` vary evenly between 20 to 200 in 10 steps.

```
ret = ss.EIG.sweep(ss.EXDC2.KA, 1, np.linspace(20, 200, 10))
```

Plot the 30th to the 50-th eigenvalues (0-based index) on the s-plane:

```
ss.EIG.plot_root_loci(ret, range(30, 51), left=-3, ymax=4, ymin=-4)
```

```
(<Figure size 640x480 with 1 Axes>,
 <AxesSubplot:xlabel='Real [$s^{-1}$]', ylabel='Imaginary [$s^{-1}$]'>)
```



Note that the marker size increases linearly as the parameters sweep from the first to the last. We recommend sweeping the parameter in an ascending order so that the larger marker size correspond to a larger parameter.

2.4.5 Cleanup

```
!andes misc -C
```

```
"/home/hacui/repos/andes/examples/kundur_full_out.txt" removed.
"/home/hacui/repos/andes/examples/kundur_full_eig.txt" removed.
```

2.5 Using CLI from Notebook

This example notebook is a supplement to the ANDES tutorial. Make sure you have read the tutorial on using the CLI first.

A brief version can be found at https://github.com/cuihantao/andes/blob/master/README.md#run-simulations

2.5.1 The ! magic in iPython

This example shows how to use the ANDES CLI from Jupyter Notebook.

It is based on the iPython magic `!`. To run a command *from within* IPython or Jupyter, place a `!` immediately before the command.

Conversely, all commands demonstrated in this notebook can be used in a terminal/shell by removing the preceeding `!` sign.

2.5.2 Set up on Windows

Windows users will need to install MSYS2 to support most of the Linux shell commands.

To install MSYS2-base, uncomment the following line and run it:

```
# !conda install -c msys2 -n base --yes m2-base
```

2.5.3 Running Shell Commands

For example, to list the directory , use `!ls`. This is equivalent to executing `ls` from the terminal.

```
!ls
```

```
demonstration  ex1.ipynb  ex3.ipynb  ex5.ipynb        ex7.ipynb  ex9.ipynb
ex10.ipynb     ex2.ipynb  ex4.ipynb  ex6.ipynb        ex8.ipynb  verification
```

Likewise, to run `andes`, use `!andes`. Addition arguments can be passed as usual.

```
!andes
```

```
    _           _         | Version 1.6.4.post10.dev0+gd1a4589d
   /_\  _ _  __| |___ ___ | Python 3.9.10 on Linux, 04/19/2022 08:30:40 PM
  / _ \| ' \/ _` / -_|_-< |
 /_/ \_\_||_\__,_\___/__/ | This program comes with ABSOLUTELY NO WARRANTY.

usage: andes [-h] [-v {1,10,20,30,40}]
             {run,plot,doc,misc,prepare,prep,selftest,st,demo} ...

positional arguments:
  {run,plot,doc,misc,prepare,prep,selftest,st,demo}
                        [run] run simulation routine; [plot] plot results;
                        [doc] quick documentation; [misc] misc. functions;
                        [prepare] prepare the numerical code; [selftest] run
                        self test;

optional arguments:
  -h, --help            show this help message and exit
  -v {1,10,20,30,40}, --verbose {1,10,20,30,40}
                        Verbosity level in 10-DEBUG, 20-INFO, 30-WARNING, or
                        40-ERROR.
```

2.5.4 Run a simulation

Pass the path to the case file and other arguments to andes from the command line as follows.

```
!andes run ../andes/cases/kundur/kundur_full.xlsx -r tds
```

```
    _           _         | Version 1.6.4.post10.dev0+gd1a4589d
   /_\  _ _  __| |___ ___ | Python 3.9.10 on Linux, 04/19/2022 08:30:41 PM
  / _ \| ' \/ _` / -_|_-< |
 /_/ \_\_||_\__,_\___/__/ | This program comes with ABSOLUTELY NO WARRANTY.

Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "../andes/cases/kundur/kundur_full.xlsx"...
Input file parsed in 0.2502 seconds.
System internal structure set up in 0.0306 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0029 seconds.
```

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```
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745104027e-07
Converged in 5 iterations in 0.0032 seconds.
Initialization for dynamics completed in 0.0278 seconds.
Initialization was successful.
Report saved to "kundur_full_out.txt" in 0.0016 seconds.

-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|########################################| 100.0/100 [00:01<00:00, 86.61%/
↪s]
Simulation completed in 1.1546 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0235 seconds.
-> Single process finished in 1.6411 seconds.
```

Case file names can be separated from the path, which can be passed to `-p`. The above command is equivanent to

```
!andes run kundur_full.xlsx -p "../andes/cases/kundur/" -r tds
```

```
    _           _         | Version 1.6.4.post10.dev0+gd1a4589d
   /_\  _ _  __| |___ ___ | Python 3.9.10 on Linux, 04/19/2022 08:30:43 PM
  / _ \| ' \/ _` / -_|_-< |
 /_/ \_\_||_\__,_\___/__/ | This program comes with ABSOLUTELY NO WARRANTY.

Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "../andes/cases/kundur/kundur_full.xlsx"...
Input file parsed in 0.2501 seconds.
System internal structure set up in 0.0305 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0029 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
```

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```
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745104027e-07
Converged in 5 iterations in 0.0032 seconds.
Initialization for dynamics completed in 0.0277 seconds.
Initialization was successful.
Report saved to "kundur_full_out.txt" in 0.0016 seconds.

-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|########################################| 100.0/100 [00:01<00:00, 86.32%/
↪s]
Simulation completed in 1.1584 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0237 seconds.
-> Single process finished in 1.6446 seconds.
```

```
!pwd
```

```
/home/hacui/repos/andes/examples
```

```
import os

os.path.isfile('../andes/cases/kundur/kundur_full.xlsx')
```

```
True
```

PSS/E RAW and DYR Files

To run a simulation using PSS/E raw and dyr files, pass the dyr file to argument `--addfile`.

For example:

```
!andes run ../andes/cases/kundur/kundur.raw --addfile ../andes/cases/kundur/
↪kundur_full.dyr -r tds
```

```
    _           _         | Version 1.6.4.post10.dev0+gd1a4589d
   /_\  _ _  __| |___ ___ | Python 3.9.10 on Linux, 04/19/2022 08:30:46 PM
  / _ \| ' \/ _` / -_|_-< |
 /_/ \_\_||_\__,_\___/__/ | This program comes with ABSOLUTELY NO WARRANTY.

Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "../andes/cases/kundur/kundur.raw"...
  MODIFIED KUNDUR'S TWO-AREA TEST SYSTEM, DISTRIBUTED WITH ANDES
```

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```
  SEE THE BOOK "POWER SYSTEM STABILITY AND CONTROL" FOR ORIGINAL DATA
Input file parsed in 0.0024 seconds.
Parsing additional file "../andes/cases/kundur/kundur_full.dyr"...
Addfile parsed in 0.2239 seconds.
System internal structure set up in 0.0297 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0028 seconds.
0: |F(x)| = 3.175850023
1: |F(x)| = 3.176155228e-08
Converged in 2 iterations in 0.0014 seconds.
Initialization for dynamics completed in 0.0276 seconds.
Initialization was successful.
Report saved to "kundur_out.txt" in 0.0014 seconds.

-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
<Toggle Toggle_1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|########################################| 100.0/100 [00:01<00:00, 86.44%/
↪s]
Simulation completed in 1.1569 seconds.
Outputs to "kundur_out.lst" and "kundur_out.npz".
Outputs written in 0.0235 seconds.
-> Single process finished in 1.6165 seconds.
```

2.5.5 Check the output `lst` file

```
!cat kundur_full_out.lst
```

```
     0,                  Time [s],                              Time [s]
     1,            delta GENROU 1,                 $\delta$ GENROU 1
     2,            delta GENROU 2,                 $\delta$ GENROU 2
     3,            delta GENROU 3,                 $\delta$ GENROU 3
     4,            delta GENROU 4,                 $\delta$ GENROU 4
     5,            omega GENROU 1,                 $\omega$ GENROU 1
     6,            omega GENROU 2,                 $\omega$ GENROU 2
     7,            omega GENROU 3,                 $\omega$ GENROU 3
     8,            omega GENROU 4,                 $\omega$ GENROU 4
     9,              e1q GENROU 1,                   $e'_q$ GENROU 1
    10,              e1q GENROU 2,                   $e'_q$ GENROU 2
```

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```
    11,              e1q GENROU 3,                   $e'_q$ GENROU 3
    12,              e1q GENROU 4,                   $e'_q$ GENROU 4
    13,              e1d GENROU 1,                   $e'_d$ GENROU 1
    14,              e1d GENROU 2,                   $e'_d$ GENROU 2
    15,              e1d GENROU 3,                   $e'_d$ GENROU 3
    16,              e1d GENROU 4,                   $e'_d$ GENROU 4
    17,              e2d GENROU 1,                  $e''_d$ GENROU 1
    18,              e2d GENROU 2,                  $e''_d$ GENROU 2
    19,              e2d GENROU 3,                  $e''_d$ GENROU 3
    20,              e2d GENROU 4,                  $e''_d$ GENROU 4
    21,              e2q GENROU 1,                  $e''_q$ GENROU 1
    22,              e2q GENROU 2,                  $e''_q$ GENROU 2
    23,              e2q GENROU 3,                  $e''_q$ GENROU 3
    24,              e2q GENROU 4,                  $e''_q$ GENROU 4
    25,             LAG_y TGOV1 1,                 $y_{LAG}$ TGOV1 1
    26,             LAG_y TGOV1 2,                 $y_{LAG}$ TGOV1 2
    27,             LAG_y TGOV1 3,                 $y_{LAG}$ TGOV1 3
    28,             LAG_y TGOV1 4,                 $y_{LAG}$ TGOV1 4
    29,              LL_x TGOV1 1,                 $x'_{LL}$ TGOV1 1
    30,              LL_x TGOV1 2,                 $x'_{LL}$ TGOV1 2
    31,              LL_x TGOV1 3,                 $x'_{LL}$ TGOV1 3
    32,              LL_x TGOV1 4,                 $x'_{LL}$ TGOV1 4
    33,                vp EXDC2 1,                     $V_p$ EXDC2 1
    34,                vp EXDC2 2,                     $V_p$ EXDC2 2
    35,                vp EXDC2 3,                     $V_p$ EXDC2 3
    36,                vp EXDC2 4,                     $V_p$ EXDC2 4
    37,              LS_y EXDC2 1,                  $y_{LS}$ EXDC2 1
    38,              LS_y EXDC2 2,                  $y_{LS}$ EXDC2 2
    39,              LS_y EXDC2 3,                  $y_{LS}$ EXDC2 3
    40,              LS_y EXDC2 4,                  $y_{LS}$ EXDC2 4
    41,              LL_x EXDC2 1,                 $x'_{LL}$ EXDC2 1
    42,              LL_x EXDC2 2,                 $x'_{LL}$ EXDC2 2
    43,              LL_x EXDC2 3,                 $x'_{LL}$ EXDC2 3
    44,              LL_x EXDC2 4,                 $x'_{LL}$ EXDC2 4
    45,              LA_y EXDC2 1,                  $y_{LA}$ EXDC2 1
    46,              LA_y EXDC2 2,                  $y_{LA}$ EXDC2 2
    47,              LA_y EXDC2 3,                  $y_{LA}$ EXDC2 3
    48,              LA_y EXDC2 4,                  $y_{LA}$ EXDC2 4
    49,               W_x EXDC2 1,                  $x'_{W}$ EXDC2 1
    50,               W_x EXDC2 2,                  $x'_{W}$ EXDC2 2
    51,               W_x EXDC2 3,                  $x'_{W}$ EXDC2 3
    52,               W_x EXDC2 4,                  $x'_{W}$ EXDC2 4
    53,                   a Bus 1,                    $\theta$ Bus 1
    54,                   a Bus 2,                    $\theta$ Bus 2
    55,                   a Bus 3,                    $\theta$ Bus 3
    56,                   a Bus 4,                    $\theta$ Bus 4
    57,                   a Bus 5,                    $\theta$ Bus 5
    58,                   a Bus 6,                    $\theta$ Bus 6
    59,                   a Bus 7,                    $\theta$ Bus 7
    60,                   a Bus 8,                    $\theta$ Bus 8
    61,                   a Bus 9,                    $\theta$ Bus 9
    62,                  a Bus 10,                   $\theta$ Bus 10
```

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```
 63,                  v Bus 1,                          $V$ Bus 1
 64,                  v Bus 2,                          $V$ Bus 2
 65,                  v Bus 3,                          $V$ Bus 3
 66,                  v Bus 4,                          $V$ Bus 4
 67,                  v Bus 5,                          $V$ Bus 5
 68,                  v Bus 6,                          $V$ Bus 6
 69,                  v Bus 7,                          $V$ Bus 7
 70,                  v Bus 8,                          $V$ Bus 8
 71,                  v Bus 9,                          $V$ Bus 9
 72,                 v Bus 10,                         $V$ Bus 10
 73,                    q PV 2,                           $q$ PV 2
 74,                    q PV 3,                           $q$ PV 3
 75,                    q PV 4,                           $q$ PV 4
 76,                 q Slack 1,                        $q$ Slack 1
 77,                 p Slack 1,                        $p$ Slack 1
 78,              Id GENROU 1,                    $I_d$ GENROU 1
 79,              Id GENROU 2,                    $I_d$ GENROU 2
 80,              Id GENROU 3,                    $I_d$ GENROU 3
 81,              Id GENROU 4,                    $I_d$ GENROU 4
 82,              Iq GENROU 1,                    $I_q$ GENROU 1
 83,              Iq GENROU 2,                    $I_q$ GENROU 2
 84,              Iq GENROU 3,                    $I_q$ GENROU 3
 85,              Iq GENROU 4,                    $I_q$ GENROU 4
 86,              vd GENROU 1,                    $V_d$ GENROU 1
 87,              vd GENROU 2,                    $V_d$ GENROU 2
 88,              vd GENROU 3,                    $V_d$ GENROU 3
 89,              vd GENROU 4,                    $V_d$ GENROU 4
 90,              vq GENROU 1,                    $V_q$ GENROU 1
 91,              vq GENROU 2,                    $V_q$ GENROU 2
 92,              vq GENROU 3,                    $V_q$ GENROU 3
 93,              vq GENROU 4,                    $V_q$ GENROU 4
 94,              tm GENROU 1,                 $\tau_m$ GENROU 1
 95,              tm GENROU 2,                 $\tau_m$ GENROU 2
 96,              tm GENROU 3,                 $\tau_m$ GENROU 3
 97,              tm GENROU 4,                 $\tau_m$ GENROU 4
 98,              te GENROU 1,                 $\tau_e$ GENROU 1
 99,              te GENROU 2,                 $\tau_e$ GENROU 2
100,              te GENROU 3,                 $\tau_e$ GENROU 3
101,              te GENROU 4,                 $\tau_e$ GENROU 4
102,              vf GENROU 1,                    $v_f$ GENROU 1
103,              vf GENROU 2,                    $v_f$ GENROU 2
104,              vf GENROU 3,                    $v_f$ GENROU 3
105,              vf GENROU 4,                    $v_f$ GENROU 4
106,         XadIfd GENROU 1,          $X_{ad}I_{fd}$ GENROU 1
107,         XadIfd GENROU 2,          $X_{ad}I_{fd}$ GENROU 2
108,         XadIfd GENROU 3,          $X_{ad}I_{fd}$ GENROU 3
109,         XadIfd GENROU 4,          $X_{ad}I_{fd}$ GENROU 4
110,             Pe GENROU 1,                    $P_e$ GENROU 1
111,             Pe GENROU 2,                    $P_e$ GENROU 2
112,             Pe GENROU 3,                    $P_e$ GENROU 3
113,             Pe GENROU 4,                    $P_e$ GENROU 4
114,             Qe GENROU 1,                    $Q_e$ GENROU 1
```

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```
  115,               Qe GENROU 2,                    $Q_e$ GENROU 2
  116,               Qe GENROU 3,                    $Q_e$ GENROU 3
  117,               Qe GENROU 4,                    $Q_e$ GENROU 4
  118,             psid GENROU 1,                 $\psi_d$ GENROU 1
  119,             psid GENROU 2,                 $\psi_d$ GENROU 2
  120,             psid GENROU 3,                 $\psi_d$ GENROU 3
  121,             psid GENROU 4,                 $\psi_d$ GENROU 4
  122,             psiq GENROU 1,                 $\psi_q$ GENROU 1
  123,             psiq GENROU 2,                 $\psi_q$ GENROU 2
  124,             psiq GENROU 3,                 $\psi_q$ GENROU 3
  125,             psiq GENROU 4,                 $\psi_q$ GENROU 4
  126,            psi2q GENROU 1,              $\psi_{aq}$ GENROU 1
  127,            psi2q GENROU 2,              $\psi_{aq}$ GENROU 2
  128,            psi2q GENROU 3,              $\psi_{aq}$ GENROU 3
  129,            psi2q GENROU 4,              $\psi_{aq}$ GENROU 4
  130,            psi2d GENROU 1,              $\psi_{ad}$ GENROU 1
  131,            psi2d GENROU 2,              $\psi_{ad}$ GENROU 2
  132,            psi2d GENROU 3,              $\psi_{ad}$ GENROU 3
  133,            psi2d GENROU 4,              $\psi_{ad}$ GENROU 4
  134,             psi2 GENROU 1,                 $\psi_a$ GENROU 1
  135,             psi2 GENROU 2,                 $\psi_a$ GENROU 2
  136,             psi2 GENROU 3,                 $\psi_a$ GENROU 3
  137,             psi2 GENROU 4,                 $\psi_a$ GENROU 4
  138,               Se GENROU 1,         $S_e(|\psi_{a}|)$ GENROU 1
  139,               Se GENROU 2,         $S_e(|\psi_{a}|)$ GENROU 2
  140,               Se GENROU 3,         $S_e(|\psi_{a}|)$ GENROU 3
  141,               Se GENROU 4,         $S_e(|\psi_{a}|)$ GENROU 4
  142,           XaqI1q GENROU 1,            $X_{aq}I_{1q}$ GENROU 1
  143,           XaqI1q GENROU 2,            $X_{aq}I_{1q}$ GENROU 2
  144,           XaqI1q GENROU 3,            $X_{aq}I_{1q}$ GENROU 3
  145,           XaqI1q GENROU 4,            $X_{aq}I_{1q}$ GENROU 4
  146,             paux TGOV1 1,                  $P_{aux}$ TGOV1 1
  147,             paux TGOV1 2,                  $P_{aux}$ TGOV1 2
  148,             paux TGOV1 3,                  $P_{aux}$ TGOV1 3
  149,             paux TGOV1 4,                  $P_{aux}$ TGOV1 4
  150,             pout TGOV1 1,                  $P_{out}$ TGOV1 1
  151,             pout TGOV1 2,                  $P_{out}$ TGOV1 2
  152,             pout TGOV1 3,                  $P_{out}$ TGOV1 3
  153,             pout TGOV1 4,                  $P_{out}$ TGOV1 4
  154,             wref TGOV1 1,              $\omega_{ref}$ TGOV1 1
  155,             wref TGOV1 2,              $\omega_{ref}$ TGOV1 2
  156,             wref TGOV1 3,              $\omega_{ref}$ TGOV1 3
  157,             wref TGOV1 4,              $\omega_{ref}$ TGOV1 4
  158,             pref TGOV1 1,                  $P_{ref}$ TGOV1 1
  159,             pref TGOV1 2,                  $P_{ref}$ TGOV1 2
  160,             pref TGOV1 3,                  $P_{ref}$ TGOV1 3
  161,             pref TGOV1 4,                  $P_{ref}$ TGOV1 4
  162,               wd TGOV1 1,              $\omega_{dev}$ TGOV1 1
  163,               wd TGOV1 2,              $\omega_{dev}$ TGOV1 2
  164,               wd TGOV1 3,              $\omega_{dev}$ TGOV1 3
  165,               wd TGOV1 4,              $\omega_{dev}$ TGOV1 4
  166,               pd TGOV1 1,                       $P_d$ TGOV1 1
```

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```
  167,                pd TGOV1 2,                      $P_d$ TGOV1 2
  168,                pd TGOV1 3,                      $P_d$ TGOV1 3
  169,                pd TGOV1 4,                      $P_d$ TGOV1 4
  170,             LL_y TGOV1 1,                    $y_{LL}$ TGOV1 1
  171,             LL_y TGOV1 2,                    $y_{LL}$ TGOV1 2
  172,             LL_y TGOV1 3,                    $y_{LL}$ TGOV1 3
  173,             LL_y TGOV1 4,                    $y_{LL}$ TGOV1 4
  174,                v EXDC2 1,                 $E_{term}$ EXDC2 1
  175,                v EXDC2 2,                 $E_{term}$ EXDC2 2
  176,                v EXDC2 3,                 $E_{term}$ EXDC2 3
  177,                v EXDC2 4,                 $E_{term}$ EXDC2 4
  178,             vout EXDC2 1,                  $v_{out}$ EXDC2 1
  179,             vout EXDC2 2,                  $v_{out}$ EXDC2 2
  180,             vout EXDC2 3,                  $v_{out}$ EXDC2 3
  181,             vout EXDC2 4,                  $v_{out}$ EXDC2 4
  182,             vref EXDC2 1,                  $V_{ref}$ EXDC2 1
  183,             vref EXDC2 2,                  $V_{ref}$ EXDC2 2
  184,             vref EXDC2 3,                  $V_{ref}$ EXDC2 3
  185,             vref EXDC2 4,                  $V_{ref}$ EXDC2 4
  186,               Se EXDC2 1,          $S_e(|V_{out}|)$ EXDC2 1
  187,               Se EXDC2 2,          $S_e(|V_{out}|)$ EXDC2 2
  188,               Se EXDC2 3,          $S_e(|V_{out}|)$ EXDC2 3
  189,               Se EXDC2 4,          $S_e(|V_{out}|)$ EXDC2 4
  190,               vi EXDC2 1,                      $V_i$ EXDC2 1
  191,               vi EXDC2 2,                      $V_i$ EXDC2 2
  192,               vi EXDC2 3,                      $V_i$ EXDC2 3
  193,               vi EXDC2 4,                      $V_i$ EXDC2 4
  194,             LL_y EXDC2 1,                    $y_{LL}$ EXDC2 1
  195,             LL_y EXDC2 2,                    $y_{LL}$ EXDC2 2
  196,             LL_y EXDC2 3,                    $y_{LL}$ EXDC2 3
  197,             LL_y EXDC2 4,                    $y_{LL}$ EXDC2 4
  198,              W_y EXDC2 1,                     $y_{W}$ EXDC2 1
  199,              W_y EXDC2 2,                     $y_{W}$ EXDC2 2
  200,              W_y EXDC2 3,                     $y_{W}$ EXDC2 3
  201,              W_y EXDC2 4,                     $y_{W}$ EXDC2 4
```

2.5.6 Plot and save to file

We found a limitation of using `andes plot` from within Notebook/iPython. The figure won't be displayed correctly. The workaround is to save the image as a file and display it from the notebook.

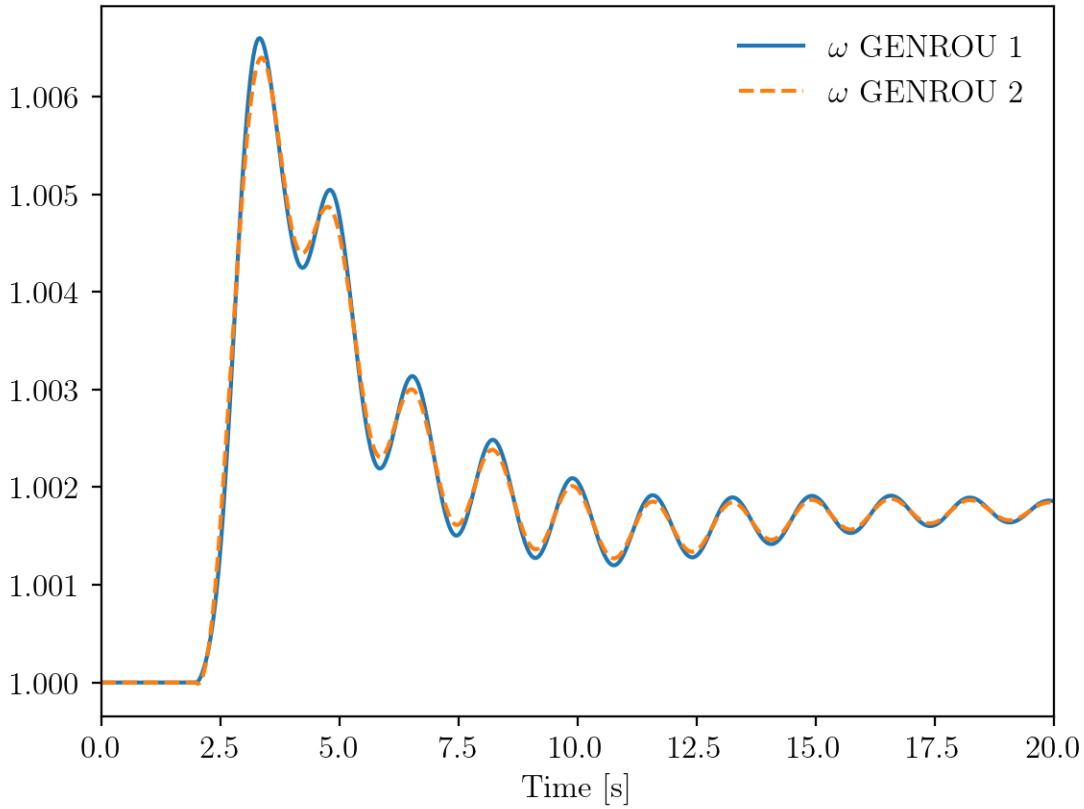
Please let us know if you have better solutions.

```
!andes plot kundur_full_out.lst 0 5 6 --save
```

```
Figure saved to "kundur_full_out_1.png".
Figure(640x480)
```

2.5.7 Display image

```
from IPython.display import Image
Image("kundur_full_out_1.png")
```



2.5.8 Using `xargs` for index lookup

A convenient tool in Linux/macOS is `xargs`, which turns the standard output of one program into arguments for another.

`andes plot --xargs` accepts an input of search pattern for variable names and returns a list of arguments, including the matched indices, that can be understood by `andes plot`.

To illustrate, let's look at an example output of `andes plot --xargs`.

```
!andes plot kundur_full_out.lst --xargs "omega GENROU"
```

```
kundur_full_out.lst 0 5 6 7 8
```

The output consists of the lst file name, the default x-axis index `0`, and the indices for the found variables. The full output can be passed to `andes plot` without modification.

We use the following command to pass the arguments:

```
!andes plot kundur_full_out.lst --xargs "omega GENROU" | xargs andes plot
```

```
Figure(640x480)
```

where `|` is the pipe operator in shell for piping the standard output of the left-hand side to the right-hand side, `xargs` captures the pipe-in and appends it to `andes plot`.

The command is equivalent to manually running

```
!andes plot kundur_full_out.lst 5 6 7 8
```

```
Figure(640x480)
```

2.5.9 Cleanup

Remove the saved `png` image files.

```
!rm -v *.png
```

```
removed 'kundur_full_out_1.png'
```

```
!andes misc -C
```

```
"/home/hacui/repos/andes/examples/kundur_full_out.npz" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.txt" removed.
"/home/hacui/repos/andes/examples/kundur_out.lst" removed.
"/home/hacui/repos/andes/examples/kundur_out.npz" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.lst" removed.
"/home/hacui/repos/andes/examples/kundur_out.txt" removed.
```

2.6 Batch Processing - Generate Cases

This notebook demonstrates creating cases in batch and running them in parallel.

2.6.1 Create Cases in Batch

The approach to create cases in batch following this procedure:

- Load the base case from file
- For each desired case output:
  - Alter parameters to the desired value
  - Save each system to a new case file

```
import andes
import numpy as np
from andes.utils.paths import get_case

andes.config_logger(stream_level=30)  # brief logging
```

```
# create directory for output cases
!rm -rf batch_cases
!mkdir -p batch_cases
```

```
kundur = get_case('kundur/kundur_full.xlsx')
ss = andes.load(kundur)
```

We demonstrate running the Kundur's system under different loading conditions.

Cases are created by modifying the `p0` of `PQ` with `idx == PQ_0`.

As always, input parameters can be inspected by accessing `Model.as_df(vin=True)`.

```
p0_base = ss.PQ.get('p0', "PQ_0")
```

Create 3 cases so that the load increases from `p0_base` to `1.2 * p0_base`.

```
N_CASES = 3  # Note: increase `N_CASES` as necessary

p0_values = np.linspace(p0_base, 1.2 * p0_base, N_CASES)
```

```
for value in p0_values:
    ss.PQ.alter('p0', 'PQ_0', value)
    file_name = f'batch_cases/kundur_p_{value:.2f}.xlsx'

    andes.io.dump(ss, 'xlsx', file_name, overwrite=True)
```

2.6.2 Parallel Simulation

Parallel simulation is easy with the command line tool.

Change directory to `batch_cases`:

```
import os

# change the Python working directory
os.chdir('batch_cases')
```

```
!ls -la
```

```
total 56
drwxr-xr-x 2 hacui hacui  4096 Apr 19 20:31 .
drwxr-xr-x 6 hacui hacui  4096 Apr 19 20:31 ..
```

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```
-rw-r--r-- 1 hacui hacui 14841 Apr 19 20:31 kundur_p_11.59.xlsx
-rw-r--r-- 1 hacui hacui 14842 Apr 19 20:31 kundur_p_12.75.xlsx
-rw-r--r-- 1 hacui hacui 14840 Apr 19 20:31 kundur_p_13.91.xlsx
```

Running from Command line

```
!andes run *.xlsx -r tds
```

```
   _           _         | Version 1.6.4.post10.dev0+gd1a4589d
  /_\  _ _  __| |___ ___ | Python 3.9.10 on Linux, 04/19/2022 08:31:06 PM
 / _ \| ' \/ _` / -_|_-< |
/_/ \_\_||_\__,_\___/__/ | This program comes with ABSOLUTELY NO WARRANTY.

Working directory: "/home/hacui/repos/andes/examples/batch_cases"
-> Processing 3 jobs on 12 CPUs.
Process 0 for "kundur_p_11.59.xlsx" started.
Process 1 for "kundur_p_12.75.xlsx" started.
Process 2 for "kundur_p_13.91.xlsx" started.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|##########################################| 100.0/100 [00:01<00:00, 89.55%/
↪s]
100%|##########################################| 100.0/100 [00:01<00:00, 87.15%/
↪s]
100%|##########################################| 100.0/100 [00:01<00:00, 83.73%/
↪s]
Log saved to "/tmp/andes-4fbaduja/andes.log".
-> Multiprocessing finished in 1.7566 seconds.
```

Number of CPUs

In some cases, you don't want the simulatino to use up all resources.

ANDES allows to control the number of processes to run in parallel through `--ncpu NCPU`, where `NCPU` is the maximum number of processes (equivalent to the number of CPU cores) allowed.

```
!andes run *.xlsx -r tds --ncpu 4
```

```
   _           _         | Version 1.6.4.post10.dev0+gd1a4589d
  /_\  _ _  __| |___ ___ | Python 3.9.10 on Linux, 04/19/2022 08:31:09 PM
 / _ \| ' \/ _` / -_|_-< |
/_/ \_\_||_\__,_\___/__/ | This program comes with ABSOLUTELY NO WARRANTY.

Working directory: "/home/hacui/repos/andes/examples/batch_cases"
-> Processing 3 jobs on 4 CPUs.
Process 0 for "kundur_p_11.59.xlsx" started.
```

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```
Process 1 for "kundur_p_12.75.xlsx" started.
Process 2 for "kundur_p_13.91.xlsx" started.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
100%|########################################| 100.0/100 [00:01<00:00, 88.46%/
↪s]
100%|########################################| 100.0/100 [00:01<00:00, 86.36%/
↪s]
100%|########################################| 100.0/100 [00:01<00:00, 83.39%/
↪s]
Log saved to "/tmp/andes-rlpeyxo9/andes.log".
-> Multiprocessing finished in 1.7693 seconds.
```

Running with APIs

Setting `pool = True` allows returning all system instances in a list.

This comes with a penalty in computation time but can be helpful if you want to extract data directly.

```
systems = andes.run('*.xlsx', routine='tds', pool=True, verbose=10)
```

```
Working directory: "/home/hacui/repos/andes/examples/batch_cases"
Found files: ['kundur_p_11.59.xlsx', 'kundur_p_12.75.xlsx', 'kundur_p_13.91.
↪xlsx']
-> Processing 3 jobs on 12 CPUs.
```

```
Cases are processed in the following order:
"kundur_p_11.59.xlsx"
"kundur_p_12.75.xlsx"
"kundur_p_13.91.xlsx"
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.<Toggle 1>: Line.
↪Line_8 status changed to 0 at t=2.0 sec.

<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
Log saved to "/tmp/andes-lmohp4sw/andes.log".
-> Multiprocessing finished in 3.2217 seconds.
```

```
systems[0]
```

```
<andes.system.System at 0x7fbaa050a070>
```

```
systems
```

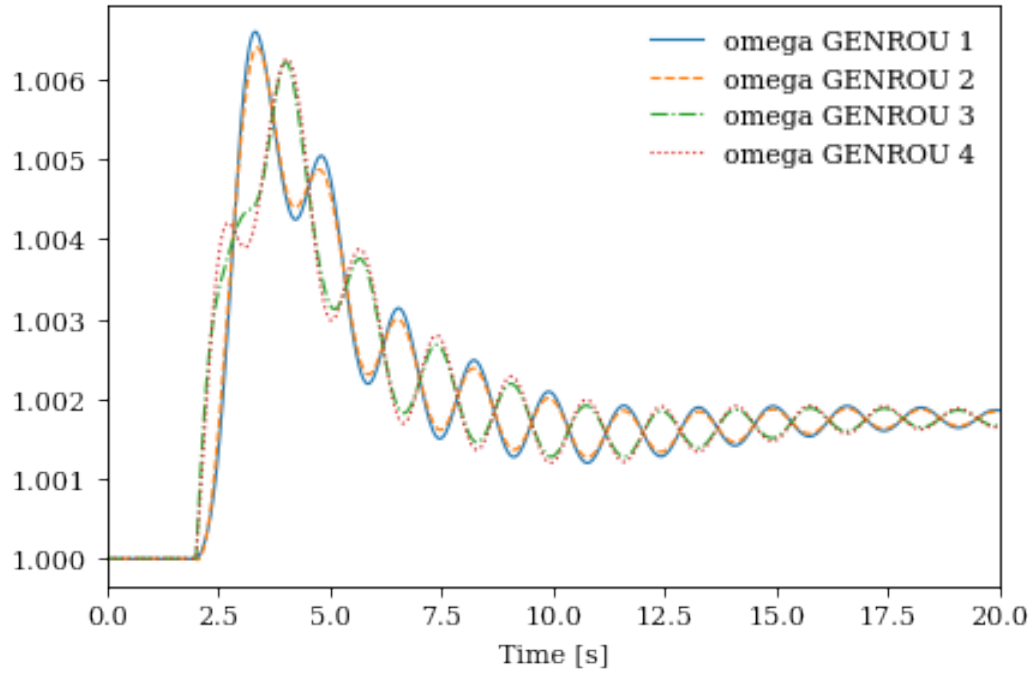
```
[<andes.system.System at 0x7fbaa050a070>,
 <andes.system.System at 0x7fba7bca2c70>,
 <andes.system.System at 0x7fba7bc9db80>]
```

Example plots

Plotting or data analyses can be carried out as usual.

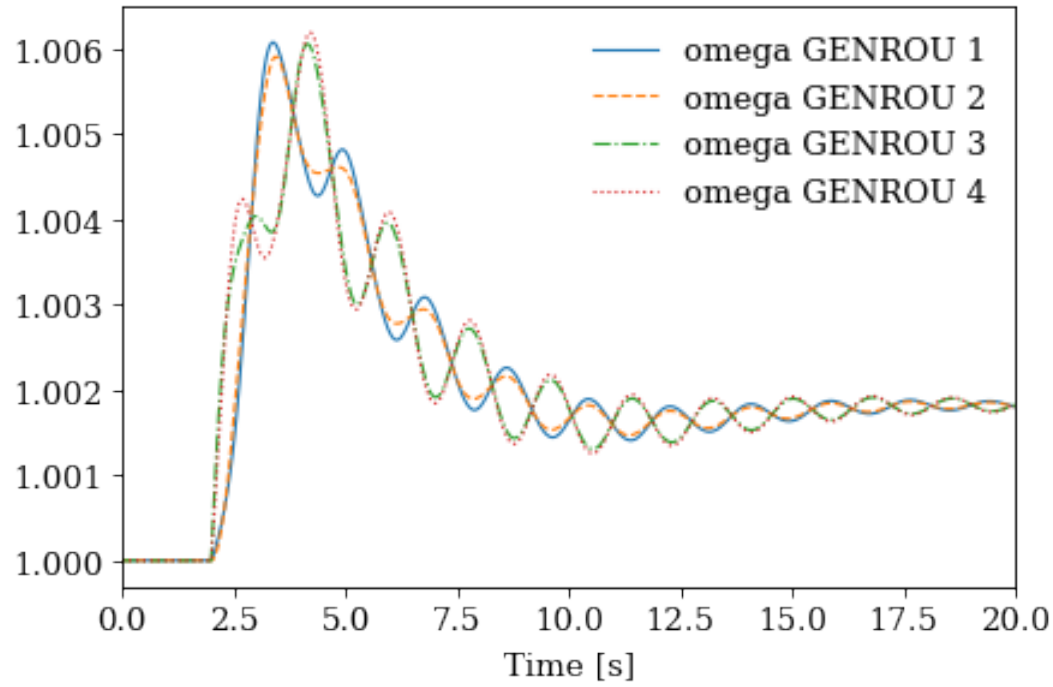
```
ss = systems[0]
```

```
systems[0].TDS.plotter.plot(ss.GENROU.omega, latex=False)
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
systems[2].TDS.plotter.plot(ss.GENROU.omega, latex=False)
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
!andes misc -C
!rm -rf batch_cases
```

```
No output file found in the working directory.
```

2.7 Batch Processing - in Memory

This notebook shows examples for batch power flow and time-domain calculations. Readers are supposed to have read the previous examples, especially Example 7 for parallel simulations.

```
import andes
import numpy as np

from matplotlib import pyplot as plt
```

2.7.1 Batch Power Flow Calculation

Use the Kundur's system as the example. Suppose we want to calculate power flow for the same system structure but for different load levels.

```
kundur = andes.utils.get_case('kundur/kundur_full.xlsx')
```

```
ss = andes.run(kundur,
               no_output=True,
               default_config=True,
               verbose=30,  # set logging level to WARNING
               )
```

```
-> Single process finished in 0.4701 seconds.
```

There are two PQ loads in the Kundur's system with `idx`es of `PQ_0` and `PQ_1`.

```
ss.PQ.as_df(vin=True)
```

```
      idx    u  name  bus     Vn     p0     q0  vmax  vmin  owner
uid
0    PQ_0  1.0  PQ_0    7  230.0  11.59 -0.735   1.1   0.9      1
1    PQ_1  1.0  PQ_1    8  230.0  15.75 -0.899   1.1   0.9      1
```

If we have a range of active power for each load, such as

```
n_samples = 3  # Note: increase `n_samples` for higher data resolution

pq0_values = np.linspace(10, 12, n_samples)
pq1_values = np.linspace(12, 18, n_samples)
```

where there are 3 samples for `PQ_0.p0` between `[10, 12]` and 3 samples for `PQ_1.p0` between `(12, 18)`.

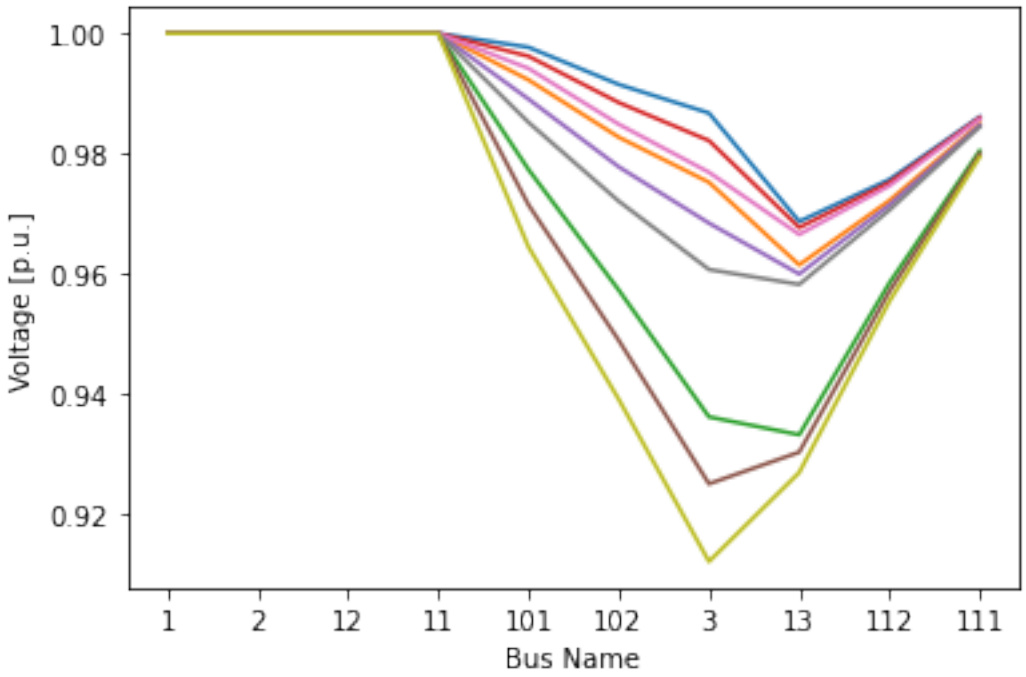
We can use a for loop to set the load values and calculate power flow for each point.

Suppose we want to retrieve the voltage magnitude for each case, we use `v_results` the voltage results. Results that are not saved will be discarded.

```
v_results = np.zeros((ss.Bus.n, n_samples ** 2))
idx = 0

for ii in pq0_values:
    ss.PQ.alter("p0", "PQ_0", ii)
    for jj in pq1_values:

        ss.PQ.alter("p0", "PQ_1", jj)

        ss.PFlow.run()
        v_results[:, idx] = ss.dae.y[ss.Bus.v.a]

        idx += 1
```

Let's plot the results.

```
lines = plt.plot(v_results)

xl = plt.xlabel('Bus Name')
yl = plt.ylabel('Voltage [p.u.]')

tk = plt.xticks(np.arange(ss.Bus.n), ss.Bus.name.v)
```



One should be aware that the for-loop based approach is single-threaded. It does not take advantage of multi-core processors.

If the total number of scenarios are huge, one should refer to Example 7 to save all scenarios to excel files and use multi-processing.

2.7.2 Batch Time-Domain Simulation

The next example shows how to run batch time-domain simulations for different events.

Suppose we want to create one scenario for each line trip event, which is actuated through `Toggle`. For the same system, we want to add Toggles for each line, run the simulation, and save results.

```
kundur = andes.utils.get_case('kundur/kundur_full.xlsx')
```

We use `andes.load()` with `setup=False` to load the test case.

It is important to note that one must pass `setup=False` so that adding Toggles can be allowed.

```
ss = andes.load(kundur, setup=False)
```

The idxes of all available lines to trip are in ss.Line.idx.v:

```
idxes = ss.Line.idx.v
```

```
ss.Toggle.as_df()
```

```
     idx  u       name model     dev  t
uid
0      1  1  Toggle_1  Line  Line_8  2
```

We use ss.add() to add two Toggles for each line at 1 second and 1.1 seconds to simulate a line opening and closing. ss.add() takes a model name, "Toggle", as the positional argument, and a dictionary for the Toggle device parameters.

A note for this particular test case is that kundur_full.xlsx already comes with a Toggle with idx==1. To not to interfere with our scenarios, we need to disable it using ss.Toggle.alter.

After adding Toggle devices, we need to manually call ss.setup() to finish the data structure setup. Then, power flow and time-domain simulation can be performed.

We store the results in a dictionary where keys are the line names and values are the systems. Code is as follows.

```
results = dict()

for idx in idxes:
    ss = andes.load(kundur, setup=False)

    ss.add('Toggle', dict(model="Line", dev=idx, t=1.0))
    ss.add('Toggle', dict(model="Line", dev=idx, t=1.1))

    ss.setup()                      # no `ss.add()` calls are allowed after␣
↪setup()
    ss.Toggle.alter('u', 1, 0.0)  # disable the existing Toggle with idx=1␣
↪(this is for the particular case)

    ss.PFlow.run()
    ss.TDS.config.tf = 5        # simulate for 5 seconds to save time
    ss.TDS.config.no_tqdm = 1   # disable progres bar printing
    ss.TDS.run()

    results[idx] = ss
```

```
<Toggle Toggle_2>: Line.Line_0 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_0 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_1 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_1 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_2 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_2 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_3 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_3 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_4 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_4 status changed to 1 at t=1.1 sec.
```

(continues on next page)

(continued from previous page)

```
<Toggle Toggle_2>: Line.Line_5 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_5 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_6 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_6 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_7 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_7 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_8 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_8 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_9 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_9 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_10 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_10 status changed to 1 at t=1.1 sec.
```

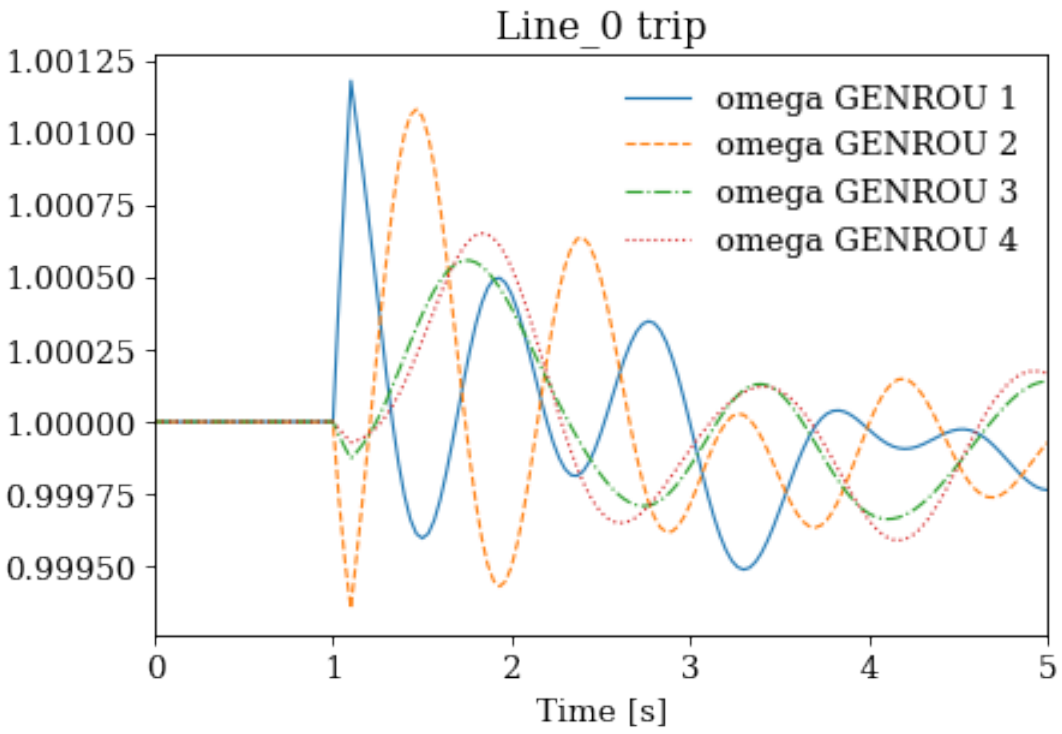
```
Time step reduced to zero. Convergence is not likely.
Simulation terminated at t=1.1001 s.
```

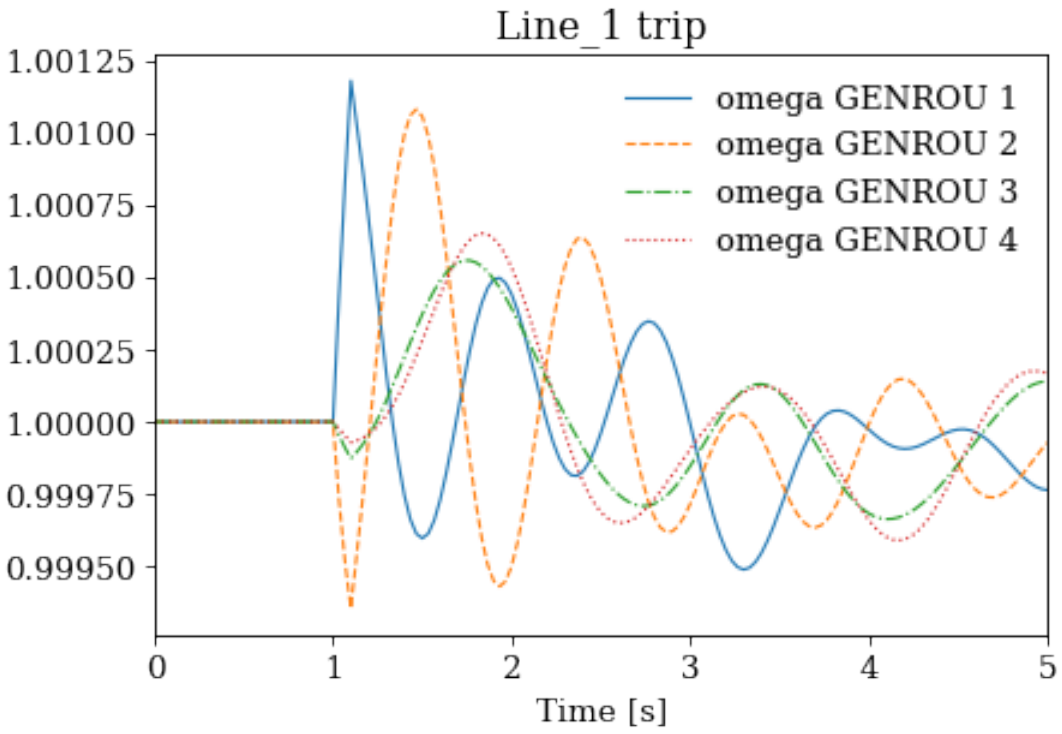
```
<Toggle Toggle_2>: Line.Line_11 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_11 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_12 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_12 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_13 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_13 status changed to 1 at t=1.1 sec.
<Toggle Toggle_2>: Line.Line_14 status changed to 0 at t=1.0 sec.
<Toggle Toggle_3>: Line.Line_14 status changed to 1 at t=1.1 sec.
```

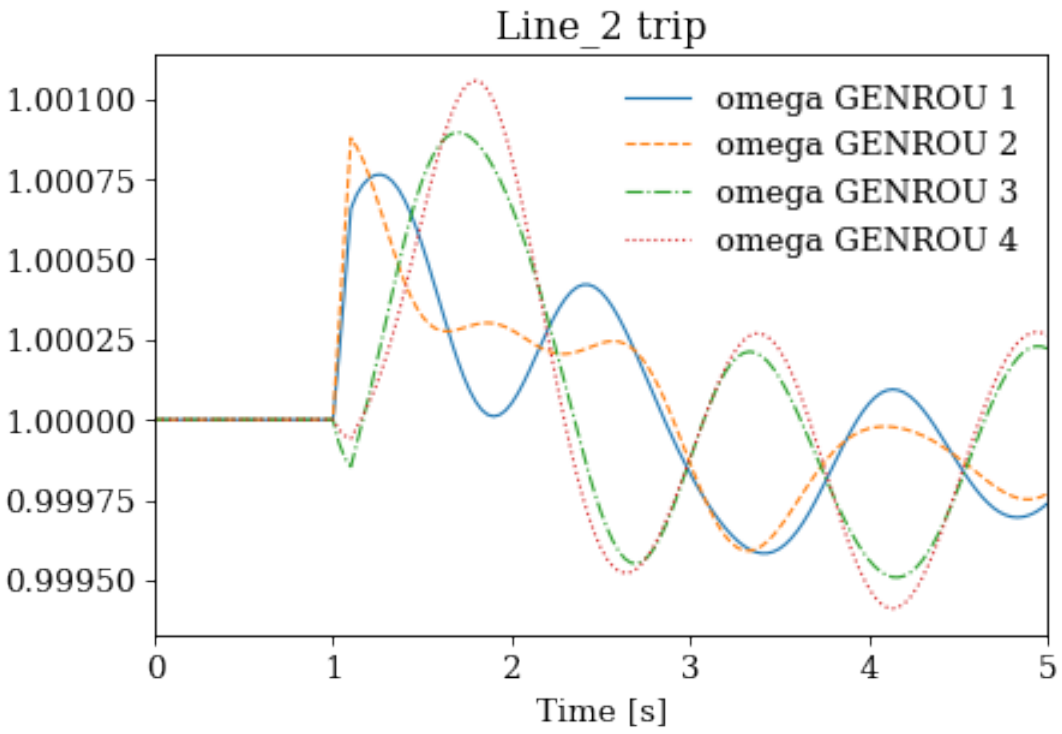
```
Jacobian matrix is singular.
Suspect diagonal elements: [55, 61]
NaN found in solution. Convergence is not likely
Simulation terminated at t=1.5808 s.
```

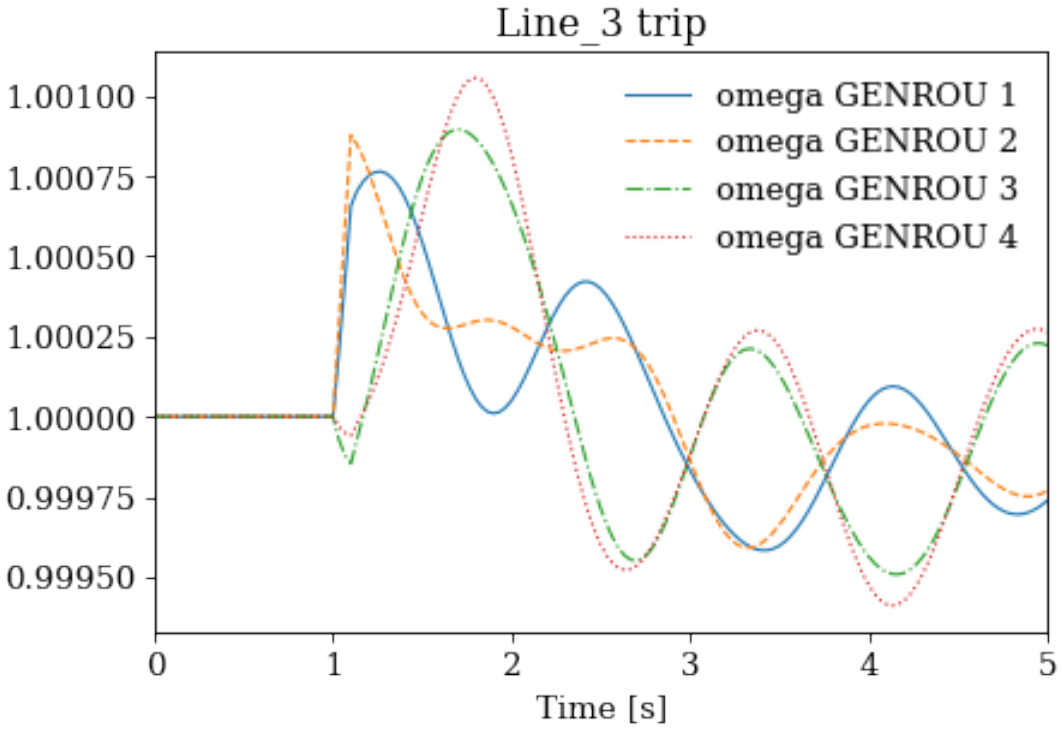
Not all cases will solve due to system instability. For the converged cases, one can export the data or plot results following Example 1.

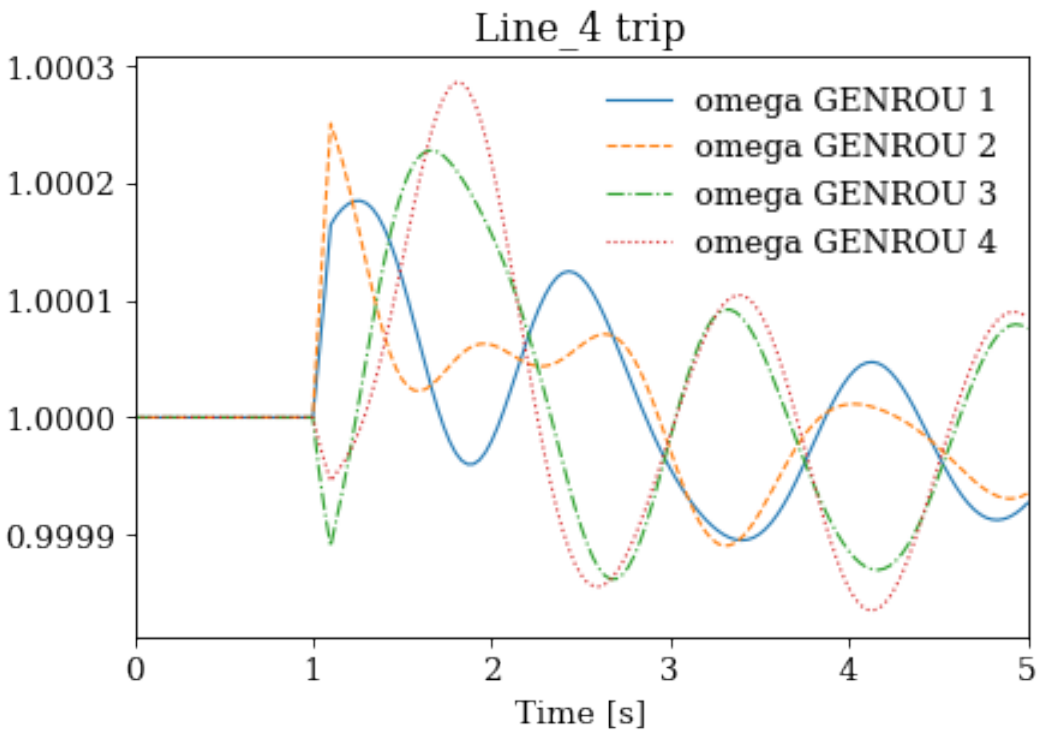
```
for idx, ss in results.items():
    ss.TDS.plt.plot(ss.GENROU.omega, title=f'{idx} trip', latex=False, dpi=80)
```

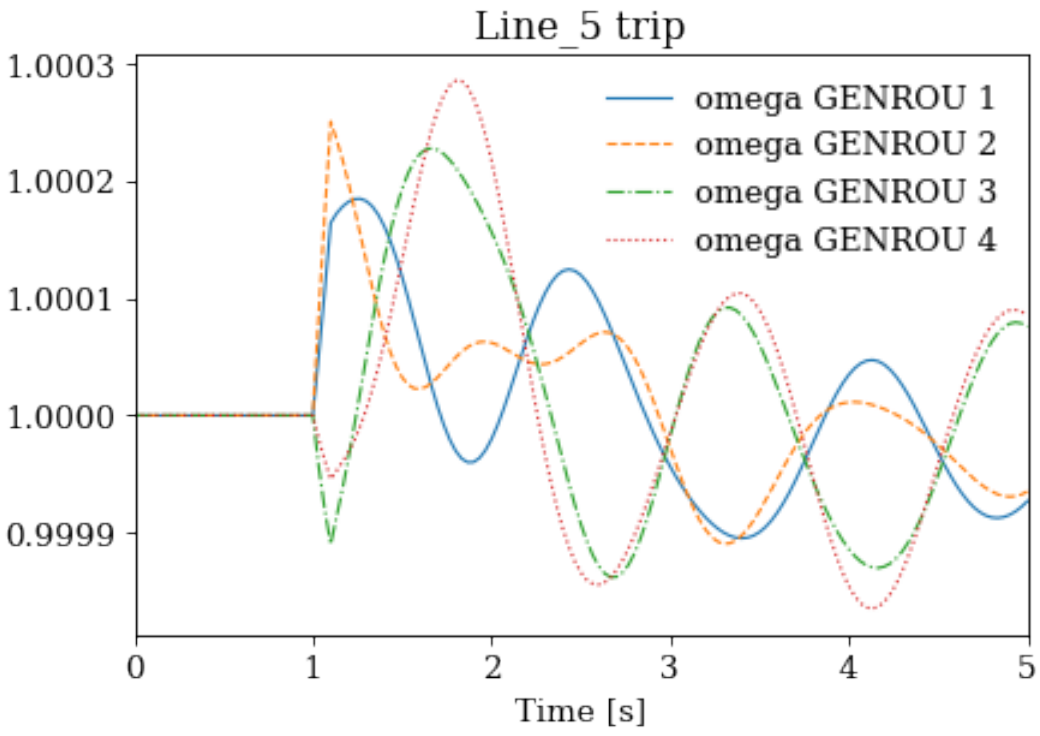

Line_0 trip
1.00125
1.00100
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]

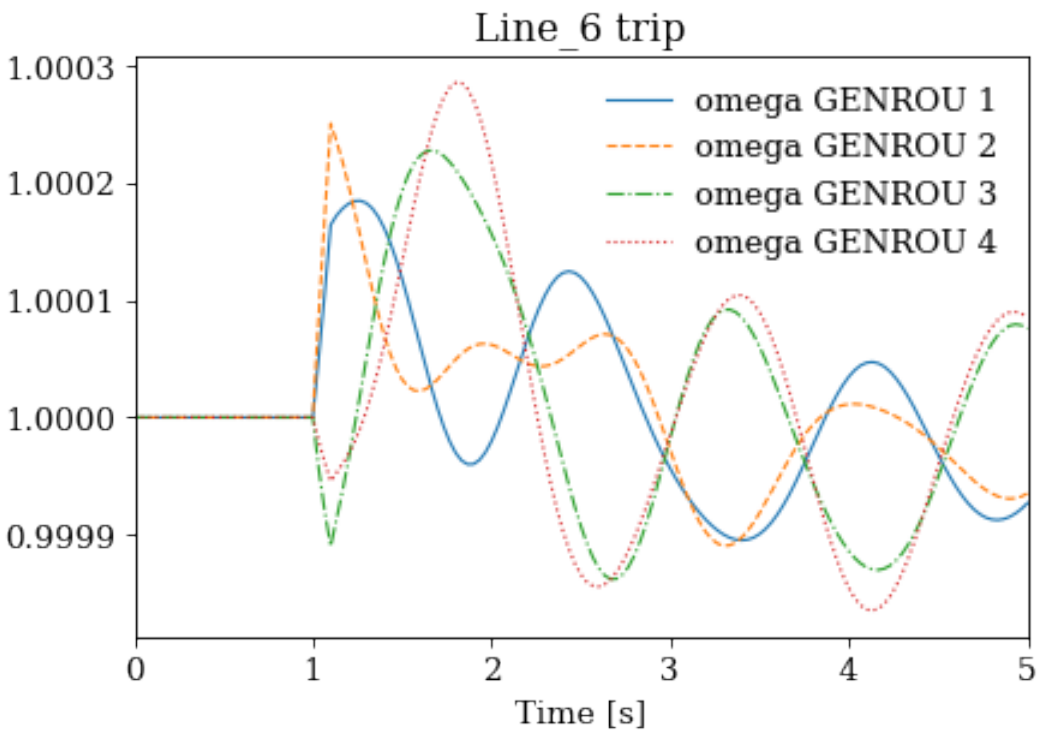

Line_1 trip
1.00125
1.00100
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]

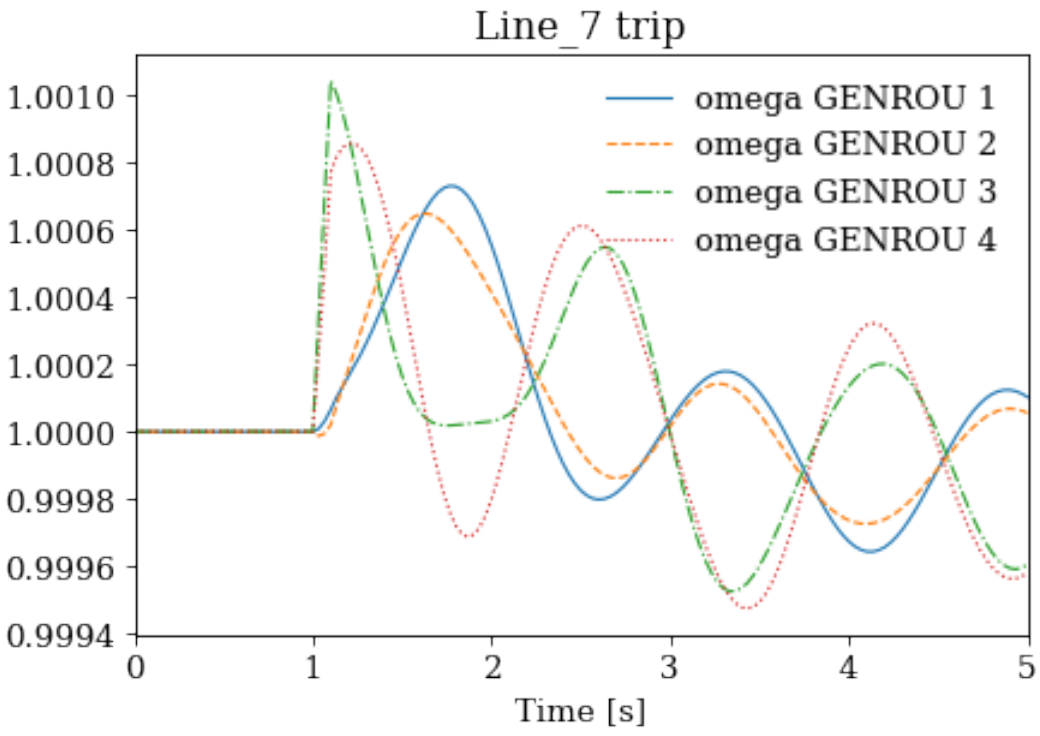

Line_2 trip
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
1.00100
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
0
1
2
3
4
5
Time [s]

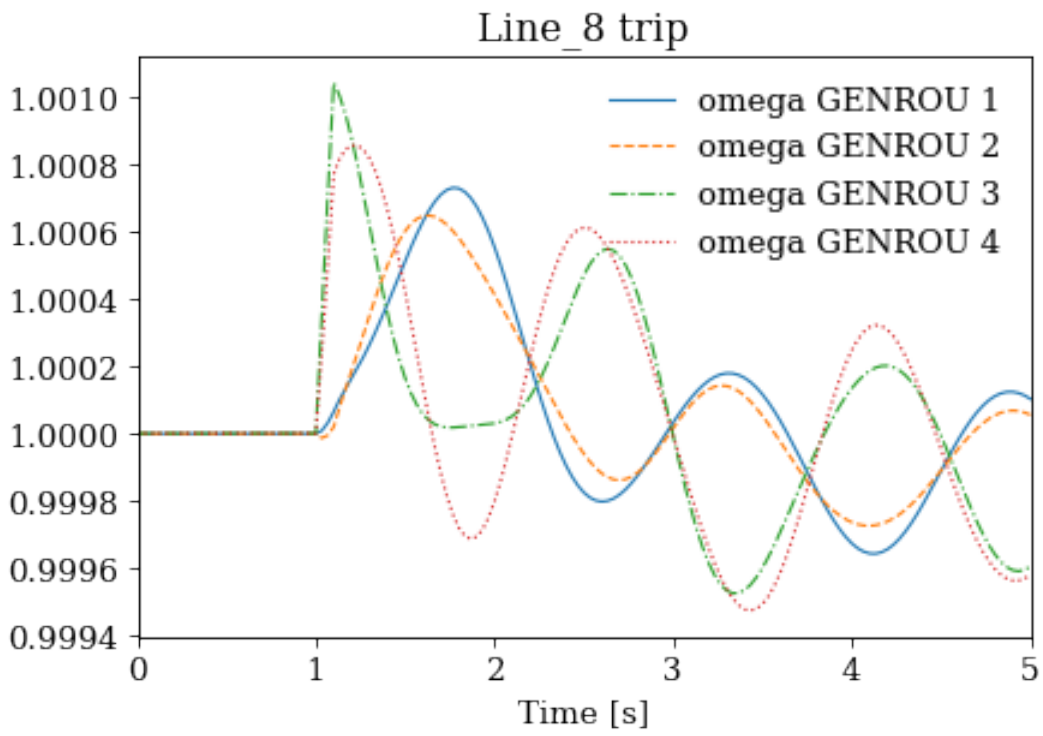

Line_3 trip
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
1.00100
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
0
1
2
3
4
5
Time [s]

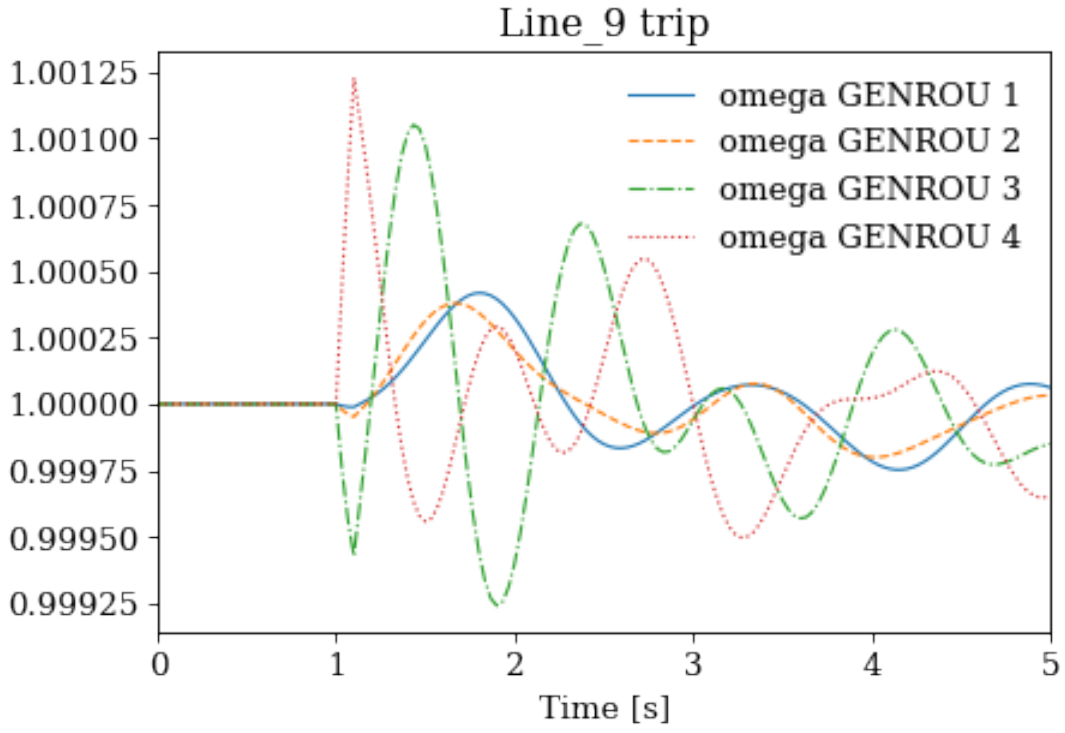

Line_4 trip
1.0003
1.0002
1.0001
1.0000
0.9999
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]

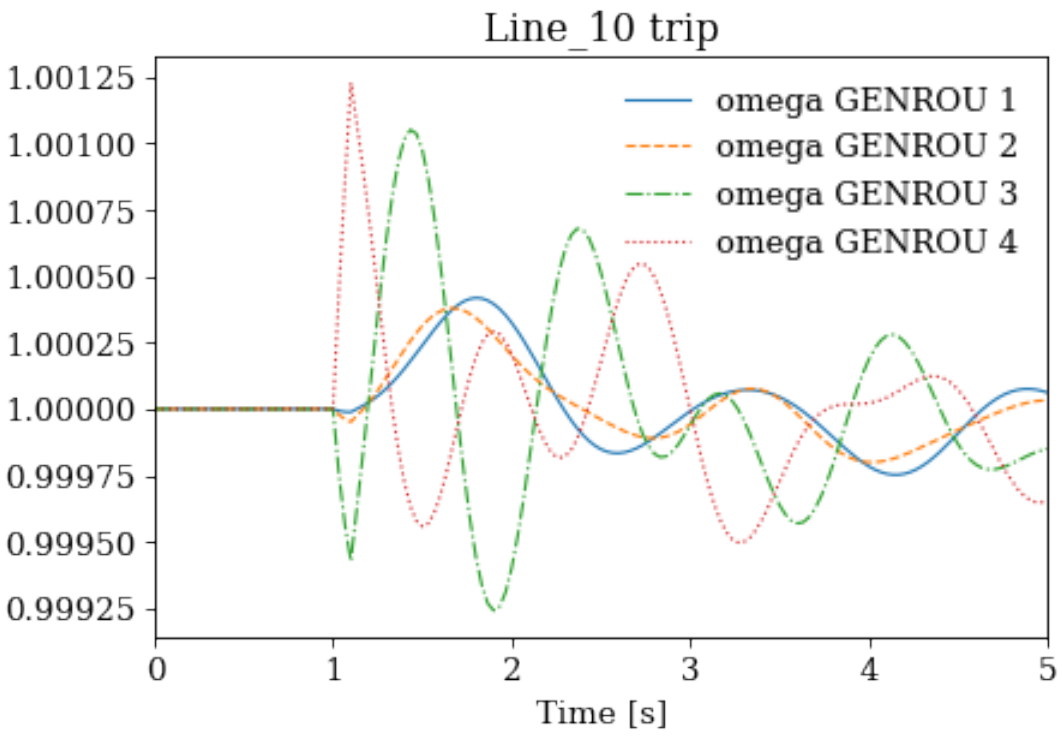

Line_5 trip
1.0003
1.0002
1.0001
1.0000
0.9999
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]

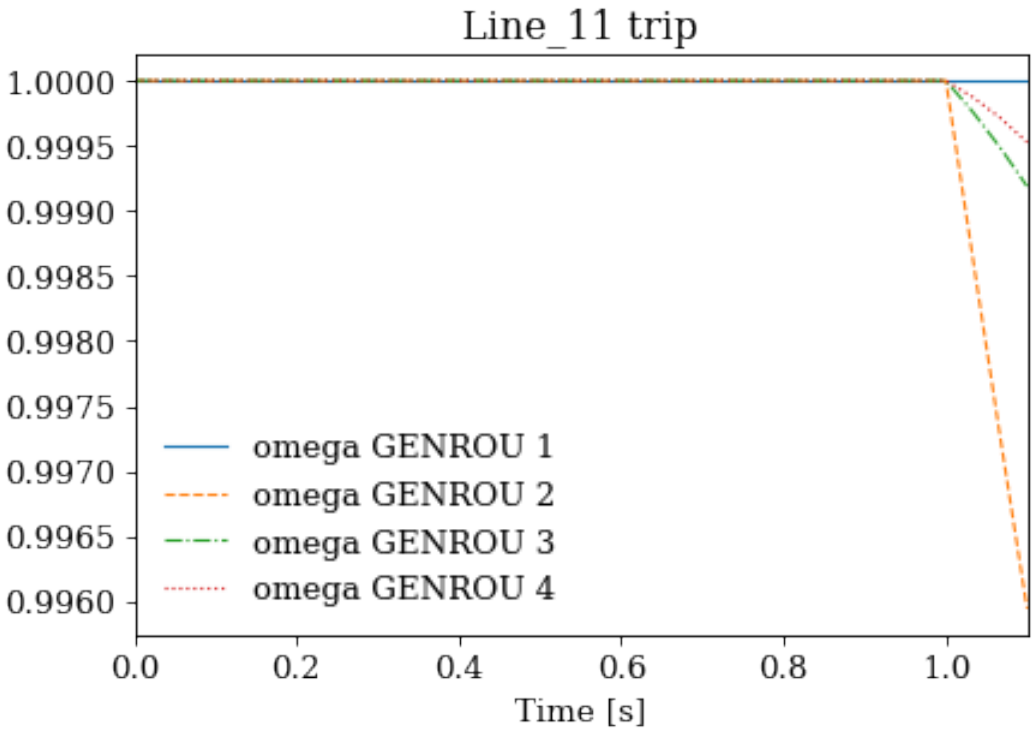

Line_6 trip
1.0003
1.0002
1.0001
1.0000
0.9999
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]

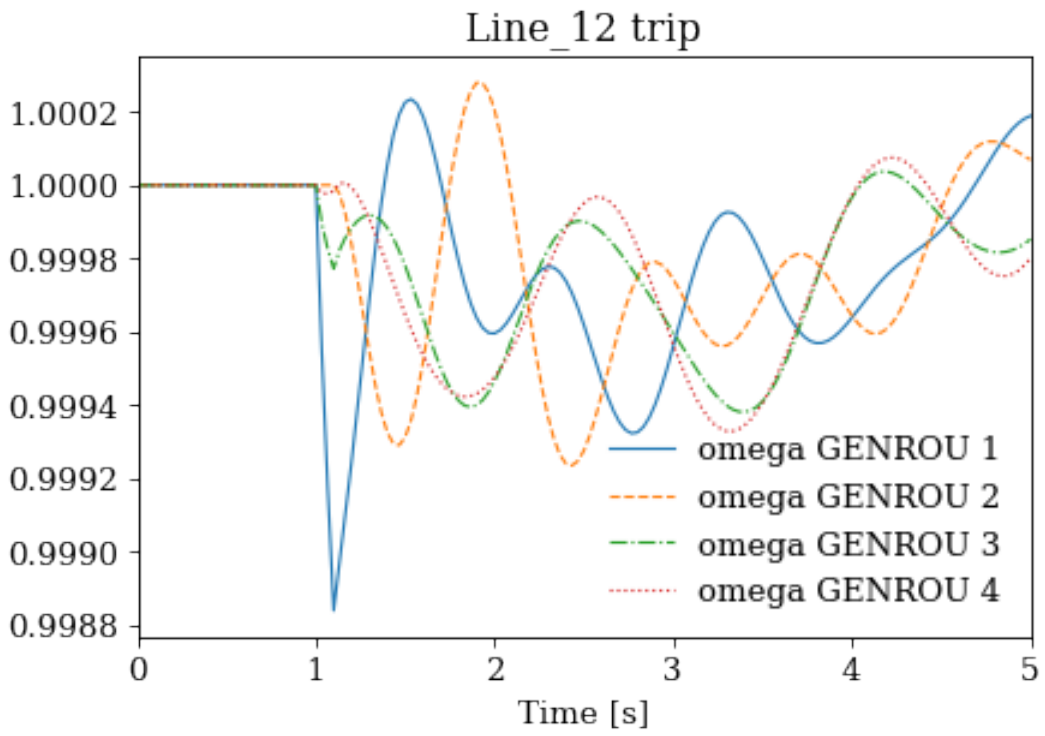

Line_7 trip
1.0010
1.0008
1.0006
1.0004
1.0002
1.0000
0.9998
0.9996
0.9994
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]

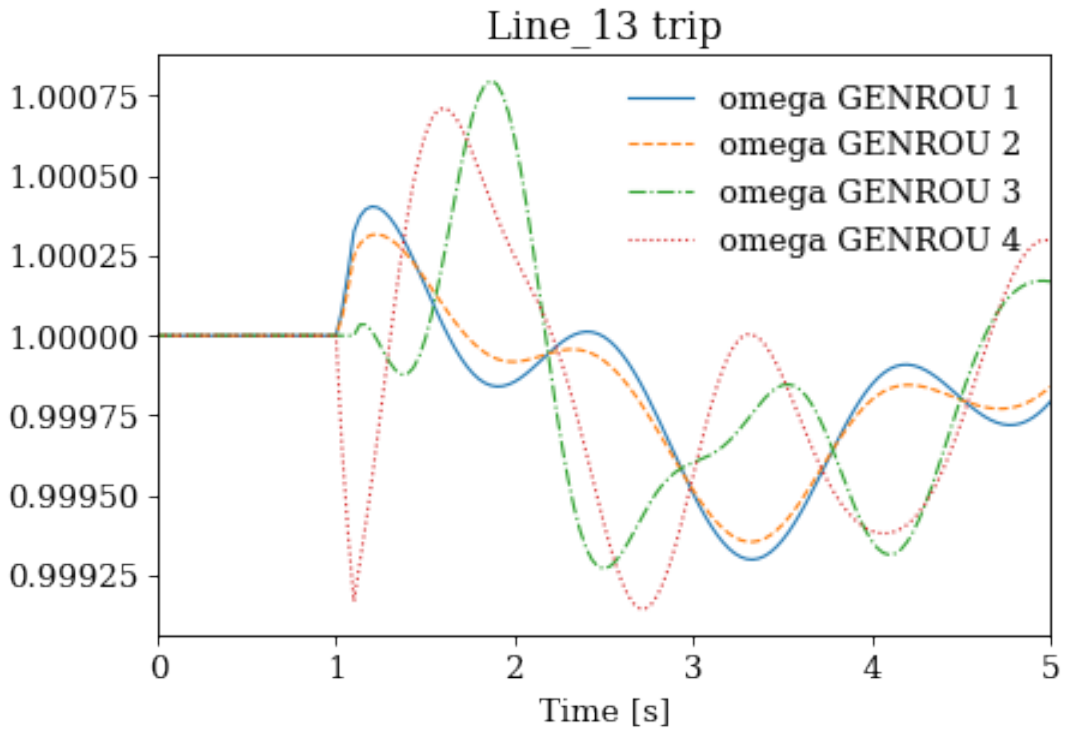

Line_8 trip
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
1.0010
1.0008
1.0006
1.0004
1.0002
1.0000
0.9998
0.9996
0.9994
0
1
2
3
4
5
Time [s]

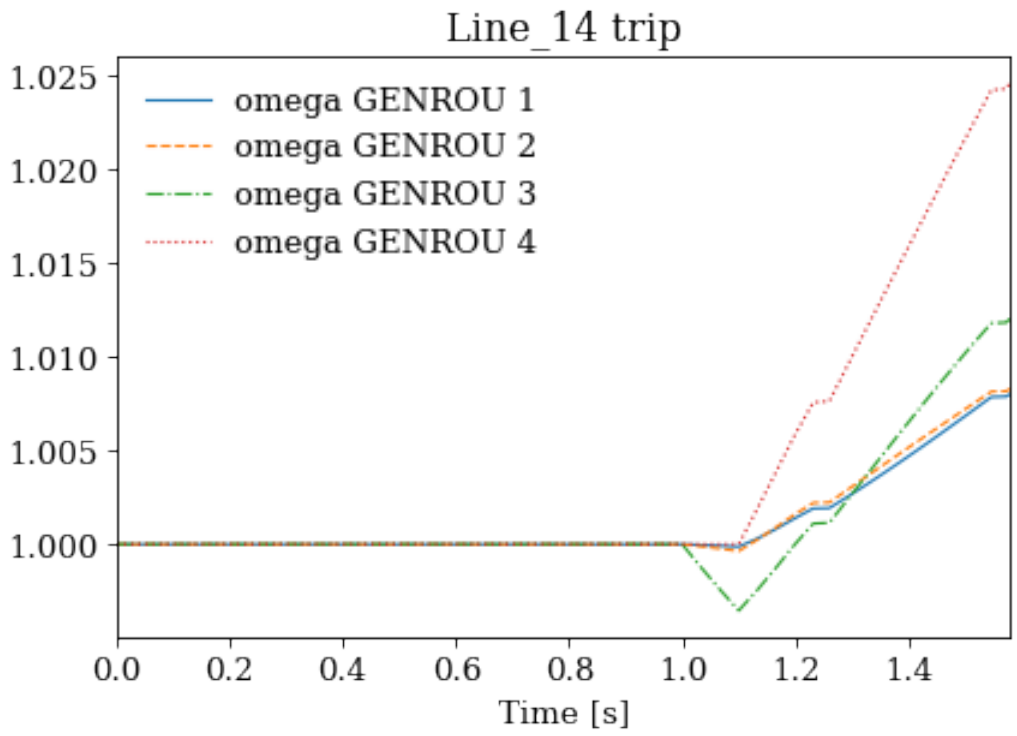

Line_9 trip
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
1.00125
1.00100
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
0.99925
0
1
2
3
4
5
Time [s]


Line_10 trip
1.00125
1.00100
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
0.99925
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0
1
2
3
4
5
Time [s]


Line_11 trip
1.0000
0.9995
0.9990
0.9985
0.9980
0.9975
0.9970
0.9965
0.9960
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4
0.0
0.2
0.4
0.6
0.8
1.0
Time [s]


Line_12 trip
1.0002
1.0000
0.9998
0.9996
0.9994
0.9992
0.9990
0.9988
0
1
2
3
4
5
Time [s]
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4


Line_13 trip
1.00075
1.00050
1.00025
1.00000
0.99975
0.99950
0.99925
0
1
2
3
4
5
Time [s]
omega GENROU 1
omega GENROU 2
omega GENROU 3
omega GENROU 4




```
!rm -rf batch_cases/
```

2.8 Changing Setpoints

This notebook shows an example of changing the generator setpoints in a time-domain simulation. Data in this example is trivial, but the example can be retrofitted for scenarios such as economic dispatch incorporation or reinforcement learning.

Steps are the folllwing:

1. Initialize a system by running the power flow,
2. Set the first simulation stop time in `TDS.config.tf`,
3. Run the simulation,
4. Update the setpoints,
5. Set the new simulation stop time and repeat from 3 until the end.

2.8.1 Step 1: Case Setup

```
import andes
from andes.utils import get_case
```

```
kundur = get_case('kundur/kundur_full.xlsx')

ss = andes.run(kundur)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.2635 seconds.
System internal structure set up in 0.0315 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0087 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745104027e-07
Converged in 5 iterations in 0.0108 seconds.
Initialization for dynamics completed in 0.0395 seconds.
Initialization was successful.
Report saved to "kundur_full_out.txt" in 0.0023 seconds.
```

```
-> Single process finished in 0.5215 seconds.
```

```
# disable the Toggle in this case
ss.Toggle.alter('u', 1, 0)
```

2.8.2 Step 2: Set the First Stop Time

```
# simulate to t=1 sec

# specify the first stop in `ss.TDS.config.tf`
ss.TDS.config.tf = 1
```

2.8.3 Step 3: Run Simulation

```
ss.TDS.run()
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-1 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
Simulation completed in 0.0245 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0039 seconds.
```

```
True
```

2.8.4 Step 4. Apply the auxiliary power setpoints to `TGOV1.paux0.v`

First, let's check the equations of TGOV1. `ss.TGOV1.paux0` is associated with equation `0 = paux - paux0`, in which `paux` is added to the power input equation.

```
print(ss.TGOV1.doc())
```

```
Model <TGOV1> in Group <TurbineGov>
TGOV1 turbine governor model.

Implements the PSS/E TGOV1 model without deadband.

Parameters

 Name  |            Description             | Default | Unit |    Properties
-------+------------------------------------+---------+------+-----------------
 idx   | unique device idx                  |         |      |
 u     | connection status                  | 1       | bool |
 name  | device name                        |         |      |
 syn   | Synchronous generator idx          |         |      | mandatory,unique
 Tn    | Turbine power rating. Equal to     |         | MVA  |
       | `Sn` if not provided.              |         |      |
```

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```
 wref0 | Base speed reference              | 1       | p.u. |
 R     | Speed regulation gain (mach. base | 0.050   | p.u. | ipower
       | default)                          |         |      |
 VMAX  | Maximum valve position            | 1.200   | p.u. | power
 VMIN  | Minimum valve position            | 0       | p.u. | power
 T1    | Valve time constant               | 0.100   |      |
 T2    | Lead-lag lead time constant       | 0.200   |      |
 T3    | Lead-lag lag time constant        | 10      |      |
 Dt    | Turbine damping coefficient       | 0       |      | power
 Sg    | Rated power from generator        | 0       | MVA  |
 ug    | Generator connection status       | 0       | bool |
 Vn    | Rated voltage from generator      | 0       | kV   |

Variables

 Name  |   Type   |             Description              | Unit | Properties
-------+----------+--------------------------------------+------+-----------
 LAG_y | State    | State in lag TF                      |      | v_str
 LL_x  | State    | State in lead-lag                    |      | v_str
 omega | ExtState | Generator speed                      | p.u. |
 paux  | Algeb    | Auxiliary power input                |      | v_str
 pout  | Algeb    | Turbine final output power           |      | v_str
 wref  | Algeb    | Speed reference variable             |      | v_str
 pref  | Algeb    | Reference power input                |      | v_str
 wd    | Algeb    | Generator speed deviation            | p.u. | v_str
 pd    | Algeb    | Pref plus speed deviation times gain | p.u. | v_str
 LL_y  | Algeb    | Output of lead-lag                   |      | v_str
 tm    | ExtAlgeb | Mechanical power interface to SynGen |      |

Initialization Equations

 Name  |   Type   | Initial Value
-------+----------+--------------
 LAG_y | State    | pd * 1 / 1
 LL_x  | State    | LAG_y
 omega | ExtState |
 paux  | Algeb    | paux0
 pout  | Algeb    | ue * tm0
 wref  | Algeb    | wref0
 pref  | Algeb    | tm0 * R
 wd    | Algeb    | 0
 pd    | Algeb    | ue * tm0
 LL_y  | Algeb    | LAG_y
 tm    | ExtAlgeb |

Differential Equations

 Name  |   Type   | RHS of Equation "T x' = f(x, y)" | T (LHS)
-------+----------+----------------------------------+--------
 LAG_y | State    | 1 * pd - 1 * LAG_y               | T1
 LL_x  | State    | (LAG_y - LL_x)                   | T3
 omega | ExtState |                                  |
```

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```
Algebraic Equations

Name  |   Type   |                RHS of Equation "0 = g(x, y)"
------+----------+-------------------------------------------------------------
 paux | Algeb    | paux0 - paux
 pout | Algeb    | ue * (LL_y - Dt * wd) - pout
 wref | Algeb    | wref0 - wref
 pref | Algeb    | pref0 * R - pref
 wd   | Algeb    | ue * (omega - wref) - wd
 pd   | Algeb    | ue*(- wd + pref + paux) * gain - pd
 LL_y | Algeb    | 1 * T2 * (LAG_y - LL_x) + 1 * LL_x * T3 - LL_y * T3+
      |          | LL_LT1_z1 * LL_LT2_z1 * (LL_y - 1 * LL_x)
 tm   | ExtAlgeb | ue * (pout - tm0)

Services

 Name  | Equation |     Type
-------+----------+-------------
 ue    | u * ug   | ConstService
 pref0 | tm0      | ConstService
 paux0 | 0        | ConstService
 gain  | ue/R     | ConstService

Discretes

  Name   |    Type    |      Info
---------+------------+---------------
 LAG_lim | AntiWindup | Limiter in Lag
 LL_LT1  | LessThan   |
 LL_LT2  | LessThan   |

Blocks

Name |     Type      | Info
-----+---------------+-----
 LAG | LagAntiWindup |
 LL  | LeadLag       |


Config Fields in [TGOV1]

   Option     | Value |                Info                | Acceptable values
--------------+-------+------------------------------------+------------------
 allow_adjust | 1     | allow adjusting upper or lower     | (0, 1)
              |       | limits                             |
 adjust_lower | 0     | adjust lower limit                 | (0, 1)
 adjust_upper | 1     | adjust upper limit                 | (0, 1)
```

```
ss.TGOV1.paux0.v
```

```
array([0., 0., 0., 0.])
```

```
# look up the original values of TGOV1 make sure they are as expected

ss.TGOV1.paux0.v
```

```
array([0., 0., 0., 0.])
```

```
# MUST use in-place assignments.
# Here, we increase the setpoint of the 0-th generator

# method 1: use in-place assignment again

ss.TGOV1.paux0.v[0] = 0.05

# method 2: use ``ss.TGOV1.alter()``

# ss.TGOV1.alter('paux0', 1, 0.05)
```

```
ss.TGOV1.paux0.v
```

```
array([0.05, 0.  , 0.  , 0.  ])
```

Continue to simulate to 2 seconds.

```
ss.TDS.config.tf = 2
```

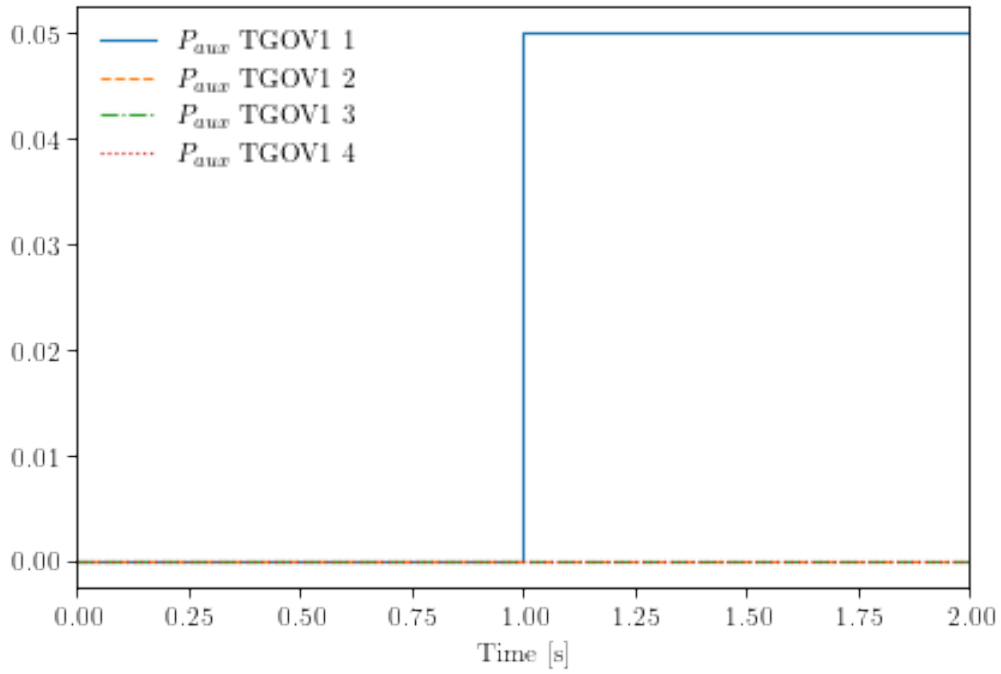
```
ss.TDS.run()
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
Simulation completed in 0.0916 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0032 seconds.
```

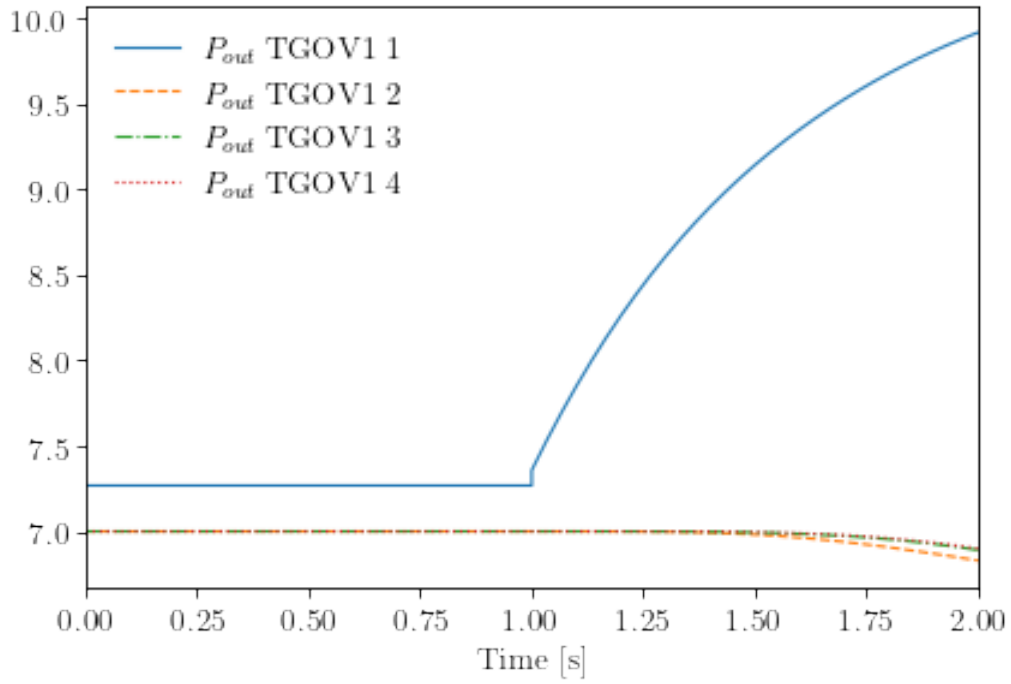
```
True
```

```
ss.TDS.plotter.plot(ss.TGOV1.paux)
```



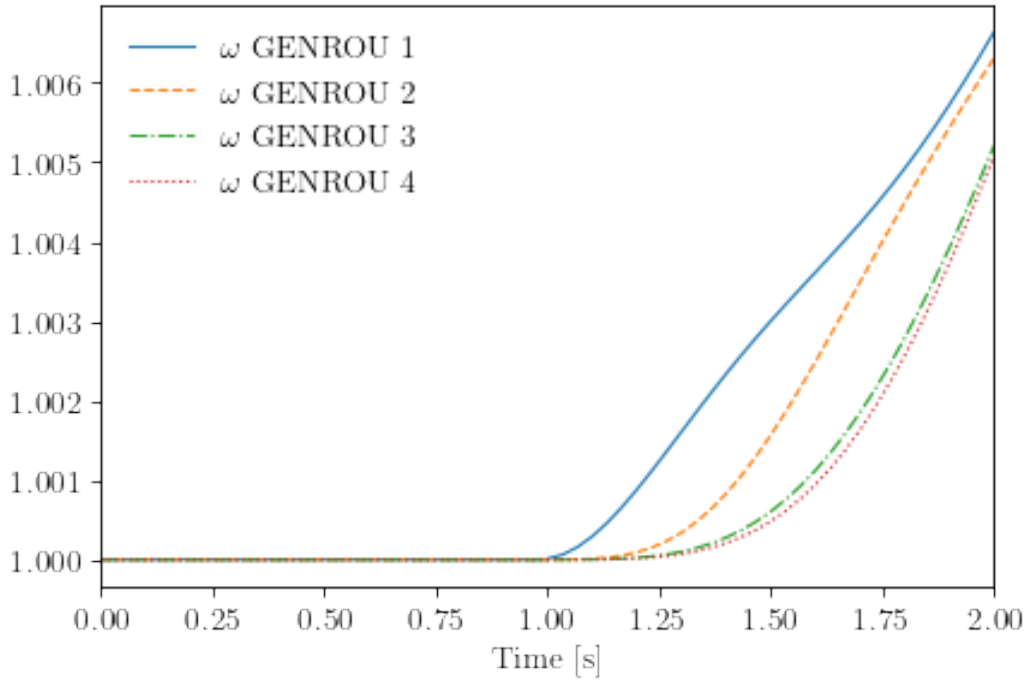

```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
ss.TDS.plotter.plot(ss.TGOV1.pout)
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
ss.TDS.plotter.plot(ss.GENROU.omega)
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

2.8.5 Step 5: Set Another New Setpoints and New Ending TIme.

In this example, we clear the auxiliary power previously set to `TGOV1.paux0.v`

```
# method 1: use in-place assignment again

ss.TGOV1.paux0.v[0] = 0.

# method 2: use ``ss.TGOV1.alter()``

# ss.TGOV1.alter('paux0', 1, 0)

# set the new ending time to 10 sec.
ss.TDS.config.tf = 10
```

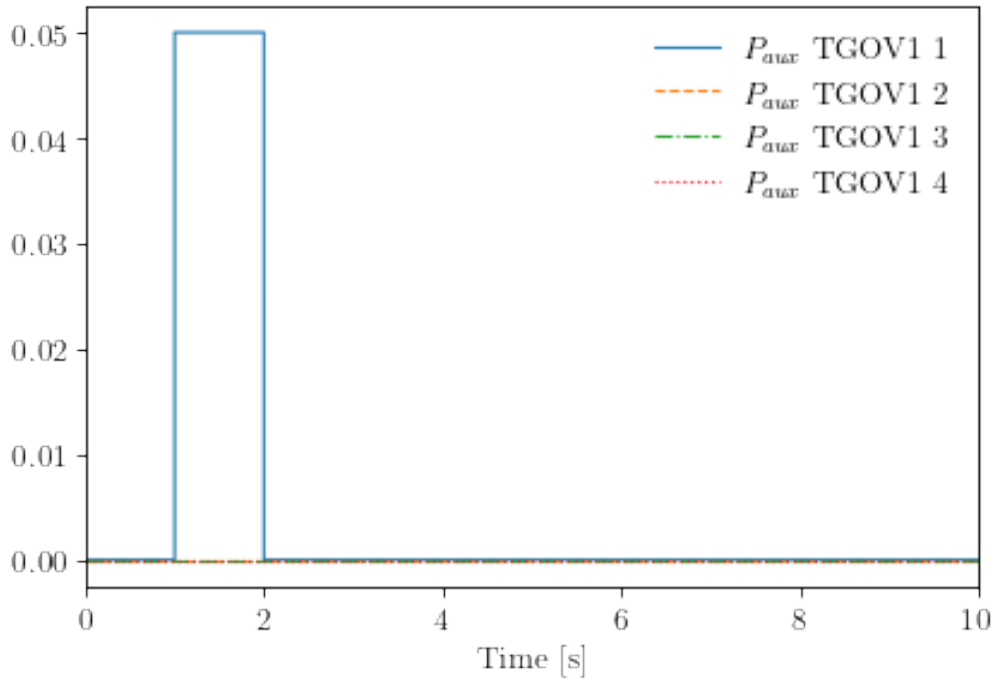
```
ss.TDS.run()
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
Simulation completed in 0.6068 seconds.
Outputs to "kundur_full_out.lst" and "kundur_full_out.npz".
Outputs written in 0.0275 seconds.
```

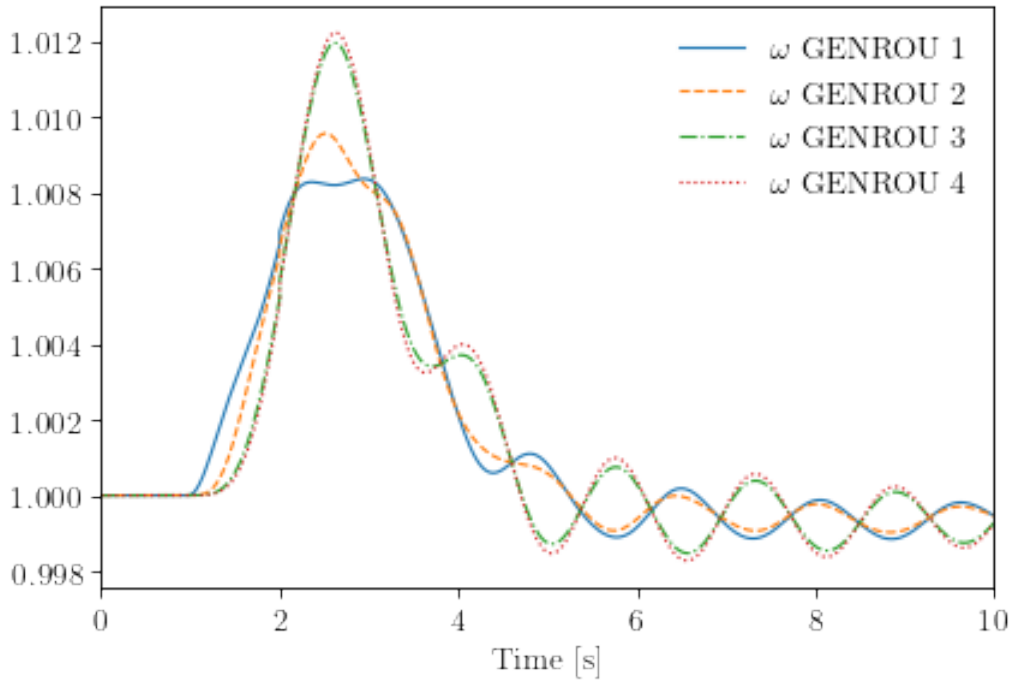
```
True
```

```
ss.TDS.plotter.plot(ss.TGOV1.paux)
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
ss.TDS.plotter.plot(ss.GENROU.omega)
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
!andes misc -C
```

```
"/home/hacui/repos/andes/examples/kundur_full_out.npz" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.txt" removed.
"/home/hacui/repos/andes/examples/kundur_full_out.lst" removed.
```

2.9 Load Frequency Control

This examples shows (1) how to trip a generator, and (2) how to drive frequency back by load shedding.

```
import andes
import numpy as np

andes.config_logger(stream_level=20)
```

2.9.1 Tripping a Generator in the IEEE 14-Bus System

```
# using the IEEE 14-bus model as an example.
# The example here contains a variety of models: generators, exciters,␣
↪turbine governors, and PSS
# To speed up, one can remove unneeded ones, e.g., PSS

ieee14_raw = andes.get_case("ieee14/ieee14.raw")
ieee14_dyr = andes.get_case("ieee14/ieee14.dyr")
```

```
# use `andes.load` to load the test system
# Need to set `setup=False` to be able to add new Toggles that turns off␣
↪generators.

ss = andes.load(ieee14_raw, addfile=ieee14_dyr, setup=False)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/ieee14/ieee14.raw"...
  IEEE 14 BUS TEST CASE
  03/06/14 CONTO           100.0  1962 W
Input file parsed in 0.0119 seconds.
Parsing additional file "/home/hacui/repos/andes/andes/cases/ieee14/ieee14.dyr
↪"...
Addfile parsed in 0.2965 seconds.
```

```
# Add a Toggle that disconnects `GENROU_2` at t=1 s

ss.add("Toggle", dict(model='SynGen', dev="GENROU_2", t=1.0))
```

```
'Toggle_3'
```

```
# Call setup manually

ss.setup()
```

```
IEEEST <IEEEST_1> added BusFreq <BusFreq_1> linked to bus <3.0>
ST2CUT <ST2CUT_2> added BusFreq <BusFreq_2> linked to bus <1.0>
ST2CUT <ST2CUT_3> added BusFreq <BusFreq_3> linked to bus <2.0>
System internal structure set up in 0.0750 seconds.
```

```
True
```

```
# double check that Toggles are set up correctly
# Check `u` of the Toggles - the first two line switches are disabled, and␣
↪the generator trip is enabled

ss.Toggle.as_df()
```

```
           idx    u       name   model       dev    t
uid
0    Toggle_1  1.0  Toggle_1    Line    Line_1  1.0
1    Toggle_2  1.0  Toggle_2    Line    Line_1  1.1
2    Toggle_3  1.0  Toggle_3  SynGen  GENROU_2  1.0
```

```
# disable existing line switches
# The IEEE 14-bus system contains predefined line switches. Disabling them to␣
↪study generator trip only.

ss.Toggle.u.v[[0, 1]] = 0
```

```
# calculate power flow

# use constant power model for PQ (we will come back to this later)

ss.PQ.config.p2p = 1
ss.PQ.config.q2q = 1
ss.PQ.config.p2z = 0
ss.PQ.config.q2z = 0

# turn off under-voltage PQ-to-Z conversion
ss.PQ.pq2z = 0

ss.PFlow.run()
```

```
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0101 seconds.
0: |F(x)| = 0.5605182134
1: |F(x)| = 0.006202200332
2: |F(x)| = 5.819382824e-06
3: |F(x)| = 6.96508129e-12
Converged in 4 iterations in 0.0111 seconds.
Initialization for dynamics completed in 0.0575 seconds.
Initialization was successful.
Report saved to "ieee14_out.txt" in 0.0083 seconds.
```

```
True
```

```
# set the first simulation stop and run it

ss.TDS.config.tf = 20
```

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```
ss.TDS.config.criteria = 0  # temporarily turn off stability criteria based␣
↪on angle separation
ss.TDS.run()
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Toggle Toggle_3>: SynGen.GENROU_2 status changed to 0 at t=1.0 sec.
```

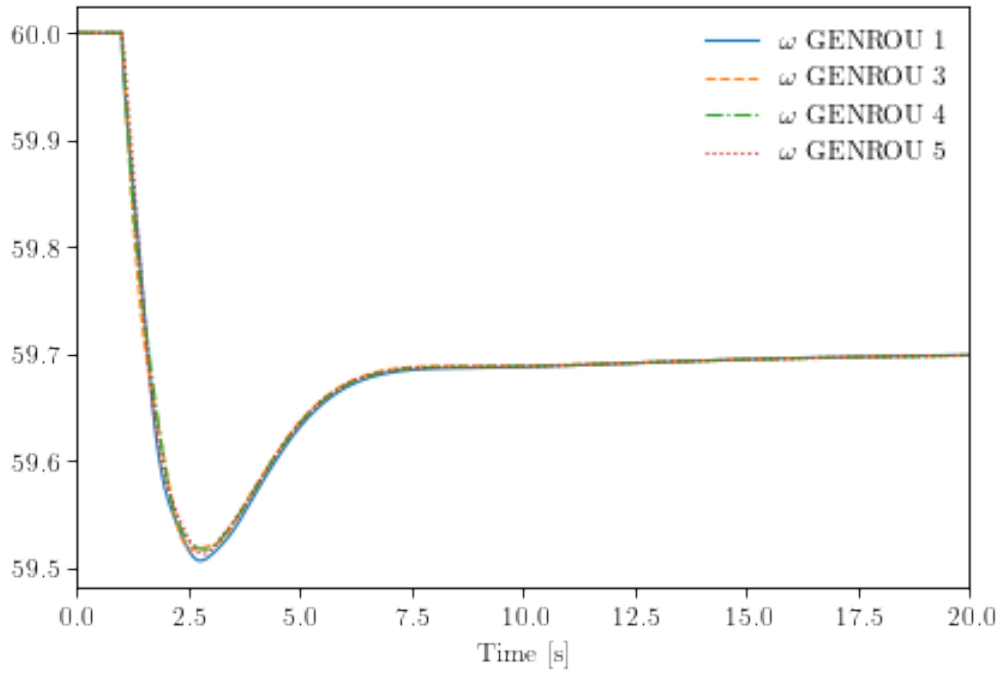
```
Simulation completed in 2.9748 seconds.
Outputs to "ieee14_out.lst" and "ieee14_out.npz".
Outputs written in 0.0421 seconds.
```

```
True
```

```
# Show the frequency response of online generators

# Refer to `plot` documentation by using `help(ss.TDS.plt.plot)` and `help(ss.
↪TDS.plt.plot_data)`
ss.TDS.load_plotter()

ss.TDS.plt.plot(ss.GENROU.omega,
                a=(0, 2, 3, 4),
                ytimes=60,
               )
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

2.9.2 Adjusting Load to Compensate for the Generation Loss

Check the power of the lost generator by inspecting the power flow inputs:

```
ss.PV.as_df()
```

```
     idx    u  name     Sn     Vn  bus  busr    p0    q0  pmax  pmin  qmax  \
uid
0      2  0.0     2  100.0   69.0    2  None  0.40  0.15   0.5   0.1  0.15
1      3  0.0     3  100.0   69.0    3  None  0.40  0.15   0.5   0.1  0.15
2      4  0.0     4  100.0  138.0    6  None  0.30  0.10   0.5   0.1  0.10
3      5  0.0     5  100.0   69.0    8  None  0.35  0.10   0.5   0.1  0.10

     qmin    v0  vmax  vmin   ra    xs
uid
0   -0.40  1.03   1.4   0.6  0.0  0.13
1   -0.10  1.01   1.4   0.6  0.0  0.13
2   -0.06  1.03   1.4   0.6  0.0  0.12
3   -0.06  1.03   1.4   0.6  0.0  0.12
```

The tripped GENROU_2 correspond to the first PV (GENROU_1 corresponds to Slack). Thus, the lost active power is 0.40 pu.

Let's compensate for that by shedding 0.4 pu of active power load at t=2.0 s.

By checking the equation documentation of PQ (using `print(ss.PQ.doc())`, we can tell that the imposed active power for time-domain simulation is from `Ppf`, because we used the constant power model with `p2p`

```
= 1.
```

```
Algebraic Equations

Name |   Type    |                RHS of Equation "0 = g(x, y)"
-----+-----------+-----------------------------------------------------------
 a   | ExtAlgeb | u * (dae_t <= 0) * (p0 * vcmp_zi + Rlb * vcmp_zl * v**2 +
     |          | Rub * vcmp_zu * v**2) + u * (dae_t > 0) * (p2p * Ppf + p2i *
     |          | Ipeq * v + p2z * Req * v**2)
 v   | ExtAlgeb | u * (dae_t <= 0) * (q0 * vcmp_zi + Xlb * vcmp_zl * v**2 +
     |          | Xub * vcmp_zu * v**2) + u * (dae_t > 0) * (q2q * Qpf + q2i *
     |          | Iqeq * v + q2z * Xeq * v**2)
```

`Ppf` may be different from `p0` specified in the data file.

```
# active power from power flow solution - make a copy

Ppf = np.array(ss.PQ.Ppf.v)

Ppf
```

```
array([0.217, 0.5  , 0.478, 0.076, 0.15 , 0.295, 0.09 , 0.035, 0.061,
       0.135, 0.2  ])
```

Reload the system and add the generator trip.

```
ss = andes.load(ieee14_raw, addfile=ieee14_dyr, setup=False)

ss.add("Toggle", dict(model='SynGen', dev="GENROU_2", t=1.0))
ss.setup()
ss.Toggle.u.v[[0, 1]] = 0

ss.PQ.config.p2p = 1
ss.PQ.config.q2q = 1
ss.PQ.config.p2z = 0
ss.PQ.config.q2z = 0
ss.PQ.pq2z = 0

ss.PFlow.run()
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded config from file "/home/hacui/.andes/andes.rc"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/ieee14/ieee14.raw"...
  IEEE 14 BUS TEST CASE
  03/06/14 CONTO           100.0  1962 W
Input file parsed in 0.0047 seconds.
Parsing additional file "/home/hacui/repos/andes/andes/cases/ieee14/ieee14.dyr
↪"...
Addfile parsed in 0.1101 seconds.
IEEEST <IEEEST_1> added BusFreq <BusFreq_1> linked to bus <3.0>
```

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```
ST2CUT <ST2CUT_2> added BusFreq <BusFreq_2> linked to bus <1.0>
ST2CUT <ST2CUT_3> added BusFreq <BusFreq_3> linked to bus <2.0>
System internal structure set up in 0.0547 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0040 seconds.
0: |F(x)| = 0.5605182134
1: |F(x)| = 0.006202200332
2: |F(x)| = 5.819382824e-06
3: |F(x)| = 6.96508129e-12
Converged in 4 iterations in 0.0065 seconds.
Initialization for dynamics completed in 0.0547 seconds.
Initialization was successful.
Report saved to "ieee14_out.txt" in 0.0028 seconds.
```

```
True
```

But let's run to 2 seconds.

```
ss.TDS.config.tf = 2.0
ss.TDS.config.criteria = 0  # temporarily turn off stability criteria based␣
↪on angle separation

ss.TDS.run()
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-2.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Toggle Toggle_3>: SynGen.GENROU_2 status changed to 0 at t=1.0 sec.
```

```
Simulation completed in 0.2567 seconds.
Outputs to "ieee14_out.lst" and "ieee14_out.npz".
Outputs written in 0.0043 seconds.
```

```
True
```

```
# all `Ppf` before shedding
```

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```
ss.PQ.Ppf.v
```

```
array([0.217, 0.5  , 0.478, 0.076, 0.15 , 0.295, 0.09 , 0.035, 0.061,
       0.135, 0.2  ])
```

And then apply the load shedding on buses 2, 3, 4, 5, 6, 9.

```
shed_buses = [2, 3, 4, 5, 6, 9]

# find the `idx` of the loads on these buses

pq_shed_idx = ss.PQ.find_idx(keys='bus', values=shed_buses)
pq_shed_idx
```

```
['PQ_1', 'PQ_2', 'PQ_3', 'PQ_4', 'PQ_5', 'PQ_6']
```

```
# get `Ppf` on these buses before shedding

pq_p = ss.PQ.get(src='Ppf', idx=pq_shed_idx, attr='v')
pq_p
```

```
array([0.217, 0.5  , 0.478, 0.076, 0.15 , 0.295])
```

```
pq_p_new = pq_p - 0.4 / len(shed_buses)

ss.PQ.set(src='Ppf', idx=pq_shed_idx, attr='v', value=pq_p_new)
```

```
True
```

```
# double check

ss.PQ.Ppf.v
```

```
array([0.15033333, 0.43333333, 0.41133333, 0.00933333, 0.08333333,
       0.22833333, 0.09      , 0.035     , 0.061     , 0.135     ,
       0.2       ])
```

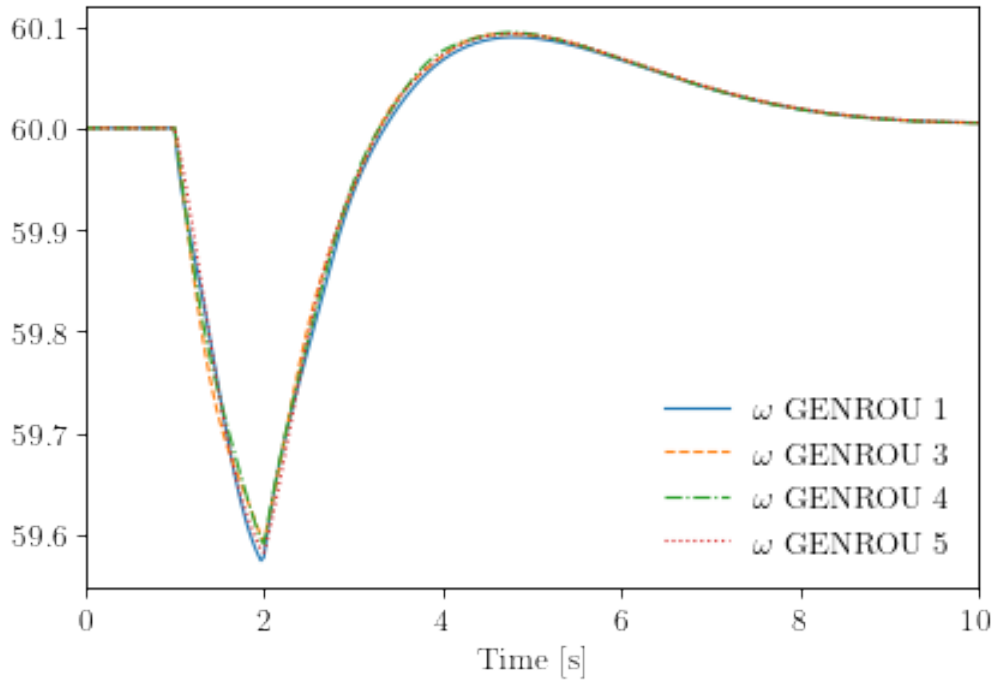
```
ss.TDS.config.tf = 10

ss.TDS.run()

ss.TDS.plt.plot(ss.GENROU.omega,
                a=(0, 2, 3, 4),
                ytimes=60,
               )
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
Simulation completed in 1.2884 seconds.
Outputs to "ieee14_out.lst" and "ieee14_out.npz".
Outputs written in 0.0211 seconds.
```




```
(<Figure size 480x320 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

```
!andes misc -C
```

```
"/home/hacui/repos/andes/examples/ieee14_out.txt" removed.
"/home/hacui/repos/andes/examples/ieee14_out.lst" removed.
"/home/hacui/repos/andes/examples/ieee14_out.npz" removed.
```

The result shows the generator speed (frequency) returns to 60 Hz after load shedding.

2.10 Profile in Notebook

2.10.1 Profiling with Python CProfiler

Before getting started, this example requires the config flag `PFlow.init_tds` to be `0`, which is the default value.

```
import andes
from andes.utils.paths import get_case

case_path = get_case("kundur/kundur_full.xlsx")
```

Passing `profile=True, no_output = True` to `run` will enable the profiler and have the results printed.

```
ss = andes.run(
    case_path, profile=True, routine="tds", no_output=True, default_
↪config=True
)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Loaded generated Python code in "/home/hacui/.andes/pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.3536 seconds.
System internal structure set up in 0.0412 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0051 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745103977e-07
Converged in 5 iterations in 0.0045 seconds.
Initialization for dynamics completed in 0.0368 seconds.
Initialization was successful.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
```

```
Simulation to t=20.00 sec completed in 0.9577 seconds.
```

```
         2126948 function calls (2100484 primitive calls) in 1.634 seconds

   Ordered by: cumulative time
   List reduced from 5556 to 40 due to restriction <40>

   ncalls  tottime  percall  cumtime  percall filename:lineno(function)
        1    0.006    0.006    1.065    1.065 /home/hacui/repos/andes/andes/
↪routines/tds.py:326(run)
      603    0.001    0.000    0.891    0.001 /home/hacui/repos/andes/andes/
↪routines/tds.py:521(itm_step)
      603    0.051    0.000    0.890    0.001 /home/hacui/repos/andes/andes/
↪routines/daeint.py:27(step)
```

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```
     2025    0.006    0.000    0.703    0.000 /home/hacui/repos/andes/andes/
↪routines/tds.py:820(fg_update)
    10176    0.060    0.000    0.646    0.000 /home/hacui/repos/andes/andes/
↪system.py:1672(call_models)
        1    0.000    0.000    0.558    0.558 /home/hacui/repos/andes/andes/
↪main.py:275(load)
 1040/207    0.003    0.000    0.423    0.002 <frozen importlib._bootstrap>
↪:1022(_find_and_load)
  960/129    0.002    0.000    0.420    0.003 <frozen importlib._bootstrap>
↪:987(_find_and_load_unlocked)
   847/34    0.001    0.000    0.419    0.012 <frozen importlib._bootstrap_
↪external>:877(exec_module)
   905/66    0.002    0.000    0.419    0.006 {built-in method builtins.exec}
  1246/34    0.001    0.000    0.418    0.012 <frozen importlib._bootstrap>
↪:233(_call_with_frames_removed)
  925/130    0.002    0.000    0.415    0.003 <frozen importlib._bootstrap>
↪:664(_load_unlocked)
     2030    0.001    0.000    0.367    0.000 /home/hacui/repos/andes/andes/
↪system.py:1047(g_update)
        1    0.000    0.000    0.355    0.355 /home/hacui/repos/andes/andes/
↪io/__init__.py:115(parse)
        1    0.000    0.000    0.353    0.353 /home/hacui/repos/andes/andes/
↪io/xlsx.py:88(read)
    20279    0.082    0.000    0.349    0.000 /home/hacui/repos/andes/andes/
↪core/model/model.py:963(g_update)
       35    0.000    0.000    0.270    0.008 /home/hacui/repos/andes/andes/
↪utils/lazyimport.py:61(__maybe_import__)
       34    0.000    0.000    0.214    0.006 /home/hacui/repos/andes/andes/
↪utils/lazyimport.py:73(__getattr__)
        1    0.000    0.000    0.213    0.213 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/__init__.py:1(<module>)
        1    0.000    0.000    0.169    0.169 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/core/api.py:1(<module>)
        1    0.000    0.000    0.161    0.161 /home/hacui/repos/andes/andes/
↪system.py:93(__init__)
  109/107    0.000    0.000    0.138    0.001 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/importlib/__init__.py:108(import_module)
  109/107    0.000    0.000    0.138    0.001 <frozen importlib._bootstrap>
↪:1038(_gcd_import)
        1    0.000    0.000    0.122    0.122 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/io/excel/_base.py:460(read_excel)
  254/196    0.000    0.000    0.108    0.001 {built-in method builtins.__
↪import__}
     2030    0.001    0.000    0.101    0.000 /home/hacui/repos/andes/andes/
↪system.py:1033(f_update)
        1    0.000    0.000    0.100    0.100 /home/hacui/repos/andes/andes/
↪system.py:1800(import_models)
    79/52    0.000    0.000    0.097    0.002 <frozen importlib._bootstrap_
↪external>:1182(exec_module)
    79/52    0.082    0.001    0.097    0.002 {built-in method _imp.exec_
↪dynamic}
1636/1630    0.009    0.000    0.097    0.000 {built-in method builtins.__
```

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```
↪build_class__}
        1    0.000    0.000    0.097    0.097 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/io/excel/_base.py:1520(__init__)
        1    0.000    0.000    0.094    0.094 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/io/excel/_openpyxl.py:534(__init__)
    20279    0.039    0.000    0.086    0.000 /home/hacui/repos/andes/andes/
↪core/model/model.py:935(f_update)
     2030    0.002    0.000    0.084    0.000 /home/hacui/repos/andes/andes/
↪system.py:989(l_update_eq)
        4    0.000    0.000    0.083    0.021 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/compat/_optional.py:81(import_optional_
↪dependency)
 1864/802    0.002    0.000    0.082    0.000 <frozen importlib._bootstrap>
↪:1053(_handle_fromlist)
        1    0.000    0.000    0.080    0.080 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/openpyxl/__init__.py:1(<module>)
     2025    0.076    0.000    0.076    0.000 /home/hacui/.andes/pycode/
↪GENROU.py:20(g_update)
        1    0.000    0.000    0.069    0.069 /home/hacui/mambaforge/envs/a/
↪lib/python3.10/site-packages/pandas/core/arrays/__init__.py:1(<module>)
    20279    0.011    0.000    0.068    0.000 /home/hacui/repos/andes/andes/
↪core/model/model.py:712(l_check_eq)


-> Single process finished in 1.7222 seconds.
```

2.10.2 Profiling with `line_profiler`.

`line_profiler` provides line-based profiling results for functions.

Install with `pip install line_profiler` and restart the notebook.

```
import andes
from andes.utils.paths import get_case

case_path = get_case("kundur/kundur_full.xlsx")
```

Profile power flow

Pass the function name to profile to the magic `%lprun`, followed by a call to the function itself or an upper-level function.

Results will be shown in a popup window.

```
%load_ext line_profiler

%lprun -f andes.routines.pflow.PFlow.run andes.run(case_path, no_output=True,␣
↪default_config=True)
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.0498 seconds.
System internal structure set up in 0.0402 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0050 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745103977e-07
Converged in 5 iterations in 0.0041 seconds.
```

```
-> Single process finished in 0.2605 seconds.
```

```
Timer unit: 1e-09 s

Total time: 0.0114298 s
File: /home/hacui/repos/andes/andes/routines/pflow.py
Function: run at line 211

Line #      Hits         Time  Per Hit   % Time  Line Contents
==============================================================
   211                                           def run(self, **kwargs):
   212                                               """
   213                                               Solve the power flow␣
↪using the selected method.
   214
   215                                               Returns
   216                                               -------
   217                                               bool
   218                                                   convergence␣
↪status
   219                                               """
   220
   221         1       1363.0   1363.0      0.0          system = self.system
   222         1        581.0    581.0      0.0          if self.config.check_
↪conn == 1:
   223         1    1378597.0    1e+06     12.1              self.system.
↪connectivity()
   224
   225         1     250450.0 250450.0      2.2          self.summary()
```

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```
   226         1    5393416.0    5e+06     47.2           self.init()
   227
   228         1        401.0    401.0      0.0           if system.dae.m == 0:
   229                                                         logger.error(
↪"Loaded case contains no power flow element.")
   230                                                         system.exit_code␣
↪= 1
   231                                                         return False
   232
   233         1        762.0    762.0      0.0           method = self.config.
↪method.lower()
   234
   235         1       4629.0   4629.0      0.0           t0, _ = elapsed()
   236
   237                                                   # ---------- Call␣
↪solution methods ----------
   238         1        251.0    251.0      0.0           if method == 'nr':
   239         1    4163484.0    4e+06     36.4               self.nr_solve()
   240                                                   elif method == 'nk':
   241                                                       self.newton_
↪krylov()
   242
   243         1       5711.0   5711.0      0.0           t1, s1 = elapsed(t0)
   244         1        311.0    311.0      0.0           self.exec_time = t1 -
↪ t0
   245
   246         1        260.0    260.0      0.0           if not self.
↪converged:
   247                                                       if abs(self.mis[-
↪1] - self.mis[-2]) < self.config.tol:
   248                                                           max_idx = np.
↪argmax(np.abs(system.dae.xy))
   249                                                           name =␣
↪system.dae.xy_name[max_idx]
   250                                                           logger.error(
↪'Mismatch is not correctable possibly due to large load-generation␣
↪imbalance.')
   251                                                           logger.error(
↪'Largest mismatch on equation associated with <%s>', name)
   252                                                   else:
   253                                                       logger.error(
↪'Power flow failed after %d iterations for "%s".', self.niter + 1, system.
↪files.case)
   254
   255                                           else:
   256         1     222407.0 222407.0      1.9               logger.info(
↪'Converged in %d iterations in %s.', self.niter + 1, s1)
   257
   258                                                   # make a copy of␣
↪power flow solutions
   259         1       3146.0   3146.0      0.0               self.x_sol =␣
↪system.dae.x.copy()
```

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```
   260         1        862.0    862.0      0.0               self.y_sol =␣
↪system.dae.y.copy()
   261
   262         1        441.0    441.0      0.0               if self.config.
↪init_tds:
   263                                                           system.TDS.
↪init()
   264         1        330.0    330.0      0.0               if self.config.
↪report:
   265         1       1803.0   1803.0      0.0                   system.PFlow.
↪report()
   266
   267         1        491.0    491.0      0.0           system.exit_code = 0␣
↪if self.converged else 1
   268         1        110.0    110.0      0.0           return self.converged
```

Alternatively, do

```
ss = andes.load(case_path, no_output=True, default_config=True)

%lprun -f ss.PFlow.run ss.PFlow.run()
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.0293 seconds.
System internal structure set up in 0.0231 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0043 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745103977e-07
Converged in 5 iterations in 0.0040 seconds.
```

```
Timer unit: 1e-09 s

Total time: 0.0109119 s
File: /home/hacui/repos/andes/andes/routines/pflow.py
Function: run at line 211
```

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```
Line #      Hits         Time  Per Hit   % Time  Line Contents
==============================================================
   211                                           def run(self, **kwargs):
   212                                               """
   213                                               Solve the power flow␣
↪using the selected method.
   214
   215                                               Returns
   216                                               -------
   217                                               bool
   218                                                   convergence␣
↪status
   219                                               """
   220
   221         1        972.0    972.0      0.0          system = self.system
   222         1        511.0    511.0      0.0          if self.config.check_
↪conn == 1:
   223         1    1557962.0    2e+06     14.3              self.system.
↪connectivity()
   224
   225         1     253977.0 253977.0      2.3          self.summary()
   226         1    4784035.0    5e+06     43.8          self.init()
   227
   228         1        451.0    451.0      0.0          if system.dae.m == 0:
   229                                                       logger.error(
↪"Loaded case contains no power flow element.")
   230                                                       system.exit_code␣
↪= 1
   231                                                       return False
   232
   233         1        842.0    842.0      0.0          method = self.config.
↪method.lower()
   234
   235         1       4840.0   4840.0      0.0          t0, _ = elapsed()
   236
   237                                               # ---------- Call␣
↪solution methods ----------
   238         1        211.0    211.0      0.0          if method == 'nr':
   239         1    4053092.0    4e+06     37.1              self.nr_solve()
   240                                               elif method == 'nk':
   241                                                   self.newton_
↪krylov()
   242
   243         1       5711.0   5711.0      0.1          t1, s1 = elapsed(t0)
   244         1        200.0    200.0      0.0          self.exec_time = t1 -
↪ t0
   245
   246         1        241.0    241.0      0.0          if not self.
↪converged:
   247                                                       if abs(self.mis[-
↪1] - self.mis[-2]) < self.config.tol:
   248                                                           max_idx = np.
```

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```
↪argmax(np.abs(system.dae.xy))
   249                                                          name =␣
↪system.dae.xy_name[max_idx]
   250                                                          logger.error(
↪'Mismatch is not correctable possibly due to large load-generation␣
↪imbalance.')
   251                                                          logger.error(
↪'Largest mismatch on equation associated with <%s>', name)
   252                                                      else:
   253                                                          logger.error(
↪'Power flow failed after %d iterations for "%s".', self.niter + 1, system.
↪files.case)
   254
   255                                                  else:
   256         1     241955.0 241955.0      2.2              logger.info(
↪'Converged in %d iterations in %s.', self.niter + 1, s1)
   257
   258                                                      # make a copy of␣
↪power flow solutions
   259         1       3116.0   3116.0      0.0              self.x_sol =␣
↪system.dae.x.copy()
   260         1        701.0    701.0      0.0              self.y_sol =␣
↪system.dae.y.copy()
   261
   262         1        562.0    562.0      0.0              if self.config.
↪init_tds:
   263                                                          system.TDS.
↪init()
   264         1        241.0    241.0      0.0              if self.config.
↪report:
   265         1       1753.0   1753.0      0.0                  system.PFlow.
↪report()
   266
   267         1        441.0    441.0      0.0          system.exit_code = 0␣
↪if self.converged else 1
   268         1        110.0    110.0      0.0          return self.converged
```

To dig into the Newton Raphson iteration steps, profile each step instead with:

```
ss = andes.load(case_path, no_output=True, default_config=True)
%lprun -f ss.PFlow.nr_step ss.PFlow.run()
```

```
Working directory: "/home/hacui/repos/andes/examples"
> Reloaded generated Python code of module "pycode".
Parsing input file "/home/hacui/repos/andes/andes/cases/kundur/kundur_full.
↪xlsx"...
Input file parsed in 0.0299 seconds.
System internal structure set up in 0.0242 seconds.
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
```

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```
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0045 seconds.
0: |F(x)| = 14.9282832
1: |F(x)| = 3.608627841
2: |F(x)| = 0.1701107882
3: |F(x)| = 0.002038626956
4: |F(x)| = 3.745103977e-07
Converged in 5 iterations in 0.0040 seconds.
```

```
Timer unit: 1e-09 s

Total time: 0.00289216 s
File: /home/hacui/repos/andes/andes/routines/pflow.py
Function: nr_step at line 104

Line #      Hits         Time  Per Hit   % Time  Line Contents
==============================================================
   104                                           def nr_step(self):
   105                                               """
   106                                               Solve a single␣
↪iteration step using the Newton-Raphson method.
   107
   108                                               Returns
   109                                               -------
   110                                               float
   111                                                   maximum absolute␣
↪mismatch
   112                                               """
   113
   114         5       2064.0    412.8      0.1          system = self.system
   115
   116                                               # ---------- Build␣
↪numerical DAE----------
   117         5    1288374.0 257674.8     44.5          self.fg_update()
   118
   119                                               # ---------- update␣
↪the Jacobian on conditions ----------
   120         5       2365.0    473.0      0.1          if self.config.
↪method != 'dishonest' or (self.niter < self.config.n_factorize):
   121         5    1263947.0 252789.4     43.7              system.j_
↪update(self.models)
   122         5       4048.0    809.6      0.1              self.solver.
↪worker.new_A = True
   123
   124                                               # ---------- prepare␣
↪and solve linear equations ----------
```

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```
  125         5      12294.0   2458.8      0.4          self.res[:system.dae.
↪n] = -system.dae.f[:]
  126         5       9229.0   1845.8      0.3          self.res[system.dae.
↪n:] = -system.dae.g[:]
  127
  128        10      15200.0   1520.0      0.5          self.A =␣
↪sparse([[system.dae.fx, system.dae.gx],
  129         5       1994.0    398.8      0.1                          ␣
↪[system.dae.fy, system.dae.gy]])
  130
  131         5       1422.0    284.4      0.0          if not self.config.
↪linsolve:
  132         5      95764.0  19152.8      3.3              self.inc = self.
↪solver.solve(self.A, self.res)
  133                                                   else:
  134                                                       self.inc = self.
↪solver.linsolve(self.A, self.res)
  135
  136         5      15670.0   3134.0      0.5          system.dae.x += np.
↪ravel(self.inc[:system.dae.n])
  137         5      11501.0   2300.2      0.4          system.dae.y += np.
↪ravel(self.inc[system.dae.n:])
  138
  139                                                   # find out variables␣
↪associated with maximum mismatches
  140         5        591.0    118.2      0.0          fmax = 0
  141         5       1232.0    246.4      0.0          if system.dae.n > 0:
  142                                                       fmax_idx = np.
↪argmax(np.abs(system.dae.f))
  143                                                       fmax = system.
↪dae.f[fmax_idx]
  144                                                       logger.debug(
↪"Max. diff mismatch %.10g on %s", fmax, system.dae.x_name[fmax_idx])
  145
  146         5      28063.0   5612.6      1.0          gmax_idx = np.
↪argmax(np.abs(system.dae.g))
  147         5       2987.0    597.4      0.1          gmax = system.dae.
↪g[gmax_idx]
  148         5      87689.0  17537.8      3.0          logger.debug("Max.␣
↪algeb mismatch %.10g on %s", gmax, system.dae.y_name[gmax_idx])
  149
  150         5       6012.0   1202.4      0.2          mis = max(abs(fmax),␣
↪abs(gmax))
  151         5      41141.0   8228.2      1.4          system.vars_to_
↪models()
  152
  153         5        570.0    114.0      0.0          return mis
```

Profile time-domain simulation

```
xy = ss.TDS.init()
```

```
Initialization for dynamics completed in 0.0209 seconds.
Initialization was successful.
```

```
%lprun -f ss.TDS.itm_step ss.TDS.run()
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-20.0 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Toggle 1>: Line.Line_8 status changed to 0 at t=2.0 sec.
```

```
Simulation to t=20.00 sec completed in 0.9426 seconds.
```

```
Timer unit: 1e-09 s

Total time: 0.882568 s
File: /home/hacui/repos/andes/andes/routines/tds.py
Function: itm_step at line 521

Line #      Hits         Time  Per Hit   % Time  Line Contents
==============================================================
   521                                           def itm_step(self):
   522                                               """
   523                                               Integrate for the␣
↪step size of ``self.h`` using implicit trapezoid method.
   524
   525                                               Returns
   526                                               -------
   527                                               bool
   528                                                   Convergence␣
↪status in ``self.converged``.
   529
   530                                               """
   531       602  882567523.0    1e+06    100.0          return self.method.
↪step(self)
```

2.10.3 Cleanup

```
!andes misc -C
```

```
No output file found in the working directory.
```

2.11 MATPOWER Interface

See also the API reference for `andes.interop.matpower`.

```
import andes

from andes.interop.matpower import (start_instance,
    to_matpower, from_matpower)
```

2.11.1 Create an Octave/MATLAB instance

```
m = start_instance()
```

2.11.2 Convert to MATPOWER

```
ss = andes.system.example()  # load an ieee14 example case

mpc = to_matpower(m, 'mpc', ss)
```

Test if the power flow of mpc can be solved

```
m.eval("runpf(mpc)")
```

```
warning: error caught while executing handle class delete method:
'osqp_mex' undefined near line 40 column 13
OSQP Error!

MATPOWER Version 7.1, 08-Oct-2020 -- AC Power Flow (Newton)

Newton's method power flow (power balance, polar) converged in 3 iterations.

Converged in 0.01 seconds
================================================================================
|     System Summary                                                          ␣
↪ |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
```

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```
Buses              14     Total Gen Capacity     400.0         -112.0 to 150.0
Generators          5     On-line Capacity       400.0         -112.0 to 150.0
Committed Gens      5     Generation (actual)    226.4               49.8
Loads              11     Load                   223.7               95.4
  Fixed            11       Fixed                223.7               95.4
  Dispatchable      0       Dispatchable          -0.0 of -0.0        -0.0
Shunts              2     Shunt (inj)            -0.0                35.3
Branches           20     Losses (I^2 * Z)        2.73               13.52
Transformers       20     Branch Charging (inj)    -                 23.8
Inter-ties          0     Total Inter-tie Flow    0.0                 0.0
Areas               1

                          Minimum                      Maximum
                  -------------------------  --------------------------------
Voltage Magnitude   1.010 p.u. @ bus 3          1.030 p.u. @ bus 2
Voltage Angle      -9.48 deg   @ bus 14         0.00 deg   @ bus 1
P Losses (I^2*R)             -                 0.50 MW    @ line 1-2
Q Losses (I^2*X)             -                 2.11 MVAr  @ line 8-7

================================================================================
|     Bus Data                                                                 ␣
↪ |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.030    0.000*    81.43    -21.62       -         -
    2  1.030   -1.764     40.00     30.44     21.70     12.70
    3  1.010   -3.537     40.00     12.60     50.00     25.00
    4  1.011   -4.410       -         -       47.80     10.00
    5  1.017   -3.843       -         -        7.60      1.60
    6  1.030   -6.453     30.00     20.99     15.00      7.50
    7  1.022   -4.885       -         -         -         -
    8  1.030   -1.540     35.00      7.40       -         -
    9  1.022   -7.246       -         -       29.50     16.60
   10  1.016   -7.415       -         -        9.00      5.80
   11  1.019   -7.080       -         -        3.50      1.80
   12  1.017   -7.473       -         -        6.10      1.60
   13  1.014   -7.721       -         -       13.50      5.80
   14  1.016   -9.481       -         -       20.00      7.00
                        --------  --------  --------  --------
               Total:    226.43     49.80    223.70     95.40

================================================================================
|     Branch Data                                                              ␣
↪ |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q␣
↪(MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  -------
↪-
```

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```
  1      1      2     50.10    -18.36    -49.60     14.29     0.503      1.53
  2      1      5     31.33     -3.26    -30.83      0.17     0.500      2.06
  3      2      3     17.79      4.11    -17.63     -8.00     0.158      0.67
  4      2      4     28.02      0.46    -27.58     -2.69     0.433      1.31
  5      2      5     22.09     -1.13    -21.83     -1.70     0.262      0.80
  6      3      4      7.63     -4.40     -7.58      3.21     0.047      0.12
  7      4      5    -25.97     -5.70     26.07      5.99     0.092      0.29
  8      6     11      6.91      2.37     -6.86     -2.27     0.048      0.10
  9      6     12      7.93      1.32     -7.86     -1.17     0.075      0.16
 10      6     13     19.15      2.76    -18.92     -2.31     0.234      0.46
 11      7      9     39.12      1.46    -39.12      0.15     0.000      1.61
 12      9     10      5.67      5.40     -5.65     -5.35     0.019      0.05
 13      9     14     13.17     -3.85    -12.94      4.34     0.229      0.49
 14     10     11     -3.35     -0.45      3.36      0.47     0.009      0.02
 15     12     13      1.76     -0.43     -1.75      0.44     0.007      0.01
 16     13     14      7.17     -3.93     -7.06      4.16     0.111      0.23
 17      4      7      4.12     -3.76     -4.12      3.83    -0.000      0.06
 18      4      9      9.22     -1.06     -9.22      1.53     0.000      0.47
 19      6      5    -18.99      7.03     18.99     -6.06     0.000      0.97
 20      8      7     35.00      7.40    -35.00     -5.29     0.000      2.11
                                                            --------   -------
↪-
                                                    Total:     2.727     13.52
```

```
mpc_sol = m.pull("mpc")  # retrieve the solution
```

One can also save the case to a MATPOWER `.m` file from Octave/MATLAB. Comment in and run the following code:

```
# m.eval("savecase('case14_andes.m', mpc)")
```

2.11.3 Convert from MATPOWER

```
system = from_matpower(m, 'mpc')
```

`m.pull()` won't work if one has run OPF in Octave/MATLAB because Oct2Py does not support custom class objects created by MATPOWER.

`from _matpower()` will read the individual fields to construct an `mpc` dict internally before creating a system.

2.11.4 Add dynamic data

One can create an Excel file with dynamic data only and use the xlsx parser to load data into system:

```
from andes.io import xlsx

xlsx.read(system, andes.get_case('ieee14/ieee14_dyn_only.xlsx'))
```

```
<andes.system.System at 0x7f8684043520>
```

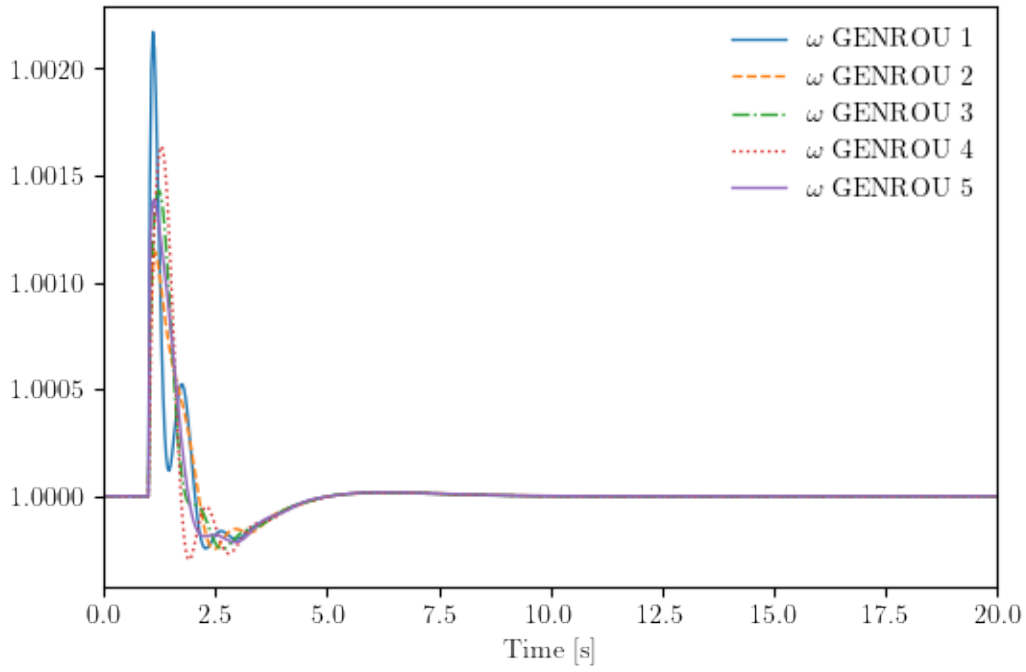
```
system.setup()

system.PFlow.run()

system.TDS.run()
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Fault 1>: Applying fault on Bus (idx=7) at t=1.0 sec.
<Fault 1>: Clearing fault on Bus (idx=7) at t=1.03333 sec.
```

```
True
```

```
system.TDS.plt.plot(system.GENROU.omega)
```




```
(<Figure size 600x400 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

Since the data in `ieee14_dyn_only.xlsx` is stripped from `ieee14/ieee14_fault.xlsx`, the

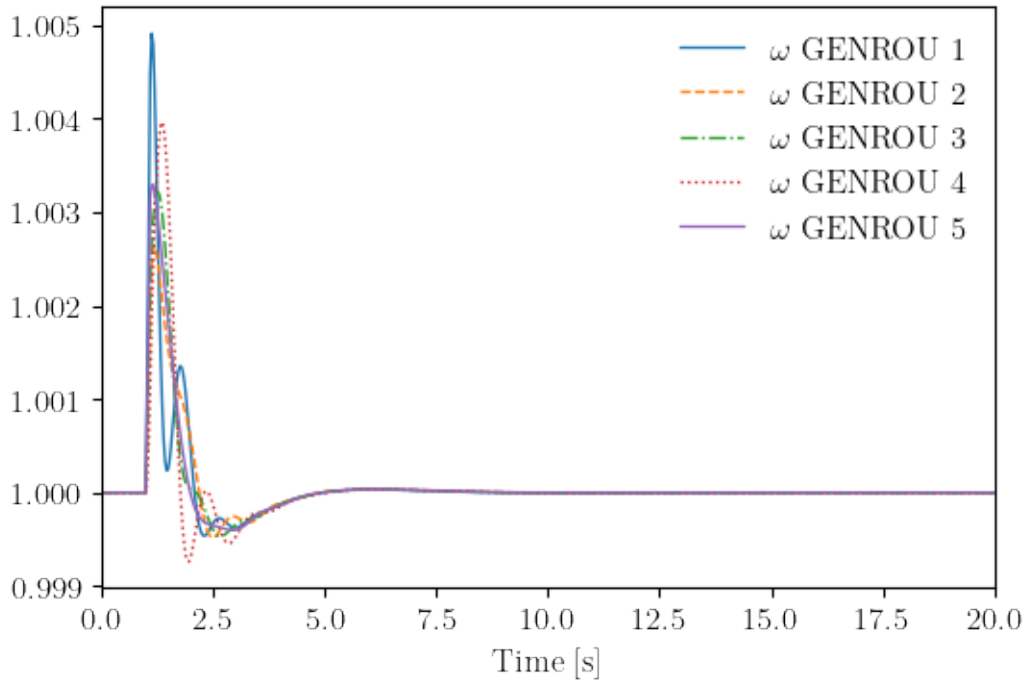
above results is identical to the simulation of the latter case:

```
ss = andes.run(andes.get_case("ieee14/ieee14_fault.xlsx"),
               routine='tds', verbose=30,
               no_output=True, default_config=True)
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
<Fault 1>: Applying fault on Bus (idx=9) at t=1.0 sec.
<Fault 1>: Clearing fault on Bus (idx=9) at t=1.1 sec.
-> Single process finished in 0.7220 seconds.
```

```
ss.TDS.plt.plot(ss.GENROU.omega)
```




```
(<Figure size 600x400 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

2.12 pandapower Interface

This example (1) shows how to convert an ANDES system (`ssa`) to a pandapower network (`ssp`), (2) benchmarks the powerflow results, (3) shows how to alter `ssa` active power setpoints according to `ssp` results.

The following clarafications you might need to know:

1. This interface tracks static power flow model in ANDES: `Bus`, `Line`, `PQ`, `Shunt`, `PV`, and `Slack`. The dynamic model in ANDES is not tracked, including but not limited to `TurbineGov`, `SynGen`, and `Exciter`.

2. The interface converts the `Slack` in ANDES to `gen` in pandapower rather than `ext_gen`.
3. **MUST NOT** verify power flow after initializing TDS in ANDES. ANDES does not allow running `PFlow` for systems with initialized TDS as it will break variable addressing.
4. If you want to track dynamic model outputs in ANDES and feedback into pandapower, you might need to manually transfer the results from ANDES to pandapower.

This interface is mainly developed by Jinning Wang.

```
import andes

from andes.interop.pandapower import to_pandapower, \
    make_link_table, runopp_map, add_gencost

andes.config_logger(20)

import pandapower as pp
import numpy as np
import pandas as pd

from math import pi
```

2.12.1 Load case

Here we use the same ANDES system `ss0` to do the pandapower conversion, which leaves the `ssa` untouched.

This will be useful if you need to modify the `ssa` parametes or setpoints.

```
ssa = andes.load(andes.get_case('ieee14/ieee14_ieeet1.xlsx'),
                 setup=False,
                 no_output=True,
                 default_config=True)
ssa.Toggle.u.v = [0, 0]
ssa.setup()

ss0 = andes.load(andes.get_case('ieee14/ieee14_ieeet1.xlsx'),
                 setup=False,
                 no_output=True,
                 default_config=True)
ss0.Toggle.u.v = [0, 0]
ss0.setup()
```

```
Working directory: "/Users/jinningwang/Documents/work/andes/docs/source/
↪examples"
> Loaded generated Python code in "/Users/jinningwang/.andes/pycode".
Generated code for <PQ> is stale.
Numerical code generation (rapid incremental mode) started...
```

```
Generating code for 1 models on 8 processes.
```

```
Saved generated pycode to "/Users/jinningwang/.andes/pycode"
> Reloaded generated Python code of module "pycode".
Generated numerical code for 1 models in 0.1328 seconds.
Parsing input file "/Users/jinningwang/Documents/work/andes/andes/cases/
↪ieee14/ieee14_ieeet1.xlsx"...
Input file parsed in 0.0441 seconds.
System internal structure set up in 0.0236 seconds.
Working directory: "/Users/jinningwang/Documents/work/andes/docs/source/
↪examples"
> Reloaded generated Python code of module "pycode".
Generated code for <PQ> is stale.
Numerical code generation (rapid incremental mode) started...
```

```
Generating code for 1 models on 8 processes.
```

```
Saved generated pycode to "/Users/jinningwang/.andes/pycode"
> Reloaded generated Python code of module "pycode".
Generated numerical code for 1 models in 0.2553 seconds.
Parsing input file "/Users/jinningwang/Documents/work/andes/andes/cases/
↪ieee14/ieee14_ieeet1.xlsx"...
Input file parsed in 0.0367 seconds.
System internal structure set up in 0.0227 seconds.
```

```
True
```

2.12.2 Convert to pandapower net

Convert ADNES system `ssa` to pandapower net `ssp`.

```
ssp = to_pandapower(ss0)
```

```
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0029 seconds.
0: |F(x)| = 0.5605182134
1: |F(x)| = 0.006202200332
2: |F(x)| = 5.819382825e-06
3: |F(x)| = 6.957087684e-12
Converged in 4 iterations in 0.0038 seconds.
Power flow results are consistent. Conversion is successful.
```

Add generator cost data.

```
gen_cost = np.array([
        [2, 0, 0, 3, 0.0430293, 20, 0],
        [2, 0, 0, 3, 0.25,      20, 0],
        [2, 0, 0, 3, 0.01,      40, 0],
        [2, 0, 0, 3, 0.01,      40, 0],
        [2, 0, 0, 3, 0.01,      40, 0]
])

add_gencost(ssp, gen_cost)
```

```
True
```

Inspect the pandapower net `ssp`.

```
ssp
```

```
This pandapower network includes the following parameter tables:
   - bus (14 elements)
   - load (11 elements)
   - gen (5 elements)
   - shunt (2 elements)
   - line (16 elements)
   - trafo (4 elements)
   - poly_cost (5 elements)
 and the following results tables:
   - res_bus (14 elements)
   - res_line (16 elements)
   - res_trafo (4 elements)
   - res_load (11 elements)
   - res_shunt (2 elements)
   - res_gen (5 elements)
```

2.12.3 Comapre Power Flow Results

Run power flow of `ssa`.

```
ssa.PFlow.run()
```

```
-> System connectivity check results:
  No islanded bus detected.
  System is interconnected.
  Each island has a slack bus correctly defined and enabled.

-> Power flow calculation
           Numba: Off
   Sparse solver: KLU
 Solution method: NR method
Power flow initialized in 0.0039 seconds.
0: |F(x)| = 0.5605182134
```

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```
1: |F(x)| = 0.006202200332
2: |F(x)| = 5.819382825e-06
3: |F(x)| = 6.957087684e-12
Converged in 4 iterations in 0.0045 seconds.
```

```
True
```

```
# ssa
ssa_res_gen = pd.DataFrame(columns=['name', 'p_mw', 'q_mvar', 'va_degree',
↪'vm_pu'])
ssa_res_gen['name'] = ssa.PV.as_df()['name']
ssa_res_gen['p_mw'] = ssa.PV.p.v * ssa.config.mva
ssa_res_gen['q_mvar'] = ssa.PV.q.v * ssa.config.mva
ssa_res_gen['va_degree'] = ssa.PV.a.v * 180 / pi
ssa_res_gen['vm_pu'] = ssa.PV.v.v
ssa_res_slack = pd.DataFrame([[ssa.Slack.name.v[0], ssa.Slack.p.v[0] * ssa.
↪config.mva,
                              ssa.Slack.q.v[0] * ssa.config.mva, ssa.Slack.a.
↪v[0] * 180 / pi,
                              ssa.Slack.v.v[0]]],
                             columns=ssa_res_gen.columns,
                             )
ssa_res_gen = pd.concat([ssa_res_gen, ssa_res_slack]).reset_index(drop=True)

# ssp
pp.runpp(ssp)
ssp_res_gen = pd.concat([ssp.gen['name'], ssp.res_gen], axis=1)

res_gen_concat = pd.concat([ssa_res_gen, ssp_res_gen], axis=1)

# ssa
ssa_pf_bus = ssa.Bus.as_df()[["name"]].copy()
ssa_pf_bus['v_andes'] = ssa.Bus.v.v
ssa_pf_bus['a_andes'] = ssa.Bus.a.v * 180 / pi

# ssp
ssp_pf_bus = ssa.Bus.as_df()[["name"]].copy()
ssp_pf_bus['v_pp'] = ssp.res_bus['vm_pu']
ssp_pf_bus['a_pp'] = ssp.res_bus['va_degree']

pf_bus_concat = pd.concat([ssa_pf_bus, ssp_pf_bus], axis=1)
```

Generation

In the table below, the left half are ANDES results, and the right half are from pandapower

```
res_gen_concat.round(4)
```

```
  name      p_mw    q_mvar  va_degree  vm_pu name      p_mw    q_mvar  va_degree ␣
↪\
0    2  40.0000  30.4361    -1.7641   1.03    2  40.0000  30.4361    -1.7641
1    3  40.0000  12.5971    -3.5371   1.01    3  40.0000  12.5971    -3.5371
2    4  30.0000  20.9866    -6.4527   1.03    4  30.0000  20.9866    -6.4527
3    5  35.0000   7.3964    -1.5400   1.03    5  35.0000   7.3964    -1.5400
4    1  81.4272 -21.6171     0.0000   1.03    1  81.4272 -21.6171     0.0000

   vm_pu
0   1.03
1   1.01
2   1.03
3   1.03
4   1.03
```

Bus voltage and angle

Likewise, the left half are ANDES results, and the right half are from pandapower

```
pf_bus_concat.round(4)
```

```
      name  v_andes  a_andes   name    v_pp    a_pp
uid
0     BUS1   1.0300   0.0000   BUS1  1.0300  0.0000
1     BUS2   1.0300  -1.7641   BUS2  1.0300 -1.7641
2     BUS3   1.0100  -3.5371   BUS3  1.0100 -3.5371
3     BUS4   1.0114  -4.4098   BUS4  1.0114 -4.4098
4     BUS5   1.0173  -3.8430   BUS5  1.0173 -3.8430
5     BUS6   1.0300  -6.4527   BUS6  1.0300 -6.4527
6     BUS7   1.0225  -4.8852   BUS7  1.0225 -4.8852
7     BUS8   1.0300  -1.5400   BUS8  1.0300 -1.5400
8     BUS9   1.0218  -7.2459   BUS9  1.0218 -7.2459
9    BUS10   1.0155  -7.4155  BUS10  1.0155 -7.4155
10   BUS11   1.0191  -7.0797  BUS11  1.0191 -7.0797
11   BUS12   1.0174  -7.4730  BUS12  1.0174 -7.4730
12   BUS13   1.0145  -7.7208  BUS13  1.0145 -7.7208
13   BUS14   1.0163  -9.4811  BUS14  1.0163 -9.4811
```

2.12.4 Generator dispatch based on OPF from pandapower

Prepare the link table.

```
# Asign the StaticGen with OPF, in this case, all the SynGen are GENROU
link_table = make_link_table(ssa)
```

```
link_table
```

```
  stg_name stg_u stg_idx bus_idx dg_idx rg_idx rexc_idx   syg_idx   exc_idx  \
0        1   1.0       1       1    NaN    NaN      NaN  GENROU_1  ESST3A_2
1        2   1.0       2       2    NaN    NaN      NaN  GENROU_2   EXST1_1
2        3   1.0       3       3    NaN    NaN      NaN  GENROU_3  ESST3A_3
3        4   1.0       4       6    NaN    NaN      NaN  GENROU_4  ESST3A_4
4        5   1.0       5       8    NaN    NaN      NaN  GENROU_5         1

   gov_idx bus_name gammap gammaq
0  TGOV1_1     BUS1    1.0    1.0
1  TGOV1_2     BUS2    1.0    1.0
2  TGOV1_3     BUS3    1.0    1.0
3  TGOV1_4     BUS6    1.0    1.0
4  TGOV1_5     BUS8    1.0    1.0
```

Note: some Jupyter notebooks may not support inline plots. You can use the following command to enable it.

```
import matplotlib
%matplotlib inline
```

```
import matplotlib
%matplotlib inline
```

Run the TDS in ADNES to 2s.

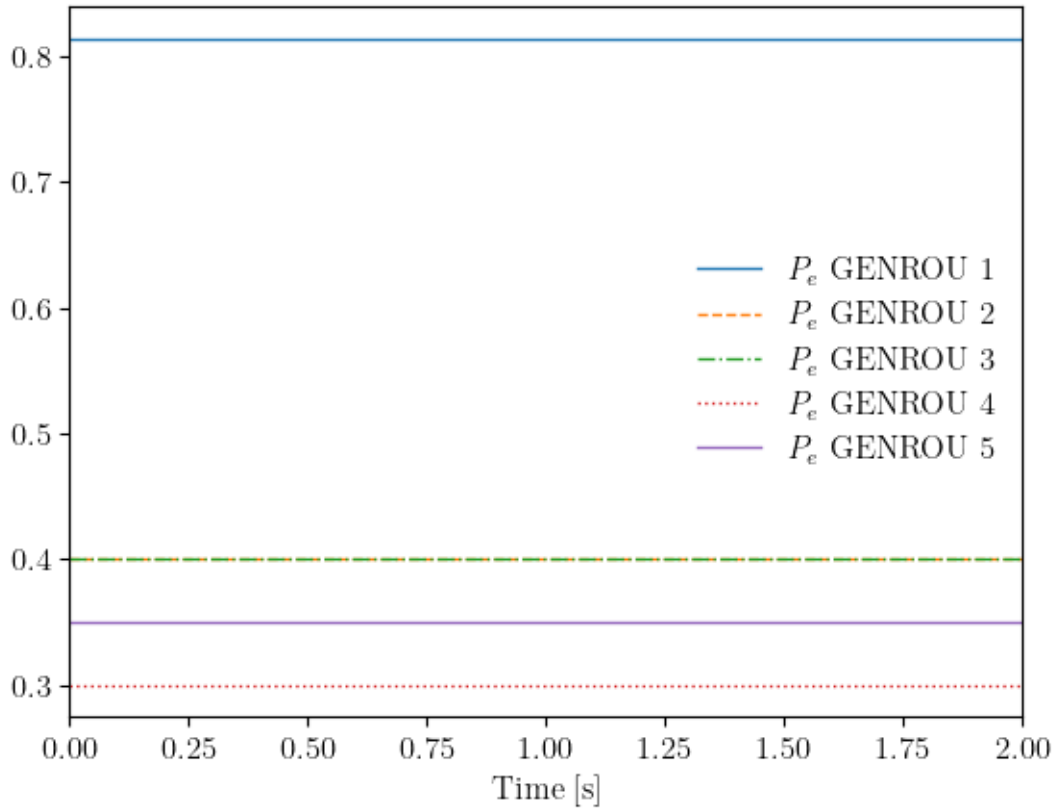
```
ssa.TDS.config.tf = 2
ssa.TDS.run()

ssa.TDS.plt.plot(ssa.GENROU.Pe)
```

```
-> Time Domain Simulation Summary:
Sparse Solver: KLU
Simulation time: 0.0-2 s.
Fixed step size: h=33.33 ms. Shrink if not converged.
Initialization for dynamics completed in 0.1282 seconds.
Initialization was successful.
```

```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
Simulation to t=2.00 sec completed in 0.0623 seconds.
```




```
(<Figure size 640x480 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

Get the OPF results from pandapower. The `ssp_res` has been converted to p.u..

```
ssp_res = runopp_map(ssp, link_table)
ssp_res
```

```
ACOPF is solved.
```

```
  stg_idx         p         q     vm_pu bus_idx  controllable dg_idx rg_idx  \
0       2       0.5  0.129107  1.096903       2          True    NaN    NaN
1       3   0.41275  0.149997  1.082551       3          True    NaN    NaN
2       4   0.34426  0.099998  1.086084       6          True    NaN    NaN
3       5  0.495878  0.085204  1.099996       8          True    NaN    NaN
4       1       0.5 -0.079016  1.100000       1          True    NaN    NaN

    syg_idx  gov_idx   exc_idx
0  GENROU_2  TGOV1_2   EXST1_1
1  GENROU_3  TGOV1_3  ESST3A_3
2  GENROU_4  TGOV1_4  ESST3A_4
3  GENROU_5  TGOV1_5         1
4  GENROU_1  TGOV1_1  ESST3A_2
```

Now dispatch the resutls into `ssa`, where the active power setpoitns are updated to `TurbinGov.pref0`.

```
ssa_gov_idx = list(ssp_res['gov_idx'][~ssp_res['gov_idx'].isna()])
ssa.TurbineGov.set(src='pref0', idx=ssa_gov_idx, attr='v', value=ssp_res['p
↪'][~ssp_res['gov_idx'].isna()])
ssa.TurbineGov.get(src='pref0', idx=ssa_gov_idx, attr='v')
```

```
array([0.49999998, 0.41274963, 0.34426   , 0.49587786, 0.50000031])
```

Now run the TDS to 50s.

```
ssa.TDS.config.tf = 50
ssa.TDS.run()
```

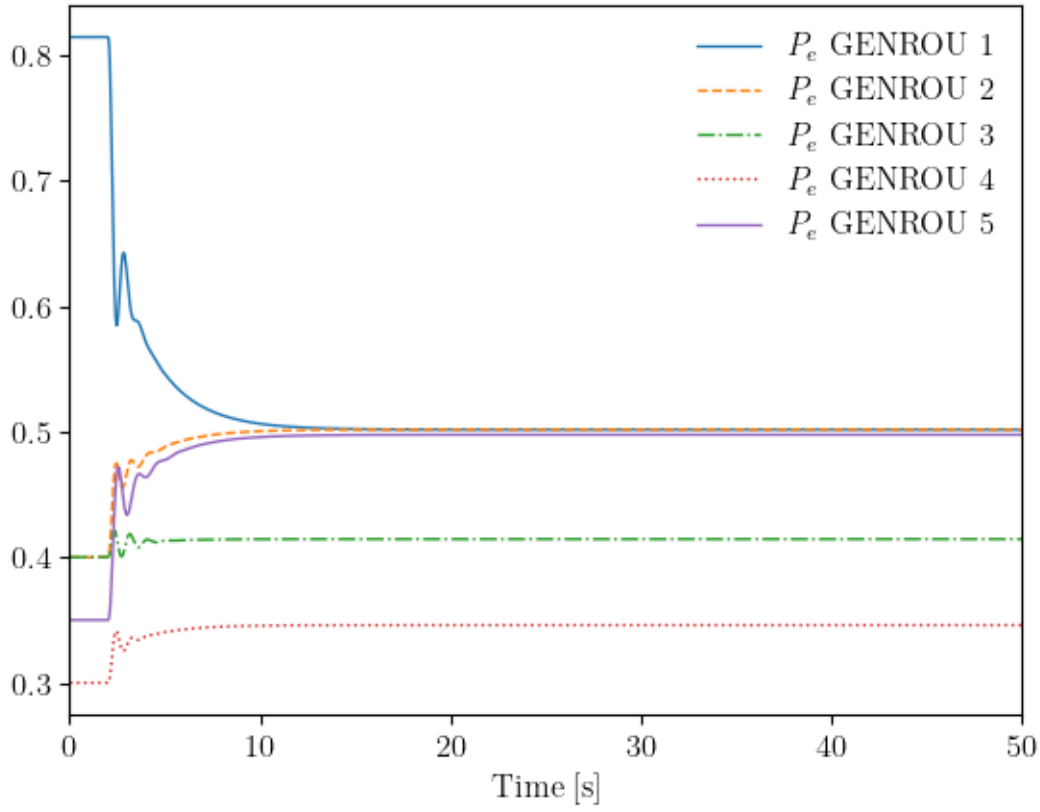
```
  0%|          | 0/100 [00:00<?, ?%/s]
```

```
Simulation to t=50.00 sec completed in 1.9001 seconds.
```

```
True
```

We can see the outputs of `GENROU` are rearranged by the OPF results.

```
ssa.TDS.plt.plot(ssa.GENROU.Pe)
```




```
(<Figure size 640x480 with 1 Axes>, <AxesSubplot:xlabel='Time [s]'>)
```

2.13 pypowsybl Interface

"PowSyBl (Power System Blocks) is an open source framework written in Java, dedicated to electrical grid modelling and simulation, licensed under the Mozilla Public License version 2.0. It is part of LF Energy, an open source foundation focused on the power systems sector, hosted within The Linux Foundation."

`pypowsybl` is the Python interface to PowSybl. For more information, please visit:

https://www.powsybl.org/pages/overview/

ANDES provides a simple interface to `pypowsybl`. The main goal is to leverage `pypowsybl` for drawing single-line diagrams and area diagrams for systems loaded in ANDES.

2.13.1 Imports

```
import andes
import pypowsybl as pp

from andes.interop.pypowsybl import to_pypowsybl
```

```
ss = andes.load(andes.get_case("ieee14/ieee14_linetrip.xlsx"))
```

2.13.2 Conversion

Convert to a pypowsybl network:

```
n = to_pypowsybl(ss)
```

Run power flow in pypowsybl:

```
results = pp.loadflow.run_ac(n)
```

2.13.3 Diagrams

`pypowsybl` provides two functions to draw diagrams:

- `get_network_area_diagram(VOLTAGE_LEVEL_ID = None, DEPTH = 0)`
- `get_single_line_diagram(CONTAINER_ID)`

These function names are self explanatory. To draw the diagram for the whole network, do

```
n.get_network_area_diagram()
```

```
<pypowsybl.network.Svg at 0x7f1f905b33d0>
```

To draw the SLD for bus 6, do

```
n.get_single_line_diagram("VL6")
```

```
<pypowsybl.network.Svg at 0x7f1e879e2760>
```

where `VL6` is the voltage level container created for Bus 6. Voltage level container is named as `VL` + bus `idx`.

To find out how to work with pypowsybl, visit its documentation at https://pypowsybl.readthedocs.io

CHAPTER

THREE

DEVELOPMENT

This chapter contains advanced topics on modeling and simulation and how they are implemented in ANDES. It aims to provide an in-depth explanation of how the ANDES framework is set up for symbolic modeling and numerical simulation. It also provides an example for interested users to implement customized DAE models.

3.1 System

3.1.1 Overview

System is the top-level class for organizing power system models and orchestrating calculations. The full API reference of System is found at *andes.system.System*.

Dynamic Imports

System dynamically imports groups, models, and routines at creation. To add new models, groups or routines, edit the corresponding file by adding entries following examples.

`andes.system.System.`**`import_models`**`(`*`self`*`)`

Import and instantiate models as System member attributes.

Models defined in `models/__init__.py` will be instantiated *sequentially* as attributes with the same name as the class name. In addition, all models will be stored in dictionary `System.models` with model names as keys and the corresponding instances as values.

Examples

`system.Bus` stores the *Bus* object, and `system.GENCLS` stores the classical generator object,

`system.models['Bus']` points the same instance as `system.Bus`.

`andes.system.System.`**`import_groups`**`(`*`self`*`)`

Import all groups classes defined in `models/group.py`.

Groups will be stored as instances with the name as class names. All groups will be stored to dictionary `System.groups`.

andes.system.System.**import_routines**(*self*)

Import routines as defined in `routines/__init__.py`.

Routines will be stored as instances with the name as class names. All routines will be stored to dictionary `System.routines`.

Examples

`System.PFlow` is the power flow routine instance, and `System.TDS` and `System.EIG` are time-domain analysis and eigenvalue analysis routines, respectively.

Code Generation

Under the hood, all models whose equations are provided in strings need be processed to generate executable functions for simulations. We call this process "code generation". Code generation utilizes SymPy, a symbolic toolbox, and can take up to one minute.

Code generation is automatically triggered upon the first ANDES run or whenever model changes are detected. Code generation only needs to run once unless the generated code is removed or model edits are detected. The generated code is then stored and reused for speed up.

The generated Python code is called `pycode`. It is a Python package (folder) with each module (a *.py* file) storing the executable Python code and metadata for numerical simulation. The default path to store `pycode` is `HOME_DIR/.andes`, where `HOME_DIR` is one's home directory.

Note: Code generation has been done if one has executed `andes`, `andes selftest`, or `andes prepare`.

Warning: For developers: when models are modified (such as adding new models or changing equation strings), code generation needs to be executed again for consistency. ANDES can automatically detect changes, and it can be manually triggered from command line using `andes prepare -i`.

andes.system.System.**prepare**(*self*, *quick=False*, *incremental=False*, *models=None*, *nomp=False*, *ncpu=1*)

Generate numerical functions from symbolically defined models.

All procedures in this function must be independent of test case.

Parameters

quick
[bool, optional] True to skip pretty-print generation to reduce code generation time.

incremental
[bool, optional] True to generate only for modified models, incrementally.

models
[list, OrderedDict, None] List or OrderedList of models to prepare

nomp
[bool] True to disable multiprocessing

> **Warning:** Generated lambda functions will be serialized to file, but pretty prints (SymPy objects) can only exist in the System instance on which prepare is called.

Notes

Option `incremental` compares the md5 checksum of all var and service strings, and only regenerate for updated models.

Examples

If one needs to print out LaTeX-formatted equations in a Jupyter Notebook, one need to generate such equations with

```
import andes
sys = andes.prepare()
```

Alternatively, one can explicitly create a System and generate the code

```
import andes
sys = andes.System()
sys.prepare()
```

`andes.system.System.`**`undill`**(*self*, *autogen_stale=True*)

Reload generated function functions, from either the `$HOME/.andes/pycode` folder.

If no change is made to models, future calls to `prepare()` can be replaced with `undill()` for acceleration.

Parameters

autogen_stale: bool
True to automatically call code generation if stale code is detected. Regardless of this option, codegen is trigger if importing existing code fails.

3.1.2 DAE Storage

`System.dae` is an instance of the numerical DAE class.

`andes.variables.dae.`**`DAE`**(*system*)

Class for storing numerical values of the DAE system, including variables, equations and first order derivatives (Jacobian matrices).

Variable values and equation values are stored as `numpy.ndarray`, while Jacobians are stored as `kvxopt.spmatrix`. The defined arrays and descriptions are as follows:

DAE Array	Description
x	Array for state variable values
y	Array for algebraic variable values
z	Array for 0/1 limiter states (if enabled)
f	Array for differential equation derivatives
Tf	Left-hand side time constant array for f
g	Array for algebraic equation mismatches

The defined scalar member attributes to store array sizes are

Scalar	Description
m	The number of algebraic variables/equations
n	The number of algebraic variables/equations
o	The number of limiter state flags

The derivatives of f and g with respect to x and y are stored in four `kvxopt.spmatrix` sparse matrices: **fx**, **fy**, **gx**, and **gy**, where the first letter is the equation name, and the second letter is the variable name.

Notes

DAE in ANDES is defined in the form of

$$T\dot{x} = f(x, y)$$
$$0 = g(x, y)$$

DAE does not keep track of the association of variable and address. Only a variable instance keeps track of its addresses.

3.1.3 Model and DAE Values

ANDES uses a decentralized architecture between models and DAE value arrays. In this architecture, variables are initialized and equations are evaluated inside each model. Then, `System` provides methods for collecting initial values and equation values into `DAE`, as well as copying solved values to each model.

The collection of values from models needs to follow protocols to avoid conflicts. Details are given in the subsection Variables.

`andes.system.System.`**`vars_to_dae`**(*self*, *model*)

Copy variables values from models to *System.dae*.

This function clears *DAE.x* and *DAE.y* and collects values from models.

`andes.system.System.`**`vars_to_models`**(*self*)

Copy variable values from *System.dae* to models.

`andes.system.System.`**`_e_to_dae`**(*self*, *eq_name: str | Tuple = ('f', 'g')*)

Helper function for collecting equation values into *System.dae.f* and *System.dae.g*.

Parameters

eq_name
['x' or 'y' or tuple] Equation type name

Matrix Sparsity Patterns

The largest overhead in building and solving nonlinear equations is the building of Jacobian matrices. This is especially relevant when we use the implicit integration approach which algebraized the differential equations. Given the unique data structure of power system models, the sparse matrices for Jacobians are built **incrementally**, model after model.

There are two common approaches to incrementally build a sparse matrix. The first one is to use simple in-place add on sparse matrices, such as doing

```
self.fx += spmatrix(v, i, j, (n, n), 'd')
```

Although the implementation is simple, it involves creating and discarding temporary objects on the right hand side and, even worse, changing the sparse pattern of `self.fx`.

The second approach is to store the rows, columns and values in an array-like object and construct the Jacobians at the end. This approach is very efficient but has one caveat: it does not allow accessing the sparse matrix while building.

ANDES uses a pre-allocation approach to avoid the change of sparse patterns by filling values into a known the sparse matrix pattern matrix. System collects the indices of rows and columns for each Jacobian matrix. Before in-place additions, ANDES builds a temporary zero-filled *spmatrix*, to which the actual Jacobian values are written later. Since these in-place add operations are only modifying existing values, it does not change the pattern and thus avoids memory copying. In addition, updating sparse matrices can be done with the exact same code as the first approach.

Still, this approach creates and discards temporary objects. It is however feasible to write a C function which takes three array-likes and modify the sparse matrices in place. This is feature to be developed, and our prototype shows a promising acceleration up to 50%.

`andes.system.System.`**`store_sparse_pattern`**(*self*, *models: OrderedDict*)

Collect and store the sparsity pattern of Jacobian matrices.

This is a runtime function specific to cases.

Notes

For *gy* matrix, always make sure the diagonal is reserved. It is a safeguard if the modeling user omitted the diagonal term in the equations.

3.1.4 Calling Model Methods

System is an orchestrator for calling shared methods of models. These API methods are defined for initialization, equation update, Jacobian update, and discrete flags update.

The following methods take an argument *models*, which should be an *OrderedDict* of models with names as keys and instances as values.

`andes.system.System.`**`init`**(*self*, *models: OrderedDict*, *routine: str*)

Initialize the variables for each of the specified models.

For each model, the initialization procedure is:

- Get values for all *ExtService*.
- Call the model *init()* method, which initializes internal variables.
- Copy variables to DAE and then back to the model.

`andes.system.System.`**`e_clear`**(*self*, *models: OrderedDict*)

Clear equation arrays in DAE and model variables.

This step must be called before calling *f_update* or *g_update* to flush existing values.

`andes.system.System.`**`l_update_var`**(*self*, *models: OrderedDict*, *niter=0*, *err=None*)

Update variable-based limiter discrete states by calling `l_update_var` of models.

This function is must be called before any equation evaluation.

`andes.system.System.`**`f_update`**(*self*, *models: OrderedDict*)

Call the differential equation update method for models in sequence.

Notes

Updated equation values remain in models and have not been collected into DAE at the end of this step.

andes.system.System.**l_update_eq**(*self*, *models: OrderedDict*, *init=False*, *niter=0*)

Update equation-dependent limiter discrete components by calling `l_check_eq` of models. Force set equations after evaluating equations.

This function is must be called after differential equation updates.

andes.system.System.**g_update**(*self*, *models: OrderedDict*)

Call the algebraic equation update method for models in sequence.

Notes

Like *f_update*, updated values have not collected into DAE at the end of the step.

andes.system.System.**j_update**(*self*, *models: OrderedDict*, *info=None*)

Call the Jacobian update method for models in sequence.

The procedure is - Restore the sparsity pattern with *andes.variables.dae.DAE.restore_sparse()* - For each sparse matrix in (fx, fy, gx, gy), evaluate the Jacobian function calls and add values.

Notes

Updated Jacobians are immediately reflected in the DAE sparse matrices (fx, fy, gx, gy).

3.1.5 Configuration

System, models and routines have a member attribute *config* for model-specific or routine-specific configurations. System manages all configs, including saving to a config file and loading back.

andes.system.System.**save_config**(*self*, *file_path=None*, *overwrite=False*)

Save all system, model, and routine configurations to an rc-formatted file.

Parameters

file_path
[str, optional] path to the configuration file default to *~/andes/andes.rc*.

overwrite
[bool, optional] If file exists, True to overwrite without confirmation. Otherwise prompt for confirmation.

Warning: Saved config is loaded back and populated *at system instance creation time*. Configs from the config file takes precedence over default config values.

Warning: It is important to note that configs from files is passed to *model constructors* during instantiation. If one needs to modify config for a run, it needs to be done before instantiating `System`, or before running `andes` from command line. Directly modifying `Model.config` may not take effect or have side effect as for the current implementation.

3.2 Group

A group is a collection of similar functional models with common variables and parameters. It is mandatory to enforce the common variables and parameters when develop new models. The common variables and parameters are typically the interface when connecting different group models.

For example, the Group *RenGen* has variables *Pe* and *Qe*, which are active power output and reactive power output. Such common variables can be retrieved by other models, such as one in the Group *RenExciter* for further calculation.

In such a way, the same variable interface is realized so that all model in the same group could carry out similar function.

GroupBase()	Base class for groups.

3.2.1 andes.models.group.GroupBase

class andes.models.group.**GroupBase**

Base class for groups.

__init__()

Methods

add(idx, model)	Register an idx from model_name to the group
add_model(name, instance)	Add a Model instance to group.
doc([export])	Return the documentation of the group in a string.
doc_all([export])	Return documentation of the group and its models.
find_idx(keys, values[, allow_none, default])	Find indices of devices that satisfy the given *key*=*value* condition.
get(src, idx[, attr, allow_none, default])	Based on the indexer, get the *attr* field of the *src* parameter or variable.
get_field(src, idx, field)	Helper function for retrieving an attribute of a member variable shared by models in this group.
get_next_idx([idx, model_name])	Get a no-conflict idx for a new device.
idx2model(idx[, allow_none])	Find model name for the given idx.
idx2uid(idx)	Convert idx to the 0-indexed unique index.
set(src, idx, attr, value)	Set the value of an attribute of a group property.
set_backref(name, from_idx, to_idx)	Set idxes to `BackRef`, and set them to models.

GroupBase.add

`GroupBase.`**`add`**(*idx*, *model*)

Register an idx from model_name to the group

Parameters

idx: Union[str, float, int]
Register an element to a model

model: Model
instance of the model

Returns

GroupBase.add_model

`GroupBase.`**`add_model`**(*name: str*, *instance*)

Add a Model instance to group.

Parameters

name
[str] Model name

instance
[Model] Model instance

Returns

None

GroupBase.doc

`GroupBase.`**`doc`**(*export='plain'*)

Return the documentation of the group in a string.

GroupBase.doc_all

`GroupBase.`**`doc_all`**(*export='plain'*)

Return documentation of the group and its models.

Parameters

export
['plain' or 'rest'] Export format, plain-text or RestructuredText

Returns

str

GroupBase.find_idx

`GroupBase.`**`find_idx`**(*keys*, *values*, *allow_none=False*, *default=None*)

Find indices of devices that satisfy the given *key=value* condition.

This method iterates over all models in this group.

GroupBase.get

`GroupBase.`**`get`**(*src: str*, *idx*, *attr: str = 'v'*, *allow_none=False*, *default=0.0*)

Based on the indexer, get the *attr* field of the *src* parameter or variable.

Parameters

src
[str] param or var name

idx
[array-like] device idx

attr
The attribute of the param or var to retrieve

allow_none
[bool] True to allow None values in the indexer

default
[float] If *allow_none* is true, the default value to use for None indexer.

Returns

The requested param or variable attribute. If *idx* is a list, return a list of values.
If *idx* is a single element, return a single value.

GroupBase.get_field

`GroupBase.`**`get_field`**(*src: str*, *idx*, *field: str*)

Helper function for retrieving an attribute of a member variable shared by models in this group.

Returns

list
A list with the length equal to `len(idx)`.

GroupBase.get_next_idx

`GroupBase.`**`get_next_idx`**(*idx=None*, *model_name=None*)

Get a no-conflict idx for a new device. Use the provided `idx` if no conflict. Generate a new one otherwise.

Parameters

idx
[str or None] Proposed idx. If None, assign a new one.

model_name
[str or None] Model name. If not, prepend the group name.

Returns

str
New device name.

GroupBase.idx2model

`GroupBase.`**`idx2model`**(*idx*, *allow_none=False*)

Find model name for the given idx.

Parameters

idx
[float, int, str, array-like] idx or idx-es of devices.

allow_none
[bool] If True, return *None* at the positions where idx is not found.

Returns

If *idx* is a list, return a list of model instances.
If *idx* is a single element, return a model instance.

GroupBase.idx2uid

`GroupBase.`**`idx2uid`**(*idx*)

Convert idx to the 0-indexed unique index.

Parameters

idx
[array-like, numbers, or str] idx of devices

Returns

list
A list containing the unique indices of the devices

GroupBase.set

`GroupBase.`**`set`**(*src: str*, *idx*, *attr*, *value*)

Set the value of an attribute of a group property. Performs `self.<src>.<attr>[idx] = value`.

The user needs to ensure that the property is shared by all models in this group.

Parameters

src
[str] Name of property.

idx
[str, int, float, array-like] Indices of devices.

attr
[str, optional, default='v'] The internal attribute of the property to get. `v` for values, `a` for address, and `e` for equation value.

value
[array-like] New values to be set

Returns

bool
True when successful.

GroupBase.set_backref

GroupBase.**set_backref**(*name*, *from_idx*, *to_idx*)

Set idxes to BackRef, and set them to models.

Attributes

class_name	
n	Total number of devices.

GroupBase.class_name

property GroupBase.**class_name**

GroupBase.n

property GroupBase.**n**

Total number of devices.

3.3 Models

This section introduces the modeling of power system devices. The terminology "model" is used to describe the mathematical representation of a *type* of device, such as synchronous generators or turbine governors. The terminology "device" is used to describe a particular instance of a model, for example, a specific generator.

To define a model in ANDES, two classes, ModelData and Model need to be utilized. Class ModelData is used for defining parameters that will be provided from input files. It provides API for adding data from devices and managing the data. Class Model is used for defining other non-input parameters, service variables, and DAE variables. It provides API for converting symbolic equations, storing Jacobian patterns, and updating equations.

The following classes are related to models:

ModelData(*args[, three_params])	Class for holding parameter data for a model.
Model([system, config])	Base class for power system DAE models.
ModelCache()	Class for caching the return value of callback functions.
ModelCall()	Class for storing generated function calls, Jacobian calls, and arguments.

3.3.1 andes.core.model.ModelData

class andes.core.model.**ModelData**(**args*, *three_params=True*, ***kwargs*)

Class for holding parameter data for a model.

This class is designed to hold the parameter data separately from model equations. Models should inherit this class to define the parameters from input files.

Inherit this class to create the specific class for holding input parameters for a new model. The recommended name for the derived class is the model name with `Data`. For example, data for *GENROU* should be named *GENROUData*.

Parameters should be defined in the `__init__` function of the derived class.

Refer to `andes.core.param` for available parameter types.

Notes

Three default parameters are pre-defined in `ModelData` and will be inherited by all models. They are

- `idx`, unique device idx of type *andes.core.param.DataParam*
- `u`, connection status of type *andes.core.param.NumParam*
- `name`, (device name of type *andes.core.param.DataParam*

In rare cases one does not want to define these three parameters, one can pass *three_params=True* to the constructor of `ModelData`.

Examples

If we want to build a class `PQData` (for static PQ load) with three parameters, *Vn*, *p0* and *q0*, we can use the following

```
from andes.core.model import ModelData, Model
from andes.core.param import IdxParam, NumParam

class PQData(ModelData):
    super().__init__()
    self.Vn = NumParam(default=110,
                       info="AC voltage rating",
                       unit='kV', non_zero=True,
                       tex_name=r'V_n')
    self.p0 = NumParam(default=0,
                       info='active power load in system base',
                       tex_name=r'p_0', unit='p.u.')
    self.q0 = NumParam(default=0,
                       info='reactive power load in system base',
                       tex_name=r'q_0', unit='p.u.')
```

In this example, all the three parameters are defined as *andes.core.param.NumParam*. In the full *PQData* class, other types of parameters also exist. For example, to store the idx of *owner*, *PQData* uses

```
self.owner = IdxParam(model='Owner', info="owner idx")
```

Attributes

cache
A cache instance for different views of the internal data.

flags
[dict] Flags to control the routine and functions that get called. If the model is using user-defined numerical calls, set *f_num*, *g_num* and *j_num* properly.

__init__(**args*, *three_params=True*, ***kwargs*)

Methods

add(**kwargs)	Add a device (an instance) to this model.
as_df([vin])	Export all parameters as a *pandas.DataFrame* object.
as_df_local()	Export local variable values and services to a DataFrame.
as_dict([vin])	Export all parameters as a dict.
find_idx(keys, values[, allow_none, default])	Find *idx* of devices whose values match the given pattern.
find_param(prop)	Find params with the given property and return in an OrderedDict.
update_from_df(df[, vin])	Update parameter values from a DataFrame.

ModelData.add

ModelData.**add**(***kwargs*)

Add a device (an instance) to this model.

Parameters

kwargs
model parameters are collected into the kwargs dictionary

Warning: This function is not intended to be used directly. Use the `add` method from System so that the index can be registered correctly.

ModelData.as_df

ModelData.**as_df**(*vin=False*)

Export all parameters as a *pandas.DataFrame* object. This function utilizes *as_dict* for preparing data.

Returns

DataFrame
A dataframe containing all model data. An *uid* column is added.

vin
[bool] If True, export all parameters from original input (`vin`).

ModelData.as_df_local

ModelData.**as_df_local**()

Export local variable values and services to a DataFrame.

ModelData.as_dict

ModelData.**as_dict**(*vin=False*)

Export all parameters as a dict.

Returns

dict
a dict with the keys being the *ModelData* parameter names and the values being an array-like of data in the order of adding. An additional *uid* key is added with the value default to range(n).

ModelData.find_idx

ModelData.**find_idx**(*keys*, *values*, *allow_none=False*, *default=False*)

Find *idx* of devices whose values match the given pattern.

Parameters

keys
[str, array-like, Sized] A string or an array-like of strings containing the names of parameters for the search criteria

values
[array, array of arrays, Sized] Values for the corresponding key to search for. If keys is a str, values should be an array of elements. If keys is a list, values should be an array of arrays, each corresponds to the key.

allow_none
[bool, Sized] Allow key, value to be not found. Used by groups.

default
[bool] Default idx to return if not found (missing)

Returns

list
indices of devices

ModelData.find_param

`ModelData.`**`find_param`**(*prop*)

Find params with the given property and return in an OrderedDict.

Parameters

prop
[str] Property name

Returns

OrderedDict

ModelData.update_from_df

`ModelData.`**`update_from_df`**(*df*, *vin=False*)

Update parameter values from a DataFrame.

Adding devices are not allowed.

3.3.2 andes.core.model.Model

`class` `andes.core.model.`**`Model`**(*system=None*, *config=None*)

Base class for power system DAE models.

After subclassing *ModelData*, subclass *Model*` to complete a DAE model. Subclasses of *Model* define DAE variables, services, and other types of parameters, in the constructor `__init__`.

Examples

Take the static PQ as an example, the subclass of *Model*, *PQ*, should look like

```
class PQ(PQData, Model):
    def __init__(self, system, config):
        PQData.__init__(self) Model.__init__(self, system, config)
```

Since *PQ* is calling the base class constructors, it is meant to be the final class and not further derived. It inherits from *PQData* and *Model* and must call constructors in the order of *PQData* and *Model*. If the derived class of *Model* needs to be further derived, it should only derive from *Model* and use a name ending with *Base*. See `andes.models.synchronous.genbase.GENBase`.

Next, in *PQ.__init__*, set proper flags to indicate the routines in which the model will be used

```
self.flags.update({'pflow': True})
```

Currently, flags *pflow* and *tds* are supported. Both are *False* by default, meaning the model is neither used in power flow nor in time-domain simulation. **A very common pitfall is forgetting to set the flag**.

Next, the group name can be provided. A group is a collection of models with common parameters and variables. Devices' idx of all models in the same group must be unique. To provide a group name, use

```
self.group = 'StaticLoad'
```

The group name must be an existing class name in `andes.models.group`. The model will be added to the specified group and subject to the variable and parameter policy of the group. If not provided with a group class name, the model will be placed in the *Undefined* group.

Next, additional configuration flags can be added. Configuration flags for models are load-time variables, specifying the behavior of a model. They can be exported to an *andes.rc* file and automatically loaded when creating the *System*. Configuration flags can be used in equation strings, as long as they are numerical values. To add config flags, use

```
self.config.add(OrderedDict((('pq2z', 1), )))
```

It is recommended to use *OrderedDict* instead of *dict*, although the syntax is verbose. Note that booleans should be provided as integers (1 or 0), since *True* or *False* is interpreted as a string when loaded from the *rc* file and will cause an error.

Next, it's time for variables and equations! The *PQ* class does not have internal variables itself. It uses its *bus* parameter to fetch the corresponding *a* and *v* variables of buses. Equation wise, it imposes an active power and a reactive power load equation.

To define external variables from *Bus*, use

```
self.a = ExtAlgeb(model='Bus', src='a',
                  indexer=self.bus, tex_name=r'\theta')
self.v = ExtAlgeb(model='Bus', src='v',
                  indexer=self.bus, tex_name=r'V')
```

Refer to the subsection Variables for more details.

The simplest *PQ* model will impose constant P and Q, coded as

```
self.a.e_str = "u * p"
self.v.e_str = "u * q"
```

where the *e_str* attribute is the equation string attribute. *u* is the connectivity status. Any parameter, config, service or variable can be used in equation strings.

Three additional scalars can be used in equations: - `dae_t` for the current simulation time (can be used if the model has flag *tds*). - `sys_f` for system frequency (from `system.config.freq`). - `sys_mva` for system base mva (from `system.config.mva`).

The above example is overly simplified. Our *PQ* model wants a feature to switch itself to a constant impedance if the voltage is out of the range *(vmin, vmax)*. To implement this, we need to introduce

a discrete component called *Limiter*, which yields three arrays of binary flags, *zi*, *zl*, and *zu* indicating in-range, below lower-limit, and above upper-limit, respectively.

First, create an attribute *vcmp* as a *Limiter* instance

```
self.vcmp = Limiter(u=self.v, lower=self.vmin, upper=self.vmax,
                    enable=self.config.pq2z)
```

where *self.config.pq2z* is a flag to turn this feature on or off. After this line, we can use *vcmp_zi*, *vcmp_zl*, and *vcmp_zu* in other equation strings.

```
self.a.e_str = "u * (p0 * vcmp_zi + " \
               "p0 * vcmp_zl * (v ** 2 / vmin ** 2) + " \
               "p0 * vcmp_zu * (v ** 2 / vmax ** 2))"

self.v.e_str = "u * (q0 * vcmp_zi + " \
               "q0 * vcmp_zl * (v ** 2 / vmin ** 2) + "\
               "q0 * vcmp_zu * (v ** 2 / vmax ** 2))"
```

Note that *PQ.a.e_str* can use the three variables from *vcmp* even before defining *PQ.vcmp*, as long as *PQ.vcmp* is defined, because *vcmp_zi* is just a string literal in *e_str*.

The two equations above implement a piece-wise power injection equation. It selects the original power demand if within range, and uses the calculated power when out of range.

Finally, to let ANDES pick up the model, the model name needs to be added to *models/__init__.py*. Follow the examples in the *OrderedDict*, where the key is the file name, and the value is the class name.

Attributes

num_params
[OrderedDict] {name: instance} of numerical parameters, including internal and external ones

__init__(*system=None*, *config=None*)

Methods

a_reset()	Reset addresses to empty and reset flags.address to `False`.
alter(src, idx, value)	Alter values of input parameters or constant service.
doc([max_width, export])	Retrieve model documentation as a string.
e_clear()	Clear equation value arrays associated with all internal variables.
externalize()	Externalize internal data as a snapshot.
f_numeric(**kwargs)	Custom fcall functions.
f_update()	Evaluate differential equations.
g_numeric(**kwargs)	Custom gcall functions.

continues on next page

Table 1 – continued from previous page

g_update()	Evaluate algebraic equations.
get(src, idx[, attr, allow_none, default])	Get the value of an attribute of a model property.
get_init_order()	Get variable initialization order and send to *logger.info*.
get_inputs([refresh])	Get an OrderedDict of the inputs to the numerical function calls.
get_md5()	Return the md5 hash of concatenated equation strings.
get_times()	Get event switch_times from *TimerParam*.
idx2uid(idx)	Convert idx to the 0-indexed unique index.
init(routine)	Numerical initialization of a model.
internalize()	Internalize snapshot data.
j_numeric(**kwargs)	Custom numeric update functions.
j_update()	Update Jacobian elements.
l_check_eq([init, niter])	Call the `check_eq` method of discrete components to update equation-dependent flags.
l_update_var(dae_t, *args[, niter, err])	Call the `check_var` method of discrete components to update the internal status flags.
list2array()	Convert all the value attributes `v` to NumPy arrays.
mock_refresh_inputs()	Use mock data to fill the inputs.
numba_jitify([parallel, cache, nopython])	Convert equation residual calls, Jacobian calls, and variable service calls into JIT compiled functions.
post_init_check()	Post init checking.
precompile()	Trigger numba compilation for this model.
prepare([quick, pycode_path, yapf_pycode])	Symbolic processing and code generation.
refresh_inputs()	This is the helper function to refresh inputs.
refresh_inputs_arg()	Refresh inputs for each function with individual argument list.
register_debug_equation(var_name)	Helper function to register a variable for debugging the initialization.
s_numeric(**kwargs)	Custom service value functions.
s_numeric_var(**kwargs)	Custom variable service value functions.
s_update()	Update service equation values.
s_update_post()	Update post-initialization services.
s_update_var()	Update values of `andes.core.service.VarService`.
set(src, idx, attr, value)	Set the value of an attribute of a model property.
set_backref(name, from_idx, to_idx)	Helper function for setting idx-es to `BackRef`.
set_in_use()	Set the *in_use* attribute.
solve_iter(name, kwargs)	Solve iterative initialization.
solve_iter_single(name, inputs, pos)	Solve iterative initialization for one given device.
store_sparse_pattern()	Store rows and columns of the non-zeros in the Jacobians for building the sparsity pattern.

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Table 1 – continued from previous page

switch_action(dae_t)	Call the switch actions.
v_numeric(**kwargs)	Custom variable initialization function.

Model.a_reset

Model.**a_reset**()

Reset addresses to empty and reset flags.address to False.

Model.alter

Model.**alter**(*src*, *idx*, *value*)

Alter values of input parameters or constant service.

If the method operates on an input parameter, the new data should be in the same base as that in the input file. This function will convert value to per unit in the system base whenever necessary.

The values for storing the input data, i.e., the parameter's vin field, will be overwritten. As a result, altered values will be reflected in the dumped case file.

Parameters

src
[str] The parameter name to alter

idx
[str, float, int] The device to alter

value
[float] The desired value

Model.doc

Model.**doc**(*max_width=78*, *export='plain'*)

Retrieve model documentation as a string.

Model.e_clear

Model.**e_clear**()

Clear equation value arrays associated with all internal variables.

Model.externalize

`Model.externalize()`

Externalize internal data as a snapshot.

Model.f_numeric

`Model.f_numeric(**kwargs)`

Custom fcall functions. Modify equations directly.

Model.f_update

`Model.f_update()`

Evaluate differential equations.

Notes

In-place equations: added to the corresponding DAE array. Non-in-place equations: in-place set to internal array to overwrite old values (and avoid clearing).

Model.g_numeric

`Model.g_numeric(**kwargs)`

Custom gcall functions. Modify equations directly.

Model.g_update

`Model.g_update()`

Evaluate algebraic equations.

Model.get

`Model.get(src: str, idx, attr: str = 'v', allow_none=False, default=0.0)`

Get the value of an attribute of a model property.

The return value is `self.<src>.<attr>[idx]`

Parameters

src
[str] Name of the model property

idx
[str, int, float, array-like] Indices of the devices

attr
[str, optional, default='v'] The attribute of the property to get. `v` for values, `a` for address, and `e` for equation value.

allow_none
[bool] True to allow None values in the indexer

default
[float] If *allow_none* is true, the default value to use for None indexer.

Returns

array-like
`self.<src>.<attr>[idx]`

Model.get_init_order

`Model.`**`get_init_order`**`()`

Get variable initialization order and send to *logger.info*.

Model.get_inputs

`Model.`**`get_inputs`**`(`*refresh=False*`)`

Get an OrderedDict of the inputs to the numerical function calls.

Parameters

refresh
[bool] Refresh the values in the dictionary. This is only used when the memory addresses of arrays change. After initialization, all array assignments are in place. To avoid overhead, refresh should not be used after initialization.

Returns

OrderedDict
The input name and value array pairs in an OrderedDict

Notes

dae.t is now a numpy.ndarray which has stable memory. There is no need to refresh *dat_t* in this version.

Model.get_md5

Model.**get_md5**()

Return the md5 hash of concatenated equation strings.

Model.get_times

Model.**get_times**()

Get event switch_times from *TimerParam*.

Returns

list
A list containing all switching times defined in TimerParams

Model.idx2uid

Model.**idx2uid**(*idx*)

Convert idx to the 0-indexed unique index.

Parameters

idx
[array-like, numbers, or str] idx of devices

Returns

list
A list containing the unique indices of the devices

Model.init

Model.**init**(*routine*)

Numerical initialization of a model.

Initialization sequence: 1. Sequential initialization based on the order of definition 2. Use Newton-Krylov method for iterative initialization 3. Custom init

Model.internalize

Model.**internalize**()

Internalize snapshot data.

Model.j_numeric

`Model.`**`j_numeric`**`(**kwargs)`

Custom numeric update functions.

This function should append indices to *_ifx*, *_jfx*, and append anonymous functions to *_vfx*. It is only called once by *store_sparse_pattern*.

Model.j_update

`Model.`**`j_update`**`()`

Update Jacobian elements.

Values are stored to `Model.triplets[jname]`, where `jname` is a jacobian name.

Returns

None

Model.l_check_eq

`Model.`**`l_check_eq`**`(init=False, niter=0, **kwargs)`

Call the `check_eq` method of discrete components to update equation-dependent flags.

This function should be called after equation updates. AntiWindup limiters use it to append pegged states to the `x_set` list.

Returns

None

Model.l_update_var

`Model.`**`l_update_var`**`(dae_t, *args, niter=None, err=None, **kwargs)`

Call the `check_var` method of discrete components to update the internal status flags.

The function is variable-dependent and should be called before updating equations.

Returns

None

Model.list2array

`Model.`**`list2array`**`()`

Convert all the value attributes `v` to NumPy arrays.

Value attribute arrays should remain in the same address afterwards. Namely, all assignments to value array should be operated in place (e.g., with [:]).

Model.mock_refresh_inputs

`Model.`**`mock_refresh_inputs`**`()`

Use mock data to fill the inputs.

This function is used to generate input data of the desired type to trigger JIT compilation.

Model.numba_jitify

`Model.`**`numba_jitify`**`(`*parallel=False*, *cache=True*, *nopython=True*`)`

Convert equation residual calls, Jacobian calls, and variable service calls into JIT compiled functions.

This function can be enabled by setting `System.config.numba = 1`.

Model.post_init_check

`Model.`**`post_init_check`**`()`

Post init checking. Warns if values of *InitChecker* are not True.

Model.precompile

`Model.`**`precompile`**`()`

Trigger numba compilation for this model.

This function requires the system to be setup, i.e., memory allocated for storage.

Model.prepare

`Model.`**`prepare`**`(`*quick=False*, *pycode_path=None*, *yapf_pycode=False*`)`

Symbolic processing and code generation.

Model.refresh_inputs

`Model.`**`refresh_inputs`**`()`

This is the helper function to refresh inputs.

The functions collects object references into `OrderedDict` *self._input* and *self._input_z*.

Returns

None

Model.refresh_inputs_arg

`Model.`**`refresh_inputs_arg`**`()`

Refresh inputs for each function with individual argument list.

Model.register_debug_equation

`Model.`**`register_debug_equation`**`(`*var_name*`)`

Helper function to register a variable for debugging the initialization.

This function needs to be called before calling `TDS.init()`, and logging level needs to be set to `DEBUG`.

Model.s_numeric

`Model.`**`s_numeric`**`(`***kwargs*`)`

Custom service value functions. Modify `Service.v` directly.

Model.s_numeric_var

`Model.`**`s_numeric_var`**`(`***kwargs*`)`

Custom variable service value functions. Modify `VarService.v` directly.

This custom numerical function is evaluated at each step/iteration before equation update.

Model.s_update

`Model.`**`s_update`**`()`

Update service equation values.

This function is only evaluated at initialization. Service values are updated sequentially. The `v` attribute of services will be assigned at a new memory address.

Model.s_update_post

`Model.`**`s_update_post`**`()`

Update post-initialization services.

Model.s_update_var

`Model.`**`s_update_var`**`()`

Update values of `andes.core.service.VarService`.

Model.set

`Model.`**`set`**`(`*src*, *idx*, *attr*, *value*`)`

Set the value of an attribute of a model property.

Performs `self.<src>.<attr>[idx] = value`. This method will not modify the input values from the case file that have not been converted to the system base. As a result, changes applied by this method will not affect the dumped case file.

To alter parameters and reflect it in the case file, use *`alter()`* instead.

Parameters

src
[str] Name of the model property

idx
[str, int, float, array-like] Indices of the devices

attr
[str, optional, default='v'] The internal attribute of the property to get. `v` for values, `a` for address, and `e` for equation value.

value
[array-like] New values to be set

Returns

bool
True when successful.

Model.set_backref

`Model.`**`set_backref`**`(`*name*, *from_idx*, *to_idx*`)`

Helper function for setting idx-es to `BackRef`.

Model.set_in_use

`Model.`**`set_in_use`**`()`

Set the *in_use* attribute. Called at the end of `System.collect_ref`.

This function is overloaded by models with *BackRef* to disable calls when no model is referencing. Models with no back references will have internal variable addresses assigned but external addresses being empty.

For internal equations that have external variables, the row indices will be non-zeros, while the col indices will be empty, which causes an error when updating Jacobians.

Setting *self.in_use* to False when *len(back_ref_instance.v) == 0* avoids this error. See COI.

Model.solve_iter

`Model.`**`solve_iter`**`(`*name*, *kwargs*`)`

Solve iterative initialization.

Model.solve_iter_single

`Model.`**`solve_iter_single`**`(`*name*, *inputs*, *pos*`)`

Solve iterative initialization for one given device.

Model.store_sparse_pattern

`Model.`**`store_sparse_pattern`**`()`

Store rows and columns of the non-zeros in the Jacobians for building the sparsity pattern.

This function converts the internal 0-indexed equation/variable address to the numerical addresses for the loaded system.

Calling sequence: For each Jacobian name, *fx*, *fy*, *gx* and *gy*, store by a) generated constant and variable Jacobians c) user-provided constant and variable Jacobians, d) user-provided block constant and variable Jacobians

Notes

If *self.n == 0*, skipping this function will avoid appending empty lists/arrays and non-empty values, which, as a combination, is not accepted by *kvxopt.spmatrix*.

Model.switch_action

Model.**switch_action**(*dae_t*)

Call the switch actions.

Parameters

dae_t
[float] Current simulation time

Returns

None

> **Warning:** Timer exported from blocks are supposed to work but have not been tested.

Model.v_numeric

Model.**v_numeric**(***kwargs*)

Custom variable initialization function.

Attributes

class_name	Return the class name

Model.class_name

property Model.**class_name**

Return the class name

3.3.3 andes.core.model.ModelCache

class andes.core.model.**ModelCache**

Class for caching the return value of callback functions.

Check ModelCache.__dict__.keys() for fields.

__init__()

Methods

add_callback(name, callback)	Add a cache attribute and a callback function for updating the attribute.
refresh([name])	Refresh the cached values

ModelCache.add_callback

ModelCache.**add_callback**(*name: str*, *callback*)

Add a cache attribute and a callback function for updating the attribute.

Parameters

name
[str] name of the cached function return value

callback
[callable] callback function for updating the cached attribute

ModelCache.refresh

ModelCache.**refresh**(*name=None*)

Refresh the cached values

Parameters

name
[str, list, optional] name or list of cached to refresh, by default None for refreshing all

3.3.4 andes.core.model.ModelCall

class andes.core.model.**ModelCall**

Class for storing generated function calls, Jacobian calls, and arguments.

__init__()

Methods

append_ijv(j_full_name, ii, jj, vv)	
clear_ijv()	
zip_ijv(j_full_name)	Return a zipped iterator for the rows, cols and vals for the specified matrix name.

ModelCall.append_ijv

ModelCall.**append_ijv**(*j_full_name*, *ii*, *jj*, *vv*)

ModelCall.clear_ijv

ModelCall.**clear_ijv**()

ModelCall.zip_ijv

ModelCall.**zip_ijv**(*j_full_name*)

Return a zipped iterator for the rows, cols and vals for the specified matrix name.

3.3.5 Cache

ModelData uses a lightweight class *andes.core.model.ModelCache* for caching its data as a dictionary or a pandas DataFrame. Four attributes are defined in *ModelData.cache*:

- *dict*: all data in a dictionary with the parameter names as keys and *v* values as arrays.
- *dict_in*: the same as *dict* except that the values are from *v_in*, the original input.
- *df*: all data in a pandas DataFrame.
- *df_in*: the same as *df* except that the values are from *v_in*.

Other attributes can be added by registering with *cache.add_callback*.

andes.core.model.ModelCache.**add_callback**(*self*, *name: str*, *callback*)

Add a cache attribute and a callback function for updating the attribute.

Parameters

name
[str] name of the cached function return value

callback
[callable] callback function for updating the cached attribute

3.3.6 Define Voltage Ratings

If a model is connected to an AC Bus or a DC Node, namely, if `bus`, `bus1`, `node` or `node1` exists as parameter, it must provide the corresponding parameter, `Vn`, `Vn1`, `Vdcn` or `Vdcn1`, for rated voltages.

Controllers not connected to Bus or Node will have its rated voltages omitted and thus `Vb = Vn = 1`, unless one uses *andes.core.param.ExtParam* to retrieve the bus/node values.

As a rule of thumb, controllers not directly connected to the network shall use system-base per unit for voltage and current parameters. Controllers (such as a turbine governor) may inherit rated power from controlled models and thus power parameters will be converted consistently.

Define a DAE Model

class andes.core.model.**Model**(*system=None*, *config=None*)

Base class for power system DAE models.

After subclassing *ModelData*, subclass *Model*` to complete a DAE model. Subclasses of *Model* define DAE variables, services, and other types of parameters, in the constructor `__init__`.

Examples

Take the static PQ as an example, the subclass of *Model*, *PQ*, should look like

```
class PQ(PQData, Model):
    def __init__(self, system, config):
        PQData.__init__(self) Model.__init__(self, system, config)
```

Since *PQ* is calling the base class constructors, it is meant to be the final class and not further derived. It inherits from *PQData* and *Model* and must call constructors in the order of *PQData* and *Model*. If the derived class of *Model* needs to be further derived, it should only derive from *Model* and use a name ending with *Base*. See `andes.models.synchronous.genbase.GENBase`.

Next, in *PQ.__init__*, set proper flags to indicate the routines in which the model will be used

```
self.flags.update({'pflow': True})
```

Currently, flags *pflow* and *tds* are supported. Both are *False* by default, meaning the model is neither used in power flow nor in time-domain simulation. **A very common pitfall is forgetting to set the flag**.

Next, the group name can be provided. A group is a collection of models with common parameters and variables. Devices' idx of all models in the same group must be unique. To provide a group name, use

```
self.group = 'StaticLoad'
```

The group name must be an existing class name in `andes.models.group`. The model will be added to the specified group and subject to the variable and parameter policy of the group. If not provided with a group class name, the model will be placed in the *Undefined* group.

Next, additional configuration flags can be added. Configuration flags for models are load-time variables, specifying the behavior of a model. They can be exported to an *andes.rc* file and automatically loaded when creating the *System*. Configuration flags can be used in equation strings, as long as they are numerical values. To add config flags, use

```
self.config.add(OrderedDict((('pq2z', 1), )))
```

It is recommended to use *OrderedDict* instead of *dict*, although the syntax is verbose. Note that booleans should be provided as integers (1 or 0), since *True* or *False* is interpreted as a string when loaded from the *rc* file and will cause an error.

Next, it's time for variables and equations! The *PQ* class does not have internal variables itself. It uses its *bus* parameter to fetch the corresponding *a* and *v* variables of buses. Equation wise, it imposes an active power and a reactive power load equation.

To define external variables from *Bus*, use

```
self.a = ExtAlgeb(model='Bus', src='a',
                  indexer=self.bus, tex_name=r'\theta')
self.v = ExtAlgeb(model='Bus', src='v',
                  indexer=self.bus, tex_name=r'V')
```

Refer to the subsection Variables for more details.

The simplest *PQ* model will impose constant P and Q, coded as

```
self.a.e_str = "u * p"
self.v.e_str = "u * q"
```

where the *e_str* attribute is the equation string attribute. *u* is the connectivity status. Any parameter, config, service or variable can be used in equation strings.

Three additional scalars can be used in equations: - `dae_t` for the current simulation time (can be used if the model has flag *tds*). - `sys_f` for system frequency (from `system.config.freq`). - `sys_mva` for system base mva (from `system.config.mva`).

The above example is overly simplified. Our *PQ* model wants a feature to switch itself to a constant impedance if the voltage is out of the range *(vmin, vmax)*. To implement this, we need to introduce a discrete component called *Limiter*, which yields three arrays of binary flags, *zi*, *zl*, and *zu* indicating in-range, below lower-limit, and above upper-limit, respectively.

First, create an attribute *vcmp* as a *Limiter* instance

```
self.vcmp = Limiter(u=self.v, lower=self.vmin, upper=self.vmax,
                    enable=self.config.pq2z)
```

where *self.config.pq2z* is a flag to turn this feature on or off. After this line, we can use *vcmp_zi*, *vcmp_zl*, and *vcmp_zu* in other equation strings.

```
self.a.e_str = "u * (p0 * vcmp_zi + " \
               "p0 * vcmp_zl * (v ** 2 / vmin ** 2) + " \
               "p0 * vcmp_zu * (v ** 2 / vmax ** 2))"
```

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```
self.v.e_str = "u * (q0 * vcmp_zi + " \
               "q0 * vcmp_zl * (v ** 2 / vmin ** 2) + "\
               "q0 * vcmp_zu * (v ** 2 / vmax ** 2))"
```

Note that *PQ.a.e_str* can use the three variables from *vcmp* even before defining *PQ.vcmp*, as long as *PQ.vcmp* is defined, because *vcmp_zi* is just a string literal in *e_str*.

The two equations above implement a piece-wise power injection equation. It selects the original power demand if within range, and uses the calculated power when out of range.

Finally, to let ANDES pick up the model, the model name needs to be added to *models/__init__.py*. Follow the examples in the *OrderedDict*, where the key is the file name, and the value is the class name.

Attributes

num_params
[OrderedDict] {name: instance} of numerical parameters, including internal and external ones

Dynamicity Under the Hood

The magic for automatic creation of variables are all hidden in `andes.core.model.Model.__setattr__()`, and the code is incredible simple. It sets the name, tex_name, and owner model of the attribute instance and, more importantly, does the book keeping. In particular, when the attribute is a `andes.core.block.Block` subclass, `__setattr__` captures the exported instances, recursively, and prepends the block name to exported ones. All these convenience owe to the dynamic feature of Python.

During the code generation phase, the symbols are created by checking the book-keeping attributes, such as *states*, *algebs*, and attributes in *Model.cache*.

In the numerical evaluation phase, *Model* provides a method, `andes.core.model.get_inputs()`, to collect the variable value arrays in a dictionary, which can be effortlessly passed as arguments to numerical functions.

3.3.7 Commonly Used Attributes in Models

The following `Model` attributes are commonly used for debugging. If the attribute is an *OrderedDict*, the keys are attribute names in str, and corresponding values are the instances.

- `params` and `params_ext`, two *OrderedDict* for internal (both numerical and non-numerical) and external parameters, respectively.
- `num_params` for numerical parameters, both internal and external.
- `states` and `algebs`, two `OrderedDict` for state variables and algebraic variables, respectively.
- `states_ext` and `algebs_ext`, two `OrderedDict` for external states and algebraics.
- `discrete`, an *OrderedDict* for discrete components.

- `blocks`, an *OrderedDict* for blocks.
- `services`, an *OrderedDict* for services with `v_str`.
- `services_ext`, an *OrderedDict* for externally retrieved services.

3.3.8 Attributes in *Model.cache*

Attributes in *Model.cache* are additional book-keeping structures for variables, parameters and services. The following attributes are defined.

- `all_vars`: all the variables.
- `all_vars_names`, a list of all variable names.
- `all_params`, all parameters.
- `all_params_names`, a list of all parameter names.
- `algebs_and_ext`, an *OrderedDict* of internal and external algebraic variables.
- `states_and_ext`, an *OrderedDict* of internal and external differential variables.
- `services_and_ext`, an *OrderedDict* of internal and external service variables.
- `vars_int`, an *OrderedDict* of all internal variables, states and then algebs.
- `vars_ext`, an *OrderedDict* of all external variables, states and then algebs.

Equation Generation

`Model.syms`, an instance of `SymProcessor`, handles the symbolic to numeric generation when called. The equation generation is a multi-step process with symbol preparation, equation generation, Jacobian generation, initializer generation, and pretty print generation.

class andes.core.**SymProcessor**(*parent*)

A helper class for symbolic processing and code generation.

Parameters

parent
[Model] The *Model* instance to process

Attributes

xy
[sympy.Matrix] variables pretty print in the order of State, ExtState, Algeb, ExtAlgeb

f
[sympy.Matrix] differential equations pretty print

g
[sympy.Matrix] algebraic equations pretty print

df
[sympy.SparseMatrix] df /d (xy) pretty print

dg
[sympy.SparseMatrix] dg /d (xy) pretty print

inputs_dict
[OrderedDict] All possible symbols in equations, including variables, parameters, discrete flags, and config flags. It has the same variables as what `get_inputs()` returns.

vars_dict
[OrderedDict] variable-only symbols, which are useful when getting the Jacobian matrices.

generate_equations()

Generate equations.

The pretty-print equations in matrices can be accessed in `self.f_matrix` and `self.g_matrix`.

generate_init()

Generate initialization equations.

generate_jacobians(*diag_eps=1e-08*)

Generate Jacobians and store to corresponding triplets.

The internal indices of equations and variables are stored, alongside the lambda functions.

For example, dg/dy is a sparse matrix whose elements are `(row, col, val)`, where `row` and `col` are the internal indices, and `val` is the numerical lambda function. They will be stored to

row -> self.calls._igy col -> self.calls._jgy val -> self.calls._vgy

generate_symbols()

Generate symbols for symbolic equation generations.

This function should run before other generate equations.

Attributes

inputs_dict
[OrderedDict] name-symbol pair of all parameters, variables and configs

vars_dict
[OrderedDict] name-symbol pair of all variables, in the order of (states_and_ext + algebs_and_ext)

Next, function `generate_equation` converts each DAE equation set to one numerical function calls and store it in `Model.calls`. The attributes for differential equation set and algebraic equation set are `f` and `g`. Differently, service variables will be generated one by one and store in an `OrderedDict` in `Model.calls.s`.

Jacobian Storage

3.3.9 Abstract Jacobian Storage

Using the `.jacobian` method on `sympy.Matrix`, the symbolic Jacobians can be easily obtained. The complexity lies in the storage of the Jacobian elements. Observed that the Jacobian equation generation happens before any system is loaded, thus only the variable indices in the variable array is available. For each non-zero item in each Jacobian matrix, ANDES stores the equation index, variable index, and the Jacobian value (either a constant number or a callable function returning an array).

Note that, again, a non-zero entry in a Jacobian matrix can be either a constant or an expression. For efficiency, constant numbers and lambdified callables are stored separately. Constant numbers, therefore, can be loaded into the sparse matrix pattern when a particular system is given.

Warning: Data structure for the Jacobian storage has changed. Pending documentation update. Please check `andes.core.common.JacTriplet` class for more details.

The triplets, the equation (row) index, variable (column) index, and values (constant numbers or callable) are stored in `Model` attributes with the name of `_{i, j, v}{Jacobian Name}{c or None}`, where `{i, j, v}` is a single character for row, column or value, `{Jacobian Name}` is a two-character Jacobian name chosen from `fx, fy, gx, and gy`, and `{c or None}` is either character `c` or no character, indicating whether it corresponds to the constants or non-constants in the Jacobian.

For example, the triplets for the constants in Jacobian `gy` are stored in `_igyc`, `_jgyc`, and `_vgyc`.

In terms of the non-constant entries in Jacobians, the callable functions are stored in the corresponding `_v{Jacobian Name}` array. Note the differences between, for example, `_vgy` an `_vgyc`: `_vgy` is a list of callables, while `_vgyc` is a list of constant numbers.

3.3.10 Concrete Jacobian Storage

When a specific system is loaded and the addresses are assigned to variables, the abstract Jacobian triplets, more specifically, the rows and columns, are replaced with the array of addresses. The new addresses and values will be stored in `Model` attributes with the names `{i, j, v}{Jacobian Name}{c or None}`. Note that there is no underscore for the concrete Jacobian triplets.

For example, if model `PV` has a list of variables `[p, q, a, v]`. The equation associated with `p` is `- u * p0`, and the equation associated with `q` is `u * (v0 - v)`. Therefore, the derivative of equation `v0 - v` over `v` is `-u`. Note that `u` is unknown at generation time, thus the value is NOT a constant and should to go `vgy`.

The values in `_igy`, `_jgy` and `_vgy` contains, respectively, `1`, `3`, and a lambda function which returns `-u`.

When a specific system is loaded, for example, a 5-bus system, the addresses for the `q` and `v` are `[11, 13, 15`, and `[5, 7, 9]`. `PV.igy` and `PV.jgy` will thus query the corresponding address list based on `PV._igy` and `PV._jgy` and store `[11, 13, 15`, and `[5, 7, 9]`.

Initialization

Value providers such as services and DAE variables need to be initialized. Services are initialized before any DAE variable. Both Services and DAE Variables are initialized *sequentially* in the order of declaration.

Each Service, in addition to the standard `v_str` for symbolic initialization, provides a `v_numeric` hook for specifying a custom function for initialization. Custom initialization functions for DAE variables, are lumped in a single function in `Model.v_numeric`.

ANDES has an *experimental* Newton-Krylov method based iterative initialization. All DAE variables with `v_iter` will be initialized using the iterative approach

Additional Numerical Equations

Addition numerical equations are allowed to complete the "hybrid symbolic-numeric" framework. Numerical function calls are useful when the model DAE is non-standard or hard to be generalized. Since the symbolic-to-numeric generation is an additional layer on top of the numerical simulation, it is fundamentally the same as user-provided numerical function calls.

ANDES provides the following hook functions in each `Model` subclass for custom numerical functions:

- `v_numeric`: custom initialization function
- `s_numeric`: custom service value function
- `g_numeric`: custom algebraic equations; update the `e` of the corresponding variable.
- `f_numeric`: custom differential equations; update the `e` of the corresponding variable.
- `j_numeric`: custom Jacobian equations; the function should append to `_i`, `_j` and `_v` structures.

For most models, numerical function calls are unnecessary and not recommended as it increases code complexity. However, when the data structure or the DAE are difficult to generalize in the symbolic framework, the numerical equations can be used.

For interested readers, see the `COI` symbolic implementation which calculated the center-of-inertia speed of generators. The `COI` could have been implemented numerically with for loops instead of `NumReduce`, `NumRepeat` and external variables.

3.4 Atomic Types

ANDES contains three types of atom classes for building DAE models. These types are parameter, variable and service.

3.4.1 Value Provider

Before addressing specific atom classes, the terminology *v-provider*, and *e-provider* are discussed. A value provider class (or *v-provider* for short) references any class with a member attribute named `v`, which should be a list or a 1-dimensional array of values. For example, all parameter classes are v-providers, since a parameter class should provide values for that parameter.

Note: In fact, all types of atom classes are v-providers, meaning that an instance of an atom class must contain values.

The values in the *v* attribute of a particular instance are values that will substitute the instance for computation. If in a model, one has a parameter

```
self.v0 = NumParam()
self.b = NumParam()

# where self.v0.v = np.array([1., 1.05, 1.1]
#   and self.b.v  = np.array([10., 10., 10.]
```

Later, this parameter is used in an equation, such as

```
self.v = ExtAlgeb(model='Bus', src='v',
                  indexer=self.bus,
                  e_str='v0 **2 * b')
```

While computing *v0 ** 2 * b*, *v0* and *b* will be substituted with the values in *self.v0.v* and *self.b.v*.

Sharing this interface *v* allows interoperability among parameters and variables and services. In the above example, if one defines *v0* as a *ConstService* instance, such as

```
self.v0 = ConstService(v_str='1.0')
```

Calculations will still work without modification.

3.4.2 Equation Provider

Similarly, an equation provider class (or *e-provider*) references any class with a member attribute named `e`, which should be a 1-dimensional array of values. The values in the *e* array are the results from the equation and will be summed to the numerical DAE at the addresses specified by the attribute *a*.

Note: Currently, only variables are *e-provider* types.

If a model has an external variable that links to Bus.v (voltage), such as

```
self.v = ExtAlgeb(model='Bus', src='v',
                  indexer=self.bus,
                  e_str='v0 **2 * b')
```

The addresses of the corresponding voltage variables will be retrieved into *self.v.a*, and the equation evaluation results will be stored in *self.v.e*

3.5 Parameters

3.5.1 Background

Parameter is a type of building atom for DAE models. Most parameters are read directly from an input file and passed to equation, and other parameters can be calculated from existing parameters.

The base class for parameters in ANDES is *BaseParam*, which defines interfaces for adding values and checking the number of values. *BaseParam* has its values stored in a plain list, the member attribute *v*. Subclasses such as *NumParam* stores values using a NumPy ndarray.

An overview of supported parameters is given below.

BaseParam([default, name, tex_name, info, ...])	The base parameter class.
DataParam([default, name, tex_name, info, ...])	An alias of the *BaseParam* class.
IdxParam([default, name, tex_name, info, ...])	An alias of *BaseParam* with an additional storage of the owner model name
NumParam(default, name, tex_name, info, ...)	A computational numerical parameter.
ExtParam(model, src[, indexer, vtype, ...])	A parameter whose values are retrieved from an external model or group.
TimerParam([callback, default, name, ...])	A parameter whose values are event occurrence times during the simulation.

andes.core.param.BaseParam

class andes.core.param.**BaseParam**(*default: float | str | int | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *mandatory: bool = False*, *export: bool = True*, *iconvert: Callable | None = None*, *oconvert: Callable | None = None*)

The base parameter class.

This class provides the basic data structure and interfaces for all types of parameters. Parameters are from input files and in general constant once initialized.

Subclasses should overload the *n()* method for the total count of elements in the value array.

Parameters

default
[str or float, optional] The default value of this parameter if None is provided

name
[str, optional] Parameter name. If not provided, it will be automatically set to the attribute name defined in the owner model.

tex_name
[str, optional] LaTeX-formatted parameter name. If not provided, *tex_name* will be assigned the same as *name*.

info
[str, optional] Descriptive information of parameter

mandatory
[bool] True if this parameter is mandatory

export
[bool] True if the parameter will be exported when dumping data into files. True for most parameters. False for `BackRef`.

Other Parameters

iconvert
[Callable] Converter to be applied to input data when a device is being added.

oconvert
[callable] Converter to be applied to internal data when outputting.

> **Warning:** The most distinct feature of BaseParam, DataParam and IdxParam is that values are stored in a list without conversion to array. BaseParam, DataParam or IdxParam are **not allowed** in equations.

Attributes

v
[list] A list holding all the values. The `BaseParam` class does not convert the `v` attribute into NumPy arrays.

property
[dict] A dict containing the truth values of the model properties.

__init__ (*default: float | str | int | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *mandatory: bool = False*, *export: bool = True*, *iconvert: Callable | None = None*, *oconvert: Callable | None = None*)

Methods

add([value])	Add a new parameter value (from a new device of the owner model) to the v list.
get_names()	Return self.name in a list.
get_property(property_name)	Check the boolean value of the given property.
set(pos, attr, value)	Set attributes of the BaseParam class to new values at the given positions.
set_all(attr, value)	Set attributes of the BaseParam class to new values for all positions.

BaseParam.add

BaseParam.**add**(*value=None*)

Add a new parameter value (from a new device of the owner model) to the v list.

Parameters

value
[str or float, optional] Parameter value of the new element. If None, the default will be used.

Notes

If the value is math.nan, it will set to None.

BaseParam.get_names

BaseParam.**get_names**()

Return self.name in a list.

This is a helper function to provide the same API as blocks or discrete components.

Returns

list
A list only containing the name of the parameter

BaseParam.get_property

BaseParam.**get_property**(*property_name: str*)

Check the boolean value of the given property. If the property does not exist in the dictionary, `False` will be returned.

Parameters

property_name
[str] Property name

Returns

The truth value of the property.

BaseParam.set

BaseParam.**set**(*pos*, *attr*, *value*)

Set attributes of the BaseParam class to new values at the given positions.

Parameters

pos
[int, list of integers] Positions in arrays where the values should be set

attr
['v', 'vin'] Name of the attribute to be set

value
[str, float or list of above] New values

BaseParam.set_all

BaseParam.**set_all**(*attr*, *value*)

Set attributes of the BaseParam class to new values for all positions.

Parameters

attr
['v', 'vin'] Name of the attribute to be set

value
[list of str, float or int] New values

Attributes

class_name	Return the class name.
n	Return the count of elements in the value array.

BaseParam.class_name

property BaseParam.**class_name**

Return the class name.

BaseParam.n

property BaseParam.**n**

Return the count of elements in the value array.

andes.core.param.DataParam

class andes.core.param.**DataParam**(*default: float | str | int | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *mandatory: bool = False*, *export: bool = True*, *iconvert: Callable | None = None*, *oconvert: Callable | None = None*)

An alias of the *BaseParam* class.

This class is used for string parameters or non-computational numerical parameters. This class does not provide a *to_array* method. All input values will be stored in *v* as a list.

See also:

andes.core.param.BaseParam
Base parameter class

__init__(*default: float | str | int | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *mandatory: bool = False*, *export: bool = True*, *iconvert: Callable | None = None*, *oconvert: Callable | None = None*)

Methods

add([value])	Add a new parameter value (from a new device of the owner model) to the v list.
get_names()	Return self.name in a list.
get_property(property_name)	Check the boolean value of the given property.
set(pos, attr, value)	Set attributes of the BaseParam class to new values at the given positions.
set_all(attr, value)	Set attributes of the BaseParam class to new values for all positions.

DataParam.add

DataParam.**add**(*value=None*)

Add a new parameter value (from a new device of the owner model) to the v list.

Parameters

value
[str or float, optional] Parameter value of the new element. If None, the default will be used.

Notes

If the value is math.nan, it will set to None.

DataParam.get_names

DataParam.**get_names**()

Return self.name in a list.

This is a helper function to provide the same API as blocks or discrete components.

Returns

list
A list only containing the name of the parameter

DataParam.get_property

DataParam.**get_property**(*property_name: str*)

Check the boolean value of the given property. If the property does not exist in the dictionary, `False` will be returned.

Parameters

property_name
[str] Property name

Returns

The truth value of the property.

DataParam.set

DataParam.**set**(*pos*, *attr*, *value*)

Set attributes of the BaseParam class to new values at the given positions.

Parameters

pos
[int, list of integers] Positions in arrays where the values should be set

attr
['v', 'vin'] Name of the attribute to be set

value
[str, float or list of above] New values

DataParam.set_all

DataParam.**set_all**(*attr*, *value*)

Set attributes of the BaseParam class to new values for all positions.

Parameters

attr
['v', 'vin'] Name of the attribute to be set

value
[list of str, float or int] New values

Attributes

class_name	Return the class name.
n	Return the count of elements in the value array.

DataParam.class_name

property DataParam.**class_name**

Return the class name.

DataParam.n

property DataParam.**n**

Return the count of elements in the value array.

andes.core.param.IdxParam

class andes.core.param.**IdxParam**(*default: float | str | int | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *mandatory: bool = False*, *unique: bool = False*, *export: bool = True*, *model: str | None = None*, *iconvert: Callable | None = None*, *oconvert: Callable | None = None*)

An alias of *BaseParam* with an additional storage of the owner model name

This class is intended for storing *idx* into other models. It can be used in the future for data consistency check.

Notes

This will be useful when, for example, one connects two TGs to one SynGen.

Examples

A PQ model connected to Bus model will have the following code

```
class PQModel(...):
    def __init__(...):
        ...
        self.bus = IdxParam(model='Bus')
```

__init__(*default: float | str | int | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *mandatory: bool = False*, *unique: bool = False*, *export: bool = True*, *model: str | None = None*, *iconvert: Callable | None = None*, *oconvert: Callable | None = None*)

Methods

add([value])	Add a new parameter value (from a new device of the owner model) to the `v` list.
get_names()	Return `self.name` in a list.
get_property(property_name)	Check the boolean value of the given property.
set(pos, attr, value)	Set attributes of the BaseParam class to new values at the given positions.
set_all(attr, value)	Set attributes of the BaseParam class to new values for all positions.

IdxParam.add

`IdxParam.`**`add`**(*value=None*)

Add a new parameter value (from a new device of the owner model) to the `v` list.

Parameters

value
[str or float, optional] Parameter value of the new element. If None, the default will be used.

Notes

If the value is `math.nan`, it will set to `None`.

IdxParam.get_names

`IdxParam.`**`get_names`**()

Return `self.name` in a list.

This is a helper function to provide the same API as blocks or discrete components.

Returns

list
A list only containing the name of the parameter

IdxParam.get_property

IdxParam.**get_property**(*property_name: str*)

Check the boolean value of the given property. If the property does not exist in the dictionary, `False` will be returned.

Parameters

property_name
[str] Property name

Returns

The truth value of the property.

IdxParam.set

IdxParam.**set**(*pos*, *attr*, *value*)

Set attributes of the BaseParam class to new values at the given positions.

Parameters

pos
[int, list of integers] Positions in arrays where the values should be set

attr
['v', 'vin'] Name of the attribute to be set

value
[str, float or list of above] New values

IdxParam.set_all

IdxParam.**set_all**(*attr*, *value*)

Set attributes of the BaseParam class to new values for all positions.

Parameters

attr
['v', 'vin'] Name of the attribute to be set

value
[list of str, float or int] New values

Attributes

class_name	Return the class name.
n	Return the count of elements in the value array.

IdxParam.class_name

property IdxParam.**class_name**

Return the class name.

IdxParam.n

property IdxParam.**n**

Return the count of elements in the value array.

andes.core.param.NumParam

class andes.core.param.**NumParam**(*default: float | str | ~typing.Callable | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *vrange: ~typing.List | ~typing.Tuple | None = None*, *vtype: ~typing.Type | None = <class 'float'>*, *iconvert: ~typing.Callable | None = None*, *oconvert: ~typing.Callable | None = None*, *non_zero: bool = False*, *non_positive: bool = False*, *non_negative: bool = False*, *mandatory: bool = False*, *power: bool = False*, *ipower: bool = False*, *voltage: bool = False*, *current: bool = False*, *z: bool = False*, *y: bool = False*, *r: bool = False*, *g: bool = False*, *dc_voltage: bool = False*, *dc_current: bool = False*, *export: bool = True*)

A computational numerical parameter.

Parameters defined using this class will have their *v* field converted to a NumPy array after adding.

The original input values will be copied to *vin*, and the system-base per-unit conversion coefficients (through multiplication) will be stored in *pu_coeff*.

Parameters

default
[str or float, optional] The default value of this parameter if no value is provided

name
[str, optional] Name of this parameter. If not provided, *name* will be set to the attribute name of the owner model.

tex_name
[str, optional] LaTeX-formatted parameter name. If not provided, *tex_name* will be assigned the same as *name*.

info
[str, optional] A description of this parameter

mandatory
[bool] True if this parameter is mandatory

unit
[str, optional] Unit of the parameter

vrange
[list, tuple, optional] Typical value range

vtype
[type, optional] Type of the `v` field. The default is `float`.

Other Parameters

Sn
[str] Name of the parameter for the device base power.

Vn
[str] Name of the parameter for the device base voltage.

non_zero
[bool] True if this parameter must be non-zero. *non_zero* can be combined with *non_positive* or *non_negative*.

non_positive
[bool] True if this parameter must be non-positive.

non_negative
[bool] True if this parameter must be non-negative.

mandatory
[bool] True if this parameter must not be None.

power
[bool] True if this parameter is a power per-unit quantity under the device base.

iconvert
[callable] Callable to convert input data from excel or others to the internal `v` field.

oconvert
[callable] Callable to convert input data from internal type to a serializable type.

ipower
[bool] True if this parameter is an inverse-power per-unit quantity under the device base.

voltage
[bool] True if the parameter is a voltage pu quantity under the device base.

current
[bool] True if the parameter is a current pu quantity under the device base.

z
[bool] True if the parameter is an AC impedance pu quantity under the device base.

y
[bool] True if the parameter is an AC admittance pu quantity under the device base.

r
[bool] True if the parameter is a DC resistance pu quantity under the device base.

g
[bool] True if the parameter is a DC conductance pu quantity under the device base.

dc_current
[bool] True if the parameter is a DC current pu quantity under device base.

dc_voltage
[bool] True if the parameter is a DC voltage pu quantity under device base.

__init__ (*default: float | str | ~typing.Callable | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *vrange: ~typing.List | ~typing.Tuple | None = None*, *vtype: ~typing.Type | None = <class 'float'>*, *iconvert: ~typing.Callable | None = None*, *oconvert: ~typing.Callable | None = None*, *non_zero: bool = False*, *non_positive: bool = False*, *non_negative: bool = False*, *mandatory: bool = False*, *power: bool = False*, *ipower: bool = False*, *voltage: bool = False*, *current: bool = False*, *z: bool = False*, *y: bool = False*, *r: bool = False*, *g: bool = False*, *dc_voltage: bool = False*, *dc_current: bool = False*, *export: bool = True*)

Methods

add([value])	Add a value to the parameter value list.
get_names()	Return `self.name` in a list.
get_property(property_name)	Check the boolean value of the given property.
restore()	Restore parameter to the original input by copying `self.vin` to `self.v`.
set(pos, attr, value)	Set attributes of the BaseParam class to new values at the given positions.
set_all(attr, value)	Set attributes of the BaseParam class to new values for all positions.
set_pu_coeff(coeff)	Store p.u.
to_array()	Converts field `v` to the NumPy array type.

NumParam.add

NumParam.**add**(*value=None*)

Add a value to the parameter value list.

In addition to BaseParam.add, this method checks for non-zero property and reset to default if is zero.

See also:

BaseParam.add
the add method of BaseParam

NumParam.get_names

NumParam.**get_names**()

Return self.name in a list.

This is a helper function to provide the same API as blocks or discrete components.

Returns

list
A list only containing the name of the parameter

NumParam.get_property

NumParam.**get_property**(*property_name: str*)

Check the boolean value of the given property. If the property does not exist in the dictionary, False will be returned.

Parameters

property_name
[str] Property name

Returns

The truth value of the property.

NumParam.restore

NumParam.**restore**()

Restore parameter to the original input by copying `self.vin` to `self.v`.

pu_coeff will not be overwritten.

NumParam.set

NumParam.**set**(*pos*, *attr*, *value*)

Set attributes of the BaseParam class to new values at the given positions.

Parameters

pos
[int, list of integers] Positions in arrays where the values should be set

attr
['v', 'vin'] Name of the attribute to be set

value
[str, float or list of above] New values

NumParam.set_all

NumParam.**set_all**(*attr*, *value*)

Set attributes of the BaseParam class to new values for all positions.

Parameters

attr
['v', 'vin'] Name of the attribute to be set

value
[list of str, float or int] New values

NumParam.set_pu_coeff

NumParam.**set_pu_coeff**(*coeff*)

Store p.u. conversion coefficient into `self.pu_coeff` and calculate the system-base per unit with `self.v = self.vin * self.pu_coeff`.

This function must be called after `self.to_array`.

Parameters

coeff
[np.ndarray] An array with the pu conversion coefficients

NumParam.to_array

NumParam.**to_array**()

Converts field `v` to the NumPy array type. to enable array-based calculation.

Must be called after adding all elements. Store a copy of original input values to field `vin`. Set `pu_coeff` to all ones.

> **Warning:** After this call, *add* will not be allowed to avoid unexpected issues.

Attributes

class_name	Return the class name.
n	Return the count of elements in the value array.

NumParam.class_name

property NumParam.**class_name**

Return the class name.

NumParam.n

property NumParam.**n**

Return the count of elements in the value array.

andes.core.param.ExtParam

class andes.core.param.**ExtParam**(*model: str*, *src: str*, *indexer=None*, *vtype=<class 'float'>*, *allow_none=False*, *default=0.0*, ***kwargs*)

A parameter whose values are retrieved from an external model or group.

Parameters

model
[str] Name of the model or group providing the original parameter

src
[str] The source parameter name

indexer
[BaseParam] A parameter defined in the model defining this ExtParam instance. *indexer.v* should contain indices into *model.src.v*. If is None, the source parameter values will be fully copied. If *model* is a group name, the indexer cannot be None.

vtype
[type, optional, default to float] Type of each element to be retrieved. Can be `str` if the ExtParam is used to access an `IdxParam`.

Attributes

parent_model
[Model] The parent model providing the original parameter.

__init__(*model: str*, *src: str*, *indexer=None*, *vtype=<class 'float'>*, *allow_none=False*, *default=0.0*, ***kwargs*)

Methods

add([value])	ExtParam has an empty *add* method.
get_names()	Return `self.name` in a list.
get_property(property_name)	Check the boolean value of the given property.
link_external(ext_model)	Update parameter values provided by external models.
restore()	ExtParam has an empty *restore* method
set(pos, attr, value)	Set attributes of the BaseParam class to new values at the given positions.
set_all(attr, value)	Set attributes of the BaseParam class to new values for all positions.
set_pu_coeff(coeff)	Store p.u.
to_array()	Convert to array when d_type is not str

ExtParam.add

ExtParam.**add**(*value=None*)

ExtParam has an empty *add* method.

ExtParam.get_names

ExtParam.**get_names**()

Return `self.name` in a list.

This is a helper function to provide the same API as blocks or discrete components.

Returns

list
A list only containing the name of the parameter

ExtParam.get_property

ExtParam.**get_property**(*property_name: str*)

Check the boolean value of the given property. If the property does not exist in the dictionary, `False` will be returned.

Parameters

property_name
[str] Property name

Returns

The truth value of the property.

ExtParam.link_external

ExtParam.**link_external**(*ext_model*)

Update parameter values provided by external models. This needs to be called before pu conversion.

Parameters

ext_model
[Model, Group] Instance of the parent model or group, provided by the System calling this method.

ExtParam.restore

ExtParam.**restore**()

ExtParam has an empty *restore* method

ExtParam.set

ExtParam.**set**(*pos*, *attr*, *value*)

Set attributes of the BaseParam class to new values at the given positions.

Parameters

pos
[int, list of integers] Positions in arrays where the values should be set

attr
['v', 'vin'] Name of the attribute to be set

value
[str, float or list of above] New values

ExtParam.set_all

ExtParam.**set_all**(*attr*, *value*)

Set attributes of the BaseParam class to new values for all positions.

Parameters

attr
['v', 'vin'] Name of the attribute to be set

value
[list of str, float or int] New values

ExtParam.set_pu_coeff

ExtParam.**set_pu_coeff**(*coeff*)

Store p.u. conversion coefficient into `self.pu_coeff` and calculate the system-base per unit with `self.v = self.vin * self.pu_coeff`.

This function must be called after `self.to_array`.

Parameters

coeff
[np.ndarray] An array with the pu conversion coefficients

ExtParam.to_array

ExtParam.**to_array**()

Convert to array when d_type is not str

Attributes

class_name	Return the class name.
n	Return the count of elements in the value array.

ExtParam.class_name

property ExtParam.**class_name**

Return the class name.

ExtParam.n

property ExtParam.**n**

Return the count of elements in the value array.

andes.core.param.TimerParam

class andes.core.param.**TimerParam**(*callback: Callable | None = None*, *default: float | str | Callable | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *non_zero: bool = False*, *mandatory: bool = False*, *export: bool = True*)

A parameter whose values are event occurrence times during the simulation.

The constructor takes an additional Callable *self.callback* for the action of the event. *TimerParam* has a default value of -1, meaning deactivated.

Examples

A connectivity status toggle class *Toggle* takes a parameter *t* for the toggle time. Inside `Toggle.__init__`, one would have

```
self.t = TimerParam()
```

The *Toggle* class also needs to define a method for togging the connectivity status

```
def _u_switch(self, is_time: np.ndarray):
    action = False
    for i in range(self.n):
        if is_time[i] and (self.u.v[i] == 1):
            instance = self.system.__dict__[self.model.v[i]]
            # get the original status and flip the value
            u0 = instance.get(src='u', attr='v', idx=self.dev.v[i])
            instance.set(src='u',
                         attr='v',
                         idx=self.dev.v[i],
                         value=1-u0)
            action = True
    return action
```

Finally, in `Toggle.__init__`, assign the function as the callback for *self.t*

```
self.t.callback = self._u_switch
```

__init__(*callback: Callable | None = None*, *default: float | str | Callable | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *non_zero: bool = False*, *mandatory: bool = False*, *export: bool = True*)

Methods

add([value])	Add a value to the parameter value list.
get_names()	Return `self.name` in a list.
get_property(property_name)	Check the boolean value of the given property.
is_time(dae_t)	Element-wise check if the DAE time is the same as the parameter value.
restore()	Restore parameter to the original input by copying `self.vin` to `self.v`.
set(pos, attr, value)	Set attributes of the BaseParam class to new values at the given positions.
set_all(attr, value)	Set attributes of the BaseParam class to new values for all positions.
set_pu_coeff(coeff)	Store p.u.
to_array()	Converts field `v` to the NumPy array type.

TimerParam.add

`TimerParam.`**`add`**(*value=None*)

Add a value to the parameter value list.

In addition to `BaseParam.add`, this method checks for non-zero property and reset to default if is zero.

See also:

BaseParam.add
the add method of BaseParam

TimerParam.get_names

`TimerParam.`**`get_names`**()

Return `self.name` in a list.

This is a helper function to provide the same API as blocks or discrete components.

Returns

list
A list only containing the name of the parameter

TimerParam.get_property

`TimerParam.`**`get_property`**(*property_name: str*)

Check the boolean value of the given property. If the property does not exist in the dictionary, `False` will be returned.

Parameters

property_name
[str] Property name

Returns

The truth value of the property.

TimerParam.is_time

`TimerParam.`**`is_time`**(*dae_t*)

Element-wise check if the DAE time is the same as the parameter value. The current implementation uses *np.equal*.

Parameters

dae_t
[float] Current simulation time

Returns

np.ndarray
The array containing the truth value of if the DAE time is close to the parameter value.

Notes

The previous implementation with *np.isclose* with default *rtol=1e-5* mistakes the immediate pre- and post-event time as in-event when simulation time is greater than 10.

TimerParam.restore

`TimerParam.`**`restore`**()

Restore parameter to the original input by copying `self.vin` to `self.v`.

pu_coeff will not be overwritten.

TimerParam.set

`TimerParam.`**`set`**(*pos*, *attr*, *value*)

Set attributes of the BaseParam class to new values at the given positions.

Parameters

pos
[int, list of integers] Positions in arrays where the values should be set

attr
['v', 'vin'] Name of the attribute to be set

value
[str, float or list of above] New values

TimerParam.set_all

`TimerParam.`**`set_all`**(*attr*, *value*)

Set attributes of the BaseParam class to new values for all positions.

Parameters

attr
['v', 'vin'] Name of the attribute to be set

value
[list of str, float or int] New values

TimerParam.set_pu_coeff

`TimerParam.`**`set_pu_coeff`**(*coeff*)

Store p.u. conversion coefficient into `self.pu_coeff` and calculate the system-base per unit with `self.v = self.vin * self.pu_coeff`.

This function must be called after `self.to_array`.

Parameters

coeff
[np.ndarray] An array with the pu conversion coefficients

TimerParam.to_array

TimerParam.**to_array**()

Converts field `v` to the NumPy array type. to enable array-based calculation.

Must be called after adding all elements. Store a copy of original input values to field `vin`. Set `pu_coeff` to all ones.

> **Warning:** After this call, *add* will not be allowed to avoid unexpected issues.

Attributes

class_name	Return the class name.
n	Return the count of elements in the value array.

TimerParam.class_name

property TimerParam.**class_name**

Return the class name.

TimerParam.n

property TimerParam.**n**

Return the count of elements in the value array.

3.6 Variables

DAE Variables, or variables for short, are unknowns to be solved using numerical or analytical methods. A variable stores values, equation values, and addresses in the DAE array. The base class for variables is *BaseVar*. In this subsection, *BaseVar* is used to represent any subclass of *VarBase* list in the table below.

BaseVar([name, tex_name, info, unit, v_str, ...])	Base variable class.
ExtVar(model, src[, indexer, allow_none, ...])	Algebraic variable that links to an external model.
State([name, tex_name, info, unit, v_str, ...])	Differential variable class, an alias of the *BaseVar*.
Algeb([name, tex_name, info, unit, v_str, ...])	Algebraic variable class, an alias of *andes.core.var.BaseVar*.
ExtState(model, src[, indexer, allow_none, ...])	External state variable type.
ExtAlgeb(model, src[, indexer, allow_none, ...])	External algebraic variable type.
AliasState(var, **kwargs)	Alias state variable.
AliasAlgeb(var, **kwargs)	Alias algebraic variable.

3.6.1 andes.core.var.BaseVar

class andes.core.var.**BaseVar**(*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *discrete:* Discrete *| None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *v_str_add: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *deps: List | None = None*, *is_output: bool | None = False*)

Base variable class.

Derived classes *State* and *Algeb* should be used to build model variables.

Parameters

info
[str, optional] Descriptive information

unit
[str, optional] Unit

tex_name
[str] LaTeX-formatted variable symbol. If is None, the value of *name* will be used.

discrete
[Discrete] Discrete component on which this variable depends. ANDES will call *check_var()* of the discrete component before initializing this variable.

name
[str, optional] Variable name. One should typically assigning the name directly because it will be automatically assigned by the model. The value of `name` will be the symbol name to be used in expressions.

Attributes

a
[array-like] variable address

v
[array-like] local-storage of the variable value

e
[array-like] local-storage of the corresponding equation value

e_str
[str] the string/symbolic representation of the equation

v_str
[str] explicit initialization equation

v_str_add
[bool] True if the value of *v_str* will be added to the variable. Useful when other models access this variable and set part of the initial value

v_iter
[str] implicit iterative equation in the form of 0 = v_iter

__init__(*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *discrete: Discrete | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *v_str_add: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *deps: List | None = None*, *is_output: bool | None = False*)

Methods

get_names()	
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Set the address of internal variables.
set_arrays(dae[, inplace, alloc])	Set the equation and values arrays.

BaseVar.get_names

BaseVar.**get_names**()

BaseVar.reset

BaseVar.**reset**()

Reset the internal numpy arrays and flags.

BaseVar.set_address

BaseVar.**set_address**(*addr: ndarray*, *contiguous=False*)

Set the address of internal variables.

Parameters

addr
[np.ndarray] The assigned address for this variable

contiguous
[bool, optional] If the addresses are contiguous

BaseVar.set_arrays

BaseVar.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Set the equation and values arrays.

Parameters

dae
[DAE] Reference to System.dae

Attributes

class_name

BaseVar.class_name

property BaseVar.**class_name**

3.6.2 andes.core.var.ExtVar

class andes.core.var.**ExtVar**(*model: str*, *src: str*, *indexer: List | ndarray | BaseParam | BaseService | None = None*, *allow_none: bool | None = False*, *name: str | None = None*, *tex_name: str | None = None*, *ename: str | None = None*, *tex_ename: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *is_input: bool | None = False*)

Algebraic variable that links to an external model.

This class is used to retrieve the addresses of a variable defined in an external model. An equation can be defined for the ExtVar. The evaluated value for the equation will be stored in the ExtVar.e attribute and added to the equations corresponding to the external variables.

Parameters

model
[str] Name of the source model

src
[str] Source variable name

indexer
[BaseParam, BaseService] A parameter of the hosting model, used as indices into

the source model and variable. If is None, the source variable address will be fully copied.

allow_none
[bool, optional, default=False] True to allow None in indexer

e_str
[string, optional, default=None] Equation string, the evaluated value of which will be added to the source residual equation

Attributes

parent_model
[Model] The parent model providing the original parameter.

uid
[array-like] An array containing the absolute indices into the parent_instance values.

e_code
[str] Equation code string; copied from the parent instance.

v_code
[str] Variable code string; copied from the parent instance.

__init__(*model: str*, *src: str*, *indexer: List | ndarray | BaseParam | BaseService | None = None*, *allow_none: bool | None = False*, *name: str | None = None*, *tex_name: str | None = None*, *ename: str | None = None*, *tex_ename: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *is_input: bool | None = False*)

Methods

get_names()	
link_external(ext_model)	Update variable addresses provided by external models
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Assigns address for equation RHS.
set_arrays(dae[, inplace, alloc])	Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

ExtVar.get_names

ExtVar.**get_names**()

ExtVar.link_external

ExtVar.**link_external**(*ext_model*)

Update variable addresses provided by external models

This method sets attributes including *parent_model*, *parent_instance*, *uid*, *a*, *n*, *e_code* and *v_code*. It initializes the *e* and *v* to zero.

Parameters

ext_model
[Model] Instance of the parent model

Returns

None

Warning: *link_external* does not check if the ExtVar type is the same as the original variable to reduce performance overhead. It will be a silent error (a dimension too small error from *dae.build_pattern*) if a model uses *ExtAlgeb* to access a *State*, or vice versa.

ExtVar.reset

ExtVar.**reset**()

Reset the internal numpy arrays and flags.

ExtVar.set_address

ExtVar.**set_address**(*addr*, *contiguous=False*)

Assigns address for equation RHS.

ExtVar.set_arrays

ExtVar.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

Attributes

class_name

ExtVar.class_name

property ExtVar.**class_name**

3.6.3 andes.core.var.State

class andes.core.var.**State**(*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *discrete: Discrete | None = None*, *t_const: BaseParam | DummyValue | BaseService | None = None*, *check_init: bool | None = True*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *deps: List | None = None*)

Differential variable class, an alias of the *BaseVar*.

Parameters

t_const
[BaseParam, DummyValue] Left-hand time constant for the differential equation. They will be collected to array `dae.Tf`. Time constants will not be used when evaluating the right-hand side specified in `e_str` but will be applied to the left-hand side.

check_init
[bool] True to check if the equation right-hand-side is zero initially. Disabling the checking can be used for integrators when the initial input may not be zero.

Examples

To implement the swing equation

$$M\dot{\omega} = \tau_m - \tau_e - D(\omega - 1)$$

Do the following in the `__init__()` of a model class:

```
self.omega = State(e_str = 'tm - te - D * (omega - 1)',
                   t_const = self.M,
                   ...
                   )
```

Note that `self.M`, the inertia parameter is given through `t_const` and is not part of `e_str`.

Attributes

e_code
[str] Equation code string, equals string literal `f`

v_code
[str] Variable code string, equals string literal `x`

__init__ (*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *discrete: Discrete | None = None*, *t_const: BaseParam | DummyValue | BaseService | None = None*, *check_init: bool | None = True*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *deps: List | None = None*)

Methods

get_names()	
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Set the address of internal variables.
set_arrays(dae[, inplace, alloc])	Set the equation and values arrays.

State.get_names

State.**get_names**()

State.reset

State.**reset**()

Reset the internal numpy arrays and flags.

State.set_address

State.**set_address**(*addr: ndarray*, *contiguous=False*)

Set the address of internal variables.

Parameters

addr
[np.ndarray] The assigned address for this variable

contiguous
[bool, optional] If the addresses are contiguous

State.set_arrays

State.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Set the equation and values arrays.

Parameters

dae
[DAE] Reference to System.dae

Attributes

class_name
e_code
v_code

State.class_name

property State.**class_name**

State.e_code

State.**e_code = 'f'**

State.v_code

State.**v_code = 'x'**

3.6.4 andes.core.var.Algeb

class andes.core.var.**Algeb**(*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *discrete: Discrete | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *v_str_add: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *deps: List | None = None*, *is_output: bool | None = False*)

Algebraic variable class, an alias of *andes.core.var.BaseVar*.

Note that residual equations corresponding to algebraic variables are given in an implicit form.

Examples

When an algebraic variable `y` and the equation `y = x + z` shall be defined, use

```
e_str = 'x + z - y'
```

because it expresses the equation `x + z - y = 0`. It is a common mistake to use `e_str = 'x + z'`, which will result in a singular Jacobian matrix because `d(x + z) / d(y)` is zero.

Attributes

e_code
[str] Equation code string, equals string literal `g`

v_code
[str] Variable code string, equals string literal `y`

__init__(*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *discrete:* Discrete *| None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *v_str_add: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *deps: List | None = None*, *is_output: bool | None = False*)

Methods

get_names()	
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Set the address of internal variables.
set_arrays(dae[, inplace, alloc])	Set the equation and values arrays.

Algeb.get_names

Algeb.**get_names**()

Algeb.reset

Algeb.**reset**()

Reset the internal numpy arrays and flags.

Algeb.set_address

Algeb.**set_address**(*addr: ndarray*, *contiguous=False*)

Set the address of internal variables.

Parameters

addr
[np.ndarray] The assigned address for this variable

contiguous
[bool, optional] If the addresses are contiguous

Algeb.set_arrays

Algeb.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Set the equation and values arrays.

Parameters

dae
[DAE] Reference to System.dae

Attributes

class_name
e_code
v_code

Algeb.class_name

property Algeb.**class_name**

Algeb.e_code

Algeb.**e_code = 'g'**

Algeb.v_code

`Algeb.v_code = 'y'`

3.6.5 andes.core.var.ExtState

class andes.core.var.**ExtState**(*model: str*, *src: str*, *indexer: List | ndarray | BaseParam | BaseService | None = None*, *allow_none: bool | None = False*, *name: str | None = None*, *tex_name: str | None = None*, *ename: str | None = None*, *tex_ename: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *is_input: bool | None = False*)

External state variable type.

> **Warning:** `ExtState` is not allowed to set `t_const`, as it may conflict with the source `State` variable.
>
> Only in rare cases should one set `e_str` for `ExtState`. The `t_const` of the source State variable is used.

__init__(*model: str*, *src: str*, *indexer: List | ndarray | BaseParam | BaseService | None = None*, *allow_none: bool | None = False*, *name: str | None = None*, *tex_name: str | None = None*, *ename: str | None = None*, *tex_ename: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *is_input: bool | None = False*)

Methods

get_names()	
link_external(ext_model)	Update variable addresses provided by external models
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Assigns address for equation RHS.
set_arrays(dae[, inplace, alloc])	Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

ExtState.get_names

ExtState.**get_names**()

ExtState.link_external

ExtState.**link_external**(*ext_model*)

Update variable addresses provided by external models

This method sets attributes including *parent_model*, *parent_instance*, *uid*, *a*, *n*, *e_code* and *v_code*. It initializes the *e* and *v* to zero.

Parameters

ext_model
[Model] Instance of the parent model

Returns

None

Warning: *link_external* does not check if the ExtVar type is the same as the original variable to reduce performance overhead. It will be a silent error (a dimension too small error from *dae.build_pattern*) if a model uses *ExtAlgeb* to access a *State*, or vice versa.

ExtState.reset

ExtState.**reset**()

Reset the internal numpy arrays and flags.

ExtState.set_address

ExtState.**set_address**(*addr*, *contiguous=False*)

Assigns address for equation RHS.

ExtState.set_arrays

ExtState.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

Attributes

class_name
e_code
r_code
t_const
v_code

ExtState.class_name

property ExtState.**class_name**

ExtState.e_code

ExtState.**e_code = 'f'**

ExtState.r_code

ExtState.**r_code = 'h'**

ExtState.t_const

ExtState.**t_const = None**

ExtState.v_code

ExtState.**v_code = 'x'**

3.6.6 andes.core.var.ExtAlgeb

class andes.core.var.**ExtAlgeb**(*model: str*, *src: str*, *indexer: List | ndarray | BaseParam | BaseService | None = None*, *allow_none: bool | None = False*, *name: str | None = None*, *tex_name: str | None = None*, *ename: str | None = None*, *tex_ename: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *is_input: bool | None = False*)

External algebraic variable type.

__init__(*model: str*, *src: str*, *indexer: List | ndarray | BaseParam | BaseService | None = None*, *allow_none: bool | None = False*, *name: str | None = None*, *tex_name: str | None = None*, *ename: str | None = None*, *tex_ename: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *v_str: str | float | None = None*, *v_iter: str | None = None*, *e_str: str | None = None*, *v_setter: bool | None = False*, *e_setter: bool | None = False*, *addressable: bool | None = True*, *export: bool | None = True*, *diag_eps: float | None = 0.0*, *is_input: bool | None = False*)

Methods

get_names()	
link_external(ext_model)	Update variable addresses provided by external models
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Assigns address for equation RHS.
set_arrays(dae[, inplace, alloc])	Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

ExtAlgeb.get_names

ExtAlgeb.**get_names**()

ExtAlgeb.link_external

ExtAlgeb.**link_external**(*ext_model*)

Update variable addresses provided by external models

This method sets attributes including *parent_model*, *parent_instance*, *uid*, *a*, *n*, *e_code* and *v_code*. It initializes the *e* and *v* to zero.

Parameters

ext_model
[Model] Instance of the parent model

Returns

None

Warning: *link_external* does not check if the ExtVar type is the same as the original variable to reduce performance overhead. It will be a silent error (a dimension too small error from *dae.build_pattern*) if a model uses *ExtAlgeb* to access a *State*, or vice versa.

ExtAlgeb.reset

ExtAlgeb.**reset**()

Reset the internal numpy arrays and flags.

ExtAlgeb.set_address

ExtAlgeb.**set_address**(*addr*, *contiguous=False*)

Assigns address for equation RHS.

ExtAlgeb.set_arrays

ExtAlgeb.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

Attributes

class_name
e_code
r_code
v_code

ExtAlgeb.class_name

property ExtAlgeb.**class_name**

ExtAlgeb.e_code

ExtAlgeb.**e_code = 'g'**

ExtAlgeb.r_code

ExtAlgeb.**r_code = 'i'**

ExtAlgeb.v_code

ExtAlgeb.**v_code = 'y'**

3.6.7 andes.core.var.AliasState

class andes.core.var.**AliasState**(*var*, ***kwargs*)

Alias state variable.

Refer to the docs of AliasAlgeb.

__init__(*var*, ***kwargs*)

Methods

get_names()	
link_external(ext_model)	Update variable addresses provided by external models
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Assigns address for equation RHS.
set_arrays(dae[, inplace, alloc])	Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

AliasState.get_names

AliasState.**get_names**()

AliasState.link_external

AliasState.**link_external**(*ext_model*)

Update variable addresses provided by external models

This method sets attributes including *parent_model*, *parent_instance*, *uid*, *a*, *n*, *e_code* and *v_code*. It initializes the *e* and *v* to zero.

Parameters

ext_model
[Model] Instance of the parent model

Returns

None

Warning: *link_external* does not check if the ExtVar type is the same as the original variable to reduce performance overhead. It will be a silent error (a dimension too small error from *dae.build_pattern*) if a model uses *ExtAlgeb* to access a *State*, or vice versa.

AliasState.reset

AliasState.**reset**()

Reset the internal numpy arrays and flags.

AliasState.set_address

AliasState.**set_address**(*addr*, *contiguous=False*)

Assigns address for equation RHS.

AliasState.set_arrays

AliasState.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

Attributes

class_name
e_code
r_code
t_const
v_code

AliasState.class_name

property AliasState.**class_name**

AliasState.e_code

AliasState.**e_code = 'f'**

AliasState.r_code

AliasState.**r_code = 'h'**

AliasState.t_const

AliasState.**t_const = None**

AliasState.v_code

AliasState.**v_code = 'x'**

3.6.8 andes.core.var.AliasAlgeb

class andes.core.var.**AliasAlgeb**(*var*, ***kwargs*)

Alias algebraic variable. Essentially ExtAlgeb that links to a a model's own variable.

AliasAlgeb is useful when the final output of a model is from a block, but the model must provide the final output in a pre-defined name. Using AliasAlgeb, A model can avoid adding an additional variable with a dummy equations.

Like ExtVar, labels of AliasAlgeb will not be saved in the final output. When plotting from file, one need to look up the original variable name.

__init__(*var*, ***kwargs*)

Methods

get_names()	
link_external(ext_model)	Update variable addresses provided by external models
reset()	Reset the internal numpy arrays and flags.
set_address(addr[, contiguous])	Assigns address for equation RHS.
set_arrays(dae[, inplace, alloc])	Access dae.h or dae.i for the RHS of external variables when e_str exists..

AliasAlgeb.get_names

AliasAlgeb.**get_names**()

AliasAlgeb.link_external

AliasAlgeb.**link_external**(*ext_model*)

Update variable addresses provided by external models

This method sets attributes including *parent_model*, *parent_instance*, *uid*, *a*, *n*, *e_code* and *v_code*. It initializes the *e* and *v* to zero.

Parameters

ext_model
[Model] Instance of the parent model

Returns

None

Warning: *link_external* does not check if the ExtVar type is the same as the original variable to reduce performance overhead. It will be a silent error (a dimension too small error from *dae.build_pattern*) if a model uses *ExtAlgeb* to access a *State*, or vice versa.

AliasAlgeb.reset

AliasAlgeb.**reset**()

Reset the internal numpy arrays and flags.

AliasAlgeb.set_address

AliasAlgeb.**set_address**(*addr*, *contiguous=False*)

Assigns address for equation RHS.

AliasAlgeb.set_arrays

AliasAlgeb.**set_arrays**(*dae*, *inplace=True*, *alloc=True*)

Access `dae.h` or `dae.i` for the RHS of external variables when `e_str` exists..

Attributes

class_name
e_code
r_code
v_code

AliasAlgeb.class_name

property AliasAlgeb.**class_name**

AliasAlgeb.e_code

AliasAlgeb.**e_code = 'g'**

AliasAlgeb.r_code

AliasAlgeb.**r_code = 'i'**

AliasAlgeb.v_code

AliasAlgeb.**v_code = 'y'**

Note that equations associated with state variables are in the form of $\mathbf{M}\dot{x} = \mathbf{f}(\mathbf{x}, \mathbf{y})$, where $\mathbf{x}$ are the differential variables, $\mathbf{y}$ are the algebraic variables, and $\mathbf{M}$ is the mass matrix, and $\mathbf{f}$ are the right-hand side of differential equations. Equations associated with algebraic variables take the form of $0 = \mathbf{g}$, where $\mathbf{g}$ are the equation right-hand side

BaseVar has two types: the differential variable type *State* and the algebraic variable type *Algeb*. State variables are described by differential equations, whereas algebraic variables are described by algebraic equations. State variables can only change continuously, while algebraic variables can be discontinuous.

Based on the model the variable is defined, variables can be internal or external. Most variables are internal and only appear in equations in the same model. Some models have "public" variables that can be accessed by other models. For example, a *Bus* defines *v* for the voltage magnitude. Each device attached to a particular bus needs to access the value and impose the reactive power injection. It can be done with *ExtAlgeb* or *ExtState*, which links with an existing variable from a model or a group.

3.6.9 Variable, Equation and Address

Subclasses of *BaseVar* are value providers and equation providers. Each *BaseVar* has member attributes *v* and *e* for variable values and equation values, respectively. The initial value of *v* is set by the initialization routine, and the initial value of *e* is set to zero. In the process of power flow calculation or time domain simulation, *v* is not directly modifiable by models but rather updated after solving non-linear equations. *e* is updated by the models and summed up before solving equations.

Each *BaseVar* also stores addresses of this variable, for all devices, in its member attribute *a*. The addresses are *0-based* indices into the numerical DAE array, *f* or *g*, based on the variable type.

For example, *Bus* has `self.a = Algeb()` as the voltage phase angle variable. For a 5-bus system, `Bus.a.a` stores the addresses of the *a* variable for all the five Bus devices. Conventionally, *Bus.a.a* will be assigned *np.array([0, 1, 2, 3, 4])*.

3.6.10 Value and Equation Strings

The most important feature of the symbolic framework is allowing to define equations using strings. There are three types of strings for a variable, stored in the following member attributes, respectively:

- *v_str*: equation string for **explicit** initialization in the form of *v = v_str(x, y)*.
- *v_iter*: equation string for **implicit** initialization in the form of *v_iter(x, y) = 0*
- *e_str*: equation string for (full or part of) the differential or algebraic equation.

The difference between *v_str* and *v_iter* should be clearly noted. *v_str* evaluates directly into the initial value, while all *v_iter* equations are solved numerically using the Newton-Krylov iterative method.

3.6.11 Values Between DAE and Models

ANDES adopts a decentralized architecture which provides each model a copy of variable values before equation evaluation. This architecture allows to parallelize the equation evaluation (in theory, or in practice if one works round the Python GIL). However, this architecture requires a coherent protocol for updating the DAE arrays and the `BaseVar` arrays. More specifically, how the variable and equations values from model `VarBase` should be summed up or forcefully set at the DAE arrays needs to be defined.

The protocol is relevant when a model defines subclasses of *BaseVar* that are supposed to be "public". Other models share this variable with *ExtAlgeb* or *ExtState*.

By default, all *v* and *e* at the same address are summed up. This is the most common case, such as a Bus connected by multiple devices: power injections from devices should be summed up.

In addition, *BaseVar* provides two flags, *v_setter* and *e_setter*, for cases when one *VarBase* needs to overwrite the variable or equation values.

3.6.12 Flags for Value Overwriting

BaseVar have special flags for handling value initialization and equation values. This is only relevant for public or external variables. The *v_setter* is used to indicate whether a particular *BaseVar* instance sets the initial value. The *e_setter* flag indicates whether the equation associated with a *BaseVar* sets the equation value.

The *v_setter* flag is checked when collecting data from models to the numerical DAE array. If *v_setter is False*, variable values of the same address will be added. If one of the variable or external variable has *v_setter is True*, it will, at the end, set the values in the DAE array to its value. Only one *BaseVar* of the same address is allowed to have *v_setter == True*.

3.6.13 A *v_setter* Example

A Bus is allowed to default the initial voltage magnitude to 1 and the voltage phase angle to 0. If a PV device is connected to a Bus device, the PV should be allowed to override the voltage initial value with the voltage set point.

In *Bus.__init__()*, one has

```
self.v = Algeb(v_str='1')
```

In *PV.__init__*, one can use

```
self.v0 = Param()
self.bus = IdxParam(model='Bus')

self.v = ExtAlgeb(src='v',
                  model='Bus',
                  indexer=self.bus,
                  v_str='v0',
                  v_setter=True)
```

where an *ExtAlgeb* is defined to access *Bus.v* using indexer *self.bus*. The *v_str* line sets the initial value to *v0*. In the variable initialization phase for *PV*, *PV.v.v* is set to *v0*.

During the value collection into *DAE.y* by the *System* class, *PV.v*, as a final *v_setter*, will overwrite the voltage magnitude for Bus devices with the indices provided in *PV.bus*.

3.7 Services

Services are helper variables outside the DAE variable list. Services are most often used for storing intermediate constants but can be used for special operations to work around restrictions in the symbolic framework. Services are value providers, meaning each service has an attribute `v` for storing service values. The base class of services is :py:mod`BaseService`, and the supported services are listed as follows.

BaseService([name, tex_name, unit, info, vtype])	Base class for Service.
OperationService([name, tex_name, info])	Base class for a type of Service which performs specific operations.

3.7.1 andes.core.service.BaseService

class andes.core.service.**BaseService**(*name: str = None*, *tex_name: str = None*, *unit: str = None*, *info: str = None*, *vtype: Type = None*)

Base class for Service.

Service is a v-provider type for holding internal and temporary values. Subclasses need to implement `v` as a member attribute or using a property decorator.

Parameters

name
[str] Instance name

Attributes

owner
[Model] The hosting/owner model instance

__init__(*name: str = None*, *tex_name: str = None*, *unit: str = None*, *info: str = None*, *vtype: Type = None*)

Methods

assign_memory(n)	Assign memory for `self.v` and set the array to zero.
get_names()	Return *name* in a list

BaseService.assign_memory

BaseService.**assign_memory**(*n*)

Assign memory for `self.v` and set the array to zero.

Parameters

n
[int] Number of elements of the value array. Provided by caller (Model.list2array).

BaseService.get_names

BaseService.**get_names**()

Return *name* in a list

Returns

list
A list only containing the name of the service variable

Attributes

class_name	Return the class name
n	Return the count of values in `self.v`.

BaseService.class_name

property BaseService.**class_name**

Return the class name

BaseService.n

property BaseService.**n**

Return the count of values in `self.v`.

Needs to be overloaded if `v` of subclasses is not a 1-dimensional array.

Returns

int
The count of elements in this variable

3.7.2 andes.core.service.OperationService

class andes.core.service.**OperationService**(*name=None*, *tex_name=None*, *info=None*)

Base class for a type of Service which performs specific operations. OperationService may not use the *assign_memory* from *BaseService*, because it can have a different size.

This class cannot be used by itself.

See also:

NumReduce
Service for Reducing linearly stored 2-D services into 1-D

NumRepeat
Service for repeating 1-D NumParam/ v-array following a

sub-pattern
IdxRepeat
Service for repeating 1-D IdxParam/ v-list following a

sub-pattern

__init__(*name=None*, *tex_name=None*, *info=None*)

Methods

assign_memory(n)	Assign memory for `self.v` and set the array to zero.
get_names()	Return *name* in a list

OperationService.assign_memory

`OperationService.`**assign_memory**(*n*)

Assign memory for `self.v` and set the array to zero.

Parameters

n
[int] Number of elements of the value array. Provided by caller (Model.list2array).

OperationService.get_names

`OperationService.`**get_names**()

Return *name* in a list

Returns

list
A list only containing the name of the service variable

Attributes

class_name	Return the class name
n	Return the count of values in `self.v`.
v	Return values stored in *self._v*.

OperationService.class_name

property OperationService.**class_name**

Return the class name

OperationService.n

property OperationService.**n**

Return the count of values in `self.v`.

Needs to be overloaded if `v` of subclasses is not a 1-dimensional array.

Returns

int
The count of elements in this variable

OperationService.v

property OperationService.**v**

Return values stored in *self._v*. May be overloaded by subclasses.

Class	Description
ConstService	Internal service for constant values.
VarService	Variable service updated at each iteration before equations.
ExtService	External service for retrieving values from value providers.
PostInitService	Constant service evaluated after TDS initialization
NumReduce	The service type for reducing linear 2-D arrays into 1-D arrays
NumRepeat	The service type for repeating a 1-D array to linear 2-D arrays
IdxRepeat	The service type for repeating a 1-D list to linear 2-D list
EventFlag	Service type for flagging changes in inputs as an event
VarHold	Hold input value when a hold signal is active
ExtendedEvent	Extend an event signal for a given period of time
DataSelect	Select optional str data if provided or use the fallback
NumSelect	Select optional numerical data if provided
DeviceFinder	Finds or creates devices linked to the given devices
BackRef	Collects idx-es for the backward references
RefFlatten	Converts BackRef list of lists into a 1-D list
InitChecker	Checks initial values against typical values
FlagValue	Flags values that equals the given value
Replace	Replace values that returns True for the given lambda func

3.7.3 Internal Constants

The most commonly used service is *ConstService*. It is used to store an array of constants, whose value is evaluated from a provided symbolic string. They are only evaluated once in the model initialization phase, ahead of variable initialization. *ConstService* comes handy when one wants to calculate intermediate constants from parameters.

For example, a turbine governor has a *NumParam R* for the droop. *ConstService* allows to calculate the inverse of the droop, the gain, and use it in equations. The snippet from a turbine governor's `__init__()` may look like

```
self.R = NumParam()
self.G = ConstService(v_str='u/R')
```

where *u* is the online status parameter. The model can thus use *G* in subsequent variable or equation strings.

class andes.core.service.**ConstService**(*v_str: str | None = None*, *v_numeric: Callable | None = None*, *vtype: type | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*)

A type of Service that stays constant once initialized.

ConstService are usually constants calculated from parameters. They are only evaluated once in the initialization phase before variables are initialized. Therefore, uninitialized variables must not be used in *v_str*`.

ConstService are evaluated *in sequence* after getting external variables and parameters and before initializing internal variables.

Parameters

name
[str] Name of the ConstService

v_str
[str] An equation string to calculate the variable value.

v_numeric
[Callable, optional] A callable which returns the value of the ConstService

v_type: type, optional, default to float
Type of element in the value array in float or complex

Attributes

v
[array-like or a scalar] ConstService value

class andes.core.service.**VarService**(*v_str: str | None = None*, *v_numeric: Callable | None = None*, *vtype: type | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*, *sequential: bool | None = True*)

Variable service that gets updated in each step/iteration before computing the residual equations. As a results, variable values from the k-th step are used to compute a `VarService` that will be used to compute the residual for the (k+1)-th step.

This class is useful when one has non-differentiable algebraic equations, which make use of *abs()*, *re* and *im*. Instead of creating *Algeb*, one can put the equation in *VarService*, which will be updated before solving algebraic equations.

Parameters

sequential
[bool, optional, default to True] True if this VarService depends on previously defined VarService and should be evaluated in sequence. False if this VarService only uses known variables.

Warning: *VarService* is not solved with other algebraic equations, meaning that there is one step "delay" between the algebraic variables and *VarService*. Use an algebraic variable whenever possible.

Examples

In ESST3A model, the voltage and current sensors (vd + jvq), (Id + jIq) estimate the sensed VE using equation

$$VE = |K_{PC} * (v_d + 1jv_q) + 1j(K_I + K_{PC} * X_L) * (I_d + 1jI_q)|$$

One can use *VarService* to implement this equation

```
self.VE = VarService(
    tex_name='V_E', info='VE', v_str='Abs(KPC*(vd + 1j*vq) + 1j*(KI +
    KPC*XL)*(Id + 1j*Iq))', )
```

class andes.core.service.**PostInitService**(*v_str: str | None = None*, *v_numeric: Callable | None = None*, *vtype: type | None = None*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *unit: str | None = None*)

Constant service that gets stored once after init.

This service is useful when one need to store initialization values stored in variables.

Examples

In ESST3A model, the *vf* variable is initialized followed by other variables. One can store the initial *vf* into *vf0* so that equation `vf - vf0 = 0` will hold.

```
self.vref0 = PostInitService(info='Initial reference voltage input',
                             tex_name='V_{ref0}', v_str='vref', )
```

Since all *ConstService* are evaluated before equation evaluation, without using PostInitService, one will need to create lots of *ConstService* to store values in the initialization path towards *vf0*, in order to correctly initialize *vf*.

3.7.4 External Constants

Service constants whose value is retrieved from an external model or group. Using *ExtService* is similar to using external variables. The values of *ExtService* will be retrieved once during the initialization phase before *ConstService* evaluation.

For example, a synchronous generator needs to retrieve the *p* and *q* values from static generators for initialization. *ExtService* is used for this purpose. In the `__init__()` of a synchronous generator model, one can define the following to retrieve *StaticGen.p* as *p0*:

```
self.p0 = ExtService(src='p',
                     model='StaticGen',
                     indexer=self.gen,
                     tex_name='P_0')
```

class andes.core.service.**ExtService**(*model: str*, *src: str*, *indexer:* BaseParam | BaseService, *attr: str = 'v'*, *allow_none: bool = False*, *default=0*, *name: str = None*, *tex_name: str = None*, *vtype=None*, *info: str = None*)

Service constants whose value is from an external model or group.

Parameters

src
[str] Variable or parameter name in the source model or group

model
[str] A model name or a group name

indexer
[IdxParam or BaseParam] An "Indexer" instance whose `v` field contains the `idx` of devices in the model or group.

Examples

A synchronous generator needs to retrieve the `p` and `q` values from static generators for initialization. `ExtService` is used for this purpose.

In a synchronous generator, one can define the following to retrieve `StaticGen.p` as `p0`:

```
class GENCLSModel(Model):
    def __init__(...):
        ...
        self.p0 = ExtService(src='p',
                             model='StaticGen',
                             indexer=self.gen,
                             tex_name='P_0')
```

3.7.5 Shape Manipulators

This section is for advanced model developer.

All generated equations operate on 1-dimensional arrays and can use algebraic calculations only. In some cases, one model would use *BackRef* to retrieve 2-dimensional indices and will use such indices to retrieve variable addresses. The retrieved addresses usually has a different length of the referencing model and cannot be used directly for calculation. Shape manipulator services can be used in such case.

NumReduce is a helper Service type which reduces a linearly stored 2-D ExtParam into 1-D Service. *NumRepeat* is a helper Service type which repeats a 1-D value into linearly stored 2-D value based on the shape from a *BackRef*.

class andes.core.service.**BackRef**(***kwargs*)

A special type of reference collector.

BackRef is used for collecting device indices of other models referencing the parent model of the *BackRef*. The *v``field will be a list of lists, each containing the `idx* of other models referencing each device of the parent model.

BackRef can be passed as indexer for params and vars, or shape for *NumReduce* and *NumRepeat*. See examples for illustration.

See also:

andes.core.service.NumReduce
A more complete example using BackRef to build the COI model

Examples

A Bus device has an *IdxParam* of *area*, storing the *idx* of area to which the bus device belongs. In `Bus.__init__()`, one has

```
self.area = IdxParam(model='Area')
```

Suppose *Bus* has the following data

idx	area	Vn
1	1	110
2	2	220
3	1	345
4	1	500

The Area model wants to collect the indices of Bus devices which points to the corresponding Area device. In `Area.__init__`, one defines

```
self.Bus = BackRef()
```

where the member attribute name *Bus* needs to match exactly model name that *Area* wants to collect *idx* for. Similarly, one can define `self.ACTopology = BackRef()` to collect devices in the *ACTopology* group that references Area.

The collection of *idx* happens in `andes.system.System._collect_ref_param()`. It has to be noted that the specific *Area* entry must exist to collect model idx-dx referencing it. For example, if *Area* has the following data

```
idx 1
```

Then, only Bus 1, 3, and 4 will be collected into *self.Bus.v*, namely, `self.Bus.v == [ [1, 3, 4] ]`.

If *Area* has data

```
idx 1 2
```

Then, *self.Bus.v* will end up with `[ [1, 3, 4], [2] ]`.

class andes.core.service.**NumReduce**(*u*, *ref: BackRef*, *fun: Callable*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

A helper Service type which reduces a linearly stored 2-D ExtParam into 1-D Service.

NumReduce works with ExtParam whose *v* field is a list of lists. A reduce function which takes an array-like and returns a scalar need to be supplied. NumReduce calls the reduce function on each of the lists and return all the scalars in an array.

Parameters

u

[ExtParam] Input ExtParam whose `v` contains linearly stored 2-dimensional values

ref
[BackRef] The BackRef whose 2-dimensional shapes are used for indexing

fun
[Callable] The callable for converting a 1-D array-like to a scalar

Examples

Suppose one wants to calculate the mean value of the `Vn` in one Area. In the `Area` class, one defines

```
class AreaModel(...):
    def __init__(...):
        ...
        # backward reference from `Bus`
        self.Bus = BackRef()

        # collect the Vn in an 1-D array
        self.Vn = ExtParam(model='Bus',
                           src='Vn',
                           indexer=self.Bus)

        self.Vn_mean = NumReduce(u=self.Vn,
                                 fun=np.mean,
                                 ref=self.Bus)
```

Suppose we define two areas, 1 and 2, the Bus data looks like

idx	area	Vn
1	1	110
2	2	220
3	1	345
4	1	500

Then, *self.Bus.v* is a list of two lists `[ [1, 3, 4], [2] ]`. *self.Vn.v* will be retrieved and linearly stored as `[110, 345, 500, 220]`. Based on the shape from *self.Bus*, `numpy.mean()` will be called on `[110, 345, 500]` and `[220]` respectively. Thus, *self.Vn_mean.v* will become `[318.33, 220]`.

class andes.core.service.**NumRepeat**(*u*, *ref*, ***kwargs*)
A helper Service type which repeats a v-provider's value based on the shape from a BackRef

Examples

NumRepeat was originally designed for computing the inertia-weighted average rotor speed (center of inertia speed). COI speed is computed with

$$\omega_{COI} = \frac{\sum M_i * \omega_i}{\sum M_i}$$

The numerator can be calculated with a mix of BackRef, ExtParam and ExtState. The denominator needs to be calculated with NumReduce and Service Repeat. That is, use NumReduce to calculate the sum, and use NumRepeat to repeat the summed value for each device.

In the COI class, one would have

```
class COIModel(...):
    def __init__(...):
        ...
        self.SynGen = BackRef()
        self.SynGenIdx = RefFlatten(ref=self.SynGen)
        self.M = ExtParam(model='SynGen',
                          src='M',
                          indexer=self.SynGenIdx)

        self.wgen = ExtState(model='SynGen',
                             src='omega',
                             indexer=self.SynGenIdx)

        self.Mt = NumReduce(u=self.M,
                                fun=np.sum,
                                ref=self.SynGen)

        self.Mtr = NumRepeat(u=self.Mt,
                               ref=self.SynGen)

        self.pidx = IdxRepeat(u=self.idx,ref=self.SynGen)
```

Finally, one would define the center of inertia speed as

```
self.wcoi = Algeb(v_str='1', e_str='-wcoi')

self.wcoi_sub = ExtAlgeb(model='COI',
                         src='wcoi',
                         e_str='M * wgen / Mtr',
                         v_str='M / Mtr',
                         indexer=self.pidx,
                         )
```

It is very worth noting that the implementation uses a trick to separate the average weighted sum into n sub-equations, each calculating the $(M_i * \omega_i)/(\sum M_i)$. Since all the variables are preserved in the sub-equation, the derivatives can be calculated correctly.

class andes.core.service.**IdxRepeat**(*u*, *ref*, ***kwargs*)

Helper class to repeat IdxParam.

This class has the same functionality as `andes.core.service.NumRepeat` but only operates on IdxParam, DataParam or NumParam.

class andes.core.service.**RefFlatten**(*ref*, ***kwargs*)

A service type for flattening `andes.core.service.BackRef` into a 1-D list.

Examples

This class is used when one wants to pass *BackRef* values as indexer.

`andes.models.coi.COI` collects referencing `andes.models.group.SynGen` with

```
self.SynGen = BackRef(info='SynGen idx lists', export=False)
```

After collecting BackRefs, *self.SynGen.v* will become a two-level list of indices, where the first level correspond to each COI and the second level correspond to generators of the COI.

Convert *self.SynGen* into 1-d as *self.SynGenIdx*, which can be passed as indexer for retrieving other parameters and variables

```
self.SynGenIdx = RefFlatten(ref=self.SynGen)

self.M = ExtParam(model='SynGen', src='M',
                  indexer=self.SynGenIdx, export=False,
                  )
```

3.7.6 Value Manipulation

class andes.core.service.**Replace**(*old_val*, *flt*, *new_val*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Replace parameters with new values if the function returns True

class andes.core.service.**ParamCalc**(*param1*, *param2*, *func*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Parameter calculation service.

Useful to create parameters calculated instantly from existing ones.

3.7.7 Idx and References

class andes.core.service.**DeviceFinder**(*u*, *link*, *idx_name: str*, *default_model: str*, *auto_find: bool | None = True*, *auto_add: bool | None = True*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*)

Service for finding `idx` of devices which are linked to the given devices.

The `auto_find` parameter controls if the device idx should be automatically looked up. The `auto_add` parameter controls if the device will be automatically added. The two parameters are not exclusive. One can skip finding the device but automatically adding it.

If `auto_find` is `True` and the `idx` is None, DeviceFinder will look up for the device. If not found and `auto_add` is `True`, DevFinder will then automatically add the devices. The `idx` of the devices that are found or added will be stored to the DeviceFinder instance, so that *DeviceFinder* can be used like any *IdxParam*.

Adding new devices are called at the beginning of *andes.system.System.setup()*.

Examples

The IEEEST stabilizer takes an optional parameter `busf` of the type *IdxParam* for specifying the connected bus frequency measurement device, which is needed for mode 6. To avoid reimplementing *BusFreq* within IEEEST, one can do

```
self.busfreq = DeviceFinder(self.busf,
                            link=self.buss, idx_name='bus',
                            default_model='BusFreq')
```

where `self.busf` is for the optional parameter for the `idx` of bus frequency estimation devices (e.g., *BusFreq*), `self.buss` is for the `idx` of buses that `self.busf` devices should measure, and `idx_name` is the name of the BusFreq parameter through which the indices of measured buses are given.

For each `None` or invalid values in `self.busf`, a *BusFreq* device will be created with its `bus` set to the corresponding value in `self.buss`. That is, `BusFreq.[idx_name].v = [link]`.

At the end, the *DeviceFinder* instance will contain the list of `BusFreq` that are are connected to *self.buss*, respectively.

In the case of any valid value in `self.busf`, that is, the value is an existing `BusFreq` device, *DeviceFinder* will return it as is without checking if the `BusFreq` device actually measures the bus specified by `self.buss`. It allows to use the measurement at a different location, but the user have to perform the data consistency check.

class andes.core.service.**BackRef**(***kwargs*)

A special type of reference collector.

BackRef is used for collecting device indices of other models referencing the parent model of the *BackRef*. The *v``field will be a list of lists, each containing the `idx* of other models referencing each device of the parent model.

BackRef can be passed as indexer for params and vars, or shape for *NumReduce* and *NumRepeat*. See examples for illustration.

See also:

andes.core.service.NumReduce
A more complete example using BackRef to build the COI model

Examples

A Bus device has an *IdxParam* of *area*, storing the *idx* of area to which the bus device belongs. In `Bus.__init__()`, one has

```
self.area = IdxParam(model='Area')
```

Suppose *Bus* has the following data

idx	area	Vn
1	1	110
2	2	220
3	1	345
4	1	500

The Area model wants to collect the indices of Bus devices which points to the corresponding Area device. In `Area.__init__`, one defines

```
self.Bus = BackRef()
```

where the member attribute name *Bus* needs to match exactly model name that *Area* wants to collect *idx* for. Similarly, one can define `self.ACTopology = BackRef()` to collect devices in the *ACTopology* group that references Area.

The collection of *idx* happens in `andes.system.System._collect_ref_param()`. It has to be noted that the specific *Area* entry must exist to collect model idx-dx referencing it. For example, if *Area* has the following data

```
idx 1
```

Then, only Bus 1, 3, and 4 will be collected into *self.Bus.v*, namely, `self.Bus.v == [ [1, 3, 4] ]`.

If *Area* has data

```
idx 1 2
```

Then, *self.Bus.v* will end up with `[ [1, 3, 4], [2] ]`.

class andes.core.service.**RefFlatten**(*ref*, ***kwargs*)

A service type for flattening `andes.core.service.BackRef` into a 1-D list.

Examples

This class is used when one wants to pass *BackRef* values as indexer.

`andes.models.coi.COI` collects referencing `andes.models.group.SynGen` with

```
self.SynGen = BackRef(info='SynGen idx lists', export=False)
```

After collecting BackRefs, *self.SynGen.v* will become a two-level list of indices, where the first level correspond to each COI and the second level correspond to generators of the COI.

Convert *self.SynGen* into 1-d as *self.SynGenIdx*, which can be passed as indexer for retrieving other parameters and variables

```
self.SynGenIdx = RefFlatten(ref=self.SynGen)

self.M = ExtParam(model='SynGen', src='M',
                  indexer=self.SynGenIdx, export=False,
                  )
```

3.7.8 Events

class andes.core.service.**EventFlag**(*u*, *vtype: type | None = None*, *name: str | None = None*, *tex_name=None*, *info=None*)

Service to flag events when the input value changes. The typical input is a *v-provider* with binary values.

Implemented by providing *self.check(**kwargs)* as *v_numeric*. *EventFlag.v* stores the values of the input variable in the most recent iteration/step.

After the evaluation of *self.check()*, *self.v* will be updated.

class andes.core.service.**ExtendedEvent**(*u*, *t_ext: int | float | BaseParam | BaseService = 0.0*, *trig: str = 'rise'*, *enable=True*, *v_disabled=0*, *extend_only=False*, *vtype: type | None = None*, *name: str | None = None*, *tex_name=None*, *info=None*)

Service for indicating an event for an extended, predefined period of time following the event disappearance.

The triggering of an event, whether the rise or fall edge, is specified through *trig*. For example, if *trig = rise*, the change of the input from 0 to 1 will be considered as an input, whereas the subsequent change back to 0 will be considered as the event end.

ExtendedEvent.v stores the flags whether the extended time has completed. Outputs will become 1 once the event starts and return to 0 when the extended time ends.

Parameters

u

[v-provider] Triggering signal where the values are 0 or 1.

trig
[str in ("rise", "fall")] Triggering edge for the beginning of an event. *rise* by default.

enable
[bool or v-provider] If disabled, the output will be *v_disabled*

extend_only
[bool] Only output during the extended period, not the event period.

> **Warning:** The performance of this class needs to be optimized.

class andes.core.service.**VarHold**(*u*, *hold*, *vtype=None*, *name=None*, *tex_name=None*, *info=None*)

Service for holding the input when the hold signal is on.

Parameters

hold
[v-provider, binary] Hold signal array with length equal to the input. For elements that are 1, the corresponding inputs are held until the hold signal returns to 0.

3.7.9 Flags

class andes.core.service.**FlagCondition**(*u*, *func*, *flag=1*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Class for flagging values based on a condition function.

By default, values whose condition function output equal that equal to True/1 will be flagged as *1*. *0* otherwise.

Parameters

u
Input parameter

func
A condition function that returns True or False.

flag
[1 by default, only 0 or 1 is accepted.] The flag for the inputs whose condition output is True.

> **Warning:** This class is not ready.
>
> *FlagCondition* can only be applied to *BaseParam* with *cache=True*. Applying to *Service* will fail unless *cache* is False (at a performance cost).

class andes.core.service.**FlagGreaterThan**(*u*, *value=0.0*, *flag=1*, *equal=False*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Service for flagging parameters > or >= the given value element-wise.

Parameters that satisfy the comparison (u > or >= value) will flagged as *flag* (1 by default).

class andes.core.service.**FlagLessThan**(*u*, *value=0.0*, *flag=1*, *equal=False*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Service for flagging parameters < or <= the given value element-wise.

Parameters that satisfy the comparison (u < or <= value) will flagged as *flag* (1 by default).

class andes.core.service.**FlagValue**(*u*, *value*, *flag=0*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Class for flagging values that equal to the given value.

By default, values that equal to *value* will be flagged as *0*. Non-matching values will be flagged as *1*.

Parameters

u
Input parameter

value
Value to flag. Can be None, string, or a number.

flag
[0 by default, only 0 or 1 is accepted.] The flag for the matched ones

Warning: *FlagNotNone* can only be applied to *BaseParam* with *cache=True*. Applying to *Service* will fail unless *cache* is False (at a performance cost).

3.7.10 Data Select

class andes.core.service.**DataSelect**(*optional*, *fallback*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*)

Class for selecting values for optional DataParam or NumParam.

This service is a v-provider that uses optional DataParam when available. Otherwise, use the fallback value.

DataParam will be tested for *None*, and NumParam will be tested with `np.isnan()`.

Notes

An use case of DataSelect is remote bus. One can do

```
self.buss = DataSelect(option=self.busr, fallback=self.bus)
```

Then, pass `self.buss` instead of `self.bus` as indexer to retrieve voltages.

Another use case is to allow an optional turbine rating. One can do

```
self.Tn = NumParam(default=None)
self.Sg = ExtParam(...)
self.Sn = DataSelect(Tn, Sg)
```

class andes.core.service.**NumSelect**(*optional*, *fallback*, *name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *ignore_cond: ~typing.Callable | None = functools.partial(<ufunc 'equal'>, 0)*)

Class for selecting values for optional NumParam.

NumSelect works with internal and external parameters.

Any values equal to `np.nan` will always be ignored. If one needs to ignore values based on additional conditions, pass it through `ignore_cond`. For example, to ignore zero values, use `ignore_cond = partial(np.equal, 0)`.

Examples

One use case is to allow an optional turbine rating. One can do

```
self.Tn = NumParam(default=None) self.Sg = ExtParam(...) self.Sn =
DataSelect(Tn, Sg)
```

3.7.11 Miscellaneous

class andes.core.service.**InitChecker**(*u*, *lower=None*, *upper=None*, *equal=None*, *not_equal=None*, *enable=True*, *error_out=False*, ***kwargs*)

Class for checking init values against known typical values.

Instances will be stored in *Model.services_post* and *Model.services_icheck*, which will be checked in *Model.post_init_check()* after initialization.

Parameters

u
v-provider to be checked

lower
[float, BaseParam, BaseVar, BaseService] lower bound

upper
[float, BaseParam, BaseVar, BaseService] upper bound

equal
[float, BaseParam, BaseVar, BaseService] values that the value from *v_str* should equal

not_equal
[float, BaseParam, BaseVar, BaseService] values that should not equal

enable
[bool] True to enable checking

Examples

Let's say generator excitation voltages are known to be in the range of 1.6 - 3.0 per unit. One can add the following instance to *GENBase*

```
self._vfc = InitChecker(u=self.vf,
                        info='vf range',
                        lower=1.8,
                        upper=3.0,
                        )
```

lower and *upper* can also take v-providers instead of float values.

One can also pass float values from Config to make it adjustable as in our implementation of `GENBase._vfc`.

class andes.core.service.**ApplyFunc**(*u*, *func*, *name=None*, *tex_name=None*, *info=None*, *cache=True*)

Class for applying a numerical function on a parameter..

Parameters

u
Input parameter

func
A condition function that returns True or False.

> **Warning:** This class is not ready.

class andes.core.service.**CurrentSign**(*bus*, *bus1*, *bus2*, *name=None*, *tex_name=None*, *info=None*)

Service for computing the sign of the current flowing through a series device.

With a given line connecting *bus1* and *bus2*, one can compute the current flow using `(v1*exp(1j*a1) - v2*exp(1j*a2)) / (r + jx)` whose value is the outflow on *bus1*.

CurrentSign can be used to compute the sign to be multiplied depending on the observing bus. For each value in *bus*, the sign will be `+1` if it appears in *bus1* or `-1` otherwise.

```
bus1          bus2
 *------>>-----*
bus(+)        bus(-)
```

class andes.core.service.**RandomService**(*func=<built-in method rand of numpy.random.mtrand.RandomState object>*, ***kwargs*)

A service type for generating random numbers.

Parameters

name
[str] Name

func
[Callable] A callable for generating the random variable.

Warning: The value will be randomized every time it is accessed. Do not use it if the value needs to be stable for each simulation step.

class andes.core.service.**SwBlock**(***, *init*, *ns*, *blocks*, *ext_sel=None*, *name=None*, *tex_name=None*, *info=None*)

Service type for switched shunt blocks.

3.8 Discrete

3.8.1 Background

The discrete component library contains a special type of block for modeling the discontinuity in power system devices. Such continuities can be device-level physical constraints or algorithmic limits imposed on controllers.

The base class for discrete components is *andes.core.discrete.Discrete*.

Discrete([name, tex_name, info, no_warn, ...])	Base discrete class.

andes.core.discrete.Discrete

class andes.core.discrete.**Discrete**(*name=None*, *tex_name=None*, *info=None*, *no_warn=False*, *min_iter=2*, *err_tol=0.01*)

Base discrete class.

Discrete classes export flag arrays (usually boolean) .

__init__(*name=None*, *tex_name=None*, *info=None*, *no_warn=False*, *min_iter=2*, *err_tol=0.01*)

Methods

check_eq(**kwargs)	This function is called in `l_check_eq` after updating equations.
check_iter_err([niter, err])	Check if the minimum iteration or maximum error is reached so that this discrete block should be enabled.
check_var(*args, **kwargs)	This function is called in `l_update_var` before evaluating equations.
get_names()	Available symbols from this class
get_tex_names()	Return tex_names of exported flags.
get_values()	
list2array(n)	Allocate memory for the discrete flags specified in *self.export_flags*.
warn_init_limit()	Warn if associated variables are initialized at limits.

Discrete.check_eq

Discrete.**check_eq**(***kwargs*)

This function is called in `l_check_eq` after updating equations.

It updates internal flags, set differential equations, and record pegged variables.

Discrete.check_iter_err

Discrete.**check_iter_err**(*niter=None*, *err=None*)

Check if the minimum iteration or maximum error is reached so that this discrete block should be enabled.

Only when both *niter* and *err* are given, (niter < min_iter) , and (err > err_tol) it will return False.

This logic will start checking the discrete states if called from an external solver that does not feed *niter* or *err* at each step.

Returns

bool
True if it should be enabled, False otherwise

Discrete.check_var

`Discrete.`**`check_var`**`(*args, **kwargs)`

This function is called in `l_update_var` before evaluating equations.

It should update internal flags only.

Parameters

adjust_upper
[bool] True to adjust the upper limit to the value of the variable. Supported by limiters.

adjust_lower
[bool] True to adjust the lower limit to the value of the variable. Supported by limiters.

Discrete.get_names

`Discrete.`**`get_names`**`()`

Available symbols from this class

Returns

Discrete.get_tex_names

`Discrete.`**`get_tex_names`**`()`

Return tex_names of exported flags.

TODO: Fix the bug described in the warning below.

Returns

list
A list of tex_names for all exported flags.

> **Warning:** If underscore _ appears in both flag tex_name and *self.tex_name* (for example, when this discrete is within a block), the exported tex_name will become invalid for SymPy. Variable name substitution will fail.

Discrete.get_values

Discrete.**get_values**()

Discrete.list2array

Discrete.**list2array**(*n*)

Allocate memory for the discrete flags specified in *self.export_flags*.

Parameters

n
[int] Number of elements in the array. Provided by the calling function.

Discrete.warn_init_limit

Discrete.**warn_init_limit**()

Warn if associated variables are initialized at limits.

Attributes

class_name

Discrete.class_name

property Discrete.**class_name**

The uniqueness of discrete components is the way it works. Discrete components take inputs, criteria, and exports a set of flags with the component-defined meanings. These exported flags can be used in algebraic or differential equations to build piece-wise equations.

For example, *Limiter* takes a v-provider as input, two v-providers as the upper and the lower bound. It exports three flags: *zi* (within bound), *zl* (below lower bound), and *zu* (above upper bound). See the code example in `models/pv.py` for an example voltage-based PQ-to-Z conversion.

It is important to note when the flags are updated. Discrete subclasses can use three methods to check and update the value and equations. Among these methods, *check_var* is called *before* equation evaluation, but *check_eq* and *set_eq* are called *after* equation update. In the current implementation, *check_var* updates flags for variable-based discrete components (such as *Limiter*). *check_eq* updates flags for equation-involved discrete components (such as *AntiWindup*). *set_var`* is currently only used by *AntiWindup* to store the pegged states.

ANDES includes the following types of discrete components.

3.8.2 Limiters

class andes.core.discrete.**Limiter**(*u*, *lower*, *upper*, *enable=True*, *name: str = None*, *tex_name: str = None*, *info: str = None*, *min_iter: int = 2*, *err_tol: float = 0.01*, *allow_adjust: bool = True*, *no_lower=False*, *no_upper=False*, *sign_lower=1*, *sign_upper=1*, *equal=True*, *no_warn=False*, *zu=0.0*, *zl=0.0*, *zi=1.0*)

Base limiter class.

This class compares values and sets limit values. Exported flags are *zi*, *zl* and *zu*.

Parameters

u
[BaseVar] Input Variable instance

lower
[BaseParam] Parameter instance for the lower limit

upper
[BaseParam] Parameter instance for the upper limit

no_lower
[bool] True to only use the upper limit

no_upper
[bool] True to only use the lower limit

sign_lower: 1 or -1
Sign to be multiplied to the lower limit

sign_upper: bool
Sign to be multiplied to the upper limit

equal
[bool] True to include equal signs in comparison (>= or <=).

no_warn
[bool] Disable initial limit warnings

zu
[0 or 1] Default value for *zu* if not enabled

zl
[0 or 1] Default value for *zl* if not enabled

zi
[0 or 1] Default value for *zi* if not enabled

Notes

If not enabled, the default flags are `zu = zl = 0`, `zi = 1`.

Attributes

zl
[array-like] Flags of elements violating the lower limit; A array of zeros and/or ones.

zi
[array-like] Flags for within the limits

zu
[array-like] Flags for violating the upper limit

class andes.core.discrete.**SortedLimiter**(*u*, *lower*, *upper*, *n_select: int = 5*, *name=None*, *tex_name=None*, *enable=True*, *abs_violation=True*, *min_iter: int = 2*, *err_tol: float = 0.01*, *allow_adjust: bool = True*, *zu=0.0*, *zl=0.0*, *zi=1.0*, *ql=0.0*, *qu=0.0*)

A limiter that sorts inputs based on the absolute or relative amount of limit violations.

Parameters

n_select
[int] the number of violations to be flagged, for each of over-limit and under-limit cases. If *n_select* == 1, at most one over-limit and one under-limit inputs will be flagged. If *n_select* is zero, heuristics will be used.

abs_violation
[bool] True to use the absolute violation. False if the relative violation abs(violation/limit) is used for sorting. Since most variables are in per unit, absolute violation is recommended.

class andes.core.discrete.**HardLimiter**(*u*, *lower*, *upper*, *enable=True*, *name: str = None*, *tex_name: str = None*, *info: str = None*, *min_iter: int = 2*, *err_tol: float = 0.01*, *allow_adjust: bool = True*, *no_lower=False*, *no_upper=False*, *sign_lower=1*, *sign_upper=1*, *equal=True*, *no_warn=False*, *zu=0.0*, *zl=0.0*, *zi=1.0*)

Hard limiter for algebraic or differential variable. This class is an alias of *Limiter*.

class andes.core.discrete.**RateLimiter**(*u*, *lower*, *upper*, *enable=True*, *no_lower=False*, *no_upper=False*, *lower_cond=1*, *upper_cond=1*, *name=None*, *tex_name=None*, *info=None*)

Rate limiter for a differential variable.

RateLimiter does not export any variable. It directly modifies the differential equation value.

> **Warning:** RateLimiter cannot be applied to a state variable that already undergoes an AntiWindup limiter. Use *AntiWindupRate* for a rate-limited anti-windup limiter.

Notes

RateLimiter inherits from Discrete to avoid internal naming conflicts with *Limiter*.

class andes.core.discrete.**AntiWindup**(*u*, *lower*, *upper*, *enable=True*, *no_warn=False*, *no_lower=False*, *no_upper=False*, *sign_lower=1*, *sign_upper=1*, *name=None*, *tex_name=None*, *info=None*, *state=None*, *allow_adjust: bool = True*)

Anti-windup limiter.

Anti-windup limiter prevents the wind-up effect of a differential variable. The derivative of the differential variable is reset if it continues to increase in the same direction after exceeding the limits. During the derivative return, the limiter will be inactive

```
if x > xmax and x dot > 0: x = xmax and x dot = 0
if x < xmin and x dot < 0: x = xmin and x dot = 0
```

This class takes one more optional parameter for specifying the equation.

Parameters

state
[State, ExtState] A State (or ExtState) whose equation value will be checked and, when condition satisfies, will be reset by the anti-windup-limiter.

class andes.core.discrete.**AntiWindupRate**(*u*, *lower*, *upper*, *rate_lower*, *rate_upper*, *no_lower=False*, *no_upper=False*, *rate_no_lower=False*, *rate_no_upper=False*, *rate_lower_cond=None*, *rate_upper_cond=None*, *enable=True*, *name=None*, *tex_name=None*, *info=None*, *allow_adjust: bool = True*)

Anti-windup limiter with rate limits

3.8.3 Comparers

class andes.core.discrete.**LessThan**(*u*, *bound*, *equal=False*, *enable=True*, *name=None*, *tex_name=None*, *info: str = None*, *cache: bool = False*, *z0=0*, *z1=1*)

Less than (<) comparison function that tests if `u < bound`.

Exports two flags: z1 and z0. For elements satisfying the less-than condition, the corresponding z1 = 1. z0 is the element-wise negation of z1.

Notes

The default z0 and z1, if not enabled, can be set through the constructor. By default, the model will not adjust the limit.

class andes.core.discrete.**Selector**(**args*, *fun*, *tex_name=None*, *info=None*)

Selection between two variables using the provided reduce function.

The reduce function should take the given number of arguments. An example function is *np.maximum.reduce* which can be used to select the maximum.

Names are in *s0*, *s1*.

> **Warning:** A potential bug when more than two inputs are provided, and values in different inputs are equal. Only two inputs are allowed.
>
> Deprecated since version 1.5.9: Use of this class for comparison-based output is discouraged. Instead, use *LessThan* and *Limiter* to construct piesewise equations.
>
> See the new implementation of `HVGate` and `LVGate`.

See also:

numpy.ufunc.reduce
NumPy reduce function

Notes

A common pitfall is the 0-based indexing in the Selector flags. Note that exported flags start from 0. Namely, *s0* corresponds to the first variable provided for the Selector constructor.

Examples

Example 1: select the largest value between *v0* and *v1* and put it into vmax.

After the definitions of *v0* and *v1*, define the algebraic variable *vmax* for the largest value, and a selector *vs*

```
self.vmax = Algeb(v_str='maximum(v0, v1)',
                  tex_name='v_{max}',
                  e_str='vs_s0 * v0 + vs_s1 * v1 - vmax')

self.vs = Selector(self.v0, self.v1, fun=np.maximum.reduce)
```

The initial value of *vmax* is calculated by `maximum(v0, v1)`, which is the element-wise maximum in SymPy and will be generated into `np.maximum(v0, v1)`. The equation of *vmax* is to select the values based on *vs_s0* and *vs_s1*.

class andes.core.discrete.**Switcher**(*u*, *options: list | Tuple*, *info: str = None*, *name: str = None*, *tex_name: str = None*, *cache=True*)

Switcher based on an input parameter.

The switch class takes one v-provider, compares the input with each value in the option list, and exports one flag array for each option. The flags are 0-indexed.

Exported flags are named with *_s0*, *_s1*, ..., with a total number of *len(options)*. See the examples section.

Notes

Switches needs to be distinguished from Selector.

Switcher is for generating flags indicating option selection based on an input parameter. Selector is for generating flags at run time based on variable values and a selection function.

Examples

The IEEEST model takes an input for selecting the signal. Options are 1 through 6. One can construct

```
self.IC = NumParam(info='input code 1-6')  # input code
self.SW = Switcher(u=self.IC, options=[0, 1, 2, 3, 4, 5, 6])
```

If the IC values from the data file ends up being

```
self.IC.v = np.array([1, 2, 2, 4, 6])
```

Then, the exported flag arrays will be

```
{'IC_s0': np.array([0, 0, 0, 0, 0]),
 'IC_s1': np.array([1, 0, 0, 0, 0]),
 'IC_s2': np.array([0, 1, 1, 0, 0]),
 'IC_s3': np.array([0, 0, 0, 0, 0]),
 'IC_s4': np.array([0, 0, 0, 1, 0]),
 'IC_s5': np.array([0, 0, 0, 0, 0]),
 'IC_s6': np.array([0, 0, 0, 0, 1])
}
```

where *IC_s0* is used for padding so that following flags align with the options.

3.8.4 Deadband

class andes.core.discrete.**DeadBand**(*u*, *center*, *lower*, *upper*, *enable=True*, *equal=False*, *zu=0.0*, *zl=0.0*, *zi=0.0*, *name=None*, *tex_name=None*, *info=None*)

The basic deadband type.

Parameters

u
[NumParam] The pre-deadband input variable

center
[NumParam] Neutral value of the output

lower
[NumParam] Lower bound

upper
[NumParam] Upper bound

enable
[bool] Enabled if True; Disabled and works as a pass-through if False.

Notes

Input changes within a deadband will incur no output changes. This component computes and exports three flags.

Three flags computed from the current input:

- zl: True if the input is below the lower threshold
- zi: True if the input is within the deadband
- zu: True if is above the lower threshold

Initial condition:

All three flags are initialized to zero. All flags are updated during *check_var* when enabled. If the deadband component is not enabled, all of them will remain zero.

Examples

Exported deadband flags need to be used in the algebraic equation corresponding to the post-deadband variable. Assume the pre-deadband input variable is *var_in* and the post-deadband variable is *var_out*. First, define a deadband instance *db* in the model using

```
self.db = DeadBand(u=self.var_in, center=self.dbc,
                   lower=self.dbl, upper=self.dbu)
```

To implement a no-memory deadband whose output returns to center when the input is within the band, the equation for *var* can be written as

```
var_out.e_str = 'var_in * (1 - db_zi) + \
                 (dbc * db_zi) - var_out'
```

class andes.core.discrete.**DeadBandRT**(*u*, *center*, *lower*, *upper*, *enable=True*)

Deadband with flags for directions of return.

Parameters

u
[NumParam] The pre-deadband input variable

center
[NumParam] Neutral value of the output

lower
[NumParam] Lower bound

upper
[NumParam] Upper bound

enable
[bool] Enabled if True; Disabled and works as a pass-through if False.

Notes

Input changes within a deadband will incur no output changes. This component computes and exports five flags. The additional two flags on top of *DeadBand* indicate the direction of return:

- zur: True if the input is/has been within the deadband and was returned from the upper threshold
- zlr: True if the input is/has been within the deadband and was returned from the lower threshold

Initial condition:

All five flags are initialized to zero. All flags are updated during *check_var* when enabled. If the deadband component is not enabled, all of them will remain zero.

Examples

To implement a deadband whose output is pegged at the nearest deadband bounds, the equation for *var* can be provided as

```
var_out.e_str = 'var_in * (1 - db_zi) + \
                 dbl * db_zlr + \
                 dbu * db_zur - var_out'
```

3.8.5 Others

class andes.core.discrete.**Average**(*u*, *mode='step'*, *delay=0*, *name=None*, *tex_name=None*, *info=None*)

Compute the average value of a BaseVar over a period of time or a number of simulation steps.

Average is based on the memory implemented in the Delay class. The same modes as in Delay are supported.

The output of the Average class is named `<INSTANCE_NAME>_v`, where *<INSTANCE_NAME>* is the instance name of Average.

class andes.core.discrete.**Delay**(*u*, *mode='step'*, *delay=0*, *name=None*, *tex_name=None*, *info=None*)

The delay class.

Delay allows to impose a predefined and fixed "delay" (in either steps or seconds) for an input variable. The amount of delay must be a scalar and has to be given when instantiating the Delay class when defining the model.

Delay implements an internal memorize to store past variable values.

The default delay mode is *step* but can be set to *time*. In the *time* mode, the value at the `current time - delay` will be interpolated based on the two nearest times and values.

Delay can be applied to a state or an algebraic variable. The exported variable is named `<INSTANCE_NAME>_v`, where *<INSTANCE_NAME>* is the name of the Delay instance.

class andes.core.discrete.**Derivative**(*u*, *name=None*, *tex_name=None*, *info=None*)

Compute the derivative of a variable using numerical differentiation.

Derivative is based on the storage implemented in the Delay class. The delay is set to *1* step so that the current and the previous step are used.

A simple first order derivative is computed using `u(t) - u(t-1) / tstep`, where `tstep` is the current step size.

Derivative is intended to be used for algebraic variables because of discontinuity. It can be applied to a state variable, but one should instead implement the right-hand side equation of the state variable in an algebraic equation to obtain the accurate derivative.

Alternatively, the washout filter (`andes.core.block.Washout`) can be used to implement a numerically stable derivative.

The output of the Derivative class is named `<INSTANCE_NAME>_v` just like `Delay`.

class andes.core.discrete.**Sampling**(*u*, *interval=1.0*, *offset=0.0*, *name=None*, *tex_name=None*, *info=None*)

Sample and hold

Sample an input variable periodically at the given time interval and hold the value until the next sample time.

For example, this class can be used to implement a 4-second sampling of the AGC signal.

The output of *Sampling* is named `<INSTANCE_NAME>_v`, where *<INSTANCE_NAME>* is the Sampling instance name.

class andes.core.discrete.**ShuntAdjust**(***, *v*, *lower*, *upper*, *bsw*, *gsw*, *dt*, *u*, *enable=True*, *min_iter=2*, *err_tol=0.01*, *name=None*, *tex_name=None*, *info=None*, *no_warn=False*)

Class for adjusting switchable shunts.

Parameters

v

[BaseVar] Voltage measurement

lower
[BaseParam] Lower voltage bound

upper
[BaseParam] Upper voltage bound

bsw
[SwBlock] SwBlock instance for susceptance

gsw
[SwBlock] SwBlock instance for conductance

dt
[NumParam] Delay time

u
[NumParam] Connection status

min_iter
[int] Minimum iteration number to enable shunt switching

err_tol
[float] Minimum iteration tolerance to enable switching

3.9 Blocks

3.9.1 Background

The block library contains commonly used blocks (such as transfer functions and nonlinear functions). Variables and equations are pre-defined for blocks to be used as "lego pieces" for scripting DAE models. The base class for blocks is `andes.core.block.Block`.

The supported blocks include `Lag`, `LeadLag`, `Washout`, `LeadLagLimit`, `PIController`. In addition, the base class for piece-wise nonlinear functions, `Piecewise` is provided. `Piecewise` is used for implementing the quadratic saturation function `MagneticQuadSat` and exponential saturation function `MagneticExpSat`.

All variables in a block must be defined as attributes in the constructor, just like variable definition in models. The difference is that the variables are "exported" from a block to the capturing model. All exported variables need to placed in a dictionary, `self.vars` at the end of the block constructor.

Blocks can be nested as advanced usage. See the following API documentation for more details.

class andes.core.block.**Block**(*name: str | None = None*, *tex_name: str | None = None*, *info: str | None = None*, *namespace: str = 'local'*)

Base class for control blocks.

Blocks are meant to be instantiated as Model attributes to provide pre-defined equation sets. Subclasses must overload the *__init__* method to take custom inputs. Subclasses of Block must overload the *define* method to provide initialization and equation strings. Exported variables, services and blocks must be constructed into a dictionary `self.vars` at the end of the constructor.

Blocks can be nested. A block can have blocks but itself as attributes and therefore reuse equations. When a block has sub-blocks, the outer block must be constructed with a``name``.

Nested block works in the following way: the parent block modifies the sub-block's `name` attribute by prepending the parent block's name at the construction phase. The parent block then exports the sub-block as a whole. When the parent Model class picks up the block, it will recursively import the variables in the block and the sub-blocks correctly. See the example section for details.

Parameters

name
[str, optional] Block name

tex_name
[str, optional] Block LaTeX name

info
[str, optional] Block description.

namespace
[str, local or parent] Namespace of the exported elements. If 'local', the block name will be prepended by the parent. If 'parent', the original element name will be used when exporting.

Warning: It is a good practice to avoid more than one level of nesting, to avoid multi-underscore variable names.

Examples

Example for two-level nested blocks. Suppose we have the following hierarchy

SomeModel instance M contains an instance of LeadLag block named A, which contains a Lag instance named B. Both A and B exports two variables `x` and `y`.

In the code for SomeModel, the following code is used to instantiate LeadLag

```
class SomeModel:
    def __init__(...)
        ... self.A = LeadLag(name='A',
                             u=self.foo1, T1=self.foo2, T2=self.foo3)
```

To use Lag in the LeadLag code, the following lines are found in the constructor of LeadLag

```
class LeadLag:
    def __init__(name, ...)
        ... self.B = Lag(u=self.y, K=self.K, T=self.T)

        # register `self.B` with the name `A` self.vars = {..., 'B':
        self.B}
```

When instantiating any block instance, its `__setattr__` function assigns names to exported variables and blocks. For the LeadLag instance with the name `A`, its member attribute `B` is assigned the name `A_B` by convention. That is, `A_B` will be set to *B.name*.

When A is picked up by `SomeModel.__setattr__`, B is captured from A's exports with the name `A_B`. Recursively, B's variables are exported, Recall that *B.name* is now `A_B`, following the naming rule (parent block's name + variable name), B's internal variables become `A_B_x` and `A_B_y`.

Again, the LeadLag instance name (`A.name` in this example) must be given when instantiating in *SomeModel*'s constructor to ensure correct name propagation. If there is more than one level of nesting, other than the terminal-level block, all names of the parent blocks must be provided at instantiation.

In such a way, B's `define()` needs no modification since the naming rule is the same. For example, B's internal y is always `{self.name}_y`, although the nested B has gotten a new name `A_B`.

define()

Function for setting the initialization and equation strings for internal variables. This method must be implemented by subclasses.

The equations should be written with the "final" variable names. Let's say the block instance is named *blk* (kept at `self.name` of the block), and an internal variable *v* is defined. The internal variable will be captured as `blk_v` by the parent model. Therefore, all equations should use `{self.name}_v` to represent variable `v`, where `{self.name}` is the name of the block at run time.

On the other hand, the names of externally provided parameters or variables are obtained by directly accessing the `name` attribute. For example, if `self.T` is a parameter provided through the block constructor, `{self.T.name}` should be used in the equation.

See also:

PIController.define
Equations for the PI Controller block

Examples

An internal variable `v` has a trivial equation `T = v`, where T is a parameter provided to the block constructor.

In the model, one has

```
class SomeModel():
    def __init__(...)
        self.input = Algeb()
        self.T = Param()

        self.blk = ExampleBlock(u=self.input, T=self.T)
```

In the ExampleBlock function, the internal variable is defined in the constructor as

```
class ExampleBlock():
    def __init__(...):
        self.v = Algeb()
        self.vars = {'v', self.v}
```

In the `define`, the equation is provided as

```
def define(self):
    self.v.v_str = '{self.T.name}'
    self.v.e_str = '{self.T.name} - {self.name}_v'
```

In the parent model, `v` from the block will be captured as `blk_v`, and the equation will evaluate into

```
self.blk_v.v_str = 'T'
self.blk_v.e_str = 'T - blk_v'
```

3.9.2 Transfer Functions

The following transfer function blocks have been implemented. They can be imported to build new models.

Linear

class andes.core.block.**Gain**(*u*, *K*, *name=None*, *tex_name=None*, *info=None*)

Gain block.

```
     ┌─────┐
u -> │  K  │ -> y
     └─────┘
```

Exports an algebraic output *y*.

define()

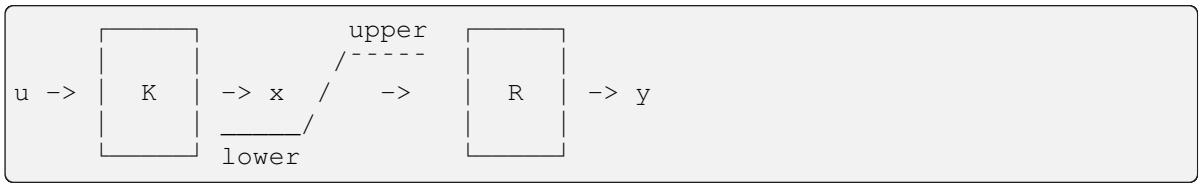
Implemented equation and the initial condition are

$$y = Ku$$
$$y^{(0)} = Ku^{(0)}$$

class andes.core.block.**GainLimiter**(*u*, *K*, *R*, *lower*, *upper*, *no_lower=False*, *no_upper=False*, *sign_lower=1*, *sign_upper=1*, *name=None*, *tex_name=None*, *info=None*)

Gain followed by a limiter and another gain.

Exports the limited output *y*, unlimited output *x*, and HardLimiter *lim*.



Parameters

u
[str, BaseVar] Input variable, or an equation string for constructing an anonymous variable

K
[str, BaseParam, BaseService] Initial gain for *u* before limiter

R
[str, BaseParam, BaseService] Post limiter gain

define()
TODO: write docstring

class andes.core.block.**Piecewise**(*u*, *points: List | Tuple*, *funs: List | Tuple*, *name=None*, *tex_name=None*, *info=None*)

Piecewise block. Outputs an algebraic variable *y*.

This block takes a list of *N* points, *[x0, x1, ...x_{n-1}]* to define N+1 ranges, namely (-inf, x0), (x0, x1), ..., (x_{n-1}, +inf). and a list of *N+1* function strings *[fun0, ..., fun_n]*.

Inputs that fall within each range applies the corresponding function. The first range (-inf, x0) applies *fun_0*, and the last range (x_{n-1}, +inf) applies the last function *fun_n*.

The function returns zero if no condition is met.

Parameters

points
[list, tuple] A list of piecewise points. Need to be provided in the constructor function.

funs
[list, tuple] A list of strings for the piecewise functions. Need to be provided in the overloaded *define* function.

define()
Build the equation string for the piecewise equations.

`self.funs` needs to be provided with the function strings corresponding to each range.

class andes.core.block.**HVGate**(*u1*, *u2*, *name=None*, *tex_name=None*, *info=None*)

High Value Gate. Outputs the maximum of two inputs.

class andes.core.block.**LVGate**(*u1*, *u2*, *name=None*, *tex_name=None*, *info=None*)

Low Value Gate. Outputs the minimum of the two inputs.

class andes.core.block.**DeadBand1**(*u*, *center*, *lower*, *upper*, *gain=1.0*, *enable=True*, *name=None*, *tex_name=None*, *info=None*, *namespace='local'*)

Deadband type 1 (linear, non-step).

Parameters

center
Default value when within the deadband. If the input is an error signal, center should be set to zero.

gain
Gain multiplied to DeadBand discrete block's output.

Notes

Block diagram

First Order

class andes.core.block.**Integrator**(*u*, *T*, *K*, *y0*, *check_init=True*, *name=None*, *tex_name=None*, *info=None*)

Integrator block.

Exports a differential variable *y*.

The initial output needs to be specified through *y0*.

define()

Implemented equation and the initial condition are

$$\dot{y} = Ku$$
$$y^{(0)} = 0$$

class andes.core.block.**IntegratorAntiWindup**(*u*, *T*, *K*, *y0*, *lower*, *upper*, *name=None*, *tex_name=None*, *info=None*, *no_warn=False*)

Integrator block with anti-windup limiter.

Exports a differential variable *y* and an AntiWindup *lim*. The initial output must be specified through *y0*.

define()

Implemented equation and the initial condition are

$$\dot{y} = Ku$$
$$y^{(0)} = 0$$

class andes.core.block.**Lag**(*u*, *T*, *K*, *D=1*, *name=None*, *tex_name=None*, *info=None*)

Lag (low pass filter) transfer function.

Exports one state variable *y* as the output.

Parameters

K
Gain

T
Time constant

D
Constant

u
Input variable

define()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - Dy)$$
$$y^{(0)} = Ku/D$$

class andes.core.block.**LagAntiWindup**(*u*, *T*, *K*, *lower*, *upper*, *D=1*, *name=None*, *tex_name=None*, *info=None*)

Lag (low pass filter) transfer function block with an anti-windup limiter.

Exports one state variable *y* as the output and one AntiWindup instance *lim*.

Parameters

K
Gain

T
Time constant

D
Constant

u
Input variable

define()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - Dy)$$
$$y^{(0)} = Ku/D$$

class andes.core.block.**LagFreeze**(*u*, *T*, *K*, *freeze*, *D=1*, *name=None*, *tex_name=None*, *info=None*)

Lag with an input to freeze the state.

During the period when the freeze signal is 1, the LagFreeze output will be frozen.

define()

Notes

Equations and initial values are

$$T\dot{y} = (1 - freeze) * (Ku - y)$$
$$y^{(0)} = Ku$$

class andes.core.block.**LagAWFreeze**(*u*, *T*, *K*, *lower*, *upper*, *freeze*, *D=1*, *name=None*, *tex_name=None*, *info=None*)

Lag with anti-windup limiter and state freeze.

Note that the output *y* is a state variable.

define()

Notes

Equations and initial values are

$$T\dot{y} = (1 - freeze)(Ku - y)$$
$$y^{(0)} = Ku$$

`y` undergoes an anti-windup limiter.

class andes.core.block.**LagRate**(*u*, *T*, *K*, *rate_lower*, *rate_upper*, *D=1*, *rate_no_lower=False*, *rate_no_upper=False*, *rate_lower_cond=None*, *rate_upper_cond=None*, *name=None*, *tex_name=None*, *info=None*)

Lag (low pass filter) transfer function block with a rate limiter.

Exports one state variable *y* as the output and one AntiWindupRate instance *lim*.

Parameters

K
Gain

T
Time constant

D
Constant

u
Input variable

define()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - y)$$
$$y^{(0)} = Ku$$

class andes.core.block.**LagAntiWindupRate**(*u*, *T*, *K*, *lower*, *upper*, *rate_lower*, *rate_upper*, *D=1*, *no_lower=False*, *no_upper=False*, *rate_no_lower=False*, *rate_no_upper=False*, *rate_lower_cond=None*, *rate_upper_cond=None*, *name=None*, *tex_name=None*, *info=None*)

Lag (low pass filter) transfer function block with a rate limiter and an anti-windup limiter.

Exports one state variable *y* as the output and one AntiWindupRate instance *lim*.

Parameters

K
Gain

T
Time constant

D
Constant

u
Input variable

define()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - Dy)$$
$$y^{(0)} = Ku/D$$

class andes.core.block.**Washout**(*u*, *T*, *K*, *name=None*, *tex_name=None*, *info=None*)

Washout filter (high pass) block.

```
      ┌─────────┐
      │   sK    │
u ->  │ ─────── │ -> y
      │ 1 + sT  │
      └─────────┘
```

Exports state *x* (symbol *x'*) and output algebraic variable *y*.

define()

Notes

Equations and initial values:

$$T\dot{x'} = (u - x')$$
$$Ty = K(u - x')$$
$$x'^{(0)} = u$$
$$y^{(0)} = 0$$

class andes.core.block.**WashoutOrLag**(*u*, *T*, *K*, *name=None*, *zero_out=True*, *tex_name=None*, *info=None*)

Washout with the capability to convert to Lag when K = 0.

Can be enabled with *zero_out*. Need to provide *name* to construct.

Exports state *x* (symbol *x'*), output algebraic variable *y*, and a LessThan block *LT*.

Parameters

zero_out
[bool, optional] If True, `sT` will become 1, and the washout will become a low-pass filter. If False, functions as a regular Washout.

define()

Notes

Equations and initial values:

$$
\begin{aligned}
T\dot{x'} &= (u - x') \\
Ty = z_0 K(u - x') + z_1 Tx \\
x'^{(0)} &= u \\
y^{(0)} &= 0
\end{aligned}
$$

where `z_0` is a flag array for the greater-than-zero elements, and `z_1` is that for the less-than or equal-to zero elements.

class andes.core.block.**LeadLag**(*u*, *T1*, *T2*, *K=1*, *zero_out=True*, *name=None*, *tex_name=None*, *info=None*)

Lead-Lag transfer function block in series implementation.

```
     ┌──────────┐
     │  1 + sT1 │
u -> │ K ─────── │ -> y
     │  1 + sT2 │
     └──────────┘
```

Exports two variables: internal state *x* and output algebraic variable *y*.

Parameters

T1
[BaseParam] Time constant 1

T2
[BaseParam] Time constant 2

zero_out
[bool] True to allow zeroing out lead-lag as a pass through (when T1=T2=0)

Notes

To allow zeroing out lead-lag as a pure gain, set `zero_out` to *True*.

define()

Notes

Implemented equations and initial values

$$
\begin{aligned}
T_2\dot{x'} &= (u - x') \\
T_2 y &= KT_1(u - x') + KT_2 x' + E_2 \text{ , where} \\
E_2 &= \begin{cases} (y - Kx') & \text{if } T_1 = T_2 = 0 \& zero\_out = True \\ 0 & \text{otherwise} \end{cases} \\
x'^{(0)} &= u \\
y^{(0)} &= Ku
\end{aligned}
$$

class andes.core.block.**LeadLagLimit**(*u*, *T1*, *T2*, *lower*, *upper*, *name=None*, *tex_name=None*, *info=None*)

Lead-Lag transfer function block with hard limiter (series implementation).

Exports four variables: state *x*, output before hard limiter *ynl*, output *y*, and AntiWindup *lim*.

define()

Notes

Implemented control block equations (without limiter) and initial values

$$
\begin{aligned}
T_2\dot{x'} &= (u - x') \\
T_2 y &= T_1(u - x') + T_2 x' \\
x'^{(0)} &= y^{(0)} = u
\end{aligned}
$$

Second Order

class andes.core.block.**Lag2ndOrd**(*u*, *K*, *T1*, *T2*, *name=None*, *tex_name=None*, *info=None*)

Second order lag transfer function (low-pass filter).

```
      ┌──────────────────────┐
      │          K           │
u ->  │ ──────────────────── │ -> y
      │ 1 + sT1 + s^2 T2     │
      └──────────────────────┘
```

Exports one two state variables (*x*, *y*), where *y* is the output.

Parameters

u
Input

K
Gain

T1
First order time constant

T2
Second order time constant

define()

Notes

Implemented equations and initial values are

$$
\begin{aligned}
T_2 \dot{x} &= Ku - y - T_1 x \\
\dot{y} &= x \\
x^{(0)} &= 0 \\
y^{(0)} &= Ku
\end{aligned}
$$

class andes.core.block.**LeadLag2ndOrd**(*u*, *T1*, *T2*, *T3*, *T4*, *zero_out=False*, *name=None*, *tex_name=None*, *info=None*)

Second-order lead-lag transfer function block.

```
      ┌──────────────────────┐
      │ 1 + sT3 + s^2 T4     │
u ->  │ ──────────────────── │ -> y
      │ 1 + sT1 + s^2 T2     │
      └──────────────────────┘
```

Exports two internal states (*x1* and *x2*) and output algebraic variable *y*.

The current implementation allows any or all parameters to be zero. Four `LessThan` blocks are used to check if the parameter values are all zero. If yes, `y = u` will be imposed in the algebraic equation.

define()

Notes

Implemented equations and initial values are

$$
\begin{aligned}
T_2\dot{x}_1 &= u - x_2 - T_1 x_1 \\
\dot{x}_2 &= x_1 \\
T_2 y &= T_2 x_2 + T_2 T_3 x_1 + T_4(u - x_2 - T_1 x_1) + E_2 \text{ , where} \\
E_2 &= \begin{cases} (y - x_2) & \text{if } T_1 = T_2 = T_3 = T_4 = 0 \& zero\_out = True \\ 0 & \text{otherwise} \end{cases} \\
x_1^{(0)} &= 0 \\
x_2^{(0)} &= y^{(0)} = u
\end{aligned}
$$

PI Controllers

class andes.core.block.**PIController**(*u*, *kp*, *ki*, *ref=0.0*, *x0=0.0*, *name=None*, *tex_name=None*, *info=None*)

Proportional Integral Controller.

The controller takes an error signal as the input. It takes an optional *ref* signal, which will be subtracted from the input.

Parameters

u
[BaseVar] The input variable instance

kp
[BaseParam] The proportional gain parameter instance

ki
[[type]] The integral gain parameter instance

define()

Define equations for the PI Controller.

Notes

One state variable `xi` and one algebraic variable `y` are added.

Equations implemented are

$$
\begin{aligned}
\dot{x_i} &= k_i * (u - ref) \\
y &= x_i + k_p * (u - ref)
\end{aligned}
$$

class andes.core.block.**PIAWHardLimit**(*u*, *kp*, *ki*, *aw_lower*, *aw_upper*, *lower*, *upper*, *no_lower=False*, *no_upper=False*, *ref=0.0*, *x0=0.0*, *name=None*, *tex_name=None*, *info=None*)

PI controller with anti-windup limiter on the integrator and hard limit on the output.

Limits `lower` and `upper` are on the final output, and `aw_lower` `aw_upper` are on the integrator.

define()

Define equations for the PI Controller.

Notes

One state variable `xi` and one algebraic variable `y` are added.

Equations implemented are

$$\dot{x_i} = k_i * (u - ref)$$
$$y = x_i + k_p * (u - ref)$$

class andes.core.block.**PITrackAW**(*u*, *kp*, *ki*, *ks*, *lower*, *upper*, *no_lower=False*, *no_upper=False*, *ref=0.0*, *x0=0.0*, *name=None*, *tex_name=None*, *info=None*)

PI with tracking anti-windup limiter

define()

Function for setting the initialization and equation strings for internal variables. This method must be implemented by subclasses.

The equations should be written with the "final" variable names. Let's say the block instance is named *blk* (kept at `self.name` of the block), and an internal variable *v* is defined. The internal variable will be captured as `blk_v` by the parent model. Therefore, all equations should use `{self.name}_v` to represent variable `v`, where `{self.name}` is the name of the block at run time.

On the other hand, the names of externally provided parameters or variables are obtained by directly accessing the `name` attribute. For example, if `self.T` is a parameter provided through the block constructor, `{self.T.name}` should be used in the equation.

See also:

PIController.define
Equations for the PI Controller block

Examples

An internal variable `v` has a trivial equation `T = v`, where T is a parameter provided to the block constructor.

In the model, one has

```
class SomeModel():
    def __init__(...)
        self.input = Algeb()
        self.T = Param()

        self.blk = ExampleBlock(u=self.input, T=self.T)
```

In the ExampleBlock function, the internal variable is defined in the constructor as

```
class ExampleBlock():
    def __init__(...):
        self.v = Algeb()
        self.vars = {'v', self.v}
```

In the `define`, the equation is provided as

```
def define(self):
    self.v.v_str = '{self.T.name}'
    self.v.e_str = '{self.T.name} - {self.name}_v'
```

In the parent model, `v` from the block will be captured as `blk_v`, and the equation will evaluate into

```
self.blk_v.v_str = 'T'
self.blk_v.e_str = 'T - blk_v'
```

class andes.core.block.**PIFreeze**(*u*, *kp*, *ki*, *freeze*, *ref=0.0*, *x0=0.0*, *name=None*, *tex_name=None*, *info=None*)

PI controller with state freeze.

Freezes state when the corresponding *freeze == 1*.

Notes

Tested in *experimental.TestPITrackAW.PIFreeze*.

define()

Notes

One state variable `xi` and one algebraic variable `y` are added.

Equations implemented are

$$\dot{x_i} = k_i * (u - ref)$$
$$y = (1 - freeze) * (x_i + k_p * (u - ref)) + freeze * y$$

class andes.core.block.**PITrackAWFreeze**(*u*, *kp*, *ki*, *ks*, *lower*, *upper*, *freeze*, *no_lower=False*, *no_upper=False*, *ref=0.0*, *x0=0.0*, *name=None*, *tex_name=None*, *info=None*)

PI controller with tracking anti-windup limiter and state freeze.

define()

Function for setting the initialization and equation strings for internal variables. This method must be implemented by subclasses.

The equations should be written with the "final" variable names. Let's say the block instance is named *blk* (kept at `self.name` of the block), and an internal variable *v* is defined. The internal variable will be captured as `blk_v` by the parent model. Therefore, all equations should use `{self.name}_v` to represent variable `v`, where `{self.name}` is the name of the block at run time.

On the other hand, the names of externally provided parameters or variables are obtained by directly accessing the `name` attribute. For example, if `self.T` is a parameter provided through the block constructor, `{self.T.name}` should be used in the equation.

See also:

PIController.define
Equations for the PI Controller block

Examples

An internal variable `v` has a trivial equation `T = v`, where T is a parameter provided to the block constructor.

In the model, one has

```
class SomeModel():
    def __init__(...)
        self.input = Algeb()
        self.T = Param()

        self.blk = ExampleBlock(u=self.input, T=self.T)
```

In the ExampleBlock function, the internal variable is defined in the constructor as

```
class ExampleBlock():
    def __init__(...):
        self.v = Algeb()
        self.vars = {'v', self.v}
```

In the `define`, the equation is provided as

```
def define(self):
    self.v.v_str = '{self.T.name}'
    self.v.e_str = '{self.T.name} - {self.name}_v'
```

In the parent model, `v` from the block will be captured as `blk_v`, and the equation will evaluate into

```
self.blk_v.v_str = 'T'
self.blk_v.e_str = 'T - blk_v'
```

class andes.core.block.**PIDController**(*u*, *kp*, *ki*, *kd*, *Td*, *name*, *ref=0.0*, *x0=0.0*, *tex_name=None*, *info=None*)

Proportional Integral Derivative Controller.

```
     ┌──────────────────────┐
     │       ki     skd     │
u -> │kp + ──── + ──────── │ -> y
     │       s    1 + sTd   │
     └──────────────────────┘
```

The controller takes an error signal as the input. It takes an optional `ref` signal, which will be subtracted from the input.

The name is suggessted to be specified the same as the instance name.

This block assembles a `PIController` and a `Washout`.

Parameters

u
[BaseVar] The input variable instance

kp
[BaseParam] The proportional gain parameter instance

ki
[BaseParam] The integral gain parameter instance

kd
[BaseParam] The derivative gain parameter instance

Td
[BaseParam] The derivative time constant parameter instance

define()

Define equations for the PID Controller.

Notes

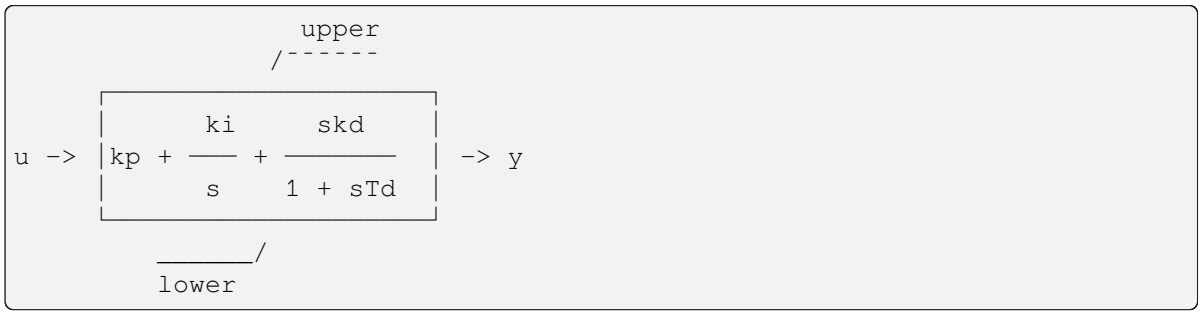
One PIController `PIC`, one Washout `xd`, and one algebraic variable `y` are added.

Equations implemented are

$$\dot{x_i} = k_i * (u - ref)$$
$$xd = Washout(u - ref)y$$
$$= x_i + k_p * (u - ref) + xd$$

class andes.core.block.**PIDAWHardLimit**(*u*, *kp*, *ki*, *kd*, *Td*, *aw_lower*, *aw_upper*, *lower*, *upper*, *name*, *no_lower=False*, *no_upper=False*, *ref=0.0*, *x0=0.0*, *tex_name=None*, *info=None*)

PID controller with anti-windup limiter on the integrator and hard limit on the output.



The controller takes an error signal as the input.

Limits `lower` and `upper` are on the final output, and `aw_lower` `aw_upper` are on the integrator.

The name is suggessted to be specified the same as the instance name.

Parameters

u
[BaseVar] The input variable instance

kp
[BaseParam] The proportional gain parameter instance

ki
[BaseParam] The integral gain parameter instance

kd
[BaseParam] The derivative gain parameter instance

Td
[BaseParam] The derivative time constant parameter instance

define()

Define equations for the PI Controller.

Notes

One state variable `xi` and one algebraic variable `y` are added.

Equations implemented are

$$\dot{x_i} = k_i * (u - ref)$$
$$y = x_i + k_p * (u - ref)$$

class andes.core.block.**PIDTrackAW**(*u*, *kp*, *ki*, *kd*, *Td*, *ks*, *lower*, *upper*, *no_lower=False*, *no_upper=False*, *ref=0.0*, *x0=0.0*, *name=None*, *tex_name=None*, *info=None*)

PID with tracking anti-windup limiter

define()

Function for setting the initialization and equation strings for internal variables. This method must be implemented by subclasses.

The equations should be written with the "final" variable names. Let's say the block instance is named *blk* (kept at `self.name` of the block), and an internal variable *v* is defined. The internal variable will be captured as `blk_v` by the parent model. Therefore, all equations should use `{self.name}_v` to represent variable `v`, where `{self.name}` is the name of the block at run time.

On the other hand, the names of externally provided parameters or variables are obtained by directly accessing the `name` attribute. For example, if `self.T` is a parameter provided through the block constructor, `{self.T.name}` should be used in the equation.

See also:

PIController.define
Equations for the PI Controller block

Examples

An internal variable `v` has a trivial equation `T = v`, where T is a parameter provided to the block constructor.

In the model, one has

```
class SomeModel():
    def __init__(...)
        self.input = Algeb()
        self.T = Param()

        self.blk = ExampleBlock(u=self.input, T=self.T)
```

In the ExampleBlock function, the internal variable is defined in the constructor as

```
class ExampleBlock():
    def __init__(...):
        self.v = Algeb()
        self.vars = {'v', self.v}
```

In the `define`, the equation is provided as

```
def define(self):
    self.v.v_str = '{self.T.name}'
    self.v.e_str = '{self.T.name} - {self.name}_v'
```

In the parent model, `v` from the block will be captured as `blk_v`, and the equation will evaluate into

```
self.blk_v.v_str = 'T'
self.blk_v.e_str = 'T - blk_v'
```

3.9.3 Saturation

class andes.models.exciter.**ExcExpSat**(*E1*, *SE1*, *E2*, *SE2*, *name=None*, *tex_name=None*, *info=None*)

Exponential exciter saturation block to calculate A and B from E1, SE1, E2 and SE2. Input parameters will be corrected and the user will be warned. To disable saturation, set either E1 or E2 to 0.

Parameters

E1
[BaseParam] First point of excitation field voltage

SE1: BaseParam
Coefficient corresponding to E1

E2
[BaseParam] Second point of excitation field voltage

SE2: BaseParam
Coefficient corresponding to E2

define()

Notes

The implementation solves for coefficients *A* and *B* which satisfy

$$E_1 S_{E1} = A e^{E1 \times B} E_2 S_{E2} = A e^{E2 \times B}$$

The solutions are given by

$$E_1 S_{E1} e^{\frac{E_1 \log\left(\frac{E_2 S_{E2}}{E_1 S_{E1}}\right)}{E_1 - E_2}} - \frac{\log\left(\frac{E_2 S_{E2}}{E_1 S_{E1}}\right)}{E_1 - E_2}$$

3.9.4 Naming Convention

We loosely follow a naming convention when using modeling blocks. An instance of a modeling block is named with a two-letter acronym, followed by a number or a meaningful but short variaiable name. The acronym and the name are spelled in one word without underscore, as the output of the block already contains `_y`.

For example, two washout filters can be names `WO1` and `WO2`. In another case, a first-order lag function for voltage sensing can be called `LGv`, or even `LG` if there is only one Lag instance in the model.

Naming conventions are not strictly enforced. Expressiveness and concision are encouraged.

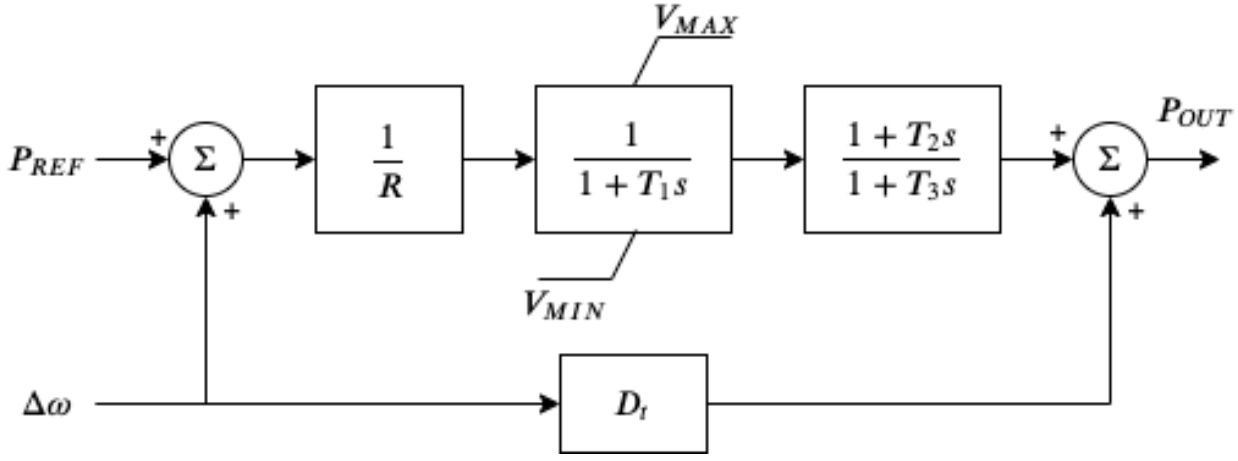
3.10 Examples

We show two examples to demonstrate modeling from equations and modeling from control block diagrams.

- The TGOV1 example shows code snippet for equation-based modeling and, as well as code for block-based modeling.
- The IEEEST example walks through the source code and explains the complete setup, including optional parameters, input selection, and manual per-unit conversion.

3.10.1 TGOV1

The *TGOV1* turbine governor model is shown as a practical example using the library.



This model is composed of a lead-lag transfer function and a first-order lag transfer function with an anti-windup limiter, which are sufficiently complex for demonstration. The corresponding differential equations

and algebraic equations are given below.

$$\begin{bmatrix} \dot{x}_{LG} \\ \dot{x}_{LL} \end{bmatrix} = \begin{bmatrix} z_{i,lim}^{LG} \left(P_d - x_{LG}\right)/T_1 \\ \left(x_{LG} - x_{LL}\right)/T_3 \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} (1-\omega) - \omega_d \\ R \times \tau_{m0} - P_{ref} \\ \left(P_{ref} + \omega_d\right)/R - P_d \\ D_t \omega_d + y_{LL} - P_{OUT} \\ \frac{T_2}{T_3}\left(x_{LG} - x_{LL}\right) + x_{LL} - y_{LL} \\ u\left(P_{OUT} - \tau_{m0}\right) \end{bmatrix}$$

where *LG* and *LL* denote the lag block and the lead-lag block, $\dot{x}_{LG}$ and $\dot{x}_{LL}$ are the internal states, y_{LL} is the lead-lag output, ω the generator speed, ω_d the generator under-speed, P_d the droop output, τ_{m0} the steady-state torque input, and P_{OUT} the turbine output that will be summed at the generator.

The code to describe the above model using equations is given below. The complete code can be found in class `TGOV1ModelAlt` in `andes/models/governor.py`.

```
def __init__(self, system, config):
  # 1. Declare parameters from case file inputs.
  self.R = NumParam(info='Turbine governor droop',
                    non_zero=True, ipower=True)
  # Other parameters are omitted.

  # 2. Declare external variables from generators.
  self.omega = ExtState(src='omega',
                 model='SynGen',
                 indexer=self.syn,
                 info='Generator speed')
  self.tm = ExtAlgeb(src='tm',
              model='SynGen',
              indexer=self.syn,
              e_str='u*(pout-tm0)',
              info='Generator torque input')

  # 3. Declare initial values from generators.
  self.tm0 = ExtService(src='tm',
               model='SynGen',
               indexer=self.syn,
               info='Initial torque input')

  # 4. Declare variables and equations.
  self.pref = Algeb(info='Reference power input',
                v_str='tm0*R',
                e_str='tm0*R-pref')
  self.wd = Algeb(info='Generator under speed',
              e_str='(1-omega)-wd')
  self.pd = Algeb(info='Droop output',
              v_str='tm0',
              e_str='(wd+pref)/R-pd')
  self.LG_x = State(info='State in the lag TF',
                v_str='pd',
```

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```
                e_str='LG_lim_zi*(pd-LG_x)/T1')
  self.LG_lim = AntiWindup(u=self.LG_x,
                  lower=self.VMIN,
                  upper=self.VMAX)
  self.LL_x = State(info='State in the lead-lag TF',
                v_str='LG_x',
                e_str='(LG_x-LL_x)/T3')
  self.LL_y = Algeb(info='Lead-lag Output',
                v_str='LG_x',
                e_str='T2/T3*(LG_x-LL_x)+LL_x-LL_y')
  self.pout = Algeb(info='Turbine output power',
                v_str='tm0',
                e_str='(LL_y+Dt*wd)-pout')
```

Another implementation of *TGOV1* makes extensive use of the modeling blocks. The resulting code is more readable as follows.

```
def __init__(self, system, config):
    TGBase.__init__(self, system, config)

    self.gain = ConstService(v_str='u/R')

    self.pref = Algeb(info='Reference power input',
                      tex_name='P_{ref}',
                      v_str='tm0 * R',
                      e_str='tm0 * R - pref',
                      )

    self.wd = Algeb(info='Generator under speed',
                    unit='p.u.',
                    tex_name=r'\omega_{dev}',
                    v_str='0',
                    e_str='(wref - omega) - wd',
                    )
    self.pd = Algeb(info='Pref plus under speed times gain',
                    unit='p.u.',
                    tex_name="P_d",
                    v_str='u * tm0',
                    e_str='u*(wd + pref + paux) * gain - pd')

    self.LAG = LagAntiWindup(u=self.pd,
                             K=1,
                             T=self.T1,
                             lower=self.VMIN,
                             upper=self.VMAX,
                             )

    self.LL = LeadLag(u=self.LAG_y,
                      T1=self.T2,
                      T2=self.T3,
                      )
```

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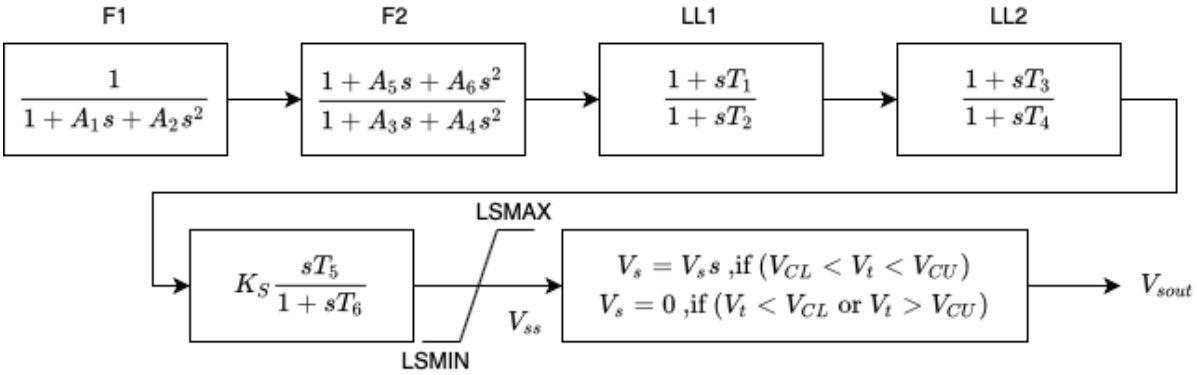
```
    self.pout.e_str = '(LL_y + Dt * wd) - pout'
```

The complete code can be found in class `TGOV1Model` in `andes/models/governor.py`.

3.10.2 IEEEST

In this example, we will explain step-by-step how *IEEEST* is programmed. The block diagram of IEEEST is given as follows. We recommend you to open up the source code in `andes/models/pss.py` and then continue reading.



First of all, modeling components are imported at the beginning.

Next, `PSSBaseData` is defined to hold parameters shared by all PSSs. `PSSBaseData` inherits from `ModelData` and calls the base constructor. There is only one field `avr` defined for the linked exciter idx.

Then, `IEEESTData` defines the input parameters for IEEEST. Use `IdxParam` for fields that store idx-es of devices that IEEEST devices link to. Use `NumParam` for numerical parameters.

PSSBase

`PSSBase` is defined for the common (external) parameters, services and variables shared by all PSSs. The class and constructor signatures are

```
class PSSBase(Model):
    def __init__(self, system, config):
        super().__init__(system, config)
```

`PSSBase` inherits from `Model` and calls the base constructor. Note that the call to `Model`'s constructor takes two positional arguments, `system` and `config` of types `System` and `ModelConfig`. Next, the group is specified, and the model flags are set.

Note: It is important to set the TDS flag to register the model. If not set, data for the model will be successfully loaded, but the variables in the model will not receive any address, and the model equations will be skipped.

There is a similar flag `self.flags.pflow` for models to participate in power flow calculations. Most dynamic models, however, are initialized after power flow.

```
self.group = 'PSS'
self.flags.tds = True
```

Next, `Replace` is used to replace input parameters that satisfy a lambda function with new values.

```
self.VCUr = Replace(self.VCU, lambda x: np.equal(x, 0.0), 999)
self.VCLr = Replace(self.VCL, lambda x: np.equal(x, 0.0), -999)
```

The value replacement happens when `VCUr` and `VCLr` is first accessed. `Replace` is executed in the model initialization phase (at the end of services update).

Next, the indices of connected generators, buses, and bus frequency measurements are retrieved. Synchronous generator idx is retrieved with

```
self.syn = ExtParam(model='Exciter', src='syn', indexer=self.avr,␣
↪export=False,
                    info='Retrieved generator idx', vtype=str)
```

Using the retrieved `self.syn`, it retrieves the buses to which the generators are connected.

```
self.bus = ExtParam(model='SynGen', src='bus', indexer=self.syn, export=False,
                    info='Retrieved bus idx', vtype=str, default=None,
                    )
```

PSS models support an optional remote bus specified through parameter `busr`. When `busr` is `None`, the generator-connected bus should be used. The following code uses `DataSelect` to select `busr` if available but falls back to `bus` otherwise.

```
self.buss = DataSelect(self.busr, self.bus, info='selected bus (bus or busr)')
```

Each PSS links to a bus frequency measurement device. If the input data does not specify one or the specified one does not exist, `DeviceFinder` can find the correct measurement device for the bus where frequency measurements should be taken.

```
self.busfreq = DeviceFinder(self.busf, link=self.buss, idx_name='bus')
```

where `busf` is the optional frequency measurement device idx, `buss` is the bus idx for which measurement device needs to be found or created.

Next, external parameters, variables and services are retrieved. Note that the PSS output `vsout` is pre-allocated but the equation string is left to specific models.

IEEESTModel

`IEEESTModel` inherits from `PSSBase` and adds specific model components. After calling `PSSBase`'s constructor, IEEESTModel adds config entries to allow specifying the model for frequency measurement, because there may be multiple frequency measurement models in the future.

```
self.config.add(OrderedDict([('freq_model', 'BusFreq')]))
self.config.add_extra('_help', {'freq_model': 'default freq. measurement model
↪'})
self.config.add_extra('_alt', {'freq_model': ('BusFreq',)})
```

We set the chosen measurement model to `busf` so that `DeviceFinder` knows which model to use if it needs to create new devices.

```
self.busf.model = self.config.freq_model
```

Next, because bus voltage is an algebraic variable, we use `Derivative` to calculate the finite difference to approximate its derivative.

```
self.dv = Derivative(self.v, tex_name='dV/dt', info='Finite difference of bus␣
↪voltage')
```

Then, we retrieve the coefficient to convert power from machine base to system base using `ConstService`, given by Sb / Sn. This is needed for input mode 3, electric power in machine base.

```
self.SnSb = ExtService(model='SynGen', src='M', indexer=self.syn, attr='pu_
↪coeff',
                       info='Machine base to sys base factor for power',
                       tex_name='(Sb/Sn)')
```

Note that the `ExtService` access the `pu_coeff` field of the `M` variables of synchronous generators. Since `M` is a machine-base power quantity, `M.pu_coeff` stores the multiplication coefficient to convert each of them from machine bases to the system base, which is Sb / Sn.

The input mode is parsed into boolean flags using `Switcher`:

```
self.SW = Switcher(u=self.MODE,
                   options=[0, 1, 2, 3, 4, 5, 6],
                   )
```

where the input `u` is the MODE parameter, and `options` is a list of accepted values. `Switcher` boolean arrays `s0`, `s1`, ..., `sN`, where `N = len(options) - 1`. We added `0` to `options` for padding so that `SW_s1` corresponds to MODE 1. It improves the readability of the code as we will see next.

The input signal `sig` is an algebraic variable given by

```
self.sig = Algeb(tex_name='S_{ig}',
                 info='Input signal',
                 )

self.sig.v_str = 'SW_s1*(omega-1) + SW_s2*0 + SW_s3*(tm0/SnSb) + ' \
                 'SW_s4*(tm-tm0) + SW_s5*v + SW_s6*0'
```

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```
self.sig.e_str = 'SW_s1*(omega-1) + SW_s2*(f-1) + SW_s3*(te/SnSb) + ' \
                 'SW_s4*(tm-tm0) + SW_s5*v + SW_s6*dv_v - sig'
```

The `v_str` and `e_str` are separated from the constructor to improve readability. They construct piece-wise functions to select the correct initial values and equations based on mode. For any variables in `v_str`, they must be defined before `sig` so that they will be initialized ahead of `sig`. Clearly, `omega`, `tm`, and `v` are defined in `PSSBase` and thus come before `sig`.

The following comes the most effective part: modeling using transfer function blocks. We utilized several blocks to describe the model from the diagram. Note that the output of a block is always the block name followed by `_y`. For example, the input of `F2` is the output of `F1`, given by `F1_y`.

```
self.F1 = Lag2ndOrd(u=self.sig, K=1, T1=self.A1, T2=self.A2)

self.F2 = LeadLag2ndOrd(u=self.F1_y, T1=self.A3, T2=self.A4,
                        T3=self.A5, T4=self.A6, zero_out=True)

self.LL1 = LeadLag(u=self.F2_y, T1=self.T1, T2=self.T2, zero_out=True)

self.LL2 = LeadLag(u=self.LL1_y, T1=self.T3, T2=self.T4, zero_out=True)

self.Vks = Gain(u=self.LL2_y, K=self.KS)

self.WO = WashoutOrLag(u=self.Vks_y, T=self.T6, K=self.T5, name='WO',
                       zero_out=True)  # WO_y == Vss

self.VLIM = Limiter(u=self.WO_y, lower=self.LSMIN, upper=self.LSMAX,
                    info='Vss limiter')

self.Vss = Algeb(tex_name='V_{ss}', info='Voltage output before output limiter
↪',
                 e_str='VLIM_zi * WO_y + VLIM_zu * LSMAX + VLIM_zl * LSMIN -␣
↪Vss')

self.OLIM = Limiter(u=self.v, lower=self.VCLr, upper=self.VCUr,
                    info='output limiter')

self.vsout.e_str = 'OLIM_zi * Vss - vsout'
```

In the end, the output equation is assigned to `vsout.e_str`. It completes the equations of the IEEEST model.

Finalize

Assemble `IEEESTData` and `IEEESTModel` into `IEEEST`:

```
class IEEEST(IEEESTData, IEEESTModel):
    def __init__(self, system, config):
        IEEESTData.__init__(self)
        IEEESTModel.__init__(self, system, config)
```

Locate and edit the file `andes/models/__init__.py`. The variable `file_classes` is a list of tuples that stores the source file and class names in strings. In each tuple, the first element is the `.py` file name in the `models` folder, and the second element is a list of class names to be imported from that file.

Find the line with `pss`, then add `IEEEST` to the corresponding list of model names. The line will look like

```
file_classes = list([
    ...
    ('pss', ['IEEEST', 'ST2CUT']),
    ...
])
```

Note in the above that the string `'IEEEST'` is used. The line above is valid as long as `from andes.models.pss import IEEEST` is valid. If the source file name does not exist in any line of `file_classes`, one may add it after all prerequisite models. For example, the `pss` line should be added after exciters (and generators, of course).

Finally, locate `andes/models/group.py`, check if the class `PSS` exist. It needs to match the group name of IEEEST. If not, create one by inheriting from `GroupBase`:

```
class PSS(GroupBase):
    """Power system stabilizer group."""

    def __init__(self):
        super().__init__()
        self.common_vars.extend(('vsout',))
```

where we added `vsout` to the `common_vars` list. All models in the PSS group must have a variable named `vsout`, which is defined in `PSSBase`.

This completes the IEEEST model. When developing new models, use `andes prepare` to generate numerical code and start debugging.

CHAPTER

FOUR

RELEASE NOTES

The APIs before v3.0.0 are in beta and may change without prior notice.

4.1 v1.9 Notes

4.1.1 v1.9.0 (2024-02-01)

- Initially, `dae.t` is set to `-1.0` during power flow calculation. TDS initialization will set `dae.t = 0.0`.
- Rewritten the islanding detection algorithm.
- In `system.py`, import `importlib.util` to workaround unexported *util* module in Python 3.10.

4.2 v1.8 Notes

4.2.1 v1.8.10 (2023-08-10)

- An internal change to the xlsx parser option. Previously, the index column was set to 0, which assumes the existence of *uid* as the header. Manually input sheets without *uid* will fail. This version unsets the index column when using pandas to parse the xlsx file.
- *Jumper* is included for connectivity check.
- Add curly brackets for LaTeX symbols from sub-blocks. Nested symbols with subscripts and superscripts now display properly.

4.2.2 v1.8.9 (2023-06-22)

- Fix *Model.alter()* for parameters that are time constants for differential equations. Altered time constants are now properly updated in `dae.Tf` and will be correctly reflected in simulation results.
- Fix a bug in connectivity check.
- Support numba for Python 3.11.

4.2.3 v1.8.8 (2023-04-24)

- Repository transferred to *github.com/curent/andes*.
- Fix for frequency-dependent load model `FLoad` by not exporting the external *bus* parameter.

4.2.4 v1.8.7 (2023-03-10)

- Added IEEE 39-bus test case with dynamics in the ANDES xlsx format. Contributed by @jinningwang.
- In *interop.pandapower*, the *_verify_pf* function will not be called if TDS has been initialized. This prevents the breaking of variable addresses.

4.2.5 v1.8.6 (2023-02-13)

- Minor fix in *timeseries.py* for backward compatibility with Python 3.6.

4.2.6 v1.8.5 (2022-12-22)

- Fixed an issue to properly handle turning off a `Jumper`.
- New interface to GridCal by @JosepFanals. GridCal installation required.
- Bug fixes in WTARA1.

4.2.7 v1.8.4 (2022-11-23)

- Fixed a bug in time stepping where step sizes were not properly reduced when the solver failed to converge.

4.2.8 v1.8.3 (2022-11-15)

- Support Python 3.11. The average performance gain is a few percent.
- Made `numba` an optional dependency because it does not yet support Python 3.11.
- Fixes a bug in the time stepping logic that causes resumed simulations to overwrite the result of the previous final step.

4.2.9 v1.8.2 (2022-10-30)

This is a minor release to support SymPy 1.11.x.

Internally, `ModelData` contains a new member field `index_bases` to record the variables by which other variables are indexed. Most variables, by default, are indexed by `idx`. Some models (such as COI) whose device can link to multiple other devices can have multiple index bases.

Index bases are currently placeholders and have not been used in the current version.

4.2.10 v1.8.1 (2022-09-24)

- New turbine governor model *HYGOV4*. Thanks to Zaid Mahmood for the contribution.
- Bug fixes to saving data to xlsx file.

4.2.11 v1.8.0 (2022-08-30)

- Internal change: drop the support for reloading generated code from `calls.pkl`. All generated code are serialized into Python files and reloaded as a `pycode` module.
- Fix an issue where cases in multiprocessing fail to serialize due to not being able to find `pycode`. `pycode` is now properly imported by the main process.
- When one needs to serialize a System object, such as during multiprocessing, one needs to manually import `pycode`. This can be done by calling `andes.system.import_pycode()`.
- Internal change: serializing with `dill` is not set to recursive by default.

4.3 v1.7 Notes

4.3.1 v1.7.8 (2022-08-24)

- Support marking tests as extra so that they are not run by default. The function names for extra tests should contain `extra_test`. To run all tests, use `andes st -e` or `andes selftest --extra`.
- Add the `new_A` flag for sparse solvers to trigger actions. Currently, only the `spsolve` solver will need to rebuild and refactorize the sparse matrix.

4.3.2 v1.7.7 (2022-08-02)

- Implemented a chattering detection and stop algorithm by increasing the step size when chattering is detected.
- `TimeSeries.get_data()` works for systems with `Output`.
- Allow freezing states associated with anti-windup limiters after a certain number of iterations to prevent chattering.

Models:

- New exciter models: ESDC1A, EXAC2.
- New grid-forming inverter models: REGF1, REGF2, REGF3.
- For `IEEEG1`, normalize `K1` through `K8` if they do not sum up to 1.0

4.3.3 v1.7.6 (2022-07-11)

- In eigenvalue analysis, added parameter sweeping and scatter plot for root loci. See revised Example 4.
- Documentation improvements.

4.3.4 v1.7.5 (2022-07-05)

- Added *Fortescue* model to support symmetric component calculation. The model allows interfacing a positive-sequence bus with three buses representing three phases. See the model description for details.
- Added *PLL2* for the Synchronously-rotating Reference Frame (SRF)-based PLL.
- *REGCP1* works identically to *REGCA1* when the *pll* parameter is empty and works with a PLL.
- *REECA1* is updated to work with *vd* of the converter. If using the `REGCA1` model, `vd = v`.
- Reverted a change in Line parameter that caused SMIB case to crash.

4.3.5 v1.7.4 (2022-07-01)

- Renamed model *Toggler* to *Toggle*.
- New model: ESAC5A. (Contributed by Ahmad Ali).
- Added documentation for creating disturbances.
- Updated documentation for modeling blocks.

4.3.6 v1.7.3 (2022-06-25)

Bug fix:

- Fix *Ipcmd* initialization equation of *REGCA1*.

Improved the interface to pandapower:

- Improved `to_pandapower` performance using vectorized conversion.
- Enhanced `make_link_table` to include group `RenGen`.

4.3.7 v1.7.2 (2022-06-07)

- Improved documentation and examples.

4.3.8 v1.7.1 (2022-05-31)

This release contains minor fixes to the documentation.

Other changes:

- In `PVD1`, Enable *pmx* limiting by default.
- In `ST2CUT`, fix the type of `busr2` and `busr` to `IdxParam`.

4.3.9 v1.7.0 (2022-05-22)

Allow incrementally offloading simulation data from memory to the output file:

- `[TDS].limit_store` is a boolean value to enable the limit for in-memory time-series storage. If set to `1`, data will be offloaded to the `npz` file every `[TDS].max_store` steps. Offloaded data will then be erased from memory.
- If you need to interact with the time-series data in memory, you need to keep `[TDS].limit_store` to `0`.

Allow specifying models, variables, and/or devices to output:

- See *Output*. The *model* field is mandatory. Leaving *varname* or *dev* blank indicates the selection of all applicable elements. For example, specifying *model* and *varname* without *dev* means that the variable for all devices will be exported.
- Plot tool works with in-memory time-series data specified by Output.

Simulation output control:

- Allow controlling the save frequency for output data in `[TDS].save_every`. The default value is `1`, which means that every step will be saved. Setting it to `4`, for example, will save data every four steps. This setting applies to the in-memory storage and the output data file.
- Setting `save_every = 0` will immediately discard all data after each simulation step.

- Added the option `[TDS].save_mode` to change the automatic simulation data dumping to manual. Accepted values are `auto` and `manual`. This option shall only be adjusted to `manual` when one is manually stepping the simulation and wants to avoid writing to the output file when the simulation reaches `TDS.config.tf`. One will need to call `TDS.save_output()` when the full simulation concludes to avoid losing unsaved data.

Other changes:

- Fix the initialization of offline synchronous generators.
- Allow styles to be set for plots using the argument `style`. To generate figures for IEEE publications, use `style=ieee` (require package `scienceplots`).
- Moved the writing of the `lst` file to the first step of simulation.
- `andes misc -C` will not remove `_out.csv` file as it is considered data for post-processing just like exported figures.

4.4 v1.6 Notes

4.4.1 v1.6.6 (2022-04-30)

- Rename `[System] call_stats` to `[System] save_stats` for clarity. If turned on, one can retrieve statistics of function calls in `TDS.call_stats`.
- Store routine execution time to routine member `execution_time`.
- Fix PSS/E parsing issues with *GAST*.
- Fix issues and update default parameters for *REGCV1* and *REGCV2*.
- Allow adjusting limits for state variables during initialization. Like for algebraic variables, the default setting automatically adjusts the upper limit but not the lower one.

4.4.2 v1.6.5 (2022-04-19)

- Added a TDS stop criteria based on rotor angle separation with reference to Power System Analysis Toolbox.
- Fix a bug for snapshot save and load. It now supports writing to and reading from `io.BytesIO()`.

4.4.3 v1.6.4 (2022-04-17)

Breaking change:

- `PV` model no longer has `p` as a variable in the DAE. `p` copies the value of `p0`. This change affects the addresses of variables.
- Changed `models.file_classes` to a list to improve the control over the class initialization sequence in the same package.

Operator splitting for internal algebraic variables:

- `VarService` can be evaluated model-internal algebraic variables outside the DAE system. This approach is known as operator splitting and is commonly used in other simulation tools.
- Operator splitting reduces the size of the DAE system but introduces a one-iteration lag between the internal algebraic variables and others in the DAE system.
- `VarService` shall be avoided for singular functions (non-continuous) and shall not be adopted to circumvent initializing algebraic equations.
- `VarService` takes an argument `sequential`, which is `True` by default. Non-sequential `VarService` shall not depend on other `VarService` calculated at the same step as they will be evaluated simultaneously.
- *`andes.interop.pandapower.to_pandapower()`* set all generators as controllable by default. Generators in converted the pandapower case are named using the `idx` of `StaticGen`.
- Bug fixes in `interop.pandapower.make_link_table()`.

Other changes:

- Added a new service type `andes.core.service.SubsService` for temporary symbols that will be substituted at code generation time.
- `TDS.plt.plot()` now accepts a list of variable objects. For example, `ss.TDS.plt.plot([ss.GENROU.omega, ss.GENROU.delta], a=[0, 1])` will plot the rotor speed and angles of the 0-th and the 1-st generator.
- Added *REGCP1* model for generic converters with PLL support.
- Fixed PSS/E parser for *HYGOV*.

4.4.4 v1.6.3 (2022-04-06)

- Adjustments in the Pandapower interface. Added `make_GSF()` for the generation shift factor matrix.
- Reduced import overhead for the command-line tool.

4.4.5 v1.6.2 (2022-03-27)

Interoperability:

- Added interoperability modules for MATPOWER (through Oct2Py), pandapower and pypowsybl.
- Added Examples and API reference for the interoperability module.
- Improved the setup script to support extra dependencies. The following extras groups are supported: `dev` and `interop`. See *Extra support package* for more information.
- Added tests for power flow calculation against MATPOWER.

Others:

- Added a shorthand command `andes.system.example()` to return a disposable system. It can be useful for quick prototyping.
- Improved the formatting and navigation of Model references.
- Models store the base values for per-unit conversion in `Model.bases`.

4.4.6 v1.6.1 (2022-03-13)

- Revamped documentation with a much improved "Getting started" section.

4.4.7 v1.6.0 (2022-03-11)

- Migrated documentation to the pydata template.
- Added compatibility with SymPy 1.9 and 1.10.

4.5 v1.5 Notes

4.5.1 v1.5.12 (2022-03-05)

- Improved PSS/E parsers for WTDTA1 model to follow PSS/E parameter definition.
- Included the Jupyter notebook examples in the documentation.
- Tweaks to the plot utility.

4.5.2 v1.5.11 (2022-02-23)

- Reduced the tolerance for tiny variable increments to be treated as zero.
- Fixed PSS/E parsers for renewable models.
- Minor renewable model fixes.

4.5.3 v1.5.10 (2022-02-01)

- Fixed one equation in *REGC_A*.

4.5.4 v1.5.9 (2022-01-31)

- Added PLL1, a simple PLL model.
- Renamed `REGCVSG` to `REGCV1` and `REGCVSG2` to `REGCV2`.
- Added an alias list for model names. See `models/__init__.py`.
- Multiprocessing now executes on all CPUs that are physical, instead of logical. A new package `psutil` needs to be installed.
- Use of `Selector` is deprecated.

4.5.5 v1.5.8 (2021-12-21)

- Full initialization debug message will be printed only when `-v 10` and `run --init` are both used.
- Improved warning of out-of-limit initialization. Variables initialized at limits will be shown only at the debug level.
- Initialization improvements for models `REGCA1` and `REECA1`.
- Added model `HYGOV`.
- Changed the default `vout` of offline exciters to zeros. All `vout` equations need to be multipled by `ue`.

4.5.6 v1.5.7 (2021-12-11)

This minor release highlights the improved debugging of initialization.

Highly verbose initialization output can be enabled when the verbose level is 10 or less. For example,

```
andes -v 10 run test.xlsx -r tds --init
```

will set the verbose level to 10 and run `test.xlsx` in the current folder, proceed to time-domain simulation but only initialize the models. Outputs will be printed to the shell where the command is executed.

To save the output to a file, use the following in a UNIX shell:

```
andes -v 10 run test.xlsx -r tds --init > info.txt 2>&1
```

where the first > pipes the output to a file named `info.txt`, and `2>&1` appends stderr (2) to stdout (1).

The other main improvement is allowing automatic limit adjustment during initialization. Due to parameter errors, some variables will be initialized to values outside the given limits. Most commercial software does not attempt to fix the parameter but rather adjust the limit in run time.

The same approach is followed in ANDES by automatically adjusting the upper limit, if exceeded, to variable initial values. The lower limit, however, is kept unadjusted by default.

Discrete components now take an argument named `allow_adjust` so that the model developer can specify if its limits can be adjusted or must be kept as is. Each model is allowed to specify three config flags to customize runtime behaviors: `allow_adjust`, `adjust_lower`, and `adjust_uppwer`. By default, `allow_adjust=True`, `adjust_upper=True`, and `adjust_lower=False`. One can modify the config file to enable or disable the limit adjustments for specific models.

Other fixes include:

- Bug fixes for `GAST` parameter `AT`.
- Bug fixes for `IEEET3`, `GAST`, `ESAC1A` and `ESST1A` when device is off to avoid matrix singularity.

4.5.7 v1.5.6 (2021-11-25)

- Allow specifying config options through command-line arguments `--config-option`.
- Added a voltage and frequency playback model `PLBVFU1`.
- Bug fixes to an SEXS equation.

4.5.8 v1.5.5 (2021-11-13)

- Added a *Timeseries* model for reading timeseries data from xlsx.
- Converted several models into Python packages.
- Bug fixes to TGOV1 equations (#226)

4.5.9 v1.5.4 (2021-11-02)

- Fixed a bug in generated `select` functions that omitted the coefficients of `__ones`.

4.5.10 v1.5.3 (2021-10-31)

- Revered special arguments for the generated `select` function.
- Stabilized the argument list of pycode. If the pycode is identical to existing ones, the existing file will not be overwritten. As a result, compiled code is fully cached.
- Partially seperated time-domain integration method into `daeint.py`.

4.5.11 v1.5.2 (2021-10-27)

- Removed `CVXOPT` dependency.
- Removed `__zeros` and `__ones` as they are no longer needed.
- Added `andes prep -c` to precompile the generated code.
- Added utility functions for saving and loading system snapshots. See `andes/utils/snapshot.py`.
- Compiled numba code is always cached.
- Bug fixes.

4.5.12 v1.5.1 (2021-10-23)

- Restored compatibility with SymPy 1.6.
- Added a group for voltage compensators.
- New models: `IEEEVC` and `GAST`.

4.5.13 v1.5.0 (2021-10-13)

- Support numba just-in-time compilation of all equation and Jacobian calls.

This option accelerates simulations by up to 30%. The acceleration is visible in medium-scale systems with multiple models. Such systems involve heavy function calls but a rather moderate load for linear equation solvers. The speed up is less significant in large-scale systems where solving equations is the major time consumer.

Numba is required and can be installed with `pip install numba` or `conda install numba`.

To turn on numba for ANDES, in the ANDES configuration under `[System]`, set `numba = 1` and `numba_cache = 1`.

The just-in-time compilation will compile the code upon the first execution based on the input types. When compilation is triggered, ANDES may appear frozen due to the compilation lag. The option `numba_cache = 1` will cache compiled machine code, so that the lag only occurs once until the next `andes prep`.

- Allow `BackRef` to populate to models through `Group`.

When model *A* stores an `IdxParam` pointing to a group, if `BackRef` with the name *A* are declared in both the group and the model, both `BackRef` will retrieve the backward references from model *A*.

- Allow `BaseVar` to accept partial initializations.

If `BaseVar.v_str_add = True`, the value of *v_str* will be added in place to variable value. An example is that voltage compensator sets part of the input voltage, and exciter reads the bus voltage. Exciter has *v.v_str_add = True* so that when compensators exist, the input voltage will be bus voltage (vbus) plus (Eterm - vbus). If no compensator exists, exciter will use bus voltages and function as expected.

- Added reserved variable names `__ones` and `__zeros` for ones and zeros with length equal to the device number.

`__ones` and `__zeros` are useful for vectorizing `choicelist` in `Piecewise` functions.

4.6 v1.4 Notes

4.6.1 v1.4.4 (2021-10-05)

- Bug fixes for refreshing generated code.

4.6.2 v1.4.3 (2021-09-25)

This release features parallel processing that cuts the time for `andes prepare` by more than half.

- `andes prepare` supports multiprocessing and uses it by default.
- Added aliases `andes st` and `andes prep` for `andes selftest` and `andes prepare`.
- `andes.config_logger` supports setting new `stream_level` and `file_level`.

New exciter models are contributed by Jinning Wang.

- Added `AC8B`, `IEEET3` and `ESAC1A`.

Other changes include disallowing numba's `nopython` mode.

4.6.3 v1.4.2 (2021-09-12)

- Bug fixes
- Dropped support for `cvxoptklu`.

4.6.4 v1.4.1 (2021-09-12)

- Bug fixes.
- Overhaul of the `prepare` and `undill` methods.
- `andes prepare` can be called for specific models through `-m`, which takes one or many model names as arguments.

4.6.5 v1.4.0 (2021-09-08)

This release highlights the distributed energy resource protection model.

- Added `DGPRCT1` model to provide DG models with voltage- and frequency-based protection following IEEE 1547-2018.
- `REECA1E` supports frequency droop on power.
- Throws TypeError if type mismatches when using ExtAlgeb and ExtState.

4.7 v1.3 Notes

4.7.1 v1.3.12 (2021-08-22)

Plot enhancements:

- `plot()` takes an argument `mark` for masking y-axis data based on the `left` and `right` range parameters.
- `TDS.plt` provides a `panoview` method for plotting an panoramic view for selected variables and devices of a model.

Models:

- Added WIP EV models and protection models.

Test case: - Added CURENT EI test system. - Added a number of IEEE 14 bus test systems for specific models.

4.7.2 v1.3.11 (2021-07-27)

- Added `REECA1E` model with inertia emulation.
- Fixed an issue where the `vtype` of services was ignored.
- Changed default DPI for plotting to 100.

4.7.3 v1.3.10 (2021-06-08)

- Bug fixes for controllers when generators are off.

4.7.4 v1.3.9 (2021-06-02)

- Bug fixes in exciters when generators are offline.
- Added *safe_div* function for initialization equations.

4.7.5 v1.3.8 (2021-06-02)

- Added `REGCVSG` model for voltage-source controlled renewables.
- Turbine governors are now aware of the generator connection status.

4.7.6 v1.3.7 (2021-05-03)

- Allow manually specifying variables needing initialization preceding a variable. Specify a list of variable names through `BaseVar.deps`.

4.7.7 v1.3.6 (2021-04-23)

- Patched ESD1 model. Converted *distributed.py* into a package.
- Bug fixes.

4.7.8 v1.3.5 (2021-03-20)

- Fixed a bug in connectivity check when bus 0 is islanded.
- Updated notebook examples.
- Updated tutorials.

4.7.9 v1.3.4 (2021-03-13)

- Fixed a bug for the generated renewable energy code.

4.7.10 v1.3.2 (2021-03-08)

- Relaxed the version requirements for NumPy and SymPy.

4.7.11 v1.3.1 (2021-03-07)

- Writes all generated Python code to `~/.andes/pycode` by default.
- Uses generated Python code by default instead of *calls.pkl*.
- Works with NumPy 1.20; works on Apple Silicon (use *miniforge*) to install native Python and NumPy for Apple Silicon.
- Generalized model initialization: automatically determines the initialization sequence and solve equations iteratively when necessary.
- In *System.config*, *save_pycode* and *use_pycode* are now deprecated.

4.7.12 v1.3.0 (2021-02-20)

- Allow *State* variable set *check_init=False* to skip initialization test. One use case is for integrators with non-zero inputs (such as state-of-charge integration).
- Solves power flow for systems with multiple areas, each with one Slack generator.
- Added *Jumper* for connecting two buses with zero impedance.
- *REGCA1* and synchronous generators can take power ratio parameters *gammap* and *gammaq*.
- New models: *IEESGO* and *IEEET1*, *EXAC4*.
- Refactored exciters, turbine governors, and renewable models into modules.

4.8 v1.2 Notes

4.8.1 v1.2.9 (2021-01-16)

- Added system connectivity check for islanded buses.
- Depend on *openpyxl* for reading excel files since *xlrd* dropped support for any format but *xlsx* since v2.0.0.

4.8.2 v1.2.7 (2020-12-08)

- Time-domain integration now evaluates anti-windup limiter before algebraic residuals. It assures that algebraic residuals are calculated with the new state values if pegged at limits.
- Fixed the conditions for Iq ramping in REGC; removed `Iqmax` and `Iqmin`.
- Added a new plot function `plotn` to allow multiple subplots in one figure.
- `TDS.config.g_scale` is now now used as a factor for scaling algebraic equations for better convergence. Setting it to 1.0 functions the same as before.

4.8.3 v1.2.6 (2020-12-01)

- Added *TGOV1N* model which sums *pref* and *paux* after the 1/droop block.
- Added *ZIP* and *FLoad* for dynamic analysis. Need to be initialized after power flow.
- Added *DAETimeSeries.get_data()* method.
- Added IEEE 14-bus test cases with solar PV (ieee14_solar.xlsx) and Generic Type 3 wind (ieee14_wt3.xlsx).

4.8.4 v1.2.5 (2020-11-19)

- Added *Summary* model to allow arbitrary information for a test case. Works in *xlsx* and *json* formats.
- PV reactive power limit works. Automatically determines the number of PVs to convert if *npv2pq=0*.
- Limiter and AntiWindup limiter can use *sign_upper=-1* and *sign_lower=-1* to negate the provided limits.
- Improved error messages for inconsistent data.
- *DAETimeSeries* functions refactored.

4.8.5 v1.2.4 (2020-11-13)

- Added switched shunt class *ShuntSw*.
- BaseParam takes *inconvert* and *oconvert* for converting parameter elements from and to files.

4.8.6 v1.2.3 (2020-11-02)

- Support variable *sys_mva* (system base mva) in equation strings.
- Default support for KVXOPT through `pip` installation.

4.8.7 v1.2.2 (2020-11-01)

New Models:

- `PVD1` model, WECC distributed PV model. Supports multiple PVD1 devices on the same bus.
- Added `ACEc` model, ACE calculation with continuous freq.

Changes and fixes:

- Renamed *TDS._itm_step* to *TDS.itm_step* as a public API.
- Allow variable *sys_f* (system frequency) in equation strings.
- Fixed ACE equation. measurement.
- Support `kvxopt` as a drop-in replacement for `cvxopt` to bring KLU to Windows (and other platforms).

- Added `kvxopt` as a dependency for PyPI installation.

4.8.8 v1.2.1 (2020-10-11)

- Renamed *models.non_jit* to *models.file_classes*.
- Removed *models/jit.py* as models have to be loaded and instantiated anyway before undill.
- Skip generating empty equation calls.

4.8.9 v1.2.0 (2020-10-10)

This version contains major refactor for speed improvement.

- Refactored Jacobian calls generation so that for each model, one call is generated for each Jacobian type.
- Refactored Service equation generation so that the exact arguments are passed.

Also contains an experimental Python code dump function.

- Controlled in `System.config`, one can turn on `save_pycode` to dump equation and Jacobian calls to `~/.andes/pycode`. Requires one call to `andes prepare`.
- The Python code dump can be reformatted with `yapf` through the config option `yapf_pycode`. Requires separate installation.
- The dumped Python code can be used for subsequent simulations through the config option `use_pycode`.

4.9 v1.1 Notes

4.9.1 v1.1.5 (2020-10-08)

- Allow plotting to existing axes with the same plot API.
- Added TGOV1DB model (TGOV1 with an input dead-band).
- Added an experimental numba support.
- Patched *LazyImport* for a snappier command-line interface.
- `andes selftest -q` now skips code generation.

4.9.2 v1.1.4 (2020-09-22)

- Support *BackRef* for groups.
- Added CLI `--pool` to use `multiprocess.Pool` for multiple cases. When combined with `--shell`, `--pool` returns `System` Objects in the list `system`.
- Fixed bugs and improved manual.

4.9.3 v1.1.3 (2020-09-05)

- Improved documentation.
- Minor bug fixes.

4.9.4 v1.1.2 (2020-09-03)

- Patched time-domain for continuing simulation.

4.9.5 v1.1.1 (2020-09-02)

- Added back quasi-real-time speed control through *--qrt* and *--kqrt KQRT*.
- Patched the time-domain routine for the final step.

4.9.6 v1.1.0 (2020-09-01)

- Defaulted *BaseVar.diag_eps* to *System.Config.diag_eps*.
- Added option *TDS.config.g_scale* to allow for scaling the algebraic mismatch with step size.
- Added induction motor models *Motor3* and *Motor5* (PSAT models).
- Allow a PFlow-TDS model to skip TDS initialization by setting *ModelFlags.tds_init* to False.
- Added Motor models *Motor3* and *Motor5*.
- Imported *get_case* and *list_cases* to the root package level.
- Added test cases (Kundur's system) with wind.

Added Generic Type 3 wind turbine component models:

- Drive-train models *WTDTA1* (dual-mass model) and *WTDS* (single-mass model).
- Aerodynamic model *WTARA1*.
- Pitch controller model *WTPTA1*.
- Torque (a.k.a. Pref) model *WTTQA1*.

4.10 v1.0 Notes

4.10.1 v1.0.8 (2020-07-29)

New features and models:

- Added renewable energy models *REECA1* and *REPCA1*.
- Added service *EventFlag* which automatically calls events if its input changes.
- Added service *ExtendedEvent* which flags an extended event for a given time.
- Added service *ApplyFunc* to apply a numeric function. For the most cases where one would need *ApplyFunc*, consider using *ConstService* first.
- Allow *selftest -q* for quick selftest by skipping codegen.
- Improved time stepping logic and convergence tests.
- Updated examples.

Default behavior changes include:

- `andes prepare` now takes three mutually exclusive arguments, *full*, *quick* and *incremental*. The command-line now defaults to the quick mode. `andes.prepare()` still uses the full mode.
- `Model.s_update` now evaluates the generated and the user-provided calls in sequence for each service in order.
- Renamed model *REGCAU1* to *REGCA1*.

4.10.2 v1.0.7 (2020-07-18)

- Use in-place assignment when updating Jacobian values in Triplets.
- Patched a major but simple bug where the Jacobian refactorization flag is set to the wrong place.
- New models: PMU, REGCAU1 (tests pending).
- New blocks: DeadBand1, PIFreeze, PITrackAW, PITrackAWFreeze (tests pending), and LagFreeze (tests pending).
- *andes plot* supports dashed horizontal and vertical lines through *hline1*, *hline2*, *vline1* and *vline2*.
- Discrete: renamed *DeadBand* to *DeadBandRT* (deadband with return).
- Service: renamed *FlagNotNone* to *FlagValue* with an option to flip the flags.
- Other tweaks.

4.10.3 v1.0.6 (2020-07-08)

- Patched step size adjustment algorithm.
- Added Area Control Error (ACE) model.

4.10.4 v1.0.5 (2020-07-02)

- Minor bug fixes for service initialization.
- Added a wrapper to call TDS.fg_update to allow passing variables from caller.
- Added pre-event time to the switch_times.

4.10.5 v1.0.4 (2020-06-26)

- Implemented compressed NumPy format (npz) for time-domain simulation output data file.
- Implemented optional attribute *vtype* for specifying data type for Service.
- Patched COI speed initialization.
- Patched PSS/E parser for two-winding transformer winding and impedance modes.

4.10.6 v1.0.3 (2020-06-02)

- Patches *PQ* model equations where the "or" logic "|" is ignored in equation strings. To adjust PQ load in time domain simulation, refer to the note in *pq.py*.
- Allow *Model.alter* to update service values.

4.10.7 v1.0.2 (2020-06-01)

- Patches the conda-forge script to use SymPy < 1.6. After SymPy version 1.5.1, comparison operations cannot be sympified. Pip installations are not affected.

4.10.8 v1.0.1 (2020-05-27)

- Generate one lambda function for each of f and g, instead of generating one for each single f/g equation. Requires to run *andes prepare* after updating.

4.10.9 v1.0.0 (2020-05-25)

This release is going to be tagged as v0.9.5 and later tagged as v1.0.0.

- Added verification results using IEEE 14-bus, NPCC, and WECC systems under folder *examples*.
- Patches GENROU and EXDC2 models.
- Updated test cases for WECC, NPCC IEEE 14-bus.
- Documentation improvements.
- Various tweaks.

4.11 Pre-v1.0.0

4.11.1 v0.9.4 (2020-05-20)

- Added exciter models EXST1, ESST3A, ESDC2A, SEXS, and IEEEX1, turbine governor model IEEEG1 (dual-machine support), and stabilizer model ST2CUT.
- Added blocks HVGate and LVGate with a work-around for sympy.maximum/ minimum.
- Added services *PostInitService* (for storing initialized values), and *VarService* (variable services that get updated) after limiters and before equations).
- Added service *InitChecker* for checking initialization values against typical values. Warnings will be issued when out of bound or equality/ inequality conditions are not met.
- Allow internal variables to be associated with a discrete component which will be updated before initialization (through *BaseVar.discrete*).
- Allow turbine governors to specify an optional *Tn* (turbine rating). If not provided, turbine rating will fall back to *Sn* (generator rating).
- Renamed *OptionalSelect* to *DataSelect*; Added *NumSelect*, the array-based version of *DataSelect*.
- Allow to regenerate code for updated models through `andes prepare -qi`.
- Various patches to allow zeroing out time constants in transfer functions.

4.11.2 v0.9.3 (2020-05-05)

This version contains bug fixes and performance tweaks.

- Fixed an *AntiWindup* issue that causes variables to stuck at limits.
- Allow `TDS.run()` to resume from a stopped simulation and run to the new end time in `TDS.config.tf`.
- Improved TDS data dump speed by not constructing DataFrame by default.
- Added tests for *kundur_full.xlsx* and *kundur_aw.xlsx* to ensure results are the same as known values.

- Other bug fixes.

4.11.3 v0.9.1 (2020-05-02)

This version accelerates computations by about 35%.

- Models with flag `collate=False`, which is the new default, will slice DAE arrays for all internal vars to reduce copying back and forth.
- The change above greatly reduced computation time. For `kundur_ieeest.xlsx`, simulation time is down from 2.50 sec to 1.64 sec.
- The side-effects include a change in variable ordering in output lst file. It also eliminated the feasibility of evaluating model equations in parallel, which has not been implemented and does not seem promising in Python.
- Separated symbolic processor and documentation generator from Model into `SymProcessor` and `Documenter` classes.
- `andes prepare` now shows progress in the console.
- Store exit code in `System.exit_code` and returns to system when called from CLI.
- Refactored the solver interface.
- Patched Config.check for routines.
- SciPy Newton-Krylov power flow solver is no longer supported.
- Patched a bug in v0.9.0 related to *dae.Tf*.

4.11.4 v0.8.8 (2020-04-28)

This update contains a quick but significant fix to boost the simulation speed by avoiding calls to empty user-defined numerical calls.

- In *Model.flags* and *Block.flags*, added *f_num*, *g_num* and *j_num* to indicate if user-defined numerical calls exist.
- In *Model.f_update*, *Model.g_update* and *Model.j_update*, check the above flags to avoid unnecessary calls to empty numeric functions.
- For the *kundur_ieeest.xlsx* case, simulation time was reduced from 3.5s to 2.7s.

4.11.5 v0.8.7 (2020-04-28)

- Changed *RefParam* to a service type called *BackRef*.
- Added *DeviceFinder*, a service type to find device idx when not provided. *DeviceFinder* will also automatically add devices if not found.
- Added *OptionalSelect*, a service type to select optional parameters if provided and select fallback ones otherwise.
- Added discrete types *Derivative*, *Delay*, and *Average*,
- Implemented full IEEEST stabilizer.
- Implemented COI for generator speed and angle measurement.

4.11.6 v0.8.6 (2020-04-21)

This release contains important documentation fixes and two new blocks.

- Fixed documentations in *andes doc* to address a misplacement of symbols and equations.
- Converted all blocks to the division-free formulation (with *dae.zf* renamed to *dae.Tf*).
- Fixed equation errors in the block documentation.
- Implemented two new blocks: Lag2ndOrd and LeadLag2ndOrd.
- Added a prototype for IEEEST stabilizer with some fixes needed.

4.11.7 v0.8.5 (2020-04-17)

- Converted the differential equations to the form of `T \dot{x} = f(x, y)`, where T is supplied to `t_const` of `State/ExtState`.
- Added the support for Config fields in documentation (in `andes doc` and on readthedocs).
- Added Config consistency checking.
- Converted *Model.idx* from a list to *DataParam*.
- Renamed the API of routines (summary, init, run, report).
- Automatically generated indices now start at 1 (i.e., "GENCLS_1" is the first GENCLS device).
- Added test cases for WECC system. The model with classical generators is verified against TSAT.
- Minor features: *andes -v 1* for debug output with levels and line numbers.

4.11.8 v0.8.4 (2020-04-07)

- Added support for JSON case files. Convert existing case file to JSON with `--convert json`.
- Added support for PSS/E dyr files, loadable with `-addfile ADDFILE`.
- Added `andes plot --xargs` for searching variable name and plotting. See example 6.
- Various bug fixes: Fault power injection fix;

4.11.9 v0.8.3 (2020-03-25)

- Improved storage for Jacobian triplets (see `andes.core.triplet.JacTriplet`).
- On-the-fly parameter alteration for power flow calculations (`Model.alter` method).
- Exported frequently used functions to the root package (`andes.config_logger`, `andes.run`, `andes.prepare` and `andes.load`).
- Return a list of System objects when multiprocessing in an interactive environment.
- Exported classes to *andes.core*.
- Various bug fixes and documentation improvements.

4.11.10 v0.8.0 (2020-02-12)

- First release of the hybrid symbolic-numeric framework in ANDES.
- A new framework is used to describe DAE models, generate equation documentation, and generate code for numerical simulation.
- Models are written in the new framework. Supported models include GENCLS, GENROU, EXDC2, TGOV1, TG2
- PSS/E raw parser, MATPOWER parser, and ANDES xlsx parser.
- Newton-Raphson power flow, trapezoidal rule for numerical integration, and full eigenvalue analysis.

4.11.11 v0.6.9 (2020-02-12)

- Version 0.6.9 is the last version for the numeric-only modeling framework.
- This version will not be updated any more. But, models, routines and functions will be ported to the new version.

CHAPTER

FIVE

MODEL REFERENCE

Use the left navigation pane to locate the group and model and view details.

Supported Groups and Models

Group	Models
ACLine	*Line*
ACShort	*Jumper*
ACTopology	*Bus*
Calculation	*ACE*, *ACEc*, *COI*
Collection	*Area*
DCLink	*Ground*, *R*, *L*, *C*, *RCp*, *RCs*, *RLs*, *RLCs*, *RLCp*
DCTopology	*Node*
DG	*PVD1*, *ESD1*, *EV1*, *EV2*
DGProtection	*DGPRCT1*, *DGPRCTExt*
DataSeries	*TimeSeries*
DynLoad	*ZIP*, *FLoad*
Exciter	*EXDC2*, *IEEEX1*, *ESDC1A*, *ESDC2A*, *EXST1*, *ESST3A*, *SEXS*, *IEEET1*, *EXAC1*, *EXAC2*, *EXAC4*, *ESS*
FreqMeasurement	*BusFreq*, *BusROCOF*
Information	*Summary*
Interface	*Fortescue*
Motor	*Motor3*, *Motor5*
OutputSelect	*Output*
PLL	*PLL1*, *PLL2*
PSS	*IEEEST*, *ST2CUT*
PhasorMeasurement	*PMU*
RenAerodynamics	*WTARA1*, *WTARV1*
RenExciter	*REECA1*, *REECA1E*, *REECA1G*
RenGen	*REGCA1*, *REGCP1*, *REGCV1*, *REGCV2*, *REGF1*, *REGF2*, *REGF3*
RenGovernor	*WTDTA1*, *WTDS*
RenPitch	*WTPTA1*
RenPlant	*REPCA1*
RenTorque	*WTTQA1*
StaticACDC	*VSCShunt*
StaticGen	*PV*, *Slack*

Table 1 – continued from previous page

Group	Models
StaticLoad	*PQ*
StaticShunt	*Shunt*, *ShuntTD*, *ShuntSw*
SynGen	*GENCLS*, *GENROU*, *PLBVFU1*
TimedEvent	*Toggle*, *Fault*, *Alter*
TurbineGov	*TG2*, *TGOV1*, *TGOV1DB*, *TGOV1N*, *TGOV1NDB*, *IEEEG1*, *IEESGO*, *GAST*, *HYGOV*, *HYGOVDB*, *H*
VoltComp	*IEEEVC*

5.1 ACLine

Common Parameters: u, name, bus1, bus2, r, x

Common Variables: v1, v2, a1, a2

Available models: *Line*

5.1.1 Line

AC transmission line model.

The model is also used for two-winding transformer. Transformers can set the tap ratio in `tap` and/or phase shift angle `phi`.

To reduce the number of variables, line injections are summed at bus equations and are not stored. Current injections are not computed.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus1		idx of from bus			
bus2		idx of to bus			
Sn	S_n	Power rating	100	*MW*	non_zero
fn	f	rated frequency	60	*Hz*	
Vn1	V_{n1}	AC voltage rating	110	*kV*	non_zero
Vn2	V_{n2}	rated voltage of bus2	110	*kV*	non_zero
r	r	line resistance	0.000	*p.u.*	z
x	x	line reactance	0.000	*p.u.*	non_zero,z
b		shared shunt susceptance	0	*p.u.*	y
g		shared shunt conductance	0	*p.u.*	y
b1	b_1	from-side susceptance	0	*p.u.*	y
g1	g_1	from-side conductance	0	*p.u.*	y
b2	b_2	to-side susceptance	0	*p.u.*	y
g2	g_2	to-side conductance	0	*p.u.*	y
trans		transformer branch flag	0	*bool*	
tap	t_{ap}	transformer branch tap ratio	1	*float*	non_negative
phi	ϕ	transformer branch phase shift in rad	0	*radian*	
rate_a	R_{ATEA}	long-term flow limit (placeholder)	0	*MVA*	
rate_b	R_{ATEB}	short-term flow limit (placeholder)	0	*MVA*	
rate_c	R_{ATEC}	emergency flow limit (placeholder)	0	*MVA*	
owner		owner code			
xcoord		x coordinates			
ycoord		y coordinates			

Variables

Name	Symbol	Type	Description	Unit	Properties
a1	a_1	ExtAlgeb	phase angle of the from bus		
a2	a_2	ExtAlgeb	phase angle of the to bus		
v1	v_1	ExtAlgeb	voltage magnitude of the from bus		
v2	v_2	ExtAlgeb	voltage magnitude of the to bus		

Initialization Equations

Name	Symbol	Type	Initial Value
a1	a_1	ExtAlgeb	
a2	a_2	ExtAlgeb	
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a1	a_1	ExtAlgeb	$u\left(-1/t_{ap}v_1v_2\left(-b_{hk}\sin\left(\phi-a_1+a_2\right)+g_{hk}\cos\left(\phi-a_1+a_2\right)\right)+1/t_{ap}^2v_1^2\left(g_h+g_{hk}\right)\right)$
a2	a_2	ExtAlgeb	$u\left(-1/t_{ap}v_1v_2\left(b_{hk}\sin\left(\phi-a_1+a_2\right)+g_{hk}\cos\left(\phi-a_1+a_2\right)\right)+v_2^2\left(g_h+g_{hk}\right)\right)$
v1	v_1	ExtAlgeb	$u\left(-1/t_{ap}v_1v_2\left(-b_{hk}\cos\left(\phi-a_1+a_2\right)-g_{hk}\sin\left(\phi-a_1+a_2\right)\right)-1/t_{ap}^2v_1^2\left(b_h+b_{hk}\right)\right)$
v2	v_2	ExtAlgeb	$u\left(1/t_{ap}v_1v_2\left(b_{hk}\cos\left(\phi-a_1+a_2\right)-g_{hk}\sin\left(\phi-a_1+a_2\right)\right)-v_2^2\left(b_h+b_{hk}\right)\right)$

Services

Name	Symbol	Equation	Type
gh	g_h	$0.5g+g_1$	ConstService
bh	b_h	$0.5b+b_1$	ConstService
gk	g_k	$0.5g+g_2$	ConstService
bk	b_k	$0.5b+b_2$	ConstService
yh	y_h	$u\left(ib_h+g_h\right)$	ConstService
yk	y_k	$u\left(ib_k+g_k\right)$	ConstService
yhk	y_{hk}	$\frac{u}{r+i(x+1.0\cdot10^{-8})+1.0\cdot10^{-8}}$	ConstService
ghk	g_{hk}	re $\left(y_{hk}\right)$	ConstService
bhk	b_{hk}	im $\left(y_{hk}\right)$	ConstService
itap	$1/t_{ap}$	$\frac{1}{t_{ap}}$	ConstService
itap2	$1/t_{ap}^2$	$\frac{1}{t_{ap}^2}$	ConstService

Config Fields in [Line]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.2 ACShort

Common Parameters: u, name, bus1, bus2

Common Variables: v1, v2, a1, a2

Available models: *Jumper*

5.2.1 Jumper

Jumper is a device to short two buses (merging two buses into one).

Jumper can connect two buses satisfying one of the following conditions:

- neither bus is voltage-controlled
- either bus is voltage-controlled
- both buses are voltage-controlled, and the voltages are the same.

If the buses are controlled in different voltages, power flow will not solve (as the power flow through the jumper will be infinite).

In the solutions, the `p` and `q` are flowing out of bus1 and flowing into bus2.

Setting a Jumper's connectivity status `u` to zero will disconnect the two buses. In the case of a system split, one will need to call `System.connectivity()` immediately following the split to detect islands.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus1		idx of from bus			
bus2		idx of to bus			

Variables

Name	Symbol	Type	Description	Unit	Properties
p	P	Algeb	active power (1 to 2)		
q	Q	Algeb	active power (1 to 2)		
a1	a_1	ExtAlgeb	phase angle of the from bus		
a2	a_2	ExtAlgeb	phase angle of the to bus		
v1	v_1	ExtAlgeb	voltage magnitude of the from bus		
v2	v_2	ExtAlgeb	voltage magnitude of the to bus		

Initialization Equations

Name	Symbol	Type	Initial Value
p	P	Algeb	
q	Q	Algeb	
a1	a_1	ExtAlgeb	
a2	a_2	ExtAlgeb	
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
p	P	Algeb	$P\left(1-u\right)+u\left(a_1-a_2\right)$
q	Q	Algeb	$P\left(1-u\right)+u\left(v_1-v_2\right)$
a1	a_1	ExtAlgeb	P
a2	a_2	ExtAlgeb	$-P$
v1	v_1	ExtAlgeb	Q
v2	v_2	ExtAlgeb	$-Q$

Config Fields in [Jumper]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.3 ACTopology

Common Parameters: u, name

Common Variables: a, v

Available models: *Bus*

5.3.1 Bus

AC Bus model.

Power balance equation have the form of `load - injection = 0`. Namely, load is positively summed, while injections are negative.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
Vn	V_n	AC voltage rating	110	*kV*	non_zero
vmax	V_{max}	Voltage upper limit	1.100	*p.u.*	
vmin	V_{min}	Voltage lower limit	0.900	*p.u.*	
v0	V_0	initial voltage magnitude	1	*p.u.*	non_zero
a0	θ_0	initial voltage phase angle	0	*rad*	
xcoord		x coordinate (longitude)	0		
ycoord		y coordinate (latitude)	0		
area		Area code			
zone		Zone code			
owner		Owner code			

Variables

Name	Symbol	Type	Description	Unit	Properties
a	θ	Algeb	voltage angle	*rad*	v_str
v	V	Algeb	voltage magnitude	*p.u.*	v_str

Initialization Equations

Name	Symbol	Type	Initial Value
a	θ	Algeb	$\theta_0 \cdot (1 - z_{flat}) + 1.0 \cdot 10^{-8} z_{flat}$
v	V	Algeb	$V_0 \cdot (1 - z_{flat}) + z_{flat}$

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	Algeb	0
v	V	Algeb	0

Config Fields in [Bus]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
flat_start	z_{flat}	0	flat start for voltages	(0, 1)

5.4 Calculation

Group of classes that calculates based on other models.

Common Parameters: u, name

Available models: *ACE*, *ACEc*, *COI*

5.4.1 ACE

Area Control Error model.

Discrete frequency sampling. System base frequency from `system.config.freq` is used.

Frequency sampling period (in seconds) can be specified in `ACE.config.interval`. The sampling start time (in seconds) can be specified in `ACE.config.offset`.

Note: area idx is automatically retrieved from *bus*.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx for freq. measurement			mandatory
bias	β	bias parameter	1	*MW/0.1Hz*	power
busf		Optional BusFreq device idx			
area			0		

Variables

Name	Symbol	Type	Description	Unit	Properties
ace	ace	Algeb	area control error	*p.u. (MW)*	
f	f	ExtAlgeb	Bus frequency	*p.u. (Hz)*	

Initialization Equations

Name	Symbol	Type	Initial Value
ace	ace	Algeb	
f	f	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
ace	ace	Algeb	$10 \cdot 1/S_{b,sys}\beta f_{sys}\left(v^{f_s}-1\right)-ace$
f	f	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
imva	$1/S_{b,sys}$	$\frac{1}{S_{b,sys}}$	ConstService

Discretes

Name	Symbol	Type	Info
fs	f_s	Sampling	Sampled freq.

Config Fields in [ACE]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
freq_model		BusFreq	default freq. measurement model	('BusFreq',)
interval		4	sampling time interval	
offset		0	sampling time offset	

5.4.2 ACEc

Area Control Error model.

Continuous frequency sampling. System base frequency from `system.config.freq` is used.

Note: area idx is automatically retrieved from *bus*.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx for freq. measurement			mandatory
bias	β	bias parameter	1	*MW/0.1Hz*	power
busf		Optional BusFreq device idx			
area			0		

Variables

Name	Symbol	Type	Description	Unit	Properties
ace	ace	Algeb	area control error	*p.u. (MW)*	
f	f	ExtAlgeb	Bus frequency	*p.u. (Hz)*	

Initialization Equations

Name	Symbol	Type	Initial Value
ace	ace	Algeb	
f	f	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
ace	ace	Algeb	$10 \cdot 1/S_{b,sys}\beta f_{sys}\,(f-1) - ace$
f	f	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
imva	$1/S_{b,sys}$	$\frac{1}{S_{b,sys}}$	ConstService

Config Fields in [ACEc]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
freq_model		BusFreq	default freq. measurement model	('BusFreq',)

5.4.3 COI

Center of inertia calculation class.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
M		Linearly stored SynGen.M	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
wgen	ω_{gen}	ExtState	Linearly stored SynGen.omega		
agen	δ_{gen}	ExtState	Linearly stored SynGen.delta		
omega	ω_{coi}	Algeb	COI speed		v_str,v_setter
delta	δ_{coi}	Algeb	COI rotor angle		v_str,v_setter
omega_sub	ω_{sub}	ExtAlgeb	COI frequency contribution of each generator		
delta_sub	δ_{sub}	ExtAlgeb	COI angle contribution of each generator		

Initialization Equations

Name	Symbol	Type	Initial Value
wgen	ω_{gen}	ExtState	
agen	δ_{gen}	ExtState	
omega	ω_{coi}	Algeb	$\omega_{gen,0,avg}$
delta	δ_{coi}	Algeb	$\delta_{gen,0,avg}$
omega_sub	ω_{sub}	ExtAlgeb	
delta_sub	δ_{sub}	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
wgen	ω_{gen}	ExtState	0	
agen	δ_{gen}	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
omega	ω_{coi}	Algeb	$-\omega_{coi}$
delta	δ_{coi}	Algeb	$-\delta_{coi}$
omega_sub	ω_{sub}	ExtAlgeb	$M_w\omega_{gen}$
delta_sub	δ_{sub}	ExtAlgeb	$M_w\delta_{gen}$

Services

Name	Symbol	Equation	Type
Mw	M_w	$\frac{M}{M_{tr}}$	ConstService
d0w	$\delta_{gen,0,w}$	$M_w\delta_{gen,0}$	ConstService
a0w	$\omega_{gen,0,w}$	$M_w\omega_{gen,0}$	ConstService

Config Fields in [COI]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.5 Collection

Collection of topology models

Common Parameters: u, name

Available models: *Area*

5.5.1 Area

Area model.

Area collects back references from the Bus model and the ACTopology group.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			

Config Fields in [Area]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6 DCLink

Basic DC links

Common Parameters: u, name

Available models: *Ground*, *R*, *L*, *C*, *RCp*, *RCs*, *RLs*, *RLCs*, *RLCp*

5.6.1 Ground

Ground model that sets the voltage of the connected DC node.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node		Node index			mandatory
voltage	V_0	Ground voltage (typically 0)	0	*p.u.*	

Variables

Name	Symbol	Type	Description	Unit	Properties
Idc	I_{dc}	Algeb	Ficticious current injection from ground		v_str
v	v	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
Idc	I_{dc}	Algeb	0
v	v	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$u\left(-V_0 + v\right)$
v	v	ExtAlgeb	$-I_{dc}$

Config Fields in [Ground]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.2 R

Resistive dc line

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
R		DC line resistance	0.010	*p.u.*	non_zero,r

Variables

Name	Symbol	Type	Description	Unit	Properties
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
Idc	I_{dc}	Algeb	$\frac{u(-v_1+v_2)}{R}$
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$-I_{dc} + \frac{u(-v_1+v_2)}{R}$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [R]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.3 L

Inductive dc line

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
L		DC line inductance	0.001	*p.u.*	non_zero,r

Variables

Name	Symbol	Type	Description	Unit	Properties
IL	I_L	State	Inductance current	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
IL	I_L	State	0
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$-u\left(v_1 - v_2\right)$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v1	v_1	ExtAlgeb	$-I_L$
v2	v_2	ExtAlgeb	I_L

Config Fields in [L]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.4 C

Capacitive dc branch

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
C		DC capacitance	0.001	*p.u.*	non_zero,g

Variables

Name	Symbol	Type	Description	Unit	Properties
vC	v_C	State	Capacitor current	*p.u.*	v_str
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
vC	v_C	State	0
Idc	I_{dc}	Algeb	0
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vC	v_C	State	$-I_{dc}u$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}\left(1-u\right)+u\left(-v_1+v_2+v_C\right)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [C]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.5 RCp

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
R	R	DC line resistance	0.010	*p.u.*	non_zero,r
C	C	DC capacitance	0.001	*p.u.*	non_zero,g

Variables

Name	Symbol	Type	Description	Unit	Properties
vC	v_C	State	Capacitor current	*p.u.*	v_str
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
vC	v_C	State	$v_1 - v_2$
Idc	I_{dc}	Algeb	$\frac{-v_1+v_2}{R}$
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vC	v_C	State	$-u\left(I_{dc}-\frac{v_C}{R}\right)$	C

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}\left(1-u\right)+u\left(-v_1+v_2+v_C\right)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [RCp]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.6 RCs

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
R	R	DC line resistance	0.010	*p.u.*	non_zero,r
C	C	DC capacitance	0.001	*p.u.*	non_zero,g

Variables

Name	Symbol	Type	Description	Unit	Properties
vC	v_C	State	Capacitor current	*p.u.*	v_str
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
vC	v_C	State	$v_1 - v_2$
Idc	I_{dc}	Algeb	$\frac{-v_1+v_2}{R}$
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vC	v_C	State	$-I_{dc}u$	C

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}\left(1-u\right)+u\left(-I_{dc}R-v_1+v_2+v_C\right)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [RCs]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.7 RLs

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
R	R	DC line resistance	0.010	*p.u.*	non_zero,r
L	L	DC line inductance	0.001	*p.u.*	non_zero,r

Variables

Name	Symbol	Type	Description	Unit	Properties
IL	I_L	State	Inductance current	*p.u.*	v_str
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
IL	I_L	State	$\frac{v_1 - v_2}{R}$
Idc	I_{dc}	Algeb	$-\frac{u(v_1 - v_2)}{R}$
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$u\left(-I_L R + v_1 - v_2\right)$	L

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$-I_L u - I_{dc}$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [RLs]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.8 RLCs

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
R	R	DC line resistance	0.010	*p.u.*	non_zero,r
L	L	DC line inductance	0.001	*p.u.*	non_zero,r
C	C	DC capacitance	0.001	*p.u.*	non_zero,g

Variables

Name	Symbol	Type	Description	Unit	Properties
IL	I_L	State	Inductance current	*p.u.*	v_str
vC	v_C	State	Capacitor current	*p.u.*	v_str
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
IL	I_L	State	0
vC	v_C	State	$v_1 - v_2$
Idc	I_{dc}	Algeb	0
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$u\left(-I_L R + v_1 - v_2 - v_C\right)$	L
vC	v_C	State	$I_L u$	C

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$-I_L - I_{dc}$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [RLCs]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.6.9 RLCp

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
R	R	DC line resistance	0.010	*p.u.*	non_zero,r
L	L	DC line inductance	0.001	*p.u.*	non_zero,r
C	C	DC capacitance	0.001	*p.u.*	non_zero,g

Variables

Name	Symbol	Type	Description	Unit	Properties
IL	I_L	State	Inductance current	*p.u.*	v_str
vC	v_C	State	Capacitor current	*p.u.*	v_str
Idc	I_{dc}	Algeb	Current from node 2 to 1	*p.u.*	v_str
v1	v_1	ExtAlgeb	DC voltage on node 1		
v2	v_2	ExtAlgeb	DC voltage on node 2		

Initialization Equations

Name	Symbol	Type	Initial Value
IL	I_L	State	0
vC	v_C	State	$v_1 - v_2$
Idc	I_{dc}	Algeb	$\frac{-v_1+v_2}{R}$
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	uv_C	L
vC	v_C	State	$-u\left(-I_L + I_{dc} - \frac{v_C}{R}\right)$	C

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}\left(1-u\right) + u\left(-v_1 + v_2 + v_C\right)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

Config Fields in [RLCp]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.7 DCTopology

Common Parameters: u, name

Common Variables: v

Available models: *Node*

5.7.1 Node

DC Node model.

A DC Node is like an AC Bus. DC devices need to be connected to Nodes to inject power flow.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
Vdcn	V_{dcn}	DC voltage rating	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
v0	V_{dc0}	initial voltage magnitude	1	*p.u.*	
xcoord		x coordinate (longitude)	0		
ycoord		y coordinate (latitude)	0		
area		Area code			
zone		Zone code			
owner		Owner code			

Variables

Name	Symbol	Type	Description	Unit	Properties
v	V_{dc}	Algeb	voltage magnitude	*p.u.*	v_str

Initialization Equations

Name	Symbol	Type	Initial Value
v	V_{dc}	Algeb	$V_{dc0} \cdot (1 - z_{flat}) + z_{flat}$

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	V_{dc}	Algeb	0

Config Fields in [Node]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
flat_start	z_{flat}	0	flat start for voltages	(0, 1)

5.8 DG

Distributed generation (small-scale).

See *SynGen* for the notes on replacing StaticGen and setting the power ratio parameters.

Common Parameters: u, name, bus, fn

Available models: *PVD1*, *ESD1*, *EV1*, *EV2*

5.8.1 PVD1

WECC Distributed PV model.

Device power rating is specified in *Sn*. Output currents are named *Ipout_y* and *Iqout_y*. Output power can be computed as `Pe = Ipout_y * v` and `Qe = Iqout_y * v`.

Frequency tripping response points *ft0*, *ft1*, *ft2*, and *ft3* must be monotinically increasing. Same rule applies to the voltage tripping response points *vt0*, *vt1*, *vt2*, and *vt3*. The program does not check these values, and the user is responsible for the parameter validity.

Frequency and voltage recovery latching is yet to be implemented.

Modifications to the active and reactive power references, typically by an external scheduling program, should write to *pref0.v* and *qref0.v* in place. AGC signals should write to *pext0.v* in place.

Maximum power limit *pmx* can be disabled by editing the configuration file by setting *plim=0*. It cannot be modified in runtime.

Reference: [1] ESIG, WECC Distributed and Small PV Plants Generic Model (PVD1), [Online], Available:

https://www.esig.energy/wiki-main-page/wecc-distributed-and-small-pv-plants-generic-model-pvd1/

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	device MVA rating	100	*MVA*	
fn	f_n	nominal frequency	60	*Hz*	
busf		Optional BusFreq measurement device idx			
xc	x_c	coupling reactance	0	*p.u.*	z
pqflag		P/Q priority for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
igreg		Remote bus idx for droop response, None for local			
qmx	q_{mx}	Max. reactive power command	0.330	*pu*	power

continues on

Table 2 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
qmn	q_{mn}	Min. reactive power command	-0.330	*pu*	power
pmx	p_{mx}	maximum power limit	9999	*pu*	power
v0	v_0	Lower limit of deadband for Vdroop response	0.800	*pu*	non_zero
v1	v_1	Upper limit of deadband for Vdroop response	1.100	*pu*	non_zero
dqdv	dq/dv	Q-V droop characteristics (negative)	-1		non_zero,power
fdbd	f_{dbd}	frequency deviation deadband	-0.017	*Hz*	non_positive
ddn	D_{dn}	Gain after f deadband	0	*pu (MW)/Hz*	non_negative,powe
ialim	I_{alim}	Apparent power limit	1.300		non_zero,non_nega
vt0	V_{t0}	Voltage tripping response curve point 0	0.880	*p.u.*	non_zero,non_nega
vt1	V_{t1}	Voltage tripping response curve point 1	0.900	*p.u.*	non_zero,non_nega
vt2	V_{t2}	Voltage tripping response curve point 2	1.100	*p.u.*	non_zero,non_nega
vt3	V_{t3}	Voltage tripping response curve point 3	1.200	*p.u.*	non_zero,non_nega
vrflag	z_{VR}	V-trip is latching (0) or self-resetting (0-1)	0		
ft0	f_{t0}	Frequency tripping response curve point 0	59.500	*Hz*	non_zero,non_nega
ft1	f_{t1}	Frequency tripping response curve point 1	59.700	*Hz*	non_zero,non_nega
ft2	f_{t2}	Frequency tripping response curve point 2	60.300	*Hz*	non_zero,non_nega
ft3	f_{t3}	Frequency tripping response curve point 3	60.500	*Hz*	non_zero,non_nega
frflag	z_{FR}	f-trip is latching (0) or self-resetting (0-1)	0		
tip	T_{ip}	Inverter active current lag time constant	0.020	*s*	non_negative
tiq	T_{iq}	Inverter reactive current lag time constant	0.020	*s*	non_negative
gammap	γ_p	Ratio of PVD1.pref0 w.r.t to that of static PV	1		
gammaq	γ_q	Ratio of PVD1.qref0 w.r.t to that of static PV	1		
recflag	z_{rec}	Enable flag for voltage and frequency recovery limiters	1		

Variables

Name	Symbol	Type	Description	Unit	Properties
Ipout_y	y_{Ipout}	State	State in lag transfer function		v_str
Iqout_y	y_{Iqout}	State	State in lag transfer function		v_str
fHz	f_{Hz}	Algeb	frequency in Hz	*Hz*	v_str
Ffl	F_{fl}	Algeb	Coeff. for under frequency		v_str
Ffh	F_{fh}	Algeb	Coeff. for over frequency		v_str
Fdev	f_{dev}	Algeb	Frequency deviation	*Hz*	v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
Fvl	F_{vl}	Algeb	Coeff. for under voltage		v_str
Fvh	F_{vh}	Algeb	Coeff. for over voltage		v_str
vp	V_p	Algeb	Sensed positive voltage		v_str
Pext	P_{ext}	Algeb	External power signal (for AGC)		v_str
Pref	P_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Psum	P_{tot}	Algeb	Sum of P signals		v_str
Qdrp	Q_{drp}	Algeb	External power signal (for AGC)		v_str
Qref	Q_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Qsum	Q_{tot}	Algeb	Sum of Q signals		v_str
Ipul	$I_{p,ul}$	Algeb	Ipcmd before Ip hard limit		v_str
Iqul	$I_{q,ul}$	Algeb	Iqcmd before Iq hard limit		v_str
Ipmax	I_{pmax}	Algeb	Upper limit of Ip		v_str
Iqmax	I_{qmax}	Algeb	Upper limit of Iq		v_str
Ipcmd_x	x_{Ipcmd}	Algeb	Value before limiter		v_str
Ipcmd_y	y_{Ipcmd}	Algeb	Output after limiter and post gain		v_str
Iqcmd_x	x_{Iqcmd}	Algeb	Value before limiter		v_str
Iqcmd_y	y_{Iqcmd}	Algeb	Output after limiter and post gain		v_str
a	θ	ExtAlgeb	bus (or igreg) phase angle	*rad.*	
v	V	ExtAlgeb	bus (or igreg) terminal voltage	*p.u.*	
f	f	ExtAlgeb	Bus frequency	*p.u.*	

Initialization Equations

Name	Symbol	Type	Initial Value
Ipout_	y_{Ipout}	State	$1.0y_{I^{pcmd}}$
Iqout_	y_{Iqout}	State	$1.0y_{I^{qcmd}}$
fHz	f_{Hz}	Algeb	ff_n
Ffl	F_{fl}	Algeb	$K_{ft01}z_i^{FL1}\left(f_{Hz}-f_{t0}\right)+z_u^{FL1}$
Ffh	F_{fh}	Algeb	$z_i^{FL2}\left(K_{ft23}\left(-f_{Hz}+f_{t2}\right)+1\right)+z_l^{FL2}$
Fdev	f_{dev}	Algeb	f_n-f_{Hz}
DB_y	y_{DB}	Algeb	$D_{dn}\left(f_{dev}z_u^{db_{DB}}+z_l^{db_{DB}}\left(-f_{dbd}+f_{dev}\right)\right)$
Fvl	F_{vl}	Algeb	$K_{vt01}z_i^{VL1}\left(V-V_{t0}\right)+z_u^{VL1}$
Fvh	F_{vh}	Algeb	$z_i^{VL2}\left(K_{vt23}\left(-V+V_{t2}\right)+1\right)+z_l^{VL2}$
vp	V_p	Algeb	$Vz_i^{VLo}+0.01z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0}u$
Pref	P_{ref}	Algeb	$P_{ref0}u$
Psum	P_{tot}	Algeb	$u\left(P_{ext}+P_{ref}+y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\left(-V_{comp}+V_{qu}\right)+q_{mx}\right)$
Qref	Q_{ref}	Algeb	$Q_{ref0}u$
Qsum	Q_{tot}	Algeb	$u\left(Q_{ref0}+dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\left(-V_{comp}+V_{q}\right.\right.\right.$
Ipul	$I_{p,ul}$	Algeb	$\frac{P_{tot}z_i^{PHL}+p_{mx}z_u^{PHL}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$\frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}$
Iqmax	I_{qmax}	Algeb	$I_{alim}s_0^{SW_{PQ}}+\sqrt{I_{qmax0}^2}s_1^{SW_{PQ}}$
Ipcmd	$x_{I^{pcmd}}$	Algeb	$I_{p,ul}$
Ipcmd	$y_{I^{pcmd}}$	Algeb	$I_{pmax}z_u^{lim_{I^{pcmd}}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+x_{I^{pcmd}}z_i^{lim_{I^{pcmd}}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)$
Iqcmd	$x_{I^{qcmd}}$	Algeb	$I_{q,ul}$
Iqcmd	$y_{I^{qcmd}}$	Algeb	$-I_{qmax}z_l^{lim_{I^{qcmd}}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+$

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd} - y_{Ipout}$	T_{ip}
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd} - y_{Iqout}$	T_{iq}

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
fHz	f_{Hz}	Algeb	$ff_n - f_{Hz}$
Ffl	F_{fl}	Algeb	$-F_{fl} + K_{ft01} z_i^{FL1} (f_{Hz} - f_{t0}) + z_u^{FL1}$
Ffh	F_{fh}	Algeb	$-F_{fh} + z_i^{FL2} (K_{ft23} (-f_{Hz} + f_{t2}) + 1) + z_l^{FL2}$
Fdev	f_{dev}	Algeb	$f_n - f_{Hz} - f_{dev}$
DB_y	y_{DB}	Algeb	$D_{dn} \left(f_{dev} z_u^{db_{DB}} + z_l^{db_{DB}} (-f_{dbd} + f_{dev}) \right) - y_{DB}$
Fvl	F_{vl}	Algeb	$-F_{vl} + K_{vt01} z_i^{VL1} (V - V_{t0}) + z_u^{VL1}$
Fvh	F_{vh}	Algeb	$-F_{vh} + z_i^{VL2} (K_{vt23} (-V + V_{t2}) + 1) + z_l^{VL2}$
vp	V_p	Algeb	$V z_i^{VLo} - V_p + 0.01 z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0} u - P_{ext}$
Pref	P_{ref}	Algeb	$P_{ref0} u - P_{ref}$
Psum	P_{tot}	Algeb	$-P_{tot} + u (P_{ext} + P_{ref} + y_{DB})$
Qdrp	Q_{drp}	Algeb	$-Q_{drp} + dq/dv u z_i^{VQ2} (-V_{comp} + v_1) + q_{mn} z_u^{VQ2} + q_{mx} u z_l^{VQ1} + u z_i^{VQ1} (dq/dv (-V_{comp} + V_{qu}) + q_{mx})$
Qref	Q_{ref}	Algeb	$Q_{ref0} u - Q_{ref}$
Qsum	Q_{tot}	Algeb	$-Q_{tot} + u (Q_{drp} + Q_{ref})$
Ipul	$I_{p,ul}$	Algeb	$-I_{p,ul} + \frac{P_{tot} z_i^{PHL} + p_{mx} z_u^{PHL}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$-I_{q,ul} + \frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$I_{alim} s_1^{SW_{PQ}} - I_{pmax} + \sqrt{I_{pmax}^2} s_0^{SW_{PQ}}$
Iqmax	I_{qmax}	Algeb	$I_{alim} s_0^{SW_{PQ}} - I_{qmax} + \sqrt{I_{qmax}^2} s_1^{SW_{PQ}}$
Ipcmd	x_{Ipcm}	Algeb	$I_{p,ul} - x_{Ipcmd}$
Ipcmd	y_{Ipcm}	Algeb	$I_{pmax} z_u^{lim_{Ipcmd}} (F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1) + x_{Ipcmd} z_i^{lim_{Ipcmd}} (F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1) - y_{Ipcmd}$
Iqcmd	x_{Iqcm}	Algeb	$I_{q,ul} - x_{Iqcmd}$
Iqcmd	y_{Iqcm}	Algeb	$-I_{qmax} z_l^{lim_{Iqcmd}} (F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1) + I_{qmax} z_u^{lim_{Iqcmd}} (F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1) + x_{Iqcmd} z_i^{lim_{Iqcmd}} (F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1) - y_{Iqcmd}$

Services

Name	Symbol	Equation	Type
pref0	P_{ref0}	$P_{0s}\gamma_p$	ConstService
qref0	Q_{ref0}	$Q_{0s}\gamma_q$	ConstService
Kft01	K_{ft01}	$\frac{1}{-f_{t0}+f_{t1}}$	ConstService
Kft23	K_{ft23}	$\frac{1}{-f_{t2}+f_{t3}}$	ConstService
Kvt01	K_{vt01}	$\frac{1}{-V_{t0}+V_{t1}}$	ConstService
Kvt23	K_{vt23}	$\frac{1}{-V_{t2}+V_{t3}}$	ConstService
Pext0	P_{ext0}	0	ConstService
Vcomp	V_{comp}	$\left\lvert Ve^{i\theta} + ix_c\left(y_{Ipout} + iy_{Iqout}\right)\right\rvert$	VarService
Vqu	V_{qu}	$v_1 - \frac{Q_{ref0}-q_{mn}}{dq/dv}$	ConstService
Vql	V_{ql}	$v_0 + \frac{-Q_{ref0}+q_{mx}}{dq/dv}$	ConstService
Ipmaxsq	I^2_{pmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Iqcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Iqcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Ipmaxsq0	I^2_{pmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2},\ \text{True}\right.\right.$	ConstService
Iqmaxsq	I^2_{qmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Ipcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Ipcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Iqmaxsq0	I^2_{qmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2},\ \text{True}\right)\right.$	ConstService

Discretes

Name	Symbol	Type	Info
SWPQ	SW_{PQ}	Switcher	
FL1	$FL1$	Limiter	Under frequency comparer
FL2	$FL2$	Limiter	Over frequency comparer
DB_db	db_{DB}	DeadBand	
VL1	$VL1$	Limiter	Under voltage comparer
VL2	$VL2$	Limiter	Over voltage comparer
VLo	VLo	Limiter	Voltage lower limit (0.01) flag
PHL	PHL	Limiter	limiter for Psum in [0, pmx]
VQ1	$VQ1$	Limiter	Under voltage comparer for Q droop
VQ2	$VQ2$	Limiter	Over voltage comparer for Q droop
Ipcmd_lim	lim_{Ipcmd}	HardLimiter	
Iqcmd_lim	lim_{Iqcmd}	HardLimiter	

Blocks

Name	Symbol	Type	Info
DB	DB	DeadBand1	frequency deviation deadband with gain
Ipcmd	I^{pcmd}	GainLimiter	Ip with limiter and coeff.
Iqcmd	I^{qcmd}	GainLimiter	Iq with limiter and coeff.
Ipout	$Ipout$	Lag	Output Ip filter
Iqout	$Iqout$	Lag	Output Iq filter

Config Fields in [PVD1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
plim	P_{lim}	1	enable input power limit check bound by [0, pmx]	(0, 1)

5.8.2 ESD1

Distributed energy storage model.

A state-of-charge limit is added to the PVD1 model. This limit is applied to Ipmax and Ipmin. The state of charge is in state variable `SOC`, which is an alias of `pIG_y`.

Reference: [1] Powerworld, Renewable Energy Electrical Control Model REEC_C Available:

https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20REEC_C.htm

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	device MVA rating	100	*MVA*	
fn	f_n	nominal frequency	60	*Hz*	
busf		Optional BusFreq measurement device idx			
xc	x_c	coupling reactance	0	*p.u.*	z
pqflag		P/Q priority for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
igreg		Remote bus idx for droop response, None for local			
qmx	q_{mx}	Max. reactive power command	0.330	*pu*	power
qmn	q_{mn}	Min. reactive power command	-0.330	*pu*	power
pmx	p_{mx}	maximum power limit	9999	*pu*	power
v0	v_0	Lower limit of deadband for Vdroop response	0.800	*pu*	non_zero
v1	v_1	Upper limit of deadband for Vdroop response	1.100	*pu*	non_zero
dqdv	dq/dv	Q-V droop characteristics (negative)	-1		non_zero,power
fdbd	f_{dbd}	frequency deviation deadband	-0.017	*Hz*	non_positive
ddn	D_{dn}	Gain after f deadband	0	*pu (MW)/Hz*	non_negative,pov
ialim	I_{alim}	Apparent power limit	1.300		non_zero,non_ne
vt0	V_{t0}	Voltage tripping response curve point 0	0.880	*p.u.*	non_zero,non_ne
vt1	V_{t1}	Voltage tripping response curve point 1	0.900	*p.u.*	non_zero,non_ne
vt2	V_{t2}	Voltage tripping response curve point 2	1.100	*p.u.*	non_zero,non_ne
vt3	V_{t3}	Voltage tripping response curve point 3	1.200	*p.u.*	non_zero,non_ne
vrflag	z_{VR}	V-trip is latching (0) or self-resetting (0-1)	0		
ft0	f_{t0}	Frequency tripping response curve point 0	59.500	*Hz*	non_zero,non_ne
ft1	f_{t1}	Frequency tripping response curve point 1	59.700	*Hz*	non_zero,non_ne
ft2	f_{t2}	Frequency tripping response curve point 2	60.300	*Hz*	non_zero,non_ne
ft3	f_{t3}	Frequency tripping response curve point 3	60.500	*Hz*	non_zero,non_ne
frflag	z_{FR}	f-trip is latching (0) or self-resetting (0-1)	0		
tip	T_{ip}	Inverter active current lag time constant	0.020	*s*	non_negative
tiq	T_{iq}	Inverter reactive current lag time constant	0.020	*s*	non_negative

continues

Table 3 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
gammap	γ_p	Ratio of PVD1.pref0 w.r.t to that of static PV	1		
gammaq	γ_q	Ratio of PVD1.qref0 w.r.t to that of static PV	1		
recflag	z_{rec}	Enable flag for voltage and frequency recovery limiters	1		
Tf	T_f	Integrator constant for SOC model	1		
SOCmin	SOC_{min}	Minimum required value for SOC in limiter	0		
SOCmax	SOC_{max}	Maximum allowed value for SOC in limiter	1		
SOCinit	SOC_{init}	Initial state of charge	0.500		
En	E_n	Rated energy capacity	100	*MWh*	
EtaC	Eta_C	Efficiency during charging	1		
EtaD	Eta_D	Efficiency during discharging	1		

Variables

Name	Symbol	Type	Description	Unit	Properties
Ipout_y	y_{Ipout}	State	State in lag transfer function		v_str
Iqout_y	y_{Iqout}	State	State in lag transfer function		v_str
pIG_y	y_{pIG}	State	Integrator output		v_str
SOC	SOC	AliasState	Alias for state of charge		
fHz	f_{Hz}	Algeb	frequency in Hz	*Hz*	v_str
Ffl	F_{fl}	Algeb	Coeff. for under frequency		v_str
Ffh	F_{fh}	Algeb	Coeff. for over frequency		v_str
Fdev	f_{dev}	Algeb	Frequency deviation	*Hz*	v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
Fvl	F_{vl}	Algeb	Coeff. for under voltage		v_str
Fvh	F_{vh}	Algeb	Coeff. for over voltage		v_str
vp	V_p	Algeb	Sensed positive voltage		v_str
Pext	P_{ext}	Algeb	External power signal (for AGC)		v_str
Pref	P_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Psum	P_{tot}	Algeb	Sum of P signals		v_str
Qdrp	Q_{drp}	Algeb	External power signal (for AGC)		v_str
Qref	Q_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Qsum	Q_{tot}	Algeb	Sum of Q signals		v_str
Ipul	$I_{p,ul}$	Algeb	Ipcmd before Ip hard limit		v_str
Iqul	$I_{q,ul}$	Algeb	Iqcmd before Iq hard limit		v_str
Ipmax	I_{pmax}	Algeb	Upper limit of Ip		v_str
Iqmax	I_{qmax}	Algeb	Upper limit of Iq		v_str
Ipcmd_x	x_{Ipcmd}	Algeb	Value before limiter		v_str
Ipcmd_y	y_{Ipcmd}	Algeb	Output after limiter and post gain		v_str
Iqcmd_x	x_{Iqcmd}	Algeb	Value before limiter		v_str
Iqcmd_y	y_{Iqcmd}	Algeb	Output after limiter and post gain		v_str
Ipmin	$Ipmin$	Algeb	Minimum value of Ip		v_str

continues on next page

Table 4 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb	bus (or igreg) phase angle	*rad.*	
v	V	ExtAlgeb	bus (or igreg) terminal voltage	*p.u.*	
f	f	ExtAlgeb	Bus frequency	*p.u.*	

Initialization Equations

Name	Symbol	Type	Initial Value
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd}$
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd}$
pIG_y	y_{pIG}	State	SOC_{init}
SOC	SOC	AliasState	
fHz	f_{Hz}	Algeb	ff_n
Ffl	F_{fl}	Algeb	$K_{ft01}z_i^{FL1}\left(f_{Hz}-f_{t0}\right)+z_u^{FL1}$
Ffh	F_{fh}	Algeb	$z_i^{FL2}\left(K_{ft23}\left(-f_{Hz}+f_{t2}\right)+1\right)+z_l^{FL2}$
Fdev	f_{dev}	Algeb	f_n-f_{Hz}
DB_y	y_{DB}	Algeb	$D_{dn}\left(f_{dev}z_u^{db_{DB}}+z_l^{db_{DB}}\left(-f_{dbd}+f_{dev}\right)\right)$
Fvl	F_{vl}	Algeb	$K_{vt01}z_i^{VL1}\left(V-V_{t0}\right)+z_u^{VL1}$
Fvh	F_{vh}	Algeb	$z_i^{VL2}\left(K_{vt23}\left(-V+V_{t2}\right)+1\right)+z_l^{VL2}$
vp	V_p	Algeb	$Vz_i^{VLo}+0.01z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0}u$
Pref	P_{ref}	Algeb	$P_{ref0}u$
Psum	P_{tot}	Algeb	$u\left(P_{ext}+P_{ref}+y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\left(-V_{comp}+V\right.\right.$
Qref	Q_{ref}	Algeb	$Q_{ref0}u$
Qsum	Q_{tot}	Algeb	$u\left(Q_{ref0}+dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\right.\right.$
Ipul	$I_{p,ul}$	Algeb	$\frac{P_{tot}z_i^{PHL}+p_{mx}z_u^{PHL}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$\frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$\left(1-z_l^{SOClim}\right)\left(I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}\right)$
Iqmax	I_{qmax}	Algeb	$I_{alim}s_0^{SW_{PQ}}+\sqrt{I_{qmax0}^2}s_1^{SW_{PQ}}$
Ipcmd_x	x_{Ipcmd}	Algeb	$I_{p,ul}$
Ipcmd_y	y_{Ipcmd}	Algeb	$I_{pmax}z_u^{lim_{Ipcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+x_{Ipcmd}z_i^{lim_{Ipcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}\right.$
Iqcmd_x	x_{Iqcmd}	Algeb	$I_{q,ul}$
Iqcmd_y	y_{Iqcmd}	Algeb	$-I_{qmax}z_l^{lim_{Iqcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+I_{qmax}z_u^{lim_{Iqcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}\right.$
Ipmin	$Ipmin$	Algeb	$\left(z_u^{SOClim}-1\right)\left(I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}\right)$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
f	f	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd} - y_{Ipout}$	T_{ip}
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd} - y_{Iqout}$	T_{iq}
pIG_y	y_{pIG}	State	$\frac{S_{b,sys}\left(-\mathrm{H}_C V y_{Ipout} z_1^{LTN} - \frac{V y_{Ipout} z_0^{LTN}}{\mathrm{H}_D}\right)}{3600 E_n}$	T_f
SOC	SOC	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
fHz	f_{Hz}	Algeb	$ff_n - f_{Hz}$
Ffl	F_{fl}	Algeb	$-F_{fl} + K_{ft01} z_i^{FL1} \left(f_{Hz} - f_{t0}\right) + z_u^{FL1}$
Ffh	F_{fh}	Algeb	$-F_{fh} + z_i^{FL2} \left(K_{ft23} \left(-f_{Hz} + f_{t2}\right) + 1\right) + z_l^{FL2}$
Fdev	f_{dev}	Algeb	$f_n - f_{Hz} - f_{dev}$
DB_y	y_{DB}	Algeb	$D_{dn} \left(f_{dev} z_u^{db_{DB}} + z_l^{db_{DB}} \left(-f_{dbd} + f_{dev}\right)\right) - y_{DB}$
Fvl	F_{vl}	Algeb	$-F_{vl} + K_{vt01} z_i^{VL1} \left(V - V_{t0}\right) + z_u^{VL1}$
Fvh	F_{vh}	Algeb	$-F_{vh} + z_i^{VL2} \left(K_{vt23} \left(-V + V_{t2}\right) + 1\right) + z_l^{VL2}$
vp	V_p	Algeb	$V z_i^{VLo} - V_p + 0.01 z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0} u - P_{ext}$
Pref	P_{ref}	Algeb	$P_{ref0} u - P_{ref}$
Psum	P_{tot}	Algeb	$-P_{tot} + u \left(P_{ext} + P_{ref} + y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$-Q_{drp} + dq/dv u z_i^{VQ2} \left(-V_{comp} + v_1\right) + q_{mn} z_u^{VQ2} + q_{mx} u z_l^{VQ1} + u z_i^{VQ1} \left(dq/dv \left(-V_{comp} + V_{qu}\right) + q_{mx}\right)$
Qref	Q_{ref}	Algeb	$Q_{ref0} u - Q_{ref}$
Qsum	Q_{tot}	Algeb	$-Q_{tot} + u \left(Q_{drp} + Q_{ref}\right)$
Ipul	$I_{p,ul}$	Algeb	$-I_{p,ul} + \frac{P_{tot} z_i^{PHL} + p_{mx} z_u^{PHL}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$-I_{q,ul} + \frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$-I_{pmax} + \left(1 - z_l^{SOClim}\right) \left(I_{alim} s_1^{SW_{PQ}} + \sqrt{I_{pmax}^2} s_0^{SW_{PQ}}\right)$
Iqmax	I_{qmax}	Algeb	$I_{alim} s_0^{SW_{PQ}} - I_{qmax} + \sqrt{I_{qmax}^2} s_1^{SW_{PQ}}$
Ipcmd	x_{Ipcmd}	Algeb	$I_{p,ul} - x_{Ipcmd}$
Ipcmd	y_{Ipcmd}	Algeb	$I_{pmax} z_u^{lim_{Ipcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + x_{Ipcmd} z_i^{lim_{Ipcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) - y_{Ipcmd}$
Iqcmd	x_{Iqcmd}	Algeb	$I_{q,ul} - x_{Iqcmd}$
Iqcmd	y_{Iqcmd}	Algeb	$-I_{qmax} z_l^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + I_{qmax} z_u^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + x_{Iqcmd} z_i^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) - y_{Iqcmd}$

Services

Name	Symbol	Equation	Type
pref0	P_{ref0}	$P_{0s}\gamma_p$	ConstService
qref0	Q_{ref0}	$Q_{0s}\gamma_q$	ConstService
Kft01	K_{ft01}	$\frac{1}{-f_{t0}+f_{t1}}$	ConstService
Kft23	K_{ft23}	$\frac{1}{-f_{t2}+f_{t3}}$	ConstService
Kvt01	K_{vt01}	$\frac{1}{-V_{t0}+V_{t1}}$	ConstService
Kvt23	K_{vt23}	$\frac{1}{-V_{t2}+V_{t3}}$	ConstService
Pext0	P_{ext0}	0	ConstService
Vcomp	V_{comp}	$\left\lvert Ve^{i\theta} + ix_c\left(y_{Ipout} + iy_{Iqout}\right)\right\rvert$	VarService
Vqu	V_{qu}	$v_1 - \frac{Q_{ref0}-q_{mn}}{dq/dv}$	ConstService
Vql	V_{ql}	$v_0 + \frac{-Q_{ref0}+q_{mx}}{dq/dv}$	ConstService
Ipmaxsq	I^2_{pmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Iqcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Iqcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Ipmaxsq0	I^2_{pmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2},\ \text{True}\right.\right.$	ConstService
Iqmaxsq	I^2_{qmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Ipcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Ipcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Iqmaxsq0	I^2_{qmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2},\ \text{True}\right)\right.$	ConstService

Discretes

Name	Symbol	Type	Info
SWPQ	SW_{PQ}	Switcher	
FL1	$FL1$	Limiter	Under frequency comparer
FL2	$FL2$	Limiter	Over frequency comparer
DB_db	db_{DB}	DeadBand	
VL1	$VL1$	Limiter	Under voltage comparer
VL2	$VL2$	Limiter	Over voltage comparer
VLo	VLo	Limiter	Voltage lower limit (0.01) flag
PHL	PHL	Limiter	limiter for Psum in [0, pmx]
VQ1	$VQ1$	Limiter	Under voltage comparer for Q droop
VQ2	$VQ2$	Limiter	Over voltage comparer for Q droop
Ipcmd_lim	lim_{Ipcmd}	HardLimiter	
Iqcmd_lim	lim_{Iqcmd}	HardLimiter	
LTN	LTN	LessThan	
SOClim	$SOClim$	HardLimiter	

Blocks

Name	Symbol	Type	Info
DB	DB	DeadBand1	frequency deviation deadband with gain
Ipcmd	I^{pcmd}	GainLimiter	Ip with limiter and coeff.
Iqcmd	I^{qcmd}	GainLimiter	Iq with limiter and coeff.
Ipout	$Ipout$	Lag	Output Ip filter
Iqout	$Iqout$	Lag	Output Iq filter
pIG	pIG	Integrator	State of charge

Config Fields in [ESD1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
plim	P_{lim}	1	enable input power limit check bound by [0, pmx]	(0, 1)

5.8.3 EV1

Electric vehicle model type 1.

Modified from ESD1 model by adding the minumum power limit *pmn*. Like *pmx*, *pmn* acts on *Psum*, the sum of the active power references.

The limiter that uses *pmx* and *pmn* is enabled by default.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	device MVA rating	100	*MVA*	
fn	f_n	nominal frequency	60	*Hz*	
busf		Optional BusFreq measurement device idx			
xc	x_c	coupling reactance	0	*p.u.*	z
pqflag		P/Q priority for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
igreg		Remote bus idx for droop response, None for local			
qmx	q_{mx}	Max. reactive power command	0.330	*pu*	power
qmn	q_{mn}	Min. reactive power command	-0.330	*pu*	power
pmx	p_{mx}	maximum power limit	9999	*pu*	power
v0	v_0	Lower limit of deadband for Vdroop response	0.800	*pu*	non_zero
v1	v_1	Upper limit of deadband for Vdroop response	1.100	*pu*	non_zero
dqdv	dq/dv	Q-V droop characteristics (negative)	-1		non_zero,power
fdbd	f_{dbd}	frequency deviation deadband	-0.017	*Hz*	non_positive
ddn	D_{dn}	Gain after f deadband	0	*pu (MW)/Hz*	non_negative,pov
ialim	I_{alim}	Apparent power limit	1.300		non_zero,non_ne
vt0	V_{t0}	Voltage tripping response curve point 0	0.880	*p.u.*	non_zero,non_ne
vt1	V_{t1}	Voltage tripping response curve point 1	0.900	*p.u.*	non_zero,non_ne
vt2	V_{t2}	Voltage tripping response curve point 2	1.100	*p.u.*	non_zero,non_ne
vt3	V_{t3}	Voltage tripping response curve point 3	1.200	*p.u.*	non_zero,non_ne
vrflag	z_{VR}	V-trip is latching (0) or self-resetting (0-1)	0		
ft0	f_{t0}	Frequency tripping response curve point 0	59.500	*Hz*	non_zero,non_ne
ft1	f_{t1}	Frequency tripping response curve point 1	59.700	*Hz*	non_zero,non_ne
ft2	f_{t2}	Frequency tripping response curve point 2	60.300	*Hz*	non_zero,non_ne
ft3	f_{t3}	Frequency tripping response curve point 3	60.500	*Hz*	non_zero,non_ne
frflag	z_{FR}	f-trip is latching (0) or self-resetting (0-1)	0		
tip	T_{ip}	Inverter active current lag time constant	0.020	*s*	non_negative
tiq	T_{iq}	Inverter reactive current lag time constant	0.020	*s*	non_negative
gammap	γ_p	Ratio of PVD1.pref0 w.r.t to that of static PV	1		

continues

Table 6 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
gammaq	γ_q	Ratio of PVD1.qref0 w.r.t to that of static PV	1		
recflag	z_{rec}	Enable flag for voltage and frequency recovery limiters	1		
Tf	T_f	Integrator constant for SOC model	1		
SOCmin	SOC_{min}	Minimum required value for SOC in limiter	0		
SOCmax	SOC_{max}	Maximum allowed value for SOC in limiter	1		
SOCinit	SOC_{init}	Initial state of charge	0.500		
En	E_n	Rated energy capacity	100	*MWh*	
EtaC	Eta_C	Efficiency during charging	1		
EtaD	Eta_D	Efficiency during discharging	1		
pmn	p_{mn}	minimum power limit	-999	*pu*	power

Variables

Name	Symbol	Type	Description	Unit	Properties
Ipout_y	y_{Ipout}	State	State in lag transfer function		v_str
Iqout_y	y_{Iqout}	State	State in lag transfer function		v_str
pIG_y	y_{pIG}	State	Integrator output		v_str
SOC	SOC	AliasState	Alias for state of charge		
fHz	f_{Hz}	Algeb	frequency in Hz	*Hz*	v_str
Ffl	F_{fl}	Algeb	Coeff. for under frequency		v_str
Ffh	F_{fh}	Algeb	Coeff. for over frequency		v_str
Fdev	f_{dev}	Algeb	Frequency deviation	*Hz*	v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
Fvl	F_{vl}	Algeb	Coeff. for under voltage		v_str
Fvh	F_{vh}	Algeb	Coeff. for over voltage		v_str
vp	V_p	Algeb	Sensed positive voltage		v_str
Pext	P_{ext}	Algeb	External power signal (for AGC)		v_str
Pref	P_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Psum	P_{tot}	Algeb	Sum of P signals		v_str
Qdrp	Q_{drp}	Algeb	External power signal (for AGC)		v_str
Qref	Q_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Qsum	Q_{tot}	Algeb	Sum of Q signals		v_str
Ipul	$I_{p,ul}$	Algeb	Ipcmd before Ip hard limit		v_str
Iqul	$I_{q,ul}$	Algeb	Iqcmd before Iq hard limit		v_str
Ipmax	I_{pmax}	Algeb	Upper limit of Ip		v_str
Iqmax	I_{qmax}	Algeb	Upper limit of Iq		v_str
Ipcmd_x	x_{Ipcmd}	Algeb	Value before limiter		v_str
Ipcmd_y	y_{Ipcmd}	Algeb	Output after limiter and post gain		v_str
Iqcmd_x	x_{Iqcmd}	Algeb	Value before limiter		v_str
Iqcmd_y	y_{Iqcmd}	Algeb	Output after limiter and post gain		v_str
Ipmin	$Ipmin$	Algeb	Minimum value of Ip		v_str

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Table 7 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb	bus (or igreg) phase angle	*rad.*	
v	V	ExtAlgeb	bus (or igreg) terminal voltage	*p.u.*	
f	f	ExtAlgeb	Bus frequency	*p.u.*	

Initialization Equations

Name	Symbol	Type	Initial Value
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd}$
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd}$
pIG_y	y_{pIG}	State	SOC_{init}
SOC	SOC	AliasState	
fHz	f_{Hz}	Algeb	ff_n
Ffl	F_{fl}	Algeb	$K_{ft01}z_i^{FL1}\left(f_{Hz}-f_{t0}\right)+z_u^{FL1}$
Ffh	F_{fh}	Algeb	$z_i^{FL2}\left(K_{ft23}\left(-f_{Hz}+f_{t2}\right)+1\right)+z_l^{FL2}$
Fdev	f_{dev}	Algeb	f_n-f_{Hz}
DB_y	y_{DB}	Algeb	$D_{dn}\left(f_{dev}z_u^{db_{DB}}+z_l^{db_{DB}}\left(-f_{dbd}+f_{dev}\right)\right)$
Fvl	F_{vl}	Algeb	$K_{vt01}z_i^{VL1}\left(V-V_{t0}\right)+z_u^{VL1}$
Fvh	F_{vh}	Algeb	$z_i^{VL2}\left(K_{vt23}\left(-V+V_{t2}\right)+1\right)+z_l^{VL2}$
vp	V_p	Algeb	$Vz_i^{VLo}+0.01z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0}u$
Pref	P_{ref}	Algeb	$P_{ref0}u$
Psum	P_{tot}	Algeb	$u\left(P_{ext}+P_{ref}+y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\left(-V_{comp}+V\right.\right.$
Qref	Q_{ref}	Algeb	$Q_{ref0}u$
Qsum	Q_{tot}	Algeb	$u\left(Q_{ref0}+dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\right.\right.$
Ipul	$I_{p,ul}$	Algeb	$\frac{P_{tot}z_i^{PHL}+p_{mn}z_l^{PHL}+p_{mx}z_u^{PHL}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$\frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$\left(1-z_l^{SOClim}\right)\left(I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}\right)$
Iqmax	I_{qmax}	Algeb	$I_{alim}s_0^{SW_{PQ}}+\sqrt{I_{qmax0}^2}s_1^{SW_{PQ}}$
Ipcmd_x	x_{Ipcmd}	Algeb	$I_{p,ul}$
Ipcmd_y	y_{Ipcmd}	Algeb	$I_{pmax}z_u^{lim_{Ipcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+x_{Ipcmd}z_i^{lim_{Ipcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}\right.$
Iqcmd_x	x_{Iqcmd}	Algeb	$I_{q,ul}$
Iqcmd_y	y_{Iqcmd}	Algeb	$-I_{qmax}z_l^{lim_{Iqcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+I_{qmax}z_u^{lim_{Iqcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}\right.$
Ipmin	$Ipmin$	Algeb	$\left(z_u^{SOClim}-1\right)\left(I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}\right)$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
f	f	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd} - y_{Ipout}$	T_{ip}
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd} - y_{Iqout}$	T_{iq}
pIG_y	y_{pIG}	State	$\frac{S_{b,sys}\left(-\mathrm{H}_C V y_{Ipout} z_1^{LTN} - \frac{V y_{Ipout} z_0^{LTN}}{\mathrm{H}_D}\right)}{3600 E_n}$	T_f
SOC	SOC	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
fHz	f_{Hz}	Algeb	$ff_n - f_{Hz}$
Ffl	F_{fl}	Algeb	$-F_{fl} + K_{ft01} z_i^{FL1} \left(f_{Hz} - f_{t0}\right) + z_u^{FL1}$
Ffh	F_{fh}	Algeb	$-F_{fh} + z_i^{FL2} \left(K_{ft23} \left(-f_{Hz} + f_{t2}\right) + 1\right) + z_l^{FL2}$
Fdev	f_{dev}	Algeb	$f_n - f_{Hz} - f_{dev}$
DB_y	y_{DB}	Algeb	$D_{dn} \left(f_{dev} z_u^{db_{DB}} + z_l^{db_{DB}} \left(-f_{dbd} + f_{dev}\right)\right) - y_{DB}$
Fvl	F_{vl}	Algeb	$-F_{vl} + K_{vt01} z_i^{VL1} \left(V - V_{t0}\right) + z_u^{VL1}$
Fvh	F_{vh}	Algeb	$-F_{vh} + z_i^{VL2} \left(K_{vt23} \left(-V + V_{t2}\right) + 1\right) + z_l^{VL2}$
vp	V_p	Algeb	$V z_i^{VLo} - V_p + 0.01 z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0} u - P_{ext}$
Pref	P_{ref}	Algeb	$P_{ref0} u - P_{ref}$
Psum	P_{tot}	Algeb	$-P_{tot} + u \left(P_{ext} + P_{ref} + y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$-Q_{drp} + dq/dv u z_i^{VQ2} \left(-V_{comp} + v_1\right) + q_{mn} z_u^{VQ2} + q_{mx} u z_l^{VQ1} + u z_i^{VQ1} \left(dq/dv \left(-V_{comp} + V_{qu}\right) + q_{mx}\right)$
Qref	Q_{ref}	Algeb	$Q_{ref0} u - Q_{ref}$
Qsum	Q_{tot}	Algeb	$-Q_{tot} + u \left(Q_{drp} + Q_{ref}\right)$
Ipul	$I_{p,ul}$	Algeb	$-I_{p,ul} + \frac{P_{tot} z_i^{PHL} + p_{mn} z_l^{PHL} + p_{mx} z_u^{PHL}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$-I_{q,ul} + \frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$-I_{pmax} + \left(1 - z_l^{SOClim}\right) \left(I_{alim} s_1^{SW_{PQ}} + \sqrt{I_{pmax}^2} s_0^{SW_{PQ}}\right)$
Iqmax	I_{qmax}	Algeb	$I_{alim} s_0^{SW_{PQ}} - I_{qmax} + \sqrt{I_{qmax}^2} s_1^{SW_{PQ}}$
Ipcmd	x_{Ipcmd}	Algeb	$I_{p,ul} - x_{Ipcmd}$
Ipcmd	y_{Ipcmd}	Algeb	$I_{pmax} z_u^{lim_{Ipcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + x_{Ipcmd} z_i^{lim_{Ipcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) - y_{Ipcmd}$
Iqcmd	x_{Iqcmd}	Algeb	$I_{q,ul} - x_{Iqcmd}$
Iqcmd	y_{Iqcmd}	Algeb	$-I_{qmax} z_l^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + I_{qmax} z_u^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + x_{Iqcmd} z_i^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) - y_{Iqcmd}$

Services

Name	Symbol	Equation	Type
pref0	P_{ref0}	$P_{0s}\gamma_p$	ConstService
qref0	Q_{ref0}	$Q_{0s}\gamma_q$	ConstService
Kft01	K_{ft01}	$\frac{1}{-f_{t0}+f_{t1}}$	ConstService
Kft23	K_{ft23}	$\frac{1}{-f_{t2}+f_{t3}}$	ConstService
Kvt01	K_{vt01}	$\frac{1}{-V_{t0}+V_{t1}}$	ConstService
Kvt23	K_{vt23}	$\frac{1}{-V_{t2}+V_{t3}}$	ConstService
Pext0	P_{ext0}	0	ConstService
Vcomp	V_{comp}	$\left\lvert Ve^{i\theta} + ix_c\left(y_{Ipout} + iy_{Iqout}\right)\right\rvert$	VarService
Vqu	V_{qu}	$v_1 - \frac{Q_{ref0}-q_{mn}}{dq/dv}$	ConstService
Vql	V_{ql}	$v_0 + \frac{-Q_{ref0}+q_{mx}}{dq/dv}$	ConstService
Ipmaxsq	I^2_{pmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Iqcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Iqcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Ipmaxsq0	I^2_{pmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2},\ \text{True}\right.\right.$	ConstService
Iqmaxsq	I^2_{qmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Ipcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Ipcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Iqmaxsq0	I^2_{qmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2},\ \text{True}\right)\right.$	ConstService

Discretes

Name	Symbol	Type	Info
SWPQ	SW_{PQ}	Switcher	
FL1	$FL1$	Limiter	Under frequency comparer
FL2	$FL2$	Limiter	Over frequency comparer
DB_db	db_{DB}	DeadBand	
VL1	$VL1$	Limiter	Under voltage comparer
VL2	$VL2$	Limiter	Over voltage comparer
VLo	VLo	Limiter	Voltage lower limit (0.01) flag
PHL	PHL	Limiter	limiter for Psum in [pmn, pmx]
VQ1	$VQ1$	Limiter	Under voltage comparer for Q droop
VQ2	$VQ2$	Limiter	Over voltage comparer for Q droop
Ipcmd_lim	lim_{Ipcmd}	HardLimiter	
Iqcmd_lim	lim_{Iqcmd}	HardLimiter	
LTN	LTN	LessThan	
SOClim	$SOClim$	HardLimiter	

Blocks

Name	Symbol	Type	Info
DB	DB	DeadBand1	frequency deviation deadband with gain
Ipcmd	I^{pcmd}	GainLimiter	Ip with limiter and coeff.
Iqcmd	I^{qcmd}	GainLimiter	Iq with limiter and coeff.
Ipout	$Ipout$	Lag	Output Ip filter
Iqout	$Iqout$	Lag	Output Iq filter
pIG	pIG	Integrator	State of charge

Config Fields in [EV1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
plim	P_{lim}	1	enable input power limit check bound by [0, pmx]	(0, 1)

5.8.4 EV2

Electric vehicle model type 2.

Derived from EV1, EV2 introduces *pcap* multiplied to *pmx*.

Psum will be limited to [pmn, pmx * pcap].

The model does not check the signs or values of *pmn*, *pmx*, or *pcap*. The input data is required to satisfy *pmn* <= *pmx* * *pcap*.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	device MVA rating	100	*MVA*	
fn	f_n	nominal frequency	60	*Hz*	
busf		Optional BusFreq measurement device idx			
xc	x_c	coupling reactance	0	*p.u.*	z
pqflag		P/Q priority for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
igreg		Remote bus idx for droop response, None for local			
qmx	q_{mx}	Max. reactive power command	0.330	*pu*	power
qmn	q_{mn}	Min. reactive power command	-0.330	*pu*	power
pmx	p_{mx}	maximum power limit	9999	*pu*	power
v0	v_0	Lower limit of deadband for Vdroop response	0.800	*pu*	non_zero
v1	v_1	Upper limit of deadband for Vdroop response	1.100	*pu*	non_zero
dqdv	dq/dv	Q-V droop characteristics (negative)	-1		non_zero,power
fdbd	f_{dbd}	frequency deviation deadband	-0.017	*Hz*	non_positive
ddn	D_{dn}	Gain after f deadband	1	*pu (MW)/Hz*	non_negative,pov
ialim	I_{alim}	Apparent power limit	1.300		non_zero,non_ne
vt0	V_{t0}	Voltage tripping response curve point 0	0.880	*p.u.*	non_zero,non_ne
vt1	V_{t1}	Voltage tripping response curve point 1	0.900	*p.u.*	non_zero,non_ne
vt2	V_{t2}	Voltage tripping response curve point 2	1.100	*p.u.*	non_zero,non_ne
vt3	V_{t3}	Voltage tripping response curve point 3	1.200	*p.u.*	non_zero,non_ne
vrflag	z_{VR}	V-trip is latching (0) or self-resetting (0-1)	0		
ft0	f_{t0}	Frequency tripping response curve point 0	59.500	*Hz*	non_zero,non_ne
ft1	f_{t1}	Frequency tripping response curve point 1	59.700	*Hz*	non_zero,non_ne
ft2	f_{t2}	Frequency tripping response curve point 2	60.300	*Hz*	non_zero,non_ne
ft3	f_{t3}	Frequency tripping response curve point 3	60.500	*Hz*	non_zero,non_ne
frflag	z_{FR}	f-trip is latching (0) or self-resetting (0-1)	0		
tip	T_{ip}	Inverter active current lag time constant	0.020	*s*	non_negative
tiq	T_{iq}	Inverter reactive current lag time constant	0.020	*s*	non_negative

continues

Table 9 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
gammap	γ_p	Ratio of PVD1.pref0 w.r.t to that of static PV	1		
gammaq	γ_q	Ratio of PVD1.qref0 w.r.t to that of static PV	1		
recflag	z_{rec}	Enable flag for voltage and frequency recovery limiters	1		
Tf	T_f	Integrator constant for SOC model	1		
SOCmin	SOC_{min}	Minimum required value for SOC in limiter	0		
SOCmax	SOC_{max}	Maximum allowed value for SOC in limiter	1		
SOCinit	SOC_{init}	Initial state of charge	0.500		
En	E_n	Rated energy capacity	100	*MWh*	
EtaC	Eta_C	Efficiency during charging	1		
EtaD	Eta_D	Efficiency during discharging	1		
pmn	p_{mn}	minimum power limit	-999	*pu*	power
pcap	p_{cap}	power ratio multiplied to pmx in [-1, 1]	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
Ipout_y	y_{Ipout}	State	State in lag transfer function		v_str
Iqout_y	y_{Iqout}	State	State in lag transfer function		v_str
pIG_y	y_{pIG}	State	Integrator output		v_str
SOC	SOC	AliasState	Alias for state of charge		
fHz	f_{Hz}	Algeb	frequency in Hz	*Hz*	v_str
Ffl	F_{fl}	Algeb	Coeff. for under frequency		v_str
Ffh	F_{fh}	Algeb	Coeff. for over frequency		v_str
Fdev	f_{dev}	Algeb	Frequency deviation	*Hz*	v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
Fvl	F_{vl}	Algeb	Coeff. for under voltage		v_str
Fvh	F_{vh}	Algeb	Coeff. for over voltage		v_str
vp	V_p	Algeb	Sensed positive voltage		v_str
Pext	P_{ext}	Algeb	External power signal (for AGC)		v_str
Pref	P_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Psum	P_{tot}	Algeb	Sum of P signals		v_str
Qdrp	Q_{drp}	Algeb	External power signal (for AGC)		v_str
Qref	Q_{ref}	Algeb	Reference power signal (for scheduling setpoint)		v_str
Qsum	Q_{tot}	Algeb	Sum of Q signals		v_str
Ipul	$I_{p,ul}$	Algeb	Ipcmd before Ip hard limit		v_str
Iqul	$I_{q,ul}$	Algeb	Iqcmd before Iq hard limit		v_str
Ipmax	I_{pmax}	Algeb	Upper limit of Ip		v_str
Iqmax	I_{qmax}	Algeb	Upper limit of Iq		v_str
Ipcmd_x	x_{Ipcmd}	Algeb	Value before limiter		v_str
Ipcmd_y	y_{Ipcmd}	Algeb	Output after limiter and post gain		v_str
Iqcmd_x	x_{Iqcmd}	Algeb	Value before limiter		v_str

continues on next page

Table 10 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
Iqcmd_y	y_{Iqcmd}	Algeb	Output after limiter and post gain		v_str
Ipmin	$Ipmin$	Algeb	Minimum value of Ip		v_str
PHLup	PHL_{upper}	Algeb	PHL upper limit		v_str
a	θ	ExtAlgeb	bus (or igreg) phase angle	*rad.*	
v	V	ExtAlgeb	bus (or igreg) terminal voltage	*p.u.*	
f	f	ExtAlgeb	Bus frequency	*p.u.*	

Initialization Equations

Name	Symbol	Type	Initial Value
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd}$
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd}$
pIG_y	y_{pIG}	State	SOC_{init}
SOC	SOC	AliasState	
fHz	f_{Hz}	Algeb	ff_n
Ffl	F_{fl}	Algeb	$K_{ft01}z_i^{FL1}\left(f_{Hz}-f_{t0}\right)+z_u^{FL1}$
Ffh	F_{fh}	Algeb	$z_i^{FL2}\left(K_{ft23}\left(-f_{Hz}+f_{t2}\right)+1\right)+z_l^{FL2}$
Fdev	f_{dev}	Algeb	f_n-f_{Hz}
DB_y	y_{DB}	Algeb	$D_{dn}\left(f_{dev}z_u^{db_{DB}}+z_l^{db_{DB}}\left(-f_{dbd}+f_{dev}\right)\right)$
Fvl	F_{vl}	Algeb	$K_{vt01}z_i^{VL1}\left(V-V_{t0}\right)+z_u^{VL1}$
Fvh	F_{vh}	Algeb	$z_i^{VL2}\left(K_{vt23}\left(-V+V_{t2}\right)+1\right)+z_l^{VL2}$
vp	V_p	Algeb	$Vz_i^{VLo}+0.01z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0}u$
Pref	P_{ref}	Algeb	$P_{ref0}u$
Psum	P_{tot}	Algeb	$u\left(P_{ext}+P_{ref}+y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/dv\left(-V_{comp}+\right.\right.$
Qref	Q_{ref}	Algeb	$Q_{ref0}u$
Qsum	Q_{tot}	Algeb	$u\left(Q_{ref0}+dq/dvuz_i^{VQ2}\left(-V_{comp}+v_1\right)+q_{mn}z_u^{VQ2}+q_{mx}uz_l^{VQ1}+uz_i^{VQ1}\left(dq/d\right.\right.$
Ipul	$I_{p,ul}$	Algeb	$\frac{PHL_{upper}z_u^{PHL2}+P_{tot}z_i^{PHL2}+p_{mn}z_l^{PHL2}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$\frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$\left(1-z_l^{SOClim}\right)\left(I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}\right)$
Iqmax	I_{qmax}	Algeb	$I_{alim}s_0^{SW_{PQ}}+\sqrt{I_{qmax0}^2}s_1^{SW_{PQ}}$
Ipcmd_x	x_{Ipcmd}	Algeb	$I_{p,ul}$
Ipcmd_y	y_{Ipcmd}	Algeb	$I_{pmax}z_u^{lim_{Ipcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+x_{Ipcmd}z_i^{lim_{Ipcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_r\right.$
Iqcmd_x	x_{Iqcmd}	Algeb	$I_{q,ul}$
Iqcmd_y	y_{Iqcmd}	Algeb	$-I_{qmax}z_l^{lim_{Iqcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}z_{rec}-z_{rec}+1\right)+I_{qmax}z_u^{lim_{Iqcmd}}\left(F_{fh}F_{fl}F_{vh}F_{vl}\right.$
Ipmin	$Ipmin$	Algeb	$\left(z_u^{SOClim}-1\right)\left(I_{alim}s_1^{SW_{PQ}}+\sqrt{I_{pmax0}^2}s_0^{SW_{PQ}}\right)$
PHLup	PHL_{upper}	Algeb	$p_{cap}p_{mx}$

Table 11 – continued from previous page

Name	Symbol	Type	Initial Value
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
f	f	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Ipout_y	y_{Ipout}	State	$1.0y_{Ipcmd} - y_{Ipout}$	T_{ip}
Iqout_y	y_{Iqout}	State	$1.0y_{Iqcmd} - y_{Iqout}$	T_{iq}
pIG_y	y_{pIG}	State	$\frac{S_{b,sys}\left(-\mathrm{H}_C V y_{Ipout} z_1^{LTN} - \frac{V y_{Ipout} z_0^{LTN}}{\mathrm{H}_D}\right)}{3600 E_n}$	T_f
SOC	SOC	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
fHz	f_{Hz}	Algeb	$ff_n - f_{Hz}$
Ffl	F_{fl}	Algeb	$-F_{fl} + K_{ft01} z_i^{FL1} \left(f_{Hz} - f_{t0}\right) + z_u^{FL1}$
Ffh	F_{fh}	Algeb	$-F_{fh} + z_i^{FL2} \left(K_{ft23} \left(-f_{Hz} + f_{t2}\right) + 1\right) + z_l^{FL2}$
Fdev	f_{dev}	Algeb	$f_n - f_{Hz} - f_{dev}$
DB_y	y_{DB}	Algeb	$D_{dn} \left(f_{dev} z_u^{db_{DB}} + z_l^{db_{DB}} \left(-f_{dbd} + f_{dev}\right)\right) - y_{DB}$
Fvl	F_{vl}	Algeb	$-F_{vl} + K_{vt01} z_i^{VL1} \left(V - V_{t0}\right) + z_u^{VL1}$
Fvh	F_{vh}	Algeb	$-F_{vh} + z_i^{VL2} \left(K_{vt23} \left(-V + V_{t2}\right) + 1\right) + z_l^{VL2}$
vp	V_p	Algeb	$V z_i^{VLo} - V_p + 0.01 z_l^{VLo}$
Pext	P_{ext}	Algeb	$P_{ext0} u - P_{ext}$
Pref	P_{ref}	Algeb	$P_{ref0} u - P_{ref}$
Psum	P_{tot}	Algeb	$-P_{tot} + u \left(P_{ext} + P_{ref} + y_{DB}\right)$
Qdrp	Q_{drp}	Algeb	$-Q_{drp} + dq/dv u z_i^{VQ2} \left(-V_{comp} + v_1\right) + q_{mn} z_u^{VQ2} + q_{mx} u z_l^{VQ1} + u z_i^{VQ1} \left(dq/dv \left(-V_{comp} + V_{qu}\right) + q_{mx}\right)$
Qref	Q_{ref}	Algeb	$Q_{ref0} u - Q_{ref}$
Qsum	Q_{tot}	Algeb	$-Q_{tot} + u \left(Q_{drp} + Q_{ref}\right)$
Ipul	$I_{p,ul}$	Algeb	$-I_{p,ul} + \frac{PHL_{upper} z_u^{PHL2} + P_{tot} z_i^{PHL2} + p_{mn} z_l^{PHL2}}{V_p}$
Iqul	$I_{q,ul}$	Algeb	$-I_{q,ul} + \frac{Q_{tot}}{V_p}$
Ipmax	I_{pmax}	Algeb	$-I_{pmax} + \left(1 - z_l^{SOClim}\right) \left(I_{alim} s_1^{SW_{PQ}} + \sqrt{I_{pmax}^2} s_0^{SW_{PQ}}\right)$
Iqmax	I_{qmax}	Algeb	$I_{alim} s_0^{SW_{PQ}} - I_{qmax} + \sqrt{I_{qmax}^2} s_1^{SW_{PQ}}$
Ipcmd	x_{Ipcmd}	Algeb	$I_{p,ul} - x_{Ipcmd}$
Ipcmd	y_{Ipcmd}	Algeb	$I_{pmax} z_u^{lim_{Ipcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + x_{Ipcmd} z_i^{lim_{Ipcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) - y_{Ipcmd}$
Iqcmd	x_{Iqcmd}	Algeb	$I_{q,ul} - x_{Iqcmd}$
Iqcmd	y_{Iqcmd}	Algeb	$-I_{qmax} z_l^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + I_{qmax} z_u^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) + x_{Iqcmd} z_i^{lim_{Iqcmd}} \left(F_{fh} F_{fl} F_{vh} F_{vl} z_{rec} - z_{rec} + 1\right) - y_{Iqcmd}$

Services

Name	Symbol	Equation	Type
pref0	P_{ref0}	$P_{0s}\gamma_p$	ConstService
qref0	Q_{ref0}	$Q_{0s}\gamma_q$	ConstService
Kft01	K_{ft01}	$\frac{1}{-f_{t0}+f_{t1}}$	ConstService
Kft23	K_{ft23}	$\frac{1}{-f_{t2}+f_{t3}}$	ConstService
Kvt01	K_{vt01}	$\frac{1}{-V_{t0}+V_{t1}}$	ConstService
Kvt23	K_{vt23}	$\frac{1}{-V_{t2}+V_{t3}}$	ConstService
Pext0	P_{ext0}	0	ConstService
Vcomp	V_{comp}	$\left\lvert Ve^{i\theta} + ix_c\left(y_{Ipout} + iy_{Iqout}\right)\right\rvert$	VarService
Vqu	V_{qu}	$v_1 - \frac{Q_{ref0}-q_{mn}}{dq/dv}$	ConstService
Vql	V_{ql}	$v_0 + \frac{-Q_{ref0}+q_{mx}}{dq/dv}$	ConstService
Ipmaxsq	I^2_{pmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Iqcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Iqcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Ipmaxsq0	I^2_{pmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{Q^2_{ref0}u^2}{V^2},\ \text{True}\right.\right.$	ConstService
Iqmaxsq	I^2_{qmax}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \left(y_{Ipcmd}\right)^2 \leq 0\right), \left(I^2_{alim} - \left(y_{Ipcmd}\right)^2,\ \text{Tru}\right.\right.$	VarService
Iqmaxsq0	I^2_{qmax0}	FixPiecewise $\left(\left(0,\ I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2} \leq 0\right), \left(I^2_{alim} - \frac{P^2_{ref0}u^2}{V^2},\ \text{True}\right)\right.$	ConstService

Discretes

Name	Symbol	Type	Info
SWPQ	SW_{PQ}	Switcher	
FL1	$FL1$	Limiter	Under frequency comparer
FL2	$FL2$	Limiter	Over frequency comparer
DB_db	db_{DB}	DeadBand	
VL1	$VL1$	Limiter	Under voltage comparer
VL2	$VL2$	Limiter	Over voltage comparer
VLo	VLo	Limiter	Voltage lower limit (0.01) flag
PHL	PHL	Limiter	limiter for Psum in [pmn, pmx]
VQ1	$VQ1$	Limiter	Under voltage comparer for Q droop
VQ2	$VQ2$	Limiter	Over voltage comparer for Q droop
Ipcmd_lim	lim_{Ipcmd}	HardLimiter	
Iqcmd_lim	lim_{Iqcmd}	HardLimiter	
LTN	LTN	LessThan	
SOClim	$SOClim$	HardLimiter	
PHL2	$PHL2$	Limiter	limiter for Psum in [pmn, pcap * pmx]

Blocks

Name	Symbol	Type	Info
DB	DB	DeadBand1	frequency deviation deadband with gain
Ipcmd	I^{pcmd}	GainLimiter	Ip with limiter and coeff.
Iqcmd	I^{qcmd}	GainLimiter	Iq with limiter and coeff.
Ipout	$Ipout$	Lag	Output Ip filter
Iqout	$Iqout$	Lag	Output Iq filter
pIG	pIG	Integrator	State of charge

Config Fields in [EV2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
plim	P_{lim}	1	enable input power limit check bound by [0, pmx]	(0, 1)

5.9 DGProtection

Protection model for DG.

Common Parameters: u, name

Available models: *DGPRCT1*, *DGPRCTExt*

5.9.1 DGPRCT1

DGPRCT1 model, follow IEEE-1547-2018. DGPRCT stands for DG protection.

A demo is provided: examples/demonstration/1.1 demo_DGPRCT1.ipynb

Target device (limited to DG group) `Psum` and `Qsum` will decrease to zero immediately when frequency/voltage protection flag is raised. Once the lock is released, `Psum` and `Qsum` will return to normal immediately.

DG group base model `PVD1` already has a degrading function which is used to degrade output under abnormal condition. it is recommended to turn it off by setting *recflag = 0*.

`fen` and `Ven` are protection enabling parameters. 1/0 is on/off.

`ue` is lock flag signal.

It should be noted that, the lock only lock the `fHz` (frequency read value) of DG model. The source values (which come from `BusFreq` f remain unchanged.)

Protection sensors (e.g., IAWfl1) are instances of `IntergratorAntiWindup`. All the protection sensors will be reset after `ue` returns to 0. Resetting action takes *Tres* to finish.

The model does not check the shedding points sequence. The input parameters are required to satisfy `fl3 < fl2 < fl1 < fu1 < fu2 < fu3`, and `ul4 < ul3 < ul2 < ul1 < uu1 < uu2 < uu3`.

Default settings:

Frequency (Hz):

(fl3, fl2), Tfl2 [(50.0, 57.5), 10s]

(fl2, fl1), Tfl1 [(57.5, 59.2), 300s]

(fu1, fu2), Tfu1 [(60.5, 61.5), 300s]

(fu2, fu3), Tfu2 [(61.5, 70.0), 10s]

Voltage (p.u.):

(vl4, vl3), Tvl3 [(0.10, 0.45), 0.16s]

(vl3, vl2), Tvl2 [(0.45, 0.60), 1s]

(vl2, vl1), Tvl1 [(0.60, 0.88), 2s]

(vu1, vu2), Tvu1 [(1.10, 1.20), 1s]

(vu2, vu3), Tvu2 [(1.20, 2.00), 0.16s]

Reference:

NERC. Bulk Power System Reliability Perspectives on the Adoption of IEEE 1547-2018. March 2020. Available:

https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Guideline_IEEE_1547-2018_BPS_Perspectives.pdf

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
dev		idx of the target device			mandatory
busfreq		Target device interface bus measurement device idx			
fen	fen	Frequency deviation protection enable. 1 for enable, 0 for disable.	1		
Ven	Ven	Voltage deviation protection enable. 1 for enable, 0 for disable.	0		
fl3	$fl3$	Under frequency shadding point 3	50	*Hz*	
fl2	$fl2$	Over frequency shadding point 2	57.500	*Hz*	
fl1	$fl1$	Under frequency shadding point 1	59.200	*Hz*	
fu1	$fu1$	Over frequency shadding point 1	60.500	*Hz*	
fu2	$fu2$	Over frequency shadding point 2	61.500	*Hz*	
fu3	$fu3$	Over frequency shadding point 3	70	*Hz*	
Tfl1	T_{fl1}	Stand time for (fl2, fl1)	300		non_negative
Tfl2	T_{fl2}	Stand time for (fl3, fl2)	10		non_negative
Tfu1	T_{fu1}	Stand time for (fu1, fu2)	300		non_negative
Tfu2	T_{fu2}	Stand time for (fu2, fu3)	10		non_negative
vl4	$vl4$	Under voltage shadding point 4	0.100	*p.u.*	
vl3	$vl3$	Under voltage shadding point 3	0.450	*p.u.*	
vl2	$vl2$	Under voltage shadding point 2	0.600	*p.u.*	
vl1	$vl1$	Under voltage shadding point 1	0.880	*p.u.*	
vu1	$vu1$	Over voltage shadding point 1	1.100	*p.u.*	
vu2	$vu2$	Over voltage shadding point 2	1.200	*p.u.*	
vu3	$vu3$	Over voltage shadding point 3	2	*p.u.*	
Tvl1	T_{vl1}	Stand time for (vl2, vl1)	2		non_negative
Tvl2	T_{vl2}	Stand time for (vl3, vl2)	1		non_negative
Tvl3	T_{vl3}	Stand time for (vl4, vl3)	0.160		non_negative
Tvu1	T_{vu1}	Stand time for (vu1, vu2)	1		non_negative
Tvu2	T_{vu2}	Stand time for (vu2, vu3)	0.160		non_negative
Tres		Integrator reset time	0.050		
bus			0		
fn			0		

Variables

Name	Symbol	Type	Description	Unit	Properties
IAWfl1_y	y_{IAWfl1}	State	AW Integrator output		v_str
IAWfl2_y	y_{IAWfl2}	State	AW Integrator output		v_str
IAWfu1_y	y_{IAWfu1}	State	AW Integrator output		v_str
IAWfu2_y	y_{IAWfu2}	State	AW Integrator output		v_str
IAWVl1_y	y_{IAWVl1}	State	AW Integrator output		v_str
IAWVl2_y	y_{IAWVl2}	State	AW Integrator output		v_str
IAWVl3_y	y_{IAWVl3}	State	AW Integrator output		v_str
IAWVu1_y	y_{IAWVu1}	State	AW Integrator output		v_str
IAWVu2_y	y_{IAWVu2}	State	AW Integrator output		v_str
fHz	f_{Hz}	Algeb	frequency in Hz		v_str
dsum	d_{tot}	Algeb	lock signal summation		v_str
ue	ue	Algeb	lock flag		v_str
f	f	ExtAlgeb	DG frequency read value	*p.u.*	
fin	fin	ExtAlgeb	original f from DG		
fHzl	$fHzl$	ExtAlgeb	Frequency measure lock		
Pext	$Pext$	ExtAlgeb	original Pext from DG		
Pref	$Pref$	ExtAlgeb	original Pref from DG		
Pdrp	$Pdrp$	ExtAlgeb	original Pdrp from DG		
Psum	$Psum$	ExtAlgeb	Active power lock		
Qdrp	$Qdrp$	ExtAlgeb	original Qdrp from DG		
Qref	$Qref$	ExtAlgeb	original Qref from DG		
Qsum	$Qsum$	ExtAlgeb	Reactive power lock		
v	v	ExtAlgeb	Bus voltage	*p.u.*	

Initialization Equations

Name	Symbol	Type	Initial Value
IAWfl1_y	y_{IAWfl1}	State	0
IAWfl2_y	y_{IAWfl2}	State	0
IAWfu1_y	y_{IAWfu1}	State	0
IAWfu2_y	y_{IAWfu2}	State	0
IAWVl1_y	y_{IAWVl1}	State	0
IAWVl2_y	y_{IAWVl2}	State	0
IAWVl3_y	y_{IAWVl3}	State	0
IAWVu1_y	y_{IAWVu1}	State	0
IAWVu2_y	y_{IAWVu2}	State	0
fHz	f_{Hz}	Algeb	ffn
dsum	d_{tot}	Algeb	0
ue	ue	Algeb	0
f	f	ExtAlgeb	
fin	fin	ExtAlgeb	
fHzl	$fHzl$	ExtAlgeb	
Pext	$Pext$	ExtAlgeb	
Pref	$Pref$	ExtAlgeb	
Pdrp	$Pdrp$	ExtAlgeb	
Psum	$Psum$	ExtAlgeb	
Qdrp	$Qdrp$	ExtAlgeb	
Qref	$Qref$	ExtAlgeb	
Qsum	$Qsum$	ExtAlgeb	
v	v	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IAWfl1_y	y_{IAWfl1}	State	$-\frac{T_{fl1}res}{Tres} + z_i^{Lfl1} \cdot (1 - res)$	1
IAWfl2_y	y_{IAWfl2}	State	$-\frac{T_{fl2}res}{Tres} + z_i^{Lfl2} \cdot (1 - res)$	1
IAWfu1_y	y_{IAWfu1}	State	$-\frac{T_{fu1}res}{Tres} + z_i^{Lfu1} \cdot (1 - res)$	1
IAWfu2_y	y_{IAWfu2}	State	$-\frac{T_{fu2}res}{Tres} + z_i^{Lfl2} \cdot (1 - res)$	1
IAWVl1_y	y_{IAWVl1}	State	$-\frac{T_{vl1}res}{Tres} + z_i^{LVl1} \cdot (1 - res)$	1
IAWVl2_y	y_{IAWVl2}	State	$-\frac{T_{vl2}res}{Tres} + z_i^{LVl2} \cdot (1 - res)$	1
IAWVl3_y	y_{IAWVl3}	State	$-\frac{T_{vl3}res}{Tres} + z_i^{LVl2} \cdot (1 - res)$	1
IAWVu1_y	y_{IAWVu1}	State	$-\frac{T_{vu1}res}{Tres} + z_i^{LVu1} \cdot (1 - res)$	1
IAWVu2_y	y_{IAWVu2}	State	$-\frac{T_{vu2}res}{Tres} + z_i^{LVu2} \cdot (1 - res)$	1

Algebraic Equations

Nam	Sym bol	Type	RHS of Equation "0 = g(x, y)"
fHz	f_{Hz}	Al-geb	$ffn - f_{Hz}$
dsum	d_{tot}	Al-geb	$Ven\left(z_i^{LVl1} z_u^{lim_{IAWVl1}} + z_i^{LVl2} z_u^{lim_{IAWVl2}} + z_i^{LVl3} z_u^{lim_{IAWVl3}} + z_i^{LVu1} z_u^{lim_{IAWVu1}} + z_i^{LVu2} z_u^{lim_{IAWV}}\right.$ $d_{tot} + fen\left(z_i^{Lfl1} z_u^{lim_{IAWfl1}} + z_i^{Lfl2} z_u^{lim_{IAWfl2}} + z_i^{Lfu1} z_u^{lim_{IAWfu1}} + z_i^{Lfu2} z_u^{lim_{IAWfu2}}\right)$
ue	ue	Al-geb	$-ue + z_u^{Ldsum}$
f	f	Ex-tAl-geb	0
fin	fin	Ex-tAl-geb	0
fHzl	fHz	Ex-tAl-geb	$-ffnue$
Pext	$Pext$	Ex-tAl-geb	0
Pref	$Pref$	Ex-tAl-geb	0
Pdrp	$Pdrp$	Ex-tAl-geb	0
Psum	$Psum$	Ex-tAl-geb	$-ue\,(Pdrp + Pext + Pref)$
Qdrp	$Qdrp$	Ex-tAl-geb	0
Qref	$Qref$	Ex-tAl-geb	0
Qsun	$Qsum$	Ex-tAl-geb	$-ue\,(Qdrp + Qref)$
v	v	Ex-tAl-geb	0

Services

Name	Symbol	Equation	Type
ltu	ltu	0.8	ConstService
ltl	ltl	0.2	ConstService
zero	$zero$	0	ConstService
res	res	0	ExtendedEvent

Discretes

Name	Symbol	Type	Info
Ldsum	$Ldsum$	Limiter	lock signal comparer, zu is to act
Lfl1	$Lfl1$	Limiter	Frequency comparer for (fl3, fl1)
Lfl2	$Lfl2$	Limiter	Frequency comparer for (fl3, fl2)
Lfu1	$Lfu1$	Limiter	Frequency comparer for (fu1, fu3)
Lfu2	$Lfu2$	Limiter	Frequency comparer for (fu2, fu3)
IAWfl1_lim	lim_{IAWfl1}	AntiWindup	Limiter in integrator
IAWfl2_lim	lim_{IAWfl2}	AntiWindup	Limiter in integrator
IAWfu1_lim	lim_{IAWfu1}	AntiWindup	Limiter in integrator
IAWfu2_lim	lim_{IAWfu2}	AntiWindup	Limiter in integrator
LVl1	$LVl1$	Limiter	Voltage comparer for (vl4, vl1)
LVl2	$LVl2$	Limiter	Voltage comparer for (vl4, vl2)
LVl3	$LVl3$	Limiter	Voltage comparer for (vl4, vl3)
LVu1	$LVu1$	Limiter	Voltage comparer for (vu1, vu3)
LVu2	$LVu2$	Limiter	Voltage comparer for (vu2, vu3)
IAWVl1_lim	lim_{IAWVl1}	AntiWindup	Limiter in integrator
IAWVl2_lim	lim_{IAWVl2}	AntiWindup	Limiter in integrator
IAWVl3_lim	lim_{IAWVl3}	AntiWindup	Limiter in integrator
IAWVu1_lim	lim_{IAWVu1}	AntiWindup	Limiter in integrator
IAWVu2_lim	lim_{IAWVu2}	AntiWindup	Limiter in integrator

Blocks

Name	Symbol	Type	Info
IAWfl1	$IAWfl1$	IntegratorAntiWindup	condition check for (fl3, fl1)
IAWfl2	$IAWfl2$	IntegratorAntiWindup	condition check for (fl3, fl2)
IAWfu1	$IAWfu1$	IntegratorAntiWindup	condition check for (fu1, fu3)
IAWfu2	$IAWfu2$	IntegratorAntiWindup	condition check for (fu2, fu3)
IAWVl1	$IAWVl1$	IntegratorAntiWindup	condition check for (Vl3, Vl1)
IAWVl2	$IAWVl2$	IntegratorAntiWindup	condition check for (Vl3, Vl2)
IAWVl3	$IAWVl3$	IntegratorAntiWindup	condition check for (Vl3, Vl2)
IAWVu1	$IAWVu1$	IntegratorAntiWindup	condition check for (Vu1, Vu3)
IAWVu2	$IAWVu2$	IntegratorAntiWindup	condition check for (Vu2, Vu3)

Config Fields in [DGPRCT1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.9.2 DGPRCTExt

DGPRCT External model, follow IEEE-1547-2018. DGPRCT stands for DG protection.

Similar to DGPRCT1, but the measured voltage can be manipulated.

A demo is provided: examples/demonstration/1.2 demo_DGPRCTExt.ipynb

This model can be applied to co-simulation, where you can input the external votage signal into ANDES. If no extertal value is applied, the votalge will remain as the initialized value.

Target device (limited to DG group) `Psum` and `Qsum` will decrease to zero immediately when frequency/voltage protection flag is raised. Once the lock is released, `Psum` and `Qsum` will return to normal immediately.

DG group base model `PVD1` already has a degrading function which is used to degrade output under abnormal condition. it is recommended to turn it off by setting *recflag = 0*.

`fen` and `Ven` are protection enabling parameters. 1/0 is on/off.

`ue` is lock flag signal.

It should be noted that, the lock only lock the `fHz` (frequency read value) of DG model. The source values (which come from `BusFreq`f remain unchanged.)

Protection sensors (e.g., IAWfl1) are instances of `IntergratorAntiWindup`. All the protection sensors will be reset after `ue` returns to 0. Resetting action takes *Tres* to finish.

The model does not check the shedding points sequence. The input parameters are required to satisfy `fl3 < fl2 < fl1 < fu1 < fu2 < fu3`, and `ul4 < ul3 < ul2 < ul1 < uu1 < uu2 < uu3`.

Default settings:

Frequency (Hz):

(fl3, fl2), Tfl2 [(50.0, 57.5), 10s]

(fl2, fl1), Tfl1 [(57.5, 59.2), 300s]

(fu1, fu2), Tfu1 [(60.5, 61.5), 300s]

(fu2, fu3), Tfu2 [(61.5, 70.0), 10s]

Voltage (p.u.):

(vl4, vl3), Tvl3 [(0.10, 0.45), 0.16s]

(vl3, vl2), Tvl2 [(0.45, 0.60), 1s]

(vl2, vl1), Tvl1 [(0.60, 0.88), 2s]

(vu1, vu2), Tvu1 [(1.10, 1.20), 1s]

(vu2, vu3), Tvu2 [(1.20, 2.00), 0.16s]

Reference:

NERC. Bulk Power System Reliability Perspectives on the Adoption of IEEE 1547-2018. March 2020. Available:

https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Guideline_IEEE_1547-2018_BPS_Perspectives.pdf

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
dev		idx of the target device			mandatory
busfreq		Target device interface bus measurement device idx			
fen	fen	Frequency deviation protection enable. 1 for enable, 0 for disable.	1		
Ven	Ven	Voltage deviation protection enable. 1 for enable, 0 for disable.	0		
fl3	$fl3$	Under frequency shadding point 3	50	*Hz*	
fl2	$fl2$	Over frequency shadding point 2	57.500	*Hz*	
fl1	$fl1$	Under frequency shadding point 1	59.200	*Hz*	
fu1	$fu1$	Over frequency shadding point 1	60.500	*Hz*	
fu2	$fu2$	Over frequency shadding point 2	61.500	*Hz*	
fu3	$fu3$	Over frequency shadding point 3	70	*Hz*	
Tfl1	T_{fl1}	Stand time for (fl2, fl1)	300		non_negative
Tfl2	T_{fl2}	Stand time for (fl3, fl2)	10		non_negative
Tfu1	T_{fu1}	Stand time for (fu1, fu2)	300		non_negative

continues on next page

Table 13 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
Tfu2	T_{fu2}	Stand time for (fu2, fu3)	10		non_negative
vl4	$vl4$	Under voltage shadding point 4	0.100	*p.u.*	
vl3	$vl3$	Under voltage shadding point 3	0.450	*p.u.*	
vl2	$vl2$	Under voltage shadding point 2	0.600	*p.u.*	
vl1	$vl1$	Under voltage shadding point 1	0.880	*p.u.*	
vu1	$vu1$	Over voltage shadding point 1	1.100	*p.u.*	
vu2	$vu2$	Over voltage shadding point 2	1.200	*p.u.*	
vu3	$vu3$	Over voltage shadding point 3	2	*p.u.*	
Tvl1	T_{vl1}	Stand time for (vl2, vl1)	2		non_negative
Tvl2	T_{vl2}	Stand time for (vl3, vl2)	1		non_negative
Tvl3	T_{vl3}	Stand time for (vl4, vl3)	0.160		non_negative
Tvu1	T_{vu1}	Stand time for (vu1, vu2)	1		non_negative
Tvu2	T_{vu2}	Stand time for (vu2, vu3)	0.160		non_negative
Tres		Integrator reset time	0.050		
bus			0		
fn			0		

Variables

Name	Symbol	Type	Description	Unit	Properties
IAWfl1_y	y_{IAWfl1}	State	AW Integrator output		v_str
IAWfl2_y	y_{IAWfl2}	State	AW Integrator output		v_str
IAWfu1_y	y_{IAWfu1}	State	AW Integrator output		v_str
IAWfu2_y	y_{IAWfu2}	State	AW Integrator output		v_str
IAWVl1_y	y_{IAWVl1}	State	AW Integrator output		v_str
IAWVl2_y	y_{IAWVl2}	State	AW Integrator output		v_str
IAWVl3_y	y_{IAWVl3}	State	AW Integrator output		v_str
IAWVu1_y	y_{IAWVu1}	State	AW Integrator output		v_str
IAWVu2_y	y_{IAWVu2}	State	AW Integrator output		v_str
fHz	f_{Hz}	Algeb	frequency in Hz		v_str
dsum	d_{tot}	Algeb	lock signal summation		v_str
ue	ue	Algeb	lock flag		v_str
f	f	ExtAlgeb	DG frequency read value	*p.u.*	
fin	fin	ExtAlgeb	original f from DG		
fHzl	$fHzl$	ExtAlgeb	Frequency measure lock		
Pext	$Pext$	ExtAlgeb	original Pext from DG		
Pref	$Pref$	ExtAlgeb	original Pref from DG		
Pdrp	$Pdrp$	ExtAlgeb	original Pdrp from DG		
Psum	$Psum$	ExtAlgeb	Active power lock		
Qdrp	$Qdrp$	ExtAlgeb	original Qdrp from DG		
Qref	$Qref$	ExtAlgeb	original Qref from DG		
Qsum	$Qsum$	ExtAlgeb	Reactive power lock		

Initialization Equations

Name	Symbol	Type	Initial Value
IAWfl1_y	y_{IAWfl1}	State	0
IAWfl2_y	y_{IAWfl2}	State	0
IAWfu1_y	y_{IAWfu1}	State	0
IAWfu2_y	y_{IAWfu2}	State	0
IAWVl1_y	y_{IAWVl1}	State	0
IAWVl2_y	y_{IAWVl2}	State	0
IAWVl3_y	y_{IAWVl3}	State	0
IAWVu1_y	y_{IAWVu1}	State	0
IAWVu2_y	y_{IAWVu2}	State	0
fHz	f_{Hz}	Algeb	ffn
dsum	d_{tot}	Algeb	0
ue	ue	Algeb	0
f	f	ExtAlgeb	
fin	fin	ExtAlgeb	
fHzl	$fHzl$	ExtAlgeb	
Pext	$Pext$	ExtAlgeb	
Pref	$Pref$	ExtAlgeb	
Pdrp	$Pdrp$	ExtAlgeb	
Psum	$Psum$	ExtAlgeb	
Qdrp	$Qdrp$	ExtAlgeb	
Qref	$Qref$	ExtAlgeb	
Qsum	$Qsum$	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IAWfl1_y	y_{IAWfl1}	State	$-\frac{T_{fl1}res}{Tres} + z_i^{Lfl1} \cdot (1 - res)$	1
IAWfl2_y	y_{IAWfl2}	State	$-\frac{T_{fl2}res}{Tres} + z_i^{Lfl2} \cdot (1 - res)$	1
IAWfu1_y	y_{IAWfu1}	State	$-\frac{T_{fu1}res}{Tres} + z_i^{Lfu1} \cdot (1 - res)$	1
IAWfu2_y	y_{IAWfu2}	State	$-\frac{T_{fu2}res}{Tres} + z_i^{Lfl2} \cdot (1 - res)$	1
IAWVl1_y	y_{IAWVl1}	State	$-\frac{T_{vl1}res}{Tres} + z_i^{LVl1} \cdot (1 - res)$	1
IAWVl2_y	y_{IAWVl2}	State	$-\frac{T_{vl2}res}{Tres} + z_i^{LVl2} \cdot (1 - res)$	1
IAWVl3_y	y_{IAWVl3}	State	$-\frac{T_{vl3}res}{Tres} + z_i^{LVl2} \cdot (1 - res)$	1
IAWVu1_y	y_{IAWVu1}	State	$-\frac{T_{vu1}res}{Tres} + z_i^{LVu1} \cdot (1 - res)$	1
IAWVu2_y	y_{IAWVu2}	State	$-\frac{T_{vu2}res}{Tres} + z_i^{LVu2} \cdot (1 - res)$	1

Algebraic Equations

Nam	Sym bol	Type	RHS of Equation "0 = g(x, y)"
fHz	f_{Hz}	Al-geb	$ffn - f_{Hz}$
dsum	d_{tot}	Al-geb	$Ven\left(z_i^{LVl1} z_u^{lim_{IAWVl1}} + z_i^{LVl2} z_u^{lim_{IAWVl2}} + z_i^{LVl3} z_u^{lim_{IAWVl3}} + z_i^{LVu1} z_u^{lim_{IAWVu1}} + z_i^{LVu2} z_u^{lim_{IAWV}}\right.$ $d_{tot} + fen\left(z_i^{Lfl1} z_u^{lim_{IAWfl1}} + z_i^{Lfl2} z_u^{lim_{IAWfl2}} + z_i^{Lfu1} z_u^{lim_{IAWfu1}} + z_i^{Lfu2} z_u^{lim_{IAWfu2}}\right)$
ue	ue	Al-geb	$-ue + z_u^{Ldsum}$
f	f	Ex-tAl-geb	0
fin	fin	Ex-tAl-geb	0
fHzl	fHz	Ex-tAl-geb	$-ffnue$
Pext	$Pext$	Ex-tAl-geb	0
Pref	$Pref$	Ex-tAl-geb	0
Pdrp	$Pdrp$	Ex-tAl-geb	0
Psum	$Psum$	Ex-tAl-geb	$-ue\,(Pdrp + Pext + Pref)$
Qdrp	$Qdrp$	Ex-tAl-geb	0
Qref	$Qref$	Ex-tAl-geb	0
Qsun	$Qsum$	Ex-tAl-geb	$-ue\,(Qdrp + Qref)$

Services

Name	Symbol	Equation	Type
ltu	ltu	0.8	ConstService
ltl	ltl	0.2	ConstService
zero	$zero$	0	ConstService
res	res	0	ExtendedEvent

Discretes

Name	Symbol	Type	Info
Ldsum	$Ldsum$	Limiter	lock signal comparer, zu is to act
Lfl1	$Lfl1$	Limiter	Frequency comparer for (fl3, fl1)
Lfl2	$Lfl2$	Limiter	Frequency comparer for (fl3, fl2)
Lfu1	$Lfu1$	Limiter	Frequency comparer for (fu1, fu3)
Lfu2	$Lfu2$	Limiter	Frequency comparer for (fu2, fu3)
IAWfl1_lim	lim_{IAWfl1}	AntiWindup	Limiter in integrator
IAWfl2_lim	lim_{IAWfl2}	AntiWindup	Limiter in integrator
IAWfu1_lim	lim_{IAWfu1}	AntiWindup	Limiter in integrator
IAWfu2_lim	lim_{IAWfu2}	AntiWindup	Limiter in integrator
LVl1	$LVl1$	Limiter	Voltage comparer for (vl4, vl1)
LVl2	$LVl2$	Limiter	Voltage comparer for (vl4, vl2)
LVl3	$LVl3$	Limiter	Voltage comparer for (vl4, vl3)
LVu1	$LVu1$	Limiter	Voltage comparer for (vu1, vu3)
LVu2	$LVu2$	Limiter	Voltage comparer for (vu2, vu3)
IAWVl1_lim	lim_{IAWVl1}	AntiWindup	Limiter in integrator
IAWVl2_lim	lim_{IAWVl2}	AntiWindup	Limiter in integrator
IAWVl3_lim	lim_{IAWVl3}	AntiWindup	Limiter in integrator
IAWVu1_lim	lim_{IAWVu1}	AntiWindup	Limiter in integrator
IAWVu2_lim	lim_{IAWVu2}	AntiWindup	Limiter in integrator

Blocks

Name	Symbol	Type	Info
IAWfl1	$IAWfl1$	IntegratorAntiWindup	condition check for (fl3, fl1)
IAWfl2	$IAWfl2$	IntegratorAntiWindup	condition check for (fl3, fl2)
IAWfu1	$IAWfu1$	IntegratorAntiWindup	condition check for (fu1, fu3)
IAWfu2	$IAWfu2$	IntegratorAntiWindup	condition check for (fu2, fu3)
IAWVl1	$IAWVl1$	IntegratorAntiWindup	condition check for (Vl3, Vl1)
IAWVl2	$IAWVl2$	IntegratorAntiWindup	condition check for (Vl3, Vl2)
IAWVl3	$IAWVl3$	IntegratorAntiWindup	condition check for (Vl3, Vl2)
IAWVu1	$IAWVu1$	IntegratorAntiWindup	condition check for (Vu1, Vu3)
IAWVu2	$IAWVu2$	IntegratorAntiWindup	condition check for (Vu2, Vu3)

Config Fields in [DGPRCTExt]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.10 DataSeries

Group for TimeSeries models.

Available models: *TimeSeries*

5.10.1 TimeSeries

Model for applying time-series data.

A TimeSeries device takes a *xlsx* data spreadsheet and applies the data to the specified device. The spreadsheet can contain multiple sheets, each with a column named `t` and multiple user-defined columns for the data. The values will be applied at the exact time instant.

The `xlsx` data spreadsheet is assumed in the same folder as the case file.

Regarding the parameters for the `TimeSeries` device:

- The column names in the `xlsx` data file need to be specified through the `fields` parameter, separated by commas.
- The parameter/service names of the device which is to be updated need to be specified through the `dests` parameter, separated by commas.

There are a few caveats with the current TimeSeries implementation:

- TimeSeries will not be applied power flow.
- The interpolation mode has yet to be implemented.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
mode		Mode for applying timeseries. 1: exact time, 2: interpolated	1		
path		Path to timeseries xlsx file.			mandatory
sheet		Sheet name to use			mandatory
fields		comma-separated field names in timeseries data			mandatory
tkey		Key for timestamps	t		
model		Model to link to			mandatory
dev		Idx of device to link to			mandatory
dests		comma-separated device fields as destinations			mandatory

Discretes

Name	Symbol	Type	Info
SW	SW	Switcher	mode switcher

Config Fields in [TimeSeries]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
silent		1	suppress output messages if is not zero	(0, 1)

5.11 DynLoad

Dynamic load group.

Common Parameters: u, name

Available models: *ZIP*, *FLoad*

5.11.1 ZIP

ZIP load model (polynomial load). This model is initialized after power flow.

Please check the config of PQ to avoid double counting. If this ZIP model is in use, one should typically set *p2p=1.0* and *q2q=1.0* while leaving the others (*p2i*, *p2z*, *q2i*, *q2z*, and *pq2z*) as zeros. This setting allows one to impose the desired powers by the static PQ and to convert them based on the percentage specified in the ZIP.

The percentages for active power, (*kpp*, *kpi*, and *kpz*) must sum up to 100. Otherwise, initialization will fail. The same applies to the reactive power percentages.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
pq		idx of the PQ to replace			mandatory
kpp	K_{pp}	Percentage of active power			mandatory
kpi	K_{pi}	Percentage of active current			mandatory
kpz	K_{pz}	Percentage of conductance			mandatory
kqp	K_{qp}	Percentage of reactive power			mandatory
kqi	K_{qi}	Percentage of reactive current			mandatory
kqz	K_{qz}	Percentage of susceptance			mandatory
bus		retrieved bux idx	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	$P_{i0}V + P_{p0} + P_{z0}V^2$
v	V	ExtAlgeb	$Q_{i0}V + Q_{p0} + Q_{z0}V^2$

Services

Name	Symbol	Equation	Type
kps	K_{psum}	$K_{pi} + K_{pp} + K_{pz}$	ConstService
kqs	K_{qsum}	$K_{qi} + K_{qp} + K_{qz}$	ConstService
rpp	r_{pp}	$\frac{K_{pp}u}{100}$	ConstService
rpi	r_{pi}	$\frac{K_{pi}u}{100}$	ConstService
rpz	r_{pz}	$\frac{K_{pz}u}{100}$	ConstService
rqp	r_{qp}	$\frac{K_{qp}u}{100}$	ConstService
rqi	r_{qi}	$\frac{K_{qi}u}{100}$	ConstService
rqz	r_{qz}	$\frac{K_{qz}u}{100}$	ConstService
pp0	P_{p0}	$P_0 r_{pp}$	ConstService
pi0	P_{i0}	$\frac{P_0 r_{pi}}{V_0}$	ConstService
pz0	P_{z0}	$\frac{P_0 r_{pz}}{V_0^2}$	ConstService
qp0	Q_{p0}	$Q_0 r_{qp}$	ConstService
qi0	Q_{i0}	$\frac{Q_0 r_{qi}}{V_0}$	ConstService
qz0	Q_{z0}	$\frac{Q_0 r_{qz}}{V_0^2}$	ConstService

Config Fields in [ZIP]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.11.2 FLoad

Voltage and frequency dependent load.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
pq		idx of the PQ to replace			mandatory
busf		optional idx of the BusFreq device to use			
kp		active power percentage	100	%	
kq		active power percentage	100	%	
Tf		filter time constant	0.020	*s*	non_negative
ap		active power voltage exponent	1		
aq		reactive power voltage exponent	0		
bp		active power frequency exponent	0		
bq		reactive power frequency exponent	0		
bus			0		

Variables

Name	Symbol	Type	Description	Unit	Properties
f	f	ExtAlgeb			
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
f	f	ExtAlgeb	
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
f	f	ExtAlgeb	0
a	θ	ExtAlgeb	$V^{ap} f^{bp} pv_0$
v	V	ExtAlgeb	$V^{aq} f^{bq} qv_0$

Services

Name	Symbol	Equation	Type
pv0	$pv0$	$\frac{P_0 V_0^{-ap} kpu}{100}$	ConstService
qv0	$qv0$	$\frac{Q_0 V_0^{-aq} kqu}{100}$	ConstService

Config Fields in [FLoad]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12 Exciter

Exciter group for synchronous generators.

Common Parameters: u, name, syn

Common Variables: vout, vi

Available models: *EXDC2*, *IEEEX1*, *ESDC1A*, *ESDC2A*, *EXST1*, *ESST3A*, *SEXS*, *IEEET1*, *EXAC1*, *EXAC2*, *EXAC4*, *ESST4B*, *AC8B*, *IEEET3*, *ESAC1A*, *ESST1A*, *ESAC5A*

5.12.1 EXDC2

EXDC2 model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
TA	T_A	Lag time constant in anti-windup lag	0.040	*p.u.*	
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
TE	T_E	Exciter integrator time constant	0.800	*p.u.*	
TF1	T_{F1}	Feedback washout time constant	1	*p.u.*	non_zero
KF1	K_{F1}	Feedback washout gain	0.030	*p.u.*	
KA	K_A	Gain in anti-windup lag TF	40	*p.u.*	
KE	K_E	Gain added to saturation	1	*p.u.*	
VRMAX	V_{RMAX}	Maximum excitation limit	7.300	*p.u.*	
VRMIN	V_{RMIN}	Minimum excitation limit	-7.300	*p.u.*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
vp	V_p	State	Voltage after saturation feedback, before speed term	*p.u.*	v_str
LS_y	y_{LS}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
W_x	x'_W	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
Se	$S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
W_y	y_W	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
Xadifd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
vp	V_p	State	v_{f0}
LS_y	y_{LS}	State	$1.0E_{term}$
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
W_x	x'_W	State	V_p
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + V_{b0}$
Se	$S_e(\|V_{out}\|)$	Algeb	S_{e0}
vi	V_i	Algeb	V_{b0}
LL_y	y_{LL}	Algeb	V_i
W_y	y_W	Algeb	0
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vp	V_p	State	$u_e\left(-K_E V_p - S_e(\|V_{out}\|)V_p + y_{LA}\right)$	T_E
LS_y	y_{LS}	State	$1.0E_{term} - y_{LS}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
W_x	x'_W	State	$V_p - x'_W$	T_{F1}
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$V_p \omega u_e - v_{out}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
Se	$S_e(\|V_{out}\|)$	Algeb	$B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + V_p\right)^2 - S_e(\|V_{out}\|) V_p$
vi	V_i	Algeb	$-V_i + V_{ref} - y_{LS} - y_W$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
W_y	y_W	Algeb	$K_{F1} \left(V_p - x'_W\right) - T_{F1} y_W$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}} \left(\text{Indicator}\left(SE_{SAT}^{2c} > 0\right) + \text{Indicator}\left(SE_{SAT}^{2c} < 0\right.\right.$	ConstService
SAT_A	A_{SAT}^q	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^q	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
Se0	S_{e0}	$\frac{B_{SAT}^q \left(A_{SAT}^q - v_{f0}\right)^2 \text{Indicator}\left(v_{f0} > A_{SAT}^q\right)}{-u_g + v_{f0} + 1}$	ConstService
vr0	V_{r0}	$v_{f0} \left(K_E + S_{e0}\right)$	ConstService
vb0	V_{b0}	$\frac{V_{r0}}{K_A}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
SL	SL	LessThan	
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag

Blocks

Name	Symbol	Type	Info
SAT	SAT	ExcQuadSat	Field voltage saturation
LS	LS	Lag	Sensing lag TF
LL	LL	LeadLag	Lead-lag for internal delays
LA	LA	LagAntiWindup	Anti-windup lag
W	W	Washout	Signal conditioner

Config Fields in [EXDC2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.2 IEEEX1

IEEEX1 Type 1 exciter (DC)

Derived from EXDC2 by varying the limiter bounds.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
TA	T_A	Lag time constant in anti-windup lag	0.040	*p.u.*	
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
TE	T_E	Exciter integrator time constant	0.800	*p.u.*	
TF1	T_{F1}	Feedback washout time constant	1	*p.u.*	non_zero
KF1	K_{F1}	Feedback washout gain	0.030	*p.u.*	
KA	K_A	Gain in anti-windup lag TF	40	*p.u.*	
KE	K_E	Gain added to saturation	1	*p.u.*	
VRMAX	V_{RMAX}	Maximum excitation limit	7.300	*p.u.*	
VRMIN	V_{RMIN}	Minimum excitation limit	-7.300	*p.u.*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
vp	V_p	State	Voltage after saturation feedback, before speed term	*p.u.*	v_str
LS_y	y_{LS}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
W_x	x'_W	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
Se	$S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
W_y	y_W	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
Xadifd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
vp	V_p	State	v_{f0}
LS_y	y_{LS}	State	$1.0E_{term}$
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
W_x	x'_W	State	V_p
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + V_{b0}$
Se	$S_e(\|V_{out}\|)$	Algeb	S_{e0}
vi	V_i	Algeb	V_{b0}
LL_y	y_{LL}	Algeb	V_i
W_y	y_W	Algeb	0
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vp	V_p	State	$u_e\left(-K_E V_p - S_e(\|V_{out}\|)V_p + y_{LA}\right)$	T_E
LS_y	y_{LS}	State	$1.0E_{term} - y_{LS}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
W_x	x'_W	State	$V_p - x'_W$	T_{F1}
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$V_p u_e - v_{out}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
Se	$S_e(\|V_{out}\|)$	Algeb	$B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + V_p\right)^2 - S_e(\|V_{out}\|)V_p$
vi	V_i	Algeb	$-V_i + V_{ref} - y_{LS} - y_W$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
W_y	y_W	Algeb	$K_{F1}\left(V_p - x'_W\right) - T_{F1} y_W$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} <$	ConstService
SAT_A	A_{SAT}^q	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^q	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT}-1)^2 (\text{Indicator}\,(a_{SAT}>0) + \text{Indicator}\,(a_{SAT}<0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
Se0	S_{e0}	$\frac{B_{SAT}^q \left(A_{SAT}^q - v_{f0}\right)^2 \text{Indicator}\left(v_{f0} > A_{SAT}^q\right)}{-u_g + v_{f0} + 1}$	ConstService
vr0	V_{r0}	$v_{f0}\left(K_E + S_{e0}\right)$	ConstService
vb0	V_{b0}	$\frac{V_{r0}}{K_A}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService
VRTMAX	$V_{RMAX} V_T$	$E_{term} V_{RMAX}$	VarService
VRTMIN	$V_{RMIN} V_T$	$E_{term} V_{RMIN}$	VarService

Discretes

Name	Symbol	Type	Info
SL	SL	LessThan	
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag

Blocks

Name	Symbol	Type	Info
SAT	SAT	ExcQuadSat	Field voltage saturation
LS	LS	Lag	Sensing lag TF
LL	LL	LeadLag	Lead-lag for internal delays
LA	LA	LagAntiWindup	Anti-windup lag
W	W	Washout	Signal conditioner

Config Fields in [IEEEX1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.3 ESDC1A

ESDC1A model.

This model derives from ESDC2A and changes the regular limits to "VRMAX" and "VRMIN".

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
VRMAX	V_{RMAX}	Max. exc. limit (0-unlimited)	7.300	*p.u.*	
VRMIN	V_{RMIN}	Min. excitation limit	-7.300	*p.u.*	
KE	K_E	Saturation feedback gain	1	*p.u.*	
TE	T_E	Integrator time constant	0.800	*p.u.*	
KF	K_F	Feedback gain	0.100		
TF1	T_{F1}	Feedback washout time constant	1	*p.u.*	non_zero,non_negative
Switch	S_w	Switch that PSS/E did not implement	0	*bool*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	0	*p.u.*	
SE2	S_{E2}	Value at second saturation point	0	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
HG_y	y_{HG}	Algeb	HVGate output		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
INT_y	y_{INT}	State	v_{f0}
WF_x	x'_{WF}	State	y_{INT}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + \frac{V_{FE0}}{K_A}$
vi	V_i	Algeb	$\frac{V_{FE0}}{K_A}$
LL_y	y_{LL}	Algeb	V_i
UEL	U_{EL}	Algeb	0
HG_y	y_{HG}	Algeb	$U_{EL} z_0^{None_{HG}} + y_{LL} z_1^{None_{HG}}$
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	S_{e0}
VFE	V_{FE}	Algeb	V_{FE0}
WF_y	y_{WF}	Algeb	0
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{LA}\right)$	T_E
WF_x	x'_{WF}	State	$-x'_{WF} + y_{INT}$	T_{F1}
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$-v_{out} + y_{INT}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-E_{term} - V_i + V_{ref} - y_{WF}$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
UEL	U_{EL}	Algeb	$-U_{EL}$
HG_y	y_{HG}	Algeb	$U_{EL} z_0^{None_{HG}} - y_{HG} + y_{LL} z_1^{None_{HG}}$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Algeb	$B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\lvert V_{out}\rvert)$
VFE	V_{FE}	Algeb	$K_E y_{INT} - V_{FE} + V_{out} * S_e(\lvert V_{out}\rvert)$
WF_y	y_{WF}	Algeb	$K_F \left(-x'_{WF} + y_{INT}\right) - T_{F1} y_{WF}$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
Xadlfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
VR-MAXc	$VRMAXc$	$V_{RMAX} - 999z_{VRMAX} + 999$	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} <$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
Se0	S_{e0}	$B_{SAT}^{q} \left(A_{SAT}^{q} - v_{f0}\right)^2 \text{Indicator}\left(v_{f0} > A_{SAT}^{q}\right)$	ConstService
vfe0	V_{FE0}	$K_E v_{f0} + S_{e0}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService
VRU	V_{RMAX}	$VRMAXc$	ConstService
VRL	V_{RMIN}	V_{RMIN}	ConstService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HG_lt	$None_{HG}$	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Transducer delay
SAT	SAT	ExcQuadSat	Field voltage saturation
LL	LL	LeadLag	Lead-lag compensator
HG	HG	HVGate	HVGate for under excitation
LA	LA	LagAntiWindup	Anti-windup lag
INT	INT	Integrator	Integrator
WF	WF	Washout	Feedback to input

Config Fields in [ESDC1A]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.4 ESDC2A

ESDC2A model.

This model is implemented as described in the PSS/E manual, except that the HVGate is not in use. Due to the HVGate and saturation function, the results are close to but different from TSAT.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
VRMAX	V_{RMAX}	Max. exc. limit (0-unlimited)	7.300	*p.u.*	
VRMIN	V_{RMIN}	Min. excitation limit	-7.300	*p.u.*	
KE	K_E	Saturation feedback gain	1	*p.u.*	
TE	T_E	Integrator time constant	0.800	*p.u.*	
KF	K_F	Feedback gain	0.100		
TF1	T_{F1}	Feedback washout time constant	1	*p.u.*	non_zero,non_negative
Switch	S_w	Switch that PSS/E did not implement	0	*bool*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	0	*p.u.*	
SE2	S_{E2}	Value at second saturation point	0	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
HG_y	y_{HG}	Algeb	HVGate output		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
INT_y	y_{INT}	State	v_{f0}
WF_x	x'_{WF}	State	y_{INT}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + \frac{V_{FE0}}{K_A}$
vi	V_i	Algeb	$\frac{V_{FE0}}{K_A}$
LL_y	y_{LL}	Algeb	V_i
UEL	U_{EL}	Algeb	0
HG_y	y_{HG}	Algeb	$U_{EL} z_0^{None_{HG}} + y_{LL} z_1^{None_{HG}}$
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	S_{e0}
VFE	V_{FE}	Algeb	V_{FE0}
WF_y	y_{WF}	Algeb	0
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{LA}\right)$	T_E
WF_x	x'_{WF}	State	$-x'_{WF} + y_{INT}$	T_{F1}
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$-v_{out} + y_{INT}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-E_{term} - V_i + V_{ref} - y_{WF}$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
UEL	U_{EL}	Algeb	$-U_{EL}$
HG_y	y_{HG}	Algeb	$U_{EL} z_0^{None_{HG}} - y_{HG} + y_{LL} z_1^{None_{HG}}$
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	$B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\|V_{out}\|)$
VFE	V_{FE}	Algeb	$K_E y_{INT} - V_{FE} + V_{out} * S_e(\|V_{out}\|)$
WF_y	y_{WF}	Algeb	$K_F \left(-x'_{WF} + y_{INT}\right) - T_{F1} y_{WF}$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
Xadlfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
VR-MAXc	$VRMAXc$	$V_{RMAX} - 999 z_{VRMAX} + 999$	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} <$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
Se0	S_{e0}	$B_{SAT}^{q} \left(A_{SAT}^{q} - v_{f0}\right)^2 \text{Indicator}\left(v_{f0} > A_{SAT}^{q}\right)$	ConstService
vfe0	V_{FE0}	$K_E v_{f0} + S_{e0}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService
VRU	$V_T V_{RMAX}$	$E_{term} VRMAXc$	VarService
VRL	$V_T V_{RMIN}$	$E_{term} V_{RMIN}$	VarService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HG_lt	$None_{HG}$	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Transducer delay
SAT	SAT	ExcQuadSat	Field voltage saturation
LL	LL	LeadLag	Lead-lag compensator
HG	HG	HVGate	HVGate for under excitation
LA	LA	LagAntiWindup	Anti-windup lag
INT	INT	Integrator	Integrator
WF	WF	Washout	Feedback to input

Config Fields in [ESDC2A]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.5 EXST1

EXST1-type static excitation system.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Measurement delay	0.010		
VIMAX	V_{IMAX}	Max. input voltage	0.200		
VIMIN	V_{IMIN}	Min. input voltage	0		
TC	T_C	LL numerator	1		
TB	T_B	LL denominator	1		
KA	K_A	Regulator gain	80		
TA	T_A	Regulator delay	0.050		
VRMAX	V_{RMAX}	Max. regulator output	8		
VRMIN	V_{RMIN}	Min. regulator output	-3		
KC	K_C	Coef. for Ifd	0.200		
KF	K_F	Feedback gain	0.100		
TF	T_F	Feedback delay	1		non_zero,non_negative
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LR_y	y_{LR}	State	State in lag transfer function		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
vl	V_l	Algeb	Input after limiter		v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vfmax	V_{fmax}	Algeb	Upper bound of output limiter		v_str
vfmin	V_{fmin}	Algeb	Lower bound of output limiter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	V_l
LR_y	y_{LR}	State	$K_A y_{LL}$
WF_x	x'_{WF}	State	y_{LR}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + \frac{v_{f0}}{K_A}$
vi	V_i	Algeb	$\frac{v_{f0}}{K_A}$
vl	V_l	Algeb	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$
LL_y	y_{LL}	Algeb	V_l
WF_y	y_{WF}	Algeb	0
vfmax	V_{fmax}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMAX}$
vfmin	V_{fmin}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMIN}$
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_l - x'_{LL}$	T_B
LR_y	y_{LR}	State	$K_A y_{LL} - y_{LR}$	T_A
WF_x	x'_{WF}	State	$-x'_{WF} + y_{LR}$	T_F
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e \left(V_{fmax} z_u^{HLR} + V_{fmin} z_l^{HLR} + y_{LR} z_i^{HLR}\right) - v_{out}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-V_i + V_{ref} - y_{LG} - y_{WF}$
vl	V_l	Algeb	$V_i z_i^{HLI} - V_l + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_l - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
WF_y	y_{WF}	Algeb	$K_F \left(-x'_{WF} + y_{LR}\right) - T_F y_{WF}$
vfmax	V_{fmax}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMAX} - V_{fmax}$
vfmin	V_{fmin}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMIN} - V_{fmin}$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
HLI	HLI	HardLimiter	Hard limiter on input
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HLR	HLR	HardLimiter	Hard limiter on regulator output

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Sensing delay
LL	LL	LeadLag	Lead-lag compensator
LR	LR	Lag	Regulator
WF	WF	Washout	Stablizing circuit feedback

Config Fields in [EXST1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.6 ESST3A

Static exciter type 3A model

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
VIMAX	V_{IMAX}	Max. input voltage	0.800		
VIMIN	V_{IMIN}	Min. input voltage	-0.100		
KM	K_M	Forward gain constant	500		
TC	T_C	Lead time constant in lead-lag	3		
TB	T_B	Lag time constant in lead-lag	15		
KA	K_A	Gain in anti-windup lag TF	50		
TA	T_A	Lag time constant in anti-windup lag	0.100		
VRMAX	V_{RMAX}	Maximum excitation limit	8	*p.u.*	
VRMIN	V_{RMIN}	Minimum excitation limit	0	*p.u.*	
KG	K_G	Feedback gain of inner field regulator	1		
KP	K_P	Potential circuit gain coeff.	4		
KI	K_I	Potential circuit gain coeff.	0.100		
VBMAX	V_{BMAX}	VB upper limit	18	*p.u.*	
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
XL	X_L	Potential source reactance	0.010		
VGMAX	V_{GMAX}	VG upper limit	4	*p.u.*	
THETAP	θ_P	Rectifier firing angle	0	*degree*	
TM	K_C	Inner field regulator forward time constant	0.100		
VMMAX	V_{MMAX}	Maximum VM limit	1	*p.u.*	
VMMIN	V_{RMIN}	Minimum VM limit	0.100	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LAW1_y	y_{LAW1}	State	State in lag TF		v_str
LAW2_y	y_{LAW2}	State	State in lag TF		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
IN	I_N	Algeb	Input to FEX		v_str
FEX_y	y_{FEX}	Algeb	Output of piecewise		v_str
VB_x	x_{VB}	Algeb	Value before limiter		v_str
VB_y	y_{VB}	Algeb	Output after limiter and post gain		v_str
VG_x	x_{VG}	Algeb	Value before limiter		v_str
VG_y	y_{VG}	Algeb	Output after limiter and post gain		v_str
vrs	V_{RS}	Algeb	VR subtract feedback VG		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
vil	V_{il}	Algeb	Input voltage after limit		v_str
HG_y	y_{HG}	Algeb	HVGate output		v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		
vd	V_d	ExtAlgeb	d-axis machine voltage		
vq	V_q	ExtAlgeb	q-axis machine voltage		
Id	I_d	ExtAlgeb	d-axis machine current		
Iq	I_q	ExtAlgeb	q-axis machine current		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	y_{HG}
LAW1_	y_{LAW}	State	$K_A y_{LL}$
LAW2_	y_{LAW}	State	$K_M V_{RS}$
omega	ω	ExtStat	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
UEL	U_{EL}	Algeb	U_{EL0}
IN	I_N	Algeb	$\text{safe}_{div}\left(K_C X_{ad} I_{fd}, V_E\right)$
FEX_y	y_{FEX}	Algeb	FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right), (1.732 -\right.$
VB_x	x_{VB}	Algeb	$V_E y_{FEX}$
VB_y	y_{VB}	Algeb	$V_{BMAX} z_u^{lim_{VB}} + x_{VB} z_i^{lim_{VB}}$
VG_x	x_{VG}	Algeb	$K_G v_{out}$
VG_y	y_{VG}	Algeb	$V_{GMAX} z_u^{lim_{VG}} + x_{VG} z_i^{lim_{VG}}$
vrs	V_{RS}	Algeb	$\frac{\text{safe}_{div}\left(v_{f0}, y_{VB}\right)}{K_M}$
vref	V_{ref}	Algeb	$E_{term} + \frac{V_{RS} + y_{VG}}{K_A}$
vi	V_i	Algeb	$-E_{term} + V_{ref}$
vil	V_{il}	Algeb	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$
HG_y	y_{HG}	Algeb	$U_{EL} z_0^{None_{HG}} + V_{il} z_1^{None_{HG}}$
LL_y	y_{LL}	Algeb	y_{HG}
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_f$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$-x'_{LL} + y_{HG}$	T_B
LAW1_y	y_{LAW1}	State	$K_A y_{LL} - y_{LAW1}$	T_A
LAW2_y	y_{LAW2}	State	$K_M V_{RS} - y_{LAW2}$	K_C
omega	ω	ExtState	0	

Algebraic Equations

Nam	Sym-bol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Al-geb	$-E_{term} + V$
vout	v_{out}	Al-geb	$u_e y_{LAW2} y_{VB} - v_{out}$
UEL	U_{EL}	Al-geb	$U_{EL0} - U_{EL}$
IN	I_N	Al-geb	$u_e \left(-I_N V_E + K_C X_{ad} I_{fd}\right)$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right), ($
VB_x	x_{VB}	Al-geb	$V_E y_{FEX} - x_{VB}$
VB_y	y_{VB}	Al-geb	$V_{BMAX} z_u^{lim_{VB}} + x_{VB} z_i^{lim_{VB}} - y_{VB}$
VG_x	x_{VG}	Al-geb	$K_G v_{out} - x_{VG}$
VG_y	y_{VG}	Al-geb	$V_{GMAX} z_u^{lim_{VG}} + x_{VG} z_i^{lim_{VG}} - y_{VG}$
vrs	V_{RS}	Al-geb	$-V_{RS} + y_{LAW1} - y_{VG}$
vref	V_{ref}	Al-geb	$V_{ref0} - V_{ref}$
vi	V_i	Al-geb	$-V_i + V_{ref} - y_{LG}$
vil	V_{il}	Al-geb	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI} - V_{il}$
HG_y	y_{HG}	Al-geb	$U_{EL} z_0^{None_{HG}} + V_{il} z_1^{None_{HG}} - y_{HG}$
LL_y	y_{LL}	Al-geb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(-x'_{LL} + y_{HG}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
vf	v_f	Ex-tAl-geb	$u_e \left(-v_{f0} + v_{out}\right)$
Xad-Ifd	$X_{ad} I_f$	Ex-tAl-geb	0
a	θ	Ex-tAl-geb	0
vbus	V	Ex-tAl-geb	0
vd	V_d	Ex-tAl-geb	0
vq	V_q	Ex-tAl-	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
KPC	K_{PC}	$K_P e^{i \text{ radians}(\theta_P)}$	ConstService
UEL0	U_{EL0}	-9999	ConstService
VE	V_E	$\lvert K_{PC}\left(V_d + iV_q\right) + i\left(I_d + iI_q\right)\left(K_I + K_{PC}X_L\right)\rvert$	VarService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
VB_lim	lim_{VB}	HardLimiter	
VG_lim	lim_{VG}	HardLimiter	
HG_lt	$None_{HG}$	LessThan	
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LAW1_lim	lim_{LAW1}	AntiWindup	Limiter in Lag
HLI	HLI	HardLimiter	Input limiter
LAW2_lim	lim_{LAW2}	AntiWindup	Limiter in Lag

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Voltage transducer
FEX	FEX	Piecewise	Piecewise function FEX
VB	VB	GainLimiter	VB with limiter
VG	VG	GainLimiter	Feedback gain with HL
HG	HG	HVGate	HVGate for under excitation
LL	LL	LeadLag	Regulator
LAW1	$LAW1$	LagAntiWindup	Lag AW on VR
LAW2	$LAW2$	LagAntiWindup	Lag AW on VM

Config Fields in [ESST3A]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.7 SEXS

Simplified Excitation System

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TATB	T_A/T_B	Time constant TA/TB	0.400		
TB	T_B	Time constant TB in LL	5		
K	K	Gain	20		non_zero
TE	T_E	AW Lag time constant	1		
EMIN	E_{MIN}	lower limit	-99		
EMAX	E_{MAX}	upper limit	99		
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LL_x	x'_{LL}	State	State in lead-lag		v_str
LAW_y	y_{LAW}	State	State in lag TF		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LL_x	x'_{LL}	State	V_i
LAW_y	y_{LAW}	State	Ky_{LL}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + \frac{v_{f0}}{K}$
vi	V_i	Algeb	$\frac{v_{f0}}{K}$
LL_y	y_{LL}	Algeb	V_i
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LAW_y	y_{LAW}	State	$Ky_{LL} - y_{LAW}$	T_E
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e y_{LAW} - v_{out}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-E_{term} - V_i + V_{ref}$
LL_y	y_{LL}	Algeb	$TA\left(V_i - x'_{LL}\right) + T_B x'_{LL} - T_B y_{LL} + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
vf	v_f	ExtAlgeb	$u_e\left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
TA	TA	$T_{A/TB}T_B$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LAW_lim	lim_{LAW}	AntiWindup	Limiter in Lag

Blocks

Name	Symbol	Type	Info
LL	LL	LeadLag	
LAW	LAW	LagAntiWindup	

Config Fields in [SEXS]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.8 IEEET1

IEEET1 exciter.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.020	*p.u.*	
KA	K_A	Regulator gain	5	*p.u.*	
TA	T_A	Lag time constant in anti-windup lag	0.040	*p.u.*	
VRMAX	V_{RMAX}	Maximum excitation limit	7.300	*p.u.*	
VRMIN	V_{RMIN}	Minimum excitation limit	-7.300	*p.u.*	
KE	K_E	Gain added to saturation	1	*p.u.*	
TE	T_E	Exciter integrator time constant	0.800	*p.u.*	
KF	K_F	Feedback gain	0.100		
TF	T_F	Feedback delay	1		non_zero,non_negative
Switch	S_w	Switch unused in PSS/E	0	*bool*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
Se	$S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LA_y	y_{LA}	State	$K_A u_e \left(V_i - y_{WF}\right)$
INT_y	y_{INT}	State	v_{f0}
WF_x	x'_{WF}	State	v_{out}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vref	V_{ref}	Algeb	$E_{term} + V_{b0}$
vi	V_i	Algeb	$-E_{term} + V_{ref}$
VFE	V_{FE}	Algeb	V_{FE0}
Se	$S_e(\|V_{out}\|)$	Algeb	S_{e0}
WF_y	y_{WF}	Algeb	0
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LA_y	y_{LA}	State	$K_A u_e \left(V_i - y_{WF}\right) - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{LA}\right)$	T_E
WF_x	x'_{WF}	State	$v_{out} - x'_{WF}$	T_F
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e \left(-v_{out} + y_{INT}\right)$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$u_e \left(-V_i + V_{ref} - y_{LG}\right)$
VFE	V_{FE}	Algeb	$u_e \left(K_E y_{INT} + S_e(\lvert V_{out}\rvert) - V_{FE}\right)$
Se	$S_e(\lvert V_{out}\rvert)$	Algeb	$B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - S_e(\lvert V_{out}\rvert)$
WF_y	y_{WF}	Algeb	$K_F \left(v_{out} - x'_{WF}\right) - T_F y_{WF}$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
VR-MAXc	$VRMAXc$	$V_{RMAX} - 999z_{VRMAX} + 999$	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} <$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
Se0	S_{e0}	$B_{SAT}^{q} \left(A_{SAT}^{q} - v_{f0}\right)^2 \text{Indicator}\left(v_{f0} > A_{SAT}^{q}\right)$	ConstService
vr0	V_{r0}	$K_E v_{f0} + S_{e0}$	ConstService
vb0	V_{b0}	$\frac{V_{r0}}{K_A}$	ConstService
vfe0	V_{FE0}	$K_E v_{f0} + S_{e0}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
SAT	SAT	ExcQuadSat	Field voltage saturation
LG	LG	Lag	Sensing delay
LA	LA	LagAntiWindup	Anti-windup lag
INT	INT	Integrator	Integrator
WF	WF	Washout	Stablizing circuit feedback

Config Fields in [IEEET1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.9 EXAC1

EXAC1 model.

Ref: https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20EXAC1.htm

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040	*p.u.*	
VRMAX	V_{RMAX}	Maximum regulator output	8	*p.u.*	
VRMIN	V_{RMIN}	Minimum regulator output	0	*p.u.*	
TE	T_E	Exciter integrator time constant	0.800	*p.u.*	non_negative
KF	K_F	Feedback gain	0.100		
TF	T_F	Feedback delay	1		non_zero,non_negative
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
KD	K_C	Ifd feedback gain	0		
KE	K_E	Saturation feedback gain	1	*p.u.*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str,v_iter
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
IN	I_N	Algeb	Input to FEX		v_str,v_iter
FEX_y	y_{FEX}	Algeb	Output of piecewise		v_str,v_iter
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Nam	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
INT_	y_{INT}	State	$-v_{f0} + y_{FEX} y_{INT}$
WF_:	x'_{WF}	State	V_{FE}
omeg	ω	ExtSta	
v	E_{term}	Al-geb	V
vout	v_{out}	Al-geb	$u_e v_{f0}$
IN	I_N	Al-geb	$-I_N y_{INT} + K_C X_{ad} I_{fd}$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right.\right.$
vi	V_i	Al-geb	$-E_{term} + V_{ref}$
LL_y	y_{LL}	Al-geb	V_i
Se	$V_{out} * S_e(\|V_{out}\|)$	Al-geb	$B_{SAT}^q \left(-A_{SAT}^q + y_{INT}\right)^2$ Indicator $\left(y_{INT} > A_{SAT}^q\right)$
VFE	V_{FE}	Al-geb	$K_C X_{ad} I_{fd} + K_E y_{INT} + V_{out} * S_e(\|V_{out}\|)$
vref	V_{ref}	Al-geb	$E_{term} + \frac{V_{FE}}{K_A}$
WF_:	y_{WF}	Al-geb	0
vf	v_f	Ex-tAl-geb	
Xad-Ifd	$X_{ad} I_{fd}$	Ex-tAl-geb	
a	θ	Ex-tAl-geb	
vbus	V	Ex-tAl-geb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{LA}\right)$	T_E
WF_x	x'_{WF}	State	$V_{FE} - x'_{WF}$	T_F
omega	ω	ExtState	0	

Algebraic Equations

Nam	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Al-geb	$-E_{term} + V$
vout	v_{out}	Al-geb	$u_e \left(-v_{out} + y_{FEX} y_{INT}\right)$
IN	I_N	Al-geb	$u_e \left(-I_N y_{INT} + K_C X_{ad} I_{fd}\right)$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\Big((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \Big(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75$
vi	V_i	Al-geb	$u_e \left(-E_{term} - V_i + V_{ref} - y_{WF}\right)$
LL_y	y_{LL}	Al-geb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Al-geb	$u_e \left(B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\lvert V_{out}\rvert)\right)$
VFE	V_{FE}	Al-geb	$u_e \left(K_C X_{ad} I_{fd} + K_E y_{INT} - V_{FE} + V_{out} * S_e(\lvert V_{out}\rvert)\right)$
vref	V_{ref}	Al-geb	$V_{ref0} - V_{ref}$
WF_	y_{WF}	Al-geb	$K_F \left(V_{FE} - x'_{WF}\right) - T_F y_{WF}$
vf	v_f	Ex-tAl-geb	$u_e \left(-v_{f0} + v_{out}\right)$
Xad-Ifd	$X_{ad} I_{fd}$	Ex-tAl-geb	0
a	θ	Ex-tAl-geb	0
vbus	V	Ex-tAl-geb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} < 0\right.$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
SAT	SAT	ExcQuadSat	Field voltage saturation
FEX	FEX	Piecewise	Piecewise function FEX
LG	LG	Lag	Voltage transducer
LL	LL	LeadLag	Regulator
LA	LA	LagAntiWindup	Lag AW on VR
INT	INT	Integrator	Integrator
WF	WF	Washout	Stablizing circuit feedback

Config Fields in [EXAC1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.10 EXAC2

EXAC2 model.

Ref: https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20EXAC2.htm

Notes

`VLR` is an input parameter, but to initialize the LVGate, an internal `VLRx` will be computed as a contant upon initialization. The constant `VLRx` will be used in the place of `VLR` in the block diagram.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040	*p.u.*	
VRMAX	V_{RMAX}	Maximum regulator output	8	*p.u.*	
VRMIN	V_{RMIN}	Minimum regulator output	0	*p.u.*	
TE	T_E	Exciter integrator time constant	0.800	*p.u.*	non_negative
KF	K_F	Feedback gain	0.100		
TF	T_F	Feedback delay	1		non_zero,non_neg
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
KD	K_C	Ifd feedback gain	0		
KE	K_E	Saturation feedback gain	1	*p.u.*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
VAMAX	V_{RMAX}	Maximum KA block output	8	*p.u.*	
VAMIN	V_{RMIN}	Minimum KA block output	0	*p.u.*	

continues on next

Table 14 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
VLR	V_{LR}	low voltage constant	0	*p.u.*	
KL	K_L	gain for low voltage	1	*p.u.*	
KH	K_H	gain for high voltage	1	*p.u.*	
KB	K_B	gain KB for regulator	1	*p.u.*	non_negative
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str,v_iter
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
IN	I_N	Algeb	Input to FEX		v_str,v_iter
FEX_y	y_{FEX}	Algeb	Output of piecewise		v_str,v_iter
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
VHA	VHA	Algeb			v_str
VL	VL	Algeb			v_str
LVG_y	y_{LVG}	Algeb	LVGate output		v_str
VR_x	x_{VR}	Algeb	Value before limiter		v_str
VR_y	y_{VR}	Algeb	Output after limiter and post gain		v_str
VLRx	$VLRx$	Algeb			v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Nam	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
INT_	y_{INT}	State	$-v_{f0} + y_{FEX} y_{INT}$
WF_:	x'_{WF}	State	V_{FE}
omeg	ω	ExtSta	
v	E_{term}	Al-geb	V
vout	v_{out}	Al-geb	$u_e v_{f0}$
IN	I_N	Al-geb	$-I_N y_{INT} + K_C X_{ad} I_{fd}$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right.\right.$
vi	V_i	Al-geb	$-E_{term} + V_{ref}$
LL_y	y_{LL}	Al-geb	V_i
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Al-geb	$B_{SAT}^q \left(-A_{SAT}^q + y_{INT}\right)^2$ Indicator $\left(y_{INT} > A_{SAT}^q\right)$
VFE	V_{FE}	Al-geb	$K_C X_{ad} I_{fd} + K_E y_{INT} + V_{out} * S_e(\lvert V_{out}\rvert)$
vref	V_{ref}	Al-geb	$E_{term} + \frac{K_L V_{FE} + \frac{V_{FE}}{K_B}}{K_A}$
WF_:	y_{WF}	Al-geb	0
VHA	VHA	Al-geb	$-K_H V_{FE} + y_{LA}$
VL	VL	Al-geb	$K_L \left(VLRx - V_{FE}\right)$
LVG_	y_{LVG}	Al-geb	$VHA z_1^{None_{LVG}} + VL z_0^{None_{LVG}}$
VR_y	x_{VR}	Al-geb	$K_B y_{LVG}$
VR_y	y_{VR}	Al-geb	$V_{RMAX} z_u^{lim_{VR}} + V_{RMIN} z_l^{lim_{VR}} + x_{VR} z_i^{lim_{VR}}$
VLR:	$VLRx$	Al-geb	V_{LR} Indicator $\left(V_{FE} + \frac{V_{FE}}{K_B K_L} < V_{LR}\right)$+$\left(V_{FE} + \frac{V_{FE}}{K_B K_L}\right)$ Indicator $\left(V_{FE} + \frac{V_{FE}}{K_B K_L} > V_{LR}\right)$
vf	v_f	Ex-tAl-geb	
Xad-Ifd	$X_{ad} I_{fd}$	Ex-tAl-geb	
a	θ	Ex-tAl-geb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{VR}\right)$	T_E
WF_x	x'_{WF}	State	$V_{FE} - x'_{WF}$	T_F
omega	ω	ExtState	0	

Algebraic Equations

Nam	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Al-geb	$-E_{term} + V$
vout	v_{out}	Al-geb	$u_e \left(-v_{out} + y_{FEX} y_{INT}\right)$
IN	I_N	Al-geb	$u_e \left(-I_N y_{INT} + K_C X_{ad} I_{fd}\right)$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\Big((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \Big(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75$
vi	V_i	Al-geb	$u_e \left(-E_{term} - V_i + V_{ref} - y_{WF}\right)$
LL_y	y_{LL}	Al-geb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Al-geb	$u_e \left(B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\lvert V_{out}\rvert)\right)$
VFE	V_{FE}	Al-geb	$u_e \left(K_C X_{ad} I_{fd} + K_E y_{INT} - V_{FE} + V_{out} * S_e(\lvert V_{out}\rvert)\right)$
vref	V_{ref}	Al-geb	$V_{ref0} - V_{ref}$
WF_y	y_{WF}	Al-geb	$K_F \left(V_{FE} - x'_{WF}\right) - T_F y_{WF}$
VHA	VHA	Al-geb	$-K_H V_{FE} - VHA + y_{LA}$
VL	VL	Al-geb	$K_L \left(VLRx - V_{FE}\right) - VL$
LVG_	y_{LVG}	Al-geb	$VHA z_1^{None_{LVG}} + VL z_0^{None_{LVG}} - y_{LVG}$
VR_x	x_{VR}	Al-geb	$K_B y_{LVG} - x_{VR}$
VR_y	y_{VR}	Al-geb	$V_{RMAX} z_u^{lim_{VR}} + V_{RMIN} z_l^{lim_{VR}} + x_{VR} z_i^{lim_{VR}} - y_{VR}$
VLR:	$VLRx$	Al-geb	$VLR_0 - VLRx$
vf	v_f	Ex-tAl-geb	$u_e \left(-v_{f0} + v_{out}\right)$
Xad-Ifd	$X_{ad} I_{fd}$	Ex-tAl-geb	0
a	θ	Ex-tAl-geb	0
vbus	V	Ex-tAl-geb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} < 0\right.$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService
VLR0	$VLR0$	$VLRx$	PostInitService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
SL	SL	LessThan	
LVG_lt	$None_{LVG}$	LessThan	
VR_lim	lim_{VR}	HardLimiter	

Blocks

Name	Symbol	Type	Info
SAT	SAT	ExcQuadSat	Field voltage saturation
FEX	FEX	Piecewise	Piecewise function FEX
LG	LG	Lag	Voltage transducer
LL	LL	LeadLag	Regulator
LA	LA	LagAntiWindup	Lag AW on VR
INT	INT	Integrator	Integrator
WF	WF	Washout	Stablizing circuit feedback
LVG	LVG	LVGate	
VR	VR	GainLimiter	

Config Fields in [EXAC2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.11 EXAC4

IEEE Type AC4 excitation system model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
VIMAX	V_{IMAX}	Max. input voltage	5		
VIMIN	V_{IMIN}	Min. input voltage	-0.100		
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040	*p.u.*	
VRMAX	V_{RMAX}	Maximum excitation limit	8	*p.u.*	
VRMIN	V_{RMIN}	Minimum excitation limit	0	*p.u.*	
KC	K_C	Reactive power compensation gain	0		
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LR_y	y_{LR}	State	State in lag transfer function		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
vfmax	V_{fmax}	Algeb	Upper bound of output limiter		v_str
vfmin	V_{fmin}	Algeb	Lower bound of output limiter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$
LR_y	y_{LR}	State	$K_A y_{LL}$
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
vi	V_i	Algeb	$\frac{v_{f0}}{K_A}$
LL_y	y_{LL}	Algeb	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$
vfmax	V_{fmax}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMAX}$
vfmin	V_{fmin}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMIN}$
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI} - x'_{LL}$	T_B
LR_y	y_{LR}	State	$K_A y_{LL} - y_{LR}$	T_A
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e \left(V_{fmax} z_u^{HLR} + V_{fmin} z_l^{HLR} + y_{LR} z_i^{HLR}\right) - v_{out}$
vi	V_i	Algeb	$-V_i + V_{ref0} - y_{LG}$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI} - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
vfmax	V_{fmax}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMAX} - V_{fmax}$
vfmin	V_{fmin}	Algeb	$-K_C X_{ad} I_{fd} + V_{RMIN} - V_{fmin}$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
vref0	V_{ref0}	$E_{term} + \frac{v_{f0}}{K_A}$	PostInitService

Discretes

Name	Symbol	Type	Info
HLI	HLI	HardLimiter	Hard limiter on input
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HLR	HLR	HardLimiter	Hard limiter on regulator output

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Sensing delay
LL	LL	LeadLag	Lead-lag compensator
LR	LR	Lag	Regulator

Config Fields in [EXAC4]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.12 ESST4B

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
KPR	K_{PR}	Proportional gain 1	1	*p.u.*	
KIR	K_{IR}	Integral gain 1	0	*p.u.*	
VRMAX	V_{RMAX}	Maximum regulator limit	8	*p.u.*	
VRMIN	V_{RMIN}	Minimum regulator limit	0	*p.u.*	
TA	T_A	Lag time constant	0.100		
KPM	K_{PM}	Proportional gain 2	1	*p.u.*	
KIM	K_{IM}	Integral gain 2	0	*p.u.*	
VMMAX	V_{RMAX}	Maximum inner loop limit	8	*p.u.*	
VMMIN	V_{RMIN}	Minimum inner loop limit	0	*p.u.*	
KG	K_G	Feedback gain of inner field regulator	1		
KP	K_P	Potential circuit gain coeff.	4		
KI	K_I	Potential circuit gain coeff.	0.100		
VBMAX	V_{BMAX}	VB upper limit	18	*p.u.*	
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
XL	X_L	Potential source reactance	0.010		
THETAP	θ_P	Rectifier firing angle	0	*degree*	
VGMAX	V_{GMAX}	VG upper limit	20	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
PI1_xi	xi_{PI1}	State	Integrator output		v_str
LA_y	y_{LA}	State	State in lag transfer function		v_str
PI2_xi	xi_{PI2}	State	Integrator output		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
IN	I_N	Algeb	Input to FEX		v_str
FEX_y	y_{FEX}	Algeb	Output of piecewise		v_str
VB_x	x_{VB}	Algeb	Value before limiter		v_str
VB_y	y_{VB}	Algeb	Output after limiter and post gain		v_str
VG_x	x_{VG}	Algeb	Value before limiter		v_str
VG_y	y_{VG}	Algeb	Output after limiter and post gain		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
PI1_ys	ys_{PI1}	Algeb	PI summation before limit		v_str
PI1_y	y_{PI1}	Algeb	PI output		v_str
PI2_ys	ys_{PI2}	Algeb	PI summation before limit		v_str
PI2_y	y_{PI2}	Algeb	PI output		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		
vd	V_d	ExtAlgeb	d-axis machine voltage		
vq	V_q	ExtAlgeb	q-axis machine voltage		
Id	I_d	ExtAlgeb	d-axis machine current		
Iq	I_q	ExtAlgeb	q-axis machine current		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
PI1_x	xi_{PI1}	State	y_{VG}
LA_y	y_{LA}	State	$1.0y_{PI1}$
PI2_x	xi_{PI2}	State	$\text{safe}_{div}\left(v_{f0}, y_{VB}\right)$
omega	ω	ExtStat	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
UEL	U_{EL}	Algeb	0
IN	I_N	Algeb	$\text{safe}_{div}\left(K_C X_{ad} I_{fd}, V_E\right)$
FEX_	y_{FEX}	Algeb	$\text{FixPiecewise}\left(\left(1,\ I_N \leq 0\right), \left(1 - 0.577 I_N,\ I_N \leq 0.433\right), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right), (1.732 -$
VB_x	x_{VB}	Algeb	$V_E y_{FEX}$
VB_y	y_{VB}	Algeb	$V_{BMAX} z_u^{lim_{VB}} + x_{VB} z_i^{lim_{VB}}$
VG_x	x_{VG}	Algeb	$K_G v_{out}$
VG_y	y_{VG}	Algeb	$V_{GMAX} z_u^{lim_{VG}} + x_{VG} z_i^{lim_{VG}}$
vref	V_{ref}	Algeb	E_{term}
vi	V_i	Algeb	$-E_{term} + V_{ref}$
PI1_y	ys_{PI1}	Algeb	$K_{PR} V_i + y_{VG}$
PI1_y	y_{PI1}	Algeb	$V_{RMAX} z_u^{lim_{PI1}} + V_{RMIN} z_l^{lim_{PI1}} + ys_{PI1} z_i^{lim_{PI1}}$
PI2_y	ys_{PI2}	Algeb	$K_{PM}\left(y_{LA} - y_{VG}\right) + \text{safe}_{div}\left(v_{f0}, y_{VB}\right)$
PI2_y	y_{PI2}	Algeb	$V_{RMAX} z_u^{lim_{PI2}} + V_{RMIN} z_l^{lim_{PI2}} + ys_{PI2} z_i^{lim_{PI2}}$
vf	v_f	ExtAlgeb	
Xadifd	$X_{ad} I_f$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
PI1_xi	xi_{PI1}	State	$K_{IR}\left(V_i + 2y_{PI1} - 2ys_{PI1}\right)$	
LA_y	y_{LA}	State	$-y_{LA} + 1.0y_{PI1}$	T_A
PI2_xi	xi_{PI2}	State	$K_{IM}\left(y_{LA} + 2y_{PI2} - y_{VG} - 2ys_{PI2}\right)$	
omega	ω	ExtState	0	

Algebraic Equations

Nam	Sym-bol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Al-geb	$-E_{term} + V$
vout	v_{out}	Al-geb	$u_e y_{PI2} y_{VB} - v_{out}$
UEL	U_{EL}	Al-geb	$-U_{EL}$
IN	I_N	Al-geb	$u_e \left(-I_N V_E + K_C X_{ad} I_{fd}\right)$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right), ($
VB_x	x_{VB}	Al-geb	$V_E y_{FEX} - x_{VB}$
VB_y	y_{VB}	Al-geb	$V_{BMAX} z_u^{lim_{VB}} + x_{VB} z_i^{lim_{VB}} - y_{VB}$
VG_x	x_{VG}	Al-geb	$K_G v_{out} - x_{VG}$
VG_y	y_{VG}	Al-geb	$V_{GMAX} z_u^{lim_{VG}} + x_{VG} z_i^{lim_{VG}} - y_{VG}$
vref	V_{ref}	Al-geb	$V_{ref0} - V_{ref}$
vi	V_i	Al-geb	$-V_i + V_{ref} - y_{LG}$
PI1_y	ys_{PI1}	Al-geb	$K_{PR} V_i + xi_{PI1} - ys_{PI1}$
PI1_y	y_{PI1}	Al-geb	$V_{RMAX} z_u^{lim_{PI1}} + V_{RMIN} z_l^{lim_{PI1}} - y_{PI1} + ys_{PI1} z_i^{lim_{PI1}}$
PI2_y	ys_{PI2}	Al-geb	$K_{PM} \left(y_{LA} - y_{VG}\right) + xi_{PI2} - ys_{PI2}$
PI2_y	y_{PI2}	Al-geb	$V_{RMAX} z_u^{lim_{PI2}} + V_{RMIN} z_l^{lim_{PI2}} - y_{PI2} + ys_{PI2} z_i^{lim_{PI2}}$
vf	v_f	Ex-tAl-geb	$u_e \left(-v_{f0} + v_{out}\right)$
Xad-Ifd	$X_{ad} I_f$	Ex-tAl-geb	0
a	θ	Ex-tAl-geb	0
vbus	V	Ex-tAl-geb	0
vd	V_d	Ex-tAl-geb	0
vq	V_q	Ex-tAl-	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
KPC	K_{PC}	$K_P e^{i \text{ radians}(\theta_P)}$	ConstService
VE	V_E	$\lvert K_{PC}\left(V_d + iV_q\right) + i\left(I_d + iI_q\right)\left(K_I + K_{PC}X_L\right)\rvert$	VarService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
VB_lim	lim_{VB}	HardLimiter	
VG_lim	lim_{VG}	HardLimiter	
PI1_lim	lim_{PI1}	HardLimiter	
PI2_lim	lim_{PI2}	HardLimiter	

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Voltage transducer
FEX	FEX	Piecewise	Piecewise function FEX
VB	VB	GainLimiter	VB with limiter
VG	VG	GainLimiter	Feedback gain with HL
PI1	$PI1$	PITrackAW	
LA	LA	Lag	Regulation delay
PI2	$PI2$	PITrackAW	

Config Fields in [ESST4B]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
ksr	K_{sr}	2	Tracking gain for outer PI controller	
ksm	K_{sm}	2	Tracking gain for inner PI controller	

5.12.13 AC8B

Exciter AC8B model.

Reference:[1],[2]

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
kP	k_P	PID proportional coeff.	10		
kI	k_I	PID integrative coeff.	10		
kD	k_D	PID derivative coeff.	10		
Td	T_d	PID derivative time constant.	0.200		
VPMAX	V_{PMAX}	PID maximum limit	999	*p.u.*	
VPMIN	V_{PMIN}	PID minimum limit	-999	*p.u.*	
VRMAX	V_{RMAX}	Maximum regulator limit	7.300	*p.u.*	
VRMIN	V_{RMIN}	Minimum regulator limit	1	*p.u.*	
VFEMAX	V_{FEMAX}	Exciter field current limit	999	*p.u.*	
VEMIN	V_{EMIN}	Minimum exciter voltage output	-999	*p.u.*	
TA	T_A	Lag time constant in anti-windup lag	0.040	*p.u.*	
KA	K_A	Gain in anti-windup lag TF	40	*p.u.*	
TE	T_E	Exciter integrator time constant	0.800	*p.u.*	
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
KE	K_E	Gain added to saturation	1	*p.u.*	
KD	K_D	Ifd feedback gain	0		
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

[1] Powerworld, Exciter AC8B, [Online], Available: https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20AC8B.htm

[2] NEPLAN, Exciters Models, [Online], Available: https://www.neplan.ch/wp-content/uploads/2015/08/Nep_EXCITERS1.pdf

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
PID_xi	xi_{PID}	State	Integrator output		v_str
PID_WO_x	$x'_{PID\,WO_{PID}}$	State	State in washout filter		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str,v_iter
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
IN	I_N	Algeb	Input to FEX		v_str,v_iter
FEX_y	y_{FEX}	Algeb	Output of piecewise		v_str,v_iter
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
OEL	O_{EL}	Algeb	Interface var for over exc. limiter		v_str
Vs	V_s	Algeb	Voltage compensation from PSS		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
PID_uin	uin_{PID}	Algeb	PID input		v_str
PID_WO_y	$y_{PID\,WO_{PID}}$	Algeb	Output of washout filter		v_str
PID_ys	ys_{PID}	Algeb	PI summation before limit		v_str
PID_y	y_{PID}	Algeb	PI output		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
PID_xi	xi_{PID}	State	$\frac{V_{FE}}{K_A}$
PID_W	$x'_{PID\,WO_I}$	State	uin_{PID}
LA_y	y_{LA}	State	$K_A y_{PID}$
INT_y	y_{INT}	State	$-v_{f0} + y_{FEX} y_{INT}$
omega	ω	ExtSta	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
IN	I_N	Algeb	$-I_N y_{INT} + K_C X_{ad} I_{fd}$
FEX_y	y_{FEX}	Algeb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.\right.\right.$
UEL	U_{EL}	Algeb	UEL_0
OEL	O_{EL}	Algeb	OEL_0
Vs	V_s	Algeb	0
vref	V_{ref}	Algeb	E_{term}
vi	V_i	Algeb	$-E_{term} + V_{ref}$
PID_uir	uin_{PID}	Algeb	V_i
PID_W	$y_{PID\,WO_I}$	Algeb	0
PID_ys	ys_{PID}	Algeb	$V_i k_P + \frac{V_{FE}}{K_A}$
PID_y	y_{PID}	Algeb	$V_{PMAX} z_u^{lim_{PID}} + V_{PMIN} z_l^{lim_{PID}} + ys_{PID} z_i^{lim_{PID}}$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Algeb	$B_{SAT}^q \left(-A_{SAT}^q + y_{INT}\right)^2$ Indicator $\left(y_{INT} > A_{SAT}^q\right)$
VFE	V_{FE}	Algeb	$K_D X_{ad} I_{fd} + K_E y_{INT} + V_{out} * S_e(\lvert V_{out}\rvert)$
vf	v_f	ExtAlgeb	
Xadlfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
PID_xi	xi_{PID}	State	$k_I \left(V_i + 2y_{PID} - 2ys_{PID}\right)$	
PID_WO_x	$x'_{PID\,WO_{PID}}$	State	$uin_{PID} - x'_{PID\,WO_{PID}}$	T_d
LA_y	y_{LA}	State	$K_A y_{PID} - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{LA}\right)$	T_E
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e \left(-v_{out} + y_{FEX} y_{INT}\right)$
IN	I_N	Algeb	$u_e \left(-I_N y_{INT} + K_C X_{ad} I_{fd}\right)$
FEX_y	y_{FEX}	Algeb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.\right.\right.$
UEL	U_{EL}	Algeb	$UEL_0 - U_{EL}$
OEL	O_{EL}	Algeb	$OEL_0 - O_{EL}$
Vs	V_s	Algeb	$-V_s$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$u_e \left(O_{EL} + U_{EL} - V_i + V_{ref} + V_s - y_{LG}\right)$
PID_uin	uin_{PID}	Algeb	$V_i - uin_{PID}$
PID_WO	$y_{PID\,WO_{PID}}$	Algeb	$-T_d y_{PID\,WO_{PID}} + k_D \left(uin_{PID} - x'_{PID\,WO_{PID}}\right)$
PID_ys	ys_{PID}	Algeb	$V_i k_P + xi_{PID} + y_{PID\,WO_{PID}} - ys_{PID}$
PID_y	y_{PID}	Algeb	$V_{PMAX} z_u^{lim_{PID}} + V_{PMIN} z_l^{lim_{PID}} - y_{PID} + ys_{PID} z_i^{lim_{PID}}$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Algeb	$u_e \left(B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\lvert V_{out}\rvert)\right)$
VFE	V_{FE}	Algeb	$u_e \left(K_D X_{ad} I_{fd} + K_E y_{INT} - V_{FE} + V_{out} * S_e(\lvert V_{out}\rvert)\right)$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
UEL0	$UEL0$	0	ConstService
OEL0	$OEL0$	0	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ (Indicator $\left(SE_{SAT}^{2c} > 0\right)$ + Indicator $\left(SE_{SAT}^{2c} < 0\right.$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
vref0	V_{ref0}	E_{term}	PostInitService

Discretes

Name	Symbol	Type	Info
PID_lim	lim_{PID}	HardLimiter	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
FEX	FEX	Piecewise	Piecewise function FEX
LG	LG	Lag	Voltage transducer
PID	PID	PIDTrackAW	PID
PID_WO	$PID\,WO_{PID}$	Washout	Washout
LA	LA	LagAntiWindup	V_{R}, Anti-windup lag
SAT	SAT	ExcQuadSat	Field voltage saturation
INT	INT	Integrator	V_E, integrator

Config Fields in [AC8B]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
ks		2	Tracking gain for PID controller	

5.12.14 IEEET3

Exciter IEEET3.

Reference:

[1] PowerWorld, Exciter IEEET3, [Online],

[2] NEPLAN, Exciters Models, [Online],

Available:

https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20IEEET3.htm

https://www.neplan.ch/wp-content/uploads/2015/08/Nep_EXCITERS1.pdf

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.020	*p.u.*	
KA	K_A	Regulator gain	5	*p.u.*	
TA	T_A	Lag time constant in anti-windup lag	0.040	*p.u.*	
VRMAX	V_{RMAX}	Maximum regulator limit	7.300	*p.u.*	
VRMIN	V_{RMIN}	Minimum regulator limit	-7.300	*p.u.*	
VBMAX	V_{BMAX}	VB upper limit	18	*p.u.*	
KE	K_E	Exciter integrator constant	1	*p.u.*	
TE	T_E	Exciter integrator time constant	1	*p.u.*	
KF	K_F	Feedback gain	0.100		
TF	T_F	Feedback delay	1		non_zero,non_negative
KP	K_P	Potential circuit gain coeff.	4		
KI	K_I	Potential circuit gain coeff.	0.100		
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LA3_y	y_{LA3}	State	State in lag TF		v_str
LA1_y	y_{LA1}	State	State in lag transfer function		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
OEL	O_{EL}	Algeb	Interface var for over exc. limiter		v_str
Vs	V_s	Algeb	Voltage compensation from PSS		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
SQE	SQE	Algeb	Square of error after mul		v_str
VB_y	y_{VB}	Algeb	Output of piecewise		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		
vd	V_d	ExtAlgeb	d-axis machine voltage		
vq	V_q	ExtAlgeb	q-axis machine voltage		
Id	I_d	ExtAlgeb	d-axis machine current		
Iq	I_q	ExtAlgeb	q-axis machine current		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LA3_y	y_{LA3}	State	$K_A u_e \left(V_i - y_{WF}\right)$
LA1_y	y_{LA1}	State	$\frac{u_e\left(V_{BMAX} z_u^{HL} + y_{VB} z_i^{HL}\right)}{K_E}$
WF_x	x'_{WF}	State	y_{LA1}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
UEL	U_{EL}	Algeb	UEL_0
OEL	O_{EL}	Algeb	OEL_0
Vs	V_s	Algeb	0
vref	V_{ref}	Algeb	$E_{term} + V_{b0}$
vi	V_i	Algeb	$-E_{term} + V_{ref}$
WF_y	y_{WF}	Algeb	0
SQE	SQE	Algeb	$V_E^2 - 0.6084 X_{ad} I_{fd}^2$
VB_y	y_{VB}	Algeb	FixPiecewise $\left((u_e y_{LA3},\ SQE \leq 0), \left(u_e \left(\sqrt{SQE} + y_{LA3}\right),\ \text{True}\right)\right)$
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	
vd	V_d	ExtAlgeb	
vq	V_q	ExtAlgeb	
Id	I_d	ExtAlgeb	
Iq	I_q	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LA3_y	y_{LA3}	State	$K_A u_e \left(V_i - y_{WF}\right) - y_{LA3}$	T_A
LA1_y	y_{LA1}	State	$-K_E y_{LA1} + u_e \left(V_{BMAX} z_u^{HL} + y_{VB} z_i^{HL}\right)$	T_E
WF_x	x'_{WF}	State	$-x'_{WF} + y_{LA1}$	T_F
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e \left(-v_{out} + y_{LA1}\right)$
UEL	U_{EL}	Algeb	$UEL_0 - U_{EL}$
OEL	O_{EL}	Algeb	$OEL_0 - O_{EL}$
Vs	V_s	Algeb	$-V_s$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$u_e \left(O_{EL} + U_{EL} - V_i + V_{ref} + V_s - y_{LG}\right)$
WF_y	y_{WF}	Algeb	$K_F \left(-x'_{WF} + y_{LA1}\right) - T_F y_{WF}$
SQE	SQE	Algeb	$-SQE + V_E^2 - 0.6084 X_{ad} I_{fd}^2$
VB_y	y_{VB}	Algeb	$-y_{VB}$+FixPiecewise $\left(\left(u_e y_{LA3},\ SQE \leq 0\right), \left(u_e \left(\sqrt{SQE} + y_{LA3}\right),\ \text{True}\right)\right)$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
Xadlfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0
vd	V_d	ExtAlgeb	0
vq	V_q	ExtAlgeb	0
Id	I_d	ExtAlgeb	0
Iq	I_q	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
VE	V_E	$\lvert iK_I\left(I_d+iI_q\right)+K_P\left(V_d+iV_q\right)\rvert$	VarService
V40	$V40$	$\sqrt{V_E^2-0.6084X_{ad}I_{fd}^2}$	ConstService
VR0	V_{R0}	$K_E v_{f0}-V_{40}$	ConstService
vb0	V_{b0}	$\frac{V_{R0}}{K_A}$	ConstService
VRMAXc	$VRMAXc$	$V_{RMAX}-999z_{VRMAX}+999$	ConstService
UEL0	$UEL0$	0	ConstService
OEL0	$OEL0$	0	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService
zeros	$zeros$	0.0	ConstService

Discretes

Name	Symbol	Type	Info
LA3_lim	lim_{LA3}	AntiWindup	Limiter in Lag
SL	SL	LessThan	
HL	HL	HardLimiter	Hard limiter for VB

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Sensing delay
LA3	$LA3$	LagAntiWindup	V_{R}, Lag Anti-Windup
LA1	$LA1$	Lag	
WF	WF	Washout	V_F, stablizing circuit feedback, washout
VB	VB	Piecewise	

Config Fields in [IEEET3]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.15 ESAC1A

Exciter ESAC1A.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010	*p.u.*	
TB	T_B	Lag time constant in lead-lag	1	*p.u.*	non_negative
TC	T_C	Lead time constant in lead-lag	1	*p.u.*	non_negative
VAMAX	V_{AMAX}	V_A upper limit	999	*p.u.*	
VAMIN	V_{AMIN}	V_A lower limit	-999	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040	*p.u.*	non_negative
VRMAX	V_{RMAX}	Max. exc. limit (0-unlimited)	7.300	*p.u.*	
VRMIN	V_{RMIN}	Min. excitation limit	-7.300	*p.u.*	
TE	T_E	Integrator time constant	0.800	*p.u.*	non_negative
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_{E1}	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_{E2}	Value at second saturation point	1	*p.u.*	
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
KD	K_D	Ifd feedback gain	0		
KE	K_E	Gain added to saturation	1		
KF	K_F	Feedback gain	0.100		
TF	T_{F1}	Feedback washout time constant	1	*p.u.*	non_zero,non_negative
Switch	S_w	Switch that PSS/E did not implement	0	*bool*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
INT_y	y_{INT}	State	Integrator output		v_str,v_iter
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
OEL	O_{EL}	Algeb	Interface var for over exc. limiter		v_str
Vs	V_s	Algeb	Voltage compensation from PSS		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
IN	I_N	Algeb	Input to FEX		v_str,v_iter
FEX_y	y_{FEX}	Algeb	Output of piecewise		v_str,v_iter
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
HVG_y	y_{HVG}	Algeb	HVGate output		v_str
LVG_y	y_{LVG}	Algeb	LVGate output		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	V_i
LA_y	y_{LA}	State	$K_A y_{LL}$
INT_	y_{INT}	State	$-v_{f0} + y_{FEX} y_{INT}$
WF_y	x'_{WF}	State	V_{FE}
omeg	ω	ExtSta	
v	E_{term}	Al-geb	V
vout	v_{out}	Al-geb	$u_e v_{f0}$
UEL	U_{EL}	Al-geb	UEL_0
OEL	O_{EL}	Al-geb	OEL_0
Vs	V_s	Al-geb	0
vref	V_{ref}	Al-geb	$E_{term} + \frac{V_{FE}}{K_A}$
IN	I_N	Al-geb	$-I_N y_{INT} + K_C X_{ad} I_{fd}$
FEX_	y_{FEX}	Al-geb	$-y_{FEX}$+FixPiecewise $\left((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \left(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75\right.\right.$
vi	V_i	Al-geb	$-E_{term} + V_{ref}$
LL_y	y_{LL}	Al-geb	V_i
HVG_	y_{HVG}	Al-geb	$U_{EL} z_0^{None_{HVG}} + y_{LA} z_1^{None_{HVG}}$
LVG_	y_{LVG}	Al-geb	$O_{EL} z_0^{None_{LVG}} + y_{HVG} z_1^{None_{LVG}}$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Al-geb	$B_{SAT}^q \left(-A_{SAT}^q + y_{INT}\right)^2$ Indicator $\left(y_{INT} > A_{SAT}^q\right)$
VFE	V_{FE}	Al-geb	$K_D X_{ad} I_{fd} + K_E y_{INT} + V_{out} * S_e(\lvert V_{out}\rvert)$
WF_y	y_{WF}	Al-geb	0
vf	v_f	Ex-tAl-geb	
Xad-Ifd	$X_{ad} I_{fd}$	Ex-tAl-geb	
a	θ	Ex-tAl-geb	
vbus	V	Ex-tAl-geb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_A y_{LL} - y_{LA}$	T_A
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{LVG}\right)$	T_E
WF_x	x'_{WF}	State	$V_{FE} - x'_{WF}$	T_{F1}
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e y_{FEX} y_{INT} - v_{out}$
UEL	U_{EL}	Algeb	$UEL_0 - U_{EL}$
OEL	O_{EL}	Algeb	$OEL_0 - O_{EL}$
Vs	V_s	Algeb	$-V_s$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
IN	I_N	Algeb	$u_e \left(-I_N y_{INT} + K_C X_{ad} I_{fd}\right)$
FEX_	y_{FEX}	Algeb	$-y_{FEX}$+FixPiecewise $\Big((1,\ I_N \leq 0), (1 - 0.577 I_N,\ I_N \leq 0.433), \Big(\sqrt{0.75 - I_N^2},\ I_N \leq 0.75$
vi	V_i	Algeb	$u_e \left(O_{EL} + U_{EL} - V_i + V_{ref} + V_s - y_{LG}\right)$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C \left(V_i - x'_{LL}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
HVG_	y_{HVG}	Algeb	$U_{EL} z_0^{None_{HVG}} - y_{HVG} + y_{LA} z_1^{None_{HVG}}$
LVG_	y_{LVG}	Algeb	$O_{EL} z_0^{None_{LVG}} + y_{HVG} z_1^{None_{LVG}} - y_{LVG}$
Se	$V_{out} * S_e(\lvert V_{out}\rvert)$	Algeb	$u_e \left(B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\lvert V_{out}\rvert)\right)$
VFE	V_{FE}	Algeb	$u_e \left(K_D X_{ad} I_{fd} + K_E y_{INT} - V_{FE} + V_{out} * S_e(\lvert V_{out}\rvert)\right)$
WF_y	y_{WF}	Algeb	$K_F \left(V_{FE} - x'_{WF}\right) - T_{F1} y_{WF}$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
Xad-Ifd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
UEL0	$UEL0$	-999	ConstService
OEL0	$OEL0$	999	ConstService
VAMAXu	$VAMAXu$	$V_{AMAX}u_e - 999u_e + 999$	ConstService
VAMINu	$VAMINu$	$V_{AMIN}u_e + 999u_e - 999$	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ $\left(\text{Indicator}\left(SE_{SAT}^{2c} > 0\right) + \text{Indicator}\left(SE_{SAT}^{2c} <\right.\right.$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
HVG_lt	$None_{HVG}$	LessThan	
LVG_lt	$None_{LVG}$	LessThan	
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
FEX	FEX	Piecewise	Piecewise function FEX
LG	LG	Lag	Voltage transducer
LL	LL	LeadLag	V_A, Lead-lag compensator
LA	LA	LagAntiWindup	V_A, Anti-windup lag
HVG	HVG	HVGate	HVGate for under excitation
LVG	LVG	LVGate	HVGate for under excitation
SAT	SAT	ExcQuadSat	Field voltage saturation
INT	INT	Integrator	V_E, integrator
WF	WF	Washout	Stablizing circuit feedback

Config Fields in [ESAC1A]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.16 ESST1A

Exciter ESST1A model.

Reference:

[1] PowerWorld, Exciter ESST1A, [Online],

[2] NEPLAN, Exciters Models, [Online],

Available: https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20ESST1A.htm

https://www.neplan.ch/wp-content/uploads/2015/08/Nep_EXCITERS1.pdf

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing time constant	0.010		
VIMAX	V_{IMAX}	Max. input voltage	0.800		
VIMIN	V_{IMIN}	Min. input voltage	-0.100		
TB	T_B	Lag time constant in lead-lag	1		
TC	T_C	Lead time constant in lead-lag	1		
TB1	T_{B1}	Lag time constant in lead-lag 1	1		
TC1	T_{C1}	Lead time constant in lead-lag 1	1		
VAMAX	V_{AMAX}	V_A upper limit	999	*p.u.*	
VAMIN	V_{AMIN}	V_A lower limit	-999	*p.u.*	
KA	K_A	Regulator gain	80		
TA	T_A	Lag time constant in regulator	0.040		
ILR	I_{LR}	Exciter output current limite reference	1		
KLR	K_{LR}	Exciter output current limiter gain	1		
VRMAX	V_{RMAX}	Maximum voltage regulator output limit	7.300	*p.u.*	
VRMIN	V_{RMIN}	Minimum voltage regulator output limit	-7.300	*p.u.*	
KF	K_F	Feedback gain	0.100		
TF	T_F	Feedback washout time constant	1		
KC	K_C	Rectifier loading factor proportional to commutating reactance	0.100		
UELc	UEL_c	Alternate UEL inputs, input code 1-3	1		
VOSc	VOS_c	Alternate Stabilizer inputs, input code 1-2	1		
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
LL1_x	x'_{LL1}	State	State in lead-lag		v_str
LA_y	y_{LA}	State	State in lag TF		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
OEL	O_{EL}	Algeb	Interface var for over exc. limiter		v_str
Vs	V_s	Algeb	Voltage compensation from PSS		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str,v_iter
SG	SG	Algeb	SG		v_str
LR_x	x_{LR}	Algeb	Value before limiter		v_str
LR_y	y_{LR}	Algeb	Output after limiter and post gain		v_str
vi	V_i	Algeb	Total input voltages	*p.u.*	v_str,v_iter
vil_x	x_{vil}	Algeb	Value before limiter		v_str
vil_y	y_{vil}	Algeb	Output after limiter and post gain		v_str
UEL2	UEL_2	Algeb	UEL_2 as HVG1 u1		v_str
HVG1_y	y_{HVG1}	Algeb	HVGate output		v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
LL1_y	y_{LL1}	Algeb	Output of lead-lag		v_str
vas	V_{As}	Algeb	V_A after subtraction, as HVG u2		v_str,v_iter
UEL3	UEL_3	Algeb	UEL_3 as HVG u1		v_str
HVG_y	y_{HVG}	Algeb	HVGate output		v_str
LVG_y	y_{LVG}	Algeb	LVGate output		v_str
vol_x	x_{vol}	Algeb	Value before limiter		v_str
vol_y	y_{vol}	Algeb	Output after limiter and post gain		v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		
vd	V_d	ExtAlgeb	d-axis machine voltage		
vq	V_q	ExtAlgeb	q-axis machine voltage		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	E_{term}
LL_x	x'_{LL}	State	y_{HVG1}
LL1_x	x'_{LL1}	State	y_{LL}
LA_y	y_{LA}	State	$K_A y_{LL1}$
WF_x	x'_{WF}	State	y_{LVG}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
UEL	U_{EL}	Algeb	UEL_0
OEL	O_{EL}	Algeb	OEL_0
Vs	V_s	Algeb	0
vref	V_{ref}	Algeb	$u_e \left(E_{term} - SGs_1^{SW_{VOS}} - U_{EL}s_1^{SW_{UEL}} + \frac{-SGs_2^{SW_{VOS}} + v_{f0} + y_{LR}}{K_A} \right)$
SG	SG	Algeb	SG_0
LR_x	x_{LR}	Algeb	$K_{LR}\left(-I_{LR} + X_{ad}I_{fd}\right)$
LR_y	y_{LR}	Algeb	$x_{LR}z_i^{lim_{LR}} + z_l^{lim_{LR}} zero$
vi	V_i	Algeb	$u_e \left(SGs_1^{SW_{VOS}} + U_{EL}s_1^{SW_{UEL}} + V_{ref} + V_s - y_{LG} - y_{WF} \right)$
vil_x	x_{vil}	Algeb	V_i
vil_y	y_{vil}	Algeb	$V_{IMAX}z_u^{lim_{vil}} + V_{IMIN}z_l^{lim_{vil}} + x_{vil}z_i^{lim_{vil}}$
UEL2	UEL_2	Algeb	$u_e \left(U_{EL}s_2^{SW_{UEL}} + llim \left(1 - s_2^{SW_{UEL}} \right) \right)$
HVG1_y	y_{HVG1}	Algeb	$UEL_2 z_0^{None_{HVG1}} + y_{vil}z_1^{None_{HVG1}}$
LL_y	y_{LL}	Algeb	y_{HVG1}
LL1_y	y_{LL1}	Algeb	y_{LL}
vas	V_{As}	Algeb	$u_e \left(SGs_2^{SW_{VOS}} + y_{LA} - y_{LR} \right)$
UEL3	UEL_3	Algeb	$u_e \left(U_{EL}s_3^{SW_{UEL}} + llim \left(1 - s_3^{SW_{UEL}} \right) \right)$
HVG_y	y_{HVG}	Algeb	$UEL_3 z_0^{None_{HVG}} + V_{As}z_1^{None_{HVG}}$
LVG_y	y_{LVG}	Algeb	$O_{EL}z_0^{None_{LVG}} + y_{HVG}z_1^{None_{LVG}}$
vol_x	x_{vol}	Algeb	y_{LVG}
vol_y	y_{vol}	Algeb	$efd_l z_l^{lim_{vol}} + efd_u z_u^{lim_{vol}} + x_{vol}z_i^{lim_{vol}}$
WF_y	y_{WF}	Algeb	0
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	
vd	V_d	ExtAlgeb	
vq	V_q	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$E_{term} - y_{LG}$	T_R
LL_x	x'_{LL}	State	$-x'_{LL} + y_{HVG1}$	T_B
LL1_x	x'_{LL1}	State	$-x'_{LL1} + y_{LL}$	T_{B1}
LA_y	y_{LA}	State	$K_A y_{LL1} - y_{LA}$	T_A
WF_x	x'_{WF}	State	$-x'_{WF} + y_{LVG}$	T_F
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e y_{vol} - v_{out}$
UEL	U_{EL}	Algeb	$UEL_0 - U_{EL}$
OEL	O_{EL}	Algeb	$OEL_0 - O_{EL}$
Vs	V_s	Algeb	$-V_s$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
SG	SG	Algeb	$-SG + SG_0$
LR_x	x_{LR}	Algeb	$K_{LR}\left(-I_{LR} + X_{ad} I_{fd}\right) - x_{LR}$
LR_y	y_{LR}	Algeb	$x_{LR} z_i^{lim_{LR}} - y_{LR} + z_l^{lim_{LR}} zero$
vi	V_i	Algeb	$-V_i + u_e \left(SG s_1^{SW_{VOS}} + U_{EL} s_1^{SW_{UEL}} + V_{ref} + V_s - y_{LG} - y_{WF}\right)$
vil_x	x_{vil}	Algeb	$V_i - x_{vil}$
vil_y	y_{vil}	Algeb	$V_{IMAX} z_u^{lim_{vil}} + V_{IMIN} z_l^{lim_{vil}} + x_{vil} z_i^{lim_{vil}} - y_{vil}$
UEL2	UEL_2	Algeb	$-UEL_2 + u_e \left(U_{EL} s_2^{SW_{UEL}} + llim\left(1 - s_2^{SW_{UEL}}\right)\right)$
HVG1_y	y_{HVG1}	Algeb	$UEL_2 z_0^{None_{HVG1}} - y_{HVG1} + y_{vil} z_1^{None_{HVG1}}$
LL_y	y_{LL}	Algeb	$T_B x'_{LL} - T_B y_{LL} + T_C\left(-x'_{LL} + y_{HVG1}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
LL1_y	y_{LL1}	Algeb	$T_{B1} x'_{LL1} - T_{B1} y_{LL1} + T_{C1}\left(-x'_{LL1} + y_{LL}\right) + \left(z_1^{LT_{LL1}}\right)^2 \left(-x'_{LL1} + y_{LL1}\right)$
vas	V_{As}	Algeb	$-V_{As} + u_e \left(SG s_2^{SW_{VOS}} + y_{LA} - y_{LR}\right)$
UEL3	UEL_3	Algeb	$-UEL_3 + u_e \left(U_{EL} s_3^{SW_{UEL}} + llim\left(1 - s_3^{SW_{UEL}}\right)\right)$
HVG_y	y_{HVG}	Algeb	$UEL_3 z_0^{None_{HVG}} + V_{As} z_1^{None_{HVG}} - y_{HVG}$
LVG_y	y_{LVG}	Algeb	$O_{EL} z_0^{None_{LVG}} + y_{HVG} z_1^{None_{LVG}} - y_{LVG}$
vol_x	x_{vol}	Algeb	$-x_{vol} + y_{LVG}$
vol_y	y_{vol}	Algeb	$efd_l z_l^{lim_{vol}} + efd_u z_u^{lim_{vol}} + x_{vol} z_i^{lim_{vol}} - y_{vol}$
WF_y	y_{WF}	Algeb	$K_F\left(-x'_{WF} + y_{LVG}\right) - T_F y_{WF}$
vf	v_f	ExtAlgeb	$u_e\left(-v_{f0} + v_{out}\right)$
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0
vd	V_d	ExtAlgeb	0
vq	V_q	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
UEL0	$UEL0$	-999	ConstService
OEL0	$OEL0$	999	ConstService
ulim	$ulim$	9999	ConstService
llim	$llim$	-9999	ConstService
SG0	$SG0$	0	ConstService
zero	$zero$	0	ConstService
VA0	V_{A0}	$-SGs_2^{SW_{VOS}} + v_{f0} + y_{LR}$	PostInitService
vref0	V_{ref0}	V_{ref}	PostInitService
efdu	efd_u	$-K_C X_{ad} I_{fd} + V_{RMAX} \lvert V_d + iV_q \rvert$	VarService
efdl	efd_l	$V_{RMIN} \lvert V_d + iV_q \rvert$	VarService

Discretes

Name	Symbol	Type	Info
SWUEL	SW_{UEL}	Switcher	
SWVOS	SW_{VOS}	Switcher	
LR_lim	lim_{LR}	HardLimiter	
vil_lim	lim_{vil}	HardLimiter	
HVG1_lt	$None_{HVG1}$	LessThan	
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
LL1_LT1	LT_{LL1}	LessThan	
LL1_LT2	LT_{LL1}	LessThan	
LA_lim	lim_{LA}	AntiWindup	Limiter in Lag
HVG_lt	$None_{HVG}$	LessThan	
LVG_lt	$None_{LVG}$	LessThan	
vol_lim	lim_{vol}	HardLimiter	

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	Voltage transducer
LR	LR	GainLimiter	Exciter output current gain limiter
vil	vil	GainLimiter	Exciter voltage input limiter
HVG1	$HVG1$	HVGate	HVGate after V_I
LL	LL	LeadLag	Lead-lag compensator
LL1	$LL1$	LeadLag	Lead-lag compensator 1
LA	LA	LagAntiWindup	V_A, Anti-windup lag
HVG	HVG	HVGate	HVGate for under excitation
LVG	LVG	LVGate	HVGate for over excitation
vol	vol	GainLimiter	Exciter output limiter
WF	WF	Washout	V_F, Stablizing circuit feedback

Config Fields in [ESST1A]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.12.17 ESAC5A

Exciter ESAC5A.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory
TR	T_R	Sensing Time Constant	0.010	*p.u*	
TA	T_A	Voltage Regulator Time Constant	0.040	*p.u*	
KA	K_A	Voltage Regulator Gain	80		
VRMIN	V_Rmin	V_R lower limit	-7.300	*p.u*	
VRMAX	V_Rmax	V_R upper limit	7.300	*p.u*	
TE	T_E	Integrator Time Constant	0.800	*p.u*	non_negative
KF	K_F	Feedback Gain	0.030		
TF1	T_{F1}	Lag Time Constant	1	*p.u*	
TF2	T_{F2}	Lead-Lag Time Constant (pole)	0.800	*p.u*	
TF3	T_{F3}	Lead-Lag Time Constant (zero)	1	*p.u*	
KE	K_E	Exciter Feedback Gain	1		
E1	E_1	First saturation point	0	*p.u.*	
SE1	S_E1	Value at first saturation point	0	*p.u.*	
E2	E_2	Second saturation point	1	*p.u.*	
SE2	S_E2	Value at second saturation point	1	*p.u.*	
ug	u_g	Generator online status	0	*bool*	
Sn	S_m	Rated power from generator	0	*MVA*	
Vn	V_m	Rated voltage from generator	0	*kV*	
bus	bus	Bus idx of the generators	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
LP_y	y_{LP}	State	State in lag transfer function		v_str
VR_y	y_{VR}	State	State in lag TF		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
WF_x	x'_{WF}	State	State in washout filter		v_str
INT_y	y_{INT}	State	Integrator output		v_str
omega	ω	ExtState	Generator speed		
v	E_{term}	Algeb	Input to exciter (bus v or Eterm)		v_str
vout	v_{out}	Algeb	Exciter final output voltage		v_str
UEL	U_{EL}	Algeb	Interface var for under exc. limiter		v_str
OEL	O_{EL}	Algeb	Interface var for over exc. limiter		v_str
Vs	V_s	Algeb	Voltage compensation from PSS		v_str
vref	V_{ref}	Algeb	Reference voltage input	*p.u.*	v_str
vi	vi	Algeb	Total voltage input	*pu*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
WF_y	y_{WF}	Algeb	Output of washout filter		v_str
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	saturation output		v_str
VFE	V_{FE}	Algeb	Combined saturation feedback	*p.u.*	v_str
vf	v_f	ExtAlgeb	Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$	ExtAlgeb	Armature excitation current		
a	θ	ExtAlgeb	Bus voltage phase angle		
vbus	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
LP_y	y_{LP}	State	E_{term}
VR_y	y_{VR}	State	$K_A vi$
LL_x	x'_{LL}	State	y_{VR}
WF_x	x'_{WF}	State	y_{LL}
INT_y	y_{INT}	State	v_{f0}
omega	ω	ExtState	
v	E_{term}	Algeb	V
vout	v_{out}	Algeb	$u_e v_{f0}$
UEL	U_{EL}	Algeb	UEL_0
OEL	O_{EL}	Algeb	OEL_0
Vs	V_s	Algeb	0
vref	V_{ref}	Algeb	$E_{term} + \frac{V_{FE}}{K_A}$
vi	vi	Algeb	$u_e \left(-E_{term} + V_{ref}\right)$
LL_y	y_{LL}	Algeb	y_{VR}
WF_y	y_{WF}	Algeb	0
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	$B^q_{SAT} \left(-A^q_{SAT} + y_{INT}\right)^2$ Indicator $\left(y_{INT} > A^q_{SAT}\right)$
VFE	V_{FE}	Algeb	$K_E y_{INT} + V_{out} * S_e(\|V_{out}\|)$
vf	v_f	ExtAlgeb	
XadIfd	$X_{ad} I_{fd}$	ExtAlgeb	
a	θ	ExtAlgeb	
vbus	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LP_y	y_{LP}	State	$E_{term} - y_{LP}$	T_R
VR_y	y_{VR}	State	$K_A vi - y_{VR}$	T_A
LL_x	x'_{LL}	State	$-x'_{LL} + y_{VR}$	T_{F2}
WF_x	x'_{WF}	State	$-x'_{WF} + y_{LL}$	T_{F1}
INT_y	y_{INT}	State	$u_e \left(-V_{FE} + y_{VR}\right)$	T_E
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v	E_{term}	Algeb	$-E_{term} + V$
vout	v_{out}	Algeb	$u_e y_{INT} - v_{out}$
UEL	U_{EL}	Algeb	$UEL_0 - U_{EL}$
OEL	O_{EL}	Algeb	$OEL_0 - O_{EL}$
Vs	V_s	Algeb	$-V_s$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	vi	Algeb	$u_e \left(V_{ref} + V_s - y_{LP} - y_{WF}\right) - vi$
LL_y	y_{LL}	Algeb	$T_{F2} x'_{LL} - T_{F2} y_{LL} + T_{F3} \left(-x'_{LL} + y_{VR}\right) + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
WF_y	y_{WF}	Algeb	$K_F \left(-x'_{WF} + y_{LL}\right) - T_{F1} y_{WF}$
Se	$V_{out} * S_e(\|V_{out}\|)$	Algeb	$u_e \left(B_{SAT}^q z_0^{SL} \left(-A_{SAT}^q + y_{INT}\right)^2 - V_{out} * S_e(\|V_{out}\|)\right)$
VFE	V_{FE}	Algeb	$u_e \left(K_E y_{INT} - V_{FE} + V_{out} * S_e(\|V_{out}\|)\right)$
vf	v_f	ExtAlgeb	$u_e \left(-v_{f0} + v_{out}\right)$
Xadifd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
vbus	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
UEL0	$UEL0$	0	ConstService
OEL0	$OEL0$	0	ConstService
VRMAXu	$VRMAXu$	$V_{Rmax}u_e - 999u_e + 999$	ConstService
VRMINu	$VRMINu$	$V_{Rmin}u_e + 999u_e - 999$	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	$E_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}}$ $\left(\text{Indicator}\left(SE_{SAT}^{2c} > 0\right) + \text{Indicator}\left(SE_{SAT}^{2c} <\right.\right.$	ConstService
SAT_A	A_{SAT}^{q}	$E_{SAT}^{2c} - \frac{E_{SAT}^{1c} - E_{SAT}^{2c}}{a_{SAT} - 1}$	ConstService
SAT_B	B_{SAT}^{q}	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 (\text{Indicator}\,(a_{SAT} > 0) + \text{Indicator}\,(a_{SAT} < 0))}{\left(E_{SAT}^{1c} - E_{SAT}^{2c}\right)^2}$	ConstService
vref0	V_{ref0}	V_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
VR_lim	lim_{VR}	AntiWindup	Limiter in Lag
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
LP	LP	Lag	Voltage transducer
VR	VR	LagAntiWindup	
LL	LL	LeadLag	
WF	WF	Washout	
SAT	SAT	ExcQuadSat	Field voltage saturation
INT	INT	Integrator	V_E, integrator

Config Fields in [ESAC5A]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.13 Experimental

Experimental group

Common Parameters: u, name

5.14 FreqMeasurement

Frequency measurements.

Common Parameters: u, name

Common Variables: f

Available models: *BusFreq*, *BusROCOF*

5.14.1 BusFreq

Bus frequency measurement. Outputs frequency in per unit value.

The bus frequency output variable is f. The frequency deviation variable is *WO_y*.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx			mandatory
Tf	T_f	input digital filter time const	0.020	*sec*	
Tw	T_w	washout time const	0.020	*sec*	
fn	f_n	nominal frequency	60	*Hz*	

Variables

Name	Symbol	Type	Description	Unit	Properties
L_y	y_L	State	State in lag transfer function		v_str
WO_x	x'_{WO}	State	State in washout filter		v_str
WO_y	y_{WO}	Algeb	frequency deviation	*p.u. (Hz)*	v_str
f	f	Algeb	frequency output	*p.u. (Hz)*	v_str
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
L_y	y_L	State	$\theta - \theta_0$
WO_x	x'_{WO}	State	y_L
WO_y	y_{WO}	Algeb	0
f	f	Algeb	1
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
L_y	y_L	State	$\theta - \theta_0 - y_L$	T_f
WO_x	x'_{WO}	State	$-x'_{WO} + y_L$	T_w

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
WO_y	y_{WO}	Algeb	$1/\omega_n \left(-x'_{WO} + y_L\right) - T_w y_{WO}$
f	f	Algeb	$-f + y_{WO} + 1$
a	θ	ExtAlgeb	0
v	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
iwn	$1/\omega_n$	$\frac{u}{2\pi f_n}$	ConstService

Blocks

Name	Symbol	Type	Info
L	L	Lag	digital filter
WO	WO	Washout	angle washout

Config Fields in [BusFreq]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.14.2 BusROCOF

Bus frequency and ROCOF measurement.

The ROCOF output variable is `Wf_y`.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx			mandatory
Tf	T_f	input digital filter time const	0.020	*sec*	
Tw	T_w	washout time const	0.020	*sec*	
fn	f_n	nominal frequency	60	*Hz*	
Tr	T_r	frequency washout time constant	0.100		

Variables

Name	Symbol	Type	Description	Unit	Properties
L_y	y_L	State	State in lag transfer function		v_str
WO_x	x'_{WO}	State	State in washout filter		v_str
Wf_x	x'_{Wf}	State	State in washout filter		v_str
WO_y	y_{WO}	Algeb	frequency deviation	*p.u. (Hz)*	v_str
f	f	Algeb	frequency output	*p.u. (Hz)*	v_str
Wf_y	y_{Wf}	Algeb	Output of washout filter		v_str
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
L_y	y_L	State	$\theta - \theta_0$
WO_x	x'_{WO}	State	y_L
Wf_x	x'_{Wf}	State	f
WO_y	y_{WO}	Algeb	0
f	f	Algeb	1
Wf_y	y_{Wf}	Algeb	0
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
L_y	y_L	State	$\theta - \theta_0 - y_L$	T_f
WO_x	x'_{WO}	State	$-x'_{WO} + y_L$	T_w
Wf_x	x'_{Wf}	State	$f - x'_{Wf}$	T_r

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
WO_y	y_{WO}	Algeb	$1/\omega_n \left(-x'_{WO} + y_L\right) - T_w y_{WO}$
f	f	Algeb	$-f + y_{WO} + 1$
Wf_y	y_{Wf}	Algeb	$-T_r y_{Wf} + f - x'_{Wf}$
a	θ	ExtAlgeb	0
v	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
iwn	$1/\omega_n$	$\frac{u}{2\pi f_n}$	ConstService

Blocks

Name	Symbol	Type	Info
L	L	Lag	digital filter
WO	WO	Washout	angle washout
Wf	Wf	Washout	frequency washout yielding ROCOF

Config Fields in [BusROCOF]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.15 Information

Group for information container models.

Available models: *Summary*

5.15.1 Summary

Class for storing system summary. Can be used for random information or notes.

Parameters

Name	Symbol	Description	Default	Unit	Properties
field		field name			
comment		information, comment, or anything			
comment2		comment field 2			
comment3		comment field 3			
comment4		comment field 4			

Config Fields in [Summary]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.16 Interface

Group for interface models.

Available models: *Fortescue*

5.16.1 Fortescue

Fortescue's symmetric component interface.

This model interfaces a positive-sequence, single-phase-equivalent bus with three buses representing three phases. It is effectively a transformer with one terminal on the primary side and three on the secondary. Only the positive sequence component on the secondary winding is used for simulation.

The positive-sequence voltage magnitude and angle of the secondary winding are named `vp` and `ap`.

The negative and zero sequence variables given in the d- and q-axis due the angle being undefined when the voltage is zero. The negative sequence voltages are `vnd` and `vnq` for the d- anx q-axis, respectively. Likewise, the zero-sequence voltages are `vzd` and `vzq`.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx for the single-phase equivalent			mandatory
busa		bus idx for phase a			mandatory
busb		bus idx for phase b			mandatory
busc		bus idx for phase c			mandatory
Sn	S_n	Power rating	100	*MW*	non_zero
r	r	resistance	0.001	*p.u.*	z
x	x	short-circuit reactance	0.025	*p.u.*	non_zero,z
g		iron loss	0	*p.u.*	y
b		magnetizing susceptance	0.005	*p.u.*	y

Variables

Name	Symbol	Type	Description	Unit	Properties
vp	V_p	Algeb	positive sequence voltage magnitude		v_str
ap	θ_p	Algeb	positive sequence voltage phase		v_str
vnd	V_{nd}	Algeb	negative sequence voltage on d-axis (cos)		v_str
vnq	V_{nq}	Algeb	negative sequence voltage on q-axis (sin)		v_str
vzd	V_{zd}	Algeb	zero sequence voltage on d-axis (cos)		v_str
vzq	V_{zq}	Algeb	zero sequence voltage on q-axis (sin)		v_str
a	θ_1	ExtAlgeb	phase angle of single-phase eq. bus		
aa	θ_a	ExtAlgeb	phase angle of bus for phase a		
ab	θ_b	ExtAlgeb	phase angle of bus for phase b		
ac	θ_c	ExtAlgeb	phase angle of bus for phase c		
v	V_1	ExtAlgeb	voltage of single-phase eq. bus		
va	V_a	ExtAlgeb	voltage of bus for phase a		
vb	V_b	ExtAlgeb	voltage of bus for phase b		
vc	V_c	ExtAlgeb	voltage of bus for phase c		

Initialization Equations

Name	Symbol	Type	Initial Value
vp	V_p	Algeb	$\frac{V_a}{3} + \frac{V_b}{3} + \frac{V_c}{3}$
ap	θ_p	Algeb	$\theta_a + \theta_b + \theta_c$
vnd	V_{nd}	Algeb	0.0
vnq	V_{nq}	Algeb	0.0
vzd	V_{zd}	Algeb	0.0
vzq	V_{zq}	Algeb	0.0
a	θ_1	ExtAlgeb	
aa	θ_a	ExtAlgeb	
ab	θ_b	ExtAlgeb	
ac	θ_c	ExtAlgeb	
v	V_1	ExtAlgeb	
va	V_a	ExtAlgeb	
vb	V_b	ExtAlgeb	
vc	V_c	ExtAlgeb	

Algebraic Equations

Nam	Sym-bol	Type	RHS of Equation "0 = g(x, y)"
vp	V_p	Algeb	$-V_p+\frac{\sqrt{(V_b \sin(120^o-\theta_a+\theta_b)-V_c \sin(120^o+\theta_a-\theta_c))^2+(V_a+V_b \cos(120^o-\theta_a+\theta_b)+V_c \cos(120^o+\theta_a-\theta_c))^2}}{3}$
ap	θ_p	Algeb	$\theta_a-\theta_p+\text{atan}_2\left(V_b \sin(120^o-\theta_a+\theta_b)-V_c \sin(120^o+\theta_a-\theta_c), V_a+V_b \cos(120^o-\theta_a+\theta_b)+\right.$
vnd	V_{nd}	Algeb	$V_a \cos(\theta_a)+V_b \cos(120^o-\theta_b)+V_c \cos(120^o+\theta_c)-V_{nd}$
vnq	V_{nq}	Algeb	$V_a \sin(\theta_a)-V_b \sin(120^o-\theta_b)+V_c \sin(120^o+\theta_c)-V_{nq}$
vzd	V_{zd}	Algeb	$V_a \cos(\theta_a)+V_b \cos(\theta_b)+V_c \cos(\theta_c)-V_{zd}$
vzq	V_{zq}	Algeb	$V_a \sin(\theta_a)+V_b \sin(\theta_b)+V_c \sin(\theta_c)-V_{zq}$
a	θ_1	ExtAlgeb	$u\left(V_1^2(g+g_{hk})-V_1V_p(b_{hk} \sin(\theta_1-\theta_p)+g_{hk} \cos(\theta_1-\theta_p))\right)$
aa	θ_a	ExtAlgeb	$\frac{u\left(-V_1V_a(-b_{hk} \sin(\theta_1-\theta_a)+g_{hk} \cos(\theta_1-\theta_a))+V_a^2(g+g_{hk})\right)}{3}$
ab	θ_b	ExtAlgeb	$\frac{u\left(-V_1V_b(b_{hk} \sin(120^o-\theta_1+\theta_b)+g_{hk} \cos(120^o-\theta_1+\theta_b))+V_b^2(g+g_{hk})\right)}{3}$
ac	θ_c	ExtAlgeb	$\frac{u\left(-V_1V_c(-b_{hk} \sin(120^o+\theta_1-\theta_c)+g_{hk} \cos(120^o+\theta_1-\theta_c))+V_c^2(g+g_{hk})\right)}{3}$
v	V_1	ExtAlgeb	$u\left(-V_1^2(b+b_{hk})-V_1V_p(-b_{hk} \cos(\theta_1-\theta_p)+g_{hk} \sin(\theta_1-\theta_p))\right)$
va	V_a	ExtAlgeb	$\frac{u\left(V_1V_a(b_{hk} \cos(\theta_1-\theta_a)+g_{hk} \sin(\theta_1-\theta_a))-V_a^2(b+b_{hk})\right)}{3}$
vb	V_b	ExtAlgeb	$\frac{u\left(V_1V_b(b_{hk} \cos(120^o-\theta_1+\theta_b)-g_{hk} \sin(120^o-\theta_1+\theta_b))-V_b^2(b+b_{hk})\right)}{3}$
vc	V_c	ExtAlgeb	$\frac{u\left(V_1V_c(b_{hk} \cos(120^o+\theta_1-\theta_c)+g_{hk} \sin(120^o+\theta_1-\theta_c))-V_c^2(b+b_{hk})\right)}{3}$

Services

Name	Symbol	Equation	Type
yhk	y_{hk}	$\frac{u}{r+ix}$	ConstService
ghk	g_{hk}	re (y_{hk})	ConstService
bhk	b_{hk}	im (y_{hk})	ConstService
d120	120^o	$\frac{2\pi}{3}$	ConstService

Config Fields in [Fortescue]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.17 Motor

Induction Motor group

Common Parameters: u, name

Available models: *Motor3*, *Motor5*

5.17.1 Motor3

Third-order induction motor model.

See "Power System Modelling and Scripting" by F. Milano.

To simulate motor startup, set the motor status `u` to `0` and use a `Toggle` to control the model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
Sn	S_n	Power rating	100		
Vn	V_n	AC voltage rating	110		
fn	f	rated frequency	60		
rs	r_s	rotor resistance	0.010		non_zero,z
xs	x_s	rotor reactance	0.150		non_zero,z
rr1	r_{R1}	1st cage rotor resistance	0.050		non_zero,z
xr1	x_{R1}	1st cage rotor reactance	0.150		non_zero,z
rr2	r_{R2}	2st cage rotor resistance	0.001		non_zero,z
xr2	x_{R2}	2st cage rotor reactance	0.040		non_zero,z
xm	x_m	magnetization reactance	5		non_zero,z
Hm	H_m	Inertia constant	3	*kWs/KVA*	power
c1	c_1	1st coeff. of Tm(w)	0.100		
c2	c_2	2nd coeff. of Tm(w)	0.020		
c3	c_3	3rd coeff. of Tm(w)	0.020		
zb	z_b	Allow working as brake	1		

Variables

Name	Symbol	Type	Description	Unit	Properties
slip	σ	State			v_str
e1d	e'_d	State	real part of 1st cage voltage		v_str
e1q	e'_q	State	imaginary part of 1st cage voltage		v_str
vd	V_d	Algeb	d-axis voltage		
vq	V_q	Algeb	q-axis voltage		
p	P	Algeb			v_str
q	Q	Algeb			v_str
Id	I_d	Algeb			v_str
Iq	I_q	Algeb			
te	τ_e	Algeb			v_str
tm	τ_m	Algeb			v_str
a	θ	ExtAlgeb	Bus voltage phase angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
slip	σ	State	$1.0u$
e1d	e'_d	State	$0.05u$
e1q	e'_q	State	$0.9u$
vd	V_d	Algeb	
vq	V_q	Algeb	
p	P	Algeb	$u\left(I_d V_d + I_q V_q\right)$
q	Q	Algeb	$u\left(I_d V_q - I_q V_d\right)$
Id	I_d	Algeb	1
Iq	I_q	Algeb	
te	τ_e	Algeb	$u\left(I_d e'_d + I_q e'_q\right)$
tm	τ_m	Algeb	$u\left(\alpha + \beta\sigma + \sigma^2 c_2\right)$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
slip	σ	State	$u\left(-\tau_e + \tau_m\right)$	M
e1d	e'_d	State	$u\left(\omega_b \sigma e'_q - \frac{I_q(-x'+x_0)+e'_d}{T'_0}\right)$	
e1q	e'_q	State	$u\left(-\omega_b \sigma e'_d - \frac{-I_d(-x'+x_0)+e'_q}{T'_0}\right)$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vd	V_d	Algeb	$-V u \sin\left(\theta\right) - V_d$
vq	V_q	Algeb	$V u \cos\left(\theta\right) - V_q$
p	P	Algeb	$-P + u\left(I_d V_d + I_q V_q\right)$
q	Q	Algeb	$-Q + u\left(I_d V_q - I_q V_d\right)$
Id	I_d	Algeb	$u\left(-I_d r_s + I_q x' + V_d - e'_d\right)$
Iq	I_q	Algeb	$u\left(-I_d x' - I_q r_s + V_q - e'_q\right)$
te	τ_e	Algeb	$-\tau_e + u\left(I_d e'_d + I_q e'_q\right)$
tm	τ_m	Algeb	$-\tau_m + u\left(\alpha + \beta\sigma + \sigma^2 c_2\right)$
a	θ	ExtAlgeb	P
v	V	ExtAlgeb	Q

Services

Name	Symbol	Equation	Type
wb	ω_b	$2\pi f$	ConstService
x0	x_0	$x_m + x_s$	ConstService
x1	x'	$\frac{x_m x_{R1}}{x_m + x_{R1}} + x_s$	ConstService
T10	T'_0	$\frac{x_m + x_{R1}}{\omega_b r_{R1}}$	ConstService
M	M	$2H_m$	ConstService
aa	α	$c_1 + c_2 + c_3$	ConstService
bb	β	$-c_2 - 2c_3$	ConstService

Config Fields in [Motor3]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.17.2 Motor5

Fifth-order induction motor model.

See "Power System Modelling and Scripting" by F. Milano.

To simulate motor startup, set the motor status `u` to `0` and use a `Toggle` to control the model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
Sn	S_n	Power rating	100		
Vn	V_n	AC voltage rating	110		
fn	f	rated frequency	60		
rs	r_s	rotor resistance	0.010		non_zero,z
xs	x_s	rotor reactance	0.150		non_zero,z
rr1	r_{R1}	1st cage rotor resistance	0.050		non_zero,z
xr1	x_{R1}	1st cage rotor reactance	0.150		non_zero,z
rr2	r_{R2}	2st cage rotor resistance	0.001		non_zero,z
xr2	x_{R2}	2st cage rotor reactance	0.040		non_zero,z
xm	x_m	magnetization reactance	5		non_zero,z
Hm	H_m	Inertia constant	3	*kWs/KVA*	power
c1	c_1	1st coeff. of Tm(w)	0.100		
c2	c_2	2nd coeff. of Tm(w)	0.020		
c3	c_3	3rd coeff. of Tm(w)	0.020		
zb	z_b	Allow working as brake	1		

Variables

Name	Symbol	Type	Description	Unit	Properties
slip	σ	State			v_str
e1d	e'_d	State	real part of 1st cage voltage		v_str
e1q	e'_q	State	imaginary part of 1st cage voltage		v_str
e2d	e''_d	State	real part of 2nd cage voltage		v_str
e2q	e''_q	State	imag part of 2nd cage voltage		v_str
vd	V_d	Algeb	d-axis voltage		
vq	V_q	Algeb	q-axis voltage		
p	P	Algeb			v_str
q	Q	Algeb			v_str
Id	I_d	Algeb			v_str
Iq	I_q	Algeb			v_str
te	τ_e	Algeb			v_str
tm	τ_m	Algeb			v_str
a	θ	ExtAlgeb	Bus voltage phase angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
slip	σ	State	$1.0u$
e1d	e'_d	State	$0.05u$
e1q	e'_q	State	$0.9u$
e2d	e''_d	State	$0.05u$
e2q	e''_q	State	$0.9u$
vd	V_d	Algeb	
vq	V_q	Algeb	
p	P	Algeb	$u\left(I_d V_d + I_q V_q\right)$
q	Q	Algeb	$u\left(I_d V_q - I_q V_d\right)$
Id	I_d	Algeb	$0.9u$
Iq	I_q	Algeb	$0.1u$
te	τ_e	Algeb	$u\left(I_d e''_d + I_q e''_q\right)$
tm	τ_m	Algeb	$u\left(\alpha + \beta\sigma + \sigma^2 c_2\right)$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
slip	σ	State	$u\left(-\tau_e + \tau_m\right)$	M
e1d	e'_d	State	$u\left(\omega_b \sigma e'_q - \frac{I_q(-x'+x_0)+e'_d}{T'_0}\right)$	
e1q	e'_q	State	$u\left(-\omega_b \sigma e'_d - \frac{-I_d(-x'+x_0)+e'_q}{T'_0}\right)$	
e2d	e''_d	State	$u\left(\omega_b \sigma e'_q - \omega_b \sigma\left(-e''_q + e'_q\right) - \frac{I_q(-x'+x_0)+e'_d}{T'_0} + \frac{-I_q(x'-x'')-e''_d+e'_d}{T''_0}\right)$	
e2q	e''_q	State	$u\left(-\omega_b \sigma e'_d + \omega_b \sigma\left(-e''_d + e'_d\right) - \frac{-I_d(-x'+x_0)+e'_q}{T'_0} + \frac{I_d(x'-x'')-e''_q+e'_q}{T''_0}\right)$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vd	V_d	Algeb	$-Vu\sin(\theta) - V_d$
vq	V_q	Algeb	$Vu\cos(\theta) - V_q$
p	P	Algeb	$-P + u\left(I_d V_d + I_q V_q\right)$
q	Q	Algeb	$-Q + u\left(I_d V_q - I_q V_d\right)$
Id	I_d	Algeb	$u\left(-I_d r_s + I_q x'' + V_d - e''_d\right)$
Iq	I_q	Algeb	$u\left(-I_d x'' - I_q r_s + V_q - e''_q\right)$
te	τ_e	Algeb	$-\tau_e + u\left(I_d e''_d + I_q e''_q\right)$
tm	τ_m	Algeb	$-\tau_m + u\left(\alpha + \beta\sigma + \sigma^2 c_2\right)$
a	θ	ExtAlgeb	P
v	V	ExtAlgeb	Q

Services

Name	Symbol	Equation	Type
wb	ω_b	$2\pi f$	ConstService
x0	x_0	$x_m + x_s$	ConstService
x1	x'	$\frac{x_m x_{R1}}{x_m + x_{R1}} + x_s$	ConstService
T10	T'_0	$\frac{x_m + x_{R1}}{\omega_b r_{R1}}$	ConstService
M	M	$2H_m$	ConstService
aa	α	$c_1 + c_2 + c_3$	ConstService
bb	β	$-c_2 - 2c_3$	ConstService
x2	x''	$\frac{x_m x_{R1} x_{R2}}{x_m x_{R1} + x_m x_{R2} + x_{R1} x_{R2}} + x_s$	ConstService
T20	T''_0	$\frac{\frac{x_m x_{R1}}{x_m + x_{R1}} + x_{R2}}{\omega_b r_{R2}}$	ConstService

Config Fields in [Motor5]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.18 OutputSelect

Group for selecting outputs.

Available models: *Output*

5.18.1 Output

Model for specifying output models and/or variables.

Parameters

Name	Symbol	Description	Default	Unit	Properties
model		Name of the model			mandatory
varname		Variable name			
dev		Device name			

Config Fields in [Output]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.19 PLL

Phase-locked loop models.

Common Parameters: u, name

Common Variables: am

Available models: *PLL1*, *PLL2*

5.19.1 PLL1

Simple Phasor Lock Loop (PLL) using one PI controller. The PI controller minimizes the error between the input and output angle.

Input bus angle signal -> Lag filter 1 with Tf -> Output angle *af_y*.

(af_y - am) -> PI Controller (Kp, Ki) -> PI_y

Estimated angle ae = (2 * pi * fn * PI_y) -> Lag filter 2 with Tp -> am.

The output signal is `am`, a state variable.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx			mandatory
fn	f_n	nominal frequency	60	*Hz*	
Kp	K_p	proportional gain	0.100		
Ki	K_i	integral gain	0.100		
Tf	T_f	input digital filter time const	0.050	*sec*	
Tp	T_p	output filter time const.	0.050	*sec*	

Variables

Name	Symbol	Type	Description	Unit	Properties
af_y	y_{af}	State	State in lag transfer function		v_str
PI_xi	xi_{PI}	State	Integrator output		v_str
ae	θ_{est}	State	PLL angle output before filter		v_str
am	θ_m	State	PLL output angle after filtering		v_str
PI_y	y_{PI}	Algeb	PI output		v_str
a	θ	ExtAlgeb	Bus voltage angle		

Initialization Equations

Name	Symbol	Type	Initial Value
af_y	y_{af}	State	θ
PI_xi	xi_{PI}	State	0.0
ae	θ_{est}	State	θ
am	θ_m	State	θ
PI_y	y_{PI}	Algeb	$K_p u \left(-\theta_m + y_{af}\right)$
a	θ	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
af_y	y_{af}	State	$\theta - y_{af}$	T_f
PI_xi	xi_{PI}	State	$K_i u \left(-\theta_m + y_{af}\right)$	
ae	θ_{est}	State	$2\pi f_n y_{PI}$	
am	θ_m	State	$\theta_{est} - \theta_m$	T_p

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
PI_y	y_{PI}	Algeb	$K_p u \left(-\theta_m + y_{af}\right) + xi_{PI} - y_{PI}$
a	θ	ExtAlgeb	0

Blocks

Name	Symbol	Type	Info
af	af	Lag	input angle signal filter
PI	PI	PIController	PI controller

Config Fields in [PLL1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.19.2 PLL2

Synchronously-rotating Reference Frame (SRF) Phasor Lock Loop (PLL).

The PLL minimizes `vq = v sin(a - am)` using a PI controller.

The output signal is `am`, a state variable.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx			mandatory
fn	f_n	nominal frequency	60	*Hz*	
Kp	K_p	proportional gain	0.100		
Ki	K_i	integral gain	0.100		

Variables

Name	Symbol	Type	Description	Unit	Properties
PI_xi	xi_{PI}	State	Integrator output		v_str
am	θ_m	State	PLL angle output		v_str
PI_y	y_{PI}	Algeb	PI output		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
PI_xi	xi_{PI}	State	0
am	θ_m	State	θ
PI_y	y_{PI}	Algeb	$K_p V \sin\left(\theta - \theta_m\right)$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
PI_xi	xi_{PI}	State	$K_i V \sin(\theta - \theta_m)$	
am	θ_m	State	$2\pi f_n y_{PI}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
PI_y	y_{PI}	Algeb	$K_p V \sin(\theta - \theta_m) + xi_{PI} - y_{PI}$
a	θ	ExtAlgeb	0
v	V	ExtAlgeb	0

Blocks

Name	Symbol	Type	Info
PI	PI	PIController	

Config Fields in [PLL2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.20 PSS

Power system stabilizer group.

Common Parameters: u, name

Common Variables: vsout

Available models: *IEEEST*, *ST2CUT*

5.20.1 IEEEST

IEEEST stabilizer model. Automatically adds frequency measurement devices if not provided.

Input signals (MODE):

1. Rotor speed deviation (p.u.),
2. Bus frequency deviation (p.u.) (*),
3. Generator P electrical in Gen MVABase (p.u.),
4. Generator accelerating power (p.u.),
5. Bus voltage (p.u.),
6. Derivative of p.u. bus voltage.

(*) Due to the frequency measurement implementation difference, mode 2 is likely to yield different results across software.

Note: Blocks are named *F1*, *F2*, *LL1*, *LL2* and *WO* in sequence. Two limiters are named *VLIM* and *OLIM* in sequence.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
avr		Exciter idx			mandatory
MODE		Input signal			mandatory
busr		Optional remote bus idx			
busf		BusFreq idx for mode 2			
A1	A_1	filter time const. (pole)	1		
A2	A_2	filter time const. (pole)	1		
A3	A_3	filter time const. (pole)	1		
A4	A_4	filter time const. (pole)	1		
A5	A_5	filter time const. (zero)	1		
A6	A_6	filter time const. (zero)	1		
T1	T_1	first leadlag time const. (zero)	1		
T2	T_2	first leadlag time const. (pole)	1		
T3	T_3	second leadlag time const. (pole)	1		
T4	T_4	second leadlag time const. (pole)	1		
T5	T_5	washout time const. (zero)	1		
T6	T_6	washout time const. (pole)	1		
KS	K_S	Gain before washout	1		
LSMAX	L_{SMAX}	Max. output limit	0.300		
LSMIN	L_{SMIN}	Min. output limit	-0.300		
VCU	V_{CU}	Upper enabling bus voltage	999	*p.u.*	
VCL	V_{CL}	Upper enabling bus voltage	-999	*p.u.*	
syn		Retrieved generator idx	0		
bus		Retrieved bus idx			
Sn	S_n	Generator power base	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
F1_x	x'_{F1}	State	State in 2nd order LPF		v_str
F1_y	y_{F1}	State	Output of 2nd order LPF		v_str
F2_x1	x'_{F2}	State	State #1 in 2nd order lead-lag		v_str
F2_x2	x''_{F2}	State	State #2 in 2nd order lead-lag		v_str
LL1_x	x'_{LL1}	State	State in lead-lag		v_str
LL2_x	x'_{LL2}	State	State in lead-lag		v_str
WO_x	x'_{WO}	State	State in washout filter		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
vsout	v_{sout}	Algeb	PSS output voltage to exciter		
sig	S_{ig}	Algeb	Input signal		v_str
F2_y	y_{F2}	Algeb	Output of 2nd order lead-lag		v_str
LL1_y	y_{LL1}	Algeb	Output of lead-lag		v_str
LL2_y	y_{LL2}	Algeb	Output of lead-lag		v_str
Vks_y	y_{Vks}	Algeb	Gain output		v_str
WO_y	y_{WO}	Algeb	Output of washout filter		v_str
Vss	V_{ss}	Algeb	Voltage output before output limiter		
tm	τ_m	ExtAlgeb	Generator mechanical input		
te	τ_e	ExtAlgeb	Generator electrical output		
v	V	ExtAlgeb	Bus (or busr, if given) terminal voltage		
f	f	ExtAlgeb	Bus frequency		
vi	v_i	ExtAlgeb	Exciter input voltage		

Initialization Equations

Name	Symbol	Type	Initial Value
F1_x	x'_{F1}	State	0
F1_y	y_{F1}	State	S_{ig}
F2_x1	x'_{F2}	State	0
F2_x2	x''_{F2}	State	y_{F1}
LL1_x	x'_{LL1}	State	y_{F2}
LL2_x	x'_{LL2}	State	y_{LL1}
WO_x	x'_{WO}	State	y_{Vks}
omega	ω	ExtState	
vsout	v_{sout}	Algeb	
sig	S_{ig}	Algeb	$u_e \left(V s_5^{SW} + s_1^{SW} \left(\omega - 1 \right) + s_4^{SW} \left(\tau_m - \tau_{m0} \right) + \frac{\tau_{m0} s_3^{SW}}{(Sb/Sn)} \right)$
F2_y	y_{F2}	Algeb	y_{F1}
LL1_y	y_{LL1}	Algeb	y_{F2}
LL2_y	y_{LL2}	Algeb	y_{LL1}
Vks_y	y_{Vks}	Algeb	$K_S y_{LL2}$
WO_y	y_{WO}	Algeb	$x'_{WO} z_1^{LT_{WO}}$
Vss	V_{ss}	Algeb	
tm	τ_m	ExtAlgeb	
te	τ_e	ExtAlgeb	
v	V	ExtAlgeb	
f	f	ExtAlgeb	
vi	v_i	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
F1_x	x'_{F1}	State	$-A_1 x'_{F1} + S_{ig} - y_{F1}$	A_2
F1_y	y_{F1}	State	x'_{F1}	
F2_x1	x'_{F2}	State	$-A_3 x'_{F2} - x''_{F2} + y_{F1}$	A_4
F2_x2	x''_{F2}	State	x'_{F2}	
LL1_x	x'_{LL1}	State	$-x'_{LL1} + y_{F2}$	T_2
LL2_x	x'_{LL2}	State	$-x'_{LL2} + y_{LL1}$	T_4
WO_x	x'_{WO}	State	$-x'_{WO} + y_{Vks}$	T_6
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vsout	v_{sout}	Algeb	$V_{ss}u_e z_i^{OLIM} - v_{sout}$
sig	S_{ig}	Algeb	$-S_{ig}+u_e\left(Vs_5^{SW}+s_1^{SW}(\omega-1)+s_2^{SW}(f-1)+s_4^{SW}(\tau_m-\tau_{m0})+s_6^{SW}v^{dV/dt}+\frac{\tau_e s_3^{SW}}{(Sb/Sn)}\right.$
F2_y	y_{F2}	Algeb	$A_4A_5x'_{F2} + A_4x''_{F2} - A_4y_{F2} + A_6(-A_3x'_{F2} - x''_{F2} + y_{F1}) + \left(z_1^{LT_{F2}}\right)^4(-x''_{F2}+y_{F2})$
LL1_y	y_{LL1}	Algeb	$T_1(-x'_{LL1}+y_{F2})+T_2x'_{LL1}-T_2y_{LL1}+\left(z_1^{LT_{LL1}}\right)^2(-x'_{LL1}+y_{LL1})$
LL2_y	y_{LL2}	Algeb	$T_3(-x'_{LL2}+y_{LL1})+T_4x'_{LL2}-T_4y_{LL2}+\left(z_1^{LT_{LL2}}\right)^2(-x'_{LL2}+y_{LL2})$
Vks_y	y_{Vks}	Algeb	$K_S y_{LL2} - y_{Vks}$
WO_y	y_{WO}	Algeb	$T_5 z_0^{LT_{WO}}(-x'_{WO}+y_{Vks})+T_6x'_{WO}z_1^{LT_{WO}}-T_6y_{WO}$
Vss	V_{ss}	Algeb	$L_{SMAX}z_u^{VLIM}+L_{SMIN}z_l^{VLIM}-V_{ss}+y_{WO}z_i^{VLIM}$
tm	τ_m	ExtAlgeb	0
te	τ_e	ExtAlgeb	0
v	V	ExtAlgeb	0
f	f	ExtAlgeb	0
vi	v_i	ExtAlgeb	$u_e v_{sout}$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_{ee}	ConstService

Discretes

Name	Symbol	Type	Info
dv	dV/dt	Derivative	Finite difference of bus voltage
SW	SW	Switcher	
F2_LT1	LT_{F2}	LessThan	
F2_LT2	LT_{F2}	LessThan	
F2_LT3	LT_{F2}	LessThan	
F2_LT4	LT_{F2}	LessThan	
LL1_LT1	LT_{LL1}	LessThan	
LL1_LT2	LT_{LL1}	LessThan	
LL2_LT1	LT_{LL2}	LessThan	
LL2_LT2	LT_{LL2}	LessThan	
WO_LT	LT_{WO}	LessThan	
VLIM	$VLIM$	Limiter	Vss limiter
OLIM	$OLIM$	Limiter	output limiter

Blocks

Name	Symbol	Type	Info
F1	$F1$	Lag2ndOrd	
F2	$F2$	LeadLag2ndOrd	
LL1	$LL1$	LeadLag	
LL2	$LL2$	LeadLag	
Vks	Vks	Gain	
WO	WO	WashoutOrLag	

Config Fields in [IEEEST]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
freq_model		BusFreq	default freq. measurement model	('BusFreq',)

5.20.2 ST2CUT

ST2CUT stabilizer model. Automatically adds frequency measurement devices if not provided.

Input signals (MODE and MODE2):

0 - Disable input signal 1 (s1) - Rotor speed deviation (p.u.), 2 (s2) - Bus frequency deviation (*) (p.u.), 3 (s3) - Generator P electrical in Gen MVABase (p.u.), 4 (s4) - Generator accelerating power (p.u.), 5 (s5) - Bus voltage (p.u.), 6 (s6) - Derivative of p.u. bus voltage.

(*) Due to the frequency measurement implementation difference, mode 2 is likely to yield different results across software.

Blocks are named *LL1*, *LL2*, *LL3*, *LL4* in sequence. Two limiters are named *VSS_lim* and *OLIM* in sequence.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
avr		Exciter idx			mandatory
MODE		Input signal 1			mandatory
busr		Remote bus 1			
busf		BusFreq idx for signal 1 mode 2			
MODE2		Input signal 2			
busr2		Remote bus 2			
busf2		BusFreq idx for signal 2 mode 2			
K1	K_1	Transducer 1 gain	1		
K2	K_2	Transducer 2 gain	1		
T1	T_1	Transducer 1 time const.	1		
T2	T_2	Transducer 2 time const.	1		
T3	T_3	Washout int. time const.	1		
T4	T_4	Washout delay time const.	0.200		
T5	T_5	Leadlag 1 time const. (1)	1		
T6	T_6	Leadlag 1 time const. (2)	0.500		
T7	T_7	Leadlag 2 time const. (1)	1		
T8	T_8	Leadlag 2 time const. (2)	1		
T9	T_9	Leadlag 3 time const. (1)	1		
T10	T_{10}	Leadlag 3 time const. (2)	0.200		
LSMAX	L_{SMAX}	Max. output limit	0.300		
LSMIN	L_{SMIN}	Min. output limit	-0.300		
VCU	V_{CU}	Upper enabling bus voltage	999	*p.u.*	
VCL	V_{CL}	Upper enabling bus voltage	-999	*p.u.*	
syn		Retrieved generator idx	0		
bus		Retrieved bus idx			
Sn	S_n	Generator power base	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
L1_y	y_{L1}	State	State in lag transfer function		v_str
L2_y	y_{L2}	State	State in lag transfer function		v_str
WO_x	x'_{WO}	State	State in washout filter		v_str
LL1_x	x'_{LL1}	State	State in lead-lag		v_str
LL2_x	x'_{LL2}	State	State in lead-lag		v_str
LL3_x	x'_{LL3}	State	State in lead-lag		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
vsout	v_{sout}	Algeb	PSS output voltage to exciter		
sig	S_{ig}	Algeb	Input signal		v_str
sig2	S_{ig2}	Algeb	Input signal 2		v_str
IN	I_N	Algeb	Sum of inputs		v_str
WO_y	y_{WO}	Algeb	Output of washout filter		v_str
LL1_y	y_{LL1}	Algeb	Output of lead-lag		v_str
LL2_y	y_{LL2}	Algeb	Output of lead-lag		v_str
LL3_y	y_{LL3}	Algeb	Output of lead-lag		v_str
VSS_x	x_{VSS}	Algeb	Value before limiter		v_str
VSS_y	y_{VSS}	Algeb	Output after limiter and post gain		v_str
tm	τ_m	ExtAlgeb	Generator mechanical input		
te	τ_e	ExtAlgeb	Generator electrical output		
v	V	ExtAlgeb	Bus (or busr, if given) terminal voltage		
f	f	ExtAlgeb	Bus frequency		
vi	v_i	ExtAlgeb	Exciter input voltage		
v2	V	ExtAlgeb	Bus (or busr2, if given) terminal voltage		
f2	f_2	ExtAlgeb	Bus frequency 2		

Initialization Equations

Name	Symbol	Type	Initial Value
L1_y	y_{L1}	State	$K_1 S_{ig}$
L2_y	y_{L2}	State	$K_2 S_{ig2}$
WO_x	x'_{WO}	State	I_N
LL1_x	x'_{LL1}	State	y_{WO}
LL2_x	x'_{LL2}	State	y_{LL1}
LL3_x	x'_{LL3}	State	y_{LL2}
omega	ω	ExtState	
vsout	v_{sout}	Algeb	
sig	S_{ig}	Algeb	$V s_5^{SW} + s_1^{SW}(\omega - 1) + s_4^{SW}(\tau_m - \tau_{m0}) + \frac{\tau_{m0} s_3^{SW}}{(Sb/Sn)}$
sig2	S_{ig2}	Algeb	$V s_5^{SW2} + s_1^{SW2}(\omega - 1) + s_4^{SW2}(\tau_m - \tau_{m0}) + \frac{\tau_{m0} s_3^{SW2}}{(Sb/Sn)}$
IN	I_N	Algeb	$u_e(y_{L1} + y_{L2})$
WO_y	y_{WO}	Algeb	$x'_{WO} z_1^{LT_{WO}}$
LL1_y	y_{LL1}	Algeb	y_{WO}
LL2_y	y_{LL2}	Algeb	y_{LL1}
LL3_y	y_{LL3}	Algeb	y_{LL2}
VSS_x	x_{VSS}	Algeb	y_{LL3}
VSS_y	y_{VSS}	Algeb	$L_{SMAX} z_u^{lim_{VSS}} + L_{SMIN} z_l^{lim_{VSS}} + x_{VSS} z_i^{lim_{VSS}}$
tm	τ_m	ExtAlgeb	
te	τ_e	ExtAlgeb	
v	V	ExtAlgeb	
f	f	ExtAlgeb	
vi	v_i	ExtAlgeb	
v2	V	ExtAlgeb	
f2	f_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
L1_y	y_{L1}	State	$K_1 S_{ig} - y_{L1}$	T_1
L2_y	y_{L2}	State	$K_2 S_{ig2} - y_{L2}$	T_2
WO_x	x'_{WO}	State	$I_N - x'_{WO}$	T_4
LL1_x	x'_{LL1}	State	$-x'_{LL1} + y_{WO}$	T_6
LL2_x	x'_{LL2}	State	$-x'_{LL2} + y_{LL1}$	T_8
LL3_x	x'_{LL3}	State	$-x'_{LL3} + y_{LL2}$	T_{10}
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vsout	v_{sout}	Algeb	$u_e y_{VSS} z_i^{OLIM} - v_{sout}$
sig	S_{ig}	Algeb	$-S_{ig} + V s_5^{SW} + s_1^{SW}(\omega - 1) + s_2^{SW}(f - 1) + s_4^{SW}(\tau_m - \tau_{m0}) + s_6^{SW} v^{dv} + \frac{\tau_e s_3^{SW}}{(Sb/Sn)}$
sig2	S_{ig2}	Algeb	$-S_{ig2} + V s_5^{SW2} + s_1^{SW2}(\omega - 1) + s_2^{SW2}(f_2 - 1) + s_4^{SW2}(\tau_m - \tau_{m0}) + s_6^{SW2} v^{dv2} + \frac{\tau_e s_3^{SW2}}{(Sb/Sn)}$
IN	I_N	Algeb	$-I_N + u_e(y_{L1} + y_{L2})$
WO_y	y_{WO}	Algeb	$T_3 z_0^{LT_{WO}}(I_N - x'_{WO}) + T_4 x'_{WO} z_1^{LT_{WO}} - T_4 y_{WO}$
LL1_y	y_{LL1}	Algeb	$T_5(-x'_{LL1} + y_{WO}) + T_6 x'_{LL1} - T_6 y_{LL1} + \left(z_1^{LT_{LL1}}\right)^2 (-x'_{LL1} + y_{LL1})$
LL2_y	y_{LL2}	Algeb	$T_7(-x'_{LL2} + y_{LL1}) + T_8 x'_{LL2} - T_8 y_{LL2} + \left(z_1^{LT_{LL2}}\right)^2 (-x'_{LL2} + y_{LL2})$
LL3_y	y_{LL3}	Algeb	$T_9(-x'_{LL3} + y_{LL2}) + T_{10} x'_{LL3} - T_{10} y_{LL3} + \left(z_1^{LT_{LL3}}\right)^2 (-x'_{LL3} + y_{LL3})$
VSS_x	x_{VSS}	Algeb	$-x_{VSS} + y_{LL3}$
VSS_y	y_{VSS}	Algeb	$L_{SMAX} z_u^{lim_{VSS}} + L_{SMIN} z_l^{lim_{VSS}} + x_{VSS} z_i^{lim_{VSS}} - y_{VSS}$
tm	τ_m	ExtAlgeb	0
te	τ_e	ExtAlgeb	0
v	V	ExtAlgeb	0
f	f	ExtAlgeb	0
vi	v_i	ExtAlgeb	$u_e v_{sout}$
v2	V	ExtAlgeb	0
f2	f_2	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
ue	u_e	uu_{ee}	ConstService
VOU	VOU	$VCUr + V_0$	ConstService
VOL	VOL	$VCLr + V_0$	ConstService

Discretes

Name	Symbol	Type	Info
dv	dv	Derivative	
dv2	$dv2$	Derivative	
SW	SW	Switcher	
SW2	$SW2$	Switcher	
WO_LT	LT_{WO}	LessThan	
LL1_LT1	LT_{LL1}	LessThan	
LL1_LT2	LT_{LL1}	LessThan	
LL2_LT1	LT_{LL2}	LessThan	
LL2_LT2	LT_{LL2}	LessThan	
LL3_LT1	LT_{LL3}	LessThan	
LL3_LT2	LT_{LL3}	LessThan	
VSS_lim	lim_{VSS}	HardLimiter	
OLIM	$OLIM$	Limiter	output limiter

Blocks

Name	Symbol	Type	Info
L1	$L1$	Lag	Transducer 1
L2	$L2$	Lag	Transducer 2
WO	WO	WashoutOrLag	
LL1	$LL1$	LeadLag	
LL2	$LL2$	LeadLag	
LL3	$LL3$	LeadLag	
VSS	VSS	GainLimiter	

Config Fields in [ST2CUT]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
freq_model		BusFreq	default freq. measurement model	('BusFreq',)

5.21 PhasorMeasurement

Phasor measurements

Common Parameters: u, name

Common Variables: am, vm

Available models: *PMU*

5.21.1 PMU

Simple phasor measurement unit model.

This model tracks the bus voltage magnitude and phase angle, each using a low-pass filter.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		bus idx			mandatory
Ta	T_a	angle filter time constant	0.100		
Tv	T_v	voltage filter time constant	0.100		

Variables

Name	Symbol	Type	Description	Unit	Properties
am	θ_m	State	phase angle measurement	*rad.*	v_str
vm	V_m	State	voltage magnitude measurement	*p.u.(kV)*	v_str
a	θ	ExtAlgeb	Bus voltage phase angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
am	θ_m	State	θ
vm	V_m	State	V
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
am	θ_m	State	$\theta - \theta_m$	T_a
vm	V_m	State	$V - V_m$	T_v

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	0
v	V	ExtAlgeb	0

Config Fields in [PMU]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.22 RenAerodynamics

Renewable aerodynamics group.

Common Parameters: u, name, rego

Common Variables: theta

Available models: *WTARA1*, *WTARV1*

5.22.1 WTARA1

Wind turbine aerodynamics model (no wind speed details).

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
rego		Renewable governor idx			mandatory
Ka	K_a	Aerodynamics gain	1	*p.u./deg.*	non_negative
theta0	θ_0	Initial pitch angle	0	*deg.*	

Variables

Name	Symbol	Type	Description	Unit	Properties
theta	θ	Algeb	Pitch angle	*rad*	v_str
Pmg	Pmg	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
theta	θ	Algeb	θ_{0r}
Pmg	Pmg	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
theta	θ	Algeb	$-\theta + \theta_{0r}$
Pmg	Pmg	ExtAlgeb	$-K_a\theta\left(\theta - \theta_0\right)$

Services

Name	Symbol	Equation	Type
theta0r	θ_{0r}	$\frac{\pi\theta_0}{180}$	ConstService

Config Fields in [WTARA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.22.2 WTARV1

Wind turbine aerodynamics model with wind velocity details.

Work is in progress.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
rego		Renewable governor idx			mandatory
nblade		number of blades	3		
ngen		number of wind generator units	50		
npole		number of poles in generator	4		
R		rotor radius	30	*m*	
ngb		gear box ratio	5		
rho		air density	1.200	*kg/m3*	
Sn	S_n		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
theta	θ	Algeb	Pitch angle	*rad*	
Pmg	Pmg	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
theta	θ	Algeb	
Pmg	Pmg	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
theta	θ	Algeb	0
Pmg	Pmg	ExtAlgeb	0

Config Fields in [WTARV1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.23 RenExciter

Renewable electrical control (exciter) group.

Common Parameters: u, name, reg

Common Variables: Pref, Qref, wg, Pord

Available models: *REECA1*, *REECA1E*, *REECA1G*

5.23.1 REECA1

Renewable energy electrical control.

There are two user-defined voltages: *Vref0* and *Vref1*.

- The difference between the initial bus voltage and *Vref0* should be within the voltage deadbands *dbd1* and *dbd2*.
- If *VFLAG=0*, the input to the second PI controller will be *Vref1*.

Regarding the additional reactive current injection during voltage dip:

- Exercise caution when coordinating the parameters `dbd1`, `dbd2`, `Vdip`, and `Vup` to avoid unintended responses.

- `Kqv` in `pu current / pu voltage deviation` controls the intensity of reactive power injection. The parameter needs to tuned properly to avoid voltage overshoot.
- When multiple renewable generators are connected to the same bus, `Kqv` shall be reduced accordingly to avoid excessive reactive power injection.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
reg		Renewable generator idx			mandatory
busr		Optional remote bus for voltage control			
PFFLAG		Power factor control flag; 1-PF control, 0-Q control		*bool*	mandatory
VFLAG		Voltage control flag; 1-Q control, 0-V control		*bool*	mandatory
QFLAG		Q control flag; 1-V or Q control, 0-const. PF or Q		*bool*	mandatory
PFLAG		P speed-dependency flag; 1-has speed dep., 0-no dep.		*bool*	mandatory
PQFLAG		P/Q priority flag for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
Vdip	V_{dip}	Low V threshold to activate Iqinj logic	0.800	*p.u.*	
Vup	V_{up}	V threshold above which to activate Iqinj logic	1.200	*p.u.*	
Trv	T_{rv}	Voltage filter time constant	0.020		
dbd1	d_{bd1}	Lower bound of the voltage deadband (<=0)	-0.020		
dbd2	d_{bd2}	Upper bound of the voltage deadband (>=0)	0.020		
Kqv	K_{qv}	Gain to compute Iqinj from V error (caution!!)	1		
Iqh1	I_{qh1}	Upper limit on Iqinj	999		
Iql1	I_{ql1}	Lower limit on Iqinj	-999		
Vref0	V_{ref0}	User defined Vref (if 0, use initial bus V)	1		
Iqfrz	I_{qfrz}	Hold Iqinj at the value for Thld (>0) seconds following a Vdip	0		
Thld	T_{hld}	Time for which Iqinj is held. Hold at Iqinj if>0; hold at State 1 if<0	0	*s*	
Thld2	T_{hld2}	Time for which IPMAX is held after voltage dip ends	0	*s*	
Tp	T_p	Filter time constant for Pe	0.020	*s*	
QMax	Q_{max}	Upper limit for reactive power regulator	999		
QMin	Q_{min}	Lower limit for reactive power regulator	-999		
VMAX	V_{max}	Upper limit for voltage control	999		
VMIN	V_{min}	Lower limit for voltage control	-999		
Kqp	K_{qp}	Proportional gain for reactive power error	1		
Kqi	K_{qi}	Integral gain for reactive power error	0.100		
Kvp	K_{vp}	Proportional gain for voltage error	1		
Kvi	K_{vi}	Integral gain for voltage error	0.100		
Vref1	V_{ref1}	Voltage ref. if VFLAG=0	1		non_zero
Tiq	T_{iq}	Filter time constant for Iq	0.020		
dPmax	d_{Pmax}	Power reference max. ramp rate (>0)	999		
dPmin	d_{Pin}	Power reference min. ramp rate (<0)	-999		
PMAX	P_{max}	Max. active power limit > 0	999		

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Name	Symbol	Description	Default	Unit	Properties
PMIN	P_{min}	Min. active power limit	0		
Imax	I_{max}	Max. apparent current limit	999		current
Tpord	T_{pord}	Filter time constant for power setpoint	0.020		
Vq1	V_{q1}	Reactive power V-I pair (point 1), voltage	0.200		
Iq1	I_{q1}	Reactive power V-I pair (point 1), current	2		current
Vq2	V_{q2}	Reactive power V-I pair (point 2), voltage	0.400		
Iq2	I_{q2}	Reactive power V-I pair (point 2), current	4		current
Vq3	V_{q3}	Reactive power V-I pair (point 3), voltage	0.800		
Iq3	I_{q3}	Reactive power V-I pair (point 3), current	8		current
Vq4	V_{q4}	Reactive power V-I pair (point 4), voltage	1		
Iq4	I_{q4}	Reactive power V-I pair (point 4), current	10		current
Vp1	V_{p1}	Active power V-I pair (point 1), voltage	0.200		
Ip1	I_{p1}	Active power V-I pair (point 1), current	2		current
Vp2	V_{p2}	Active power V-I pair (point 2), voltage	0.400		
Ip2	I_{p2}	Active power V-I pair (point 2), current	4		current
Vp3	V_{p3}	Active power V-I pair (point 3), voltage	0.800		
Ip3	I_{p3}	Active power V-I pair (point 3), current	8		current
Vp4	V_{p4}	Active power V-I pair (point 4), voltage	1		
Ip4	I_{p4}	Active power V-I pair (point 4), current	12		current
bus		Retrieved bus idx			
gen		Retrieved StaticGen idx			
Sn	S_n		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
s0_y	y_{s0}	State	State in lag transfer function		v_str
S1_y	y_{S_1}	State	State in lag transfer function		v_str
PIQ_xi	xi_{PIQ}	State	Integrator output		v_str
s4_y	y_{s_4}	State	State in lag transfer function		v_str
pfilt_y	$y_{P_{filt}}$	State	State in lag TF		v_str
s5_y	y_{s5}	State	State in lag TF		v_str
PIV_xi	xi_{PIV}	State	Integrator output		v_str
Pord	$Pord$	AliasState	Alias of s5_y		
vp	V_p	Algeb	Sensed lower-capped voltage		v_str
pfaref	Φ_{ref}	Algeb	power factor angle ref	*rad*	v_str
Qref	Q_{ref}	Algeb	external Q ref	*p.u.*	v_str
Qcpf	Q_{cpf}	Algeb	Q calculated from P and power factor	*p.u.*	v_str
PFsel	$PFsel$	Algeb	Output of PFFLAG selector		v_str
Qerr	Q_{err}	Algeb	Reactive power error		v_str
PIQ_ys	ys_{PIQ}	Algeb	PI summation before limit		v_str

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Table 18 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
PIQ_y	y_{PIQ}	Algeb	PI output		v_str
Vsel_x	x_{Vsel}	Algeb	Value before limiter		v_str
Vsel_y	y_{Vsel}	Algeb	Output after limiter and post gain		v_str
Verr	V_{err}	Algeb	Voltage error (Vref0)		v_str
dbV_y	y_{dbV}	Algeb	Deadband type 1 output		v_str
Iqinj	I_{qinj}	Algeb	Additional Iq signal during under- or over-voltage		v_str
wg	ω_g	Algeb	Drive train generator speed		v_str
Pref	P_{ref}	Algeb	external P ref	*p.u.*	v_str
Psel	P_{sel}	Algeb	Output selection of PFLAG		v_str
VDL1_y	$y_{V_{DL1}}$	Algeb	Output of piecewise		v_str
VDL2_y	$y_{V_{DL2}}$	Algeb	Output of piecewise		v_str
Ipmax	I_{pmax}	Algeb	Upper limit on Ipcmd		v_str
Iqmax	I_{qmax}	Algeb	Upper limit on Iqcmd		v_str
PIV_ys	ys_{PIV}	Algeb	PI summation before limit		v_str
PIV_y	y_{PIV}	Algeb	PI output		v_str
Qsel	Q_{sel}	Algeb	Selection output of QFLAG		v_str
IpHL_x	x_{IpHL}	Algeb	Value before limiter		v_str
IpHL_y	y_{IpHL}	Algeb	Output after limiter and post gain		v_str
IqHL_x	x_{IqHL}	Algeb	Value before limiter		v_str
IqHL_y	y_{IqHL}	Algeb	Output after limiter and post gain		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V_d	ExtAlgeb	d-axis bus voltage magnitude		
Pe	Pe	ExtAlgeb	Retrieved Pe of RenGen		
Qe	Qe	ExtAlgeb	Retrieved Qe of RenGen		
Ipcmd	$Ipcmd$	ExtAlgeb	Retrieved Ipcmd of RenGen		
Iqcmd	$Iqcmd$	ExtAlgeb	Retrieved Iqcmd of RenGen		

Initialization Equations

Name	Symbol	Type	Initial Value
s0_y	y_{s0}	State	V_d
S1_y	y_{S_1}	State	Pe
PIQ_xi	xi_{PIQ}	State	0.0
s4_y	y_{s_4}	State	$\frac{PFsel}{V_p}$
pfilt_y	$y_{P_{filt}}$	State	P_{ref}
s5_y	y_{s5}	State	P_{sel}
PIV_xi	xi_{PIV}	State	$-Iqcmd_0 s_1^{SW_V}$
Pord	$Pord$	AliasState	
vp	V_p	Algeb	$V_d z_i^{VLower} + 0.01 z_l^{VLower}$
pfaref	Φ_{ref}	Algeb	Φ_{ref0}
Qref	Q_{ref}	Algeb	$-q_{ref0}$

Table 19 – continued from previous pa

Name	Symbol	Type	Initial Value
Qcpf	Q_{cpf}	Algeb	Q_0
PFsel	$PFsel$	Algeb	$Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}}$
Qerr	Q_{err}	Algeb	$PFsel z_i^{PFlim} + Q_{max}z_u^{PFlim} + Q_{min}z_l^{PFlim} - Qe$
PIQ_ys	ys_{PIQ}	Algeb	$K_{qp}Q_{err}s_1^{SW_V}$
PIQ_y	y_{PIQ}	Algeb	$V_{max}z_u^{lim_{PIQ}} + V_{min}z_l^{lim_{PIQ}} + ys_{PIQ}z_i^{lim_{PIQ}}$
Vsel_x	x_{Vsel}	Algeb	$s_0^{SW_V}\left(Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}} + V_{ref1}\right) + s_1^{SW_V}y_{PIQ}$
Vsel_y	y_{Vsel}	Algeb	$V_{max}z_u^{lim_{Vsel}} + V_{min}z_l^{lim_{Vsel}} + x_{Vsel}z_i^{lim_{Vsel}}$
Verr	V_{err}	Algeb	$V_{ref0} - y_{s0}$
dbV_y	y_{dbV}	Algeb	$1.0z_l^{db_{dbV}}\left(V_{err} - d_{bd1}\right) + 1.0z_u^{db_{dbV}}\left(V_{err} - d_{bd2}\right)$
Iqinj	I_{qinj}	Algeb	$K_{qv}y_{dbV}z_{Vdip} + fThld\left(1 - z_{Vdip}\right)\left(I_{qfrz}p_{Thld} + K_{qv}n_{Thld}y_{dbV}\right)$
wg	ω_g	Algeb	1.0
Pref	P_{ref}	Algeb	$\frac{P_0}{\omega_g}$
Psel	P_{sel}	Algeb	$\omega_g s_1^{SW_P}y_{P_{filt}} + s_0^{SW_P}y_{P_{filt}}$
VDL1_y	$y_{V_{DL1}}$	Algeb	FixPiecewise $\left(\left(I_{q1},\ V_{q1} \geq y_{s0}\right), \left(I_{q1} + k_{Vq12}\left(-V_{q1} + y_{s0}\right),\ V_{q2} \geq y_{s0}\right), \left(I_{q2} + k_{Vq23}\right.\right.$
VDL2_y	$y_{V_{DL2}}$	Algeb	FixPiecewise $\left(\left(I_{p1},\ V_{p1} \geq y_{s0}\right), \left(I_{p1} + k_{Vp12}\left(-V_{p1} + y_{s0}\right),\ V_{p2} \geq y_{s0}\right), \left(I_{p2} + k_{Vp23}\right.\right.$
Ipmax	I_{pmax}	Algeb	$(1 - fThld_2)\left(\sqrt{I_{pmax20,nn}^2}s_0^{SW_{PQ}} + s_1^{SW_{PQ}}\left(z_{VDL2}\left(I_{maxr}\left(1 - VDL2c\right) + VDL2\right.\right.\right.$
Iqmax	I_{qmax}	Algeb	$\sqrt{I_{qmax,nn}^2}s_1^{SW_{PQ}} + s_0^{SW_{PQ}}\left(z_{VDL1}\left(I_{maxr}\left(1 - VDL1c\right) + VDL1cy_{V_{DL1}}\right) - 100000\right.$
PIV_ys	ys_{PIV}	Algeb	$-Iqcmd_0s_1^{SW_V} + K_{vp}s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right)$
PIV_y	y_{PIV}	Algeb	$I_{qmax}z_u^{lim_{PIV}} + I_{qmin}z_l^{lim_{PIV}} + ys_{PIV}z_i^{lim_{PIV}}$
Qsel	Q_{sel}	Algeb	$s_0^{SW_V}y_{s_4} + s_1^{SW_V}y_{PIV}$
IpHL_x	x_{IpHL}	Algeb	$\frac{y_{s5}}{V_p}$
IpHL_y	y_{IpHL}	Algeb	$I_{pmax}z_u^{lim_{IpHL}} + I_{pmin}z_l^{lim_{IpHL}} + x_{IpHL}z_i^{lim_{IpHL}}$
IqHL_x	x_{IqHL}	Algeb	$I_{qinj} + Q_{sel}$
IqHL_y	y_{IqHL}	Algeb	$I_{qmax}z_u^{lim_{IqHL}} + I_{qmin}z_l^{lim_{IqHL}} + x_{IqHL}z_i^{lim_{IqHL}}$
a	θ	ExtAlgeb	
v	V_d	ExtAlgeb	
Pe	Pe	ExtAlgeb	
Qe	Qe	ExtAlgeb	
Ipcmd	$Ipcmd$	ExtAlgeb	
Iqcmd	$Iqcmd$	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s0_y	y_{s0}	State	$V_d - y_{s0}$	T_{rv}
S1_y	y_{S_1}	State	$Pe - y_{S_1}$	T_p
PIQ_xi	xi_{PIQ}	State	$K_{qi}\left(1 - z_{Vdip}\right)\left(Q_{err}s_1^{SW_V} + 2y_{PIQ} - 2ys_{PIQ}\right)$	
s4_y	y_{s_4}	State	$\left(1 - z_{Vdip}\right)\left(\frac{PFsel}{V_p} - y_{s_4}\right)$	T_{iq}
pfilt_y	$y_{P_{filt}}$	State	$P_{ref} - y_{P_{filt}}$	0.02
s5_y	y_{s5}	State	$\left(1 - z_{Vdip}\right)\left(P_{sel} - y_{s5}\right)$	T_{pord}
PIV_xi	xi_{PIV}	State	$K_{vi}\left(1 - z_{Vdip}\right)\left(s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right) + 2y_{PIV} - 2ys_I\right.$	
Pord	$Pord$	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vp	V_p	Algeb	$V_d z_i^{VLower} - V_p + 0.01 z_l^{VLower}$
pfaref	Φ_{ref}	Algeb	$\Phi_{ref0} - \Phi_{ref}$
Qref	Q_{ref}	Algeb	$-Q_{ref} - q_{ref0}$
Qcpf	Q_{cpf}	Algeb	$\left(1 - z_1^{zp}\right)\left(-Q_{cpf} + y_{S_1}\tan\left(\Phi_{ref}\right)\right)$
PFsel	$PFsel$	Algeb	$-PFsel + Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}}$
Qerr	Q_{err}	Algeb	$PFsel z_i^{PFlim} - Q_{err} + Q_{max}z_u^{PFlim} + Q_{min}z_l^{PFlim} - Qe$
PIQ_ys	ys_{PIQ}	Algeb	$\left(1 - z_{Vdip}\right)\left(K_{qp}Q_{err}s_1^{SW_V} + xi_{PIQ} - ys_{PIQ}\right)$
PIQ_y	y_{PIQ}	Algeb	$\left(1 - z_{Vdip}\right)\left(V_{max}z_u^{lim_{PIQ}} + V_{min}z_l^{lim_{PIQ}} - y_{PIQ} + ys_{PIQ}z_i^{lim_{PIQ}}\right)$
Vsel_x	x_{Vsel}	Algeb	$s_0^{SW_V}\left(Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}} + V_{ref1}\right) + s_1^{SW_V}y_{PIQ} - x_{Vsel}$
Vsel_y	y_{Vsel}	Algeb	$V_{max}z_u^{lim_{Vsel}} + V_{min}z_l^{lim_{Vsel}} + x_{Vsel}z_i^{lim_{Vsel}} - y_{Vsel}$
Verr	V_{err}	Algeb	$-V_{err} + V_{ref0} - y_{s0}$
dbV_y	y_{dbV}	Algeb	$-y_{dbV} + 1.0z_l^{db_{dbV}}\left(V_{err} - d_{bd1}\right) + 1.0z_u^{db_{dbV}}\left(V_{err} - d_{bd2}\right)$
Iqinj	I_{qinj}	Algeb	$-I_{qinj} + K_{qv}y_{dbV}z_{Vdip} + fThld\left(1 - z_{Vdip}\right)\left(I_{qfrz}p_{Thld} + K_{qv}n_{Thld}y_{dbV}\right)$
wg	ω_g	Algeb	$1.0 - \omega_g$
Pref	P_{ref}	Algeb	$\frac{P_0}{\omega_g} - P_{ref}$
Psel	P_{sel}	Algeb	$-P_{sel} + \omega_g s_1^{SW_P}y_{P_{filt}} + s_0^{SW_P}y_{P_{filt}}$
VDL1_y	$y_{V_{DL1}}$	Algeb	$-y_{V_{DL1}} + \text{FixPiecewise}\left(\left(I_{q1},\ V_{q1} \geq y_{s0}\right), \left(I_{q1} + k_{Vq12}\left(-V_{q1} + y_{s0}\right),\ V_{q2} \geq y_{s0}\right), (I_{q}\right.$
VDL2_y	$y_{V_{DL2}}$	Algeb	$-y_{V_{DL2}} + \text{FixPiecewise}\left(\left(I_{p1},\ V_{p1} \geq y_{s0}\right), \left(I_{p1} + k_{Vp12}\left(-V_{p1} + y_{s0}\right),\ V_{p2} \geq y_{s0}\right), (I\right.$
Ipmax	I_{pmax}	Algeb	$-I_{pmax} + Ipmaxhf Thld_2 + \left(1 - fThld_2\right)\left(\sqrt{I_{pmax2}^2}s_0^{SW_{PQ}} + s_1^{SW_{PQ}}\left(z_{VDL2}\left(I_{max}\right.\right.\right.$
Iqmax	I_{qmax}	Algeb	$\sqrt{I_{qmax2}^2}s_1^{SW_{PQ}} - I_{qmax} + s_0^{SW_{PQ}}\left(z_{VDL1}\left(I_{maxr}\left(1 - VDL1c\right) + VDL1cy_{V_{DL1}}\right) -\right.$
PIV_ys	ys_{PIV}	Algeb	$\left(1 - z_{Vdip}\right)\left(K_{vp}s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right) + xi_{PIV} - ys_{PIV}\right)$
PIV_y	y_{PIV}	Algeb	$\left(1 - z_{Vdip}\right)\left(I_{qmax}z_u^{lim_{PIV}} + I_{qmin}z_l^{lim_{PIV}} - y_{PIV} + ys_{PIV}z_i^{lim_{PIV}}\right)$

Table 20 – continued from previou

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Qsel	Q_{sel}	Algeb	$-Q_{sel} + s_0^{SW_V} y_{s_4} + s_1^{SW_V} y_{PIV}$
IpHL_x	x_{IpHL}	Algeb	$-x_{IpHL} + \frac{y_{s5}}{V_p}$
IpHL_y	y_{IpHL}	Algeb	$I_{pmax} z_u^{lim_{IpHL}} + I_{pmin} z_l^{lim_{IpHL}} + x_{IpHL} z_i^{lim_{IpHL}} - y_{IpHL}$
IqHL_x	x_{IqHL}	Algeb	$I_{qinj} + Q_{sel} - x_{IqHL}$
IqHL_y	y_{IqHL}	Algeb	$I_{qmax} z_u^{lim_{IqHL}} + I_{qmin} z_l^{lim_{IqHL}} + x_{IqHL} z_i^{lim_{IqHL}} - y_{IqHL}$
a	θ	ExtAlgeb	0
v	V_d	ExtAlgeb	0
Pe	Pe	ExtAlgeb	0
Qe	Qe	ExtAlgeb	0
Ipcmd	$Ipcmd$	ExtAlgeb	$-Ipcmd_0 + y_{IpHL}$
Iqcmd	$Iqcmd$	ExtAlgeb	$-Iqcmd_0 - y_{IqHL}$

Services

Name	Symbol	Equation	Type
Ipcmd0	$Ipcmd0$	$\frac{P_0}{V_d}$	ConstService
Iqcmd0	$Iqcmd0$	$-\frac{Q_0}{V_d}$	ConstService
pfaref0	Φ_{ref0}	$\text{atan}_2(Q_0, P_0)$	ConstService
Volt_dip	z_{Vdip}	$1 - z_i^{V_{cmp}}$	VarService
qref0	q_{ref0}	$Iqcmd_0 s_0^{SW_V} \left(V_d z_i^{VLower} + 0.01 z_l^{VLower}\right) + s_1^{SW_V} \left(V_d - V_{ref1}\right)$	ConstService
PIQ_flag	z_{PIQ}^{flag}	0	EventFlag
s4_flag	$z_{s_4}^{flag}$	0	EventFlag
pThld	p_{Thld}	Indicator $(T_{hld} > 0)$	ConstService
nThld	n_{Thld}	Indicator $(T_{hld} < 0)$	ConstService
Thld_abs	$\|Thld\|$	$\|T_{hld}\|$	ConstService
fThld	$fThld$	0	ExtendedEvent
s5_flag	z_{s5}^{flag}	0	EventFlag
kVq12	k_{Vq12}	$\frac{-I_{q1}+I_{q2}}{-V_{q1}+V_{q2}}$	ConstService
kVq23	k_{Vq23}	$\frac{-I_{q2}+I_{q3}}{-V_{q2}+V_{q3}}$	ConstService
kVq34	k_{Vq34}	$\frac{-I_{q3}+I_{q4}}{-V_{q3}+V_{q4}}$	ConstService
zVDL1	z_{VDL1}	$I_{q1} \le I_{q2} \wedge I_{q2} \le I_{q3} \wedge I_{q3} \le I_{q4} \wedge V_{q1} \le V_{q2} \wedge V_{q2} \le V_{q3} \wedge V_{q3} \le V_{q4}$	ConstService
kVp12	k_{Vp12}	$\frac{-I_{p1}+I_{p2}}{-V_{p1}+V_{p2}}$	ConstService
kVp23	k_{Vp23}	$\frac{-I_{p2}+I_{p3}}{-V_{p2}+V_{p3}}$	ConstService
kVp34	k_{Vp34}	$\frac{-I_{p3}+I_{p4}}{-V_{p3}+V_{p4}}$	ConstService
zVDL2	z_{VDL2}	$I_{p1} \le I_{p2} \wedge I_{p2} \le I_{p3} \wedge I_{p3} \le I_{p4} \wedge V_{p1} \le V_{p2} \wedge V_{p2} \le V_{p3} \wedge V_{p3} \le V_{p4}$	ConstService
fThld2	$fThld2$	0	ExtendedEvent
VDL1c	$VDL1c$	$y_{V_{DL1}} < I_{maxr}$	VarService
VDL2c	$VDL2c$	$y_{V_{DL2}} < I_{maxr}$	VarService

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Table 21 – continued from previous page

Name	Symbol	Equation	Type
Ipmax2sq0	$I^2_{pmax20,nn}$	FixPiecewise $\left((0,\ I^2_{max} - Iqcmd^2_0 \leq 0),\ (I^2_{max} - Iqcmd^2_0,\ \text{True})\right)$	ConstService
Ipmax2sq	I^2_{pmax2}	FixPiecewise $\left(\left(0,\ I^2_{max} - y^2_{IqHL} \leq 0\right),\ \left(I^2_{max} - y^2_{IqHL},\ \text{True}\right)\right)$	VarService
Ipmaxh	$Ipmaxh$	0	VarHold
Iqmax2sq0	$I^2_{qmax,nn}$	FixPiecewise $\left((0,\ I^2_{max} - Ipcmd^2_0 \leq 0),\ (I^2_{max} - Ipcmd^2_0,\ \text{True})\right)$	ConstService
Iqmax2sq	I^2_{qmax2}	FixPiecewise $\left(\left(0,\ I^2_{max} - y^2_{IpHL} \leq 0\right),\ \left(I^2_{max} - y^2_{IpHL},\ \text{True}\right)\right)$	VarService
Ipmin	I_{pmin}	0.0	ConstService
PIV_flag	z^{flag}_{PIV}	0	EventFlag

Discretes

Name	Symbol	Type	Info
SWPF	SW_{PF}	Switcher	
SWV	SW_V	Switcher	
SWQ	SW_V	Switcher	
SWP	SW_P	Switcher	
SWPQ	SW_{PQ}	Switcher	
zp	zp	IsEqual	
Vcmp	V_{cmp}	Limiter	Voltage dip comparator
VLower	$VLower$	Limiter	Limiter for lower voltage cap
PFlim	$PFlim$	Limiter	
PIQ_lim	lim_{PIQ}	HardLimiter	
Vsel_lim	lim_{Vsel}	HardLimiter	
dbV_db	db_{dbV}	DeadBand	
pfilt_lim	$lim_{P_{filt}}$	RateLimiter	Rate limiter in Lag
s5_lim	lim_{s5}	AntiWindup	Limiter in Lag
PIV_lim	lim_{PIV}	HardLimiter	
IpHL_lim	lim_{IpHL}	HardLimiter	
IqHL_lim	lim_{IqHL}	HardLimiter	

Blocks

Name	Symbol	Type	Info
s0	$s0$	Lag	Voltage filter
S1	S_1	Lag	Pe filter
PIQ	PIQ	PITrackAWFreeze	
Vsel	$Vsel$	GainLimiter	Selection output of VFLAG
s4	s_4	LagFreeze	Filter for calculated voltage with freeze
dbV	dbV	DeadBand1	Deadband for voltage error (ref0)
pfilt	P_{filt}	LagRate	Active power filter with rate limits
s5	$s5$	LagAWFreeze	
VDL1	V_{DL1}	Piecewise	Piecewise linear characteristics of Vq-Iq
VDL2	V_{DL2}	Piecewise	Piecewise linear characteristics of Vp-Ip
PIV	PIV	PITrackAWFreeze	
IpHL	$IpHL$	GainLimiter	
IqHL	$IqHL$	GainLimiter	

Config Fields in [REECA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
kqs	K_{qs}	2	Q PI controller tracking gain	
kvs	K_{vs}	2	Voltage PI controller tracking gain	
tpfilt	T_{pfilt}	0.020	Time const. for Pref filter	

5.23.2 REECA1E

REGCA1 with inertia emulation and primary frequency droop. Measurements are based on frequency measurement model.

Bus ROCOF obtained from `BusROCOF` devices.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
reg		Renewable generator idx			mandatory

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Table 22 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
busr		Optional remote bus for voltage control			
PFFLAG		Power factor control flag; 1-PF control, 0-Q control		*bool*	mandatory
VFLAG		Voltage control flag; 1-Q control, 0-V control		*bool*	mandatory
QFLAG		Q control flag; 1-V or Q control, 0-const. PF or Q		*bool*	mandatory
PFLAG		P speed-dependency flag; 1-has speed dep., 0-no dep.		*bool*	mandatory
PQFLAG		P/Q priority flag for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
Vdip	V_{dip}	Low V threshold to activate Iqinj logic	0.800	*p.u.*	
Vup	V_{up}	V threshold above which to activate Iqinj logic	1.200	*p.u.*	
Trv	T_{rv}	Voltage filter time constant	0.020		
dbd1	d_{bd1}	Lower bound of the voltage deadband (<=0)	-0.020		
dbd2	d_{bd2}	Upper bound of the voltage deadband (>=0)	0.020		
Kqv	K_{qv}	Gain to compute Iqinj from V error (caution!!)	1		
Iqh1	I_{qh1}	Upper limit on Iqinj	999		
Iql1	I_{ql1}	Lower limit on Iqinj	-999		
Vref0	V_{ref0}	User defined Vref (if 0, use initial bus V)	1		
Iqfrz	I_{qfrz}	Hold Iqinj at the value for Thld (>0) seconds following a Vdip	0		
Thld	T_{hld}	Time for which Iqinj is held. Hold at Iqinj if>0; hold at State 1 if<0	0	*s*	
Thld2	T_{hld2}	Time for which IPMAX is held after voltage dip ends	0	*s*	
Tp	T_p	Filter time constant for Pe	0.020	*s*	
QMax	Q_{max}	Upper limit for reactive power regulator	999		
QMin	Q_{min}	Lower limit for reactive power regulator	-999		
VMAX	V_{max}	Upper limit for voltage control	999		
VMIN	V_{min}	Lower limit for voltage control	-999		
Kqp	K_{qp}	Proportional gain for reactive power error	1		
Kqi	K_{qi}	Integral gain for reactive power error	0.100		
Kvp	K_{vp}	Proportional gain for voltage error	1		
Kvi	K_{vi}	Integral gain for voltage error	0.100		
Vref1	V_{ref1}	Voltage ref. if VFLAG=0	1		non_zero
Tiq	T_{iq}	Filter time constant for Iq	0.020		
dPmax	d_{Pmax}	Power reference max. ramp rate (>0)	999		
dPmin	d_{Pin}	Power reference min. ramp rate (<0)	-999		
PMAX	P_{max}	Max. active power limit > 0	999		
PMIN	P_{min}	Min. active power limit	0		
Imax	I_{max}	Max. apparent current limit	999		current
Tpord	T_{pord}	Filter time constant for power setpoint	0.020		
Vq1	V_{q1}	Reactive power V-I pair (point 1), voltage	0.200		
Iq1	I_{q1}	Reactive power V-I pair (point 1), current	2		current
Vq2	V_{q2}	Reactive power V-I pair (point 2), voltage	0.400		
Iq2	I_{q2}	Reactive power V-I pair (point 2), current	4		current
Vq3	V_{q3}	Reactive power V-I pair (point 3), voltage	0.800		
Iq3	I_{q3}	Reactive power V-I pair (point 3), current	8		current
Vq4	V_{q4}	Reactive power V-I pair (point 4), voltage	1		
Iq4	I_{q4}	Reactive power V-I pair (point 4), current	10		current
Vp1	V_{p1}	Active power V-I pair (point 1), voltage	0.200		

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Table 22 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
Ip1	I_{p1}	Active power V-I pair (point 1), current	2		current
Vp2	V_{p2}	Active power V-I pair (point 2), voltage	0.400		
Ip2	I_{p2}	Active power V-I pair (point 2), current	4		current
Vp3	V_{p3}	Active power V-I pair (point 3), voltage	0.800		
Ip3	I_{p3}	Active power V-I pair (point 3), current	8		current
Vp4	V_{p4}	Active power V-I pair (point 4), voltage	1		
Ip4	I_{p4}	Active power V-I pair (point 4), current	12		current
Kf	K_{df}	gain for frequency deviation	0		
Kdf	K_{df}	gain for rate-of-change of frequency	0		
busroc		Optional BusROCOF device idx			
bus		Retrieved bus idx			
gen		Retrieved StaticGen idx			
Sn	S_n		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
s0_y	y_{s0}	State	State in lag transfer function		v_str
S1_y	y_{S_1}	State	State in lag transfer function		v_str
PIQ_xi	xi_{PIQ}	State	Integrator output		v_str
s4_y	y_{s_4}	State	State in lag transfer function		v_str
pfilt_y	$y_{P_{filt}}$	State	State in lag TF		v_str
s5_y	y_{s5}	State	State in lag TF		v_str
PIV_xi	xi_{PIV}	State	Integrator output		v_str
Pord	$Pord$	AliasState	Alias of s5_y		
vp	V_p	Algeb	Sensed lower-capped voltage		v_str
pfaref	Φ_{ref}	Algeb	power factor angle ref	*rad*	v_str
Qref	Q_{ref}	Algeb	external Q ref	*p.u.*	v_str
Qcpf	Q_{cpf}	Algeb	Q calculated from P and power factor	*p.u.*	v_str
PFsel	$PFsel$	Algeb	Output of PFFLAG selector		v_str
Qerr	Q_{err}	Algeb	Reactive power error		v_str
PIQ_ys	ys_{PIQ}	Algeb	PI summation before limit		v_str
PIQ_y	y_{PIQ}	Algeb	PI output		v_str
Vsel_x	x_{Vsel}	Algeb	Value before limiter		v_str
Vsel_y	y_{Vsel}	Algeb	Output after limiter and post gain		v_str
Verr	V_{err}	Algeb	Voltage error (Vref0)		v_str
dbV_y	y_{dbV}	Algeb	Deadband type 1 output		v_str
Iqinj	I_{qinj}	Algeb	Additional Iq signal during under- or over-voltage		v_str
wg	ω_g	Algeb	Drive train generator speed		v_str
Pref	P_{ref}	Algeb	external P ref	*p.u.*	v_str
Psel	P_{sel}	Algeb	Output selection of PFLAG		v_str

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Table 23 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
VDL1_y	$y_{V_{DL1}}$	Algeb	Output of piecewise		v_str
VDL2_y	$y_{V_{DL2}}$	Algeb	Output of piecewise		v_str
Ipmax	I_{pmax}	Algeb	Upper limit on Ipcmd		v_str
Iqmax	I_{qmax}	Algeb	Upper limit on Iqcmd		v_str
PIV_ys	ys_{PIV}	Algeb	PI summation before limit		v_str
PIV_y	y_{PIV}	Algeb	PI output		v_str
Qsel	Q_{sel}	Algeb	Selection output of QFLAG		v_str
IpHL_x	x_{IpHL}	Algeb	Value before limiter		v_str
IpHL_y	y_{IpHL}	Algeb	Output after limiter and post gain		v_str
IqHL_x	x_{IqHL}	Algeb	Value before limiter		v_str
IqHL_y	y_{IqHL}	Algeb	Output after limiter and post gain		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V_d	ExtAlgeb	d-axis bus voltage magnitude		
Pe	Pe	ExtAlgeb	Retrieved Pe of RenGen		
Qe	Qe	ExtAlgeb	Retrieved Qe of RenGen		
Ipcmd	$Ipcmd$	ExtAlgeb	Retrieved Ipcmd of RenGen		
Iqcmd	$Iqcmd$	ExtAlgeb	Retrieved Iqcmd of RenGen		
df	df	ExtAlgeb	Bus frequency deviation		
dfdt	$dfdt$	ExtAlgeb	Bus ROCOF	*p.u.*	

Initialization Equations

Name	Symbol	Type	Initial Value
s0_y	y_{s0}	State	V_d
S1_y	y_{S_1}	State	Pe
PIQ_xi	xi_{PIQ}	State	0.0
s4_y	y_{s_4}	State	$\frac{PFsel}{V_p}$
pfilt_y	$y_{P_{filt}}$	State	P_{ref}
s5_y	y_{s5}	State	P_{sel}
PIV_xi	xi_{PIV}	State	$-Iqcmd_0 s_1^{SW_V}$
Pord	$Pord$	AliasState	
vp	V_p	Algeb	$V_d z_i^{VLower} + 0.01 z_l^{VLower}$
pfaref	Φ_{ref}	Algeb	Φ_{ref0}
Qref	Q_{ref}	Algeb	$-q_{ref0}$
Qcpf	Q_{cpf}	Algeb	Q_0
PFsel	$PFsel$	Algeb	$Q_{cpf} s_1^{SW_{PF}} + Q_{ref} s_0^{SW_{PF}}$
Qerr	Q_{err}	Algeb	$PFsel z_i^{PFlim} + Q_{max} z_u^{PFlim} + Q_{min} z_l^{PFlim} - Qe$
PIQ_ys	ys_{PIQ}	Algeb	$K_{qp} Q_{err} s_1^{SW_V}$
PIQ_y	y_{PIQ}	Algeb	$V_{max} z_u^{lim_{PIQ}} + V_{min} z_l^{lim_{PIQ}} + ys_{PIQ} z_i^{lim_{PIQ}}$
Vsel_x	x_{Vsel}	Algeb	$s_0^{SW_V} \left(Q_{cpf} s_1^{SW_{PF}} + Q_{ref} s_0^{SW_{PF}} + V_{ref1} \right) + s_1^{SW_V} y_{PIQ}$

Table 24 – continued from previous pa

Name	Symbol	Type	Initial Value
Vsel_y	y_{Vsel}	Algeb	$V_{max}z_u^{lim_{Vsel}} + V_{min}z_l^{lim_{Vsel}} + x_{Vsel}z_i^{lim_{Vsel}}$
Verr	V_{err}	Algeb	$V_{ref0} - y_{s0}$
dbV_y	y_{dbV}	Algeb	$1.0z_l^{db_{dbV}}\left(V_{err} - d_{bd1}\right) + 1.0z_u^{db_{dbV}}\left(V_{err} - d_{bd2}\right)$
Iqinj	I_{qinj}	Algeb	$K_{qv}y_{dbV}z_{Vdip} + fThld\left(1 - z_{Vdip}\right)\left(I_{qfrz}p_{Thld} + K_{qv}n_{Thld}y_{dbV}\right)$
wg	ω_g	Algeb	1.0
Pref	P_{ref}	Algeb	$\frac{P_0}{\omega_g}$
Psel	P_{sel}	Algeb	$\omega_g s_1^{SW_P}y_{P_{filt}} + s_0^{SW_P}y_{P_{filt}}$
VDL1_y	$y_{V_{DL1}}$	Algeb	FixPiecewise $\left(\left(I_{q1},\ V_{q1} \geq y_{s0}\right), \left(I_{q1} + k_{Vq12}\left(-V_{q1} + y_{s0}\right),\ V_{q2} \geq y_{s0}\right), \left(I_{q2} + k_{Vq23}\right.\right.$
VDL2_y	$y_{V_{DL2}}$	Algeb	FixPiecewise $\left(\left(I_{p1},\ V_{p1} \geq y_{s0}\right), \left(I_{p1} + k_{Vp12}\left(-V_{p1} + y_{s0}\right),\ V_{p2} \geq y_{s0}\right), \left(I_{p2} + k_{Vp23}\right.\right.$
Ipmax	I_{pmax}	Algeb	$\left(1 - fThld_2\right)\left(\sqrt{I_{pmax20,nn}^2}s_0^{SW_{PQ}} + s_1^{SW_{PQ}}\left(z_{VDL2}\left(I_{maxr}\left(1 - VDL2c\right) + VDL2\right.\right.\right.$
Iqmax	I_{qmax}	Algeb	$\sqrt{I_{qmax,nn}^2}s_1^{SW_{PQ}} + s_0^{SW_{PQ}}\left(z_{VDL1}\left(I_{maxr}\left(1 - VDL1c\right) + VDL1cy_{V_{DL1}}\right) - 100000\right.$
PIV_ys	ys_{PIV}	Algeb	$-Iqcmd_0 s_1^{SW_V} + K_{vp}s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right)$
PIV_y	y_{PIV}	Algeb	$I_{qmax}z_u^{lim_{PIV}} + I_{qmin}z_l^{lim_{PIV}} + ys_{PIV}z_i^{lim_{PIV}}$
Qsel	Q_{sel}	Algeb	$s_0^{SW_V}y_{s_4} + s_1^{SW_V}y_{PIV}$
IpHL_x	x_{IpHL}	Algeb	$\frac{y_{s5}}{V_p}$
IpHL_y	y_{IpHL}	Algeb	$I_{pmax}z_u^{lim_{IpHL}} + I_{pmin}z_l^{lim_{IpHL}} + x_{IpHL}z_i^{lim_{IpHL}}$
IqHL_x	x_{IqHL}	Algeb	$I_{qinj} + Q_{sel}$
IqHL_y	y_{IqHL}	Algeb	$I_{qmax}z_u^{lim_{IqHL}} + I_{qmin}z_l^{lim_{IqHL}} + x_{IqHL}z_i^{lim_{IqHL}}$
a	θ	ExtAlgeb	
v	V_d	ExtAlgeb	
Pe	Pe	ExtAlgeb	
Qe	Qe	ExtAlgeb	
Ipcmd	$Ipcmd$	ExtAlgeb	
Iqcmd	$Iqcmd$	ExtAlgeb	
df	df	ExtAlgeb	
dfdt	$dfdt$	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s0_y	y_{s0}	State	$V_d - y_{s0}$	T_{rv}
S1_y	y_{S_1}	State	$Pe - y_{S_1}$	T_p
PIQ_xi	xi_{PIQ}	State	$K_{qi}\left(1 - z_{Vdip}\right)\left(Q_{err}s_1^{SW_V} + 2y_{PIQ} - 2ys_{PIQ}\right)$	
s4_y	y_{s_4}	State	$\left(1 - z_{Vdip}\right)\left(\frac{PFsel}{V_p} - y_{s_4}\right)$	T_{iq}
pfilt_y	$y_{P_{filt}}$	State	$P_{ref} - y_{P_{filt}}$	0.02
s5_y	y_{s5}	State	$\left(1 - z_{Vdip}\right)\left(P_{sel} - y_{s5}\right)$	T_{pord}
PIV_xi	xi_{PIV}	State	$K_{vi}\left(1 - z_{Vdip}\right)\left(s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right) + 2y_{PIV} - 2ys_I\right.$	
Pord	$Pord$	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vp	V_p	Algeb	$V_d z_i^{VLower} - V_p + 0.01 z_l^{VLower}$
pfaref	Φ_{ref}	Algeb	$\Phi_{ref0} - \Phi_{ref}$
Qref	Q_{ref}	Algeb	$-Q_{ref} - q_{ref0}$
Qcpf	Q_{cpf}	Algeb	$\left(1 - z_1^{zp}\right)\left(-Q_{cpf} + y_{S_1}\tan\left(\Phi_{ref}\right)\right)$
PFsel	$PFsel$	Algeb	$-PFsel + Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}}$
Qerr	Q_{err}	Algeb	$PFsel z_i^{PFlim} - Q_{err} + Q_{max}z_u^{PFlim} + Q_{min}z_l^{PFlim} - Qe$
PIQ_ys	ys_{PIQ}	Algeb	$\left(1 - z_{Vdip}\right)\left(K_{qp}Q_{err}s_1^{SW_V} + xi_{PIQ} - ys_{PIQ}\right)$
PIQ_y	y_{PIQ}	Algeb	$\left(1 - z_{Vdip}\right)\left(V_{max}z_u^{lim_{PIQ}} + V_{min}z_l^{lim_{PIQ}} - y_{PIQ} + ys_{PIQ}z_i^{lim_{PIQ}}\right)$
Vsel_x	x_{Vsel}	Algeb	$s_0^{SW_V}\left(Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}} + V_{ref1}\right) + s_1^{SW_V}y_{PIQ} - x_{Vsel}$
Vsel_y	y_{Vsel}	Algeb	$V_{max}z_u^{lim_{Vsel}} + V_{min}z_l^{lim_{Vsel}} + x_{Vsel}z_i^{lim_{Vsel}} - y_{Vsel}$
Verr	V_{err}	Algeb	$-V_{err} + V_{ref0} - y_{s0}$
dbV_y	y_{dbV}	Algeb	$-y_{dbV} + 1.0z_l^{db_{dbV}}\left(V_{err} - d_{bd1}\right) + 1.0z_u^{db_{dbV}}\left(V_{err} - d_{bd2}\right)$
Iqinj	I_{qinj}	Algeb	$-I_{qinj} + K_{qv}y_{dbV}z_{Vdip} + fThld\left(1 - z_{Vdip}\right)\left(I_{qfrz}p_{Thld} + K_{qv}n_{Thld}y_{dbV}\right)$
wg	ω_g	Algeb	$1.0 - \omega_g$
Pref	P_{ref}	Algeb	$-K_{df}df - K_{df}dfdt + \frac{P_0}{\omega_g} - P_{ref}$
Psel	P_{sel}	Algeb	$-P_{sel} + \omega_g s_1^{SW_P}y_{P_{filt}} + s_0^{SW_P}y_{P_{filt}}$
VDL1_y	$y_{V_{DL1}}$	Algeb	$-y_{V_{DL1}} + \text{FixPiecewise}\left(\left(I_{q1},\ V_{q1} \geq y_{s0}\right), \left(I_{q1} + k_{Vq12}\left(-V_{q1} + y_{s0}\right),\ V_{q2} \geq y_{s0}\right), (I_{q}\right.$
VDL2_y	$y_{V_{DL2}}$	Algeb	$-y_{V_{DL2}} + \text{FixPiecewise}\left(\left(I_{p1},\ V_{p1} \geq y_{s0}\right), \left(I_{p1} + k_{Vp12}\left(-V_{p1} + y_{s0}\right),\ V_{p2} \geq y_{s0}\right), (I\right.$
Ipmax	I_{pmax}	Algeb	$-I_{pmax} + Ipmaxhf Thld_2 + \left(1 - fThld_2\right)\left(\sqrt{I_{pmax2}^2}s_0^{SW_{PQ}} + s_1^{SW_{PQ}}\left(z_{VDL2}\left(I_{max}\right.\right.\right.$
Iqmax	I_{qmax}	Algeb	$\sqrt{I_{qmax2}^2}s_1^{SW_{PQ}} - I_{qmax} + s_0^{SW_{PQ}}\left(z_{VDL1}\left(I_{maxr}\left(1 - VDL1c\right) + VDL1cy_{V_{DL1}}\right) -\right.$
PIV_ys	ys_{PIV}	Algeb	$\left(1 - z_{Vdip}\right)\left(K_{vp}s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right) + xi_{PIV} - ys_{PIV}\right)$
PIV_y	y_{PIV}	Algeb	$\left(1 - z_{Vdip}\right)\left(I_{qmax}z_u^{lim_{PIV}} + I_{qmin}z_l^{lim_{PIV}} - y_{PIV} + ys_{PIV}z_i^{lim_{PIV}}\right)$

Table 25 – continued from previou

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Qsel	Q_{sel}	Algeb	$-Q_{sel} + s_0^{SW_V} y_{s_4} + s_1^{SW_V} y_{PIV}$
IpHL_x	x_{IpHL}	Algeb	$-x_{IpHL} + \frac{y_{s5}}{V_p}$
IpHL_y	y_{IpHL}	Algeb	$I_{pmax} z_u^{lim_{IpHL}} + I_{pmin} z_l^{lim_{IpHL}} + x_{IpHL} z_i^{lim_{IpHL}} - y_{IpHL}$
IqHL_x	x_{IqHL}	Algeb	$I_{qinj} + Q_{sel} - x_{IqHL}$
IqHL_y	y_{IqHL}	Algeb	$I_{qmax} z_u^{lim_{IqHL}} + I_{qmin} z_l^{lim_{IqHL}} + x_{IqHL} z_i^{lim_{IqHL}} - y_{IqHL}$
a	θ	ExtAlgeb	0
v	V_d	ExtAlgeb	0
Pe	Pe	ExtAlgeb	0
Qe	Qe	ExtAlgeb	0
Ipcmd	$Ipcmd$	ExtAlgeb	$-Ipcmd_0 + y_{IpHL}$
Iqcmd	$Iqcmd$	ExtAlgeb	$-Iqcmd_0 - y_{IqHL}$
df	df	ExtAlgeb	0
dfdt	$dfdt$	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
Ipcmd0	$Ipcmd0$	$\frac{P_0}{V_d}$	ConstService
Iqcmd0	$Iqcmd0$	$-\frac{Q_0}{V_d}$	ConstService
pfaref0	Φ_{ref0}	$\text{atan}_2(Q_0, P_0)$	ConstService
Volt_dip	z_{Vdip}	$1 - z_i^{V_{cmp}}$	VarService
qref0	q_{ref0}	$Iqcmd_0 s_0^{SW_V} \left(V_d z_i^{VLower} + 0.01 z_l^{VLower}\right) + s_1^{SW_V} (V_d - V_{ref1})$	ConstService
PIQ_flag	z_{PIQ}^{flag}	0	EventFlag
s4_flag	$z_{s_4}^{flag}$	0	EventFlag
pThld	p_{Thld}	Indicator $(T_{hld} > 0)$	ConstService
nThld	n_{Thld}	Indicator $(T_{hld} < 0)$	ConstService
Thld_abs	$\lvert Thld \rvert$	$\lvert T_{hld} \rvert$	ConstService
fThld	$fThld$	0	ExtendedEvent
s5_flag	z_{s5}^{flag}	0	EventFlag
kVq12	k_{Vq12}	$\frac{-I_{q1}+I_{q2}}{-V_{q1}+V_{q2}}$	ConstService
kVq23	k_{Vq23}	$\frac{-I_{q2}+I_{q3}}{-V_{q2}+V_{q3}}$	ConstService
kVq34	k_{Vq34}	$\frac{-I_{q3}+I_{q4}}{-V_{q3}+V_{q4}}$	ConstService
zVDL1	z_{VDL1}	$I_{q1} \le I_{q2} \wedge I_{q2} \le I_{q3} \wedge I_{q3} \le I_{q4} \wedge V_{q1} \le V_{q2} \wedge V_{q2} \le V_{q3} \wedge V_{q3} \le V_{q4}$	ConstService
kVp12	k_{Vp12}	$\frac{-I_{p1}+I_{p2}}{-V_{p1}+V_{p2}}$	ConstService
kVp23	k_{Vp23}	$\frac{-I_{p2}+I_{p3}}{-V_{p2}+V_{p3}}$	ConstService
kVp34	k_{Vp34}	$\frac{-I_{p3}+I_{p4}}{-V_{p3}+V_{p4}}$	ConstService
zVDL2	z_{VDL2}	$I_{p1} \le I_{p2} \wedge I_{p2} \le I_{p3} \wedge I_{p3} \le I_{p4} \wedge V_{p1} \le V_{p2} \wedge V_{p2} \le V_{p3} \wedge V_{p3} \le V_{p4}$	ConstService
fThld2	$fThld2$	0	ExtendedEvent

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Table 26 – continued from previous page

Name	Symbol	Equation	Type
VDL1c	$VDL1c$	$y_{V_{DL1}} < I_{maxr}$	VarService
VDL2c	$VDL2c$	$y_{V_{DL2}} < I_{maxr}$	VarService
Ipmax2sq0	$I^2_{pmax20,nn}$	FixPiecewise $\left((0,\ I^2_{max} - Iqcmd^2_0 \leq 0), (I^2_{max} - Iqcmd^2_0,\ \text{True})\right)$	ConstService
Ipmax2sq	I^2_{pmax2}	FixPiecewise $\left(\left(0,\ I^2_{max} - y^2_{IqHL} \leq 0\right), \left(I^2_{max} - y^2_{IqHL},\ \text{True}\right)\right)$	VarService
Ipmaxh	$Ipmaxh$	0	VarHold
Iqmax2sq0	$I^2_{qmax,nn}$	FixPiecewise $\left((0,\ I^2_{max} - Ipcmd^2_0 \leq 0), (I^2_{max} - Ipcmd^2_0,\ \text{True})\right)$	ConstService
Iqmax2sq	I^2_{qmax2}	FixPiecewise $\left(\left(0,\ I^2_{max} - y^2_{IpHL} \leq 0\right), \left(I^2_{max} - y^2_{IpHL},\ \text{True}\right)\right)$	VarService
Ipmin	I_{pmin}	0.0	ConstService
PIV_flag	z^{flag}_{PIV}	0	EventFlag

Discretes

Name	Symbol	Type	Info
SWPF	SW_{PF}	Switcher	
SWV	SW_V	Switcher	
SWQ	SW_V	Switcher	
SWP	SW_P	Switcher	
SWPQ	SW_{PQ}	Switcher	
zp	zp	IsEqual	
Vcmp	V_{cmp}	Limiter	Voltage dip comparator
VLower	$VLower$	Limiter	Limiter for lower voltage cap
PFlim	$PFlim$	Limiter	
PIQ_lim	lim_{PIQ}	HardLimiter	
Vsel_lim	lim_{Vsel}	HardLimiter	
dbV_db	db_{dbV}	DeadBand	
pfilt_lim	$lim_{P_{filt}}$	RateLimiter	Rate limiter in Lag
s5_lim	lim_{s5}	AntiWindup	Limiter in Lag
PIV_lim	lim_{PIV}	HardLimiter	
IpHL_lim	lim_{IpHL}	HardLimiter	
IqHL_lim	lim_{IqHL}	HardLimiter	

Blocks

Name	Symbol	Type	Info
s0	$s0$	Lag	Voltage filter
S1	S_1	Lag	Pe filter
PIQ	PIQ	PITrackAWFreeze	
Vsel	$Vsel$	GainLimiter	Selection output of VFLAG
s4	s_4	LagFreeze	Filter for calculated voltage with freeze
dbV	dbV	DeadBand1	Deadband for voltage error (ref0)
pfilt	P_{filt}	LagRate	Active power filter with rate limits
s5	$s5$	LagAWFreeze	
VDL1	V_{DL1}	Piecewise	Piecewise linear characteristics of Vq-Iq
VDL2	V_{DL2}	Piecewise	Piecewise linear characteristics of Vp-Ip
PIV	PIV	PITrackAWFreeze	
IpHL	$IpHL$	GainLimiter	
IqHL	$IqHL$	GainLimiter	

Config Fields in [REECA1E]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
kqs	K_{qs}	2	Q PI controller tracking gain	
kvs	K_{vs}	2	Voltage PI controller tracking gain	
tpfilt	T_{pfilt}	0.020	Time const. for Pref filter	

5.23.3 REECA1G

REECA1G is a variant of REECA1E.

REECA1G uses speed from synchronous generators.

The application of this model is limited because it is uncommon to connect a SynGen on the same bus as a RenGen.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
reg		Renewable generator idx			mandatory
busr		Optional remote bus for voltage control			
PFFLAG		Power factor control flag; 1-PF control, 0-Q control		*bool*	mandatory
VFLAG		Voltage control flag; 1-Q control, 0-V control		*bool*	mandatory
QFLAG		Q control flag; 1-V or Q control, 0-const. PF or Q		*bool*	mandatory
PFLAG		P speed-dependency flag; 1-has speed dep., 0-no dep.		*bool*	mandatory
PQFLAG		P/Q priority flag for I limit; 0-Q priority, 1-P priority		*bool*	mandatory
Vdip	V_{dip}	Low V threshold to activate Iqinj logic	0.800	*p.u.*	
Vup	V_{up}	V threshold above which to activate Iqinj logic	1.200	*p.u.*	
Trv	T_{rv}	Voltage filter time constant	0.020		
dbd1	d_{bd1}	Lower bound of the voltage deadband (<=0)	-0.020		
dbd2	d_{bd2}	Upper bound of the voltage deadband (>=0)	0.020		
Kqv	K_{qv}	Gain to compute Iqinj from V error (caution!!)	1		
Iqh1	I_{qh1}	Upper limit on Iqinj	999		
Iql1	I_{ql1}	Lower limit on Iqinj	-999		
Vref0	V_{ref0}	User defined Vref (if 0, use initial bus V)	1		
Iqfrz	I_{qfrz}	Hold Iqinj at the value for Thld (>0) seconds following a Vdip	0		
Thld	T_{hld}	Time for which Iqinj is held. Hold at Iqinj if>0; hold at State 1 if<0	0	*s*	
Thld2	T_{hld2}	Time for which IPMAX is held after voltage dip ends	0	*s*	
Tp	T_p	Filter time constant for Pe	0.020	*s*	
QMax	Q_{max}	Upper limit for reactive power regulator	999		
QMin	Q_{min}	Lower limit for reactive power regulator	-999		
VMAX	V_{max}	Upper limit for voltage control	999		
VMIN	V_{min}	Lower limit for voltage control	-999		
Kqp	K_{qp}	Proportional gain for reactive power error	1		
Kqi	K_{qi}	Integral gain for reactive power error	0.100		
Kvp	K_{vp}	Proportional gain for voltage error	1		
Kvi	K_{vi}	Integral gain for voltage error	0.100		
Vref1	V_{ref1}	Voltage ref. if VFLAG=0	1		non_zero
Tiq	T_{iq}	Filter time constant for Iq	0.020		
dPmax	d_{Pmax}	Power reference max. ramp rate (>0)	999		
dPmin	d_{Pin}	Power reference min. ramp rate (<0)	-999		
PMAX	P_{max}	Max. active power limit > 0	999		
PMIN	P_{min}	Min. active power limit	0		
Imax	I_{max}	Max. apparent current limit	999		current
Tpord	T_{pord}	Filter time constant for power setpoint	0.020		
Vq1	V_{q1}	Reactive power V-I pair (point 1), voltage	0.200		
Iq1	I_{q1}	Reactive power V-I pair (point 1), current	2		current
Vq2	V_{q2}	Reactive power V-I pair (point 2), voltage	0.400		

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Table 27 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
Iq2	I_{q2}	Reactive power V-I pair (point 2), current	4		current
Vq3	V_{q3}	Reactive power V-I pair (point 3), voltage	0.800		
Iq3	I_{q3}	Reactive power V-I pair (point 3), current	8		current
Vq4	V_{q4}	Reactive power V-I pair (point 4), voltage	1		
Iq4	I_{q4}	Reactive power V-I pair (point 4), current	10		current
Vp1	V_{p1}	Active power V-I pair (point 1), voltage	0.200		
Ip1	I_{p1}	Active power V-I pair (point 1), current	2		current
Vp2	V_{p2}	Active power V-I pair (point 2), voltage	0.400		
Ip2	I_{p2}	Active power V-I pair (point 2), current	4		current
Vp3	V_{p3}	Active power V-I pair (point 3), voltage	0.800		
Ip3	I_{p3}	Active power V-I pair (point 3), current	8		current
Vp4	V_{p4}	Active power V-I pair (point 4), voltage	1		
Ip4	I_{p4}	Active power V-I pair (point 4), current	12		current
Kf	K_{df}	gain for frequency deviation	0		
sg		synchronous gen idx			mandatory
bus		Retrieved bus idx			
gen		Retrieved StaticGen idx			
Sn	S_n		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
s0_y	y_{s0}	State	State in lag transfer function		v_str
S1_y	y_{S_1}	State	State in lag transfer function		v_str
PIQ_xi	xi_{PIQ}	State	Integrator output		v_str
s4_y	y_{s_4}	State	State in lag transfer function		v_str
pfilt_y	$y_{P_{filt}}$	State	State in lag TF		v_str
s5_y	y_{s5}	State	State in lag TF		v_str
PIV_xi	xi_{PIV}	State	Integrator output		v_str
Pord	$Pord$	AliasState	Alias of s5_y		
omega	ω	ExtState	generator speed	*pu*	
vp	V_p	Algeb	Sensed lower-capped voltage		v_str
pfaref	Φ_{ref}	Algeb	power factor angle ref	*rad*	v_str
Qref	Q_{ref}	Algeb	external Q ref	*p.u.*	v_str
Qcpf	Q_{cpf}	Algeb	Q calculated from P and power factor	*p.u.*	v_str
PFsel	$PFsel$	Algeb	Output of PFFLAG selector		v_str
Qerr	Q_{err}	Algeb	Reactive power error		v_str
PIQ_ys	ys_{PIQ}	Algeb	PI summation before limit		v_str
PIQ_y	y_{PIQ}	Algeb	PI output		v_str
Vsel_x	x_{Vsel}	Algeb	Value before limiter		v_str
Vsel_y	y_{Vsel}	Algeb	Output after limiter and post gain		v_str

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Table 28 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
Verr	V_{err}	Algeb	Voltage error (Vref0)		v_str
dbV_y	y_{dbV}	Algeb	Deadband type 1 output		v_str
Iqinj	I_{qinj}	Algeb	Additional Iq signal during under- or over-voltage		v_str
wg	ω_g	Algeb	Drive train generator speed		v_str
Pref	P_{ref}	Algeb	external P ref	*p.u.*	v_str
Psel	P_{sel}	Algeb	Output selection of PFLAG		v_str
VDL1_y	$y_{V_{DL1}}$	Algeb	Output of piecewise		v_str
VDL2_y	$y_{V_{DL2}}$	Algeb	Output of piecewise		v_str
Ipmax	I_{pmax}	Algeb	Upper limit on Ipcmd		v_str
Iqmax	I_{qmax}	Algeb	Upper limit on Iqcmd		v_str
PIV_ys	ys_{PIV}	Algeb	PI summation before limit		v_str
PIV_y	y_{PIV}	Algeb	PI output		v_str
Qsel	Q_{sel}	Algeb	Selection output of QFLAG		v_str
IpHL_x	x_{IpHL}	Algeb	Value before limiter		v_str
IpHL_y	y_{IpHL}	Algeb	Output after limiter and post gain		v_str
IqHL_x	x_{IqHL}	Algeb	Value before limiter		v_str
IqHL_y	y_{IqHL}	Algeb	Output after limiter and post gain		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V_d	ExtAlgeb	d-axis bus voltage magnitude		
Pe	Pe	ExtAlgeb	Retrieved Pe of RenGen		
Qe	Qe	ExtAlgeb	Retrieved Qe of RenGen		
Ipcmd	$Ipcmd$	ExtAlgeb	Retrieved Ipcmd of RenGen		
Iqcmd	$Iqcmd$	ExtAlgeb	Retrieved Iqcmd of RenGen		

Initialization Equations

Name	Symbol	Type	Initial Value
s0_y	y_{s0}	State	V_d
S1_y	y_{S_1}	State	Pe
PIQ_xi	xi_{PIQ}	State	0.0
s4_y	y_{s_4}	State	$\frac{PFsel}{V_p}$
pfilt_y	$y_{P_{filt}}$	State	P_{ref}
s5_y	y_{s5}	State	P_{sel}
PIV_xi	xi_{PIV}	State	$-Iqcmd_0 s_1^{SW_V}$
Pord	$Pord$	AliasState	
omega	ω	ExtState	
vp	V_p	Algeb	$V_d z_i^{VLower} + 0.01 z_l^{VLower}$
pfaref	Φ_{ref}	Algeb	Φ_{ref0}
Qref	Q_{ref}	Algeb	$-q_{ref0}$
Qcpf	Q_{cpf}	Algeb	Q_0
PFsel	$PFsel$	Algeb	$Q_{cpf} s_1^{SW_{PF}} + Q_{ref} s_0^{SW_{PF}}$

Table 29 – continued from previous pa

Name	Symbol	Type	Initial Value
Qerr	Q_{err}	Algeb	$PFsel z_i^{PFlim} + Q_{max} z_u^{PFlim} + Q_{min} z_l^{PFlim} - Qe$
PIQ_ys	ys_{PIQ}	Algeb	$K_{qp} Q_{err} s_1^{SW_V}$
PIQ_y	y_{PIQ}	Algeb	$V_{max} z_u^{lim_{PIQ}} + V_{min} z_l^{lim_{PIQ}} + ys_{PIQ} z_i^{lim_{PIQ}}$
Vsel_x	x_{Vsel}	Algeb	$s_0^{SW_V} \left(Q_{cpf} s_1^{SW_{PF}} + Q_{ref} s_0^{SW_{PF}} + V_{ref1} \right) + s_1^{SW_V} y_{PIQ}$
Vsel_y	y_{Vsel}	Algeb	$V_{max} z_u^{lim_{Vsel}} + V_{min} z_l^{lim_{Vsel}} + x_{Vsel} z_i^{lim_{Vsel}}$
Verr	V_{err}	Algeb	$V_{ref0} - y_{s0}$
dbV_y	y_{dbV}	Algeb	$1.0 z_l^{db_{dbV}} \left(V_{err} - d_{bd1} \right) + 1.0 z_u^{db_{dbV}} \left(V_{err} - d_{bd2} \right)$
Iqinj	I_{qinj}	Algeb	$K_{qv} y_{dbV} z_{Vdip} + fThld \left(1 - z_{Vdip}\right) \left(I_{qfrz} p_{Thld} + K_{qv} n_{Thld} y_{dbV} \right)$
wg	ω_g	Algeb	1.0
Pref	P_{ref}	Algeb	$\frac{P_0}{\omega_g}$
Psel	P_{sel}	Algeb	$\omega_g s_1^{SW_P} y_{P_{filt}} + s_0^{SW_P} y_{P_{filt}}$
VDL1_y	$y_{V_{DL1}}$	Algeb	FixPiecewise $\left((I_{q1},\ V_{q1} \geq y_{s0}), (I_{q1} + k_{Vq12} \left(-V_{q1} + y_{s0}\right),\ V_{q2} \geq y_{s0}), (I_{q2} + k_{Vq23}\right.$
VDL2_y	$y_{V_{DL2}}$	Algeb	FixPiecewise $\left((I_{p1},\ V_{p1} \geq y_{s0}), (I_{p1} + k_{Vp12} \left(-V_{p1} + y_{s0}\right),\ V_{p2} \geq y_{s0}), (I_{p2} + k_{Vp23}\right.$
Ipmax	I_{pmax}	Algeb	$(1 - fThld_2) \left(\sqrt{I_{pmax20,nn}^2} s_0^{SW_{PQ}} + s_1^{SW_{PQ}} \left(z_{VDL2} \left(I_{maxr} \left(1 - VDL2c\right) + VDL2\right.\right.\right.$
Iqmax	I_{qmax}	Algeb	$\sqrt{I_{qmax,nn}^2} s_1^{SW_{PQ}} + s_0^{SW_{PQ}} \left(z_{VDL1} \left(I_{maxr} \left(1 - VDL1c\right) + VDL1c y_{V_{DL1}} \right) - 100000\right.$
PIV_ys	ys_{PIV}	Algeb	$-Iqcmd_0 s_1^{SW_V} + K_{vp} s_1^{SW_V} \left(-s_0^{SW_V} y_{s0} + y_{Vsel} \right)$
PIV_y	y_{PIV}	Algeb	$I_{qmax} z_u^{lim_{PIV}} + I_{qmin} z_l^{lim_{PIV}} + ys_{PIV} z_i^{lim_{PIV}}$
Qsel	Q_{sel}	Algeb	$s_0^{SW_V} y_{s_4} + s_1^{SW_V} y_{PIV}$
IpHL_x	x_{IpHL}	Algeb	$\frac{y_{s5}}{V_p}$
IpHL_y	y_{IpHL}	Algeb	$I_{pmax} z_u^{lim_{IpHL}} + I_{pmin} z_l^{lim_{IpHL}} + x_{IpHL} z_i^{lim_{IpHL}}$
IqHL_x	x_{IqHL}	Algeb	$I_{qinj} + Q_{sel}$
IqHL_y	y_{IqHL}	Algeb	$I_{qmax} z_u^{lim_{IqHL}} + I_{qmin} z_l^{lim_{IqHL}} + x_{IqHL} z_i^{lim_{IqHL}}$
a	θ	ExtAlgeb	
v	V_d	ExtAlgeb	
Pe	Pe	ExtAlgeb	
Qe	Qe	ExtAlgeb	
Ipcmd	$Ipcmd$	ExtAlgeb	
Iqcmd	$Iqcmd$	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s0_y	y_{s0}	State	$V_d - y_{s0}$	T_{rv}
S1_y	y_{S_1}	State	$Pe - y_{S_1}$	T_p
PIQ_xi	xi_{PIQ}	State	$K_{qi}\left(1 - z_{Vdip}\right)\left(Q_{err}s_1^{SW_V} + 2y_{PIQ} - 2ys_{PIQ}\right)$	
s4_y	y_{s_4}	State	$\left(1 - z_{Vdip}\right)\left(\frac{PFsel}{V_p} - y_{s_4}\right)$	T_{iq}
pfilt_y	$y_{P_{filt}}$	State	$P_{ref} - y_{P_{filt}}$	0.02
s5_y	y_{s5}	State	$\left(1 - z_{Vdip}\right)\left(P_{sel} - y_{s5}\right)$	T_{pord}
PIV_xi	xi_{PIV}	State	$K_{vi}\left(1 - z_{Vdip}\right)\left(s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right) + 2y_{PIV} - 2ys_I\right.$	
Pord	$Pord$	AliasState	0	
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vp	V_p	Algeb	$V_d z_i^{VLower} - V_p + 0.01 z_l^{VLower}$
pfaref	Φ_{ref}	Algeb	$\Phi_{ref0} - \Phi_{ref}$
Qref	Q_{ref}	Algeb	$-Q_{ref} - q_{ref0}$
Qcpf	Q_{cpf}	Algeb	$\left(1 - z_1^{zp}\right)\left(-Q_{cpf} + y_{S_1}\tan\left(\Phi_{ref}\right)\right)$
PFsel	$PFsel$	Algeb	$-PFsel + Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}}$
Qerr	Q_{err}	Algeb	$PFsel z_i^{PFlim} - Q_{err} + Q_{max}z_u^{PFlim} + Q_{min}z_l^{PFlim} - Qe$
PIQ_ys	ys_{PIQ}	Algeb	$\left(1 - z_{Vdip}\right)\left(K_{qp}Q_{err}s_1^{SW_V} + xi_{PIQ} - ys_{PIQ}\right)$
PIQ_y	y_{PIQ}	Algeb	$\left(1 - z_{Vdip}\right)\left(V_{max}z_u^{lim_{PIQ}} + V_{min}z_l^{lim_{PIQ}} - y_{PIQ} + ys_{PIQ}z_i^{lim_{PIQ}}\right)$
Vsel_x	x_{Vsel}	Algeb	$s_0^{SW_V}\left(Q_{cpf}s_1^{SW_{PF}} + Q_{ref}s_0^{SW_{PF}} + V_{ref1}\right) + s_1^{SW_V}y_{PIQ} - x_{Vsel}$
Vsel_y	y_{Vsel}	Algeb	$V_{max}z_u^{lim_{Vsel}} + V_{min}z_l^{lim_{Vsel}} + x_{Vsel}z_i^{lim_{Vsel}} - y_{Vsel}$
Verr	V_{err}	Algeb	$-V_{err} + V_{ref0} - y_{s0}$
dbV_y	y_{dbV}	Algeb	$-y_{dbV} + 1.0z_l^{db_{dbV}}\left(V_{err} - d_{bd1}\right) + 1.0z_u^{db_{dbV}}\left(V_{err} - d_{bd2}\right)$
Iqinj	I_{qinj}	Algeb	$-I_{qinj} + K_{qv}y_{dbV}z_{Vdip} + fThld\left(1 - z_{Vdip}\right)\left(I_{qfrz}p_{Thld} + K_{qv}n_{Thld}y_{dbV}\right)$
wg	ω_g	Algeb	$1.0 - \omega_g$
Pref	P_{ref}	Algeb	$-K_{df}\left(\omega - 1\right) + \frac{P_0}{\omega_g} - P_{ref}$
Psel	P_{sel}	Algeb	$-P_{sel} + \omega_g s_1^{SW_P}y_{P_{filt}} + s_0^{SW_P}y_{P_{filt}}$
VDL1_y	$y_{V_{DL1}}$	Algeb	$-y_{V_{DL1}} + \text{FixPiecewise}\left(\left(I_{q1},\ V_{q1} \geq y_{s0}\right), \left(I_{q1} + k_{Vq12}\left(-V_{q1} + y_{s0}\right),\ V_{q2} \geq y_{s0}\right), \left(I\right.\right.$
VDL2_y	$y_{V_{DL2}}$	Algeb	$-y_{V_{DL2}} + \text{FixPiecewise}\left(\left(I_{p1},\ V_{p1} \geq y_{s0}\right), \left(I_{p1} + k_{Vp12}\left(-V_{p1} + y_{s0}\right),\ V_{p2} \geq y_{s0}\right), \left(I\right.\right.$
Ipmax	I_{pmax}	Algeb	$-I_{pmax} + Ipmaxhf Thld_2 + \left(1 - fThld_2\right)\left(\sqrt{I_{pmax2}^2}s_0^{SW_{PQ}} + s_1^{SW_{PQ}}\left(z_{VDL2}\left(I_{max}\right.\right.\right.$
Iqmax	I_{qmax}	Algeb	$\sqrt{I_{qmax2}^2}s_1^{SW_{PQ}} - I_{qmax} + s_0^{SW_{PQ}}\left(z_{VDL1}\left(I_{maxr}\left(1 - VDL1c\right) + VDL1cy_{V_{DL1}}\right) -$
PIV_ys	ys_{PIV}	Algeb	$\left(1 - z_{Vdip}\right)\left(K_{vp}s_1^{SW_V}\left(-s_0^{SW_V}y_{s0} + y_{Vsel}\right) + xi_{PIV} - ys_{PIV}\right)$

Table 30 – continued from previou

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
PIV_y	y_{PIV}	Algeb	$(1 - z_{Vdip}) \left(I_{qmax} z_u^{lim_{PIV}} + I_{qmin} z_l^{lim_{PIV}} - y_{PIV} + ys_{PIV} z_i^{lim_{PIV}} \right)$
Qsel	Q_{sel}	Algeb	$-Q_{sel} + s_0^{SW_V} y_{s_4} + s_1^{SW_V} y_{PIV}$
IpHL_x	x_{IpHL}	Algeb	$-x_{IpHL} + \frac{y_{s5}}{V_p}$
IpHL_y	y_{IpHL}	Algeb	$I_{pmax} z_u^{lim_{IpHL}} + I_{pmin} z_l^{lim_{IpHL}} + x_{IpHL} z_i^{lim_{IpHL}} - y_{IpHL}$
IqHL_x	x_{IqHL}	Algeb	$I_{qinj} + Q_{sel} - x_{IqHL}$
IqHL_y	y_{IqHL}	Algeb	$I_{qmax} z_u^{lim_{IqHL}} + I_{qmin} z_l^{lim_{IqHL}} + x_{IqHL} z_i^{lim_{IqHL}} - y_{IqHL}$
a	θ	ExtAlgeb	0
v	V_d	ExtAlgeb	0
Pe	Pe	ExtAlgeb	0
Qe	Qe	ExtAlgeb	0
Ipcmd	$Ipcmd$	ExtAlgeb	$-Ipcmd_0 + y_{IpHL}$
Iqcmd	$Iqcmd$	ExtAlgeb	$-Iqcmd_0 - y_{IqHL}$

Services

Name	Symbol	Equation	Type
Ipcmd0	$Ipcmd0$	$\frac{P_0}{V_d}$	ConstService
Iqcmd0	$Iqcmd0$	$-\frac{Q_0}{V_d}$	ConstService
pfaref0	Φ_{ref0}	$\text{atan}_2(Q_0, P_0)$	ConstService
Volt_dip	z_{Vdip}	$1 - z_i^{V_{cmp}}$	VarService
qref0	q_{ref0}	$Iqcmd_0 s_0^{SW_V} \left(V_d z_i^{VLower} + 0.01 z_l^{VLower} \right) + s_1^{SW_V} \left(V_d - V_{ref1} \right)$	ConstService
PIQ_flag	z_{PIQ}^{flag}	0	EventFlag
s4_flag	$z_{s_4}^{flag}$	0	EventFlag
pThld	p_{Thld}	Indicator $(T_{hld} > 0)$	ConstService
nThld	n_{Thld}	Indicator $(T_{hld} < 0)$	ConstService
Thld_abs	$\lvert Thld \rvert$	$\lvert T_{hld} \rvert$	ConstService
fThld	$fThld$	0	ExtendedEvent
s5_flag	z_{s5}^{flag}	0	EventFlag
kVq12	k_{Vq12}	$\frac{-I_{q1}+I_{q2}}{-V_{q1}+V_{q2}}$	ConstService
kVq23	k_{Vq23}	$\frac{-I_{q2}+I_{q3}}{-V_{q2}+V_{q3}}$	ConstService
kVq34	k_{Vq34}	$\frac{-I_{q3}+I_{q4}}{-V_{q3}+V_{q4}}$	ConstService
zVDL1	z_{VDL1}	$I_{q1} \le I_{q2} \wedge I_{q2} \le I_{q3} \wedge I_{q3} \le I_{q4} \wedge V_{q1} \le V_{q2} \wedge V_{q2} \le V_{q3} \wedge V_{q3} \le V_{q4}$	ConstService
kVp12	k_{Vp12}	$\frac{-I_{p1}+I_{p2}}{-V_{p1}+V_{p2}}$	ConstService
kVp23	k_{Vp23}	$\frac{-I_{p2}+I_{p3}}{-V_{p2}+V_{p3}}$	ConstService
kVp34	k_{Vp34}	$\frac{-I_{p3}+I_{p4}}{-V_{p3}+V_{p4}}$	ConstService
zVDL2	z_{VDL2}	$I_{p1} \le I_{p2} \wedge I_{p2} \le I_{p3} \wedge I_{p3} \le I_{p4} \wedge V_{p1} \le V_{p2} \wedge V_{p2} \le V_{p3} \wedge V_{p3} \le V_{p4}$	ConstService
fThld2	$fThld2$	0	ExtendedEvent
VDL1c	$VDL1c$	$y_{V_{DL1}} < I_{maxr}$	VarService

continues on next page

Table 31 – continued from previous page

Name	Symbol	Equation	Type
VDL2c	$VDL2c$	$y_{V_{DL2}} < I_{maxr}$	VarService
Ipmax2sq0	$I^2_{pmax20,nn}$	FixPiecewise $\left((0,\ I^2_{max} - Iqcmd_0^2 \leq 0), (I^2_{max} - Iqcmd_0^2,\ \text{True})\right)$	ConstService
Ipmax2sq	I^2_{pmax2}	FixPiecewise $\left(\left(0,\ I^2_{max} - y^2_{IqHL} \leq 0\right), \left(I^2_{max} - y^2_{IqHL},\ \text{True}\right)\right)$	VarService
Ipmaxh	$Ipmaxh$	0	VarHold
Iqmax2sq0	$I^2_{qmax,nn}$	FixPiecewise $\left((0,\ I^2_{max} - Ipcmd_0^2 \leq 0), (I^2_{max} - Ipcmd_0^2,\ \text{True})\right)$	ConstService
Iqmax2sq	I^2_{qmax2}	FixPiecewise $\left(\left(0,\ I^2_{max} - y^2_{IpHL} \leq 0\right), \left(I^2_{max} - y^2_{IpHL},\ \text{True}\right)\right)$	VarService
Ipmin	I_{pmin}	0.0	ConstService
PIV_flag	z^{flag}_{PIV}	0	EventFlag

Discretes

Name	Symbol	Type	Info
SWPF	SW_{PF}	Switcher	
SWV	SW_V	Switcher	
SWQ	SW_V	Switcher	
SWP	SW_P	Switcher	
SWPQ	SW_{PQ}	Switcher	
zp	zp	IsEqual	
Vcmp	V_{cmp}	Limiter	Voltage dip comparator
VLower	$VLower$	Limiter	Limiter for lower voltage cap
PFlim	$PFlim$	Limiter	
PIQ_lim	lim_{PIQ}	HardLimiter	
Vsel_lim	lim_{Vsel}	HardLimiter	
dbV_db	db_{dbV}	DeadBand	
pfilt_lim	$lim_{P_{filt}}$	RateLimiter	Rate limiter in Lag
s5_lim	lim_{s5}	AntiWindup	Limiter in Lag
PIV_lim	lim_{PIV}	HardLimiter	
IpHL_lim	lim_{IpHL}	HardLimiter	
IqHL_lim	lim_{IqHL}	HardLimiter	

Blocks

Name	Symbol	Type	Info
s0	$s0$	Lag	Voltage filter
S1	S_1	Lag	Pe filter
PIQ	PIQ	PITrackAWFreeze	
Vsel	$Vsel$	GainLimiter	Selection output of VFLAG
s4	s_4	LagFreeze	Filter for calculated voltage with freeze
dbV	dbV	DeadBand1	Deadband for voltage error (ref0)
pfilt	P_{filt}	LagRate	Active power filter with rate limits
s5	$s5$	LagAWFreeze	
VDL1	V_{DL1}	Piecewise	Piecewise linear characteristics of Vq-Iq
VDL2	V_{DL2}	Piecewise	Piecewise linear characteristics of Vp-Ip
PIV	PIV	PITrackAWFreeze	
IpHL	$IpHL$	GainLimiter	
IqHL	$IqHL$	GainLimiter	

Config Fields in [REECA1G]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
kqs	K_{qs}	2	Q PI controller tracking gain	
kvs	K_{vs}	2	Voltage PI controller tracking gain	
tpfilt	T_{pfilt}	0.020	Time const. for Pref filter	

5.24 RenGen

Renewable generator (converter) group.

See *SynGen* for the notes on replacing StaticGen and setting the power ratio parameters.

Attention is needed for the power base `Sn`. When replacing a synchronous generator, the renewable generator should have the same or larger `Sn`. Improper `Sn` will cause the initial values to exceed typical per-unit ranges and cause the initialization to fail.

Common Parameters: u, name, bus, gen, Sn

Common Variables: Pe, Qe

Available models: *REGCA1*, *REGCP1*, *REGCV1*, *REGCV2*, *REGF1*, *REGF2*, *REGF3*

5.24.1 REGCA1

Renewable energy generator model type A.

Implements `REGCA1` in PSS/E, or `REGC_A` in PSLF and Powerworld.

Volim is the voltage limit for high voltage reactive current management, which should be large than static bus voltage (Volim > v), or initialization error will occur.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	Model MVA base	100	*MVA*	
Tg	T_g	converter time const.	0.100	*s*	
Rrpwr	R_{rpwr}	Low voltage power logic (LVPL) ramp limit	10	*p.u.*	
Brkpt	B_{rkpt}	LVPL characteristic voltage 2	1	*p.u.*	
Zerox	Z_{erox}	LVPL characteristic voltage 1	0.500	*p.u*	
Lvplsw	z_{Lvplsw}	Low volt. P logic: 1-enable, 0-disable	1	*bool*	
Lvpl1	L_{vpl1}	LVPL gain at Brkpt	1	*p.u*	
Volim	V_{olim}	Voltage lim for high volt. reactive current mgnt.	1.200	*p.u.*	
Lvpnt1	L_{vpnt1}	High volt. point for low volt. active current mgnt.	0.800	*p.u.*	
Lvpnt0	L_{vpnt0}	Low volt. point for low volt. active current mgnt.	0.400	*p.u.*	
Iolim	I_{olim}	lower current limit for high volt. reactive current mgnt.	-1.500	*p.u. (mach base)*	current
Tfltr	T_{fltr}	Voltage filter T const for low volt. active current mgnt.	0.100	*s*	
Khv	K_{hv}	Overvolt. compensation gain in high volt. reactive current mgnt.	0.700		
Iqrmax	I_{qrmax}	Upper limit on the ROC for reactive current	1	*p.u.*	current
Iqrmin	I_{qrmin}	Lower limit on the ROC for reactive current	-1	*p.u.*	current
Accel	A_{ccel}	Acceleration factor	0		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
ra	r_a		0		
xs	x_s		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
S1_y	y_{S_1}	State	State in lag TF		v_str
S2_y	y_{S_2}	State	State in lag transfer function		v_str
S0_y	y_{S_0}	State	State in lag TF		v_str
LVG_y	$y_{L_{VG}}$	Algeb	Output of piecewise		v_str
Ipcmd	I_{pcmd}	Algeb	current component for active power		v_str
Iqcmd	I_{qcmd}	Algeb	current component for reactive power		v_str
LVPL_y	$y_{L_{VPL}}$	Algeb	Output of piecewise		v_str
Ipout	I_{pout}	Algeb	Output Ip current		v_str
HVG_x	$x_{H_{VG}}$	Algeb	Value before limiter		v_str
HVG_y	$y_{H_{VG}}$	Algeb	Output after limiter and post gain		v_str
Iqout_x	x_{Iqout}	Algeb	Value before limiter		v_str
Iqout_y	y_{Iqout}	Algeb	Output after limiter and post gain		v_str
Pe	P_e	Algeb	Active power output		v_str
Qe	Q_e	Algeb	Reactive power output		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		
vd	vd	AliasAlgeb	Alias of v		

Initialization Equations

Name	Symbol	Type	Initial Value
S1_y	y_{S_1}	State	$-I_{qcmd}$
S2_y	y_{S_2}	State	$1.0V$
S0_y	y_{S_0}	State	I_{pcmd}
LVG_y	$y_{L_{VG}}$	Algeb	FixPiecewise $\left((0,\ L_{vpnt0} \geq V), (k_{LVG}\left(-L_{vpnt0}+V\right),\ L_{vpnt1} \geq V), (1,\ \text{True})\right)$
Ipcmd	I_{pcmd}	Algeb	$\frac{I_{pcmd0}\,\text{Indicator}\left(y_{L_{VG}}>0\right)}{y_{L_{VG}}} + \text{Indicator}\left(y_{L_{VG}} \leq 0\right)$
Iqcmd	I_{qcmd}	Algeb	I_{qcmd0}
LVPL_	$y_{L_{VPL}}$	Algeb	FixPiecewise $\left((9999 - 9999 z_{Lvplsw},\ Z_{erox} \geq y_{S_2}), (k_{LVPL}\left(-Z_{erox}+y_{S_2}\right) - 9999 z_{Lvplsw} + 9\right.$
Ipout	I_{pout}	Algeb	$I_{pcmd} y_{L_{VG}}$
HVG_	$x_{H_{VG}}$	Algeb	$K_{hv}\left(V - V_{olim}\right)$
HVG_	$y_{H_{VG}}$	Algeb	$x_{H_{VG}} z_i^{lim_{H_{VG}}}$
Iqout_	$x_{I^{qout}}$	Algeb	$-y_{H_{VG}} + y_{S_1}$
Iqout_	$y_{I^{qout}}$	Algeb	$I_{olim} z_l^{lim_{I^{qout}}} + x_{I^{qout}} z_i^{lim_{I^{qout}}}$
Pe	P_e	Algeb	P_0
Qe	Q_e	Algeb	Q_0
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
vd	vd	AliasAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
S1_y	y_{S_1}	State	$-I_{qcmd} - y_{S_1}$	T_g
S2_y	y_{S_2}	State	$1.0V - y_{S_2}$	T_{fltr}
S0_y	y_{S_0}	State	$I_{pcmd} - y_{S_0}$	T_g

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
LVG_	$y_{L_{VG}}$	Algeb	$-y_{L_{VG}}$+FixPiecewise $\left((0,\ L_{vpnt0} \geq V), (k_{LVG}\left(-L_{vpnt0}+V\right),\ L_{vpnt1} \geq V), (1,\ \text{True})\right)$
Ipcmd	I_{pcmd}	Algeb	$-I_{pcmd} + Ipcmd_{0LVG}$
Iqcmd	I_{qcmd}	Algeb	$I_{qcmd0} - I_{qcmd}$
LVPL	$y_{L_{VPL}}$	Algeb	$-y_{L_{VPL}}$+FixPiecewise $\left((9999 - 9999z_{Lvplsw},\ Z_{erox} \geq y_{S_2}), (k_{LVPL}\left(-Z_{erox}+y_{S_2}\right) - 9999z_{L}\right.$
Ipout	I_{pout}	Algeb	$-I_{pout} + y_{L_{VG}} y_{S_0}$
HVG_	$x_{H_{VG}}$	Algeb	$K_{hv}\left(V - V_{olim}\right) - x_{H_{VG}}$
HVG_	$y_{H_{VG}}$	Algeb	$x_{H_{VG}} z_i^{lim_{H_{VG}}} - y_{H_{VG}}$
Iqout_	$x_{I^{qout}}$	Algeb	$-x_{I^{qout}} - y_{H_{VG}} + y_{S_1}$
Iqout_	$y_{I^{qout}}$	Algeb	$I_{olim} z_l^{lim_{I^{qout}}} + x_{I^{qout}} z_i^{lim_{I^{qout}}} - y_{I^{qout}}$
Pe	P_e	Algeb	$I_{pout} V - P_e$
Qe	Q_e	Algeb	$-Q_e + V y_{I^{qout}}$
a	θ	ExtAlgeb	$-P_e$
v	V	ExtAlgeb	$-Q_e$
vd	vd	AliasAlgeb	0

Services

Name	Symbol	Equation	Type
p0	P_0	$P_{0s}\gamma_P$	ConstService
q0	Q_0	$Q_{0s}\gamma_Q$	ConstService
q0gt0	$z_{q0>0}$	Indicator $(Q_0 > 0)$	ConstService
q0lt0	$z_{q0<0}$	Indicator $(Q_0 < 0)$	ConstService
Ipcmd0	I_{pcmd0}	$\frac{P_0}{V}$	ConstService
Iqcmd0	I_{qcmd0}	$-\frac{Q_0}{V}$	ConstService
Ipcmd0_LVG	$Ipcmd0_LVG$	I_{pcmd}	PostInitService
kLVG	k_{LVG}	$\frac{1}{-L_{vpnt0}+L_{vpnt1}}$	ConstService
kLVPL	k_{LVPL}	$\frac{L_{vpl1} z_{Lvplsw}}{B_{rkpt}-Z_{erox}}$	ConstService

Discretes

Name	Symbol	Type	Info
S1_lim	lim_{S_1}	AntiWindupRate	Limiter in Lag
S0_lim	lim_{S_0}	AntiWindupRate	Limiter in Lag
HVG_lim	$lim_{H_{VG}}$	HardLimiter	
Iqout_lim	$lim_{I^{qout}}$	HardLimiter	

Blocks

Name	Symbol	Type	Info
LVG	L_{VG}	Piecewise	Ip gain during low voltage
S1	S_1	LagAntiWindupRate	Iqcmd delay
S2	S_2	Lag	Voltage filter with no anti-windup
LVPL	L_{VPL}	Piecewise	Low voltage Ipcmd upper limit
S0	S_0	LagAntiWindupRate	
HVG	H_{VG}	GainLimiter	High voltage gain block
Iqout	I^{qout}	GainLimiter	Iq output block

Config Fields in [REGCA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.24.2 REGCP1

Renewable energy generator model (REGC_A) with PLL.

A PLL device can be specified for estimating the phase angle at the coupling bus through the `pll` parameter:

- If `pll` is not given, the accurate bus angle will be used.
- If `pll` is not a valid PLL device, the program will error out.
- The program does not check if the provided `pll` actually measures the bus on which the converter is at.

One needs to carefully tune the PLL parameters to match the desired performance.

All other remarks for `REGCA1` apply.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	Model MVA base	100	*MVA*	
Tg	T_g	converter time const.	0.100	*s*	
Rrpwr	R_{rpwr}	Low voltage power logic (LVPL) ramp limit	10	*p.u.*	
Brkpt	B_{rkpt}	LVPL characteristic voltage 2	1	*p.u.*	
Zerox	Z_{erox}	LVPL characteristic voltage 1	0.500	*p.u*	
Lvplsw	z_{Lvplsw}	Low volt. P logic: 1-enable, 0-disable	1	*bool*	
Lvpl1	L_{vpl1}	LVPL gain at Brkpt	1	*p.u*	
Volim	V_{olim}	Voltage lim for high volt. reactive current mgnt.	1.200	*p.u.*	
Lvpnt1	L_{vpnt1}	High volt. point for low volt. active current mgnt.	0.800	*p.u.*	
Lvpnt0	L_{vpnt0}	Low volt. point for low volt. active current mgnt.	0.400	*p.u.*	
Iolim	I_{olim}	lower current limit for high volt. reactive current mgnt.	-1.500	*p.u. (mach base)*	current
Tfltr	T_{fltr}	Voltage filter T const for low volt. active current mgnt.	0.100	*s*	
Khv	K_{hv}	Overvolt. compensation gain in high volt. reactive current mgnt.	0.700		
Iqrmax	I_{qrmax}	Upper limit on the ROC for reactive current	1	*p.u.*	current
Iqrmin	I_{qrmin}	Lower limit on the ROC for reactive current	-1	*p.u.*	current
Accel	A_{ccel}	Acceleration factor	0		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
pll		Phase-lock loop device idx			
ra	r_a		0		
xs	x_s		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
S1_y	y_{S_1}	State	State in lag TF		v_str
S2_y	y_{S_2}	State	State in lag transfer function		v_str
S0_y	y_{S_0}	State	State in lag TF		v_str
am	θ_m	ExtState	Measured angle		
LVG_y	$y_{L_{VG}}$	Algeb	Output of piecewise		v_str
Ipcmd	I_{pcmd}	Algeb	current component for active power		v_str
Iqcmd	I_{qcmd}	Algeb	current component for reactive power		v_str
LVPL_y	$y_{L_{VPL}}$	Algeb	Output of piecewise		v_str
Ipout	I_{pout}	Algeb	Output Ip current		v_str
HVG_x	$x_{H_{VG}}$	Algeb	Value before limiter		v_str
HVG_y	$y_{H_{VG}}$	Algeb	Output after limiter and post gain		v_str
Iqout_x	x_{Iqout}	Algeb	Value before limiter		v_str
Iqout_y	y_{Iqout}	Algeb	Output after limiter and post gain		v_str
Pe	P_e	Algeb	Active power output		v_str
Qe	Q_e	Algeb	Reactive power output		v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
S1_y	y_{S_1}	State	$-I_{qcmd}$
S2_y	y_{S_2}	State	$1.0V$
S0_y	y_{S_0}	State	I_{pcmd}
am	θ_m	ExtStat	
LVG_y	$y_{L_{VG}}$	Algeb	FixPiecewise $\left((0,\ L_{vpnt0} \geq V), (k_{LVG}\left(-L_{vpnt0}+V\right),\ L_{vpnt1} \geq V), (1,\ \text{True})\right)$
Ipcmd	I_{pcmd}	Algeb	$\frac{I_{pcmd0}\,\text{Indicator}\left(y_{L_{VG}}>0\right)}{y_{L_{VG}}} + \text{Indicator}\left(y_{L_{VG}} \leq 0\right)$
Iqcmd	I_{qcmd}	Algeb	I_{qcmd0}
LVPL_	$y_{L_{VPL}}$	Algeb	FixPiecewise $\left((9999 - 9999 z_{Lvplsw},\ Z_{erox} \geq y_{S_2}), (k_{LVPL}\left(-Z_{erox}+y_{S_2}\right) - 9999 z_{Lvplsw} + 99\right.$
Ipout	I_{pout}	Algeb	$I_{pcmd} y_{L_{VG}}$
HVG_	$x_{H_{VG}}$	Algeb	$K_{hv}\left(V - V_{olim}\right)$
HVG_	$y_{H_{VG}}$	Algeb	$x_{H_{VG}} z_i^{lim_{H_{VG}}}$
Iqout_	$x_{I^{qout}}$	Algeb	$-y_{H_{VG}} + y_{S_1}$
Iqout_	$y_{I^{qout}}$	Algeb	$I_{olim} z_l^{lim_{I^{qout}}} + x_{I^{qout}} z_i^{lim_{I^{qout}}}$
Pe	P_e	Algeb	P_0
Qe	Q_e	Algeb	Q_0
vd	V_d	Algeb	V
vq	V_q	Algeb	0
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
S1_y	y_{S_1}	State	$-I_{qcmd} - y_{S_1}$	T_g
S2_y	y_{S_2}	State	$1.0V - y_{S_2}$	T_{fltr}
S0_y	y_{S_0}	State	$I_{pcmd} - y_{S_0}$	T_g
am	θ_m	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
LVG_	$y_{L_{VG}}$	Algeb	$-y_{L_{VG}}$+FixPiecewise $\left((0,\ L_{vpnt0} \geq V), (k_{LVG}\left(-L_{vpnt0}+V\right),\ L_{vpnt1} \geq V), (1,\ \text{True})\right)$
Ipcmd	I_{pcmd}	Algeb	$-I_{pcmd} + Ipcmd_{0LVG}$
Iqcmd	I_{qcmd}	Algeb	$I_{qcmd0} - I_{qcmd}$
LVPL_	$y_{L_{VPL}}$	Algeb	$-y_{L_{VPL}}$+FixPiecewise $\left((9999 - 9999z_{Lvplsw},\ Z_{erox} \geq y_{S_2}), (k_{LVPL}\left(-Z_{erox}+y_{S_2}\right) - 9999z_{Lv}\right.$
Ipout	I_{pout}	Algeb	$-I_{pout} + y_{L_{VG}} y_{S_0}$
HVG_	$x_{H_{VG}}$	Algeb	$K_{hv}\left(V - V_{olim}\right) - x_{H_{VG}}$
HVG_	$y_{H_{VG}}$	Algeb	$x_{H_{VG}} z_i^{lim_{H_{VG}}} - y_{H_{VG}}$
Iqout_	$x_{I^{qout}}$	Algeb	$-x_{I^{qout}} - y_{H_{VG}} + y_{S_1}$
Iqout_	$y_{I^{qout}}$	Algeb	$I_{olim} z_l^{lim_{I^{qout}}} + x_{I^{qout}} z_i^{lim_{I^{qout}}} - y_{I^{qout}}$
Pe	P_e	Algeb	$I_{pout} V_d - P_e + V_q y_{I^{qout}}$
Qe	Q_e	Algeb	$-I_{pout} V_q - Q_e + V_d y_{I^{qout}}$
vd	V_d	Algeb	$V\cos\left(z_{hetam}\left(\theta - \theta_m\right)\right) - V_d$
vq	V_q	Algeb	$-V\sin\left(z_{hetam}\left(\theta - \theta_m\right)\right) - V_q$
a	θ	ExtAlgeb	$-P_e$
v	V	ExtAlgeb	$-Q_e$

Services

Name	Symbol	Equation	Type
p0	P_0	$P_{0s}\gamma_P$	ConstService
q0	Q_0	$Q_{0s}\gamma_Q$	ConstService
q0gt0	$z_{q0>0}$	Indicator $(Q_0 > 0)$	ConstService
q0lt0	$z_{q0<0}$	Indicator $(Q_0 < 0)$	ConstService
Ipcmd0	I_{pcmd0}	$\frac{P_0}{V}$	ConstService
Iqcmd0	I_{qcmd0}	$-\frac{Q_0}{V}$	ConstService
Ipcmd0_LVG	$Ipcmd0_LVG$	I_{pcmd}	PostInitService
kLVG	k_{LVG}	$\frac{1}{-L_{vpnt0}+L_{vpnt1}}$	ConstService
kLVPL	k_{LVPL}	$\frac{L_{vpl1}z_{Lvplsw}}{B_{rkpt}-Z_{erox}}$	ConstService

Discretes

Name	Symbol	Type	Info
S1_lim	lim_{S_1}	AntiWindupRate	Limiter in Lag
S0_lim	lim_{S_0}	AntiWindupRate	Limiter in Lag
HVG_lim	$lim_{H_{VG}}$	HardLimiter	
Iqout_lim	$lim_{I^{qout}}$	HardLimiter	

Blocks

Name	Symbol	Type	Info
LVG	L_{VG}	Piecewise	Ip gain during low voltage
S1	S_1	LagAntiWindupRate	Iqcmd delay
S2	S_2	Lag	Voltage filter with no anti-windup
LVPL	L_{VPL}	Piecewise	Low voltage Ipcmd upper limit
S0	S_0	LagAntiWindupRate	
HVG	H_{VG}	GainLimiter	High voltage gain block
Iqout	I^{qout}	GainLimiter	Iq output block

Config Fields in [REGCP1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.24.3 REGCV1

Voltage-controlled VSC with VSG control.

Includes double-loop PI control and swing equation based VSG control. Voltage measurement delays are ignored.

Notes

- Extreme care needs to be taken when coordinating the PI controller parameters.
- Setting the primary frequency control droop `kw` can improve small-signal stability.
- The droop `kv` for voltage control (pu voltage / pu Q change), if used, needs to be chosen carefully. In most cases, `kv` should be a very small positive value if not zero.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
coi2		center of inertia 2 index			
Sn	S_n	Model MVA base	100	*MVA*	
fn	f	rated frequency	60		
Tc	T_c	switch time constant	0.010	*s*	
kw	k_ω	speed droop on active power (reciprocal of droop)	0	*p.u.*	non_negative,ipower
kv	k_v	reactive power droop on voltage	0	*p.u.*	non_negative,power
M	M	Emulated startup time constant (M=2H)	10	*s*	power
D	D	Emulated damping coefficient	0	*p.u.*	power
ra	r_a	resistance	0		z
xs	x_s	reactance	0.200		z
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
Kpvd	kp_{vd}	vd controller proportional gain	0.500	*p.u.*	power
Kivd	ki_{vd}	vd controller integral gain	0.020	*p.u.*	power
Kpvq	kp_{vq}	vq controller proportional gain	0.500	*p.u.*	power
Kivq	ki_{vq}	vq controller integral gain	0.020	*p.u.*	power
KpId	kp_{di}	Id controller proportional gain	0.200	*p.u.*	power
KiId	ki_{di}	Id controller integral gain	0.010	*p.u.*	power
KpIq	kp_{qi}	Iq controller proportional gain	0.200	*p.u.*	power
KiIq	ki_{qi}	Iq controller integral gain	0.010	*p.u.*	power

Variables

Name	Symbol	Type	Description	Unit	Properties
dw	$\Delta\omega$	State	delta virtual rotor speed	*pu (Hz)*	v_str
delta	δ	State	virtual delta	*rad*	v_str
PIvd_xi	xi_{PIvd}	State	Integrator output		v_str
PIvq_xi	xi_{PIvq}	State	Integrator output		v_str
PIId_xi	xi_{PIId}	State	Integrator output		v_str
PIIq_xi	xi_{PIIq}	State	Integrator output		v_str
udLag_y	y_{udLag}	State	State in lag transfer function		v_str
uqLag_y	y_{uqLag}	State	State in lag transfer function		v_str
ud	ud	AliasState	Alias of udLag_y		
uq	uq	AliasState	Alias of uqLag_y		
Pref2	P_{ref2}	Algeb	active power reference after adjusting by frequency		v_str
vref2	v_{ref2}	Algeb	voltage reference after adjusted by reactive power		v_str
omega	ω	Algeb	virtual rotor speed	*pu (Hz)*	v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
Pe	P_e	Algeb	active power injection from VSC		v_str
Qe	Q_e	Algeb	reactive power injection from VSC		v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
PIvd_y	y_{PIvd}	Algeb	PI output		v_str
PIvq_y	y_{PIvq}	Algeb	PI output		v_str
PIId_y	y_{PIId}	Algeb	PI output		v_str
PIIq_y	y_{PIIq}	Algeb	PI output		v_str
udref	u_{dref}	Algeb	ud reference		v_str
uqref	u_{qref}	Algeb	uq reference		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		
Idref	$Idref$	AliasAlgeb	Alias of PIvd_y		
Iqref	$Iqref$	AliasAlgeb	Alias of PIvq_y		

Initialization Equations

Name	Symbol	Type	Initial Value
dw	$\Delta\omega$	State	0
delta	δ	State	θ
PIvd_xi	xi_{PIvd}	State	I_{d0}
PIvq_xi	xi_{PIvq}	State	I_{q0}
PIId_xi	xi_{PIId}	State	0.0
PIIq_xi	xi_{PIIq}	State	0.0
udLag_y	y_{udLag}	State	u_{dref}
uqLag_y	y_{uqLag}	State	u_{qref}
ud	ud	AliasState	
uq	uq	AliasState	
Pref2	P_{ref2}	Algeb	$P_{ref}u$
vref2	v_{ref2}	Algeb	$V_{ref}u$
omega	ω	Algeb	u
vd	V_d	Algeb	v_{d0}
vq	V_q	Algeb	v_{q0}
Pe	P_e	Algeb	P_{ref}
Qe	Q_e	Algeb	Q_{ref}
Id	I_d	Algeb	I_{d0}
Iq	I_q	Algeb	I_{q0}
PIvd_y	y_{PIvd}	Algeb	$I_{d0} + kp_{vd}\left(V_d - v_{ref2}\right)$
PIvq_y	y_{PIvq}	Algeb	$I_{q0} + V_q kp_{vq}$
PIId_y	y_{PIId}	Algeb	$kp_{di}\left(I_d - y_{PIvd}\right)$
PIIq_y	y_{PIIq}	Algeb	$kp_{qi}\left(I_q - y_{PIvq}\right)$
udref	u_{dref}	Algeb	u_{dref0}
uqref	u_{qref}	Algeb	u_{qref0}
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
Idref	$Idref$	AliasAlgeb	
Iqref	$Iqref$	AliasAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
dw	$\Delta\omega$	State	$-D\Delta\omega - P_e + P_{ref2}$	M
delta	δ	State	$2\pi\Delta\omega f$	
PIvd_xi	xi_{PIvd}	State	$ki_{vd}\left(V_d - v_{ref2}\right)$	
PIvq_xi	xi_{PIvq}	State	$V_q ki_{vq}$	
PIId_xi	xi_{PIId}	State	$ki_{di}\left(I_d - y_{PIvd}\right)$	
PIIq_xi	xi_{PIIq}	State	$ki_{qi}\left(I_q - y_{PIvq}\right)$	
udLag_y	y_{udLag}	State	$u_{dref} - y_{udLag}$	T_c
uqLag_y	y_{uqLag}	State	$u_{qref} - y_{uqLag}$	T_c
ud	ud	AliasState	0	
uq	uq	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Pref2	P_{ref2}	Algeb	$-P_{ref2} + P_{ref}u - \Delta\omega k_\omega$
vref2	v_{ref2}	Algeb	$V_{ref} + k_v\left(-Q_e + Q_{ref}u\right) - v_{ref2}$
omega	ω	Algeb	$\Delta\omega - \omega + 1$
vd	V_d	Algeb	$Vu\cos\left(\delta - \theta\right) - V_d$
vq	V_q	Algeb	$-Vu\sin\left(\delta - \theta\right) - V_q$
Pe	P_e	Algeb	$I_d V_d + I_q V_q - P_e$
Qe	Q_e	Algeb	$I_d V_q - I_q V_d - Q_e$
Id	I_d	Algeb	$I_d r_a - I_q x_s + V_d - y_{udLag}$
Iq	I_q	Algeb	$I_d x_s + I_q r_a + V_q - y_{uqLag}$
PIvd_y	y_{PIvd}	Algeb	$kp_{vd}\left(V_d - v_{ref2}\right) + xi_{PIvd} - y_{PIvd}$
PIvq_y	y_{PIvq}	Algeb	$V_q kp_{vq} + xi_{PIvq} - y_{PIvq}$
PIId_y	y_{PIId}	Algeb	$kp_{di}\left(I_d - y_{PIvd}\right) + xi_{PIId} - y_{PIId}$
PIIq_y	y_{PIIq}	Algeb	$kp_{qi}\left(I_q - y_{PIvq}\right) + xi_{PIIq} - y_{PIIq}$
udref	u_{dref}	Algeb	$-Iqref x_s + V_d - u_{dref} + y_{PIId}$
uqref	u_{qref}	Algeb	$Idref x_s + V_q - u_{qref} + y_{PIIq}$
a	θ	ExtAlgeb	$-P_e u$
v	V	ExtAlgeb	$-Q_e u$
Idref	$Idref$	AliasAlgeb	0
Iqref	$Iqref$	AliasAlgeb	0

Services

Name	Symbol	Equation	Type
Pref	P_{ref}	$P_{0s}\gamma_P$	ConstService
Qref	Q_{ref}	$Q_{0s}\gamma_Q$	ConstService
ixs	$1/xs$	$\frac{1}{x_s}$	ConstService
Id0	I_{d0}	$\frac{P_{ref}u}{V}$	ConstService
Iq0	I_{q0}	$-\frac{Q_{ref}u}{V}$	ConstService
vd0	v_{d0}	Vu	ConstService
vq0	v_{q0}	0	ConstService
udref0	u_{dref0}	$I_{d0}r_a - I_{q0}x_s + v_{d0}$	ConstService
uqref0	u_{qref0}	$I_{d0}x_s + I_{q0}r_a + v_{q0}$	ConstService

Blocks

Name	Symbol	Type	Info
PIvd	$PIvd$	PIController	
PIvq	$PIvq$	PIController	
PIId	$PIId$	PIController	
PIIq	$PIIq$	PIController	
udLag	$udLag$	Lag	
uqLag	$uqLag$	Lag	

Config Fields in [REGCV1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.24.4 REGCV2

Voltage-controlled VSC with VSG control.

The inner-loop current PI controllers are replaced with lag transfer functions.

Notes

To avoid small-signal stability issues, one take extreme care in setting the PI control gains `Kpvd`, `Kivd`, `Kpvq`, and `Kivq`, and the emulated inertia `M` and damping `D`.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
coi2		center of inertia 2 index			
Sn	S_n	Model MVA base	100	*MVA*	
fn	f	rated frequency	60		
Tc	T_c	switch time constant	0.010	*s*	
kw	k_ω	speed droop on active power (reciprocal of droop)	0	*p.u.*	non_negative,ipower
kv	k_v	reactive power droop on voltage	0	*p.u.*	non_negative,power
M	M	Emulated startup time constant (M=2H)	10	*s*	power
D	D	Emulated damping coefficient	0	*p.u.*	power
ra	r_a	resistance	0		z
xs	x_s	reactance	0.200		z
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
Kpvd	kp_{vd}	vd controller proportional gain	0.500	*p.u.*	power
Kivd	ki_{vd}	vd controller integral gain	0.020	*p.u.*	power
Kpvq	kp_{vq}	vq controller proportional gain	0.500	*p.u.*	power
Kivq	ki_{vq}	vq controller integral gain	0.020	*p.u.*	power
Tiq	T_{Iq}		0.010		
Tid	T_{Id}		0.010		

Variables

Name	Symbol	Type	Description	Unit	Properties
dw	$\Delta\omega$	State	delta virtual rotor speed	*pu (Hz)*	v_str
delta	δ	State	virtual delta	*rad*	v_str
PIvd_xi	xi_{PIvd}	State	Integrator output		v_str
PIvq_xi	xi_{PIvq}	State	Integrator output		v_str
LGId_y	y_{LGId}	State	State in lag transfer function		v_str
LGIq_y	y_{LGIq}	State	State in lag transfer function		v_str
Pref2	P_{ref2}	Algeb	active power reference after adjusting by frequency		v_str
vref2	v_{ref2}	Algeb	voltage reference after adjusted by reactive power		v_str
omega	ω	Algeb	virtual rotor speed	*pu (Hz)*	v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
Pe	P_e	Algeb	active power injection from VSC		v_str
Qe	Q_e	Algeb	reactive power injection from VSC		v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
PIvd_y	y_{PIvd}	Algeb	PI output		v_str
PIvq_y	y_{PIvq}	Algeb	PI output		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		
Idref	$Idref$	AliasAlgeb	Alias of PIvd_y		
Iqref	$Iqref$	AliasAlgeb	Alias of PIvq_y		

Initialization Equations

Name	Symbol	Type	Initial Value
dw	$\Delta\omega$	State	0
delta	δ	State	θ
PIvd_xi	xi_{PIvd}	State	I_{d0}
PIvq_xi	xi_{PIvq}	State	I_{q0}
LGId_y	y_{LGId}	State	y_{PIvd}
LGIq_y	y_{LGIq}	State	y_{PIvq}
Pref2	P_{ref2}	Algeb	$P_{ref}u$
vref2	v_{ref2}	Algeb	$V_{ref}u$
omega	ω	Algeb	u
vd	V_d	Algeb	v_{d0}
vq	V_q	Algeb	v_{q0}
Pe	P_e	Algeb	P_{ref}
Qe	Q_e	Algeb	Q_{ref}
Id	I_d	Algeb	I_{d0}
Iq	I_q	Algeb	I_{q0}
PIvd_y	y_{PIvd}	Algeb	$I_{d0} + kp_{vd}\left(V_d - v_{ref2}\right)$
PIvq_y	y_{PIvq}	Algeb	$I_{q0} + V_q kp_{vq}$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
Idref	$Idref$	AliasAlgeb	
Iqref	$Iqref$	AliasAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
dw	$\Delta\omega$	State	$-D\Delta\omega - P_e + P_{ref2}$	M
delta	δ	State	$2\pi\Delta\omega f$	
PIvd_xi	xi_{PIvd}	State	$ki_{vd}\left(V_d - v_{ref2}\right)$	
PIvq_xi	xi_{PIvq}	State	$V_q ki_{vq}$	
LGId_y	y_{LGId}	State	$-y_{LGId} + y_{PIvd}$	T_{Id}
LGIq_y	y_{LGIq}	State	$-y_{LGIq} + y_{PIvq}$	T_{Iq}

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Pref2	P_{ref2}	Algeb	$-P_{ref2} + P_{ref}u - \Delta\omega k_\omega$
vref2	v_{ref2}	Algeb	$V_{ref} + k_v\left(-Q_e + Q_{ref}u\right) - v_{ref2}$
omega	ω	Algeb	$\Delta\omega - \omega + 1$
vd	V_d	Algeb	$Vu\cos\left(\delta - \theta\right) - V_d$
vq	V_q	Algeb	$-Vu\sin\left(\delta - \theta\right) - V_q$
Pe	P_e	Algeb	$I_dV_d + I_qV_q - P_e$
Qe	Q_e	Algeb	$I_dV_q - I_qV_d - Q_e$
Id	I_d	Algeb	$-I_d + y_{LGId}$
Iq	I_q	Algeb	$-I_q + y_{LGIq}$
PIvd_y	y_{PIvd}	Algeb	$kp_{vd}\left(V_d - v_{ref2}\right) + xi_{PIvd} - y_{PIvd}$
PIvq_y	y_{PIvq}	Algeb	$V_qkp_{vq} + xi_{PIvq} - y_{PIvq}$
a	θ	ExtAlgeb	$-P_eu$
v	V	ExtAlgeb	$-Q_eu$
Idref	$Idref$	AliasAlgeb	0
Iqref	$Iqref$	AliasAlgeb	0

Services

Name	Symbol	Equation	Type
Pref	P_{ref}	$P_{0s}\gamma_P$	ConstService
Qref	Q_{ref}	$Q_{0s}\gamma_Q$	ConstService
ixs	$1/xs$	$\frac{1}{x_s}$	ConstService
Id0	I_{d0}	$\frac{P_{ref}u}{V}$	ConstService
Iq0	I_{q0}	$-\frac{Q_{ref}u}{V}$	ConstService
vd0	v_{d0}	Vu	ConstService
vq0	v_{q0}	0	ConstService

Blocks

Name	Symbol	Type	Info
PIvd	$PIvd$	PIController	
PIvq	$PIvq$	PIController	
LGId	$LGId$	Lag	
LGIq	$LGIq$	Lag	

Config Fields in [REGCV2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.24.5 REGF1

Grid-forming inverter using droop.

Implementation of EPRI Memorandum

D. Ramasubramanian, "PROPOSAL FOR SUITE OF GENERIC GRID FORMING (GFM) POSITIVE SEQUENCE MODELS"

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	Model MVA base	100	*MVA*	
rf	r_a	resistance	0		z
xf	x_s	reactance	0.200		z
Vdip	V_{dip}	V threshold to freeze states	0.800	*p.u.*	
Tfrz	T_{frz}	Time to keep state frozen	0		
PQFLAG		P/Q priority flag; 0-Q priority, 1-P priority	1	*bool*	
fn	f	rated frequency	60		
dwmax	$\Delta\omega_{max}$	maximum value of frequency deviation	75		
dwmin	$\Delta\omega_{min}$	minimum value of frequency deviation	-75		
wdrp	ω_{drp}	frequency droop percentage	0.033		
Qdrp	Q_{drp}	Voltage droop percentage	0.045		
Tr	T_c	transducer time constant	0.005	*s*	
Te	T_e	ouput state time constant	0.005	*s*	
KPi	K_{Pi}	current control proportional gain	0.500		non_negative
KIi	K_{Ii}	current control integral gain	20		non_negative
KPv	K_{Pv}	voltage control proportional gain	3		non_negative
KIv	K_{Iv}	voltage control integral gain	10		non_negative
Pmax	P_{max}	max. active power	1		non_negative,power
Pmin	P_{min}	min. active power	-1		power
KPplim	K_{Pplim}	Kp for P limits	5		non_negative
KIplim	K_{Iplim}	KI for P limits	30		non_negative

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Table 32 – continued from previous page

Name	Symbol	Description	Default	Unit	Properties
Qmax	Q_{max}	max. reactive power	1		non_negative,power
Qmin	Q_{min}	min. reactive power	-1		power
KPqlim	K_{Pqlim}	Kp for Q limits	0.100		non_negative
KIqlim	K_{Iqlim}	KI for Q limits	1.500		non_negative
Tpm	T_{pm}	power signal input delay (3 Delta t)	0.025		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		

Variables

Name	Symbol	Type	Description	Unit	Properties
Psen_y	y_{Psen}	State	State in lag transfer function		v_str
Qsen_y	y_{Qsen}	State	State in lag transfer function		v_str
Psig_y	y_{Psig}	State	State in lag TF		v_str
Qsig_y	y_{Qsig}	State	State in lag TF		v_str
PIplim_xi	xi_{PIplim}	State	Integrator output		v_str
PIqlim_xi	xi_{PIqlim}	State	Integrator output		v_str
delta	δ	State	virtual delta	*rad*	v_str
PIvd_xi	xi_{PIvd}	State	Integrator output		v_str
PIvq_xi	xi_{PIvq}	State	Integrator output		v_str
PIId_xi	xi_{PIId}	State	Integrator output		v_str
PIIq_xi	xi_{PIIq}	State	Integrator output		v_str
udLag_y	y_{udLag}	State	State in lag transfer function		v_str
uqLag_y	y_{uqLag}	State	State in lag transfer function		v_str
ud	ud	AliasState	Alias of udLag_y		
uq	uq	AliasState	Alias of uqLag_y		
Paux	$Paux$	Algeb			v_str
Qaux	$Qaux$	Algeb			v_str
PIplim_y	y_{PIplim}	Algeb	PI output		v_str
PIqlim_y	y_{PIqlim}	Algeb	PI output		v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
Pe	P_e	Algeb	active power injection from VSC		v_str
Qe	Q_e	Algeb	reactive power injection from VSC		v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
dw_x	x_{dw}	Algeb	Value before limiter		v_str
dw_y	y_{dw}	Algeb	Output after limiter and post gain		v_str
vref2	v_{ref2}	Algeb	voltage reference after droop		v_str
PIvd_y	y_{PIvd}	Algeb	PI output		v_str
PIvq_y	y_{PIvq}	Algeb	PI output		v_str

continues on next page

Table 33 – continued from previous page

Name	Symbol	Type	Description	Unit	Properties
PIId_y	y_{PIId}	Algeb	PI output		v_str
PIIq_y	y_{PIIq}	Algeb	PI output		v_str
udref	u_{dref}	Algeb	ud reference		v_str
uqref	u_{qref}	Algeb	uq reference		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		
Idref	$Idref$	AliasAlgeb	Alias of PIvd_y		
Iqref	$Iqref$	AliasAlgeb	Alias of PIvq_y		

Initialization Equations

Name	Symbol	Type	Initial Value
Psen_y	y_{Psen}	State	P_e
Qsen_y	y_{Qsen}	State	Q_e
Psig_y	y_{Psig}	State	$Paux + y_{Psen}$
Qsig_y	y_{Qsig}	State	$Qaux + y_{Qsen}$
PIplim_xi	xi_{PIplim}	State	y_{Psen}
PIqlim_xi	xi_{PIqlim}	State	y_{Qsen}
delta	δ	State	θ
PIvd_xi	xi_{PIvd}	State	I_{d0}
PIvq_xi	xi_{PIvq}	State	I_{q0}
PIId_xi	xi_{PIId}	State	0.0
PIIq_xi	xi_{PIIq}	State	0.0
udLag_y	y_{udLag}	State	u_{dref}
uqLag_y	y_{uqLag}	State	u_{qref}
ud	ud	AliasState	
uq	uq	AliasState	
Paux	$Paux$	Algeb	0
Qaux	$Qaux$	Algeb	0
PIplim_y	y_{PIplim}	Algeb	$K_{Pplim}\left(-y_{Psen} + y_{Psig}\right) + y_{Psen}$
PIqlim_y	y_{PIqlim}	Algeb	$K_{Pqlim}\left(-y_{Qsen} + y_{Qsig}\right) + y_{Qsen}$
vd	V_d	Algeb	v_{d0}
vq	V_q	Algeb	v_{q0}
Pe	P_e	Algeb	P_{ref}
Qe	Q_e	Algeb	Q_{ref}
Id	I_d	Algeb	I_{d0}
Iq	I_q	Algeb	I_{q0}
dw_x	x_{dw}	Algeb	$\omega_{drp} w_0 \left(y_{PIplim} - y_{Psen}\right)$
dw_y	y_{dw}	Algeb	$\Delta\omega_{max} z_u^{lim_{dw}} + \Delta\omega_{min} z_l^{lim_{dw}} + x_{dw} z_i^{lim_{dw}}$
vref2	v_{ref2}	Algeb	$V_{ref} u$
PIvd_y	y_{PIvd}	Algeb	$I_{d0} + K_{Pv}\left(-V_d + v_{ref2}\right)$

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Table 34 – continued from previous page

Name	Symbol	Type	Initial Value
PIvq_y	y_{PIvq}	Algeb	$I_{q0} - K_{Pv} V_q$
PIId_y	y_{PIId}	Algeb	$K_{Pi} \left(-I_d + y_{PIvd}\right)$
PIIq_y	y_{PIIq}	Algeb	$K_{Pi} \left(-I_q + y_{PIvq}\right)$
udref	u_{dref}	Algeb	u_{dref0}
uqref	u_{qref}	Algeb	u_{qref0}
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
Idref	$Idref$	AliasAlgeb	
Iqref	$Iqref$	AliasAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Psen_y	y_{Psen}	State	$P_e - y_{Psen}$	T_c
Qsen_y	y_{Qsen}	State	$Q_e - y_{Qsen}$	T_c
Psig_y	y_{Psig}	State	$Paux + y_{Psen} - y_{Psig}$	T_{pm}
Qsig_y	y_{Qsig}	State	$Qaux + y_{Qsen} - y_{Qsig}$	T_{pm}
PIplim_xi	xi_{PIplim}	State	$K_{Iplim} \left(-y_{Psen} + y_{Psig}\right)$	
PIqlim_xi	xi_{PIqlim}	State	$K_{Iqlim} \left(-y_{Qsen} + y_{Qsig}\right)$	
delta	δ	State	y_{dw}	
PIvd_xi	xi_{PIvd}	State	$K_{Iv} \left(-V_d + v_{ref2}\right)$	
PIvq_xi	xi_{PIvq}	State	$-K_{Iv} V_q$	
PIId_xi	xi_{PIId}	State	$K_{Ii} \left(-I_d + y_{PIvd}\right)$	
PIIq_xi	xi_{PIIq}	State	$K_{Ii} \left(-I_q + y_{PIvq}\right)$	
udLag_y	y_{udLag}	State	$u_{dref} - y_{udLag}$	T_e
uqLag_y	y_{uqLag}	State	$u_{qref} - y_{uqLag}$	T_e
ud	ud	AliasState	0	
uq	uq	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Paux	$Paux$	Algeb	$Paux$
Qaux	$Qaux$	Algeb	$Qaux$
PIplim_y	y_{PIplim}	Algeb	$K_{Pplim}\left(-y_{Psen}+y_{Psig}\right)+xi_{PIplim}-y_{PIplim}$
PIqlim_y	y_{PIqlim}	Algeb	$K_{Pqlim}\left(-y_{Qsen}+y_{Qsig}\right)+xi_{PIqlim}-y_{PIqlim}$
vd	V_d	Algeb	$Vu\cos\left(\delta-\theta\right)-V_d$
vq	V_q	Algeb	$-Vu\sin\left(\delta-\theta\right)-V_q$
Pe	P_e	Algeb	$I_dV_d+I_qV_q-P_e$
Qe	Q_e	Algeb	$I_dV_q-I_qV_d-Q_e$
Id	I_d	Algeb	$I_dr_a-I_qx_s+V_d-y_{udLag}$
Iq	I_q	Algeb	$I_dx_s+I_qr_a+V_q-y_{uqLag}$
dw_x	x_{dw}	Algeb	$\omega_{drp}w_0\left(y_{PIplim}-y_{Psen}\right)-x_{dw}$
dw_y	y_{dw}	Algeb	$\Delta\omega_{max}z_u^{lim_{dw}}+\Delta\omega_{min}z_l^{lim_{dw}}+x_{dw}z_i^{lim_{dw}}-y_{dw}$
vref2	v_{ref2}	Algeb	$Q_{drp}\left(uy_{PIqlim}-y_{Qsen}\right)+V_{ref}-v_{ref2}$
PIvd_y	y_{PIvd}	Algeb	$K_{Pv}\left(-V_d+v_{ref2}\right)+xi_{PIvd}-y_{PIvd}$
PIvq_y	y_{PIvq}	Algeb	$-K_{Pv}V_q+xi_{PIvq}-y_{PIvq}$
PIId_y	y_{PIId}	Algeb	$K_{Pi}\left(-I_d+y_{PIvd}\right)+xi_{PIId}-y_{PIId}$
PIIq_y	y_{PIIq}	Algeb	$K_{Pi}\left(-I_q+y_{PIvq}\right)+xi_{PIIq}-y_{PIIq}$
udref	u_{dref}	Algeb	$I_dr_a-I_qx_s+V_d-u_{dref}+y_{PIId}$
uqref	u_{qref}	Algeb	$I_dx_s+I_qr_a+V_q-u_{qref}+y_{PIIq}$
a	θ	ExtAlgeb	$-P_eu$
v	V	ExtAlgeb	$-Q_eu$
Idref	$Idref$	AliasAlgeb	0
Iqref	$Iqref$	AliasAlgeb	0

Services

Name	Symbol	Equation	Type
Pref	P_{ref}	$P_{0s}\gamma_P$	ConstService
Qref	Q_{ref}	$Q_{0s}\gamma_Q$	ConstService
w0	$w0$	$2\pi f$	ConstService
ixf	$1/xf$	$\frac{1}{x_s}$	ConstService
Id0	I_{d0}	$\frac{P_{ref}u}{V}$	ConstService
Iq0	I_{q0}	$-\frac{Q_{ref}u}{V}$	ConstService
vd0	v_{d0}	Vu	ConstService
vq0	v_{q0}	0	ConstService
udref0	u_{dref0}	$I_{d0}r_a-I_{q0}x_s+v_{d0}$	ConstService
uqref0	u_{qref0}	$I_{d0}x_s+I_{q0}r_a+v_{q0}$	ConstService

Discretes

Name	Symbol	Type	Info
Psig_lim	lim_{Psig}	AntiWindup	Limiter in Lag
Qsig_lim	lim_{Qsig}	AntiWindup	Limiter in Lag
dw_lim	lim_{dw}	HardLimiter	

Blocks

Name	Symbol	Type	Info
Psen	$Psen$	Lag	
Qsen	$Qsen$	Lag	
Psig	$Psig$	LagAntiWindup	
Qsig	$Qsig$	LagAntiWindup	
PIplim	$PIplim$	PIController	
PIqlim	$PIqlim$	PIController	
dw	dw	GainLimiter	
PIvd	$PIvd$	PIController	
PIvq	$PIvq$	PIController	
PIId	$PIId$	PIController	
PIIq	$PIIq$	PIController	
udLag	$udLag$	Lag	
uqLag	$uqLag$	Lag	

Config Fields in [REGF1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.24.6 REGF2

Grid-forming inverter with VSM control.

Implementation of EPRI Memorandum

D. Ramasubramanian, "PROPOSAL FOR SUITE OF GENERIC GRID FORMING (GFM) POSITIVE SEQUENCE MODELS"

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	Model MVA base	100	*MVA*	
rf	r_a	resistance	0		z
xf	x_s	reactance	0.200		z
Vdip	V_{dip}	V threshold to freeze states	0.800	*p.u.*	
Tfrz	T_{frz}	Time to keep state frozen	0		
PQFLAG		P/Q priority flag; 0-Q priority, 1-P priority	1	*bool*	
fn	f	rated frequency	60		
dwmax	$\Delta\omega_{max}$	maximum value of frequency deviation	75		
dwmin	$\Delta\omega_{min}$	minimum value of frequency deviation	-75		
wdrp	ω_{drp}	frequency droop percentage	0.033		
Qdrp	Q_{drp}	Voltage droop percentage	0.045		
Tr	T_c	transducer time constant	0.005	*s*	
Te	T_e	ouput state time constant	0.005	*s*	
KPi	K_{Pi}	current control proportional gain	0.500		non_negative
KIi	K_{Ii}	current control integral gain	20		non_negative
KPv	K_{Pv}	voltage control proportional gain	3		non_negative
KIv	K_{Iv}	voltage control integral gain	10		non_negative
Pmax	P_{max}	max. active power	1		non_negative,power
Pmin	P_{min}	min. active power	-1		power
KPplim	K_{Pplim}	Kp for P limits	5		non_negative
KIplim	K_{Iplim}	KI for P limits	30		non_negative
Qmax	Q_{max}	max. reactive power	1		non_negative,power
Qmin	Q_{min}	min. reactive power	-1		power
KPqlim	K_{Pqlim}	Kp for Q limits	0.100		non_negative
KIqlim	K_{Iqlim}	KI for Q limits	1.500		non_negative
Tpm	T_{pm}	power signal input delay (3 Delta t)	0.025		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
mf	M_f	VSM inertia constant	0.150		
dd	d_d	VSM damping factor	0.110		
pll		PLL device idx (optional)			

Variables

Name	Symbol	Type	Description	Unit	Properties
Psen_y	y_{Psen}	State	State in lag transfer function		v_str
Qsen_y	y_{Qsen}	State	State in lag transfer function		v_str
Psig_y	y_{Psig}	State	State in lag TF		v_str
Qsig_y	y_{Qsig}	State	State in lag TF		v_str
PIplim_xi	xi_{PIplim}	State	Integrator output		v_str
PIqlim_xi	xi_{PIqlim}	State	Integrator output		v_str
delta	δ	State	virtual delta	*rad*	v_str
INTw_y	y_{INTw}	State	Integrator output		v_str
PIvd_xi	xi_{PIvd}	State	Integrator output		v_str
PIvq_xi	xi_{PIvq}	State	Integrator output		v_str
PIId_xi	xi_{PIId}	State	Integrator output		v_str
PIIq_xi	xi_{PIIq}	State	Integrator output		v_str
udLag_y	y_{udLag}	State	State in lag transfer function		v_str
uqLag_y	y_{uqLag}	State	State in lag transfer function		v_str
ud	ud	AliasState	Alias of udLag_y		
uq	uq	AliasState	Alias of uqLag_y		
Paux	$Paux$	Algeb			v_str
Qaux	$Qaux$	Algeb			v_str
PIplim_y	y_{PIplim}	Algeb	PI output		v_str
PIqlim_y	y_{PIqlim}	Algeb	PI output		v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
Pe	P_e	Algeb	active power injection from VSC		v_str
Qe	Q_e	Algeb	reactive power injection from VSC		v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
wref	ω_{ref}	Algeb	speed ref	*pu*	v_str
dw_x	x_{dw}	Algeb	Value before limiter		v_str
dw_y	y_{dw}	Algeb	Output after limiter and post gain		v_str
vref2	v_{ref2}	Algeb	voltage reference after droop		v_str
PIvd_y	y_{PIvd}	Algeb	PI output		v_str
PIvq_y	y_{PIvq}	Algeb	PI output		v_str
PIId_y	y_{PIId}	Algeb	PI output		v_str
PIIq_y	y_{PIIq}	Algeb	PI output		v_str
udref	u_{dref}	Algeb	ud reference		v_str
uqref	u_{qref}	Algeb	uq reference		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		
plldw	$\Delta\omega_{PLL}$	ExtAlgeb	PLL measured freq. deviation		
Idref	$Idref$	AliasAlgeb	Alias of PIvd_y		
Iqref	$Iqref$	AliasAlgeb	Alias of PIvq_y		

Initialization Equations

Name	Symbol	Type	Initial Value
Psen_y	y_{Psen}	State	P_e
Qsen_y	y_{Qsen}	State	Q_e
Psig_y	y_{Psig}	State	$Paux + y_{Psen}$
Qsig_y	y_{Qsig}	State	$Qaux + y_{Qsen}$
PIplim_xi	xi_{PIplim}	State	y_{Psen}
PIqlim_xi	xi_{PIqlim}	State	y_{Qsen}
delta	δ	State	θ
INTw_y	y_{INTw}	State	ω_{ref}
PIvd_xi	xi_{PIvd}	State	I_{d0}
PIvq_xi	xi_{PIvq}	State	I_{q0}
PIId_xi	xi_{PIId}	State	0.0
PIIq_xi	xi_{PIIq}	State	0.0
udLag_y	y_{udLag}	State	u_{dref}
uqLag_y	y_{uqLag}	State	u_{qref}
ud	ud	AliasState	
uq	uq	AliasState	
Paux	$Paux$	Algeb	0
Qaux	$Qaux$	Algeb	0
PIplim_y	y_{PIplim}	Algeb	$K_{Pplim}\left(-y_{Psen} + y_{Psig}\right) + y_{Psen}$
PIqlim_y	y_{PIqlim}	Algeb	$K_{Pqlim}\left(-y_{Qsen} + y_{Qsig}\right) + y_{Qsen}$
vd	V_d	Algeb	v_{d0}
vq	V_q	Algeb	v_{q0}
Pe	P_e	Algeb	P_{ref}
Qe	Q_e	Algeb	Q_{ref}
Id	I_d	Algeb	I_{d0}
Iq	I_q	Algeb	I_{q0}
wref	ω_{ref}	Algeb	1
dw_x	x_{dw}	Algeb	$w_0\left(-\omega_{ref} + y_{INTw}\right)$
dw_y	y_{dw}	Algeb	$\Delta\omega_{max} z_u^{lim_{dw}} + \Delta\omega_{min} z_l^{lim_{dw}} + x_{dw} z_i^{lim_{dw}}$
vref2	v_{ref2}	Algeb	$V_{ref} u$
PIvd_y	y_{PIvd}	Algeb	$I_{d0} + K_{Pv}\left(-V_d + v_{ref2}\right)$
PIvq_y	y_{PIvq}	Algeb	$I_{q0} - K_{Pv} V_q$
PIId_y	y_{PIId}	Algeb	$K_{Pi}\left(-I_d + y_{PIvd}\right)$
PIIq_y	y_{PIIq}	Algeb	$K_{Pi}\left(-I_q + y_{PIvq}\right)$
udref	u_{dref}	Algeb	u_{dref0}
uqref	u_{qref}	Algeb	u_{qref0}
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
plldw	$\Delta\omega_{PLL}$	ExtAlgeb	
Idref	$Idref$	AliasAlgeb	
Iqref	$Iqref$	AliasAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Psen_y	y_{Psen}	State	$P_e - y_{Psen}$	T_c
Qsen_y	y_{Qsen}	State	$Q_e - y_{Qsen}$	T_c
Psig_y	y_{Psig}	State	$Paux + y_{Psen} - y_{Psig}$	T_{pm}
Qsig_y	y_{Qsig}	State	$Qaux + y_{Qsen} - y_{Qsig}$	T_{pm}
PI-plim_xi	xi_{PIplim}	State	$K_{Iplim}\left(-y_{Psen} + y_{Psig}\right)$	
PIqlim_xi	xi_{PIqlim}	State	$K_{Iqlim}\left(-y_{Qsen} + y_{Qsig}\right)$	
delta	δ	State	y_{dw}	
INTw_y	y_{INTw}	State	$\Delta\omega_{PLL}\omega_{drp}d_d + \omega_{drp}\left(y_{PIplim} - y_{Psen}\right) + \omega_{ref} - y_{INTw}$	T_{int}
PIvd_xi	xi_{PIvd}	State	$K_{Iv}\left(-V_d + v_{ref2}\right)$	
PIvq_xi	xi_{PIvq}	State	$-K_{Iv}V_q$	
PIId_xi	xi_{PIId}	State	$K_{Ii}\left(-I_d + y_{PIvd}\right)$	
PIIq_xi	xi_{PIIq}	State	$K_{Ii}\left(-I_q + y_{PIvq}\right)$	
udLag_y	y_{udLag}	State	$u_{dref} - y_{udLag}$	T_e
uqLag_y	y_{uqLag}	State	$u_{qref} - y_{uqLag}$	T_e
ud	ud	AliasState	0	
uq	uq	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Paux	$Paux$	Algeb	$Paux$
Qaux	$Qaux$	Algeb	$Qaux$
PIplim_y	y_{PIplim}	Algeb	$K_{Pplim}\left(-y_{Psen}+y_{Psig}\right)+xi_{PIplim}-y_{PIplim}$
PIqlim_y	y_{PIqlim}	Algeb	$K_{Pqlim}\left(-y_{Qsen}+y_{Qsig}\right)+xi_{PIqlim}-y_{PIqlim}$
vd	V_d	Algeb	$Vu\cos\left(\delta-\theta\right)-V_d$
vq	V_q	Algeb	$-Vu\sin\left(\delta-\theta\right)-V_q$
Pe	P_e	Algeb	$I_dV_d+I_qV_q-P_e$
Qe	Q_e	Algeb	$I_dV_q-I_qV_d-Q_e$
Id	I_d	Algeb	$I_dr_a-I_qx_s+V_d-y_{udLag}$
Iq	I_q	Algeb	$I_dx_s+I_qr_a+V_q-y_{uqLag}$
wref	ω_{ref}	Algeb	$1-\omega_{ref}$
dw_x	x_{dw}	Algeb	$w_0\left(-\omega_{ref}+y_{INTw}\right)-x_{dw}$
dw_y	y_{dw}	Algeb	$\Delta\omega_{max}z_u^{lim_{dw}}+\Delta\omega_{min}z_l^{lim_{dw}}+x_{dw}z_i^{lim_{dw}}-y_{dw}$
vref2	v_{ref2}	Algeb	$Q_{drp}\left(uy_{PIqlim}-y_{Qsen}\right)+V_{ref}-v_{ref2}$
PIvd_y	y_{PIvd}	Algeb	$K_{Pv}\left(-V_d+v_{ref2}\right)+xi_{PIvd}-y_{PIvd}$
PIvq_y	y_{PIvq}	Algeb	$-K_{Pv}V_q+xi_{PIvq}-y_{PIvq}$
PIId_y	y_{PIId}	Algeb	$K_{Pi}\left(-I_d+y_{PIvd}\right)+xi_{PIId}-y_{PIId}$
PIIq_y	y_{PIIq}	Algeb	$K_{Pi}\left(-I_q+y_{PIvq}\right)+xi_{PIIq}-y_{PIIq}$
udref	u_{dref}	Algeb	$I_dr_a-I_qx_s+V_d-u_{dref}+y_{PIId}$
uqref	u_{qref}	Algeb	$I_dx_s+I_qr_a+V_q-u_{qref}+y_{PIIq}$
a	θ	ExtAlgeb	$-P_eu$
v	V	ExtAlgeb	$-Q_eu$
plldw	$\Delta\omega_{PLL}$	ExtAlgeb	0
Idref	$Idref$	AliasAlgeb	0
Iqref	$Iqref$	AliasAlgeb	0

Services

Name	Symbol	Equation	Type
Pref	P_{ref}	$P_{0s}\gamma_P$	ConstService
Qref	Q_{ref}	$Q_{0s}\gamma_Q$	ConstService
w0	$w0$	$2\pi f$	ConstService
ixf	$1/xf$	$\frac{1}{x_s}$	ConstService
Id0	I_{d0}	$\frac{P_{ref}u}{V}$	ConstService
Iq0	I_{q0}	$-\frac{Q_{ref}u}{V}$	ConstService
vd0	v_{d0}	Vu	ConstService
vq0	v_{q0}	0	ConstService
Tint	T_{int}	$M_f\omega_{drp}$	ConstService
udref0	u_{dref0}	$I_{d0}r_a-I_{q0}x_s+v_{d0}$	ConstService
uqref0	u_{qref0}	$I_{d0}x_s+I_{q0}r_a+v_{q0}$	ConstService

Discretes

Name	Symbol	Type	Info
Psig_lim	lim_{Psig}	AntiWindup	Limiter in Lag
Qsig_lim	lim_{Qsig}	AntiWindup	Limiter in Lag
dw_lim	lim_{dw}	HardLimiter	

Blocks

Name	Symbol	Type	Info
Psen	$Psen$	Lag	
Qsen	$Qsen$	Lag	
Psig	$Psig$	LagAntiWindup	
Qsig	$Qsig$	LagAntiWindup	
PIplim	$PIplim$	PIController	
PIqlim	$PIqlim$	PIController	
INTw	$INTw$	Integrator	
dw	dw	GainLimiter	
PIvd	$PIvd$	PIController	
PIvq	$PIvq$	PIController	
PIId	$PIId$	PIController	
PIIq	$PIIq$	PIController	
udLag	$udLag$	Lag	
uqLag	$uqLag$	Lag	

Config Fields in [REGF2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.24.7 REGF3

Grid-forming inverter with dVOC.

Implementation of EPRI Memorandum

D. Ramasubramanian, "PROPOSAL FOR SUITE OF GENERIC GRID FORMING (GFM) POSITIVE SEQUENCE MODELS"

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	Model MVA base	100	*MVA*	
rf	r_a	resistance	0		z
xf	x_s	reactance	0.200		z
Vdip	V_{dip}	V threshold to freeze states	0.800	*p.u.*	
Tfrz	T_{frz}	Time to keep state frozen	0		
PQFLAG		P/Q priority flag; 0-Q priority, 1-P priority	1	*bool*	
fn	f	rated frequency	60		
dwmax	$\Delta\omega_{max}$	maximum value of frequency deviation	75		
dwmin	$\Delta\omega_{min}$	minimum value of frequency deviation	-75		
wdrp	ω_{drp}	frequency droop percentage	0.033		
Qdrp	Q_{drp}	Voltage droop percentage	0.045		
Tr	T_c	transducer time constant	0.005	*s*	
Te	T_e	ouput state time constant	0.005	*s*	
KPi	K_{Pi}	current control proportional gain	0.500		non_negative
KIi	K_{Ii}	current control integral gain	20		non_negative
KPv	K_{Pv}	voltage control proportional gain	3		non_negative
KIv	K_{Iv}	voltage control integral gain	10		non_negative
Pmax	P_{max}	max. active power	1		non_negative,power
Pmin	P_{min}	min. active power	-1		power
KPplim	K_{Pplim}	Kp for P limits	5		non_negative
KIplim	K_{Iplim}	KI for P limits	30		non_negative
Qmax	Q_{max}	max. reactive power	1		non_negative,power
Qmin	Q_{min}	min. reactive power	-1		power
KPqlim	K_{Pqlim}	Kp for Q limits	0.100		non_negative
KIqlim	K_{Iqlim}	KI for Q limits	1.500		non_negative
Tpm	T_{pm}	power signal input delay (3 Delta t)	0.025		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		

Variables

Name	Symbol	Type	Description	Unit	Properties
Psen_y	y_{Psen}	State	State in lag transfer function		v_str
Qsen_y	y_{Qsen}	State	State in lag transfer function		v_str
Psig_y	y_{Psig}	State	State in lag TF		v_str
Qsig_y	y_{Qsig}	State	State in lag TF		v_str
PIplim_xi	xi_{PIplim}	State	Integrator output		v_str
PIqlim_xi	xi_{PIqlim}	State	Integrator output		v_str
delta	δ	State	virtual delta	*rad*	v_str
vref2	$vref_2$	State			v_str
PIvd_xi	xi_{PIvd}	State	Integrator output		v_str
PIvq_xi	xi_{PIvq}	State	Integrator output		v_str
PIId_xi	xi_{PIId}	State	Integrator output		v_str
PIIq_xi	xi_{PIIq}	State	Integrator output		v_str
udLag_y	y_{udLag}	State	State in lag transfer function		v_str
uqLag_y	y_{uqLag}	State	State in lag transfer function		v_str
ud	ud	AliasState	Alias of udLag_y		
uq	uq	AliasState	Alias of uqLag_y		
Paux	$Paux$	Algeb			v_str
Qaux	$Qaux$	Algeb			v_str
PIplim_y	y_{PIplim}	Algeb	PI output		v_str
PIqlim_y	y_{PIqlim}	Algeb	PI output		v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
Pe	P_e	Algeb	active power injection from VSC		v_str
Qe	Q_e	Algeb	reactive power injection from VSC		v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
wref	ω_{ref}	Algeb	speed ref	*pu*	v_str
Vref	$Vref$	Algeb			v_str
dw_x	x_{dw}	Algeb	Value before limiter		v_str
dw_y	y_{dw}	Algeb	Output after limiter and post gain		v_str
derv	dV	Algeb	input to voltage integrator		v_str
PIvd_y	y_{PIvd}	Algeb	PI output		v_str
PIvq_y	y_{PIvq}	Algeb	PI output		v_str
PIId_y	y_{PIId}	Algeb	PI output		v_str
PIIq_y	y_{PIIq}	Algeb	PI output		v_str
udref	u_{dref}	Algeb	ud reference		v_str
uqref	u_{qref}	Algeb	uq reference		v_str
a	θ	ExtAlgeb	Bus voltage angle		
v	V	ExtAlgeb	Bus voltage magnitude		
Idref	$Idref$	AliasAlgeb	Alias of PIvd_y		
Iqref	$Iqref$	AliasAlgeb	Alias of PIvq_y		

Initialization Equations

Name	Symbol	Type	Initial Value
Psen_y	y_{Psen}	State	P_e
Qsen_y	y_{Qsen}	State	Q_e
Psig_y	y_{Psig}	State	$Paux + y_{Psen}$
Qsig_y	y_{Qsig}	State	$Qaux + y_{Qsen}$
PIplim_xi	xi_{PIplim}	State	y_{Psen}
PIqlim_xi	xi_{PIqlim}	State	y_{Qsen}
delta	δ	State	θ
vref2	$vref_2$	State	V_d
PIvd_xi	xi_{PIvd}	State	I_{d0}
PIvq_xi	xi_{PIvq}	State	I_{q0}
PIId_xi	xi_{PIId}	State	0.0
PIIq_xi	xi_{PIIq}	State	0.0
udLag_y	y_{udLag}	State	u_{dref}
uqLag_y	y_{uqLag}	State	u_{qref}
ud	ud	AliasState	
uq	uq	AliasState	
Paux	$Paux$	Algeb	0
Qaux	$Qaux$	Algeb	0
PIplim_y	y_{PIplim}	Algeb	$K_{Pplim}\left(-y_{Psen} + y_{Psig}\right) + y_{Psen}$
PIqlim_y	y_{PIqlim}	Algeb	$K_{Pqlim}\left(-y_{Qsen} + y_{Qsig}\right) + y_{Qsen}$
vd	V_d	Algeb	v_{d0}
vq	V_q	Algeb	v_{q0}
Pe	P_e	Algeb	P_{ref}
Qe	Q_e	Algeb	Q_{ref}
Id	I_d	Algeb	I_{d0}
Iq	I_q	Algeb	I_{q0}
wref	ω_{ref}	Algeb	1
Vref	$Vref$	Algeb	V_{ref}
dw_x	x_{dw}	Algeb	$\frac{\omega_{drp} w_0 \left(y_{PIplim} - y_{Psen}\right)}{vref_2^2}$
dw_y	y_{dw}	Algeb	$\Delta\omega_{max} z_u^{lim_{dw}} + \Delta\omega_{min} z_l^{lim_{dw}} + x_{dw} z_i^{lim_{dw}}$
derv	dV	Algeb	0
PIvd_y	y_{PIvd}	Algeb	$I_{d0} + K_{Pv}\left(-V_d + vref_2\right)$
PIvq_y	y_{PIvq}	Algeb	$I_{q0} - K_{Pv} V_q$
PIId_y	y_{PIId}	Algeb	$K_{Pi}\left(-I_d + y_{PIvd}\right)$
PIIq_y	y_{PIIq}	Algeb	$K_{Pi}\left(-I_q + y_{PIvq}\right)$
udref	u_{dref}	Algeb	u_{dref0}
uqref	u_{qref}	Algeb	u_{qref0}
a	θ	ExtAlgeb	
v	V	ExtAlgeb	
Idref	$Idref$	AliasAlgeb	
Iqref	$Iqref$	AliasAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Psen_y	y_{Psen}	State	$P_e - y_{Psen}$	T_c
Qsen_y	y_{Qsen}	State	$Q_e - y_{Qsen}$	T_c
Psig_y	y_{Psig}	State	$Paux + y_{Psen} - y_{Psig}$	T_{pm}
Qsig_y	y_{Qsig}	State	$Qaux + y_{Qsen} - y_{Qsig}$	T_{pm}
PIplim_xi	xi_{PIplim}	State	$K_{Iplim}\left(-y_{Psen} + y_{Psig}\right)$	
PIqlim_xi	xi_{PIqlim}	State	$K_{Iqlim}\left(-y_{Qsen} + y_{Qsig}\right)$	
delta	δ	State	y_{dw}	
vref2	$vref_2$	State	dVw_0	
PIvd_xi	xi_{PIvd}	State	$K_{Iv}\left(-V_d + vref_2\right)$	
PIvq_xi	xi_{PIvq}	State	$-K_{Iv}V_q$	
PIId_xi	xi_{PIId}	State	$K_{Ii}\left(-I_d + y_{PIvd}\right)$	
PIIq_xi	xi_{PIIq}	State	$K_{Ii}\left(-I_q + y_{PIvq}\right)$	
udLag_y	y_{udLag}	State	$u_{dref} - y_{udLag}$	T_e
uqLag_y	y_{uqLag}	State	$u_{qref} - y_{uqLag}$	T_e
ud	ud	AliasState	0	
uq	uq	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Paux	$Paux$	Algeb	$Paux$
Qaux	$Qaux$	Algeb	$Qaux$
PIplim_y	y_{PIplim}	Algeb	$K_{Pplim}\left(-y_{Psen}+y_{Psig}\right)+xi_{PIplim}-y_{PIplim}$
PIqlim_y	y_{PIqlim}	Algeb	$K_{Pqlim}\left(-y_{Qsen}+y_{Qsig}\right)+xi_{PIqlim}-y_{PIqlim}$
vd	V_d	Algeb	$Vu\cos\left(\delta-\theta\right)-V_d$
vq	V_q	Algeb	$-Vu\sin\left(\delta-\theta\right)-V_q$
Pe	P_e	Algeb	$I_dV_d+I_qV_q-P_e$
Qe	Q_e	Algeb	$I_dV_q-I_qV_d-Q_e$
Id	I_d	Algeb	$I_dr_a-I_qx_s+V_d-y_{udLag}$
Iq	I_q	Algeb	$I_dx_s+I_qr_a+V_q-y_{uqLag}$
wref	ω_{ref}	Algeb	$1-\omega_{ref}$
Vref	$Vref$	Algeb	$V_{ref}-Vref$
dw_x	x_{dw}	Algeb	$\frac{\omega_{drp}w_0\left(y_{PIplim}-y_{Psen}\right)}{vref_2^2}-x_{dw}$
dw_y	y_{dw}	Algeb	$\Delta\omega_{max}z_u^{lim_{dw}}+\Delta\omega_{min}z_l^{lim_{dw}}+x_{dw}z_i^{lim_{dw}}-y_{dw}$
derv	dV	Algeb	$Kdvocvref_2\left(Vref-vref_2\right)\left(Vref+vref_2\right)+\frac{\omega_{drp}\left(y_{PIqlim}-y_{Qsen}\right)}{vref_2}-dV$
PIvd_y	y_{PIvd}	Algeb	$K_{Pv}\left(-V_d+vref_2\right)+xi_{PIvd}-y_{PIvd}$
PIvq_y	y_{PIvq}	Algeb	$-K_{Pv}V_q+xi_{PIvq}-y_{PIvq}$
PIId_y	y_{PIId}	Algeb	$K_{Pi}\left(-I_d+y_{PIvd}\right)+xi_{PIId}-y_{PIId}$
PIIq_y	y_{PIIq}	Algeb	$K_{Pi}\left(-I_q+y_{PIvq}\right)+xi_{PIIq}-y_{PIIq}$
udref	u_{dref}	Algeb	$I_dr_a-I_qx_s+V_d-u_{dref}+y_{PIId}$
uqref	u_{qref}	Algeb	$I_dx_s+I_qr_a+V_q-u_{qref}+y_{PIIq}$
a	θ	ExtAlgeb	$-P_eu$
v	V	ExtAlgeb	$-Q_eu$
Idref	$Idref$	AliasAlgeb	0
Iqref	$Iqref$	AliasAlgeb	0

Services

Name	Symbol	Equation	Type
Pref	P_{ref}	$P_{0s}\gamma_P$	ConstService
Qref	Q_{ref}	$Q_{0s}\gamma_Q$	ConstService
w0	$w0$	$2\pi f$	ConstService
ixf	$1/xf$	$\frac{1}{x_s}$	ConstService
Id0	I_{d0}	$\frac{P_{ref}u}{V}$	ConstService
Iq0	I_{q0}	$-\frac{Q_{ref}u}{V}$	ConstService
vd0	v_{d0}	Vu	ConstService
vq0	v_{q0}	0	ConstService
Kdvoc	$Kdvoc$	$\frac{400000000\omega_{drp}}{\left(99990000-2\left(100-100Q_{drp}\right)^2\right)^2}$	ConstService
udref0	u_{dref0}	$I_{d0}r_a - I_{q0}x_s + v_{d0}$	ConstService
uqref0	u_{qref0}	$I_{d0}x_s + I_{q0}r_a + v_{q0}$	ConstService

Discretes

Name	Symbol	Type	Info
Psig_lim	lim_{Psig}	AntiWindup	Limiter in Lag
Qsig_lim	lim_{Qsig}	AntiWindup	Limiter in Lag
dw_lim	lim_{dw}	HardLimiter	

Blocks

Name	Symbol	Type	Info
Psen	$Psen$	Lag	
Qsen	$Qsen$	Lag	
Psig	$Psig$	LagAntiWindup	
Qsig	$Qsig$	LagAntiWindup	
PIplim	$PIplim$	PIController	
PIqlim	$PIqlim$	PIController	
dw	dw	GainLimiter	
PIvd	$PIvd$	PIController	
PIvq	$PIvq$	PIController	
PIId	$PIId$	PIController	
PIIq	$PIIq$	PIController	
udLag	$udLag$	Lag	
uqLag	$uqLag$	Lag	

Config Fields in [REGF3]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.25 RenGovernor

Renewable turbine governor group.

Common Parameters: u, name, ree, w0, Sn, Pe0

Common Variables: Pm, wr0, wt, wg, s3_y

Available models: *WTDTA1*, *WTDS*

5.25.1 WTDTA1

WTDTA wind turbine drive-train model.

One can set `Htfrac` to `0` to simulate a single-mass drive train. `Htfrac` has to be within `[0, 1]`

User-provided reference speed should be specified in parameter *w0*. Internally, *w0* is set to the algebraic variable *wr0*.

Note for PSS/E dyr parser:

In PSS/E doc, *Freq1* is said to be Hz, but exported data from PSS/E 34 uses per unit. ANDES requires `Freq1` in per unit frequency.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
ree		Renewable exciter idx			mandatory
H	H_t	Total inertia constant	3	*MWs/MVA*	non_zero,non_negative,power
DAMP	$Damp$	Damp coefficient	0	*p.u. (gen base)*	power
Ht-frac	D_{shaft}	Turbine inertia fraction (Hturb/H)	0.500		power
Freq1	$Freq1$	First shaft torsional resonant frequency, p.u. (Hz)	1	*p.u. (Hz)*	
Dshaft	D_{shaft}	Shaft damping factor	1	*p.u. (gen base)*	power
w0	ω_0	Default speed if not using a torque model	1	*p.u.*	
reg			0		
Sn	S_n		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
s1_y	y_{s1}	State	Integrator output		v_str
s2_y	y_{s2}	State	Integrator output		v_str
s3_y	y_{s3}	State	Integrator output		v_str
wt	ω_t	AliasState	Alias of s1_y		
wg	ω_g	AliasState	Alias of s2_y		
wr0	ω_{r0}	Algeb	speed set point	*p.u.*	v_str
Pm	P_m	Algeb	Mechanical power		v_str
pd	P_d	Algeb	Output after damping		v_str
wge	wge	ExtAlgeb			
Pe	Pe	ExtAlgeb	Retrieved Pe of RenGen		

Initialization Equations

Name	Symbol	Type	Initial Value
s1_y	y_{s1}	State	ω_{r0}
s2_y	y_{s2}	State	ω_{r0}
s3_y	y_{s3}	State	$\frac{P_{e0}}{\omega_{r0}}$
wt	ω_t	AliasState	
wg	ω_g	AliasState	
wr0	ω_{r0}	Algeb	ω_0
Pm	P_m	Algeb	P_{e0}
pd	P_d	Algeb	0
wge	wge	ExtAlgeb	
Pe	Pe	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s1_y	y_{s1}	State	$-1.0P_d + \frac{1.0P_m}{y_{s1}} - 1.0y_{s3}$	$2H_t$
s2_y	y_{s2}	State	$-1.0Damp\left(-\omega_0 + y_{s2}\right) + 1.0P_d - \frac{1.0Pe}{y_{s2}} + 1.0y_{s3}$	$2H_g$
s3_y	y_{s3}	State	$K_{shaft}\left(y_{s1} - y_{s2}\right)$	1.0
wt	ω_t	AliasState	0	
wg	ω_g	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
wr0	ω_{r0}	Algeb	$\omega_0 - \omega_{r0}$
Pm	P_m	Algeb	$-P_m + P_{e0}$
pd	P_d	Algeb	$D_{shaft}\left(y_{s1} - y_{s2}\right) - P_d$
wge	wge	ExtAlgeb	$y_{s2} - 1.0$
Pe	Pe	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
Ht2	$2H_t$	$2D_{shaft}H_t$	ConstService
Hg2	$2H_g$	$2H_t\left(1 - D_{shaft}\right)$	ConstService
Kshaft	K_{shaft}	$\frac{0.5 \cdot 2H_g 2H_t Freq_1^2}{H_t}$	ConstService

Blocks

Name	Symbol	Type	Info
s1	$s1$	Integrator	
s2	$s2$	Integrator	
s3	$s3$	Integrator	

Config Fields in [WTDTA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.25.2 WTDS

Custom wind turbine model with a single swing-equation.

This model is used to simulate the mechanical swing of the combined machine and turbine mass. The speed output is `s1_y` which will be fed to `RenExciter.wg`.

`PFLAG` needs to be set to `1` in exciter to consider speed for Pref.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
ree		Renewable exciter idx			mandatory
H	H_t	Total inertia	3	*MWs/MVA*	non_zero,non_negative,power
D	D_{shaft}	Damping coefficient	1	*p.u.*	power
w0	ω_0	Default speed if not using a torque model	1	*p.u.*	
reg			0		
Sn	S_n		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
s1_y	y_{s1}	State	Integrator output		v_str
s3_y	y_{s3}	State	Unused state variable		
wt	ω_t	AliasState	Alias of s1_y		
wg	ω_g	AliasState	Alias of s1_y		
Pm	P_m	Algeb	Mechanical power		v_str
wr0	ω_{r0}	Algeb	speed set point	*p.u.*	v_str
wge	wge	ExtAlgeb			
Pe	Pe	ExtAlgeb	Retrieved Pe of RenGen		

Initialization Equations

Name	Symbol	Type	Initial Value
s1_y	y_{s1}	State	ω_{r0}
s3_y	y_{s3}	State	
wt	ω_t	AliasState	
wg	ω_g	AliasState	
Pm	P_m	Algeb	P_{e0}
wr0	ω_{r0}	Algeb	ω_0
wge	wge	ExtAlgeb	
Pe	Pe	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s1_y	y_{s1}	State	$-1.0D_{shaft}\left(-\omega_{r0}+y_{s1}\right)+\frac{1.0(P_m-Pe)}{wge}$	$2H$
s3_y	y_{s3}	State	0	
wt	ω_t	AliasState	0	
wg	ω_g	AliasState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Pm	P_m	Algeb	$-P_m+P_{e0}$
wr0	ω_{r0}	Algeb	$\omega_0-\omega_{r0}$
wge	wge	ExtAlgeb	$y_{s1}-1.0$
Pe	Pe	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
H2	$2H$	$2H_t$	ConstService
Kshaft	K_{shaft}	1.0	ConstService

Blocks

Name	Symbol	Type	Info
s1	$s1$	Integrator	

Config Fields in [WTDS]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.26 RenPitch

Renewable generator pitch controller group.

Common Parameters: u, name, rea

Available models: *WTPTA1*

5.26.1 WTPTA1

Wind turbine pitch control model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
rea		Renewable aerodynamics model idx			mandatory
Kiw	K_{iw}	Pitch-control integral gain	0.100	*p.u.*	
Kpw	K_{pw}	Pitch-control proportional gain	0	*p.u.*	
Kic	K_{ic}	Pitch-compensation integral gain	0.100	*p.u.*	
Kpc	K_{pc}	Pitch-compensation proportional gain	0	*p.u.*	
Kcc	K_{cc}	Gain for P diff	0	*p.u.*	
Tp	T_{θ}	Blade response time const.	0.300	*s*	
thmax	θ_{max}	Max. pitch angle	30	*deg.*	
thmin	θ_{min}	Min. pitch angle	0	*deg.*	
dthmax	θ_{max}	Max. pitch angle rate	5	*deg.*	
dthmin	θ_{min}	Min. pitch angle rate	-5	*deg.*	
rego			0		
ree			0		

Variables

Name	Symbol	Type	Description	Unit	Properties
PIc_xi	xi_{PI_c}	State	Integrator output		v_str
PIw_xi	xi_{PI_w}	State	Integrator output		v_str
LG_y	y_{LG}	State	State in lag TF		v_str
wt	wt	ExtState			
Pord	$Pord$	ExtState			
PIc_yul	$y_{PI_c}^{ul}$	Algeb			v_str
PIc_y	y_{PI_c}	Algeb	PI output		v_str
wref	ω_{ref}	Algeb	optional speed reference		v_str
PIw_yul	$y_{PI_w}^{ul}$	Algeb			v_str
PIw_y	y_{PI_w}	Algeb	PI output		v_str
theta	θ	ExtAlgeb			
Pref	$Pref$	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
PIc_xi	xi_{PI_c}	State	0.0
PIw_xi	xi_{PI_w}	State	0.0
LG_y	y_{LG}	State	$1.0y_{PI_c} + 1.0y_{PI_w}$
wt	wt	ExtState	
Pord	$Pord$	ExtState	
PIc_yul	$y_{PI_c}^{ul}$	Algeb	$K_{pc}\left(Pord - Pref\right)$
PIc_y	y_{PI_c}	Algeb	$\theta_{max} z_u^{hl_{PI_c}} + \theta_{min} z_l^{hl_{PI_c}} + y_{PI_c}^{ul} z_i^{hl_{PI_c}}$
wref	ω_{ref}	Algeb	wt
PIw_yul	$y_{PI_w}^{ul}$	Algeb	$K_{pw}\left(K_{cc}\left(Pord - Pref\right) - \omega_{ref} + wt\right)$
PIw_y	y_{PI_w}	Algeb	$\theta_{max} z_u^{hl_{PI_w}} + \theta_{min} z_l^{hl_{PI_w}} + y_{PI_w}^{ul} z_i^{hl_{PI_w}}$
theta	θ	ExtAlgeb	
Pref	$Pref$	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
PIc_xi	xi_{PI_c}	State	$K_{ic}\left(Pord - Pref\right)$	
PIw_xi	xi_{PI_w}	State	$K_{iw}\left(K_{cc}\left(Pord - Pref\right) - \omega_{ref} + wt\right)$	
LG_y	y_{LG}	State	$-y_{LG} + 1.0y_{PI_c} + 1.0y_{PI_w}$	T_θ
wt	wt	ExtState	0	
Pord	$Pord$	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
PIc_yul	$y^{ul}_{PI_c}$	Algeb	$K_{pc}\left(Pord - Pref\right) + xi_{PI_c} - y^{ul}_{PI_c}$
PIc_y	y_{PI_c}	Algeb	$\theta_{max} z_u^{hl_{PI_c}} + \theta_{min} z_l^{hl_{PI_c}} + y^{ul}_{PI_c} z_i^{hl_{PI_c}} - y_{PI_c}$
wref	ω_{ref}	Algeb	$-\omega_{ref} + wref_0$
PIw_yul	$y^{ul}_{PI_w}$	Algeb	$K_{pw}\left(K_{cc}\left(Pord - Pref\right) - \omega_{ref} + wt\right) + xi_{PI_w} - y^{ul}_{PI_w}$
PIw_y	y_{PI_w}	Algeb	$\theta_{max} z_u^{hl_{PI_w}} + \theta_{min} z_l^{hl_{PI_w}} + y^{ul}_{PI_w} z_i^{hl_{PI_w}} - y_{PI_w}$
theta	θ	ExtAlgeb	$-\theta_0 + y_{LG}$
Pref	$Pref$	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
wref0	$wref0$	ω_{ref}	PostInitService

Discretes

Name	Symbol	Type	Info
PIc_aw	aw_{PI_c}	AntiWindup	
PIc_hl	hl_{PI_c}	HardLimiter	
PIw_aw	aw_{PI_w}	AntiWindup	
PIw_hl	hl_{PI_w}	HardLimiter	
LG_lim	lim_{LG}	AntiWindupRate	Limiter in Lag

Blocks

Name	Symbol	Type	Info
PIc	PI_c	PIAWHardLimit	PI for active power diff compensation
PIw	PI_w	PIAWHardLimit	PI for speed and active power deviation
LG	LG	LagAntiWindupRate	Output lag anti-windup rate limiter

Config Fields in [WTPTA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.27 RenPlant

Renewable plant control group.

Common Parameters: u, name

Available models: *REPCA1*

5.27.1 REPCA1

REPCA1: renewable energy power plat control model.

The output of the model, `Pext` and `Qext`, are the increment signals of active and reactive power for the electrical control model.

Notes for PSS/E DYR parser:

1. If ICONs M+1 and M+2 are set to 0 when using generator power, an error will be thrown by the parser, saying "<REPCA1> cannot retrieve <bus1> from <ACLine> using <line>: KeyError('Group <ACLine> does not contain device with idx=False')". Manual effort is required to run the converted file. In the REPCA1 sheet, provide the idx of a line that connects to the RenGen bus.
2. PSS/E enters ICONs M+3 as a string in single quotes. The pair of single quotes need to be removed, or the conversion will fail.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
ree		RenExciter idx			mandatory
line		Idx of line that connect to measured bus			mandatory
busr		Optional remote bus for voltage and freq. measurement			
busf		BusFreq idx for mode 2			
VCFlag		Droop flag; 0-with droop if power factor ctrl, 1-line drop comp.		*bool*	mandatory
RefFlag		Q/V select; 0-Q control, 1-V control		*bool*	mandatory
Fflag		Frequency control flag; 0-disable, 1-enable		*bool*	mandatory

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Name	Symbol	Description	Default	Unit	Properties
PLflag		Pline ctrl. flag; 0-disable, 1-enable	True	*bool*	
Tfltr	T_{fltr}	V or Q filter time const.	0.020		
Kp	K_p	Q proportional gain	1		
Ki	K_i	Q integral gain	0.100		
Tft	T_{ft}	Lead time constant	1		
Tfv	T_{fv}	Lag time constant	1		
Vfrz	V_{frz}	Voltage below which s2 is frozen	0.800		
Rc	R_c	Line drop compensation R			
Xc	X_c	Line drop compensation R			
Kc	K_c	Reactive power compensation gain	0		
emax	e_{max}	Upper limit on deadband output	999		
emin	e_{min}	Lower limit on deadband output	-999		
dbd1	d_{bd1}	Lower threshold for reactive power control deadband (<=0)	-0.100		
dbd2	d_{bd2}	Upper threshold for reactive power control deadband (>=0)	0.100		
Qmax	Q_{max}	Upper limit on output of V-Q control	999		
Qmin	Q_{min}	Lower limit on output of V-Q control	-999		
Kpg	K_{pg}	Proportional gain for power control	1		
Kig	K_{ig}	Integral gain for power control	0.100		
Tp	T_p	Time constant for P measurement	0.020		
fdbd1	f_{dbd1}	Lower threshold for freq. error deadband	-0.000	*p.u. (Hz)*	
fdbd2	f_{dbd2}	Upper threshold for freq. error deadband	0.000	*p.u. (Hz)*	
femax	f_{emax}	Upper limit for freq. error	0.050		
femin	f_{emin}	Lower limit for freq. error	-0.050		
Pmax	P_{max}	Upper limit on power error (used by PI ctrl.)	999	*p.u. (MW)*	power
Pmin	P_{min}	Lower limit on power error (used by PI ctrl.)	-999	*p.u. (MW)*	power
Tg	T_g	Power controller lag time constant	0.020		
Ddn	D_{dn}	Reciprocal of droop for over-freq. conditions	10		
Dup	D_{up}	Reciprocal of droop for under-freq. conditions	10		
reg		Retrieved RenGen idx			
bus		Retrieved bus idx			
bus1		Retrieved Line.bus1 idx			
bus2		Retrieved Line.bus2 idx			
r		Retrieved Line.r			
x		Retrieved Line.x			

Variables

Name	Symbol	Type	Description	Unit	Properties
s0_y	y_{s_0}	State	State in lag transfer function		v_str
s1_y	y_{s_1}	State	State in lag transfer function		v_str
s2_xi	xi_{s_2}	State	Integrator output		v_str

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Name	Symbol	Type	Description	Unit	Properties
s3_x	x'_{s_3}	State	State in lead-lag		v_str
s4_y	y_{s_4}	State	State in lag transfer function		v_str
s5_xi	xi_{s_5}	State	Integrator output		v_str
s6_y	y_{s_6}	State	State in lag transfer function		v_str
Vref	Q_{ref}	Algeb			v_str
Qlinef	Q_{linef}	Algeb			v_str
Refsel	R_{efsel}	Algeb			v_str
dbd_y	$y_{d^{bd}}$	Algeb	Deadband type 1 output		v_str
enf	e_{nf}	Algeb	e Hardlimit output before freeze		v_str
s2_ys	ys_{s_2}	Algeb	PI summation before limit		v_str
s2_y	y_{s_2}	Algeb	PI output		v_str
s3_y	y_{s_3}	Algeb	Output of lead-lag		v_str
ferr	f_{err}	Algeb	Frequency deviation	*p.u. (Hz)*	v_str
fdbd_y	$y_{f^{dbd}}$	Algeb	Deadband type 1 output		v_str
Plant_pref	P_{ref}	Algeb	Plant P ref		v_str
Plerr	P_{lerr}	Algeb	Pline error		v_str
Perr	P_{err}	Algeb	Power error before fe limits		v_str
s5_ys	ys_{s_5}	Algeb	PI summation before limit		v_str
s5_y	y_{s_5}	Algeb	PI output		v_str
Pext	P_{ext}	ExtAlgeb	Pref from RenExciter renamed as Pext		
Qext	Q_{ext}	ExtAlgeb	Qref from RenExciter renamed as Qext		
v	V	ExtAlgeb	Bus (or busr, if given) terminal voltage		
a	θ	ExtAlgeb	Bus (or busr, if given) phase angle		
f	f	ExtAlgeb	Bus frequency	*p.u.*	
v1	V_1	ExtAlgeb	Voltage at Line.bus1		
v2	V_2	ExtAlgeb	Voltage at Line.bus2		
a1	θ_1	ExtAlgeb	Angle at Line.bus1		
a2	θ_2	ExtAlgeb	Angle at Line.bus2		

Initialization Equations

Name	Symbol	Type	Initial Value
s0_y	y_{s_0}	State	$V_{comp}s_1^{SW_{VC}} + s_0^{SW_{VC}}\left(K_cQ_{line} + V\right)$
s1_y	y_{s_1}	State	Q_{line}
s2_xi	xi_{s_2}	State	0.0
s3_x	x'_{s_3}	State	y_{s_2}
s4_y	y_{s_4}	State	P_{line}
s5_xi	xi_{s_5}	State	0.0
s6_y	y_{s_6}	State	y_{s_5}
Vref	Q_{ref}	Algeb	V_{ref0}
Qlinef	Q_{linef}	Algeb	Q_{line0}

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Name	Symbol	Type	Initial Value
Refsel	R_{efsel}	Algeb	$s_0^{SW_{Ref}}\left(Q_{linef} - y_{s_1}\right) + s_1^{SW_{Ref}}\left(Q_{ref} - y_{s_0}\right)$
dbd_y	$y_{d^{bd}}$	Algeb	$1.0 z_l^{db_{d^{bd}}}\left(R_{efsel} - d_{bd1}\right) + 1.0 z_u^{db_{d^{bd}}}\left(R_{efsel} - d_{bd2}\right)$
enf	e_{nf}	Algeb	$e_{max} z_u^{e_{HL}} + e_{min} z_l^{e_{HL}} + y_{d^{bd}} z_i^{e_{HL}}$
s2_ys	ys_{s_2}	Algeb	$K_p e_{hld}$
s2_y	y_{s_2}	Algeb	$Q_{max} z_u^{lim_{s_2}} + Q_{min} z_l^{lim_{s_2}} + ys_{s_2} z_i^{lim_{s_2}}$
s3_y	y_{s_3}	Algeb	y_{s_2}
ferr	f_{err}	Algeb	$-f + f_{ref}$
fdbd_y	$y_{f^{dbd}}$	Algeb	$1.0 z_l^{db_{f^{dbd}}}\left(-f_{dbd1} + f_{err}\right) + 1.0 z_u^{db_{f^{dbd}}}\left(-f_{dbd2} + f_{err}\right)$
Plant_pref	P_{ref}	Algeb	P_{line0}
Plerr	P_{lerr}	Algeb	$P_{ref} - y_{s_4}$
Perr	P_{err}	Algeb	$D_{dn} y_{f^{dbd}} z_1^{f_{dlt0}} + D_{up} y_{f^{dbd}} z_0^{f_{dlt0}} + P_{lerr} s_1^{SW_{PL}}$
s5_ys	ys_{s_5}	Algeb	$K_{pg}\left(P_{err} z_i^{f_{eHL}} + f_{emax} z_u^{f_{eHL}} + f_{emin} z_l^{f_{eHL}}\right)$
s5_y	y_{s_5}	Algeb	$P_{max} z_u^{lim_{s_5}} + P_{min} z_l^{lim_{s_5}} + ys_{s_5} z_i^{lim_{s_5}}$
Pext	P_{ext}	ExtAlgeb	
Qext	Q_{ext}	ExtAlgeb	
v	V	ExtAlgeb	
a	θ	ExtAlgeb	
f	f	ExtAlgeb	
v1	V_1	ExtAlgeb	
v2	V_2	ExtAlgeb	
a1	θ_1	ExtAlgeb	
a2	θ_2	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s0_y	y_{s_0}	State	$V_{comp} s_1^{SW_{VC}} + s_0^{SW_{VC}}\left(K_c Q_{line} + V\right) - y_{s_0}$	T_{fltr}
s1_y	y_{s_1}	State	$Q_{line} - y_{s_1}$	T_{fltr}
s2_xi	xi_{s_2}	State	$K_i\left(e_{hld} + 2y_{s_2} - 2ys_{s_2}\right)$	
s3_x	x'_{s_3}	State	$-x'_{s_3} + y_{s_2}$	T_{fv}
s4_y	y_{s_4}	State	$P_{line} - y_{s_4}$	T_p
s5_xi	xi_{s_5}	State	$K_{ig}\left(P_{err} z_i^{f_{eHL}} + f_{emax} z_u^{f_{eHL}} + f_{emin} z_l^{f_{eHL}} + 2y_{s_5} - 2ys_{s_5}\right)$	
s6_y	y_{s_6}	State	$y_{s_5} - y_{s_6}$	T_g

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Vref	Q_{ref}	Algeb	$-Q_{ref} + V_{ref0}$
Qlinef	Q_{linef}	Algeb	$Q_{line0} - Q_{linef}$
Refsel	R_{efsel}	Algeb	$-R_{efsel} + s_0^{SW_{Ref}} \left(Q_{linef} - y_{s_1}\right) + s_1^{SW_{Ref}} \left(Q_{ref} - y_{s_0}\right)$
dbd_y	$y_{d^{bd}}$	Algeb	$-y_{d^{bd}} + 1.0 z_l^{db_{d^{bd}}} \left(R_{efsel} - d_{bd1}\right) + 1.0 z_u^{db_{d^{bd}}} \left(R_{efsel} - d_{bd2}\right)$
enf	e_{nf}	Algeb	$e_{max} z_u^{e_{HL}} + e_{min} z_l^{e_{HL}} - e_{nf} + y_{d^{bd}} z_i^{e_{HL}}$
s2_ys	ys_{s_2}	Algeb	$K_p e_{hld} + xi_{s_2} - ys_{s_2}$
s2_y	y_{s_2}	Algeb	$Q_{max} z_u^{lim_{s_2}} + Q_{min} z_l^{lim_{s_2}} - y_{s_2} + ys_{s_2} z_i^{lim_{s_2}}$
s3_y	y_{s_3}	Algeb	$T_{ft} \left(-x'_{s_3} + y_{s_2}\right) + T_{fv} x'_{s_3} - T_{fv} y_{s_3} + \left(z_1^{LT_{s_3}}\right)^2 \left(-x'_{s_3} + y_{s_3}\right)$
ferr	f_{err}	Algeb	$-f - f_{err} + f_{ref}$
fdbd_y	$y_{f^{dbd}}$	Algeb	$-y_{f^{dbd}} + 1.0 z_l^{db_{f^{dbd}}} \left(-f_{dbd1} + f_{err}\right) + 1.0 z_u^{db_{f^{dbd}}} \left(-f_{dbd2} + f_{err}\right)$
Plant_pref	P_{ref}	Algeb	$P_{line0} - P_{ref}$
Plerr	P_{lerr}	Algeb	$-P_{lerr} + P_{ref} - y_{s_4}$
Perr	P_{err}	Algeb	$D_{dn} y_{f^{dbd}} z_1^{f_{dlt0}} + D_{up} y_{f^{dbd}} z_0^{f_{dlt0}} - P_{err} + P_{lerr} s_1^{SW_{PL}}$
s5_ys	ys_{s_5}	Algeb	$K_{pg} \left(P_{err} z_i^{f_{eHL}} + f_{emax} z_u^{f_{eHL}} + f_{emin} z_l^{f_{eHL}}\right) + xi_{s_5} - ys_{s_5}$
s5_y	y_{s_5}	Algeb	$P_{max} z_u^{lim_{s_5}} + P_{min} z_l^{lim_{s_5}} - y_{s_5} + ys_{s_5} z_i^{lim_{s_5}}$
Pext	P_{ext}	ExtAlgeb	$s_1^{SW_F} y_{s_6}$
Qext	Q_{ext}	ExtAlgeb	y_{s_3}
v	V	ExtAlgeb	0
a	θ	ExtAlgeb	0
f	f	ExtAlgeb	0
v1	V_1	ExtAlgeb	0
v2	V_2	ExtAlgeb	0
a1	θ_1	ExtAlgeb	0
a2	θ_2	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
Isign	I_{sign}	0	CurrentSign
Iline	I_{line}	$\frac{I_{sign}\left(V_1 e^{i\theta_1} - V_2 e^{i\theta_2}\right)}{r+ix}$	VarService
Iline0	I_{line0}	I_{line}	ConstService
Pline	P_{line}	re $\left(I_{sign} V_1 \text{ conj } \left(\frac{V_1 e^{i\theta_1} - V_2 e^{i\theta_2}}{r+ix}\right) e^{i\theta_1}\right)$	VarService
Pline0	P_{line0}	P_{line}	ConstService
Qline	Q_{line}	im $\left(I_{sign} V_1 \text{ conj } \left(\frac{V_1 e^{i\theta_1} - V_2 e^{i\theta_2}}{r+ix}\right) e^{i\theta_1}\right)$	VarService
Qline0	Q_{line0}	Q_{line}	ConstService
Vcomp	V_{comp}	$\left\lvert I_{line}\left(R_{cs} + iX_{cs}\right) - V e^{i\theta}\right\rvert$	VarService
Vref0	V_{ref0}	$V_{comp} s_1^{SW_{VC}} + s_0^{SW_{VC}} \left(K_c Q_{line0} + V\right)$	ConstService
zf	z_f	f_{rz} Indicator $\left(V < V_{frz}\right)$	VarService
eHld	e_{hld}	0	VarHold
Freq_ref	f_{ref}	1.0	ConstService

Discretes

Name	Symbol	Type	Info
SWVC	SW_{VC}	Switcher	
SWRef	SW_{Ref}	Switcher	
SWF	SW_F	Switcher	
SWPL	SW_{PL}	Switcher	
dbd_db	db_{dbd}	DeadBand	
eHL	e_{HL}	Limiter	Hardlimit on deadband output
s2_lim	lim_{s_2}	HardLimiter	
s3_LT1	LT_{s_3}	LessThan	
s3_LT2	LT_{s_3}	LessThan	
fdbd_db	db_{fdbd}	DeadBand	
fdlt0	f_{dlt0}	LessThan	frequency deadband output less than zero
feHL	f_{eHL}	Limiter	Limiter for power (frequency) error
s5_lim	lim_{s_5}	HardLimiter	

Blocks

Name	Symbol	Type	Info
s0	s_0	Lag	V filter
s1	s_1	Lag	
dbd	d^{bd}	DeadBand1	
s2	s_2	PITrackAW	PI controller for eHL output
s3	s_3	LeadLag	
s4	s_4	Lag	Pline filter
fdbd	f^{dbd}	DeadBand1	frequency error deadband
s5	s_5	PITrackAW	PI for fe limiter output
s6	s_6	Lag	Output filter for Pext

Config Fields in [REPCA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
kqs	K_{qs}	2	Tracking gain for reactive power PI controller	
ksg	K_{sg}	2	Tracking gain for active power PI controller	
freeze	f_{rz}	1	Voltage dip freeze flag; 1-enable, 0-disable	

5.28 RenTorque

Renewable torque (Pref) controller.

Common Parameters: u, name

Available models: *WTTQA1*

5.28.1 WTTQA1

Wind turbine generator torque (Pref) model.

PI state freeze following voltage dip has not been implemented.

Resets *wg* in *REECA1* model to 1.0 when torque model is connected. This effectively ignores *PFLAG* of *REECA1*.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
rep		RenPitch controller idx			mandatory
Kip	K_{ip}	Pref-control integral gain	0.100	*p.u.*	
Kpp	K_{pp}	Pref-control proportional gain	0	*p.u.*	
Tp	T_p	Pe sensing time const.	0.050	*s*	
Twref	T_{wref}	Speed reference time const.	30	*s*	
Temax	T_{emax}	Max. electric torque	1.200	*p.u.*	power
Temin	T_{emin}	Min. electric torque	0	*p.u.*	power
Tflag		Tflag; 1-power error, 0-speed error		*bool*	mandatory
p1	p_1	Active power point 1	0.200	*p.u.*	power
sp1	s_{p1}	Speed power point 1	0.580	*p.u.*	
p2	p_2	Active power point 2	0.400	*p.u.*	power
sp2	s_{p2}	Speed power point 2	0.720	*p.u.*	
p3	p_3	Active power point 3	0.600	*p.u.*	power
sp3	s_{p3}	Speed power point 3	0.860	*p.u.*	
p4	p_4	Active power point 4	0.800	*p.u.*	power
sp4	s_{p4}	Speed power point 4	1	*p.u.*	
Tn	T_n	Turbine rating. Use Sn from gov if none.	nan	*MVA*	
rea			0		
rego			0		
ree			0		
reg			0		
Sngo	$S_{n,go}$		0		
w0	ω_0		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
s1_y	y_{s_1}	State	State in lag transfer function		v_str
s2_y	y_{s_2}	State	State in lag transfer function		v_str
PI_xi	xi_{PI}	State	Integrator output		v_str
wg	ω_g	ExtState			v_str,v_setter
wt	ω_t	ExtState			v_str,v_setter
s3_y	y_{s3}	ExtState			v_str,v_setter
fPe_y	$y_{f_{Pe}}$	Algeb	Output of piecewise		v_str
Tsel	T_{sel}	Algeb	Output after Tflag selector		v_str
PI_yul	y_{PI}^{ul}	Algeb			v_str
PI_y	y_{PI}	Algeb	PI output		v_str
Pe	P_e	ExtAlgeb			
wr0	ω_{r0}	ExtAlgeb	Retrieved initial w0 from RenGovernor		v_str,v_setter
wge	ω_{ge}	ExtAlgeb			v_str,v_setter
Pref	P_{ref}	ExtAlgeb			v_str,v_setter

Initialization Equations

Nam	Sym-bol	Type	Initial Value
s1_y	y_{s_1}	State	$1.0P_e$
s2_y	y_{s_2}	State	$1.0y_{f_{Pe}}$
PI_xi	xi_{PI}	State	$\frac{P_{ref0}}{y_{f_{Pe}}}$
wg	ω_g	ExtSta	$y_{f_{Pe}}$
wt	ω_t	ExtSta	$y_{f_{Pe}}$
s3_y	y_{s3}	ExtSta	$\frac{P_{ref0}}{\omega_g}$
fPe_y	$y_{f_{Pe}}$	Al-geb	FixPiecewise $\left((s_{p1},\ p_1 \geq y_{s_1}), (k_{p1}\left(-p_1 + y_{s_1}\right) + s_{p1},\ p_2 \geq y_{s_1}), (k_{p2}\left(-p_2 + y_{s_1}\right) + s_{p2},\ p_3 \geq y_{s}\right.$
Tsel	T_{sel}	Al-geb	$s_0^{SW_T}\left(-\omega_g + y_{s_2}\right) + \frac{s_1^{SW_T}\left(P_e - P_{ref0}\right)}{\omega_g}$
PI_yu	y_{PI}^{ul}	Al-geb	$K_{pp}T_{sel} + \frac{P_{ref0}}{y_{f_{Pe}}}$
PI_y	y_{PI}	Al-geb	$T_{emax}z_u^{hl_{PI}} + T_{emin}z_l^{hl_{PI}} + y_{PI}^{ul}z_i^{hl_{PI}}$
Pe	P_e	Ex-tAl-geb	
wr0	ω_{r0}	Ex-tAl-geb	$y_{f_{Pe}}$
wge	ω_{ge}	Ex-tAl-geb	1.0
Pref	P_{ref}	Ex-tAl-geb	$\omega_g y_{PI}$

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
s1_y	y_{s_1}	State	$1.0P_e - y_{s_1}$	T_p
s2_y	y_{s_2}	State	$1.0y_{f_{Pe}} - y_{s_2}$	T_{wref}
PI_xi	xi_{PI}	State	$K_{ip}T_{sel}$	
wg	ω_g	ExtState	0	
wt	ω_t	ExtState	0	
s3_y	y_{s3}	ExtState	0	

Algebraic Equations

Nam	Sym-bol	Type	RHS of Equation "0 = g(x, y)"
fPe_y	$y_{f_{Pe}}$	Al-geb	$-y_{f_{Pe}}$+FixPiecewise $\left((s_{p1},\ p_1 \geq y_{s_1}), (k_{p1}\left(-p_1 + y_{s_1}\right) + s_{p1},\ p_2 \geq y_{s_1}), (k_{p2}\left(-p_2 + y_{s_1}\right) + s_{p2},\right.$
Tsel	T_{sel}	Al-geb	$-T_{sel} + s_0^{SW_T}\left(-\omega_g + y_{s_2}\right) + \frac{s_1^{SW_T}\left(P_e - P_{ref0}\right)}{\omega_g}$
PI_yı	y_{PI}^{ul}	Al-geb	$K_{pp}T_{sel} + xi_{PI} - y_{PI}^{ul}$
PI_y	y_{PI}	Al-geb	$T_{emax}z_u^{hl_{PI}} + T_{emin}z_l^{hl_{PI}} + y_{PI}^{ul}z_i^{hl_{PI}} - y_{PI}$
Pe	P_e	Ex-tAl-geb	0
wr0	ω_{r0}	Ex-tAl-geb	$-\omega_0 + y_{f_{Pe}}$
wge	ω_{ge}	Ex-tAl-geb	$1 - y_{f_{Pe}}$
Pref	P_{ref}	Ex-tAl-geb	$-\frac{P_{ref0}}{\omega_{ge}} + \omega_g y_{PI}$

Services

Name	Symbol	Equation	Type
kp1	k_{p1}	$\frac{-s_{p1}+s_{p2}}{-p_1+p_2}$	ConstService
kp2	k_{p2}	$\frac{-s_{p2}+s_{p3}}{-p_2+p_3}$	ConstService
kp3	k_{p3}	$\frac{-s_{p3}+s_{p4}}{-p_3+p_4}$	ConstService

Discretes

Name	Symbol	Type	Info
SWT	SW_T	Switcher	
PI_aw	aw_{PI}	AntiWindup	
PI_hl	hl_{PI}	HardLimiter	

Blocks

Name	Symbol	Type	Info
s1	s_1	Lag	Pe filter
fPe	f_{Pe}	Piecewise	Piecewise Pe to wref mapping
s2	s_2	Lag	speed filter
PI	PI	PIAWHardLimit	PI controller

Config Fields in [WTTQA1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.29 StaticACDC

AC DC device for power flow

Common Parameters: u, name

Available models: *VSCShunt*

5.29.1 VSCShunt

Data for VSC Shunt in power flow

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		idx of connected bus			mandatory
node1		Node 1 index			mandatory
node2		Node 2 index			mandatory
Vn	V_n	AC voltage rating	110		non_zero
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	*kV*	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	*kV*	non_zero
Idcn	I_{dcn}	DC current rating	1	*kA*	non_zero
rsh	r_{sh}	AC interface resistance	0.003	*ohm*	z
xsh	x_{sh}	AC interface reactance	0.060	*ohm*	z
control		Control method: 0-PQ, 1-PV, 2-vQ or 3-vV			mandatory
v0		AC voltage setting (PV or vV) or initial guess (PQ or vQ)	1		
p0		AC active power setting	0	*pu*	
q0		AC reactive power setting	0	*pu*	
vdc0	v_{dc0}	DC voltage setting	1	*pu*	
k0		Loss coefficient - constant	0		
k1		Loss coefficient - linear	0		
k2		Loss coefficient - quadratic	0		
droop		Enable dc voltage droop control	0	*boolean*	
K		Droop coefficient	0		
vhigh		Upper voltage threshold in droop control	9999	*pu*	
vlow		Lower voltage threshold in droop control	0	*pu*	
vshmax		Maximum ac interface voltage	1.100	*pu*	
vshmin		Minimum ac interface voltage	0.900	*pu*	
Ishmax		Maximum ac current	2	*pu*	

Variables

Name	Symbol	Type	Description	Unit	Properties
ash	θ_{sh}	Algeb	voltage phase behind the transformer	*rad*	v_str
vsh	V_{sh}	Algeb	voltage magnitude behind transformer	*p.u.*	v_str
psh	P_{sh}	Algeb	active power injection into VSC	*p.u.*	v_str
qsh	Q_{sh}	Algeb	reactive power injection into VSC		v_str
pdc	P_{dc}	Algeb	DC power injection		v_str
a	a	ExtAlgeb	AC bus voltage phase		
v	v	ExtAlgeb	AC bus voltage magnitude		
v1	v_1	ExtAlgeb	DC node 1 voltage		
v2	v_2	ExtAlgeb	DC node 2 voltage		

Initialization Equations

Name	Symbol	Type	Initial Value
ash	θ_{sh}	Algeb	a
vsh	V_{sh}	Algeb	v_0
psh	P_{sh}	Algeb	$p_0 \left(s_0^{mode} + s_1^{mode}\right)$
qsh	Q_{sh}	Algeb	$q_0 \left(s_0^{mode} + s_2^{mode}\right)$
pdc	P_{dc}	Algeb	0
a	a	ExtAlgeb	
v	v	ExtAlgeb	
v1	v_1	ExtAlgeb	
v2	v_2	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
ash	θ_{sh}	Algeb	$-P_{sh} + u \left(V_{sh} b_{sh} v \sin\left(\theta_{sh} - a\right) - V_{sh} g_{sh} v \cos\left(\theta_{sh} - a\right) + g_{sh} v^2\right)$
vsh	V_{sh}	Algeb	$-Q_{sh} + u \left(V_{sh} b_{sh} v \cos\left(\theta_{sh} - a\right) + V_{sh} g_{sh} v \sin\left(\theta_{sh} - a\right) - b_{sh} v^2\right)$
psh	P_{sh}	Algeb	$u \left(-P_{sh} + p_0\right) \left(s_0^{mode} + s_1^{mode}\right) + u \left(s_2^{mode} + s_3^{mode}\right) \left(v_1 - v_2 - v_{dc0}\right)$
qsh	Q_{sh}	Algeb	$u \left(-Q_{sh} + q_0\right) \left(s_0^{mode} + s_2^{mode}\right) + u \left(s_1^{mode} + s_3^{mode}\right) \left(-v + v_0\right)$
pdc	P_{dc}	Algeb	$P_{dc} + u \left(V_{sh}^2 g_{sh} - V_{sh} b_{sh} v \sin\left(\theta_{sh} - a\right) - V_{sh} g_{sh} v \cos\left(\theta_{sh} - a\right)\right)$
a	a	ExtAlgeb	$-P_{sh}$
v	v	ExtAlgeb	$-Q_{sh}$
v1	v_1	ExtAlgeb	$-\frac{P_{dc}}{v_1 - v_2}$
v2	v_2	ExtAlgeb	$\frac{P_{dc}}{v_1 - v_2}$

Services

Name	Symbol	Equation	Type
gsh	g_{sh}	$\frac{\mathrm{re}\,(r_{sh})-\mathrm{im}\,(x_{sh})}{(\mathrm{re}\,(r_{sh})-\mathrm{im}\,(x_{sh}))^2+(\mathrm{re}\,(x_{sh})+\mathrm{im}\,(r_{sh}))^2}$	ConstService
bsh	b_{sh}	$\frac{-\mathrm{re}\,(x_{sh})-\mathrm{im}\,(r_{sh})}{(\mathrm{re}\,(r_{sh})-\mathrm{im}\,(x_{sh}))^2+(\mathrm{re}\,(x_{sh})+\mathrm{im}\,(r_{sh}))^2}$	ConstService

Discretes

Name	Symbol	Type	Info
mode	$mode$	Switcher	

Config Fields in [VSCShunt]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.30 StaticGen

Static generator group.

Static generators include PV and Slack, which are used to impose algebraic equations. Static generators are used primarily for power flow.

Static generators do not have the modeling details for stability simulation. Although some of them can stay for time-domain simulation, most of them should be substituted by dynamic generators, including synchronous generators and inverter-based resources upon TDS initialization.

The substitution is done by setting the `gen` field of a dynamic generator to refer to the static generator. To replace one StaticGen by multiple dynamic generators, see the notes in *SynGen*. Generators connected to the same bus need to have their *gammap* and *gammaq*, respectively, summed up to be exactly 1.0.

TDS initialization will ensure that the dynamic generators impose the same amount of power as the static generator. At the end of initialization, *StaticGen*'s that have been substituted will have their connectivity status `u` changed to `0`.

Common Parameters: u, name, Sn, Vn, p0, q0, ra, xs, subidx

Common Variables: q, a, v

Available models: *PV*, *Slack*

5.30.1 PV

Static PV generator with reactive power limit checking and PV-to-PQ conversion.

pv2pq = 1 turns on the conversion. It starts from iteration *min_iter* or when the convergence error drops below *err_tol*.

The PV-to-PQ conversion first ranks the reactive violations. A maximum number of *npv2pq* PVs above the upper limit, and a maximum of *npv2pq* PVs below the lower limit will be converted to PQ, which sets the reactive power to *pmax* or *pmin*.

If *pv2pq* is *1* (enabled) and *npv2pq* is *0*, heuristics will be used to determine the number of PVs to be converted for each iteration.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
Sn	S_n	Power rating	100		non_zero
Vn	V_n	AC voltage rating	110		non_zero
subidx		index for generators on the same bus			
bus		idx of the installed bus			mandatory
busr		bus idx for remote voltage control			
p0	p_0	active power set point in system base	0	*p.u.*	
q0	q_0	reactive power set point in system base	0	*p.u.*	
pmax	p_{max}	maximum active power in system base	999	*p.u.*	
pmin	p_{min}	minimum active power in system base	-1	*p.u.*	
qmax	q_{max}	maximim reactive power in system base	999	*p.u.*	
qmin	q_{min}	minimum reactive power in system base	-999	*p.u.*	
v0	v_0	voltage set point	1		
vmax	v_{max}	maximum voltage voltage	1.400		
vmin	v_{min}	minimum allowed voltage	0.600		
ra	r_a	armature resistance	0		
xs	x_s	armature reactance	0.300		
busv0	V_{0bus}		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
q	q	Algeb	actual reactive power generation	*p.u.*	v_str
a	θ	ExtAlgeb			
v	V	ExtAlgeb			v_str,v_setter

Initialization Equations

Name	Symbol	Type	Initial Value
q	q	Algeb	$q_0 u$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	$V_{0bus}\left(1-u\right)+uv_0$

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
q	q	Algeb	$u\left(z_i^{qlim}\left(-V+v_0\right)+z_l^{qlim}\left(-q+q_{min}\right)+z_u^{qlim}\left(-q+q_{max}\right)\right)$
a	θ	ExtAlgeb	$-pu$
v	V	ExtAlgeb	$-qu$

Services

Name	Symbol	Equation	Type
p	p	p_0	ConstService

Discretes

Name	Symbol	Type	Info
qlim	$qlim$	SortedLimiter	

Config Fields in [PV]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
pv2pq	z_{pv2pq}	0	convert PV to PQ in PFlow at Q limits	(0, 1)
npv2pq	n_{pv2pq}	0	max. # of conversion each iteration, 0 - auto	>=0
min_iter	sw_{iter}	2	iteration number starting from which to enable switching	int
err_tol	ϵ_{tol}	0.010	iteration error below which to enable switching	float
abs_violation		1	use absolute (1) or relative (0) limit violation	(0, 1)

5.30.2 Slack

Slack generator.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
Sn	S_n	Power rating	100		non_zero
Vn	V_n	AC voltage rating	110		non_zero
subidx		index for generators on the same bus			
bus		idx of the installed bus			mandatory
busr		bus idx for remote voltage control			
p0	p_0	active power set point in system base	0	*p.u.*	
q0	q_0	reactive power set point in system base	0	*p.u.*	
pmax	p_{max}	maximum active power in system base	999	*p.u.*	
pmin	p_{min}	minimum active power in system base	-1	*p.u.*	
qmax	q_{max}	maximim reactive power in system base	999	*p.u.*	
qmin	q_{min}	minimum reactive power in system base	-999	*p.u.*	
v0	v_0	voltage set point	1		
vmax	v_{max}	maximum voltage voltage	1.400		
vmin	v_{min}	minimum allowed voltage	0.600		
ra	r_a	armature resistance	0		
xs	x_s	armature reactance	0.300		
a0	θ_0	reference angle set point	0		
busv0	V_{0bus}		0		
busa0	θ_{0bus}		0		

Variables

Name	Symbol	Type	Description	Unit	Properties
q	q	Algeb	actual reactive power generation	*p.u.*	v_str
p	p	Algeb	actual active power generation	*p.u.*	v_str
a	θ	ExtAlgeb			v_str,v_setter
v	V	ExtAlgeb			v_str,v_setter

Initialization Equations

Name	Symbol	Type	Initial Value
q	q	Algeb	$q_0 u$
p	p	Algeb	$p_0 u$
a	θ	ExtAlgeb	$\theta_0 u + \theta_{0bus}\left(1-u\right)$
v	V	ExtAlgeb	$V_{0bus}\left(1-u\right) + u v_0$

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
q	q	Algeb	$u\left(z_i^{qlim}\left(-V+v_0\right) + z_l^{qlim}\left(-q+q_{min}\right) + z_u^{qlim}\left(-q+q_{max}\right)\right)$
p	p	Algeb	$u\left(z_i^{plim}\left(-\theta+\theta_0\right) + z_l^{plim}\left(-p+p_{min}\right) + z_u^{plim}\left(-p+p_{max}\right)\right)$
a	θ	ExtAlgeb	$-pu$
v	V	ExtAlgeb	$-qu$

Discretes

Name	Symbol	Type	Info
qlim	$qlim$	SortedLimiter	
plim	$plim$	SortedLimiter	

Config Fields in [Slack]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
pv2pq	z_{pv2pq}	0	convert PV to PQ in PFlow at Q limits	(0, 1)
npv2pq	n_{pv2pq}	0	max. # of conversion each iteration, 0 - auto	>=0
min_iter	sw_{iter}	2	iteration number starting from which to enable switching	int
err_tol	ϵ_{tol}	0.010	iteration error below which to enable switching	float
abs_violation		1	use absolute (1) or relative (0) limit violation	(0, 1)
av2pv	z_{av2pv}	0	convert Slack to PV in PFlow at P limits	(0, 1)

5.31 StaticLoad

Static load group.

Common Parameters: u, name

Available models: *PQ*

5.31.1 PQ

PQ load model.

Implements an automatic pq2z conversion during power flow when the voltage is outside [vmin, vmax]. The conversion can be turned off by setting *pq2z* to 0 in the Config file.

Before time-domain simulation, PQ load will be converted to impedance, current source, and power source based on the weights in the Config file.

Weights (p2p, p2i, p2z) corresponds to the weights for constant power, constant current and constant impedance. p2p, p2i and p2z must be in decimal numbers and sum up exactly to 1. The same rule applies to (q2q, q2i, q2z).

To alter the PQ load in terms of power during simulation, one needs to set the conversion weights to preserve the constant power portion. For example, the PQ can remain as constant power load by setting

```
ss.PQ.config.p2p = 1.0
ss.PQ.config.p2i = 0
ss.PQ.config.p2z = 0

ss.PQ.config.q2q = 1.0
ss.PQ.config.q2i = 0
ss.PQ.config.q2z = 0
```

Then, the constant power portion can be altered by changing the `Ppf` and `Qpf` constants for active power and reactive power.

The equivalent constant current components are in constants `Ipeq` and `Iqeq` for active and reactive current, and the equivalent impedances are in `Req` and `Xeq`.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		linked bus idx			mandatory
Vn	V_n	AC voltage rating	110	kV	non_zero
p0	p_0	active power load in system base	0	*p.u.*	
q0	q_0	reactive power load in system base	0	*p.u.*	
vmax	v_{max}	max voltage before switching to impedance	1.200		
vmin	v_{min}	min voltage before switching to impedance	0.800		
owner		owner idx			

Variables

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Nam	Sym-bol	Type	RHS of Equation "0 = g(x, y)"	
a	θ	Ex-tAl-geb	$u\left(I_{peq}V\gamma_{p2i} + P_{pf}\gamma_{p2p} + R_{eq}V^2\gamma_{p2z}\right)$ Indicator $(t_{dae} \geq 0)$ $u\left(R_{lb}V^2 z_l^{vcmp} + R_{ub}V^2 z_u^{vcmp} + p_0 z_i^{vcmp}\right)$ Indicator $(t_{dae} < 0)$	+
v	V	Ex-tAl-geb	$u\left(I_{qeq}V\gamma_{q2i} + Q_{pf}\gamma_{q2q} + V^2 X_{eq}\gamma_{q2z}\right)$ Indicator $(t_{dae} \geq 0)$ $u\left(V^2 X_{lb} z_l^{vcmp} + V^2 X_{ub} z_u^{vcmp} + q_0 z_i^{vcmp}\right)$ Indicator $(t_{dae} < 0)$	+

Services

Name	Symbol	Equation	Type
Rub	R_{ub}	$\frac{p_0}{v_{max}^2}$	ConstService
Xub	X_{ub}	$\frac{q_0}{v_{max}^2}$	ConstService
Rlb	R_{lb}	$\frac{p_0}{v_{min}^2}$	ConstService
Xlb	X_{lb}	$\frac{q_0}{v_{min}^2}$	ConstService
Ppf	P_{pf}	$R_{lb}V_0^2 z_l^{vcmp} + R_{ub}V_0^2 z_u^{vcmp} + p_0 z_i^{vcmp}$	ConstService
Qpf	Q_{pf}	$V_0^2 X_{lb} z_l^{vcmp} + V_0^2 X_{ub} z_u^{vcmp} + q_0 z_i^{vcmp}$	ConstService
Req	R_{eq}	$\frac{P_{pf}}{V_0^2}$	ConstService
Xeq	X_{eq}	$\frac{Q_{pf}}{V_0^2}$	ConstService
Ipeq	I_{peq}	$\frac{P_{pf}}{V_0}$	ConstService
Iqeq	I_{qeq}	$\frac{Q_{pf}}{V_0}$	ConstService

Discretes

Name	Symbol	Type	Info
vcmp	$vcmp$	Limiter	

Config Fields in [PQ]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
pq2z	z_{pq2z}	1	pq2z conversion if out of voltage limits	(0, 1)
p2p	γ_{p2p}	0	P constant power percentage for TDS. Must have (p2p+p2i+p2z)=1	float
p2i	γ_{p2i}	0	P constant current percentage	float
p2z	γ_{p2z}	1	P constant impedance percentage	float
q2q	γ_{q2q}	0	Q constant power percentage for TDS. Must have (q2q+q2i+q2z)=1	float
q2i	γ_{q2i}	0	Q constant current percentage	float
q2z	γ_{q2z}	1	Q constant impedance percentage	float

5.32 StaticShunt

Static shunt compensator group.

Common Parameters: u, name

Available models: *Shunt*, *ShuntTD*, *ShuntSw*

5.32.1 Shunt

Phasor-domain shunt compensator Model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		idx of connected bus			mandatory
Sn	S_n	Power rating	100		non_zero
Vn	V_n	AC voltage rating	110		non_zero
g	g	shunt conductance (real part)	0		y
b	b	shunt susceptance (positive as capacitive)	0		y
fn	f_n	rated frequency	60		

Variables

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	$V^2 gu$
v	V	ExtAlgeb	$-V^2 bu$

Config Fields in [Shunt]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.32.2 ShuntTD

Static shunt model with inverse transformation from phasor to time-domain.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		idx of connected bus			mandatory
Sn	S_n	Power rating	100		non_zero
Vn	V_n	AC voltage rating	110		non_zero
g	g	shunt conductance (real part)	0		y
b	b	shunt susceptance (positive as capacitive)	0		y
fn	f_n	rated frequency	60		

Variables

Name	Symbol	Type	Description	Unit	Properties
vta	V_{ta}	Algeb			v_str
vtb	V_{tb}	Algeb			v_str
vtc	V_{tc}	Algeb			v_str
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
vta	V_{ta}	Algeb	$\frac{\sqrt{3}V\cos\left(\theta+2\pi f_{sys}t_{dae}\right)}{3}$
vtb	V_{tb}	Algeb	$-\frac{\sqrt{3}V\cos\left(\theta+2\pi f_{sys}t_{dae}+\frac{\pi}{3}\right)}{3}$
vtc	V_{tc}	Algeb	$-\frac{\sqrt{3}V\sin\left(\theta+2\pi f_{sys}t_{dae}+\frac{\pi}{6}\right)}{3}$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vta	V_{ta}	Algeb	$\frac{\sqrt{3}V\cos\left(\theta+2\pi f_{sys}t_{dae}\right)}{3} - V_{ta}$
vtb	V_{tb}	Algeb	$-\frac{\sqrt{3}V\cos\left(\theta+2\pi f_{sys}t_{dae}+\frac{\pi}{3}\right)}{3} - V_{tb}$
vtc	V_{tc}	Algeb	$-\frac{\sqrt{3}V\sin\left(\theta+2\pi f_{sys}t_{dae}+\frac{\pi}{6}\right)}{3} - V_{tc}$
a	θ	ExtAlgeb	V^2gu
v	V	ExtAlgeb	$-V^2bu$

Config Fields in [ShuntTD]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.32.3 ShuntSw

Switched Shunt Model.

Parameters *gs*, *bs* and *bs* must be entered in string literals, comma-separated. They need to have the same length.

For example, in the excel file, one can put

```
gs = [0, 0]
bs = [0.2, 0.2]
ns = [2, 4]
```

To use individual shunts as fixed shunts, set the corresponding *ns = 0* or *ns = [0]*.

The effective shunt susceptances and conductances are stored in services *beff* and *geff*.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		idx of connected bus			mandatory
Sn	S_n	Power rating	100		non_zero
Vn	V_n	AC voltage rating	110		non_zero
g	g	shunt conductance (real part)	0		y
b	b	shunt susceptance (positive as capacitive)	0		y
fn	f_n	rated frequency	60		
gs		a list literal of switched conductances blocks	0	*p.u.*	y
bs		a list literal of switched susceptances blocks	0	*p.u.*	y
ns		a list literal of the element numbers in each switched block	[0]		
vref		voltage reference	1	*p.u.*	non_zero,non_negative
dv		voltage error deadband	0.050	*p.u.*	non_zero,non_negative
dt		delay before two consecutive switching	30	*seconds*	non_negative

Variables

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb			
v	V	ExtAlgeb			

Initialization Equations

Name	Symbol	Type	Initial Value
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	$V^2 geffu$
v	V	ExtAlgeb	$-V^2 beffu$

Services

Name	Symbol	Equation	Type
vlo	v_{lo}	$-dv + vref$	ConstService
vup	v_{up}	$dv + vref$	ConstService

Discretes

Name	Symbol	Type	Info
adj	adj	ShuntAdjust	shunt adjuster

Config Fields in [ShuntSw]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
min_iter	sw_{iter}	2	iteration number starting from which to enable switching	int
err_tol	ϵ_{tol}	0.010	iteration error below which to enable switching	float

5.33 SynGen

Synchronous generator group.

SynGen replaces StaticGen upon the initialization of dynamic studies. SynGen and inverter-based resources contain parameters `gammap` and `gammaq` for splitting the initial power of a StaticGen into multiple dynamic ones.

`gammap`, for example, is the active power ratio of the dynamic generator to the static one. If a StaticGen is supposed to be replaced by one SynGen, the `gammap` and `gammaq` should both be `1`.

It is critical to ensure that `gammap` and `gammaq`, respectively, of all dynamic power sources sum up to 1.0. Otherwise, the initial power injections imposed by dynamic sources will differ from the static ones. The initialization will then fail with mismatches power injection equations corresponding to bus `a` and `v`.

Common Parameters: u, name, Sn, Vn, fn, bus, M, D, subidx

Common Variables: omega, delta

Available models: *GENCLS*, *GENROU*, *PLBVFU1*

5.33.1 GENCLS

Classical generator model.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
coi		center of inertia index			
coi2		center of inertia index			
Sn	S_n	Power rating	100	*MVA*	
Vn	V_n	AC voltage rating	110		
fn	f	rated frequency	60		
D	D	Damping coefficient	0		power
M	M	machine start up time (2H)	6		non_zero,non_negative,power
ra	r_a	armature resistance	0		z
xl	x_l	leakage reactance	0		z
xd1	x'_d	d-axis transient reactance	0.302		z
kp	k_p	active power feedback gain	0		
kw	k_w	speed feedback gain	0		
S10	$S_{1.0}$	first saturation factor	0		
S12	$S_{1.2}$	second saturation factor	1		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
subidx		Generator idx in plant; only used by PSS/E data	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
delta	δ	State	rotor angle	*rad*	v_str
omega	ω	State	rotor speed	*pu (Hz)*	v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
tm	τ_m	Algeb	mechanical torque		v_str
te	τ_e	Algeb	electric torque		v_str
vf	v_f	Algeb	excitation voltage	*pu*	v_str
XadIfd	$X_{ad}I_{fd}$	Algeb	d-axis armature excitation current	*p.u (kV)*	v_str
Pe	P_e	Algeb	active power injection		v_str
Qe	Q_e	Algeb	reactive power injection		v_str
psid	ψ_d	Algeb	d-axis flux		v_str
psiq	ψ_q	Algeb	q-axis flux		v_str
a	θ	ExtAlgeb	Bus voltage phase angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
delta	δ	State	δ_0
omega	ω	State	u
Id	I_d	Algeb	$I_{d0}u$
Iq	I_q	Algeb	$I_{q0}u$
vd	V_d	Algeb	$V_{d0}u$
vq	V_q	Algeb	$V_{q0}u$
tm	τ_m	Algeb	τ_{m0}
te	τ_e	Algeb	$\tau_{m0}u$
vf	v_f	Algeb	uv_{f0}
XadIfd	$X_{ad}I_{fd}$	Algeb	uv_{f0}
Pe	P_e	Algeb	$u\left(I_{d0}V_{d0} + I_{q0}V_{q0}\right)$
Qe	Q_e	Algeb	$u\left(I_{d0}V_{q0} - I_{q0}V_{d0}\right)$
psid	ψ_d	Algeb	$\psi_{d0}u$
psiq	ψ_q	Algeb	$\psi_{q0}u$
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
delta	δ	State	$2\pi f u\left(\omega - 1\right)$	
omega	ω	State	$u\left(-D\left(\omega - 1\right) - \tau_e + \tau_m\right)$	M

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Id	I_d	Algeb	$I_d x'_d + \psi_d - v_f$
Iq	I_q	Algeb	$I_q x'_d + \psi_q$
vd	V_d	Algeb	$V u \sin\left(\delta - \theta\right) - V_d$
vq	V_q	Algeb	$V u \cos\left(\delta - \theta\right) - V_q$
tm	τ_m	Algeb	$-\tau_m + \tau_{m0}$
te	τ_e	Algeb	$-\tau_e + u\left(-I_d\psi_q + I_q\psi_d\right)$
vf	v_f	Algeb	$uv_{f0} - v_f$
XadIfd	$X_{ad}I_{fd}$	Algeb	$-X_{ad}I_{fd} + uv_{f0}$
Pe	P_e	Algeb	$-P_e + u\left(I_d V_d + I_q V_q\right)$
Qe	Q_e	Algeb	$-Q_e + u\left(I_d V_q - I_q V_d\right)$
psid	ψ_d	Algeb	$-\psi_d + u\left(I_q r_a + V_q\right)$
psiq	ψ_q	Algeb	$\psi_q + u\left(I_d r_a + V_d\right)$
a	θ	ExtAlgeb	$-u\left(I_d V_d + I_q V_q\right)$
v	V	ExtAlgeb	$-u\left(I_d V_q - I_q V_d\right)$

Services

Name	Symbol	Equation	Type
p0	P_0	$P_{0s}\gamma_P$	ConstService
q0	Q_0	$Q_{0s}\gamma_Q$	ConstService
_V	V_c	$Ve^{i\theta}$	ConstService
_S	S	$P_0 - iQ_0$	ConstService
_I	I_c	$\frac{S}{\text{conj}\,(V_c)}$	ConstService
_E	E	$I_c\,(r_a + ix'_d) + V_c$	ConstService
_deltac	δ_c	$\log\left(\frac{E}{\lvert E\rvert}\right)$	ConstService
delta0	δ_0	$u\,\text{im}\,(\delta_c)$	ConstService
vdq	V_{dq}	$V_c u e^{-\delta_c + 0.5i\pi}$	ConstService
Idq	I_{dq}	$I_c u e^{-\delta_c + 0.5i\pi}$	ConstService
Id0	I_{d0}	$\text{re}\,(I_{dq})$	ConstService
Iq0	I_{q0}	$\text{im}\,(I_{dq})$	ConstService
vd0	V_{d0}	$\text{re}\,(V_{dq})$	ConstService
vq0	V_{q0}	$\text{im}\,(V_{dq})$	ConstService
tm0	τ_{m0}	$u\,(I_{d0}\,(I_{d0}r_a + V_{d0}) + I_{q0}\,(I_{q0}r_a + V_{q0}))$	ConstService
psid0	ψ_{d0}	$I_{q0}r_a u + V_{q0}$	ConstService
psiq0	ψ_{q0}	$-I_{d0}r_a u - V_{d0}$	ConstService
vf0	v_{f0}	$I_{d0}x'_d + I_{q0}r_a + V_{q0}$	ConstService

Config Fields in [GENCLS]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
vf_lower		1	lower limit for vf warning	
vf_upper		5	upper limit for vf warning	

5.33.2 GENROU

Round rotor generator with quadratic saturation.

Notes

Parameters:

- `xd2` and `xq2` must be equal to pass initialization.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
coi		center of inertia index			
coi2		center of inertia index			
Sn	S_n	Power rating	100	*MVA*	
Vn	V_n	AC voltage rating	110		
fn	f	rated frequency	60		
D	D	Damping coefficient	0		power
M	M	machine start up time (2H)	6		non_zero,non_negative,power
ra	r_a	armature resistance	0		z
xl	x_l	leakage reactance	0		z
xd1	x'_d	d-axis transient reactance	0.302		z
kp	k_p	active power feedback gain	0		
kw	k_w	speed feedback gain	0		
S10	$S_{1.0}$	first saturation factor	0		
S12	$S_{1.2}$	second saturation factor	1		
gammap	γ_P	P ratio of linked static gen	1		
gammaq	γ_Q	Q ratio of linked static gen	1		
xd	x_d	d-axis synchronous reactance	1.900		z
xq	x_q	q-axis synchronous reactance	1.700		z
xd2	x''_d	d-axis sub-transient reactance	0.300		z
xq1	x'_q	q-axis transient reactance	0.500		z
xq2	x''_q	q-axis sub-transient reactance	0.300		z
Td10	T'_{d0}	d-axis transient time constant	8		
Td20	T''_{d0}	d-axis sub-transient time constant	0.040		
Tq10	T'_{q0}	q-axis transient time constant	0.800		
Tq20	T''_{q0}	q-axis sub-transient time constant	0.020		
subidx		Generator idx in plant; only used by PSS/E data	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
delta	δ	State	rotor angle	*rad*	v_str
omega	ω	State	rotor speed	*pu (Hz)*	v_str
e1q	e'_q	State	q-axis transient voltage		v_str
e1d	e'_d	State	d-axis transient voltage		v_str
e2d	e''_d	State	d-axis sub-transient voltage		v_str
e2q	e''_q	State	q-axis sub-transient voltage		v_str
Id	I_d	Algeb	d-axis current		v_str
Iq	I_q	Algeb	q-axis current		v_str
vd	V_d	Algeb	d-axis voltage		v_str
vq	V_q	Algeb	q-axis voltage		v_str
tm	τ_m	Algeb	mechanical torque		v_str
te	τ_e	Algeb	electric torque		v_str
vf	v_f	Algeb	excitation voltage	*pu*	v_str
XadIfd	$X_{ad}I_{fd}$	Algeb	d-axis armature excitation current	*p.u (kV)*	v_str
Pe	P_e	Algeb	active power injection		v_str
Qe	Q_e	Algeb	reactive power injection		v_str
psid	ψ_d	Algeb	d-axis flux		v_str
psiq	ψ_q	Algeb	q-axis flux		v_str
psi2q	ψ_{aq}	Algeb	q-axis air gap flux		v_str
psi2d	ψ_{ad}	Algeb	d-axis air gap flux		v_str
psi2	ψ_a	Algeb	air gap flux magnitude		v_str
Se	$S_e(\lvert\psi_a\rvert)$	Algeb	saturation output		v_str
XaqI1q	$X_{aq}I_{1q}$	Algeb	q-axis reaction	*p.u (kV)*	v_str
a	θ	ExtAlgeb	Bus voltage phase angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
delta	δ	State	δ_0
omega	ω	State	u
e1q	e'_q	State	ue'_{q0}
e1d	e'_d	State	ue'_{d0}
e2d	e''_d	State	ue''_{d0}
e2q	e''_q	State	ue''_{q0}
Id	I_d	Algeb	$I_{d0}u$
Iq	I_q	Algeb	$I_{q0}u$
vd	V_d	Algeb	$V_{d0}u$
vq	V_q	Algeb	$V_{q0}u$
tm	τ_m	Algeb	τ_{m0}
te	τ_e	Algeb	$\tau_{m0}u$
vf	v_f	Algeb	uv_{f0}
XadIfd	$X_{ad}I_{fd}$	Algeb	uv_{f0}
Pe	P_e	Algeb	$u\left(I_{d0}V_{d0} + I_{q0}V_{q0}\right)$
Qe	Q_e	Algeb	$u\left(I_{d0}V_{q0} - I_{q0}V_{d0}\right)$
psid	ψ_d	Algeb	$\psi_{d0}u$
psiq	ψ_q	Algeb	$\psi_{q0}u$
psi2q	ψ_{aq}	Algeb	$\psi_{aq0}u$
psi2d	ψ_{ad}	Algeb	$\psi_{ad0}u$
psi2	ψ_a	Algeb	$u\left\|\psi''_{0,dq}\right\|$
Se	$S_e(\|\psi_a\|)$	Algeb	$S_{e0}u$
XaqI1q	$X_{aq}I_{1q}$	Algeb	0
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
delta	δ	State	$2\pi f u\left(\omega - 1\right)$	
omega	ω	State	$u\left(-D\left(\omega - 1\right) - \tau_e + \tau_m\right)$	M
e1q	e'_q	State	$-X_{ad}I_{fd} + v_f$	T'_{d0}
e1d	e'_d	State	$-X_{aq}I_{1q}$	T'_{q0}
e2d	e''_d	State	$-I_d\left(x'_d - x_l\right) - e''_d + e'_q$	T''_{d0}
e2q	e''_q	State	$I_q\left(-x_l + x'_q\right) - e''_q + e'_d$	T''_{q0}

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Id	I_d	Algeb	$I_d x''_d + \psi_d - \psi_{ad}$
Iq	I_q	Algeb	$I_q x''_q + \psi_q + \psi_{aq}$
vd	V_d	Algeb	$V u \sin(\delta - \theta) - V_d$
vq	V_q	Algeb	$V u \cos(\delta - \theta) - V_q$
tm	τ_m	Algeb	$-\tau_m + \tau_{m0}$
te	τ_e	Algeb	$-\tau_e + u\left(-I_d \psi_q + I_q \psi_d\right)$
vf	v_f	Algeb	$u v_{f0} - v_f$
XadIfd	$X_{ad} I_{fd}$	Algeb	$-X_{ad} I_{fd} + u\left(S_e(\lvert\psi_a\rvert)\psi_{ad} + e'_q + \left(-x'_d + x_d\right)\left(I_d \gamma_{d1} - \gamma_{d2} e''_d + \gamma_{d2} e'_q\right)\right)$
Pe	P_e	Algeb	$-P_e + u\left(I_d V_d + I_q V_q\right)$
Qe	Q_e	Algeb	$-Q_e + u\left(I_d V_q - I_q V_d\right)$
psid	ψ_d	Algeb	$-\psi_d + u\left(I_q r_a + V_q\right)$
psiq	ψ_q	Algeb	$\psi_q + u\left(I_d r_a + V_d\right)$
psi2q	ψ_{aq}	Algeb	$\gamma_{q1} e'_d - \psi_{aq} + e''_q\left(1 - \gamma_{q1}\right)$
psi2d	ψ_{ad}	Algeb	$\gamma_{d1} e'_q + \gamma_{d2} e''_d\left(x'_d - x_l\right) - \psi_{ad}$
psi2	ψ_a	Algeb	$-\psi_a^2 + \psi_{ad}^2 + \psi_{aq}^2$
Se	$S_e(\lvert\psi_a\rvert)$	Algeb	$B^q_{S_{AT}} z_0^{SL}\left(-A^q_{S_{AT}} + \psi_a\right)^2 - S_e(\lvert\psi_a\rvert)\psi_a$
XaqI1q	$X_{aq} I_{1q}$	Algeb	$S_e(\lvert\psi_a\rvert)\gamma_{qd}\psi_{aq} - X_{aq} I_{1q} + e'_d + \left(x_q - x'_q\right)\left(-I_q \gamma_{q1} - \gamma_{q2} e''_q + \gamma_{q2} e'_d\right)$
a	θ	ExtAlgeb	$-u\left(I_d V_d + I_q V_q\right)$
v	V	ExtAlgeb	$-u\left(I_d V_q - I_q V_d\right)$

Services

Name	Symbol	Equation	Type
p0	P_0	$P_{0s} \gamma_P$	ConstService
q0	Q_0	$Q_{0s} \gamma_Q$	ConstService
gd1	γ_{d1}	$\frac{-x_l + x''_d}{x'_d - x_l}$	ConstService
gq1	γ_{q1}	$\frac{-x_l + x''_q}{-x_l + x'_q}$	ConstService
gd2	γ_{d2}	$\frac{x'_d - x''_d}{\left(x'_d - x_l\right)^2}$	ConstService
gq2	γ_{q2}	$\frac{-x''_q + x'_q}{\left(-x_l + x'_q\right)^2}$	ConstService
gqd	γ_{qd}	$\frac{-x_l + x_q}{x_d - x_l}$	ConstService
_S12	$S_{1.2}$	$S_{1.2} -_f S12 + 1$	ConstService
SAT_E1	$E^{1c}_{S_{AT}}$	1.0	ConstService
SAT_E2	$E^{2c}_{S_{AT}}$	$3.2 - 2 z^{SE2}_{S_{AT}}$	ConstService
SAT_SE1	$SE^{1c}_{S_{AT}}$	$S_{1.0}$	ConstService

continues on next page

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Name	Symbol	Equation	Type
SAT_SE2	$SE^{2c}_{S_{AT}}$	$S_{1.2} - 2z^{SE2}_{S_{AT}} + 2$	ConstService
SAT_a	$a_{S_{AT}}$	$\sqrt{\frac{E^{1c}_{S_{AT}} SE^{1c}_{S_{AT}}}{E^{2c}_{S_{AT}} SE^{2c}_{S_{AT}}}} \left(\text{Indicator}\left(SE^{2c}_{S_{AT}} > 0\right) + \text{Indicator}\left(SE^{2c}_{S_{AT}} < 0\right)\right)$	ConstService
SAT_A	$A^q_{S_{AT}}$	$E^{2c}_{S_{AT}} - \frac{E^{1c}_{S_{AT}} - E^{2c}_{S_{AT}}}{a_{S_{AT}} - 1}$	ConstService
SAT_B	$B^q_{S_{AT}}$	$\frac{E^{2c}_{S_{AT}} SE^{2c}_{S_{AT}} \left(a_{S_{AT}} - 1\right)^2 \left(\text{Indicator}\left(a_{S_{AT}} > 0\right) + \text{Indicator}\left(a_{S_{AT}} < 0\right)\right)}{\left(E^{1c}_{S_{AT}} - E^{2c}_{S_{AT}}\right)^2}$	ConstService
_V	V_c	$V e^{i\theta}$	ConstService
_S	S	$P_0 - iQ_0$	ConstService
_Zs	Z_s	$r_a + ix''_d$	ConstService
_It	I_t	$\frac{S}{\text{conj}\left(V_c\right)}$	ConstService
_Is	I_s	$I_t + \frac{V_c}{Z_s}$	ConstService
psi20	ψ''_0	$I_s Z_s$	ConstService
psi20_arg	$\theta_{\psi''0}$	$\arg\left(\psi''_0\right)$	ConstService
psi20_abs	$\lvert\psi''_0\rvert$	$\lvert\psi''_0\rvert$	ConstService
_It_arg	θ_{It0}	$\arg\left(I_t\right)$	ConstService
_psi20_It_arg	$\theta_{\psi aIt}$	$-\theta_{It0} + \theta_{\psi''0}$	ConstService
Se0	S_{e0}	$\frac{B^q_{S_{AT}} \left(-A^q_{S_{AT}} + \lvert\psi''_0\rvert\right)^2 \text{Indicator}\left(\lvert\psi''_0\rvert \geq A^q_{S_{AT}}\right)}{\lvert\psi''_0\rvert}$	ConstService
_a	a'	$\lvert\psi''_0\rvert \left(S_{e0}\gamma_{qd} + 1\right)$	ConstService
_b	b'	$\left(-x_q + x''_q\right) \lvert I_t\rvert$	ConstService
delta0	δ_0	$\theta_{\psi''0} + \text{atan}\left(\frac{b' \cos\left(\theta_{\psi aIt}\right)}{-a' + b' \sin\left(\theta_{\psi aIt}\right)}\right)$	ConstService
_Tdq	T_{dq}	$-i \sin\left(\delta_0\right) + \cos\left(\delta_0\right)$	ConstService
psi20_dq	$\psi''_{0,dq}$	$T_{dq}\psi''_0$	ConstService
It_dq	$I_{t,dq}$	$\text{conj}\left(I_t T_{dq}\right)$	ConstService
psi2d0	ψ_{ad0}	$\text{re}\left(\psi''_{0,dq}\right)$	ConstService
psi2q0	ψ_{aq0}	$-\text{im}\left(\psi''_{0,dq}\right)$	ConstService
Id0	I_{d0}	$\text{im}\left(I_{t,dq}\right)$	ConstService
Iq0	I_{q0}	$\text{re}\left(I_{t,dq}\right)$	ConstService
vd0	V_{d0}	$-I_{d0}r_a + I_{q0}x''_q + \psi_{aq0}$	ConstService
vq0	V_{q0}	$-I_{d0}x''_d - I_{q0}r_a + \psi_{ad0}$	ConstService
tm0	τ_{m0}	$u\left(I_{d0}\left(I_{d0}r_a + V_{d0}\right) + I_{q0}\left(I_{q0}r_a + V_{q0}\right)\right)$	ConstService
vf0	v_{f0}	$I_{d0}\left(x_d - x''_d\right) + \psi_{ad0}\left(S_{e0} + 1\right)$	ConstService
psid0	ψ_{d0}	$I_{q0}r_a u + V_{q0}$	ConstService
psiq0	ψ_{q0}	$-I_{d0}r_a u - V_{d0}$	ConstService
e1q0	e'_{q0}	$I_{d0}\left(x'_d - x_d\right) - S_{e0}\psi_{ad0} + v_{f0}$	ConstService
e1d0	e'_{d0}	$I_{q0}\left(x_q - x'_q\right) - S_{e0}\gamma_{qd}\psi_{aq0}$	ConstService
e2d0	e''_{d0}	$I_{d0}\left(-x_d + x_l\right) - S_{e0}\psi_{ad0} + v_{f0}$	ConstService
e2q0	e''_{q0}	$-I_{q0}\left(x_l - x_q\right) - S_{e0}\gamma_{qd}\psi_{aq0}$	ConstService

Discretes

Name	Symbol	Type	Info
SL	SL	LessThan	

Blocks

Name	Symbol	Type	Info
SAT	S_{AT}	ExcQuadSat	

Config Fields in [GENROU]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
vf_lower		1	lower limit for vf warning	
vf_upper		5	upper limit for vf warning	

5.33.3 PLBVFU1

PLBVFU1 model: playback of voltage and frequency as a generator.

The internal voltage and frequency are named `Vflt` and `omega`. Rotor angle is named `delta`.

The current implementation relies on a `TimeSeries` device to provide the voltage and frequency signals. See `ieee14_plbvfu1.xlsx` and `plbvf.xlsx` in `andes/cases/ieee14` for an example.

Voltage and frequeny data needs to be specified in per unit. Nominal values are not yet supported.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		interface bus id			mandatory
gen		static generator index			mandatory
Sn	S_n	Power rating	100	*MVA*	
Vn	V_n	AC voltage rating	110		
ra	r_a	armature resistance	0		z
xs	x_s	generator transient reactance	0.200		non_zero,z
fn	f_n	rated frequency	60		
Vflag		playback voltage signal	1	*bool*	
fflag		playback frequency signal	1	*bool*	
filename		playback file name		*string*	mandatory
Vscale	V_{scale}	playback voltage scale	1	*pu*	non_negative
fscale	f_{scale}	playback frequency scale	1	*pu*	non_negative
Tv	T_v	filtering time constant for voltage	0.200	*s*	non_negative
Tf	T_f	filtering time constant for frequency	0.200	*s*	non_negative
subidx		Generator idx in plant; only used by PSS/E data	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
Vflt	V_{flt}	State	filtered voltage	*pu*	v_str
omega	ω	State	filtered frequency	*pu*	v_str
delta	δ	State	rotor angle	*rad*	v_str
a	θ	ExtAlgeb	Bus voltage phase angle		
v	V	ExtAlgeb	Bus voltage magnitude		

Initialization Equations

Name	Symbol	Type	Initial Value
Vflt	V_{flt}	State	$1/V_{scale}Vts - V_{offs}$
omega	ω	State	$1/f_{scale}fts - f_{offs}$
delta	δ	State	δ_0
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
Vflt	V_{flt}	State	$1/V_{scale}Vts - V_{flt} - V_{offs}$	T_v
omega	ω	State	$1/f_{scale}fts - \omega - f_{offs}$	T_f
delta	δ	State	$2\pi f_n u\,(\omega - 1)$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	$-\frac{VV_{flt}x_s \sin(\delta-\theta)}{r_a^2+x_s^2} + \frac{Vr_a\left(V-V_{flt}\cos(\delta-\theta)\right)}{r_a^2+x_s^2}$
v	V	ExtAlgeb	$\frac{VV_{flt}r_a \sin(\delta-\theta)}{r_a^2+x_s^2} + \frac{Vx_s\left(V-V_{flt}\cos(\delta-\theta)\right)}{r_a^2+x_s^2}$

Services

Name	Symbol	Equation	Type
zs	zs	$r_a + ix_s$	ConstService
zs2n	$zs2n$	$r_a^2 - x_s^2$	ConstService
Ec	E_c	$Ve^{i\theta} + (r_a + ix_s)\,\mathrm{conj}\left(\frac{(p+iq)e^{-i\theta}}{V}\right)$	ConstService
E0	E_0	$\lvert E_c\rvert$	ConstService
delta0	δ_0	$\arg(E_c)$	ConstService
Vts	Vts	0	ConstService
fts	fts	0	ConstService
ifscale	$1/f_{scale}$	$\frac{1}{f_{scale}}$	ConstService
iVscale	$1/V_{scale}$	$\frac{1}{V_{scale}}$	ConstService
foffs	f_{offs}	$1/f_{scale}fts - 1$	ConstService
Voffs	V_{offs}	$1/V_{scale}Vts - E_0$	ConstService

Config Fields in [PLBVFU1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.34 TimedEvent

Timed event group

Common Parameters: u, name

Available models: *Toggle*, *Fault*, *Alter*

5.34.1 Toggle

Time-based connectivity status toggle.

Toggle is used to toggle the connection status (online/offline) of a device at the predefined time. Both the model name (or group name) and the device idx need to be specified. It effectively negates the `u` field of the connected device.

Toggle can be useful to implement disconnection, connection, and reconnection of devices. For example, a line trip can be implemented by setting `Line` to the `model` field and the corresponding line's `idx` to the `dev` field.

Multiple Toggles can be added to the same device at different times. Adding two Toggles for an initially connected line with `t=0.1` and `t=0.2`, for instance, will disconnect the line at t=0.1 sec and reconnect it at t=0.2 sec.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
model		model or group name of the device			mandatory
dev		idx of the device to control			mandatory
t		switch time for connection status	-1		mandatory

Services

Name	Symbol	Equation	Type
_u	u	1	ConstService

Config Fields in [Toggle]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.34.2 Fault

Three-phase-to-ground fault.

A Fault device is used to apply and clear three-phase-to-ground fault to the given bus. One can set two time parameters, `tf` and `tc`, for the fault-on and fault-clearance time, respectively, although only `tf` is mandatory.

A fault is implemented by a very small internal shunt impedance to be connected at the fault-on time. Its reactance and resistance are specified by the parameters `xf` and `rf`.

To implement a fault and its clearance by tripping a line, one can combine `Fault` and `Toggle`. That is, clear a fault in concurrence with a Toggle. The user needs to ensure data consistency so that the line trip actually clears the fault.

Non-convergence can occur in the proximity of a fault due to various reasons, including network power transfer capability limitation and parameter issues of controllers.

When a fault gets cleared, algebraic variables change drastically. E.g., voltages can go from nearly zero back to 1.0. As we are using Newton's method for solving the DAE, the initial values are crucial for the immediate step after fault clearance.

This Fault model restores the pre-fault values for algebraic variables `Fault.config.scale` is the scaling factor to be multiplied to the pre-fault values for adjusting the initial values. Some trial and error are expected for severe disturbances, combined with increasing the fault reactance `xf`.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
bus		linked bus idx			mandatory
tf		Bus fault start time	-1	*second*	mandatory
tc		Bus fault end time	-1	*second*	
xf	x_f	Fault to ground reactance (positive)	0.000	*p.u.(sys)*	
rf	x_f	Fault to ground resistance (positive)	0	*p.u.(sys)*	

Variables

Name	Symbol	Type	Description	Unit	Properties
a	θ	ExtAlgeb	Bus voltage angle	*p.u.(kV)*	
v	V	ExtAlgeb	Bus voltage magnitude	*p.u.(kV)*	

Initialization Equations

Name	Symbol	Type	Initial Value
a	θ	ExtAlgeb	
v	V	ExtAlgeb	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	$V^2 g_f u u_f$
v	V	ExtAlgeb	$-V^2 b_f u u_f$

Services

Name	Symbol	Equation	Type
gf	g_f	$\frac{\mathrm{re}\left(x_f\right)-\mathrm{im}\left(x_f\right)}{\left(\mathrm{re}\left(x_f\right)-\mathrm{im}\left(x_f\right)\right)^2+\left(\mathrm{re}\left(x_f\right)+\mathrm{im}\left(x_f\right)\right)^2}$	ConstService
bf	b_f	$\frac{-\mathrm{re}\left(x_f\right)-\mathrm{im}\left(x_f\right)}{\left(\mathrm{re}\left(x_f\right)-\mathrm{im}\left(x_f\right)\right)^2+\left(\mathrm{re}\left(x_f\right)+\mathrm{im}\left(x_f\right)\right)^2}$	ConstService
uf	u_f	0	ConstService

Config Fields in [Fault]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
restore		1	restore algebraic variables to pre-fault values	(0, 1)
mode		1	1. restore all algeb variables, 2. fault bus only	(1, 2, 3)
scale		1	scaling factor of restored algebraic values	

5.34.3 Alter

Model for altering device internal data at predefined time.

Alter is useful to apply load changing, tap changing, step response, etc. can be applied to parameters and constant services but cannot be used to update variables.

Alter is implemented by applying the given calculation to the v field of the linked parameter or constant. Alter will not affect other parameters or constants that depend on the altered variable.

It is not uncommon for equations to depend on intermediate constants rather than the input parameters. Therefore, one will need to inspect model equations to determine the parameter/service to be altered.

Examples

To apply a PQ load change, according to *PQ*, one needs to set the load model to constant power and alter `Ppf` and `Qpf`. Altering `p0` and `q0` will have no impact as they are not used in the equations for time-domain simulation.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
t		switch time for connection status	-1		mandatory
model		model or group name of the device			mandatory
dev		idx of the device to alter			mandatory
src		model source field (param or service)			mandatory
attr		attribute (e.g., v) of the source field	v		
method		alteration method in +, -, *, /, =			mandatory
amount		the amount to apply			mandatory
rand		use uniform ramdom sampling	0		
lb		lower bound of random sampling	0		
ub		upper bound of random sampling	0		

Discretes

Name	Symbol	Type	Info
SW	SW	Switcher	Switcher for alteration method

Config Fields in [Alter]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35 TurbineGov

Turbine governor group for synchronous generator.

Common Parameters: u, name

Common Variables: pout

Available models: *TG2*, *TGOV1*, *TGOV1DB*, *TGOV1N*, *TGOV1NDB*, *IEEEG1*, *IEESGO*, *GAST*, *HYGOV*, *HYGOVDB*, *HYGOV4*

5.35.1 TG2

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
pmax	p_{max}	Maximum power output	999	*p.u.*	power
pmin	p_{min}	Minimum power output	0	*p.u.*	power
dbl	L_{db}	Deadband lower limit	-0.000	*p.u.*	
dbu	U_{db}	Deadband upper limit	0.000	*p.u.*	
dbc	C_{db}	Deadband neutral value	0	*p.u.*	
T1	T_1	Transient gain time	0.200		
T2	T_2	Governor time constant	10		
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
ll_x	x'_{ll}	State	State in lead-lag		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
w_d	ω_{dev}	Algeb	Generator speed deviation before dead band (positive for under speed)		v_str
w_dm	ω_{dm}	Algeb	Measured speed deviation after dead band		v_str
w_dmg	ω_{dmG}	Algeb	Speed deviation after dead band after gain		v_str
ll_y	y_{ll}	Algeb	Output of lead-lag		v_str
pnl	P_{nl}	Algeb	Power output before hard limiter		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
ll_x	x'_{ll}	State	ω_{dmG}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
w_d	ω_{dev}	Algeb	0
w_dm	ω_{dm}	Algeb	0
w_dmg	ω_{dmG}	Algeb	0
ll_y	y_{ll}	Algeb	ω_{dmG}
pnl	P_{nl}	Algeb	τ_{m0}
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
ll_x	x'_{ll}	State	$\omega_{dmG} - x'_{ll}$	T_2
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$P_{nl} z_i^{plim} - P_{out} + p_{max} z_u^{plim} + p_{min} z_l^{plim}$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
w_d	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(-\omega + \omega_{ref}\right)$
w_dm	ω_{dm}	Algeb	$L_{db} z_l r^{w_d b} + U_{db} z_u r^{w_d b} + \omega_{dev} \left(1 - z_i^{w_d b}\right) - \omega_{dm}$
w_dmg	ω_{dmG}	Algeb	$G\omega_{dm} - \omega_{dmG}$
ll_y	y_{ll}	Algeb	$T_1 \left(\omega_{dmG} - x'_{ll}\right) + T_2 x'_{ll} - T_2 y_{ll} + \left(z_1^{LT_{ll}}\right)^2 \left(-x'_{ll} + y_{ll}\right)$
pnl	P_{nl}	Algeb	$-P_{nl} + P_{ref0} + y_{ll}$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u}{R}$	ConstService

Discretes

Name	Symbol	Type	Info
w_db	$w_d b$	DeadBandRT	
ll_LT1	LT_{ll}	LessThan	
ll_LT2	LT_{ll}	LessThan	
plim	$plim$	HardLimiter	

Blocks

Name	Symbol	Type	Info
ll	ll	LeadLag	

Config Fields in [TG2]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)
deadband	$z_{deadband}$	0	enable input dead band	(0, 1)
hardlimit	$z_{hardlimit}$	1	enable output hard limit	(0, 1)

5.35.2 TGOV1

TGOV1 turbine governor model.

Implements the PSS/E TGOV1 model without deadband.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
VMAX	V_{max}	Maximum valve position	1.200	*p.u.*	power
VMIN	V_{min}	Minimum valve position	0	*p.u.*	power
T1	T_1	Valve time constant	0.100		
T2	T_2	Lead-lag lead time constant	0.200		
T3	T_3	Lead-lag lag time constant	10		
Dt	D_t	Turbine damping coefficient	0		power
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LAG_y	y_{LAG}	State	State in lag TF		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
pd	P_d	Algeb	Pref plus speed deviation times gain	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LAG_y	y_{LAG}	State	P_d
LL_x	x'_{LL}	State	y_{LAG}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	$R\tau_{m0}$
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	$\tau_{m0} u_e$
LL_y	y_{LL}	Algeb	y_{LAG}
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LAG_y	y_{LAG}	State	$P_d - y_{LAG}$	T_1
LL_x	x'_{LL}	State	$-x'_{LL} + y_{LAG}$	T_3
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(-D_t \omega_{dev} + y_{LL}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$P_{ref0} R - P_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$G u_e \left(P_{aux} + P_{ref} - \omega_{dev}\right) - P_d$
LL_y	y_{LL}	Algeb	$T_2 \left(-x'_{LL} + y_{LAG}\right) + T_3 x'_{LL} - T_3 y_{LL} + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u_e}{R}$	ConstService

Discretes

Name	Symbol	Type	Info
LAG_lim	lim_{LAG}	AntiWindup	Limiter in Lag
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	

Blocks

Name	Symbol	Type	Info
LAG	LAG	LagAntiWindup	
LL	LL	LeadLag	

Config Fields in [TGOV1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.3 TGOV1DB

TGOV1 turbine governor model with speed input deadband.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
VMAX	V_{max}	Maximum valve position	1.200	*p.u.*	power
VMIN	V_{min}	Minimum valve position	0	*p.u.*	power
T1	T_1	Valve time constant	0.100		
T2	T_2	Lead-lag lead time constant	0.200		
T3	T_3	Lead-lag lag time constant	10		
Dt	D_t	Turbine damping coefficient	0		power
dbL	db_L	Lower bound of deadband	0	*p.u.*	
dbU	db_U	Upper bound of deadband	0	*p.u.*	
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LAG_y	y_{LAG}	State	State in lag TF		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
pd	P_d	Algeb	Pref plus speed deviation times gain	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LAG_y	y_{LAG}	State	P_d
LL_x	x'_{LL}	State	y_{LAG}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	$R\tau_{m0}$
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	$\tau_{m0} u_e$
LL_y	y_{LL}	Algeb	y_{LAG}
DB_y	y_{DB}	Algeb	$1.0 z_l^{db_{DB}} \left(\omega_{dev} - db_L\right) + 1.0 z_u^{db_{DB}} \left(\omega_{dev} - db_U\right)$
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LAG_y	y_{LAG}	State	$P_d - y_{LAG}$	T_1
LL_x	x'_{LL}	State	$-x'_{LL} + y_{LAG}$	T_3
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-D_t y_{DB} - P_{out} + y_{LL}$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$P_{ref0} R - P_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$G u_e \left(P_{aux} + P_{ref} - y_{DB}\right) - P_d$
LL_y	y_{LL}	Algeb	$T_2 \left(-x'_{LL} + y_{LAG}\right) + T_3 x'_{LL} - T_3 y_{LL} + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
DB_y	y_{DB}	Algeb	$-y_{DB} + 1.0 z_l^{db_{DB}} \left(\omega_{dev} - db_L\right) + 1.0 z_u^{db_{DB}} \left(\omega_{dev} - db_U\right)$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u_e}{R}$	ConstService

Discretes

Name	Symbol	Type	Info
LAG_lim	lim_{LAG}	AntiWindup	Limiter in Lag
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
DB_db	db_{DB}	DeadBand	

Blocks

Name	Symbol	Type	Info
LAG	LAG	LagAntiWindup	
LL	LL	LeadLag	
DB	DB	DeadBand1	deadband for speed deviation

Config Fields in [TGOV1DB]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.4 TGOV1N

New TGOV1 (TGOV1N) turbine governor model.

The TGOV1N model that sums `pref` and `paux` signals after the droop. This model is useful for incorporating AGC and scheduling signals, which will not be multiplied by `1/R` like in the original TGOV1 model.

Scheduling changes should write to `pref0.v` in place. AGC signal should write to `paux0.v` in place.

Modifying `tm0` is not allowed.

Examples

To update all `paux0` values to `paux_new`, which contains the new values, do

```
ss.TGOV1N.paux0.v[:] = paux_new  # in-place update of the `paux0.v` array
```

instead of

```
ss.TGOV1N.paux0.v = paux_new  # error; changes the reference of `paux0.v`
```

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
VMAX	V_{max}	Maximum valve position	1.200	*p.u.*	power
VMIN	V_{min}	Minimum valve position	0	*p.u.*	power
T1	T_1	Valve time constant	0.100		
T2	T_2	Lead-lag lead time constant	0.200		
T3	T_3	Lead-lag lag time constant	10		
Dt	D_t	Turbine damping coefficient	0		power
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LAG_y	y_{LAG}	State	State in lag TF		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
pd	P_d	Algeb	Pref plus speed deviation times gain	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LAG_y	y_{LAG}	State	P_d
LL_x	x'_{LL}	State	y_{LAG}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	τ_{m0}
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	$\tau_{m0} u_e$
LL_y	y_{LL}	Algeb	y_{LAG}
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LAG_y	y_{LAG}	State	$P_d - y_{LAG}$	T_1
LL_x	x'_{LL}	State	$-x'_{LL} + y_{LAG}$	T_3
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(-D_t \omega_{dev} + y_{LL}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$P_{ref0} - P_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$-P_d + u_e \left(-G\omega_{dev} + P_{aux} + P_{ref}\right)$
LL_y	y_{LL}	Algeb	$T_2 \left(-x'_{LL} + y_{LAG}\right) + T_3 x'_{LL} - T_3 y_{LL} + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u_e}{R}$	ConstService

Discretes

Name	Symbol	Type	Info
LAG_lim	lim_{LAG}	AntiWindup	Limiter in Lag
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	

Blocks

Name	Symbol	Type	Info
LAG	LAG	LagAntiWindup	
LL	LL	LeadLag	

Config Fields in [TGOV1N]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.5 TGOV1NDB

TGOV1N turbine governor model with speed input deadband.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
VMAX	V_{max}	Maximum valve position	1.200	*p.u.*	power
VMIN	V_{min}	Minimum valve position	0	*p.u.*	power
T1	T_1	Valve time constant	0.100		
T2	T_2	Lead-lag lead time constant	0.200		
T3	T_3	Lead-lag lag time constant	10		
Dt	D_t	Turbine damping coefficient	0		power
dbL	db_L	Lower bound of deadband	0	*p.u.*	
dbU	db_U	Upper bound of deadband	0	*p.u.*	
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LAG_y	y_{LAG}	State	State in lag TF		v_str
LL_x	x'_{LL}	State	State in lead-lag		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
pd	P_d	Algeb	Pref plus speed deviation times gain	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LAG_y	y_{LAG}	State	P_d
LL_x	x'_{LL}	State	y_{LAG}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	τ_{m0}
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	$\tau_{m0} u_e$
LL_y	y_{LL}	Algeb	y_{LAG}
DB_y	y_{DB}	Algeb	$1.0 z_l^{db_{DB}} \left(\omega_{dev} - db_L\right) + 1.0 z_u^{db_{DB}} \left(\omega_{dev} - db_U\right)$
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LAG_y	y_{LAG}	State	$P_d - y_{LAG}$	T_1
LL_x	x'_{LL}	State	$-x'_{LL} + y_{LAG}$	T_3
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-D_t y_{DB} - P_{out} + y_{LL}$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$P_{ref0} - P_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$-P_d + u_e \left(G y_{DB} + P_{aux} + P_{ref}\right)$
LL_y	y_{LL}	Algeb	$T_2 \left(-x'_{LL} + y_{LAG}\right) + T_3 x'_{LL} - T_3 y_{LL} + \left(z_1^{LT_{LL}}\right)^2 \left(-x'_{LL} + y_{LL}\right)$
DB_y	y_{DB}	Algeb	$-y_{DB} + 1.0 z_l^{db_{DB}} \left(\omega_{dev} - db_L\right) + 1.0 z_u^{db_{DB}} \left(\omega_{dev} - db_U\right)$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u_e}{R}$	ConstService

Discretes

Name	Symbol	Type	Info
LAG_lim	lim_{LAG}	AntiWindup	Limiter in Lag
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
DB_db	db_{DB}	DeadBand	

Blocks

Name	Symbol	Type	Info
LAG	LAG	LagAntiWindup	
LL	LL	LeadLag	
DB	DB	DeadBand1	deadband for speed deviation

Config Fields in [TGOV1NDB]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.6 IEEEG1

IEEE Type 1 Speed-Governing Model.

If only one generator is connected, its *idx* must be given to *syn*, and *syn2* must be left blank. Each generator must provide data in its *Sn* base.

syn is connected to the high-pressure output (PHP) and the optional *syn2* is connected to the low- pressure output (PLP).

The speed deviation of generator 1 (syn) is measured. If the turbine rating *Tn* is not specified, the sum of *Sn* of all connected generators will be used.

Normally, K1 + K2 + ... + K8 = 1.0. If the second generator is not connected, K1 + K3 + K5 + K7 = 1, and K2 + K4 + K6 + K8 = 0. If K1 to K8 do not sum up to 1.0, they will be normalized. The normalized parameters are called `K1n` through `K8n`.

If initialization error occurs for variable `vs`, it is due to the limits `PMIN` and `PMAX`.

IEEEG1 does not yet support the change of reference (scheduling).

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
syn2		Optional SynGen idx			
K	K	Gain (1/R) in mach. base	20	*p.u. (power)*	power
T1	T_1	Gov. lag time const.	1		
T2	T_2	Gov. lead time const.	1		
T3	T_3	Valve controller time const.	0.100		
UO	U_o	Max. valve opening rate	0.100	*p.u./sec*	
UC	U_c	Max. valve closing rate	-0.100	*p.u./sec*	
PMAX	P_{MAX}	Max. turbine power	5		power
PMIN	P_{MIN}	Min. turbine power	0		power
T4	T_4	Inlet piping/steam bowl time constant	0.400		
K1	K_1	Fraction of power from HP	0.500		
K2	K_2	Fraction of power from LP	0		
T5	T_5	Time constant of 2nd boiler pass	8		
K3	K_3	Fraction of HP shaft power after 2nd boiler pass	0.500		
K4	K_4	Fraction of LP shaft power after 2nd boiler pass	0		
T6	T_6	Time constant of 3rd boiler pass	0.500		
K5	K_5	Fraction of HP shaft power after 3rd boiler pass	0		

continues on next page

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Name	Symbol	Description	Default	Unit	Properties
K6	K_6	Fraction of LP shaft power after 3rd boiler pass	0		
T7	T_7	Time constant of 4th boiler pass	0.050		
K7	K_7	Fraction of HP shaft power after 4th boiler pass	0		
K8	K_8	Fraction of LP shaft power after 4th boiler pass	0		
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	
Sg2	S_{n2}	Rated power of Syn2	0	*MVA*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LL_x	x'_{LL}	State	State in lead-lag		v_str
IAW_y	y_{IAW}	State	AW Integrator output		v_str
L4_y	y_{L4}	State	State in lag transfer function		v_str
L5_y	y_{L5}	State	State in lag transfer function		v_str
L6_y	y_{L6}	State	State in lag transfer function		v_str
L7_y	y_{L7}	State	State in lag transfer function		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
wd	ω_{dev}	Algeb	Generator under speed	*p.u.*	v_str
LL_y	y_{LL}	Algeb	Output of lead-lag		v_str
vs	V_s	Algeb	Valve speed		v_str
vsl	V_{sl}	Algeb	Valve move speed after limiter		v_str
PHP	P_{HP}	Algeb	HP output		v_str
PLP	P_{LP}	Algeb	LP output		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		
tm2	τ_{m2}	ExtAlgeb	Mechanical power to syn2		

Initialization Equations

Name	Symbol	Type	Initial Value
LL_x	x'_{LL}	State	ω_{dev}
IAW_y	y_{IAW}	State	tm_{012}
L4_y	y_{L4}	State	y_{IAW}
L5_y	y_{L5}	State	y_{L4}
L6_y	y_{L6}	State	y_{L5}
L7_y	y_{L7}	State	y_{L6}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
wd	ω_{dev}	Algeb	0
LL_y	y_{LL}	Algeb	ω_{dev}
vs	V_s	Algeb	0
vsl	V_{sl}	Algeb	$U_c z_l^{HL} + U_o z_u^{HL} + V_s z_i^{HL}$
PHP	P_{HP}	Algeb	$u_e \left(K_{1n} y_{L4} + K_{3n} y_{L5} + K_{5n} y_{L6} + K_{7n} y_{L7}\right)$
PLP	P_{LP}	Algeb	$u_e \left(K_{2n} y_{L4} + K_{4n} y_{L5} + K_{6n} y_{L6} + K_{8n} y_{L7}\right)$
tm	τ_m	ExtAlgeb	
tm2	τ_{m2}	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LL_x	x'_{LL}	State	$\omega_{dev} - x'_{LL}$	T_1
IAW_y	y_{IAW}	State	V_{sl}	1
L4_y	y_{L4}	State	$y_{IAW} - y_{L4}$	T_4
L5_y	y_{L5}	State	$y_{L4} - y_{L5}$	T_5
L6_y	y_{L6}	State	$y_{L5} - y_{L6}$	T_6
L7_y	y_{L7}	State	$y_{L6} - y_{L7}$	T_7
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$P_{HP} u_e - P_{out}$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(-\omega + \omega_{ref}\right)$
LL_y	y_{LL}	Algeb	$KT_1 x'_{LL} + KT_2 \left(\omega_{dev} - x'_{LL}\right) - T_1 y_{LL} + \left(z_1^{LT_{LL}}\right)^2 \left(-K x'_{LL} + y_{LL}\right)$
vs	V_s	Algeb	$-V_s + \frac{u_e (P_{aux} + tm_{012} - y_{IAW} + y_{LL})}{T_3}$
vsl	V_{sl}	Algeb	$U_c z_l^{HL} + U_o z_u^{HL} + V_s z_i^{HL} - V_{sl}$
PHP	P_{HP}	Algeb	$-P_{HP} + u_e \left(K_{1n} y_{L4} + K_{3n} y_{L5} + K_{5n} y_{L6} + K_{7n} y_{L7}\right)$
PLP	P_{LP}	Algeb	$-P_{LP} + u_e \left(K_{2n} y_{L4} + K_{4n} y_{L5} + K_{6n} y_{L6} + K_{8n} y_{L7}\right)$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$
tm2	τ_{m2}	ExtAlgeb	$u_e z_{syn2} \left(P_{LP} - \tau_{m02}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
_sumK18	$\sum_{i=1}^{8} K_i$	$K_1 + K_2 + K_3 + K_4 + K_5 + K_6 + K_7 + K_8$	ConstService
_Kcoeff	K_{coeff}	$\frac{1}{\sum_{i=1}^{8} K_i}$	ConstService
K1n	K_{1n}	$K_1 K_{coeff}$	ConstService
K2n	K_{2n}	$K_2 K_{coeff}$	ConstService
K3n	K_{3n}	$K_3 K_{coeff}$	ConstService
K4n	K_{4n}	$K_4 K_{coeff}$	ConstService
K5n	K_{5n}	$K_5 K_{coeff}$	ConstService
K6n	K_{6n}	$K_6 K_{coeff}$	ConstService
K7n	K_{7n}	$K_7 K_{coeff}$	ConstService
K8n	K_{8n}	$K_8 K_{coeff}$	ConstService
_tm0K2	${}_tm0K2$	$\tau_{m0} z_{syn2} \left(K_{2n} + K_{4n} + K_{6n} + K_{8n}\right)$	PostInitService
_tm02K1	${}_tm02K1$	$\tau_{m02} \left(K_{1n} + K_{3n} + K_{5n} + K_{7n}\right)$	PostInitService
tm012	$tm012$	$\tau_{m02} + \tau_{m0}$	ConstService

Discretes

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HL	HL	HardLimiter	Limiter on valve speed
IAW_lim	lim_{IAW}	AntiWindup	Limiter in integrator

Blocks

Name	Symbol	Type	Info
LL	LL	LeadLag	Signal conditioning for wd
IAW	IAW	IntegratorAntiWindup	Valve position integrator
L4	$L4$	Lag	first process
L5	$L5$	Lag	second (reheat) process
L6	$L6$	Lag	third process
L7	$L7$	Lag	fourth (second reheat) process

Config Fields in [IEEEG1]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.7 IEESGO

IEEE Standard Governor (IEESGO).

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
T1	T_1	Controller lag	0.020		
T2	T_2	Lead compensation	1		
T3	T_3	Governor lag	1		
T4	T_4	Steam inlet delay	0.500		
T5	T_5	Reheater delay	10		
T6	T_6	Crossover delay	0.500		
K1	K_1	1/pu regulation	0.020		
K2	K_2	fraction K2	1		
K3	K_3	fraction K3	1		
PMAX	P_{MAX}	Max. turbine power	5		power
PMIN	P_{MIN}	Min. turbine power	0		power
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
F1_y	y_{F1}	State	State in lag transfer function		v_str
F2_x	x'_{F2}	State	State in lead-lag		v_str
F3_y	y_{F3}	State	State in lag transfer function		v_str
F4_y	y_{F4}	State	State in lag transfer function		v_str
F5_y	y_{F5}	State	State in lag transfer function		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
F2_y	y_{F2}	Algeb	Output of lead-lag		v_str
HL_x	x_{HL}	Algeb	Value before limiter		v_str
HL_y	y_{HL}	Algeb	Output after limiter and post gain		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
F1_y	y_{F1}	State	$K_1 u_e \left(\omega - \omega_{ref}\right)$
F2_x	x'_{F2}	State	y_{F1}
F3_y	y_{F3}	State	$1.0 y_{HL}$
F4_y	y_{F4}	State	$K_2 y_{F3}$
F5_y	y_{F5}	State	$K_3 y_{F4}$
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
F2_y	y_{F2}	Algeb	y_{F1}
HL_x	x_{HL}	Algeb	$1.0 u_e \left(P_{aux} + P_{ref0} - y_{F2}\right)$
HL_y	y_{HL}	Algeb	$1.0 P_{MAX} z_u^{lim_{HL}} + 1.0 P_{MIN} z_l^{lim_{HL}} + 1.0 x_{HL} z_i^{lim_{HL}}$
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
F1_y	y_{F1}	State	$K_1 u_e \left(\omega - \omega_{ref}\right) - y_{F1}$	T_1
F2_x	x'_{F2}	State	$-x'_{F2} + y_{F1}$	T_3
F3_y	y_{F3}	State	$-y_{F3} + 1.0 y_{HL}$	T_4
F4_y	y_{F4}	State	$K_2 y_{F3} - y_{F4}$	T_5
F5_y	y_{F5}	State	$K_3 y_{F4} - y_{F5}$	T_6
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(y_{F3} \cdot \left(1 - K_2\right) + y_{F4} \cdot \left(1 - K_3\right) + y_{F5}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
F2_y	y_{F2}	Algeb	$1.0 T_2 \left(-x'_{F2} + y_{F1}\right) + 1.0 T_3 x'_{F2} - T_3 y_{F2} + \left(z_1^{LT_{F2}}\right)^2 \left(-1.0 x'_{F2} + y_{F2}\right)$
HL_x	x_{HL}	Algeb	$1.0 u_e \left(P_{aux} + P_{ref0} - y_{F2}\right) - x_{HL}$
HL_y	y_{HL}	Algeb	$1.0 P_{MAX} z_u^{lim_{HL}} + 1.0 P_{MIN} z_l^{lim_{HL}} + 1.0 x_{HL} z_i^{lim_{HL}} - y_{HL}$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService

Discretes

Name	Symbol	Type	Info
F2_LT1	LT_{F2}	LessThan	
F2_LT2	LT_{F2}	LessThan	
HL_lim	lim_{HL}	HardLimiter	

Blocks

Name	Symbol	Type	Info
F1	$F1$	Lag	
F2	$F2$	LeadLag	
HL	HL	GainLimiter	
F3	$F3$	Lag	
F4	$F4$	Lag	
F5	$F5$	Lag	

Config Fields in [IEESGO]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.8 GAST

GAST turbine governor model.

Reference:

[1] Neplan, TURBINE-GOVERNOR GAST, [Online],

Available:

https://www.neplan.ch/wp-content/uploads/2015/08/Nep_TURBINES_GOV.pdf

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
VMAX	V_{max}	Maximum valve position	1.200	*p.u.*	power
VMIN	V_{min}	Minimum valve position	0	*p.u.*	power
KT	K_T	Temperature limiter gain	5		
AT	A_T	Ambient temperature load limit	1		power
T1	T_1	Valve time constant	0.100		
T2	T_2	Lead-lag lead time constant	0.200		
T3	T_3	Lead-lag lag time constant	10		
Dt	D_t	Turbine damping coefficient	0		power
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LAG_y	y_{LAG}	State	State in lag TF		v_str
LG2_y	y_{LG2}	State	State in lag transfer function		v_str
LG3_y	y_{LG3}	State	State in lag transfer function		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator under speed	*p.u.*	v_str
pd	P_d	Algeb	Pref plus under speed times gain	*p.u.*	v_str
v9	V_9	Algeb	V_9 for LVGate input		v_str
LVG_y	y_{LVG}	Algeb	LVGate output		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LAG_y	y_{LAG}	State	y_{LVG}
LG2_y	y_{LG2}	State	y_{LAG}
LG3_y	y_{LG3}	State	y_{LG2}
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	$R\tau_{m0}$
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	$\tau_{m0} u_e$
v9	V_9	Algeb	$u_e \left(A_T + K_T \left(A_T - \tau_{m0}\right)\right)$
LVG_y	y_{LVG}	Algeb	$P_d \tilde{z}_1^{None_{LVG}} + V_9 \tilde{z}_0^{None_{LVG}}$
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LAG_y	y_{LAG}	State	$-y_{LAG} + y_{LVG}$	T_1
LG2_y	y_{LG2}	State	$y_{LAG} - y_{LG2}$	T_2
LG3_y	y_{LG3}	State	$y_{LG2} - y_{LG3}$	T_3
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(-D_t \omega_{dev} + y_{LG2}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$P_{ref0} R - P_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$G u_e \left(P_{aux} + P_{ref} - \omega_{dev}\right) - P_d$
v9	V_9	Algeb	$-V_9 + u_e \left(A_T + K_T \left(A_T - y_{LG3}\right)\right)$
LVG_y	y_{LVG}	Algeb	$P_d z_1^{None_{LVG}} + V_9 z_0^{None_{LVG}} - y_{LVG}$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u_e}{R}$	ConstService

Discretes

Name	Symbol	Type	Info
LVG_lt	$None_{LVG}$	LessThan	
LAG_lim	lim_{LAG}	AntiWindup	Limiter in Lag

Blocks

Name	Symbol	Type	Info
LVG	LVG	LVGate	LVGate
LAG	LAG	LagAntiWindup	
LG2	$LG2$	Lag	Lag T2
LG3	$LG3$	Lag	Lag T3

Config Fields in [GAST]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.9 HYGOV

HYGOV turbine governor model.

Implements the PSS/E HYGOV model without deadband.

Reference:

[1] PSSE, Model Library, HYGOV

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
r	r	Temporary droop (R<r)	1	*p.u.*	ipower
GMAX	G_{max}	Maximum governor response	1	*p.u.*	power
GMIN	G_{min}	Minimum governor response	0	*p.u.*	power
VELM	$VELM$	Gate velocity limit	0.300	*p.u.*	power
Tf	T_f	Filter time constant	0.050		
Tr	T_r	Governor time constant	1		
Tg	T_g	Servo time constant	0.050		
Dt	D_t	Turbine damping coefficient	0		power
qNL	q_{NL}	No-load flow at nominal head	0.100		power
Tw	T_w	Water inertia time constant constant	1		
At	A_t	Turbine gain	1		
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
gtpos	δ	State	State in gate position (c)	*rad*	v_str
LAG_y	y_{LAG}	State	State in lag transfer function		v_str
q_y	y_q	State	Integrator output		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
pd	P_d	Algeb	Pref plus speed deviation times gain	*p.u.*	v_str
dg	dg	Algeb	desired gate (c)	*p.u.*	v_str
h	h	Algeb	turbine head	*p.u.*	v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	P_d
gtpos	δ	State	q_0
LAG_y	y_{LAG}	State	dg
q_y	y_q	State	q_0
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	Rq_0
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	0
dg	dg	Algeb	q_0
h	h	Algeb	1
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$P_d - y_{LG}$	T_f
gtpos	δ	State	y_{LG}	
LAG_y	y_{LAG}	State	$dg - y_{LAG}$	T_g
q_y	y_q	State	$1 - \frac{y_q^2}{y_{LAG}^2}$	T_w
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(A_t h \left(-q_{NL} + y_q\right) - D_t \omega_{dev} y_{LAG}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$-P_{ref} + Rq_0$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$-P_d + u_e \left(P_{aux} + P_{ref} - Rdg - \omega_{dev}\right)$
dg	dg	Algeb	$1/r y_{LG} + \delta - dg$
h	h	Algeb	$-h + \frac{y_q^2}{y_{LAG}^2}$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
VELMn	$-VELM$	$-VELM$	ConstService
tr	$r * Tr$	$T_r r$	ConstService
gr	$1/r$	$\frac{1}{r}$	ConstService
ratel	$rate_l$	$-1/r - VELM$	ConstService
rateu	$rate_u$	$-1/r + VELM$	ConstService
q0	q_0	$q_{NL} + \frac{\tau_{m0}}{A_t}$	ConstService
dgl	dg_{lower}	$-1/r y_{LG} - VELM$	VarService
dgu	dg_{upper}	$-1/r y_{LG} + VELM$	VarService

Discretes

Name	Symbol	Type	Info
dg_lim	lim_{dg}	AntiWindupRate	gate velocity and position limiter

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	filter after speed deviation (e)
LAG	LAG	Lag	gate opening (g)
q	q	Integrator	turbine flow (q)

Config Fields in [HYGOV]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.10 HYGOVDB

HYGOV turbine governor model with speed input deadband.

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
R	R	Speed regulation gain (mach. base default)	0.050	*p.u.*	ipower
r	r	Temporary droop (R<r)	1	*p.u.*	ipower
GMAX	G_{max}	Maximum governor response	1	*p.u.*	power
GMIN	G_{min}	Minimum governor response	0	*p.u.*	power
VELM	$VELM$	Gate velocity limit	0.300	*p.u.*	power
Tf	T_f	Filter time constant	0.050		
Tr	T_r	Governor time constant	1		
Tg	T_g	Servo time constant	0.050		
Dt	D_t	Turbine damping coefficient	0		power
qNL	q_{NL}	No-load flow at nominal head	0.100		power
Tw	T_w	Water inertia time constant constant	1		
At	A_t	Turbine gain	1		
dbL	db_L	Lower bound of deadband	0	*p.u.*	
dbU	db_U	Upper bound of deadband	0	*p.u.*	
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
LG_y	y_{LG}	State	State in lag transfer function		v_str
gtpos	δ	State	State in gate position (c)	*rad*	v_str
LAG_y	y_{LAG}	State	State in lag transfer function		v_str
q_y	y_q	State	Integrator output		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
pd	P_d	Algeb	Pref plus speed deviation times gain	*p.u.*	v_str
dg	dg	Algeb	desired gate (c)	*p.u.*	v_str
h	h	Algeb	turbine head	*p.u.*	v_str
DB_y	y_{DB}	Algeb	Deadband type 1 output		v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
LG_y	y_{LG}	State	P_d
gtpos	δ	State	q_0
LAG_y	y_{LAG}	State	dg
q_y	y_q	State	q_0
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	Rq_0
wd	ω_{dev}	Algeb	0
pd	P_d	Algeb	0
dg	dg	Algeb	q_0
h	h	Algeb	1
DB_y	y_{DB}	Algeb	$1.0 z_l^{db_{DB}} \left(\omega_{dev} - db_L\right) + 1.0 z_u^{db_{DB}} \left(\omega_{dev} - db_U\right)$
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$P_d - y_{LG}$	T_f
gtpos	δ	State	y_{LG}	
LAG_y	y_{LAG}	State	$dg - y_{LAG}$	T_g
q_y	y_q	State	$1 - \frac{y_q^2}{y_{LAG}^2}$	T_w
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(A_t h \left(-q_{NL} + y_q\right) - D_t \omega_{dev} y_{LAG}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$-P_{ref} + Rq_0$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
pd	P_d	Algeb	$-P_d + u_e \left(P_{aux} + P_{ref} - Rdg - y_{DB}\right)$
dg	dg	Algeb	$1/r y_{LG} + \delta - dg$
h	h	Algeb	$-h + \frac{y_q^2}{y_{LAG}^2}$
DB_y	y_{DB}	Algeb	$-y_{DB} + 1.0 z_l^{db_{DB}} \left(\omega_{dev} - db_L\right) + 1.0 z_u^{db_{DB}} \left(\omega_{dev} - db_U\right)$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
VELMn	$-VELM$	$-VELM$	ConstService
tr	$r * Tr$	$T_r r$	ConstService
gr	$1/r$	$\frac{1}{r}$	ConstService
ratel	$rate_l$	$-1/r - VELM$	ConstService
rateu	$rate_u$	$-1/r + VELM$	ConstService
q0	q_0	$q_{NL} + \frac{\tau_{m0}}{A_t}$	ConstService
dgl	dg_{lower}	$-1/r y_{LG} - VELM$	VarService
dgu	dg_{upper}	$-1/r y_{LG} + VELM$	VarService

Discretes

Name	Symbol	Type	Info
dg_lim	lim_{dg}	AntiWindupRate	gate velocity and position limiter
DB_db	db_{DB}	DeadBand	

Blocks

Name	Symbol	Type	Info
LG	LG	Lag	filter after speed deviation (e)
LAG	LAG	Lag	gate opening (g)
q	q	Integrator	turbine flow (q)
DB	DB	DeadBand1	deadband for speed deviation

Config Fields in [HYGOVDB]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.35.11 HYGOV4

HYGOV4 turbine governor model.

Implements the PSS/E HYGOV4 model with the following ignored:

- input deadband DB1
- valve position deadband DB2
- nonlinear function bewteen GV and P_{GV}

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
syn		Synchronous generator idx			mandatory,unique
Tn	T_n	Turbine power rating. Equal to *Sn* if not provided.	0	*MVA*	
wref0	ω_{ref0}	Base speed reference	1	*p.u.*	
Rperm	R_{perm}	Speed Regulation Gain (mach. base default)	0.500	*p.u.*	ipower
Rtemp	R_{temp}	Temporary Droop (Rtemp < Rperm)	1	*p.u.*	ipower
UO	U_O	Maximum Gate opening velocity	1	*p.u.*	power
UC	U_C	Maximum Gate closing velocity	0	*p.u.*	power
PMAX	P_{MAX}	Maximum Gate opening	1	*p.u.*	power
PMIN	P_{MIN}	Minimum Gate opening	0	*p.u.*	power
Tp	T_p	Pilot servo time constant	0.050		
Tg	T_g	Gate servo time constant	0.050		
Tr	T_r	Dashpot time constant	0.050		
Tw	T_w	Water inertia time constant	1		
At	A_t	Turbine gain	1		
Dturb	D_{turb}	Turbine Damping Factor	0		power
Hdam	H_{dam}	Head available at dam	1		power
qNL	q_{NL}	No-Load flow at nominal head	0.100		power
Sg	S_n	Rated power from generator	0	*MVA*	
ug	u_g	Generator connection status	0	*bool*	
Vn	V_n	Rated voltage from generator	0	*kV*	

Variables

Name	Symbol	Type	Description	Unit	Properties
GATE_y	y_{GATE}	State	AW Integrator output		v_str
WO_x	x'_{WO}	State	State in washout filter		v_str
LAG_y	y_{LAG}	State	State in lag transfer function		v_str
q_y	y_q	State	Integrator output		v_str
omega	ω	ExtState	Generator speed	*p.u.*	
paux	P_{aux}	Algeb	Auxiliary power input		v_str
pout	P_{out}	Algeb	Turbine final output power		v_str
wref	ω_{ref}	Algeb	Speed reference variable		v_str
pref	P_{ref}	Algeb	Reference power input		v_str
wd	ω_{dev}	Algeb	Generator speed deviation	*p.u.*	v_str
SV_x	x_{SV}	Algeb	Value before limiter		v_str
SV_y	y_{SV}	Algeb	Output after limiter and post gain		v_str
WO_y	y_{WO}	Algeb	Output of washout filter		v_str
Psum	P_{sum}	Algeb	summation of power input to servo	*p.u.*	v_str
trhead	$trhead$	Algeb	turbine head	*p.u.*	v_str
tm	τ_m	ExtAlgeb	Mechanical power interface to SynGen		

Initialization Equations

Name	Symbol	Type	Initial Value
GATE_y	y_{GATE}	State	$\frac{q_0}{H_{dam}^{0.5}}$
WO_x	x'_{WO}	State	y_{GATE}
LAG_y	y_{LAG}	State	P_{sum}
q_y	y_q	State	q_0
omega	ω	ExtState	
paux	P_{aux}	Algeb	P_{aux0}
pout	P_{out}	Algeb	$\tau_{m0} u_e$
wref	ω_{ref}	Algeb	ω_{ref0}
pref	P_{ref}	Algeb	$\frac{R_{perm} q_0}{H_{dam}^{0.5}}$
wd	ω_{dev}	Algeb	0
SV_x	x_{SV}	Algeb	$1/T_g y_{LAG}$
SV_y	y_{SV}	Algeb	$U_C z_l^{lim_{SV}} + U_O z_u^{lim_{SV}} + x_{SV} z_i^{lim_{SV}}$
WO_y	y_{WO}	Algeb	0
Psum	P_{sum}	Algeb	0
trhead	$trhead$	Algeb	H_{dam}
tm	τ_m	ExtAlgeb	

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
GATE_y	y_{GATE}	State	y_{SV}	1
WO_x	x'_{WO}	State	$-x'_{WO} + y_{GATE}$	T_r
LAG_y	y_{LAG}	State	$P_{sum} - y_{LAG}$	T_p
q_y	y_q	State	$H_{dam} - trhead$	T_w
omega	ω	ExtState	0	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$-P_{out} + u_e \left(A_t trhead \left(-q_{NL} + y_q\right) - D_{turb}\omega_{dev} y_{GATE}\right)$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$\frac{R_{perm} q_0}{H_{dam}^{0.5}} - P_{ref}$
wd	ω_{dev}	Algeb	$-\omega_{dev} + u_e \left(\omega - \omega_{ref}\right)$
SV_x	x_{SV}	Algeb	$1/T_g y_{LAG} - x_{SV}$
SV_y	y_{SV}	Algeb	$U_C z_l^{lim_{SV}} + U_O z_u^{lim_{SV}} + x_{SV} z_i^{lim_{SV}} - y_{SV}$
WO_y	y_{WO}	Algeb	$R_{temp} * T_r \left(-x'_{WO} + y_{GATE}\right) - T_r y_{WO}$
Psum	P_{sum}	Algeb	$-P_{sum} + u_e \left(P_{aux} + P_{ref} - R_{perm} y_{GATE} - \omega_{dev} - y_{WO}\right)$
trhead	$trhead$	Algeb	$-trhead + \frac{y_q^2}{y_{GATE}^2}$
tm	τ_m	ExtAlgeb	$u_e \left(P_{out} - \tau_{m0}\right)$

Services

Name	Symbol	Equation	Type
ue	u_e	uu_g	ConstService
pref0	P_{ref0}	τ_{m0}	ConstService
paux0	P_{aux0}	0	ConstService
iTg	$1/T_g$	$\frac{u}{T_g}$	ConstService
R	$R_{temp} + R_{perm}$	$R_{perm} + R_{temp}$	ConstService
TrRtemp	$R_{temp} * T_r$	$R_{temp} T_r$	ConstService
q0	q_0	$q_{NL} + \frac{\tau_{m0}}{A_t H_{dam}}$	ConstService

Discretes

Name	Symbol	Type	Info
SV_lim	lim_{SV}	HardLimiter	
GATE_lim	lim_{GATE}	AntiWindup	Limiter in integrator

Blocks

Name	Symbol	Type	Info
SV	SV	GainLimiter	servo gain and limiters
GATE	$GATE$	IntegratorAntiWindup	Gate position
WO	WO	Washout	Washout feedback with T_r
LAG	LAG	Lag	lag block with T_p, outputs velocity
q	q	Integrator	turbine flow (q)

Config Fields in [HYGOV4]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

5.36 Undefined

The undefined group. Holds models with no `group`.

Common Parameters: u, name

5.37 VoltComp

Voltage compensator group for synchronous generators.

Common Parameters: u, name, rc, xc

Common Variables: vcomp

Available models: *IEEEVC*

5.37.1 IEEEVC

Voltage compensator IEEEVC model.

Reference:

[1] PowerWorld, Voltage Compensator, IEEEVC, [Online],

[2] NEPLAN, Exciters Models, [Online],

Available:

https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Voltage%20Compensator%20IEEEVC.htm?TocPath=%7C%7C%7CIEEEVC%7C_____0

https://www.neplan.ch/wp-content/uploads/2015/08/Nep_EXCITERS1.pdf

Parameters

Name	Symbol	Description	Default	Unit	Properties
idx		unique device idx			
u	u	connection status	1	*bool*	
name		device name			
avr		Exciter idx			mandatory
rc	r_c	Active compensation degree.	0		z
xc	x_c	Reactive compensation degree.	0		z
syn		Retrieved generator idx	0		

Variables

Name	Symbol	Type	Description	Unit	Properties
vcomp	v_{comp}	Algeb	Compensator output voltage to exciter		v_str
v	V	ExtAlgeb	Retrieved bus terminal voltage		
vd	V_d	ExtAlgeb	d-axis machine voltage		
vq	V_q	ExtAlgeb	q-axis machine voltage		
Id	I_d	ExtAlgeb	d-axis machine current		
Iq	I_q	ExtAlgeb	q-axis machine current		
Eterm	$Eterm$	ExtAlgeb			v_str

Initialization Equations

Name	Symbol	Type	Initial Value
vcomp	v_{comp}	Algeb	$-Vu + V_{CT}$
v	V	ExtAlgeb	
vd	V_d	ExtAlgeb	
vq	V_q	ExtAlgeb	
Id	I_d	ExtAlgeb	
Iq	I_q	ExtAlgeb	
Eterm	$Eterm$	ExtAlgeb	v_{comp}

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vcomp	v_{comp}	Algeb	$-Vu + V_{CT} - v_{comp}$
v	V	ExtAlgeb	0
vd	V_d	ExtAlgeb	0
vq	V_q	ExtAlgeb	0
Id	I_d	ExtAlgeb	0
Iq	I_q	ExtAlgeb	0
Eterm	$Eterm$	ExtAlgeb	v_{comp}

Services

Name	Symbol	Equation	Type
vct	V_{CT}	$u \left\| V_d + iV_q + (I_d + iI_q)(r_c + ix_c) \right\|$	VarService

Config Fields in [IEEEVC]

Option	Symbol	Value	Info	Accepted values
allow_adjust		1	allow adjusting upper or lower limits	(0, 1)
adjust_lower		0	adjust lower limit	(0, 1)
adjust_upper		1	adjust upper limit	(0, 1)

CHAPTER

SIX

API REFERENCE

6.1 System

andes.system	System class for power system data and methods
andes.variables	Variable package with classes for numerical DAE.

6.1.1 andes.system

System class for power system data and methods

Functions

example([setup, no_output])	Return an *andes.system.System* object for the `ieee14_linetrip.xlsx` as an example.
fix_view_arrays(system)	Point NumPy arrays without OWNDATA (termed "view arrays" here) to the source array.
import_pycode([user_pycode_path])	Helper function to import generated pycode in the following priority:
load_config_rc([conf_path])	Load config from an rc-formatted file.
reload_submodules(module_name)	Helper function for reloading an existing module and its submodules.

example

`andes.system.`**`example`**(*setup=True*, *no_output=True*, ***kwargs*)

Return an *andes.system.System* object for the `ieee14_linetrip.xlsx` as an example.

This function is useful when a user wants to quickly get a System object for testing.

Returns

System
An example *andes.system.System* object.

fix_view_arrays

andes.system.**fix_view_arrays**(*system*)

Point NumPy arrays without OWNDATA (termed "view arrays" here) to the source array.

This function properly sets `v` and `e` arrays of internal variables as views of the corresponding DAE arrays.

Inputs will be refreshed for each model.

Parameters

system
[andes.system.System] System object to be fixed

import_pycode

andes.system.**import_pycode**(*user_pycode_path=None*)

Helper function to import generated pycode in the following priority:

1. a user-provided path from CLI. Currently, this is only for specifying the path to store the generated pycode via `andes prepare`.
2. `~/.andes/pycode`. This is where pycode is stored by default.
3. `<andes_package_root>/pycode`. One can store pycode in the ANDES package folder and ship a full package, which does not require code generation.

load_config_rc

andes.system.**load_config_rc**(*conf_path=None*)

Load config from an rc-formatted file.

Parameters

conf_path
[None or str] Path to the config file. If is *None*, the function body will not run.

Returns

configparse.ConfigParser

reload_submodules

andes.system.**reload_submodules**(*module_name*)

Helper function for reloading an existing module and its submodules.

It is used to reload the `pycode` module after regenerating code.

Classes

ExistingModels()	Storage class for existing models
System([case, name, config, config_path, ...])	System contains models and routines for modeling and simulation.

andes.system.ExistingModels

class andes.system.**ExistingModels**

Storage class for existing models

__init__()

Methods

andes.system.System

class andes.system.**System**(*case: str | None = None*, *name: str | None = None*, *config: Dict | None = None*, *config_path: str | None = None*, *default_config: bool | None = False*, *options: Dict | None = None*, *no_undill: bool | None = False*, *autogen_stale: bool | None = True*, ***kwargs*)

System contains models and routines for modeling and simulation.

System contains a several special *OrderedDict* member attributes for housekeeping. These attributes include *models*, *groups*, *routines* and *calls* for loaded models, groups, analysis routines, and generated numerical function calls, respectively.

Parameters

no_undill
[bool, optional, default=False] True to disable the call to `System.undill()` at the end of object creation. False by default.

autogen_stale
[bool, optional, default=True] True to automatically generate code for stale models.

Notes

System stores model and routine instances as attributes. Model and routine attribute names are the same as their class names. For example, *Bus* is stored at `system.Bus`, the power flow calculation routine is at `system.PFlow`, and the numerical DAE instance is at `system.dae`. See attributes for the list of attributes.

Attributes

dae
[andes.variables.dae.DAE] Numerical DAE storage

files
[andes.variables.fileman.FileMan] File path storage

config
[andes.core.Config] System config storage

models
[OrderedDict] model name and instance pairs

groups
[OrderedDict] group name and instance pairs

routines
[OrderedDict] routine name and instance pairs

__init__(*case: str | None = None*, *name: str | None = None*, *config: Dict | None = None*, *config_path: str | None = None*, *default_config: bool | None = False*, *options: Dict | None = None*, *no_undill: bool | None = False*, *autogen_stale: bool | None = True*, ***kwargs*)

Methods

add(model[, param_dict])	Add a device instance for an existing model.
as_dict([vin, skip_empty])	Return system data as a dict where the keys are model names and values are dicts.
calc_pu_coeff()	Perform per unit value conversion.
call_models(method, models, *args, **kwargs)	Call methods on the given models.
collect_config()	Collect config data from models.
collect_ref()	Collect indices into *BackRef* for all models.
connectivity([info])	Perform connectivity check for system.
e_clear(models)	Clear equation arrays in DAE and model variables.
f_update(models)	Call the differential equation update method for models in sequence.
fg_to_dae()	Collect equation values into the DAE arrays.
find_devices()	Add dependent devices for all model based on *DeviceFinder*.

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Table 1 – continued from previous page

find_models(flag[, skip_zero])	Find models with at least one of the flags as True.
from_ipysheet(model, sheet[, vin])	Set an ipysheet object back to model.
g_islands()	Reset algebraic mismatches for islanded buses.
g_update(models)	Call the algebraic equation update method for models in sequence.
get_z(models)	Get all discrete status flags in a numpy array.
import_groups()	Import all groups classes defined in `models/group.py`.
import_models()	Import and instantiate models as System member attributes.
import_routines()	Import routines as defined in `routines/__init__.py`.
init(models, routine)	Initialize the variables for each of the specified models.
j_islands()	Set gy diagonals to eps for a and v variables of islanded buses.
j_update(models[, info])	Call the Jacobian update method for models in sequence.
l_update_eq(models[, init, niter])	Update equation-dependent limiter discrete components by calling `l_check_eq` of models.
l_update_var(models[, niter, err])	Update variable-based limiter discrete states by calling `l_update_var` of models.
link_ext_param([model])	Retrieve values for `ExtParam` for the given models.
precompile([models, nomp, ncpu])	Trigger precompilation for the given models.
prepare([quick, incremental, models, nomp, ncpu])	Generate numerical functions from symbolically defined models.
reload(case, **kwargs)	Reload a new case in the same System object.
remove_pycapsule()	Remove PyCapsule objects in solvers.
reset([force])	Reset to the state after reading data and setup (before power flow).
s_update_post(models)	Update variable services by calling `s_update_post` of models.
s_update_var(models)	Update variable services by calling `s_update_var` of models.
save_config([file_path, overwrite])	Save all system, model, and routine configurations to an rc-formatted file.
set_address(models)	Set addresses for differential and algebraic variables.
set_config([config])	Set configuration for the System object.
set_dae_names(models)	Set variable names for differential and algebraic variables, right-hand side of external equations, and discrete flags.
set_output_subidx(models)	Process `andes.models.misc.Output` data and store the sub-indices into `dae.xy`.

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Table 1 – continued from previous page

set_var_arrays(models[, inplace, alloc])	Set arrays (*v* and *e*) for internal variables to access dae arrays in place.
setup()	Set up system for studies.
store_adder_setter(models)	Store non-inplace adders and setters for variables and equations.
store_existing()	Store existing models in *System.existing*.
store_no_check_init(models)	Store differential variables with `check_init == False`.
store_sparse_pattern(models)	Collect and store the sparsity pattern of Jacobian matrices.
store_switch_times(models[, eps])	Store event switching time in a sorted Numpy array in `System.switch_times` and an OrderedDict `System.switch_dict`.
summary()	Print out system summary.
supported_models([export])	Return the support group names and model names in a table.
switch_action(models)	Invoke the actions associated with switch times.
to_ipysheet(model[, vin])	Return an ipysheet object for editing in Jupyter Notebook.
undill([autogen_stale])	Reload generated function functions, from either the `$HOME/.andes/pycode` folder.
vars_to_dae(model)	Copy variables values from models to *System.dae*.
vars_to_models()	Copy variable values from *System.dae* to models.

System.add

`System.`**`add`**(*model*, *param_dict=None*, ***kwargs*)

Add a device instance for an existing model.

This methods calls the `add` method of *model* and registers the device *idx* to group.

System.as_dict

`System.`**`as_dict`**(*vin=False*, *skip_empty=True*)

Return system data as a dict where the keys are model names and values are dicts. Each dict has parameter names as keys and corresponding data in an array as values.

Returns

OrderedDict

System.calc_pu_coeff

System.**calc_pu_coeff**()

Perform per unit value conversion.

This function calculates the per unit conversion factors, stores input parameters to *vin*, and perform the conversion.

System.call_models

System.**call_models**(*method: str*, *models: OrderedDict*, **args*, ***kwargs*)

Call methods on the given models.

Parameters

method
[str] Name of the model method to be called

models
[OrderedDict, list, str] Models on which the method will be called

args
Positional arguments to be passed to the model method

kwargs
Keyword arguments to be passed to the model method

Returns

The return value of the models in an OrderedDict

System.collect_config

System.**collect_config**()

Collect config data from models.

Returns

dict
a dict containing the config from devices; class names are keys and configs in a dict are values.

System.collect_ref

System.**collect_ref**()

Collect indices into *BackRef* for all models.

System.connectivity

System.**connectivity**(*info=True*)

Perform connectivity check for system.

Parameters

info
[bool] True to log connectivity summary.

System.e_clear

System.**e_clear**(*models: OrderedDict*)

Clear equation arrays in DAE and model variables.

This step must be called before calling *f_update* or *g_update* to flush existing values.

System.f_update

System.**f_update**(*models: OrderedDict*)

Call the differential equation update method for models in sequence.

Notes

Updated equation values remain in models and have not been collected into DAE at the end of this step.

System.fg_to_dae

System.**fg_to_dae**()

Collect equation values into the DAE arrays.

Additionally, the function resets the differential equations associated with variables pegged by anti-windup limiters.

System.find_devices

System.**find_devices**()

Add dependent devices for all model based on *DeviceFinder*.

System.find_models

System.**find_models**(*flag: str | Tuple | None*, *skip_zero: bool = True*)

Find models with at least one of the flags as True.

Parameters

flag
[list, str] Flags to find

skip_zero
[bool] Skip models with zero devices

Returns

OrderedDict
model name : model instance

> **Warning:** Checking the number of devices has been centralized into this function. `models` passed to most System calls must be retrieved from here.

System.from_ipysheet

System.**from_ipysheet**(*model: str*, *sheet*, *vin: bool = False*)

Set an ipysheet object back to model.

System.g_islands

System.**g_islands**()

Reset algebraic mismatches for islanded buses.

System.g_update

System.**g_update**(*models: OrderedDict*)

Call the algebraic equation update method for models in sequence.

Notes

Like *f_update*, updated values have not collected into DAE at the end of the step.

System.get_z

System.**get_z**(*models: OrderedDict*)

Get all discrete status flags in a numpy array. Values are written to `dae.z` in place.

Returns

numpy.array

System.import_groups

System.**import_groups**()

Import all groups classes defined in `models/group.py`.

Groups will be stored as instances with the name as class names. All groups will be stored to dictionary `System.groups`.

System.import_models

System.**import_models**()

Import and instantiate models as System member attributes.

Models defined in `models/__init__.py` will be instantiated *sequentially* as attributes with the same name as the class name. In addition, all models will be stored in dictionary `System.models` with model names as keys and the corresponding instances as values.

Examples

`system.Bus` stores the *Bus* object, and `system.GENCLS` stores the classical generator object,

`system.models['Bus']` points the same instance as `system.Bus`.

System.import_routines

System.**import_routines**()

Import routines as defined in `routines/__init__.py`.

Routines will be stored as instances with the name as class names. All routines will be stored to dictionary `System.routines`.

Examples

`System.PFlow` is the power flow routine instance, and `System.TDS` and `System.EIG` are time-domain analysis and eigenvalue analysis routines, respectively.

System.init

System.**init**(*models: OrderedDict*, *routine: str*)

Initialize the variables for each of the specified models.

For each model, the initialization procedure is:

- Get values for all *ExtService*.
- Call the model *init()* method, which initializes internal variables.
- Copy variables to DAE and then back to the model.

System.j_islands

System.**j_islands**()

Set gy diagonals to eps for *a* and *v* variables of islanded buses.

System.j_update

System.**j_update**(*models: OrderedDict*, *info=None*)

Call the Jacobian update method for models in sequence.

The procedure is - Restore the sparsity pattern with *andes.variables.dae.DAE.restore_sparse()* - For each sparse matrix in (fx, fy, gx, gy), evaluate the Jacobian function calls and add values.

Notes

Updated Jacobians are immediately reflected in the DAE sparse matrices (fx, fy, gx, gy).

System.l_update_eq

`System.`**`l_update_eq`**(*models: OrderedDict*, *init=False*, *niter=0*)

Update equation-dependent limiter discrete components by calling `l_check_eq` of models. Force set equations after evaluating equations.

This function is must be called after differential equation updates.

System.l_update_var

`System.`**`l_update_var`**(*models: OrderedDict*, *niter=0*, *err=None*)

Update variable-based limiter discrete states by calling `l_update_var` of models.

This function is must be called before any equation evaluation.

System.link_ext_param

`System.`**`link_ext_param`**(*model=None*)

Retrieve values for `ExtParam` for the given models.

System.precompile

`System.`**`precompile`**(*models: OrderedDict | None = None*, *nomp: bool = False*, *ncpu: int = 1*)

Trigger precompilation for the given models.

Arguments are the same as `prepare`.

System.prepare

`System.`**`prepare`**(*quick=False*, *incremental=False*, *models=None*, *nomp=False*, *ncpu=1*)

Generate numerical functions from symbolically defined models.

All procedures in this function must be independent of test case.

Parameters

quick
[bool, optional] True to skip pretty-print generation to reduce code generation time.

incremental
[bool, optional] True to generate only for modified models, incrementally.

models
[list, OrderedDict, None] List or OrderedList of models to prepare

nomp
[bool] True to disable multiprocessing

Warning: Generated lambda functions will be serialized to file, but pretty prints (SymPy objects) can only exist in the System instance on which prepare is called.

Notes

Option `incremental` compares the md5 checksum of all var and service strings, and only re-generate for updated models.

Examples

If one needs to print out LaTeX-formatted equations in a Jupyter Notebook, one need to generate such equations with

```
import andes
sys = andes.prepare()
```

Alternatively, one can explicitly create a System and generate the code

```
import andes
sys = andes.System()
sys.prepare()
```

System.reload

System.**reload**(*case*, ***kwargs*)
Reload a new case in the same System object.

System.remove_pycapsule

System.**remove_pycapsule**()
Remove PyCapsule objects in solvers.

System.reset

System.**reset**(*force=False*)

Reset to the state after reading data and setup (before power flow).

> **Warning:** If TDS is initialized, reset will lead to unpredictable state.

System.s_update_post

System.**s_update_post**(*models: OrderedDict*)

Update variable services by calling `s_update_post` of models.

This function is called at the end of *System.init()*.

System.s_update_var

System.**s_update_var**(*models: OrderedDict*)

Update variable services by calling `s_update_var` of models.

This function is must be called before any equation evaluation after limiter update function *l_update_var*.

System.save_config

System.**save_config**(*file_path=None*, *overwrite=False*)

Save all system, model, and routine configurations to an rc-formatted file.

Parameters

file_path
[str, optional] path to the configuration file default to *~/andes/andes.rc*.

overwrite
[bool, optional] If file exists, True to overwrite without confirmation. Otherwise prompt for confirmation.

> **Warning:** Saved config is loaded back and populated *at system instance creation time*. Configs from the config file takes precedence over default config values.

System.set_address

`System.`**`set_address`**(*models*)

Set addresses for differential and algebraic variables.

System.set_config

`System.`**`set_config`**(*config=None*)

Set configuration for the System object.

Config for models are routines are passed directly to their constructors.

System.set_dae_names

`System.`**`set_dae_names`**(*models*)

Set variable names for differential and algebraic variables, right-hand side of external equations, and discrete flags.

System.set_output_subidx

`System.`**`set_output_subidx`**(*models*)

Process `andes.models.misc.Output` data and store the sub-indices into `dae.xy`.

Parameters

models
[OrderedDict] Models currently in use for the routine

System.set_var_arrays

`System.`**`set_var_arrays`**(*models*, *inplace=True*, *alloc=True*)

Set arrays (*v* and *e*) for internal variables to access dae arrays in place.

This function needs to be called after de-serializing a System object, where the internal variables are incorrectly assigned new memory.

Parameters

models
[OrderedDict, list, Model, optional] Models to execute.

inplace
[bool] True to retrieve arrays that share memory with dae

alloc
[bool] True to allocate for arrays internally

System.setup

System.**setup**()

Set up system for studies.

This function is to be called after adding all device data.

System.store_adder_setter

System.**store_adder_setter**(*models*)

Store non-inplace adders and setters for variables and equations.

System.store_existing

System.**store_existing**()

Store existing models in *System.existing*.

TODO: Models with *TimerParam* will need to be stored anyway. This will allow adding switches on the fly.

System.store_no_check_init

System.**store_no_check_init**(*models*)

Store differential variables with `check_init == False`.

System.store_sparse_pattern

System.**store_sparse_pattern**(*models: OrderedDict*)

Collect and store the sparsity pattern of Jacobian matrices.

This is a runtime function specific to cases.

Notes

For *gy* matrix, always make sure the diagonal is reserved. It is a safeguard if the modeling user omitted the diagonal term in the equations.

System.store_switch_times

System.**store_switch_times**(*models*, *eps=0.0001*)

Store event switching time in a sorted Numpy array in System.switch_times and an OrderedDict System.switch_dict.

System.switch_dict has keys as event times and values as the OrderedDict of model names and instances associated with the event.

Parameters

models
[OrderedDict] model name : model instance

eps
[float] The small time step size to use immediately before and after the event

Returns

array-like
self.switch_times

System.summary

System.**summary**()

Print out system summary.

System.supported_models

System.**supported_models**(*export='plain'*)

Return the support group names and model names in a table.

Returns

str
A table-formatted string for the groups and models

System.switch_action

System.**switch_action**(*models: OrderedDict*)

Invoke the actions associated with switch times.

This function will not be called if flat=True is passed to system.

System.to_ipysheet

System.**to_ipysheet**(*model: str*, *vin: bool = False*)

Return an ipysheet object for editing in Jupyter Notebook.

System.undill

System.**undill**(*autogen_stale=True*)

Reload generated function functions, from either the `$HOME/.andes/pycode` folder.

If no change is made to models, future calls to `prepare()` can be replaced with `undill()` for acceleration.

Parameters

autogen_stale: bool
True to automatically call code generation if stale code is detected. Regardless of this option, codegen is trigger if importing existing code fails.

System.vars_to_dae

System.**vars_to_dae**(*model*)

Copy variables values from models to *System.dae*.

This function clears *DAE.x* and *DAE.y* and collects values from models.

System.vars_to_models

System.**vars_to_models**()

Copy variable values from *System.dae* to models.

6.1.2 andes.variables

Variable package with classes for numerical DAE.

Modules

andes.variables.dae
andes.variables.fileman
andes.variables.report

andes.variables.dae

Classes

DAE(system)	Class for storing numerical values of the DAE system, including variables, equations and first order derivatives (Jacobian matrices).
DAETimeSeries([dae])	DAE time series data.

andes.variables.dae.DAE

class andes.variables.dae.**DAE**(*system*)

Class for storing numerical values of the DAE system, including variables, equations and first order derivatives (Jacobian matrices).

Variable values and equation values are stored as `numpy.ndarray`, while Jacobians are stored as `kvxopt.spmatrix`. The defined arrays and descriptions are as follows:

DAE Array	Description
x	Array for state variable values
y	Array for algebraic variable values
z	Array for 0/1 limiter states (if enabled)
f	Array for differential equation derivatives
Tf	Left-hand side time constant array for f
g	Array for algebraic equation mismatches

The defined scalar member attributes to store array sizes are

Scalar	Description
m	The number of algebraic variables/equations
n	The number of algebraic variables/equations
o	The number of limiter state flags

The derivatives of f and g with respect to x and y are stored in four `kvxopt.spmatrix` sparse matrices: **fx**, **fy**, **gx**, and **gy**, where the first letter is the equation name, and the second letter is the variable name.

Notes

DAE in ANDES is defined in the form of

$$T\dot{x} = f(x, y)$$
$$0 = g(x, y)$$

DAE does not keep track of the association of variable and address. Only a variable instance keeps track of its addresses.

__init__(*system*)

Methods

alloc_or_extend_names()	Allocate empty lists for names for the given size.
build_pattern(name)	Build sparse matrices with stored patterns.
clear_arrays()	Reset equation and variable arrays to empty.
clear_fg()	Resets equation arrays to empty.
clear_ijv()	Clear stored triplets.
clear_ts()	Drop the TimeSeries data and create a new one.
clear_xy()	Reset variable arrays to empty.
clear_z()	Reset status arrays to empty
get_name(arr)	Helper function for geting the list of variable names based on the array name.
get_size(name)	Get the size of an array or sparse matrix based on name.
print_array(name[, values, tol])	Debug helper to print array values and names.
request_address(array_name, ndevice, nvar[, ...])	Interface for requesting addresses for a model.
reset()	Reset array sizes to zero and clear all arrays.
resize_arrays()	Resize arrays to the new sizes *m* and *n*, and *o*.
restore_sparse([names])	Restore all sparse matrices to the sparsity pattern filled with zeros (for variable Jacobian elements) and non-zero constants.
set_t(t)	Helper function for setting time in-place.
store()	Store values for the current time step to the TimeSeries storage.
store_sparse_ijv(name, row, col, val)	Store the sparse pattern triplets.
write_lst(lst_path)	Dump the variable name lst file.
write_npy(file_path)	Write TDS data into NumPy uncompressed format.
write_npz(file_path)	Write TDS data into NumPy compressed format.

DAE.alloc_or_extend_names

DAE.**alloc_or_extend_names**()

Allocate empty lists for names for the given size.

DAE.build_pattern

DAE.**build_pattern**(*name*)

Build sparse matrices with stored patterns.

Call to *store_row_col_idx* should be made before this function.

Parameters

name
[name] jac name

DAE.clear_arrays

DAE.**clear_arrays**()

Reset equation and variable arrays to empty.

DAE.clear_fg

DAE.**clear_fg**()

Resets equation arrays to empty.

DAE.clear_ijv

DAE.**clear_ijv**()

Clear stored triplets.

DAE.clear_ts

DAE.**clear_ts**()

Drop the TimeSeries data and create a new one.

DAE.clear_xy

DAE.**clear_xy**()

Reset variable arrays to empty.

DAE.clear_z

DAE.**clear_z**()

Reset status arrays to empty

DAE.get_name

DAE.**get_name**(*arr*)

Helper function for geting the list of variable names based on the array name.

Parameters

arr
[str] Array name in 'f', 'g', 'x', 'y', 'z'.

DAE.get_size

DAE.**get_size**(*name*)

Get the size of an array or sparse matrix based on name.

Parameters

name
[str (f, g, fx, gy, etc.)] array/sparse name

Returns

tuple
sizes of each element in a tuple

DAE.print_array

DAE.**print_array**(*name*, *values=None*, *tol=None*)

Debug helper to print array values and names.

Parameters

name
[str] array name in 'f', 'g', 'x', 'y'

values
[array-like, optional] substitute array values to use

tol
[float, optional] tolerance value to use. Values below *tol* will not be displayed

DAE.request_address

DAE.**request_address**(*array_name: str*, *ndevice*, *nvar*, *collate=False*)

Interface for requesting addresses for a model.

Parameters

array_name
[str] array name in 'x' and 'y'

ndevice
[int] number of devices

nvar
[int] number of variables

collate
[bool, optional] False if the same variable for different devices are contiguous. True if variables for the same devices should collate. Note: setting `collate` to True will degrade the performance.

Returns

list
A list of arrays for each variable.

DAE.reset

DAE.**reset**()

Reset array sizes to zero and clear all arrays.

DAE.resize_arrays

DAE.**resize_arrays**()

Resize arrays to the new sizes *m* and *n*, and *o*.

If `m > len(self.y)` or `n > len(self.x`, arrays will be extended. Otherwise, new empty arrays will be sliced, starting from 0 to the given size.

> **Warning:** This function should not be called directly. Instead, it is called in `System.set_address` which re-points variables used in power flow to the new array for dynamic analyses.

DAE.restore_sparse

DAE.**restore_sparse**(*names=None*)

Restore all sparse matrices to the sparsity pattern filled with zeros (for variable Jacobian elements) and non-zero constants.

Parameters

names
[None or list] List of Jacobian names to restore sparsity pattern

DAE.set_t

DAE.**set_t**(*t*)

Helper function for setting time in-place.

DAE.store

DAE.**store**()

Store values for the current time step to the TimeSeries storage. Values include variables, equation RHS and discrete states.

DAE.store_sparse_ijv

DAE.**store_sparse_ijv**(*name*, *row*, *col*, *val*)

Store the sparse pattern triplets.

This function is to be called by System after building the complete sparsity pattern for each Jacobian matrix.

Parameters

name
[str] sparse Jacobian matrix name

row
[np.ndarray] all row indices

col
[np.ndarray] all col indices

val
[np.ndarray] all values

DAE.write_lst

DAE.**write_lst**(*lst_path*)

Dump the variable name lst file.

Parameters

lst_path
Path to the lst file.

Returns

bool
succeed flag

DAE.write_npy

DAE.**write_npy**(*file_path*)

Write TDS data into NumPy uncompressed format.

DAE.write_npz

DAE.**write_npz**(*file_path*)

Write TDS data into NumPy compressed format.

The function supports writing out all values at once or writing them out incrementally.

Attributes

fg	Return a concatenated array of [f, g].
x_name_output	Return a list of state var names selected by Output.
x_tex_name_output	Return a list of state var LaTeX names selected by Output.
xy	Return a concatenated array of [x, y].
xy_name	Return a concatenated list of all variable names without format.
xy_tex_name	Return a concatenated list of all variable names in LaTeX format.
xyz	Return a concatenated array of [x, y].
xyz_name	Return a concatenated list of all variable names without format.
xyz_tex_name	Return a concatenated list of all variable names in LaTeX format.
y_name_output	Return a list of algeb var names selected by Output.
y_tex_name_output	Return a list of algeb var LaTeX names selected by Output.

DAE.fg

property DAE.**fg**

Return a concatenated array of [f, g].

DAE.x_name_output

property DAE.**x_name_output**

Return a list of state var names selected by Output.

DAE.x_tex_name_output

property DAE.**x_tex_name_output**

Return a list of state var LaTeX names selected by Output.

DAE.xy

property DAE.**xy**
Return a concatenated array of [x, y].

DAE.xy_name

property DAE.**xy_name**
Return a concatenated list of all variable names without format.

DAE.xy_tex_name

property DAE.**xy_tex_name**
Return a concatenated list of all variable names in LaTeX format.

DAE.xyz

property DAE.**xyz**
Return a concatenated array of [x, y].

DAE.xyz_name

property DAE.**xyz_name**
Return a concatenated list of all variable names without format.

DAE.xyz_tex_name

property DAE.**xyz_tex_name**
Return a concatenated list of all variable names in LaTeX format.

DAE.y_name_output

property DAE.**y_name_output**
Return a list of algeb var names selected by Output.

DAE.y_tex_name_output

property DAE.**y_tex_name_output**

Return a list of algeb var LaTeX names selected by Output.

andes.variables.dae.DAETimeSeries

class andes.variables.dae.**DAETimeSeries**(*dae=None*)

DAE time series data.

__init__(*dae=None*)

Methods

get_data(base_vars, *[, a, rhs])	Get time-series data, either for a variable or for the equation associated with the variable.
reset()	Reset the internal storage and erase all data.
unpack([df, attr, warn_empty])	Unpack dict-stored data into arrays and/or dataframes.
unpack_df(attr)	Construct pandas dataframes.
unpack_np(attr[, warn_empty])	Unpack dict data into numpy arrays.

DAETimeSeries.get_data

DAETimeSeries.**get_data**(*base_vars:* BaseVar | *List[*BaseVar*]*, *, *a=None*, *rhs:* *bool* *= False*)

Get time-series data, either for a variable or for the equation associated with the variable.

Parameters

base_var
[BaseVar or a sequence of BaseVar(s)] The variable types and internal addresses are used for looking up the data.

a
[an array/list of int or None] Sub-indices into the address of *base_var*. Applied to each variable.

Returns

np.ndarray
A two-dimensional array. Each row corresponds to one time step. Each column corresponds to a different different variable.

DAETimeSeries.reset

DAETimeSeries.**reset**()

Reset the internal storage and erase all data.

DAETimeSeries.unpack

DAETimeSeries.**unpack**(*df=False*, *attr=None*, *warn_empty=True*)

Unpack dict-stored data into arrays and/or dataframes.

Parameters

df

[bool] True to construct DataFrames *self.df* and *self.df_z* (time-consuming).

attr

[str, optional] Attribute name to unpack. If None, unpack all.

Returns

True when done.

DAETimeSeries.unpack_df

DAETimeSeries.**unpack_df**(*attr*)

Construct pandas dataframes.

DAETimeSeries.unpack_np

DAETimeSeries.**unpack_np**(*attr*, *warn_empty=True*)

Unpack dict data into numpy arrays.

Attributes

df	Short-hand for the xy dataframe.

DAETimeSeries.df

property DAETimeSeries.**df**

Short-hand for the xy dataframe.

andes.variables.fileman

Functions

add_suffix(fullname, suffix)	Add suffix to a full file name.

add_suffix

andes.variables.fileman.**add_suffix**(*fullname*, *suffix*)

Add suffix to a full file name.

Classes

FileMan([case])	Define a File Manager class for System

andes.variables.fileman.FileMan

class andes.variables.fileman.**FileMan**(*case=None*, ***kwargs*)

Define a File Manager class for System

__init__(*case=None*, ***kwargs*)

Initialize the output file names. For inputs, all absolute paths will be respected. All relative paths are relative to *input_path*.

case: must be full path to case

output: desired name for format conversion output

input_path: default path for input files that only contains file name. If *input_path* is not provided,

it will be derived from the path of *case*.

output_path: path for output files. Default to current working directory where *andes* is invoked.

Methods

get_fullpath([fullname])	Return the original full path if full path is specified, otherwise search in the case file path.
set([case])	Perform the input and output set up.

FileMan.get_fullpath

FileMan.**get_fullpath**(*fullname=None*)

Return the original full path if full path is specified, otherwise search in the case file path.

Parameters

fullname
[str, optional] Full name of the file. If relative, prepend *input_path*. Otherwise, leave it as is.

FileMan.set

FileMan.**set**(*case=None*, ***kwargs*)

Perform the input and output set up.

andes.variables.report

Functions

report_info(system)	

report_info

andes.variables.report.**report_info**(*system*)

Classes

Report(system)	Report class to store system static analysis reports

andes.variables.report.Report

class andes.variables.report.**Report**(*system*)

Report class to store system static analysis reports

__init__(*system*)

Methods

update()	Update values based on the requested content
write()	Write report to file.

Report.update

Report.**update**()

Update values based on the requested content

Report.write

Report.**write**()

Write report to file.

Attributes

info

Report.info

property Report.**info**

6.2 Routines

andes.routines	Package for ANDES analysis routines.

6.2.1 andes.routines

Package for ANDES analysis routines.

Modules

andes.routines.base	Base class for ANDES calculation routines.
andes.routines.criteria	Stability criteria module.
andes.routines.daeint	Integration methods for DAE.
andes.routines.eig	Module for eigenvalue analysis.
andes.routines.pflow	Module for power flow calculation.
andes.routines.tds	ANDES module for time-domain simulation.

andes.routines.base

Base class for ANDES calculation routines.

Classes

BaseRoutine([system, config])	Base routine class.

andes.routines.base.BaseRoutine

class andes.routines.base.**BaseRoutine**(*system=None*, *config=None*)

Base routine class.

Provides references to system, config, and solver.

__init__(*system=None*, *config=None*)

Methods

doc([max_width, export])	Routine documentation interface.
init()	Routine initialization interface.
report(**kwargs)	Report interface.
run(**kwargs)	Routine main entry point.
summary(**kwargs)	Summary interface

BaseRoutine.doc

BaseRoutine.**doc**(*max_width=78*, *export='plain'*)

Routine documentation interface.

BaseRoutine.init

BaseRoutine.**init**()

Routine initialization interface.

BaseRoutine.report

BaseRoutine.**report**(***kwargs*)

Report interface.

BaseRoutine.run

BaseRoutine.**run**(***kwargs*)

Routine main entry point.

BaseRoutine.summary

BaseRoutine.**summary**(***kwargs*)

Summary interface

Attributes

class_name

BaseRoutine.class_name

property BaseRoutine.**class_name**

andes.routines.criteria

Stability criteria module.

Functions

deltadelta(delta, diff_limit)	Test if a system is stable by comparing the maximum rotor angle difference with a threshold.

deltadelta

andes.routines.criteria.**deltadelta**(*delta*, *diff_limit*)

Test if a system is stable by comparing the maximum rotor angle difference with a threshold.

Returns

bool
True if the system is stable, False otherwise.

andes.routines.daeint

Integration methods for DAE.

Classes

BackEuler()	Backward Euler's integration method.
ImplicitIter()	Base class for implicit iterative methods.
Trapezoid()	Trapezoidal methods.

andes.routines.daeint.BackEuler

class andes.routines.daeint.**BackEuler**

Backward Euler's integration method.

__init__(**args*, ***kwargs*)

Methods

calc_jac(tds, gxs, gys)	Build full Jacobian matrix `Ac` for Trapezoid method.
calc_q(x, f, Tf, h, x0, f0)	Calculate the residual of algebraized differential equations.
step(tds)	Integrate with Implicit Trapezoidal Method (ITM) to the current time.

BackEuler.calc_jac

static BackEuler.**calc_jac**(*tds*, *gxs*, *gys*)

Build full Jacobian matrix `Ac` for Trapezoid method.

BackEuler.calc_q

static BackEuler.**calc_q**(*x*, *f*, *Tf*, *h*, *x0*, *f0*)

Calculate the residual of algebraized differential equations.

Notes

Numba jit somehow slows down this function for the 14-bus and the 2k-bus systems.

BackEuler.step

static BackEuler.**step**(*tds*)

Integrate with Implicit Trapezoidal Method (ITM) to the current time.

This function has an internal Newton-Raphson loop for algebraized semi-explicit DAE. The function returns the convergence status when done but does NOT progress simulation time.

Returns

bool
Convergence status in `tds.converged`.

andes.routines.daeint.ImplicitIter

class andes.routines.daeint.**ImplicitIter**

Base class for implicit iterative methods.

__init__(**args*, ***kwargs*)

Methods

calc_jac(tds, gxs, gys)	
calc_q(x, f, Tf, h, x0, f0)	
step(tds)	Integrate with Implicit Trapezoidal Method (ITM) to the current time.

ImplicitIter.calc_jac

static ImplicitIter.**calc_jac**(*tds*, *gxs*, *gys*)

ImplicitIter.calc_q

static ImplicitIter.**calc_q**(*x*, *f*, *Tf*, *h*, *x0*, *f0*)

ImplicitIter.step

static ImplicitIter.**step**(*tds*)

Integrate with Implicit Trapezoidal Method (ITM) to the current time.

This function has an internal Newton-Raphson loop for algebraized semi-explicit DAE. The function returns the convergence status when done but does NOT progress simulation time.

Returns

bool
Convergence status in `tds.converged`.

andes.routines.daeint.Trapezoid

class andes.routines.daeint.**Trapezoid**

Trapezoidal methods.

__init__(**args*, ***kwargs*)

Methods

calc_jac(tds, gxs, gys)	Build full Jacobian matrix `Ac` for Trapezoid method.
calc_q(x, f, Tf, h, x0, f0)	Calculate the residual of algebraized differential equations.
step(tds)	Integrate with Implicit Trapezoidal Method (ITM) to the current time.

Trapezoid.calc_jac

static Trapezoid.**calc_jac**(*tds*, *gxs*, *gys*)

Build full Jacobian matrix `Ac` for Trapezoid method.

Trapezoid.calc_q

static Trapezoid.**calc_q**(*x*, *f*, *Tf*, *h*, *x0*, *f0*)

Calculate the residual of algebraized differential equations.

Notes

Numba jit somehow slows down this function for the 14-bus and the 2k-bus systems.

Trapezoid.step

static Trapezoid.**step**(*tds*)

Integrate with Implicit Trapezoidal Method (ITM) to the current time.

This function has an internal Newton-Raphson loop for algebraized semi-explicit DAE. The function returns the convergence status when done but does NOT progress simulation time.

Returns

bool
Convergence status in `tds.converged`.

andes.routines.eig

Module for eigenvalue analysis.

Classes

EIG(system, config)	Eigenvalue analysis routine

andes.routines.eig.EIG

class andes.routines.eig.**EIG**(*system*, *config*)

Eigenvalue analysis routine

__init__(*system*, *config*)

Methods

calc_As([dense])	Return state matrix and store to `self.As`.
calc_eig([As])	Calculate eigenvalues and right eigen vectors.
calc_pfactor([As])	Compute participation factor of states in eigenvalues.
doc([max_width, export])	Routine documentation interface.
export_mat()	Export state matrix to a `<CaseName>_As.mat` file with the variable name `As`, where `<CaseName>` is the test case name.
find_zero_states()	Find the indices of states associated with zero time constants in `x`.
init()	Routine initialization interface.
plot([mu, fig, ax, left, right, ymin, ymax, ...])	Plot utility for eigenvalues in the S domain.
plot_root_loci(results, eig_indices[, ax, ...])	Plot the root loci.
post_process()	Post processing of eigenvalues.
report([x_name])	Save eigenvalue analysis reports.
run(**kwargs)	Run small-signal stability analysis.
stats()	Return statistics of results in a string.
summary()	Print out a summary to `logger.info`.
sweep(params, idxes, values)	Parameter sweep for root loci plot.

EIG.calc_As

EIG.**calc_As**(*dense=True*)

Return state matrix and store to `self.As`.

Returns

kvxopt.matrix
state matrix

Notes

For systems in the mass-matrix formulation,

$$T\dot{x} = f(x, y)$$
$$0 = g(x, y)$$

Assume T is non-singular, the state matrix is calculated from

$$A_s = T^{-1}(f_x - f_y * g_y^{-1} * g_x)$$

EIG.calc_eig

EIG.**calc_eig**(*As=None*)

Calculate eigenvalues and right eigen vectors.

This function is a wrapper to `np.linalg.eig`. Results are returned but not stored to `EIG`.

Returns

np.array(dtype=complex)
eigenvalues

np.array()
right eigenvectors

EIG.calc_pfactor

EIG.**calc_pfactor**(*As=None*)

Compute participation factor of states in eigenvalues.

Each row in the participation factor correspond to one state, and each column correspond to one mode.

Parameters

As
[np.array or None] State matrix to process. If None, use `self.As`.

Returns

np.array(dtype=complex)
eigenvalues

np.array
participation factor matrix

EIG.doc

`EIG.doc(max_width=78, export='plain')`

Routine documentation interface.

EIG.export_mat

`EIG.export_mat()`

Export state matrix to a `<CaseName>_As.mat` file with the variable name `As`, where `<CaseName>` is the test case name.

State variable names are stored in variables `x_name` and `x_tex_name`.

Returns

bool
True if successful

EIG.find_zero_states

`EIG.find_zero_states()`

Find the indices of states associated with zero time constants in `x`.

EIG.init

`EIG.init()`

Routine initialization interface.

EIG.plot

`EIG.plot(mu=None, fig=None, ax=None, left=-6, right=0.5, ymin=-8, ymax=8, damping=0.05, line_width=0.5, s=40, dpi=None, figsize=None, base_color='black', show=True, latex=True, style='default')`

Plot utility for eigenvalues in the S domain.

Parameters

mu
[array, optional] an array of complex eigenvalues

fig
[figure handl, optional] existing matplotlib figure handle

ax
[axis handle, optional] existing axis handle

left
[int, optional] left tick for the x-axis, by default -6

right
[float, optional] right tick, by default 0.5

ymin
[int, optional] bottom tick, by default -8

ymax
[int, optional] top tick, by default 8

damping
[float, optional] damping value for which the dash plots are drawn

line_width
[float, optional] default line width, by default 0.5

s
[float or array-like, shape (n,), optional] The marker size in points**2

dpi
[int, optional] figure dpi

figsize
[[type], optional] default figure size, by default None

base_color
[str, optional] base color for negative eigenvalues

show
[bool, optional] True to show figure after plot, by default True

latex
[bool, optional] True to use latex, by default True

Returns

figure
matplotlib figure object

axis
matplotlib axis object

EIG.plot_root_loci

EIG.**plot_root_loci**(*results*, *eig_indices*, *ax=None*, *dpi=None*, *figsize=None*, *draw_line=False*, *arrow_threshold=0.2*, ***kwargs*)

Plot the root loci.

Markers increase in size for the first parameter through the last.

Parameters

results
[dict] Eigenvalue results from parameter sweeping

eig_indices
[Iterable] A list of eigenvalue indices to plot. The indices are 0-based, whereas the indices in the eigenvalue analysis report are 1-based.

ax
[matplotlib.axes.Axes or None] Axes to plot on. If None, create a new figure.

dpi
[int or None] DPI of the figure. If None, use the default DPI.

figsize
[tuple or None] Figure size. If None, use the default size.

draw_line
[bool, optional, False by default] If True, draw lines to connect the roots. Note that due to the non-fixed ordering of eigenvalues, lines will largely connect different modesl

arrow_threshold
[float] Threshold for plotting arrows. If the begin and end points of a locus is shorter than this threshold, no arrow is plotted.

Returns

matplotlib.figure.Figure
Figure containing the plot.

matplotlib.axes.Axes
Axes of the plot.

Examples

To plot the root loci of the first two eigenvalues, do

```
fig, ax = ss.EIG.plot_root_loci(ret, [0, 1])
```

where `ret` is the return of *andes.routines.eig.EIG.sweep()*.

EIG.post_process

EIG.**post_process**()

Post processing of eigenvalues.

EIG.report

EIG.**report**(*x_name=None*, ***kwargs*)

Save eigenvalue analysis reports.

Returns

None

EIG.run

EIG.**run**(***kwargs*)

Run small-signal stability analysis.

EIG.stats

EIG.**stats**()

Return statistics of results in a string.

EIG.summary

EIG.**summary**()

Print out a summary to `logger.info`.

EIG.sweep

EIG.**sweep**(*params*, *idxes*, *values*)

Parameter sweep for root loci plot.

Parameters

params
[list of NumParam or ConstService] list of parameters indices to sweep. For example, `[ss.GENCLS.M]` for GENCLS.M. To update `ss.GENCLS.M` for two generators, `params` should be set to `[ss.GENCLS.M, ss.GENCLS.M]`.

idxes
[list of int or str] list of indices to sweep. For example, `["GENCLS_1", "GENCLS_2"]` for the indices of GENCLS whose corresponding parameter will be updated. The length of `idxes` must match that of `params` and `values`.

values: list of lists
New values of the parameters. Each element in `values` is a list for the corresponding element in `params` and `idxes`.

Returns

dict
A dictionary of the results where the keys are 0-indexed count of parameter set, and the values are dictionaries. Each value dictionary contains a `mu` field for the eigenvalues.

Examples

To apply 10 parameters evenly spaced between 1 and 10 to `ss.GENCLS.M` of `GENCLS_1`, do

```
ret = ss.EIG.sweep(ss.GENCLS.M, "GENCLS_1", np.linspace(1, 2, 10))
```

This is equivalent to the following just for convenience.

```
ret = ss.EIG.sweep([ss.GENCLS.M],
                   ["GENCLS_1"],
                   [np.linspace(1, 2, 10)])
```

Attributes

class_name

EIG.class_name

property EIG.**class_name**

andes.routines.pflow

Module for power flow calculation.

Classes

PFlow([system, config])	Power flow calculation routine.

andes.routines.pflow.PFlow

class andes.routines.pflow.**PFlow**(*system=None*, *config=None*)

Power flow calculation routine.

__init__(*system=None*, *config=None*)

Methods

doc([max_width, export])	Routine documentation interface.
fg_update()	Evaluate the limiters and residual equations.
init()	Initialize variables for power flow.
newton_krylov([verbose])	Full Newton-Krylov method from SciPy.
nr_solve()	Solve the power flow problem using itertive Newton's method.
nr_step()	Solve a single iteration step using the Newton-Raphson method.
report()	Write power flow report to a plain-text file.
run(**kwargs)	Solve the power flow using the selected method.
summary()	Output a summary for the PFlow routine.

PFlow.doc

PFlow.**doc**(*max_width=78*, *export='plain'*)

Routine documentation interface.

PFlow.fg_update

PFlow.**fg_update**()

Evaluate the limiters and residual equations.

PFlow.init

PFlow.**init**()

Initialize variables for power flow.

PFlow.newton_krylov

PFlow.**newton_krylov**(*verbose=True*)

Full Newton-Krylov method from SciPy.

Parameters

verbose
True if verbose.

Returns

bool
Convergence status

> **Warning:** The result might be wrong if discrete are in use!

PFlow.nr_solve

PFlow.**nr_solve**()

Solve the power flow problem using itertive Newton's method.

PFlow.nr_step

PFlow.**nr_step**()

Solve a single iteration step using the Newton-Raphson method.

Returns

float
maximum absolute mismatch

PFlow.report

PFlow.**report**()

Write power flow report to a plain-text file.

Returns

bool
True if report was written, False otherwise.

PFlow.run

PFlow.**run**(***kwargs*)

Solve the power flow using the selected method.

Returns

bool
convergence status

PFlow.summary

PFlow.**summary**()

Output a summary for the PFlow routine.

Attributes

class_name

PFlow.class_name

property PFlow.**class_name**

andes.routines.tds

ANDES module for time-domain simulation.

Classes

TDS([system, config])	Time-domain simulation routine.

andes.routines.tds.TDS

class andes.routines.tds.**TDS**(*system=None*, *config=None*)

Time-domain simulation routine.

Some cases may be sensitive to large convergence tolerance `config.tol`. If numerical oscillation happens, try reducing `config.tol` to `1e-6`.

__init__(*system=None*, *config=None*)

Methods

calc_h([resume])	Calculate the time step size during the TDS.
check_criteria()	Check stability criteria.
do_switch()	Checks if is an event time and perform switch if true.
doc([max_width, export])	Routine documentation interface.
fg_update(models[, init])	Perform one round of evaluation for one iteration step.
init()	Initialize the status, storage and values for TDS.
init_resume()	Initialize a resumed simulation.
itm_step()	Integrate for the step size of `self.h` using implicit trapezoid method.
load_plotter()	Manually load a plotter into `TDS.plotter`.
report(**kwargs)	Report interface.
reset()	Reset internal states to pre-init condition.
rewind(t)	TODO: rewind to a past time.
run([no_summary])	Run time-domain simulation using numerical integration.
save_output([npz])	Save the simulation data into two files: a *.lst* file and a *.npz* file.
set_method([name])	Set DAE solution method.
streaming_init()	Send out initialization variables and process init from modules.
streaming_step()	Sync, handle and streaming for each integration step.
summary()	Print out a summary of TDS options to logger.info.
test_init()	Test if the TDS initialization is successful.

TDS.calc_h

TDS.**calc_h**(*resume=False*)

Calculate the time step size during the TDS.

Parameters

resume
[bool] If True, calculate the initial step size.

Returns

float
computed time step size stored in `self.h`

Notes

A heuristic function is used for variable time step size

```
     min(0.50 * h, hmin), if niter >= 15
h =  max(1.10 * h, hmax), if niter <= 6
     min(0.95 * h, hmin), otherwise
```

TDS.check_criteria

TDS.**check_criteria**()

Check stability criteria.

TDS.do_switch

TDS.**do_switch**()

Checks if is an event time and perform switch if true.

TDS.doc

TDS.**doc**(*max_width=78*, *export='plain'*)

Routine documentation interface.

TDS.fg_update

TDS.**fg_update**(*models*, *init=False*)

Perform one round of evaluation for one iteration step. The following operations are performed in order:

- variable service updating through `s_update_var`
- discrete flags updating through `l_update_var`
- evaluation of the right-hand-side of `f`
- equation-dependent discrete flags updating through `l_update_eq`
- evaluation of the right-hand-side of `g`
- collection of residuals into dae through `fg_to_dae`.

TDS.init

TDS.**init**()

Initialize the status, storage and values for TDS.

Returns

array-like
The initial values of xy.

TDS.init_resume

TDS.**init_resume**()

Initialize a resumed simulation.

TDS.itm_step

TDS.**itm_step**()

Integrate for the step size of `self.h` using implicit trapezoid method.

Returns

bool
Convergence status in `self.converged`.

TDS.load_plotter

TDS.**load_plotter**()

Manually load a plotter into TDS.plotter.

TDS.report

TDS.**report**(***kwargs*)

Report interface.

TDS.reset

TDS.**reset**()

Reset internal states to pre-init condition.

TDS.rewind

TDS.**rewind**(*t*)

TODO: rewind to a past time.

TDS.run

TDS.**run**(*no_summary=False*, ***kwargs*)

Run time-domain simulation using numerical integration.

The default method is the Implicit Trapezoidal Method (ITM).

TDS.save_output

TDS.**save_output**(*npz=True*)

Save the simulation data into two files: a *.lst* file and a *.npz* file.

This function saves the output regardless of the *files.no_output* flag.

Parameters

npz
[bool] True to save in npz format; False to save in npy format.

Returns

bool
True if files are written. False otherwise.

TDS.set_method

TDS.**set_method**(*name: str = 'trapezoid'*)

Set DAE solution method.

Parameters

name
[str, optional, default: 'trapezoid'] DAE solver name

TDS.streaming_init

TDS.**streaming_init**()

Send out initialization variables and process init from modules.

Returns

None

TDS.streaming_step

TDS.**streaming_step**()

Sync, handle and streaming for each integration step.

Returns

None

TDS.summary

TDS.**summary**()

Print out a summary of TDS options to logger.info.

Returns

None

TDS.test_init

TDS.**test_init**()

Test if the TDS initialization is successful.

This function update `dae.f` and `dae.g` and checks if the residuals are zeros.

Attributes

class_name

TDS.class_name

property TDS.**class_name**

6.3 Plot

andes.plot	The ANDES plotting tool.

6.3.1 andes.plot

The ANDES plotting tool.

Functions

eig_plot(name, args)	
parse_y(y, upper[, lower])	Parse command-line input for Y indices and return a list of indices
set_font([family, size, style, weight])	Sets the font for matplotlib.
set_latex()	Enables LaTeX for matplotlib based on the *with_latex* option and *dvipng* availability.
set_style([style])	Set matplotlib style.
tdsplot(filename, y[, x, to_csv, find, ...])	TDS plot main function based on the new TDSData class.

eig_plot

andes.plot.**eig_plot**(*name*, *args*)

parse_y

andes.plot.**parse_y**(*y*, *upper*, *lower=0*)

Parse command-line input for Y indices and return a list of indices

Parameters

y
[Union[List, Set, Tuple]]

Input for Y indices. Could be single item (with or without colon), or multiple items

upper
[int] Upper limit. In the return list y, y[i] <= uppwer.

lower
[int] Lower limit. In the return list y, y[i] >= lower.

Returns

set_font

andes.plot.**set_font**(*family='serif'*, *size=12*, *style='normal'*, *weight='normal'*)

Sets the font for matplotlib.

Parameters

family
[str] Font family.

size
[int] Font size.

style
[str] Font style.

weight
[str] Font weight.

set_latex

andes.plot.**set_latex**()

Enables LaTeX for matplotlib based on the *with_latex* option and *dvipng* availability.

Returns

bool
True for LaTeX on, False for off

set_style

andes.plot.**set_style**(*style='default'*)

Set matplotlib style.

Parameters

style
[str] *default*, *ieee* (require *scienceplots*), or other available styles (see *matplotlib.pyplot.style.available*).

tdsplot

andes.plot.**tdsplot**(*filename*, *y*, *x=(0,)*, *to_csv=False*, *find=None*, *xargs=None*, *exclude=None*, ***kwargs*)

TDS plot main function based on the new TDSData class.

Parameters

filename
[str] Path to the ANDES TDS output data file. Works without extension.

x
[list or int, optional] The index for the x-axis variable. x=0 by default for time

y
[list or int] The indices for the y-axis variable

to_csv
[bool] True if need to export to a csv file

find
[str, optional] if not none, specify the variable name to find

xargs
[str, optional] similar to find, but return the result indices with file name, x idx name for xargs

exclude
[str, optional] variable name pattern to exclude

Returns

TDSData object

Classes

TDSData([full_name, mode, dae, path])	A data container for loading and plotting results from Andes time-domain simulation.

andes.plot.TDSData

class andes.plot.**TDSData**(*full_name=None*, *mode='file'*, *dae=None*, *path=None*)

A data container for loading and plotting results from Andes time-domain simulation.

__init__(*full_name=None*, *mode='file'*, *dae=None*, *path=None*)

Methods

bqplot_data(xdata, ydata, *[, xheader, ...])	Plot with `bqplot`.
data_to_df()	Convert to pandas.DataFrame
export_csv([path, idx, header, formatted, ...])	Export to a csv file.
find(query[, exclude, formatted, idx_only])	Return variable names and indices matching *query*.
get_call([backend])	Get the internal *plot_data* function for the specified backend.
get_header(idx[, formatted])	Return a list of the variable names at the given indices.
get_values(idx)	Return the variable values at the given indices.
guess_event_time()	Guess the event starting time from the input data by checking when the values start to change
load_dae()	Load from DAE time series.
load_lst()	Load the lst file into internal data structures *_idx*, *_fname*, *_uname*, and counts the number of variables to *nvars*.
load_npy_or_csv([delimiter])	Load the npy, zpy or (the legacy) csv file into the internal data structure *self._xy*.
panoview(mdl, vars, *[, ncols, idx, a, figsize])	Panoramic view of variables of a given model instance.
plot(yidx[, xidx, a, ytimes, ycalc, left, ...])	Entry function for plotting.
plot_data(xdata, ydata, *[, xheader, ...])	Plot lines for the supplied data and options.
plotn(nrows, ncols, yidxes[, xidxes, dpi, ...])	Plot multiple subfigures in one figure.

TDSData.bqplot_data

TDSData.**bqplot_data**(*xdata*, *ydata*, *, *xheader=None*, *yheader=None*, *xlabel=None*, *ylabel=None*, *left=None*, *right=None*, *ymin=None*, *ymax=None*, *legend=True*, *grid=False*, *fig=None*, *dpi=None*, *line_width=1.0*, *greyscale=False*, *savefig=None*, *save_format=None*, *title=None*, ***kwargs*)

Plot with `bqplot`. Experimental and incomplete.

TDSData.data_to_df

TDSData.**data_to_df**()

Convert to pandas.DataFrame

TDSData.export_csv

TDSData.**export_csv**(*path=None*, *idx=None*, *header=None*, *formatted=False*, *sort_idx=True*, *fmt='%.18e'*)

Export to a csv file.

Parameters

path
[str] path of the csv file to save

idx
[None or array-like, optional] the indices of the variables to export. Export all by default

header
[None or array-like, optional] customized header if not *None*. Use the names from the lst file by default

formatted
[bool, optional] Use LaTeX-formatted header. Does not apply when using customized header

sort_idx
[bool, optional] Sort by idx or not, # TODO: implement sort

fmt
[str] cell formatter

Returns

str
The path of the exported csv file

TDSData.find

TDSData.**find**(*query*, *exclude=None*, *formatted=False*, *idx_only=False*)

Return variable names and indices matching *query*.

Parameters

query
[str] The string for querying variables. Multiple conditions can be separated by comma without space.

exclude
[str, optional] A string pattern to be excluded

formatted
[bool, optional] True to return formatted names, False otherwise

idx_only
[bool, optional] True if only return indices

Returns

(list, list)
(List of found indices, list of found names)

TDSData.get_call

TDSData.**get_call**(*backend=None*)

Get the internal *plot_data* function for the specified backend.

TDSData.get_header

TDSData.**get_header**(*idx*, *formatted=False*)

Return a list of the variable names at the given indices.

Parameters

idx
[list or int] The indices of the variables to retrieve

formatted
[bool] True to retrieve latex-formatted names, False for unformatted names

Returns

list
A list of variable names (headers)

TDSData.get_values

TDSData.**get_values**(*idx*)

Return the variable values at the given indices.

Parameters

idx
[list] The indicex of the variables to retrieve. *idx=0* is for Time. Variable indices start at 1.

Returns

np.ndarray
Variable data

TDSData.guess_event_time

TDSData.**guess_event_time**()

Guess the event starting time from the input data by checking when the values start to change

TDSData.load_dae

TDSData.**load_dae**()

Load from DAE time series.

TDSData.load_lst

TDSData.**load_lst**()

Load the lst file into internal data structures *_idx*, *_fname*, *_uname*, and counts the number of variables to *nvars*.

Returns

None

TDSData.load_npy_or_csv

TDSData.**load_npy_or_csv**(*delimiter=','*)

Load the npy, zpy or (the legacy) csv file into the internal data structure *self._xy*.

Parameters

delimiter
[str, optional] The delimiter for the case file. Default to comma.

Returns

None

TDSData.panoview

`TDSData.`**`panoview`**(*mdl*, *vars*, *, *ncols=3*, *idx=None*, *a=None*, *figsize=None*, ***kwargs*)

Panoramic view of variables of a given model instance.

Select variables through `vars`. Select devices through `idx` or `a`, which has a higher priority.

This function also takes other arguments recognizable by `self.plot`.

Parameters

mdl
[ModelBase] Model instance

var
[list of str] A list of variable names to display

ncol
[int] Number of columns

idx
[list] A list of device idx-es for showing

a
[list of int] A list of device 0-based positions for showing

figsize
[tuple] Figure size for plotting

Examples

To plot `omega` and `delta` of GENROUs `GENROU_1` and `GENROU_2`:

```
system.TDS.plt.plot(system.GENROU,
                    vars=['omega', 'delta'],
                    idx=['GENROU_1', 'GENROU_2'])
```

TDSData.plot

`TDSData.`**`plot`**(*yidx*, *xidx=(0,)*, *, *a=None*, *ytimes=None*, *ycalc=None*, *left=None*, *right=None*, *ymin=None*, *ymax=None*, *xlabel=None*, *ylabel=None*, *xheader=None*, *yheader=None*, *legend=None*, *grid=False*, *greyscale=False*, *latex=True*, *dpi=None*, *line_width=1.0*, *font_size=12*, *savefig=None*, *save_format=None*, *show=True*, *title=None*, *linestyles=None*, *use_bqplot=False*, *hline1=None*, *hline2=None*, *vline1=None*, *vline2=None*, *hline=None*, *vline=None*, *fig=None*, *ax=None*, *backend=None*, *set_xlim=True*, *set_ylim=True*, *autoscale=False*, *legend_bbox=None*, *legend_loc=None*, *legend_ncol=1*, *figsize=None*, *color=None*, ***kwargs*)

Entry function for plotting.

This function retrieves the x and y values based on the *xidx* and *yidx* inputs, applies scaling functions *ytimes* and *ycalc* sequentially, and delegates the plotting to the backend.

Parameters

yidx
[list or int] The indices for the y-axis variables

xidx
[tuple or int, optional] The index for the x-axis variable

a
[tuple or list, optional] The 0-indexed sub-indices into *yidx* to plot.

ytimes
[float, optional] A scaling factor to apply to all y values.

left
[float] The starting value of the x axis

right
[float] The ending value of the x axis

ymin
[float] The minimum value of the y axis

ymax
[float] The maximum value of the y axis

ylabel
[str] Text label for the y axis

yheader
[list] A list containing the variable names for the y-axis variable

title
[str] Title string to be shown at the top

fig
Existing figure object to draw the axis on.

ax
Existing axis object to draw the lines on.

Returns

(fig, ax)
Figure and axis handles for matplotlib backend.

fig
Figure object for bqplot backend.

Other Parameters

ycalc: callable, optional
A callable to apply to all y values after scaling with *ytimes*.

xlabel
[str] Text label for the x axis

xheader
[list] A list containing the variable names for the x-axis variable

legend
[bool] True to show legend and False otherwise

legend_ncol
[int] Number of columns in legend

legend_bbox
[tuple of two floats] legend box to anchor

grid
[bool] True to show grid and False otherwise

latex
[bool] True to enable latex and False to disable

greyscale
[bool] True to use greyscale, False otherwise

savefig
[bool or str] True to save to png figure file. str is treated as the output file name.

save_format
[str] File extension string (pdf, png or jpg) for the savefig format

dpi
[int] Dots per inch for screen print or save. *savefig* uses a minimum of 200 dpi

line_width
[float] Plot line width

font_size
[float] Text font size (labels and legends)

figsize
[tuple] Figure size passed when creating new figure

show
[bool] True to show the image

backend
[str or None] *bqplot* to use the bqplot backend in notebook. None for matplotlib.

hline1: float, optional
Dashed horizontal line 1

hline2: float, optional
Dashed horizontal line 2

vline1: float, optional
Dashed horizontal line 1

vline2: float, optional
Dashed vertical line 2

hline: float or Iterable
y-axis location of horizontal line(s)

vline: float or Iterable
x-axis location of vertical line(s)

TDSData.plot_data

TDSData.**plot_data**(*xdata*, *ydata*, *, *xheader=None*, *yheader=None*, *xlabel=None*, *ylabel=None*, *linestyles=None*, *left=None*, *right=None*, *ymin=None*, *ymax=None*, *legend=None*, *grid=False*, *fig=None*, *ax=None*, *latex=True*, *dpi=None*, *line_width=1.0*, *font_size=12*, *greyscale=False*, *savefig=None*, *save_format=None*, *show=True*, *title=None*, *hline1=None*, *hline2=None*, *vline1=None*, *hline=None*, *vline=None*, *vline2=None*, *set_xlim=True*, *set_ylim=True*, *autoscale=False*, *figsize=None*, *legend_bbox=None*, *legend_loc=None*, *legend_ncol=1*, *mask=True*, *color=None*, *style='default'*, ***kwargs*)

Plot lines for the supplied data and options.

This functions takes *xdata* and *ydata* values. If you provide variable indices instead of values, use *plot()*.

See the argument lists of *plot()* for more.

Parameters

xdata
[array-like] An array-like object containing the values for the x-axis variable

ydata
[array] An array containing the values of each variables for the y-axis variable. The row of *ydata* must match the row of *xdata*. Each column correspondings to a variable.

mask
[bool] If enabled (1), when specifying axis limits, only data in the limits will be used for plotting to optimize for autoscaling. It is done through an index mask.

Returns

(fig, ax)
The figure and axis handles

Examples

To plot the results of arithmetic calculation of variables, retrieve the values, do the calculation, and plot with *plot_data*.

```
>>> v = ss.dae.ts.y[:, ss.PVD1.v.a]
>>> Ipcmd = ss.dae.ts.y[:, ss.PVD1.Ipcmd_y.a]
>>> t = ss.dae.ts.t
```

```
>>> ss.TDS.plt.plot_data(t, v * Ipcmd,
>>>                      xlabel='Time [s]',
>>>                      ylabel='Ipcmd [pu]')
```

TDSData.plotn

`TDSData.`**`plotn`**(*nrows: int*, *ncols: int*, *yidxes*, *xidxes=None*, ***, *dpi=None*, *titles=None*, *a=None*, *figsize=None*, *xlabel=None*, *ylabel=None*, *sharex=None*, *sharey=None*, *show=True*, *xlabel_offs=(0.5, 0.01)*, *ylabel_offs=(0.05, 0.5)*, *hspace=0.2*, *wspace=0.2*, ***kwargs*)

Plot multiple subfigures in one figure.

Parameters `xidxes`, `a`, `xlabels` and `ylabels`, if provided, must have the same length as `yidxes`.

Parameters

nrows
[int] number of rows

ncols
[int] number of cols

yidx
A list of *BaseVar* or index lists.

6.4 I/O

andes.io	ANDES input parsers and output formatters.

6.4.1 andes.io

ANDES input parsers and output formatters.

Functions

dump(system, output_format[, full_path, ...])	Dump the System data into the requested output format.
get_output_ext(out_format)	Helper function to get the output extension for the given output format.
guess(system)	Guess the input format based on extension and content.
parse(system)	Parse input file with the given format in *system.files.input_format*.
read_file_like(infile)	Read a file-like object and return a list of splitted lines.

dump

andes.io.**dump**(*system*, *output_format*, *full_path=None*, *overwrite=False*, ***kwargs*)

Dump the System data into the requested output format.

Parameters

system
System object

output_format
[str] Output format name. 'xlsx' will be used if is not an instance of *str*.

Returns

bool
True if successful; False otherwise.

get_output_ext

andes.io.**get_output_ext**(*out_format*)

Helper function to get the output extension for the given output format.

Parameters

out_format
[str] Output format name.

Returns

str
[file extension without dot or empty if not supported]

guess

`andes.io.guess`(*system*)

Guess the input format based on extension and content.

Also stores the format name to *system.files.input_format*.

Parameters

system
[System] System instance with the file name set to *system.files*

Returns

str
format name

parse

`andes.io.parse`(*system*)

Parse input file with the given format in *system.files.input_format*.

Returns

bool
True if successful; False otherwise.

read_file_like

`andes.io.read_file_like`(*infile: str | IOBase*)

Read a file-like object and return a list of splitted lines.

Modules

andes.io.json	JSON reader and writer for ANDES.
andes.io.matpower	Simple MATPOWER format parser
andes.io.psse	PSS/E file parser.
andes.io.streaming	Simulation data streaming interface for CURENT DiME2.
andes.io.txt	Output TXT file formatter.
andes.io.xlsx	Excel reader and writer for ANDES power system parameters

andes.io.json

JSON reader and writer for ANDES.

Functions

read(system, infile)	Read JSON file with ANDES model data into an empty system.
testlines(infile)	
write(system, outfile[, skip_empty, overwrite])	Write loaded ANDES system data into a JSON file.

read

andes.io.json.**read**(*system*, *infile: str | IOBase*)

Read JSON file with ANDES model data into an empty system.

Parameters

system
[System] Empty System instance

infile
[str or io.BaseIO] str: path to the input file; or io.BaseIO: a stream to read from

Returns

System
System instance after succeeded

testlines

andes.io.json.**testlines**(*infile*)

write

andes.io.json.**write**(*system*, *outfile*, *skip_empty=True*, *overwrite=None*, ***kwargs*)

Write loaded ANDES system data into a JSON file.

Parameters

system
[System] A loaded system with parameters

outfile
[str] Path to the output file

skip_empty
[bool] Skip output of empty models (n = 0)

overwrite
[bool] None to prompt for overwrite selection; True to overwrite; False to not overwrite

Returns

bool
True if file written; False otherwise

andes.io.matpower

Simple MATPOWER format parser

Functions

m2mpc(infile)	Parse MATPOWER file and return a dictionary with the data.
mpc2system(mpc, system)	Load an mpc dict into an empty ANDES system.
read(system, file)	Read a MATPOWER data file into mpc, and build andes device elements.
system2mpc(system)	Convert data from an ANDES system to an mpc dict.
testlines(infile)	Test if this file is in the MATPOWER format.

m2mpc

andes.io.matpower.**m2mpc**(*infile: str*) → dict

Parse MATPOWER file and return a dictionary with the data.

Supported fields include

- baseMVA
- bus
- bus_names
- gen
- branch
- gencost (parsed but not used)
- areas (parsed but not used)

Parameters

infile
[str] Path to the MATPOWER file.

Returns

dict
mpc struct names : numpy arrays

mpc2system

andes.io.matpower.**mpc2system**(*mpc: dict*, *system*) → bool

Load an mpc dict into an empty ANDES system.

Parameters

system
[andes.system.System] Empty system to load the data into.

mpc
[dict] mpc struct names : numpy arrays

Returns

bool
True if successful, False otherwise.

read

andes.io.matpower.**read**(*system*, *file*)

Read a MATPOWER data file into mpc, and build andes device elements.

system2mpc

andes.io.matpower.**system2mpc**(*system*) → dict

Convert data from an ANDES system to an mpc dict.

In the `gen` section, slack generators preceeds PV generators.

testlines

andes.io.matpower.**testlines**(*infile*)

Test if this file is in the MATPOWER format.

NOT YET IMPLEMENTED.

andes.io.psse

PSS/E file parser.

Include a RAW parser and a DYR parser.

Functions

get_block_lines(b, mdata)	Return the number of lines based on the block index in the RAW file.
read(system, file)	Read PSS/E RAW file v32/v33 formats.
read_add(system, file)	Read an addition PSS/E dyr file.
sort_psse_models(dyr_yaml, system)	Sort supported models so that model names are ordered by dependency.
testlines(infile)	Check the raw file for frequency base.

get_block_lines

andes.io.psse.**get_block_lines**(*b*, *mdata*)

Return the number of lines based on the block index in the RAW file.

read

andes.io.psse.**read**(*system*, *file*)

Read PSS/E RAW file v32/v33 formats.

read_add

andes.io.psse.**read_add**(*system*, *file*)

Read an addition PSS/E dyr file.

Parameters

system
[System] System instance to which data will be loaded

file
[str] Path to the additional *dyr* file

Returns

bool
data parsing status

sort_psse_models

andes.io.psse.**sort_psse_models**(*dyr_yaml*, *system*)

Sort supported models so that model names are ordered by dependency.

Dependency is determined by checking the `find` key in `psse-dyr.yaml` for each model.

Returns

list
The sequence of model names for loading parameters.

testlines

andes.io.psse.**testlines**(*infile*)

Check the raw file for frequency base.

andes.io.streaming

Simulation data streaming interface for CURENT DiME2.

Classes

Streaming(system)	ANDES data streaming class to interface with CURENT LTB.

andes.io.streaming.Streaming

class andes.io.streaming.**Streaming**(*system*)

ANDES data streaming class to interface with CURENT LTB.

__init__(*system*)

Methods

build_init()	Build *Varheader*, *Idxvgs* and *SysParam* after power flow routine
connect()	Connect to DiME 2 server.
finalize()	Send DONE signal when simulation completes
handle_alter(Alter)	Handle parameter altering
handle_event(Event)	Handle Fault, Breaker, Syn and Load Events
record_module_init(name, init_var)	Record the variable requests from modules
send_init([recepient])	Broadcast *Varheader*, *Idxvgs* and *SysParam* to all DiME clients after power flow routine
sync_and_handle()	Sync until the queue is empty.
transpose_matlab_row(a)	
vars_to_modules()	Stream the results from the last step to modules
vars_to_pmu()	Broadcast all PMU measurements and BusFreq measurements in the variable *pmudata*

Streaming.build_init

Streaming.**build_init**()

Build *Varheader*, *Idxvgs* and *SysParam* after power flow routine

Streaming.connect

Streaming.**connect**()

Connect to DiME 2 server.

If dime_address is specified from the command-line, streaming will be automatically enabled. Otherwise, settings from the Config file will be used.

Streaming.finalize

Streaming.**finalize**()

Send DONE signal when simulation completes

Returns

None

Streaming.handle_alter

Streaming.**handle_alter**(*Alter*)

Handle parameter altering

Streaming.handle_event

Streaming.**handle_event**(*Event*)

Handle Fault, Breaker, Syn and Load Events

Streaming.record_module_init

Streaming.**record_module_init**(*name*, *init_var*)

Record the variable requests from modules

Streaming.send_init

Streaming.**send_init**(*recepient='all'*)

Broadcast *Varheader*, *Idxvgs* and *SysParam* to all DiME clients after power flow routine

Streaming.sync_and_handle

Streaming.**sync_and_handle**()

Sync until the queue is empty. Handle sync'ed commands.

Streaming.transpose_matlab_row

static Streaming.**transpose_matlab_row**(*a*)

Streaming.vars_to_modules

Streaming.**vars_to_modules**()

Stream the results from the last step to modules

Returns

None

Streaming.vars_to_pmu

Streaming.**vars_to_pmu**()

Broadcast all PMU measurements and BusFreq measurements in the variable *pmudata*

andes.io.txt

Output TXT file formatter.

Functions

dump_data(text, header, rowname, data, file)	

dump_data

andes.io.txt.**dump_data**(*text*, *header*, *rowname*, *data*, *file*, *width=18*, *precision=5*)

andes.io.xlsx

Excel reader and writer for ANDES power system parameters

This module utilizes openpyxl, xlsxwriter and pandas.Frame.

While I like the simplicity of the dome format, spreadsheets are easier to view and edit.

Functions

read(system, infile)	Read an xlsx file with ANDES model data into an empty system
testlines(infile)	
write(system, outfile[, skip_empty, ...])	Write loaded ANDES system data into an xlsx file

read

andes.io.xlsx.**read**(*system*, *infile*)

Read an xlsx file with ANDES model data into an empty system

Parameters

system
[System] Empty System instance

infile
[str or file-like] Path to the input file, or a file-like object

Returns

System
System instance after succeeded

testlines

andes.io.xlsx.**testlines**(*infile*)

write

andes.io.xlsx.**write**(*system*, *outfile*, *skip_empty=True*, *overwrite=None*, *add_book=None*, ***kwargs*)

Write loaded ANDES system data into an xlsx file

Parameters

system
[System] A loaded system with parameters

outfile
[str] Path to the output file

skip_empty
[bool] Skip output of empty models (n = 0)

overwrite
[bool, optional] None to prompt for overwrite selection; True to overwrite; False to not overwrite

add_book
[str, optional] An optional model to be added to the output spreadsheet

Returns

bool
True if file written; False otherwise

6.5 Interoperability

andes.interop	Interopability package between Andes and other software.

6.5.1 andes.interop

Interopability package between Andes and other software.

To install dependencies, do:

```
pip install andes[interop]
```

To install dependencies for *development*, in the ANDES source code folder, do:

```
pip install -e .[interop]
```

Modules

andes.interop.gridcal	Basic GridCal (4.6.1) interface, based on the pandapower interface written by Jinning Wang
andes.interop.matpower	Interoperability with MATPOWER through `matpower-pip`.
andes.interop.pandapower	Simple pandapower (2.7.0) interface
andes.interop.pypowsybl	Interoperability with pypowsybl.

andes.interop.gridcal

Basic GridCal (4.6.1) interface, based on the pandapower interface written by Jinning Wang

Author: Josep Fanals (@JosepFanals)

Functions

require_gridcal(f)	Decorator for functions that require GridCal.
to_gridcal(ssa[, verify, tol])	Convert an ANDES system to a GridCal grid.

require_gridcal

andes.interop.gridcal.**require_gridcal**(*f*)

Decorator for functions that require GridCal.

to_gridcal

andes.interop.gridcal.**to_gridcal**(*ssa*, *verify=True*, *tol=1e-06*)

Convert an ANDES system to a GridCal grid.

Parameters

ssa
[andes.system.System] The ANDES system to be converted

verify
[bool] If True, the converted network will be verified with the source ANDES system using AC power flow.

tol
[float] The tolerance of error when comparing power flow solutions.

Returns

GridCal.Engine.Core.multi_circuit.MultiCircuit
A GridCal net with the same bus, branch, gen, and load data as the ANDES system

Notes

Handling of the following parameters:

- By default, all generators in `ssp` are controllable unless user-defined controllability is given
- The online status of generators are determined by the online status of `StaticGen` that connected to the `SynGen` or `DG`
- `ssp.gen.name` is from `ssa.StaticGen.idx`, which should be unique

andes.interop.matpower

Interoperability with MATPOWER through `matpower-pip`.

Please install the Python package `matpower` and configure MATLAB or Octave, following the instructions at matpower-pip.

To create a MATLAB/Octave instance, do:

```
from andes.interop.matpower import start_instance

m = start_instance()
```

Functions

from_matpower(m, varname[, system])	Retrieve a MATPOWER mpc case from a MATLAB/Octave instance.
require_matpower(f)	Decorator for functions that require matpower.
to_matpower(m, varname, system)	Send an ANDES case to a running MATLAB instance.

from_matpower

andes.interop.matpower.**from_matpower**(*m*, *varname*, *system=None*)

Retrieve a MATPOWER mpc case from a MATLAB/Octave instance.

Parameters

m
[MATLAB/Octave instance] Instance from which to retrieve the MATPOWER case.

varname
[str] Name of the variable in the MATPOWER MPC format to retrieve.

Returns

System
System from the mpc case. The system will not have been set up.

Examples

To retrieve a case from MATPOWER from instance `m`, do the following:

```
from andes.interop.matpower import start_instance, to_matpower, from_
↪matpower

system = from_matpower(m, 'mpc')
```

One can create an Excel file with dynamic data only and use the `xlsx` parser to load data into `system`:

```
from andes.io import xlsx

xlsx.read(system, andes.get_case('ieee14/ieee14_dyn_only.xlsx'))
```

The `ieee14_dyn_only.xlsx` is an example spreadsheet that only contains dynamic components. One will need to create the `idx` correctly for dynamic components to match these from the MATPOWER case. If not sure about the indices, one can save the ANDES system to an Excel file, using:

```
xlsx.write(system, 'system_static.xlsx')
```

require_matpower

andes.interop.matpower.**require_matpower**(*f*)

Decorator for functions that require matpower.

to_matpower

andes.interop.matpower.**to_matpower**(*m*, *varname*, *system*)

Send an ANDES case to a running MATLAB instance.

Parameters

m
[MATLAB/Octave instance] Instance to which to send the MATPOWER case.

varname
[str] Name of the variable to store the mpc case in MATLAB/Octave.

system
[*System*] System whose power flow data to send to MATPOWER.

Examples

The code below will create an IEEE 14-bus example system in ANDES, convert it to MATPOWER's case, and send to the MATLAB/Octave instance.

```
import andes

from andes.interop.matpower import (start_instance,
    to_matpower, from_matpower)

m = start_instance()

ss = andes.system.example()
mpc = to_matpower(m, 'mpc', ss)

m.eval("runpf(mpc)")

mpc_out = m.pull("mpc")  # retrieve the mpc case from MATLAB/Octave
```

andes.interop.pandapower

Simple pandapower (2.7.0) interface

Functions

add_gencost(ssp, gen_cost)	Add cost function to converted pandapower net *ssp*.
build_group_table(ssa, group, columns[, ...])	Build the table for devices in a group in an ANDES System.
make_GSF(ppn[, verify, using_sparse_solver])	Build the Generation Shift Factor matrix of a pandapower net.
make_link_table(ssa)	Build the link table for generators and generator controllers in an ANDES System, including `SynGen` and `DG` for now.
require_pandapower(f)	Decorator for functions that require pandapower.
runopp_map(ssp, link_table, **kwargs)	Run OPF in pandapower using `pp.runopp()` and map results back to ANDES based on the link table.
to_pandapower(ssa[, ctrl, verify, tol])	Convert an ANDES system to a pandapower network for power flow studies.

add_gencost

`andes.interop.pandapower.`**`add_gencost`**(*ssp*, *gen_cost*)

Add cost function to converted pandapower net *ssp*.

The cost data follows the same format of pypower and matpower.

Now only poly_cost is supported.

Parameters

ssp
The pandapower net

gen_cost
[array] generator cost data

build_group_table

`andes.interop.pandapower.`**`build_group_table`**(*ssa*, *group*, *columns*, *mdl_name=[]*)

Build the table for devices in a group in an ANDES System.

Parameters

ssa
[andes.system.System] The ANDES system to build the table

group
[string] The ANDES group

columns
[list of string] The common columns of a group that to be included in the table.

mdl_name
[list of string] The list of models that to be included in the table. Default as all models.

Returns

DataFrame
The output Dataframe contains the columns from the device

make_GSF

`andes.interop.pandapower.`**`make_GSF`**(*ppn*, *verify=True*, *using_sparse_solver=False*)

Build the Generation Shift Factor matrix of a pandapower net.

Parameters

ppn
[pandapower.network.Network] Pandapower network

verify
[bool] True to verify the GSF with that from DC power flow

using_sparse_solver
[bool] True to use a sparse solver for pandapower maktPTDF

Returns

np.ndarray
The GSF array

make_link_table

`andes.interop.pandapower.`**`make_link_table`**(*ssa*)

Build the link table for generators and generator controllers in an ANDES System, including `SynGen` and `DG` for now.

Parameters

ssa
[andes.system.System] The ANDES system to link

Returns

DataFrame
Each column in the output Dataframe contains the `idx` of linked `StaticGen`,

Bus, DG, RenGen, RenExciter, SynGen, Exciter, and TurbineGov, gammap, gammaq.

require_pandapower

andes.interop.pandapower.**require_pandapower**(*f*)

Decorator for functions that require pandapower.

runopp_map

andes.interop.pandapower.**runopp_map**(*ssp*, *link_table*, ***kwargs*)

Run OPF in pandapower using pp.runopp() and map results back to ANDES based on the link table.

Parameters

ssp
[pandapower network] The pandapower network

link_table
[DataFrame] The link table of ANDES system

Returns

DataFrame
The DataFrame contains the OPF results with columns p_mw, q_mvar, vm_pu in p.u., and the corresponding idx of StaticGen, Exciter, TurbineGov in ANDES.

Notes

- The pandapower net and the ANDES system must have same base MVA.
- Multiple DG connected to the same StaticGen will be converted to one generator. The power is dispatched to each DG by the power ratio gammap

to_pandapower

andes.interop.pandapower.**to_pandapower**(*ssa*, *ctrl=[]*, *verify=True*, *tol=1e-06*)

Convert an ANDES system to a pandapower network for power flow studies.

Parameters

ssa
[andes.system.System] The ANDES system to be converted

ctrl
[list] The controlability of generators. The length should be the same with the number of `StaticGen`. If not given, controllability of generators will be assigned by default. Example input: [1, 0, 1, ...]; `PV` first, then `Slack`.

verify
[bool] If True, the converted network will be verified with the source ANDES system using AC power flow.

tol
[float] The tolerance of error.

Returns

pandapower.auxiliary.pandapowerNet
A pandapower net with the same bus, branch, gen, and load data as the ANDES system

Notes

Handling of the following parameters:

- This interface tracks static power flow model in ANDES: *Bus*, *Line*, *PQ*, *Shunt*, *PV*, and *Slack*. However, it does not track the dynamic models in ANDES, including but not limited to *TurbineGov*, *SynGen*, and *Exciter*.
- The interface converts the `Slack` in ANDES to `gen` in pandapower rather than `ext_gen`.
- MUST NOT verify power flow after initializing TDS in ANDES. ANDES does not allow running `PFlow` for systems with initialized TDS as it will break variable addressing.
- If you want to track dynamic model outputs in ANDES and feedback into pandapower, you might need to manually transfer the results from ANDES to pandapower.
- Generator cost is not included in the conversion. Use `add_gencost()` to add cost data.
- By default, all generators in `ssp` are controllable unless user-defined controllability is given
- The online status of generators are determined by the online status of `StaticGen` that connected to the `SynGen` or `DG`
- `ssp.gen.name` is from `ssa.StaticGen.idx`, which should be unique

andes.interop.pypowsybl

Interoperability with pypowsybl.

Functions

require_pypowsybl(f)	Decorator for functions that require pypowsybl.
to_pypowsybl(ss)	Convert an ANDES system to a pypowsybl network.

require_pypowsybl

andes.interop.pypowsybl.**require_pypowsybl**(*f*)

Decorator for functions that require pypowsybl.

to_pypowsybl

andes.interop.pypowsybl.**to_pypowsybl**(*ss*)

Convert an ANDES system to a pypowsybl network.

Parameters

ss
[andes.system.System] The ANDES system to be converted.

Returns

pypowsybl.network.Network

Warning:

- Power flow results are not verified.

Notes

- Only the BUS_BREAKER topology is supported.
- Each bus has a voltage level named "VL" followed by the bus idx.
- Buses connected by transformers are in the same substation.

Examples

One can utilize pypowsybl to draw network topology. For example,

```
ss = andes.system.example()
n = to_pypowsybl(ss)
results = pp.loadflow.run_ac(n)
```

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```
n.get_network_area_diagram()  # show diagram for system
n.get_single_line_diagram("VL6")  # show single-line diagram for bus 6
```

6.6 Others

andes.cli	ANDES command-line interface and argument parsers.
andes.main	Main entry point for the ANDES CLI and scripting interfaces.
andes.utils.paths	Utility functions for loading andes stock test cases
andes.utils.snapshot	Utility functions for saving and loading snapshots.
andes.utils.widgets	Support for Jupyter widgets.

6.6.1 andes.cli

ANDES command-line interface and argument parsers.

Functions

create_parser()	Create a parser for the command-line interface.
main()	Entry point of the ANDES command-line interface.
preamble()	Log the ANDES command-line preamble at the *logging.INFO* level

create_parser

andes.cli.**create_parser**()

Create a parser for the command-line interface.

Returns

argparse.ArgumentParser
Parser with all ANDES options

main

andes.cli.**main**()

Entry point of the ANDES command-line interface.

preamble

andes.cli.**preamble**()

Log the ANDES command-line preamble at the *logging.INFO* level

6.6.2 andes.main

Main entry point for the ANDES CLI and scripting interfaces.

Functions

config_logger([stream_level, stream, file, ...])	Configure an ANDES logger with a *FileHandler* and a *StreamHandler*.
demo(**kwargs)	TODO: show some demonstrations from CLI.
doc([attribute, list_supported, config])	Quick documentation from command-line.
edit_conf([edit_config])	Edit the Andes config file which occurs first in the search path.
find_log_path(lg)	Find the file paths of the FileHandlers.
load(case[, codegen, setup, use_input_path])	Load a case and set up a system without running routine.
misc([edit_config, save_config, ...])	Miscellaneous commands.
plot(*args, **kwargs)	Wrapper for the plot tool.
prepare([quick, incremental, models, ...])	Run code generation.
print_license()	Print out Andes license to stdout.
remove_output([recursive])	Remove the outputs generated by Andes, including power flow reports `_out.txt`, time-domain list `_out.lst` and data `_out.dat`, eigenvalue analysis report `_eig.txt`.
run(filename[, input_path, verbose, ...])	Entry point to run ANDES routines.
run_case(case, *[, routine, profile, ...])	Run single simulation case for the given full path.
save_conf([config_path, overwrite])	Save the Andes config to a file at the path specified by `save_config`.
selftest([quick, extra])	Run unit tests.
set_logger_level(lg, type_to_set, level)	Set logging level for the given type of handler.
versioninfo()	Print version info for ANDES and dependencies.

config_logger

andes.main.**config_logger**(*stream_level=20*, ***, *stream=True*, *file=True*, *log_file='andes.log'*, *log_path=None*, *file_level=10*)

Configure an ANDES logger with a *FileHandler* and a *StreamHandler*.

This function is called at the beginning of `andes.main.main()`. Updating `stream_level` and `file_level` is now supported.

Parameters

stream
[bool, optional] Create a *StreamHandler* for *stdout* if `True`. If `False`, the handler will not be created.

file
[bool, optionsl] True if logging to `log_file`.

log_file
[str, optional] Logg file name for *FileHandler*, `'andes.log'` by default. If `None`, the *FileHandler* will not be created.

log_path
[str, optional] Path to store the log file. By default, the path is generated by get_log_dir() in utils.misc.

stream_level
[{10, 20, 30, 40, 50}, optional] *StreamHandler* verbosity level.

file_level
[{10, 20, 30, 40, 50}, optional] *FileHandler* verbosity level.

Returns

None

demo

andes.main.**demo**(***kwargs*)

TODO: show some demonstrations from CLI.

doc

andes.main.**doc**(*attribute=None*, *list_supported=False*, *config=False*, ***kwargs*)

Quick documentation from command-line.

edit_conf

andes.main.**edit_conf**(*edit_config: str | bool | None = ''*)

Edit the Andes config file which occurs first in the search path.

Parameters

edit_config
[bool] If `True`, try to open up an editor and edit the config file. Otherwise returns.

Returns

bool
`True` is a config file is found and an editor is opened. `False` if `edit_config` is False.

find_log_path

andes.main.**find_log_path**(*lg*)

Find the file paths of the FileHandlers.

load

andes.main.**load**(*case*, *codegen=False*, *setup=True*, *use_input_path=True*, ***kwargs*)

Load a case and set up a system without running routine. Return a system.

Takes other kwargs recognizable by `System`, such as `addfile`, `input_path`, and `no_putput`.

Parameters

case: str
Path to the test case

codegen
[bool, optional] Call full *System.prepare* on the returned system. Set to True if one need to inspect pretty-print equations and run simulations.

setup
[bool, optional] Call *System.setup* after loading

use_input_path
[bool, optional] True to use the `input_path` argument to behave the same as `andes.main.run`.

Warning: If one need to add devices in addition to these from the case file, do `setup=False` and call `System.add()` to add devices. When done, manually invoke `setup()` to set up the system.

misc

andes.main.**misc**(*edit_config=''*, *save_config=''*, *show_license=False*, *clean=True*, *recursive=False*, *overwrite=None*, *version=False*, ***kwargs*)

Miscellaneous commands.

plot

andes.main.**plot**(**args*, ***kwargs*)

Wrapper for the plot tool.

prepare

andes.main.**prepare**(*quick=False*, *incremental=False*, *models=None*, *precompile=False*, *nomp=False*, ***kwargs*)

Run code generation.

Parameters

full
[bool] True to run full prep with formatted equations. Useful in interactive mode and during document generation.

ncpu
[int] Number of cores to be used for parallel processing.

cli
[bool] True to indicate running from CLI. It will set *quick* to True if not *full*.

precompile
[bool] True to compile model function calls after code generation.

Returns

System object if *cli* is *False*; exit_code 0 otherwise.

Warning: The default behavior has changed since v1.0.8: when *cli* is *True* and *full* is not *True*, quick code generation will be used.

print_license

andes.main.**print_license**()

Print out Andes license to stdout.

remove_output

andes.main.**remove_output**(*recursive=False*)

Remove the outputs generated by Andes, including power flow reports `_out.txt`, time-domain list `_out.lst` and data `_out.dat`, eigenvalue analysis report `_eig.txt`.

Parameters

recursive
[bool] Recursively clean all subfolders

Returns

bool
`True` is the function body executes with success. `False` otherwise.

run

andes.main.**run**(*filename*, *input_path=''*, *verbose=20*, *mp_verbose=30*, *ncpu=1*, *pool=False*, *cli=False*, *codegen=False*, *shell=False*, ***kwargs*)

Entry point to run ANDES routines.

Parameters

filename
[str] file name (or pattern)

input_path
[str, optional] input search path

verbose
[int, 10 (DEBUG), 20 (INFO), 30 (WARNING), 40 (ERROR), 50 (CRITICAL)] Verbosity level. If `config_logger` is called prior to `run`, this option will be ignored.

mp_verbose
[int] Verbosity level for multiprocessing tasks

ncpu
[int, optional] Number of cpu cores to use in parallel

pool: bool, optional
Use Pool for multiprocessing to return a list of created Systems.

kwargs
Other supported keyword arguments

cli
[bool, optional] If is running from command-line. If True, returns exit code instead of System

codegen
[bool, optional] Run full code generation for System before loading case. Only used for single test case.

shell
[bool, optional] If True, enter IPython shell after routine.

Returns

System or exit_code
An instance of system (if *cli* == *False*) or an exit code otherwise..

run_case

`andes.main.run_case`(*case*, *, *routine='pflow'*, *profile=False*, *convert=''*, *convert_all=''*, *add_book=None*, *codegen=False*, *autogen_stale=True*, *remove_pycapsule=False*, ***kwargs*)

Run single simulation case for the given full path. Use `run` instead of `run_case` whenever possible.

Argument `input_path` will not be prepended to `case`.

Arguments recognizable by `load` can be passed to `run_case`.

Parameters

case
[str] Full path to the test case

routine
[str, ('pflow', 'tds', 'eig')] Computation routine to run

profile
[bool, optional] True to enable profiler

convert
[str, optional] Format name for case file conversion.

convert_all
[str, optional] Format name for case file conversion, output sheets for all available devices.

add_book
[str, optional] Name of the device to be added to an excel case as a new sheet.

codegen
[bool, optional] True to run codegen

autogen_stale
[bool, optional] True to automatically generate code for stale models

remove_pycapsule
[bool, optional] True to remove pycapsule from C libraries. Useful when dill serialization is needed.

save_conf

`andes.main.`**`save_conf`**(*config_path=None*, *overwrite=None*, ***kwargs*)

Save the Andes config to a file at the path specified by `save_config`. The save action will not run if `save_config = ''`.

Parameters

config_path
[None or str, optional, (" by default)] Path to the file to save the config file. If the path is an emtpy string, the save action will not run. Save to *~/.andes/andes.conf* if `None`.

Returns

bool
`True` is the save action is run. `False` otherwise.

selftest

`andes.main.`**`selftest`**(*quick=False*, *extra=False*, ***kwargs*)

Run unit tests.

set_logger_level

`andes.main.`**`set_logger_level`**(*lg*, *type_to_set*, *level*)

Set logging level for the given type of handler.

versioninfo

`andes.main.`**`versioninfo`**()

Print version info for ANDES and dependencies.

6.6.3 andes.utils.paths

Utility functions for loading andes stock test cases

Functions

andes_root()	Return the path to the folder of the ANDES package.
cases_root()	Return the root path to the stock cases
confirm_overwrite(outfile[, overwrite])	Confirm overwriting a file.
get_case(rpath[, check])	Return the path to a stock case for a given path relative to `andes/cases`.
get_config_path([file_name])	Return the path of the config file to be loaded.
get_dot_andes_path()	Return the path to `$HOME/.andes`
get_log_dir()	Get the directory for log file.
get_pycode_path([pycode_path, mkdir])	Get the path to the `pycode` folder.
list_cases([rpath, no_print])	List stock cases under a given folder relative to `andes/cases`
tests_root()	Return the root path to the stock cases

andes_root

andes.utils.paths.**andes_root**()

Return the path to the folder of the ANDES package.

cases_root

andes.utils.paths.**cases_root**()

Return the root path to the stock cases

confirm_overwrite

andes.utils.paths.**confirm_overwrite**(*outfile*, *overwrite=None*)

Confirm overwriting a file.

get_case

andes.utils.paths.**get_case**(*rpath*, *check=True*)

Return the path to a stock case for a given path relative to `andes/cases`.

To list all cases, use `andes.list_cases()`.

Parameters

check
[bool] True to check if file exists

Examples

To get the path to the case *kundur_full.xlsx* under folder *kundur*, do

```
andes.get_case('kundur/kundur_full.xlsx')
```

get_config_path

andes.utils.paths.**get_config_path**(*file_name='andes.rc'*)

Return the path of the config file to be loaded.

Search Priority: 1. current directory; 2. home directory.

Parameters

file_name
[str, optional] Config file name with the default as `andes.rc`.

Returns

Config path in string if found; None otherwise.

get_dot_andes_path

andes.utils.paths.**get_dot_andes_path**()

Return the path to `$HOME/.andes`

get_log_dir

andes.utils.paths.**get_log_dir**()

Get the directory for log file.

The default is `<tempdir>/andes`, where `<tempdir>` is provided by `tempfile.gettempdir()`.

Returns

str
The path to the temporary logging directory

get_pycode_path

andes.utils.paths.**get_pycode_path**(*pycode_path=None*, *mkdir=False*)
Get the path to the `pycode` folder.

list_cases

andes.utils.paths.**list_cases**(*rpath='.'*, *no_print=False*)
List stock cases under a given folder relative to `andes/cases`

tests_root

andes.utils.paths.**tests_root**()
Return the root path to the stock cases

Classes

DisplayablePath(path, parent_path, is_last)

andes.utils.paths.DisplayablePath

class andes.utils.paths.**DisplayablePath**(*path*, *parent_path*, *is_last*)

__init__(*path*, *parent_path*, *is_last*)

Methods

displayable()
make_tree(root[, parent, is_last, criteria])

DisplayablePath.displayable

DisplayablePath.**displayable**()

DisplayablePath.make_tree

classmethod DisplayablePath.**make_tree**(*root*, *parent=None*, *is_last=False*, *criteria=None*)

Attributes

display_filename_prefix_last
display_filename_prefix_middle
display_parent_prefix_last
display_parent_prefix_middle
displayname

DisplayablePath.display_filename_prefix_last

DisplayablePath.**display_filename_prefix_last = '└──'**

DisplayablePath.display_filename_prefix_middle

DisplayablePath.**display_filename_prefix_middle = '├──'**

DisplayablePath.display_parent_prefix_last

DisplayablePath.**display_parent_prefix_last = '│ '**

DisplayablePath.display_parent_prefix_middle

DisplayablePath.**display_parent_prefix_middle = ' '**

DisplayablePath.displayname

property DisplayablePath.**displayname**

6.6.4 andes.utils.snapshot

Utility functions for saving and loading snapshots.

Code Examples:

1. Setup base case and save the snapshot for once:

```
import andes

ss = andes.run(andes.get_case("ieee14/ieee14_linetrip.xlsx"))
ss.Toggle.u.v[:] = 0  # turn off line trips for the base case
xy = ss.TDS.init()

andes.utils.snapshot.save_ss("ieee14_snapshot.pkl", ss)
```

2. For every scenario afterwards, load the snapshot and apply disturbances:

```
import andes

ss = andes.utils.snapshot.load_ss("ieee14_snapshot.pkl")

# apply specific disturbances
ss.GENROU.omega.v[0] = 1.02

ss.TDS.run()
```

Functions

load_ss(path)	Load an ANDES snapshot and return a System object.
save_ss(path, system)	Save a system with all internal states as a snapshot.

load_ss

andes.utils.snapshot.**load_ss**(*path*)

Load an ANDES snapshot and return a System object.

Parameters

path
[str] Path to the snapshot file.

Returns

andes.system.System
The loaded system object

save_ss

andes.utils.snapshot.**save_ss**(*path*, *system*)

Save a system with all internal states as a snapshot.

Returns

Path to the saved snapshot.

> **Warning:** One limitation of the current implementation is version dependency. The snapshots only work with the specific ANDES version that created it.

6.6.5 andes.utils.widgets

Support for Jupyter widgets.

Please manually install the following dependencies:

- ipywidgets
- ipysheet

If you are using JupyterLab, do

```
jupyter labextension install @jupyter-widgets/jupyterlab-manager
```

Functions

edit_sheet(system, model)	Use ipysheet to edit parameters of one model.
edit_system(system)	Edit a loaded ANDES System with ipywidgets.
on_close(b)	Callback for the Close botton.
on_update(b)	Callback for the Update button.

edit_sheet

andes.utils.widgets.**edit_sheet**(*system*, *model: str*)

Use ipysheet to edit parameters of one model.

edit_system

andes.utils.widgets.**edit_system**(*system*)

Edit a loaded ANDES System with ipywidgets.

on_close

andes.utils.widgets.**on_close**(*b*)

Callback for the Close botton. Closes ipywidget objects.

on_update

andes.utils.widgets.**on_update**(*b*)

Callback for the Update button. Sets new parameters back to System.

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