
ANDES Manual

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ANDES is a Python-based free software package for power system simulation, control and analysis. It establishes a unique **hybrid symbolic-numeric framework** for modeling differential algebraic equations (DAEs) for numerical analysis. Main features of ANDES include

- a unique hybrid symbolic-numeric approach to modeling with automatic numerical code generation for simulation
- a rich library of transfer functions and discontinuous components (including limiters, deadbands, and saturation) available for prototyping models, which can be effortlessly instantiated as multiple devices for system analysis
- comes with the Newton method for power flow calculation, the implicit trapezoidal method for time-domain simulation, and full eigenvalue analysis
- strictly 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 immediately supported
- an always up-to-date equation documentation of implemented models

ANDES is currently under active development. Use the following resources, in addition to the tutorial, to get involved.

- Checkout the Notebook examples in the [examples folder](#)
- Try ANDES in Jupyter Notebook [with Binder](#)
- Read the online manual at <https://andes.readthedocs.io>
- Download the PDF manual at [download](#)
- Report issues in the [GitHub issues page](#)
- Learn version control with [the command-line git](#) or [GitHub Desktop](#)

This work was supported in part by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under NSF Award Number EEC-1041877 and the **CURRENT** Industry Partnership Program. **ANDES is made open source as part of the CURENT Large Scale Testbed project.**

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

ANDES can be installed in Python 3.6+.

1.1 Environment

1.1.1 Setting Up Miniconda

We recommend the Miniconda distribution that includes the conda package manager and Python. Downloaded and install the latest Miniconda (x64, with Python 3) from <https://conda.io/miniconda.html>.

Step 1: Open terminal (for Linux or macOS) or *Anaconda Prompt* (for Windows, not the *cmd* program). Create a conda environment for ANDES (recommended)

```
conda create --name andes python=3.7
```

Activate the new environment with

```
conda activate andes
```

Environment activation needs to be executed every time a new Anaconda Prompt or shell is open.

Step 2: Add the conda-forge channel and set it as default

```
conda config --add channels conda-forge  
conda config --set channel_priority flexible
```

1.1.2 Existing Python Environment (Advanced)

This is for advanced user only and is not recommended on Microsoft Windows. Please skip it if you have set up a Conda environment.

Instead of using Conda, if you prefer an existing Python environment, you can install ANDES with *pip*:

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

If you see a *Permission denied* error, you will need to install the packages locally with *-user*

1.2 Install ANDES

ANDES can be installed in the user mode and the development mode.

1.2.1 User Mode

If you want to use ANDES without modifying the source code, you can install it in the user mode.

In the Anaconda environment, run

```
conda install andes
```

1.2.2 Developer Mode (Recommended)

If you want to hack into the code and, for example, develop new models or routines, please install it in the development mode (recommended). The development mode has the same usage as the user mode. In addition, changes to the source code will be reflected immediately without having to re-install the package.

Step 1: Get ANDES source code

Download the ANDES source code from <https://github.com/cuihantao/andes> and extract all files to the path of your choice. You can also `git clone` the source code (recommended).

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

Step 2: Install dependencies

In the Anaconda environment, use `cd` to change directory to the ANDES root folder.

Install dependencies with

```
conda install --file requirements.txt  
conda install --file requirements-dev.txt
```

Step 3: Install ANDES in the development mode using

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

Pip will take care of the rest.

1.3 Troubleshooting

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

This usually happens when `andes` is not installed in a Conda environment but instead in a system-wide Python whose library path was not correctly set in environment variables.

The easiest fix is to install `andes` in a Conda environment.

1.4 Performance Packages (Advanced)

The following two forks of `cvxopt`, `cvxoptklu`, `cvxopt` with `spmatrix.ipadd` are optional but can significantly boost the performance of ANDES. **Installation requires a C compiler**, `openblas` and `SuiteSparse` libraries.

Note: Performance packages can be safely skipped and will not affect the functionality of ANDES.

Warning: We have not tried to compile either package on Windows. Refer to the CVXOPT installation instructions for Windows at <http://cvxopt.org/install/index.html#windows>

1.4.1 cvxoptklu

`cvxoptklu` is a fork of the CVXOPT with KLU by Uriel Sandoval (@sanurielf). In addition to UMF-PACK, `cvxoptklu` interfaces `cvxopt` to KLU, which is roughly 20% faster than UMF-PACK for circuit simulation based on our testing.

Warning: There is likely a bug in the KLU interface which, for some cases, may segfault after applying a disturbance. The cause of the issue is currently unknown.

If you encounter a segfault while running time-domain simulation and was using the KLU solver, please switch back to UMF-PACK by setting `sparselib = umfpack` or enable `linsolve` through `linsolve = 1` for KLU, which re-factorizes the Jacobian matrix for each linear system solving step. Another solution is to use fixed time step size and reduce the step size from 1/30 s to 1/60s, but this is case specific.

This issue will not affect users who does not have `cvxoptklu` installed.

To install `cvxoptklu`, on Debian GNU/Linux, one can do

```
sudo apt install libopenblas-dev libsuitesparse-dev
pip install cvxoptklu
```

On macOS, one can install with homebrew using

```
brew install openblas suitesparse  
pip install cvxoptklu
```

To install from source code, use the repository at <https://github.com/cuihantao/cvxoptklu>.

1.4.2 CVXOPT with ipadd

To install our fork of `cvxopt` with `spmatrix.ipadd`, one need to clone the repository and compile from source.

```
git clone https://github.com/curent/cvxopt  
cd cvxopt  
python setup.py build
```

The compilation may display some warnings, but make sure there is no error. Then, install it with

```
python setup.py install
```

ANDES can be used as a command-line tool or a library. The command-line interface (CLI) comes 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 cheat sheet if you are looking for quick help.

2.1 Command Line Usage

2.1.1 Basic Usage

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 and help commands:

```

      _ _ _ _ _ | Version 0.8.4
    / _ \ _ _ _ _ | Python 3.7.1 on Darwin, 04/07/2020 10:22:17 PM
   / _ \ | ' \ / _ \ / _ \ _ < |
  / _ \ \ _ \ | | _ \ _ \ _ \ / _ \ | This program comes with ABSOLUTELY NO WARRANTY.

usage: andes [-h] [-v {10,20,30,40,50}]
           {run,plot,misc,prepare,doc,selftest} ...

positional arguments:
  {run,plot,misc,prepare,doc,selftest}
    [run] run simulation routine; [plot] plot simulation
    results; [doc] quick documentation; [prepare] run the
    symbolic-to-numeric preparation; [misc] miscellaneous
    functions.

```

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```
optional arguments:
  -h, --help            show this help message and exit
  -v {10,20,30,40,50}, --verbose {10,20,30,40,50}
                        Program logging level in 10-DEBUG, 20-INFO,
                        30-WARNING, 40-ERROR or 50-CRITICAL.
```

The first level of commands are chosen from {run,plot,misc,prepare,selftest}. Each command contains a group of sub-commands, which can be looked up with `-h`. For example, use `andes run -h` to look up the sub-commands in `run`. The most commonly used commands will be explained in the following.

`andes` has an option for the program verbosity level, controlled by `-v` or `--verbose`. Accepted levels are the same as in the logging module: 10 - DEBUG, 20 - INFO, 30 - WARNING, 40 - ERROR, 50 - CRITICAL. To show debugging outputs, use `-v 10`.

2.1.2 andes selftest

After installing ANDES, it is encouraged to use `andes selftest` to run tests and check the basic functionality. It might take a minute to run the whole self-test suite. Results are printed as the tests proceed. An example output looks like

```
ANDES 0.8.1 (Git commit id gc954fc1, Python 3.7.3 on Linux)
Session: hcui7, 03/22/2020 11:02:35 AM
This program comes with ABSOLUTELY NO WARRANTY.

test_docs (test_1st_system.TestCodegen) ... ok
test_alter_param (test_case.Test5Bus) ... ok
test_as_df (test_case.Test5Bus) ... ok
test_cache_refresn (test_case.Test5Bus) ... ok
test_count (test_case.Test5Bus) ... ok
test_idx (test_case.Test5Bus) ... ok
test_init_order (test_case.Test5Bus) ... ok
test_names (test_case.Test5Bus) ... ok
test_pflow (test_case.Test5Bus) ... ok
test_pflow_reset (test_case.Test5Bus) ... ok
test_tds_init (test_case.Test5Bus) ... ok
test_eig_run (test_case.TestKundur2Area) ... ok
test_tds_run (test_case.TestKundur2Area) ... ok
test_npcc_raw (test_case.TestNPCCRAW) ... ok
test_npcc_raw_convert (test_case.TestNPCCRAW) ... ok
test_npcc_raw_tds (test_case.TestNPCCRAW) ... No dynamic component loaded.
ok
test_main_doc (test_cli.TestCLI) ... ok
test_misc (test_cli.TestCLI) ... ok
test_limiter (test_discrete.TestDiscrete) ... ok
test_sorted_limiter (test_discrete.TestDiscrete) ... ok
test_switcher (test_discrete.TestDiscrete) ... ok
test_tree (test_paths.TestPaths) ... ok
test_pflow_mpc (test_pflow_matpower.TestMATPOWER) ... ok
```

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```
-----
Ran 23 tests in 13.834s
```

```
OK
```

Test cases can grow, and there could be more cases than above. Make sure that all tests have passed.

Warning: ANDES is getting updates frequently. After updating your copy, please run `andes selftest` 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.

2.1.3 andes prepare

The symbolically defined models in ANDES need to be generated into numerical code for simulation. The code generation can be manually called with `andes prepare`. Generated code are stored in folder `andes/calls.pkl` in your home directory. In addition, `andes selftest` implicitly calls the code generation. If you are using ANDES as a package in the user mode, you won't need to call it again.

For developers, `andes prepare` needs to be called immediately following any model equation modification. Otherwise, simulation results will not reflect the new equations and will likely lead to an error.

Option `-q` or `--quick` can be used to speed up the code generation. It skips the generation of \LaTeX -formatted equations, which are only used in documentation and the interactive mode.

Option `-i` or `--incremental` can be used to further speed up the code generation during model development. `andes prepare -qi` only generates code for models with modified equations.

2.1.4 andes run

`andes run` is the entry point for power system analysis routines. `andes run` takes one positional argument, `filename`, along with other optional keyword arguments. `filename` is the test case path, either relative or absolute. Without other options, ANDES will run power flow calculation for the provided file.

Routine

Option `-r` or `-routine` is used for specifying the analysis routine, followed by the routine name. Available routine names include `pflow`, `tds`, `eig`. `pflow` for power flow, `tds` for time domain simulation, and `eig` for eigenvalue analysis. `pflow` is default even if `-r` is not given.

For example, to run time-domain simulation for `kundur_full.xlsx` in the *current directory*, run

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

The file is located at `andes/cases/kundur/kundur_full.xlsx` relative to the source code root folder. Use `cd` to change directory to that folder on your machine.

Two output files, `kundur_full_out.lst` and `kundur_full_out.npy` will be created for variable names and values, respectively.

Likewise, to run eigenvalue analysis for `kundur_full.xlsx`, use

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

The eigenvalue report will be written in a text file named `kundur_full_eig.txt`.

Power flow

To perform a power flow study for test case named `kundur_full.xlsx` in the current directory, run

```
andes run kundur_full.xlsx
```

The full path to the case file is also accepted, for example,

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

Power flow reports will be saved to the current directory in which `andes` is called. The power flow report contains four sections: a) system statistics, b) ac bus and dc node data, c) ac line data, and d) the initialized values of other algebraic variables and state variables.

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:

```
ANDES 0.6.8 (Git commit id 0ace2bc0, Python 3.7.6 on Darwin)
Session: hcui7, 02/09/2020 10:35:37 PM

Parsing input file </Users/hcui7/repos/andes/tests/kundur_full.xlsx>
Input file kundur_full.xlsx parsed in 0.5425 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 0.0080 second.
Report saved to </Users/hcui7/repos/andes/tests/kundur_full_out.txt> in 0.
↪0036 second.
-> Time Domain Simulation:
Initialization tests passed.
```

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```

Initialization successful in 0.0152 second.
 0%|                                     | 0/100 [00:00<?, ?%/
↪s]
  <Toggle 0>: Applying status toggle on Line idx=Line_8
100%|-----| 100/100 [00:03<00:00, 28.99%/s]
Simulation completed in 3.4500 seconds.
TDS outputs saved in 0.0377 second.
-> Single process finished in 4.4310 seconds.

```

This execution first solves the power flow as a starting point. Next, the numerical integration simulates 20 seconds, during which a predefined breaker opens at 2 seconds.

TDS produces two output files by default: a NumPy data file `ieee14_syn_out.npy` and a variable name list file `ieee14_syn_out.lst`. The list file contains 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.

Disable output

The output files can be disabled with option `--no-output` or `-n`. It is useful when only computation is needed without saving the results.

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`.

Multiprocessing

ANDES takes multiple files inputs or wildcard. Multiprocessing will be triggered if more than one valid input files are found. For example, to run power flow for files with a prefix of `case5` and a suffix (file extension) of `.m`, run

```
andes run case5*.m
```

Test cases that match the pattern, including `case5.m` and `case57.m`, 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 operation system responsiveness.

Format converter

ANDES recognizes a few input formats and can convert input systems into the `xlsx` format. This function is useful when one wants to use models that are unique in ANDES.

The command for converting is `--convert` (or `-c`), following the output format (only `xlsx` is currently supported). For example, to convert `case5.m` into the `xlsx` format, run

```
andes run case5.m --convert xlsx
```

The output will look like

```
ANDES 0.6.8 (Git commit id 0ace2bc0, Python 3.7.6 on Darwin)
Session: hcui7, 02/09/2020 10:22:14 PM

Parsing input file </Users/hcui7/repos/andes/cases/matpower/case5.m>
CASE5 Power flow data for modified 5 bus, 5 gen case based on PJM 5-bus
↳system
Input file case5.m parsed in 0.0033 second.
xlsx file written to </Users/hcui7/repos/andes/cases/matpower/case5.xlsx>
Converted file /Users/hcui7/repos/andes/cases/matpower/case5.xlsx written in
↳0.5079 second.
-> Single process finished in 0.8765 second.
```

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

In case one wants to create template sheets to add models later, `--convert-all` can be used instead.

If one wants to add workbooks to an existing `xlsx` file, one can combine option `--add-book ADD_BOOK` (or `-b ADD_BOOK`), where `ADD_BOOK` can be a single model name or comma-separated model names (without any space). For example,

```
andes run wecc.raw -c -b Toggler
```

will convert file `wecc.raw` into an ANDES `xlsx` file and append a template workbook for *Toggler* at the end.

Warning: With `--add-book`, the `xlsx` file will be overwritten. Any **empty or non-existent models** will be REMOVED.

PSS/E inputs

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

```
andes run wecc.raw
```

and run a no-disturbance time-domain simulation using

```
andes run wecc.raw --addfile wecc_full.dyr -r tds
```

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 and run (see the previous subsection).

The alternative is to edit the dyr file 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 Toggler:

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

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

```
Line   'Toggler'   Line_2   1 /
Line   'Toggler'   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”.

Note: When working with PSS/E data, the recommended practice is to edit model dynamic parameters directly in the dyr file so that the data can be easily used by other tools.

2.1.5 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 <i>out</i> . 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 example, to plot the generator speed variable of synchronous generator 1 `omega GENROU 0` versus time, read the indices of the variable (2) and time (0), run

```
andes plot kundur_full_out.lst 0 2
```

In this command, `andes plot` is the plotting command for TDS output files. `kundur_full_out.lst` is list file name. 0 is the index of Time for the x-axis. 2 is the index of ω GENROU 0. Note that for the file name, either `kundur_full_out.lst` or `kundur_full_out.npy` works, as the program will automatically extract the file name.

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

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

Other optional arguments are listed in the following.

optional arguments:

Argument	Description
optional arguments:	
-h, -help	show this help message and exit
-xmin LEFT	minimum value for X axis
-xmax RIGHT	maximum value for X axis
-ymax YMAX	maximum value for Y axis
-ymin YMIN	minimum value for Y axis
-find FIND	find variable indices that matches the given pattern
-xargs XARGS	find variable indices and return as a list of arguments usable with " <code> xargs andes plot</code> "
-exclude EXCLUDE	pattern to exclude in find or xargs results
-x XLABEL, -xlabel XLABEL	x-axis label text
-y YLABEL, -ylabel YLABEL	y-axis label text
-s, -savefig	save figure. The default fault is <i>png</i> .
-format SAVE_FORMAT	format for savefig. Common formats such as <i>png</i> , <i>pdf</i> , <i>jpg</i> are supported
-dpi DPI	image resolution in dot per inch (DPI)
-g, -grid	grid on
-greyscale	greyscale on
-d, -no-latex	disable \LaTeX formatting
-n, -no-show	do not show the plot window
-ytimes YTIMES	scale the y-axis values by YTIMES
-c, -tocsv	convert npy output to csv

2.1.6 andes doc

`andes doc` is a tool for quick lookup of model and routine documentation. It is intended as a quick way for documentation.

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. If you are looking for full documentation, visit andes.readthedocs.io.

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

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

    Time-based connectivity status toggler.

Parameters

Name | Description | Default | Unit | Type |
--
--
--
u | connection status | 1 | bool | NumParam |
name | device name | | | DataParam |
model | Model or Group of the device | | | DataParam |
--mandatory
dev | to control | | | |
dev | idx of the device to control | | | IdxParam |
--mandatory
t | switch time for connection | -1 | | TimerParam |
--mandatory
status | 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
StaticACDC | VSCShunt
StaticGen | PV, Slack
StaticLoad | PQ
StaticShunt | Shunt
SynGen | GENCLS, GENROU
```

(continues on next page)

(continued from previous page)

TimedEvent	Toggler, 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

2.1.7 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. `--save-config` saves all configs to a file. By default, it saves to `~/.andes/andes.conf` file, where `~` is the path to your home directory.

With `--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 automatically 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

`-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).

2.2 Interactive Usage

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

2.2.1 Jupyter Notebook

Jupyter notebook is used as an example. Jupyter notebook can be installed with

```
conda install jupyter notebook
```

After the installation, change directory to the folder that you wish to store notebooks, 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 at the top right corner.

2.2.2 Import

Like other Python libraries, ANDES can be imported into an interactive Python environment.

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

The `config_logger` is needed to print logging information in the current session. Otherwise, information messages will be silenced, and only warnings and error will be printed.

To enable debug messages, use

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

If you have not run `andes prepare`, use the command once to generate code

```
>>> andes.prepare()
```

2.2.3 Create Test System

Before running studies, a "System" object needs to be create to hold the system data. The System object can be created by passing the path to the case file the `entrypoint` function. 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/hcui7/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/hcui7/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.

Naming convention for the `System` attributes are as follows

- Model attributes share the same name as class names. For example, `ss.Bus` is the `Bus` 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`.

2.2.4 Inspect Parameter

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

Input parameters for each model instance is in the `cache.df_in` attribute. For example, to view the input parameters for `Bus`, use

```
>>> ss.Bus.cache.df_in
```

A table will be printed with the columns being each parameter and the rows being `Bus` instances. Parameter in the table is the same as the input file without per-unit conversion.

Parameters are converted to per unit values under system base. To view the per unit values, use the `cache.df` attribute. For example, to view the system-base per unit value of `GENROU`, use

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

2.2.5 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()
```

2.2.6 Plotting TDS Results

TDS comes with a plotting utility for interactive 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)
```

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

2.2.7 Pretty Print of Equations

Each ANDES models offers pretty print of $\text{L}^{\text{A}}\text{T}_{\text{E}}\text{X}$ -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 several seconds to complete. 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 $T\dot{\mathbf{x}} = \mathbf{f}$
- `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`.

2.2.8 Examples in Jupyter Notebook

Congratulations! You have finished the ANDES tutorial. Check out more examples in Jupyter Notebook in the *examples* folder of the repository at [here](#). You can run the examples in a live Jupyter Notebook online using [Binder](#).

2.3 I/O Formats

2.3.1 Input Formats

ANDES currently supports the following input formats:

- ANDES Excel (.xlsx)
- PSS/E RAW (.raw) and DYR (.dyr)
- MATPOWER (.m)

2.3.2 ANDES xlsx Format

The ANDES xlsx format is a newly introduced format since v0.8.0. This format uses Microsoft Excel for conveniently viewing and editing model parameters. You can use [LibreOffice](#) or [WPS Office](#) alternatively to Microsoft Excel.

xlsx Format Definition

The ANDES xlsx format contains multiple workbooks (tabs at the bottom). Each workbook contains the parameters of all instances of the model, whose name is the workbook name. The first row in a worksheet is used for the names of parameters available to the model. Starting from the second row, each row corresponds to an instance with the parameters in the corresponding columns. An example of the `Bus` workbook is shown in the following.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
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			

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

- `uid` is an internally generated unique instance index. This column can be left empty if the xlsx file is being manually created. Exporting the xlsx file with `--convert` will automatically assign the `uid`.
- `idx` is the unique instance index for referencing. An unique `idx` should be provided explicitly for each instance. Accepted types for `idx` include numbers and strings without spaces.
- `name` is the instance name.
- `u` is the connectivity status of the instance. Accepted values are 0 and 1. Unexpected behaviors may occur if other numerical values are assigned.

As mentioned above, `idx` is the unique index for an instance to be referenced. For example, a `PQ` instance can reference a `Bus` instance so that the `PQ` is connected to the `Bus`. This is done through providing the `idx` of the desired bus as the `bus` parameter of the `PQ`.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
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						
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	
14																	
15																	
16																	
17																	
18																	
19																	
20																	
21																	

In the example PQ workbook shown above, there are two PQ instances on buses with `idx` being 7 and 8, respectively.

Convert to xlsx

Please refer to the `--convert` command for converting a recognized file to xlsx. See [format converter](#) for more detail.

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. For example, 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 .

2.4 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/>

2.5 Make Documentation

The documentation can be made locally into a variety of formats. To make HTML documentation, change directory to docs, and do

```
make html
```

After a minute, HTML documentation will be saved to docs/build/html with the index page being index.html.

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)

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.

```
class andes.system.System(case: Optional[str] = None, name: Optional[str] =
                        None, config_path: Optional[str] = None, options: Op-
                        tional[Dict[KT, VT]] = None, **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.

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

Note: *andes.System* is an alias of *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 `devices/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 groups will be stored to dictionary `System.groups`.

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 symbolically defined equations need to be generated into anonymous function calls for accelerating numerical simulations. This process is automatically invoked for the first time ANDES is run command line. It takes several seconds up to a minute to finish the generation.

Note: Code generation has been done if one has executed `andes`, `andes selftest`, or `andes prepare`.

Warning: When models are modified (such as adding new models or changing equation strings), code generation needs to be executed again for consistency. It can be more conveniently triggered from command line with `andes prepare -qi`.

`andes.system.System.prepare(self, quick=False, incremental=False)`

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.

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()
```

Since the process is slow, generated numerical functions (Python Callable) will be serialized into a file for future speed up. The package used for serializing/de-serializing numerical calls is `dill`. System has a function called `dill` for serializing using the `dill` package.

`andes.system.System.dill(self)`

Serialize generated numerical functions in *System.calls* with package *dill*.

The serialized file will be stored to `~/andes/calls.pkl`, where `~` is the home directory path.

Notes

This function sets `dill.settings['recurse'] = True` to serialize the function calls recursively.

`andes.system.System.undill(self)`

Deserialize the function calls from `~/andes/calls.pkl` with `dill`.

If no change is made to models, future calls to `prepare()` can be replaced with `undill()` for acceleration.

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 `cvxopt.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 `cvxopt.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

$$\begin{aligned} T\dot{x} &= f(x, y) \\ 0 &= g(x, y) \end{aligned}$$

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: Union[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: collections.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: collections.OrderedDict)`

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: collections.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*: *collections.OrderedDict*)
 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*: *Union[str, List[T], collections.OrderedDict, None]* = *None*)
 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*: *collections.OrderedDict*)
 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*: *Union[str, List[T], collections.OrderedDict, None]* = *None*)
 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*: *collections.OrderedDict*)
 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.get_config` (*self*)
 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.

```
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.

```
andes.system.System.load_config(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`

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 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.

3.2.1 Model Data

```
class andes.core.model.ModelData(*args, **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 *GENCLS* should be named *GENCLSData*.

Parameters should be defined in the `__init__` function of the derived class.

Refer to `andes.core.param` for available parameter types.

Notes

Two default parameters, *u* (connection status of type `andes.core.param.NumParam`), and *name* (device name of type `andes.core.param.DataParam`) are pre-defined in `ModelData`, and will be inherited by all models.

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.

Cache

ModelData uses a lightweight class `andes.core.model.Cache` 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.Cache.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

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 $V_b = V_n = 1$, 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.

3.2.2 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* defines 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 looks 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`.

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 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. It 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 variables can be used in equation strings. An addition variable *dae_t* for the current

simulation time can be used if the model has flag *tds*.

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 implements a piecewise 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

3.2.3 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.

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.

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.

3.2.4 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.model.SymProcessor` (*parent*)

A helper class for symbolic processing and code generation.

Parameters

parent [Model] The *Model* instance to document

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.

non_vars_dict [OrderedDict] symbols in `input_syms` but not in `var_syms`.

generate_init()

Generate lambda functions for initial values.

generate_jacobians()

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)`

non_vars_dict [OrderedDict] name-symbol pair of all non-variables, namely, `(inputs_dict - vars_dict)`

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_lambdify`.

3.2.5 Jacobian Storage

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` and `_vgyc`: `_vgy` is a list of callables, while `_vgyc` is a list of constant numbers.

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 $-u * p_0$, and the equation associated with `q` is $u * (v_0 - v)$. Therefore, the derivative of equation $v_0 - v$ 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]`.

3.2.6 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

3.2.7 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.

3.3 Atom Types

ANDES contains three types of atom classes for building DAE models. These types are parameter, variable and service.

3.3.1 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.

3.3.2 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.a*, and the equation evaluation results will be stored in *self.v.e*

3.4 Parameters

3.4.1 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.

Subclasses	Description
DataParam	An alias of <i>BaseParam</i> . Can be used for any non-numerical parameters.
NumParam	The numerical parameter type. Used for all parameters in equations
IdxParam	The parameter type for storing <i>idx</i> into other models
ExtParam	Externally defined parameter
TimerParam	Parameter for storing the action time of events

3.4.2 Data Parameters

```
class andes.core.param.BaseParam(default: Union[float, str, int, None] = None, name:
                                Optional[str] = None, tex_name: Optional[str]
                                = None, info: Optional[str] = None, unit: Op-
                                tional[str] = None, mandatory: bool = False, ex-
                                port: bool = True)
```

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*.

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.

```
class andes.core.param.DataParam(default: Union[float, str, int, None] = None, name:
                                Optional[str] = None, tex_name: Optional[str] =
                                None, info: Optional[str] = None, unit: Op-
                                tional[str] = None, mandatory: bool = False, ex-
                                port: bool = True)
```

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

```
class andes.core.param.IdxParam(default: Union[float, str, int, None] = None, name:
                                Optional[str] = None, tex_name: Optional[str] =
                                None, info: Optional[str] = None, unit: Op-
                                tional[str] = None, mandatory: bool = False,
                                unique: bool = False, export: bool = True, model:
                                Optional[str] = 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')
```

3.4.3 Numeric Parameters

```
class andes.core.param.NumParam (default: Union[float, str, Callable, None] = None,
                                name: Optional[str] = None, tex_name: Op-
                                tional[str] = None, info: Optional[str] = None, unit:
                                Optional[str] = None, vrange: Union[List[T], Tu-
                                ple, None] = None, non_zero: bool = False, posi-
                                tive: 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

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

positive: bool True if this parameter must be positive

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

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

3.4.4 External Parameters

class `andes.core.param.ExtParam` (*model: str, src: str, indexer=None, dtype=<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.

Attributes

parent_model [Model] The parent model providing the original parameter.

3.4.5 Timer Parameter

class `andes.core.param.TimerParam` (*callback: Optional[Callable] = None, default: Union[float, str, Callable, None] = None, name: Optional[str] = None, tex_name: Optional[str] = None, info: Optional[str] = None, unit: Optional[str] = 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 toggler class *Toggler* takes a parameter t for the toggle time. Inside *Toggler*.`__init__`, one would have

```
self.t = TimerParam()
```

The *Toggler* class also needs to define a method for toggling 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 *Toggler*.`__init__`, assign the function as the callback for *self.t*

```
self.t.callback = self._u_switch
```

3.5 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.

Class	Description
State	A state variable and associated diff. equation $T\dot{x} = f$
Algeb	An algebraic variable and an associated algebraic equation $0 = g$
ExtState	An external state variable and part of the differential equation (uncommon)
ExtAlgeb	An external algebraic variable and part of the algebraic equation

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.

3.5.1 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])`.

3.5.2 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.

3.5.3 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.

3.5.4 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*.

3.5.5 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*.

```
class andes.core.var.BaseVar (name: Optional[str] = None, tex_name: Optional[str] =
                             None, info: Optional[str] = None, unit: Optional[str] =
                             None, v_str: Union[str, float, None] = None, v_iter: Op-
                             tional[str] = None, e_str: Optional[str] = None, discrete:
                             Optional[andes.core.discrete.Discrete] = None, v_setter:
                             Optional[bool] = False, e_setter: Optional[bool] =
                             False, addressable: Optional[bool] = True, export: Op-
                             tional[bool] = True, diag_eps: Optional[float] = 0.0)
```

Base variable class.

Derived classes *State* and *Algeb* should be used to build model variables.

Parameters

name [str, optional] Variable name

info [str, optional] Descriptive information

unit [str, optional] Unit

tex_name [str] LaTeX-formatted variable name. If is None, use *name* instead.

discrete [Discrete] Associated discrete component. Will call *check_var* on the discrete component.

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

```
class andes.core.var.ExtVar(model: str, src: str, indexer: Union[List[T],
    numpy.ndarray, andes.core.param.BaseParam, andes.core.service.BaseService, None] = None, allow_none:
    Optional[bool] = False, name: Optional[str] = None,
    tex_name: Optional[str] = None, info: Optional[str]
    = None, unit: Optional[str] = None, v_str: Union[str,
    float, None] = None, v_iter: Optional[str] = None,
    e_str: Optional[str] = None, v_setter: Optional[bool]
    = False, e_setter: Optional[bool] = False, addressable:
    Optional[bool] = True, export: Optional[bool] = True,
    diag_eps: Optional[float] = 0.0)
```

Externally defined algebraic variable

This class is used to retrieve the addresses of externally- defined variable. The *e* value of the *ExtVar* will be added to the corresponding address in the DAE equation.

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] True to allow None in indexer

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.

```
class andes.core.var.State (name: Optional[str] = None, tex_name: Optional[str]
    = None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None,
    v_iter: Optional[str] = None, e_str: Optional[str] = None, discrete: Optional[andes.core.discrete.Discrete] =
    None, t_const: Union[andes.core.param.BaseParam, andes.core.common.DummyValue, None] = None, v_setter:
    Optional[bool] = False, e_setter: Optional[bool] = False, addressable: Optional[bool] = True, export: Optional[bool]
    = True, diag_eps: Optional[float] = 0.0)
```

Differential variable class, an alias of the *BaseVar*.

Parameters

t_const [BaseParam, DummyValue] Left-hand time constant for the differential equation. Time constants will not be evaluated as part of the differential equation. They will be collected to array *dae.Tf* to multiply to the right-hand side *dae.f*.

Attributes

e_code [str] Equation code string, equals string literal *f*

v_code [str] Variable code string, equals string literal *x*

```
class andes.core.var.Algeb (name: Optional[str] = None, tex_name: Optional[str] =
    None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None, v_iter:
    Optional[str] = None, e_str: Optional[str] = None, discrete:
    Optional[andes.core.discrete.Discrete] = None, v_setter:
    Optional[bool] = False, e_setter: Optional[bool] = False,
    addressable: Optional[bool] = True, export: Optional[bool]
    = True, diag_eps: Optional[float] = 0.0)
```

Algebraic variable class, an alias of the *BaseVar*.

Attributes

e_code [str] Equation code string, equals string literal *g*

v_code [str] Variable code string, equals string literal *y*

```
class andes.core.var.ExtState (model: str, src: str, indexer: Union[List[T],
    numpy.ndarray, andes.core.param.BaseParam, andes.core.service.BaseService, None] = None,
    allow_none: Optional[bool] = False, name: Optional[str] = None, tex_name: Optional[str] = None,
    info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None, v_iter:
    Optional[str] = None, e_str: Optional[str] = None,
    v_setter: Optional[bool] = False, e_setter:
    Optional[bool] = False, addressable: Optional[bool]
    = True, export: Optional[bool] = True, diag_eps:
    Optional[float] = 0.0)
```

External state variable type.

Warning: `ExtState` is not allowed to set `t_const`, as it will conflict with the source `State` variable. In fact, one should not set `e_str` for `ExtState`.

```
class andes.core.var.ExtAlgeb(model: str, src: str, indexer: Union[List[T],
    numpy.ndarray, andes.core.param.BaseParam, andes.core.service.BaseService, None] = None, allow_none: Optional[bool] = False, name: Optional[str] = None, tex_name: Optional[str] = None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None, v_iter: Optional[str] = None, e_str: Optional[str] = None, v_setter: Optional[bool] = False, e_setter: Optional[bool] = False, addressable: Optional[bool] = True, export: Optional[bool] = True, diag_eps: Optional[float] = 0.0)
```

External algebraic variable type.

3.6 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 `BaseService`, and the supported services are listed as follows.

Class	Description
<code>ConstService</code>	Internal service for constant values.
<code>ExtService</code>	External service for retrieving values from value providers.
<code>NumReduce</code>	The service type for reducing linear 2-D arrays into 1-D arrays
<code>NumRepeat</code>	The service type for repeating a 1-D array to linear 2-D arrays
<code>IdxRepeat</code>	The service type for repeating a 1-D list to linear 2-D list

3.6.1 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: Optional[str] = None, v_numeric:
                                         Optional[Callable] = None, vtype: Op-
                                         tional[type] = None, name: Optional[str] =
                                         None, tex_name=None, info=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`.

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

Attributes

v [array-like or a scalar] ConstService value

3.6.2 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:
                                         Union[andes.core.param.BaseParam,
                                         andes.core.service.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 GENCLSMModel(Model):
    def __init__(...):
        ...
        self.p0 = ExtService(src='p',
                             model='StaticGen',
                             indexer=self.gen,
                             tex_name='P_0')
```

3.6.3 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: andes.core.service.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 V_n in one Area. In the `Area` class, one defines

```
class AreaModel(...):
    def __init__(...):
        ...
        # backward reference from `Bus`
        self.Bus = BackRef()

        # collect the  $V_n$  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	V_n
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,
                  )
```

3.6.4 Device Finder

```
class andes.core.service.DeviceFinder(u, link, idx_name, name=None,
                                     tex_name=None, info=None)
```

Service for finding indices of optionally linked devices.

If not provided, *DeviceFinder* will add devices at the beginning of *System.setup*.

Examples

IEEEEST stabilizer takes an optional *busf* (IdxParam) for specifying the connected BusFreq, which is needed for mode 6. To avoid reimplementing *BusFreq* within IEEEEST, one can do

```
self.busfreq = DeviceFinder(self.busf, link=self.buss, idx_name='bus')
```

where *self.busf* is the optional input, *self.buss* is the bus indices that *busf* should measure, and *idx_name* is the name of a BusFreq parameter through which the measured bus indices are specified. For each *None* values in *self.busf*, a *BusFreq* is created to measure the corresponding bus in *self.buss*.

That is, *BusFreq[idx_name].v = [link]*. *DeviceFinder* will find / create *BusFreq* devices so that the returned list of *BusFreq* indices are connected to *self.buss*, respectively.

3.7 Discrete

3.7.1 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*.

```
class andes.core.discrete.Discrete (name=None, tex_name=None, info=None)
    Base discrete class.
```

Discrete classes export flag arrays (usually boolean) .

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.

3.7.2 Limiters

```
class andes.core.discrete.Limiter (u, lower, upper, enable=True, name=None,
                                   tex_name=None, info=None, no_upper=False,
                                   no_lower=False, equal=True, 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

equal: bool True to include equal signs in comparison (\geq or \leq).

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, enable=True, n_select:
Optional[int] = None, name=None,
tex_name=None)
```

A comparer with the top value selection.

```
class andes.core.discrete.HardLimiter(u, lower, upper, enable=True,
name=None, tex_name=None, info=None,
no_upper=False, no_lower=False,
equal=True, 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.AntiWindup(u, lower, upper, enable=True,
no_lower=False, no_upper=False,
name=None, tex_name=None, info=None,
state=None)
```

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.

3.7.3 Comparers

```
class andes.core.discrete.LessThan(u, bound, equal=False, enable=True,
name=None, tex_name=None, cache=False,
z0=0, z1=1)
```

Less than (<) comparison function.

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.

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.

See also:

`numpy.ufunc.reduce` NumPy reduce function

`andes.core.block.HVGate`

`andes.core.block.LVGate`

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: Union[list, Tuple], 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 IEEEEST 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=[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([1, 0, 0, 0, 0]),
 'IC_s1': np.array([0, 1, 1, 0, 0]),
 'IC_s2': np.array([0, 0, 0, 0, 0]),
 'IC_s3': np.array([0, 0, 0, 1, 0]),
 'IC_s4': np.array([0, 0, 0, 0, 0]),
 'IC_s5': np.array([0, 0, 0, 0, 1])
}
```

3.7.4 Deadband

```
class andes.core.discrete.DeadBand(u, center, lower, upper, enable=True,
                                   equal=True, 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) + \\\n                (dbc * db_zi) - var_out'
```

3.8 Blocks

3.8.1 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 be 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: Optional[str] = None, tex_name: Optional[str] =
                             None, info: Optional[str] = None, namespace: str = 'lo-
                             cal')
```

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
|
LeadLag A  exports (x, y)
|
Lag B      exports (x, y)
```

SomeModel instance M contains an instance of LeadLag block named A, which contains an instance of a Lag block named B. Both A and B exports two variables `x` and `y`.

In the code of Model, 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)
        self.vars = {..., 'A': self.A}

```

The `__setattr__` magic of `LeadLag` takes over the construction and assigns `A_B` to `B.name`, given `A`'s name provided at run time. `self.A` is exported with the internal name `A` at the end.

Again, the `LeadLag` instance name (`A` in this example) MUST be provided in *SomeModel*'s constructor for the name prepending to work correctly. If there is more than one level of nesting, other than the leaf-level block, all parent blocks' names must be provided at instantiation.

When `A` is picked up by *SomeModel*.`__setattr__`, `B` is captured from `A`'s exports. 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`.

In this 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 `B` has gotten a new name `A_B`.

3.8.2 Transfer Functions

The following transfer function blocks have been implemented. They can be imported to build new models.

Algebraic

```

class andes.core.block.Gain(u, K, name=None, tex_name=None, info=None)
    Gain block.

```

$$u \rightarrow \boxed{K} \rightarrow y$$

Exports an algebraic output `y`.

```

define()
    Implemented equation and the initial condition are

```

$$y = Ku$$

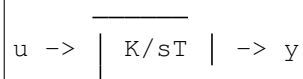
$$y^{(0)} = Ku^{(0)}$$

First Order

```

class andes.core.block.Integrator(u, T, K, y0, name=None, tex_name=None,
                                   info=None)
    Integrator block.

```

Exports a differential variable y . The initial output is specified by $y0$ and default to zero.

define()

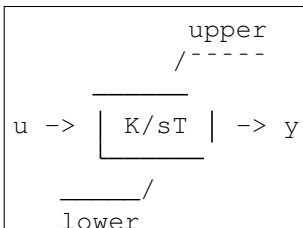
Implemented equation and the initial condition are

$$\dot{y} = Ku$$

$$y^{(0)} = 0$$

class andes.core.block.**IntegratorAntiWindup**($u, T, K, y0, lower, upper,$
 $name=None, tex_name=None,$
 $info=None$)

Integrator block with anti-windup limiter.



Exports a differential variable y and an AntiWindup lim . The initial output must be specified through $y0$.

define()

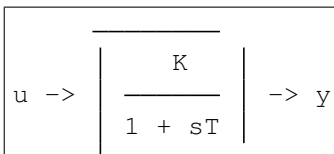
Implemented equation and the initial condition are

$$\dot{y} = Ku$$

$$y^{(0)} = 0$$

class andes.core.block.**Lag**($u, T, K, name=None, tex_name=None, info=None$)

Lag (low pass filter) transfer function.



Exports one state variable y as the output.

Parameters

K Gain

T Time constant

u Input variable

define()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - y)$$

$$y^{(0)} = Ku$$

class andes.core.block.**LagAntiWindup**(*u, T, K, lower, upper, 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

u Input variable

define()

Notes

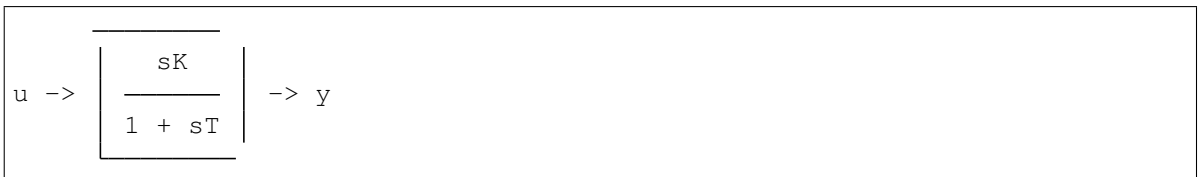
Equations and initial values are

$$T\dot{y} = (Ku - y)$$

$$y^{(0)} = Ku$$

class andes.core.block.**Washout**(*u, T, K, name=None, tex_name=None, info=None*)

Washout filter (high pass) block.



Exports state x (symbol x') and output algebraic variable y .

define()

Notes

Equations and initial values:

$$\begin{aligned}Tx' &= (u - x') \\Ty &= K(u - x') \\x'^{(0)} &= u \\y^{(0)} &= 0\end{aligned}$$

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:

$$\begin{aligned}Tx' &= (u - x') \\Ty &= z_0K(u - x') + z_1Tx \\x'^{(0)} &= u \\y^{(0)} &= 0\end{aligned}$$

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.

Second Order

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

$$u \rightarrow \left[K \frac{1 + sT1}{1 + sT2} \right] \rightarrow y$$

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

$$\begin{aligned}
 T_2 \dot{x}' &= (u - x') \\
 T_2 y &= K T_1 (u - x') + K T_2 x' + E_2, \text{ where} \\
 E_2 &= \begin{cases} (y - K x') & \text{if } T_1 = T_2 = 0 \& \text{zero_out} = \text{True} \\ 0 & \text{otherwise} \end{cases} \\
 x'^{(0)} &= u \\
 y^{(0)} &= K u
 \end{aligned}$$

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)

$$u \rightarrow \left[\frac{1 + sT_1}{1 + sT_2} \right] \begin{matrix} \text{upper} \\ \hline \text{lower} \end{matrix} \rightarrow y_{nl} \begin{matrix} / \text{-----} \\ / \end{matrix} \rightarrow y$$

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

$$\begin{aligned}
 T_2 \dot{x}' &= (u - x') \\
 T_2 y &= T_1 (u - x') + T_2 x' \\
 x'^{(0)} &= y^{(0)} = u
 \end{aligned}$$

class andes.core.block.**Lag2ndOrd** (*u, K, T1, T2, name=None, tex_name=None, info=None*)

Second order lag transfer function (low-pass filter)



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

$$T_2 \dot{x} = Ku - y - T_1 x$$

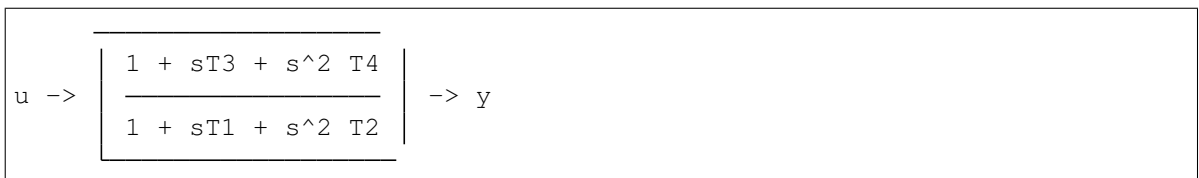
$$\dot{y} = x$$

$$x^{(0)} = 0$$

$$y^{(0)} = Ku$$

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



Exports two internal states ($x1$ and $x2$) and output algebraic variable y .

TODO: instead of implementing *zero_out* using *LessThan* and an additional term, consider correcting all parameters to 1 if all are 0.

define()

Notes

Implemented equations and initial values are

$$\begin{aligned}
T_2 \dot{x}_1 &= u - x_2 - T_1 x_1 \\
\dot{x}_2 &= x_1 \\
T_2 y &= T_2 x_2 + T_2 T_3 x_1 + T_4 (u - x_2 - T_1 x_1) + E_2, \text{ where} \\
E_2 &= \begin{cases} (y - x_2) & \text{if } T_1 = T_2 = T_3 = T_4 = 0 \& zero_out = True \\ 0 & \text{otherwise} \end{cases} \\
x_1^{(0)} &= 0 \\
x_2^{(0)} &= y^{(0)} = u
\end{aligned}$$

3.8.3 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

$$E_1 S_{E1} = A e^{E_1 \times B} E_2 S_{E2} = A e^{E_2 \times B}$$

The solutions are given by

$$E_1 S_{E1} e^{\frac{E_1 \log \left(\frac{E_2 S_{E2}}{E_1 S_{E1}} \right)}{E_1 - E_2}} - \frac{\log \left(\frac{E_2 S_{E2}}{E_1 S_{E1}} \right)}{E_1 - E_2}$$

3.8.4 Others

Value Selector

class andes.core.block.**HVGate** (*u1*, *u2*, *name=None*, *tex_name=None*, *info=None*)
 High Value Gate. Outputs the maximum of two inputs.



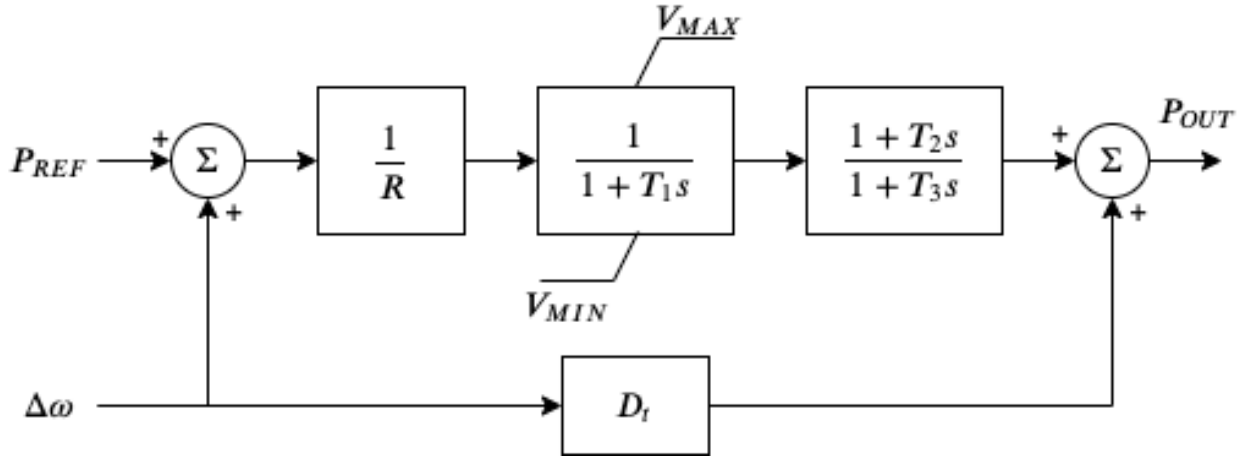
class andes.core.block.LVGate (u1, u2, name=None, tex_name=None, info=None)
 Low Value Gate. Outputs the minimum of the two inputs.



3.9 Examples

3.9.1 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.

$$\begin{bmatrix} \dot{x}_{LG} \\ \dot{x}_{LL} \end{bmatrix} = \begin{bmatrix} z_{i,lim}^{LG} (P_d - x_{LG}) / T_1 \\ (x_{LG} - x_{LL}) / T_3 \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} (1 - \omega) - \omega_d \\ R \times \tau_{m0} - P_{ref} \\ (P_{ref} + \omega_d) / R - P_d \\ D_t \omega_d + y_{LL} - P_{OUT} \\ \frac{T_2}{T_3} (x_{LG} - x_{LL}) + x_{LL} - y_{LL} \\ u (P_{OUT} - \tau_{m0}) \end{bmatrix}$$

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 for the above model is demonstrated as follows. The complete code can be found in `andes/models/governor.py`.

```
def __init__(self):
    # 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',
                      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',
```

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```
e_str='(LL_y+Dt*wd)-pout')
```


4.1 Directory

ANDES comes with several test cases in the `andes/cases/` folder. 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.

The test case library will continue to build as more models get implemented.

A tree view of the test directory is as follows.

```
cases/
├── 5bus/
│   └── pjm5bus.xlsx
├── GBnetwork/
│   ├── GBnetwork.m
│   ├── GBnetwork.xlsx
│   └── README.md
├── ieee14/
│   ├── ieee14.dyr
│   └── ieee14.raw
└── kundur/
    ├── kundur_aw.xlsx
    ├── kundur_coi.xlsx
    ├── kundur_coi_empty.xlsx
    ├── kundur_esdc2a.xlsx
    ├── kundur_esst3a.xlsx
    ├── kundur_exdc2_zero_tb.xlsx
    ├── kundur_exst1.xlsx
    ├── kundur_freq.xlsx
    └── kundur_full.dyr
```

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—	kundur_full.raw
—	kundur_full.xlsx
—	kundur_gentrip.xlsx
—	kundur_ieeeeg1.xlsx
—	kundur_ieeeest.xlsx
—	kundur_sexs.xlsx
—	kundur_st2cut.xlsx
—	matpower/
—	case118.m
—	case14.m
—	case300.m
—	case5.m
—	nordic44/
—	N44_BC.dyr
—	N44_BC.raw
—	README.md
—	npcc/
—	npcc.raw
—	npcc_full.dyr
—	wecc/
—	wecc.raw
—	wecc.xlsx
—	wecc_full.dyr
—	wecc_gencls.dyr
—	wsc9/
—	wsc9.raw
—	wsc9.xlsx

4.2 MATPOWER Cases

MATPOWER cases have 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.

The numerical library used for sparse matrix factorization is KLU. In addition, Jacobians are updated in place `spmatrix.ipadd`. Computations are performed on macOS 10.15.4 with i9-9980H, 16 GB 2400 MHz DDR4, running ANDES 0.9.1, CVXOPT 1.2.4 and NumPy 1.18.1.

The statistics of convergence, number of iterations, and solution time (including equation evaluation, Jacobian, and factorization time) are reported in the following table. The computation time may vary depending on operating system and hardware.

File Name	Converged?	# of Iterations	Time [s]
case30.m	1	3	0.012
case_ACTIVSg500.m	1	3	0.019
case13659pegase.m	1	5	0.531
case9Q.m	1	3	0.011
case_ACTIVSg200.m	1	2	0.013

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Table 1 – continued from previous page

File Name	Converged?	# of Iterations	Time [s]
case24_ieee_rts.m	1	4	0.014
case300.m	1	5	0.026
case6495rte.m	1	5	0.204
case39.m	1	1	0.009
case18.m	1	4	0.013
case_RTS_GMLC.m	1	3	0.014
case1951rte.m	1	3	0.047
case6ww.m	1	3	0.010
case5.m	1	3	0.010
case69.m	1	3	0.014
case6515rte.m	1	4	0.168
case2383wp.m	1	6	0.084
case30Q.m	1	3	0.011
case2868rte.m	1	4	0.074
case1354pegase.m	1	4	0.047
case2848rte.m	1	3	0.063
case4_dist.m	1	3	0.010
case6470rte.m	1	4	0.175
case2746wp.m	1	4	0.074
case_SyntheticUSA.m	1	21	11.120
case118.m	1	3	0.014
case30pwl.m	1	3	0.021
case57.m	1	3	0.017
case89pegase.m	1	5	0.024
case6468rte.m	1	6	0.232
case2746wop.m	1	4	0.075
case85.m	1	3	0.011
case22.m	1	2	0.008
case4gs.m	1	3	0.012
case14.m	1	2	0.010
case_ACTIVSg10k.m	1	4	0.251
case2869pegase.m	1	6	0.136
case_ieee30.m	1	2	0.010
case2737sop.m	1	5	0.087
case9target.m	1	5	0.013
case1888rte.m	1	2	0.037
case145.m	1	3	0.018
case_ACTIVSg2000.m	1	3	0.059
case_ACTIVSg70k.m	1	15	7.043
case9241pegase.m	1	6	0.497
case9.m	1	3	0.010
case141.m	1	3	0.012
case_ACTIVSg25k.m	1	7	1.040

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Table 1 – continued from previous page

File Name	Converged?	# of Iterations	Time [s]
case118.m	1	3	0.015
case1354pegase.m	1	4	0.048
case13659pegase.m	1	5	0.523
case14.m	1	2	0.011
case141.m	1	3	0.013
case145.m	1	3	0.017
case18.m	1	4	0.012
case1888rte.m	1	2	0.037
case1951rte.m	1	3	0.052
case22.m	1	2	0.011
case2383wp.m	1	6	0.086
case24_ieee_rts.m	1	4	0.015
case2736sp.m	1	4	0.074
case2737sop.m	1	5	0.108
case2746wop.m	1	4	0.093
case2746wp.m	1	4	0.089
case2848rte.m	1	3	0.065
case2868rte.m	1	4	0.079
case2869pegase.m	1	6	0.137
case30.m	1	3	0.033
case300.m	1	5	0.102
case30Q.m	1	3	0.013
case30pwl.m	1	3	0.013
case39.m	1	1	0.008
case4_dist.m	1	3	0.010
case4gs.m	1	3	0.010
case5.m	1	3	0.011
case57.m	1	3	0.015
case6468rte.m	1	6	0.229
case6470rte.m	1	4	0.170
case6495rte.m	1	5	0.198
case6515rte.m	1	4	0.169
case69.m	1	3	0.012
case6ww.m	1	3	0.011
case85.m	1	3	0.013
case89pegase.m	1	5	0.020
case9.m	1	3	0.010
case9241pegase.m	1	6	0.487
case9Q.m	1	3	0.013
case9target.m	1	5	0.015
case_ACTIVSg10k.m	1	4	0.257
case_ACTIVSg200.m	1	2	0.014
case_ACTIVSg2000.m	1	3	0.058

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Table 1 – continued from previous page

File Name	Converged?	# of Iterations	Time [s]
case_ACTIVSg25k.m	1	7	1.118
case_ACTIVSg500.m	1	3	0.027
case_ACTIVSg70k.m	1	15	6.931
case_RTS_GMLC.m	1	3	0.014
case_SyntheticUSA.m	1	21	11.103
case_ieee30.m	1	2	0.010
case3375wp.m	0	•	0.061
case33bw.m	0	•	0.007
case3120sp.m	0	•	0.037
case3012wp.m	0	•	0.082
case3120sp.m	0	•	0.039
case3375wp.m	0	•	0.059
case33bw.m	0	•	0.007

Model References

Supported Groups and Models

Group	Models
ACLine	Line
ACTopology	Bus
Calculation	ACE, COI
Collection	Area
DCLink	Ground, R, L, C, RCp, RCs, RLs, RLCs, RLCp
DCTopology	Node
Exciter	EXDC2, IEEEEX1, ESDC2A, EXST1, ESST3A, SEXS
Experimental	PI2, TestDB1, TestPI
FreqMeasurement	BusFreq, BusROCOF
PSS	IEEEEST, ST2CUT
PhasorMeasurement	PMU
StaticACDC	VSCShunt
StaticGen	PV, Slack
StaticLoad	PQ
StaticShunt	Shunt
SynGen	GENCLS, GENROU
TimedEvent	Toggler, Fault
TurbineGov	TG2, TGOV1, IEEEG1
Undefined	REGCAU1

5.1 ACLine

Common Parameters: u, name

Available models: *Line*

5.1.1 Line

Group *ACLine*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
bus1		idx of from bus			IdxParam	
bus2		idx of to bus			IdxParam	
Sn	S_n	Power rating	100		NumParam	non_zero
fn	f	rated frequency	60		NumParam	
Vn1	V_{n1}	AC voltage rating	110		NumParam	non_zero
Vn2	V_{n2}	rated voltage of bus2	110		NumParam	non_zero
r	r	line resistance	0.000		NumParam	z
x	x	line reactance	0.000		NumParam	z
b		shared shunt susceptance	0		NumParam	y
g		shared shunt conductance	0		NumParam	y
b1	b_1	from-side susceptance	0		NumParam	
g1	g_1	from-side conductance	0		NumParam	
b2	b_2	to-side susceptance	0		NumParam	
g2	g_2	to-side conductance	0		NumParam	
trans		transformer branch flag	0		NumParam	
tap	t_{ap}	transformer branch tap ratio	1		NumParam	
phi	ϕ	transformer branch phase shift in rad	0		NumParam	
owner		owner code			IdxParam	
xcoord		x coordinates			DataParam	
ycoord		y coordinates			DataParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
a1	a_1		phase angle of the from bus		
a2	a_2		phase angle of the to bus		
v1	v_1		voltage magnitude of the from bus		
v2	v_2		voltage magnitude of the to bus		

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a1	a_1	ExtAlgeb	$u \left(-\frac{v_1 v_2 (-b_{hk} \sin(\phi - a_1 + a_2) + g_{hk} \cos(\phi - a_1 + a_2))}{t_{ap}} + \frac{v_1^2 (g_h + g_{hk})}{t_{ap}^2} \right)$
a2	a_2	ExtAlgeb	$u \left(v_2^2 (g_h + g_{hk}) - \frac{v_1 v_2 (b_{hk} \sin(\phi - a_1 + a_2) + g_{hk} \cos(\phi - a_1 + a_2))}{t_{ap}} \right)$
v1	v_1	ExtAlgeb	$u \left(-\frac{v_1 v_2 (-b_{hk} \cos(\phi - a_1 + a_2) - g_{hk} \sin(\phi - a_1 + a_2))}{t_{ap}} - \frac{v_1^2 (b_h + b_{hk})}{t_{ap}^2} \right)$
v2	v_2	ExtAlgeb	$u \left(-v_2^2 (b_h + b_{hk}) + \frac{v_1 v_2 (b_{hk} \cos(\phi - a_1 + a_2) - g_{hk} \sin(\phi - a_1 + a_2))}{t_{ap}} \right)$

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	$u (ib_h + g_h)$	ConstService
yk	y_k	$u (ib_k + g_k)$	ConstService
yhk	y_{hk}	$\frac{u}{r + i(x + 1.0 \cdot 10^{-8}) + 1.0 \cdot 10^{-8}}$	ConstService
ghk	g_{hk}	$\text{re}(y_{hk})$	ConstService
bhk	b_{hk}	$\text{im}(y_{hk})$	ConstService

5.2 ACTopology

Common Parameters: u, name

Common Variables: a, v

Available models: *Bus*

5.2.1 Bus

Group *ACTopology*

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	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
Vn	V_n	AC voltage rating	110	<i>kV</i>	NumParam	non_zero
vmax	V_{max}	Voltage upper limit	1.100	<i>p.u.</i>	NumParam	
vmin	V_{min}	Voltage lower limit	0.900	<i>p.u.</i>	NumParam	
v0	V_0	initial voltage magnitude	1	<i>p.u.</i>	NumParam	non_zero
a0	θ_0	initial voltage phase angle	0	<i>rad</i>	NumParam	
xcoord		x coordinate (longitude)	0		DataParam	
ycoord		y coordinate (latitude)	0		DataParam	
area		Area code			IdxParam	
zone		Zone code			IdxParam	
owner		Owner code			IdxParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
a	θ	$\theta_0 (1 - z_{flat}) + 1.0 \cdot 10^{-8} z_{flat}$	voltage angle	<i>rad</i>	v_str
v	V	$V_0 (1 - z_{flat}) + z_{flat}$	voltage magnitude	<i>p.u.</i>	v_str

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
flat_start	z_{flat}	0	flat start for voltages	(0, 1)

5.3 Calculation

Group of classes that calculates based on other models.

Common Parameters: u, name

Available models: *ACE*, *COI*

5.3.1 ACE

Group *Calculation*

Area Control Error model.

Note: area idx is automatically retrieved from *bus*.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
bus		bus idx for freq. measurement			IdxParam	mandatory
bias	β	bias parameter	1	<i>MW/0.1Hz</i>	NumParam	power
busf		Optional BusFreq idx			IdxParam	
area			0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
ace	ace		area control error	<i>MW (p.u.)</i>	
f	f		Bus frequency		

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
ace	ace	Algeb	$10\beta (v^{f_s} - 1) - ace$
f	f	ExtAlgeb	0

Discrete

Name	Symbol	Type	Info
fs	f_s	Sampling	Sampled freq.

Config Fields in [ACE]

Option	Symbol	Value	Info	Accepted values
freq_model		BusFreq	default freq. measurement model	('BusFreq',)
interval		4	sampling time interval	
offset		0	sampling time offset	

5.3.2 COI

Group *Calculation*

Center of inertia calculation class.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
M		Linearly stored SynGen.M	0		ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Properties
wgen	ω_{gen}		Linearly stored SynGen.omega		
agen	δ_{gen}		Linearly stored SynGen.delta		
omega	ω_{coi}	$\omega_{gen,0,avg}$	COI speed		v_str,v_setter
delta	δ_{coi}	$\delta_{gen,0,avg}$	COI rotor angle		v_str,v_setter
omega_sub	ω_{sub}		COI frequency contribution of each generator		
delta_sub	δ_{sub}		COI angle contribution of each generator		

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

5.4 Collection

Collection of topology models

Common Parameters: *u*, *name*

Available models: *Area*

5.4.1 Area

Group *Collection*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
<i>idx</i>		unique device idx			DataParam	
<i>u</i>	<i>u</i>	connection status	1	<i>bool</i>	NumParam	
<i>name</i>		device name			DataParam	
<i>Vn</i>			0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
<i>a</i>	<i>a</i>		Bus voltage angle		
<i>v</i>	<i>v</i>		Bus voltage magnitude		

Algebraic Equations

Name	Symbol	Type	RHS of Equation " $0 = g(x, y)$ "
<i>a</i>	<i>a</i>	ExtAlgeb	0
<i>v</i>	<i>v</i>	ExtAlgeb	0

5.5 DCLink

Basic DC links

Common Parameters: *u*, *name*

Available models: *Ground*, *R*, *L*, *C*, *RCp*, *RCs*, *RLs*, *RLCs*, *RLCp*

5.5.1 Ground

Group *DCLink*

Ground model that sets the voltage of the connected DC node.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node		Node index			IdxParam	mandatory
voltage	V_0	Ground voltage (typically 0)	0	<i>p.u.</i>	NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
Idc	I_{dc}	0	Fictitious current injection from ground		v_str
v	v				

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$u(-V_0 + v)$
v	v	ExtAlgeb	$-I_{dc}$

5.5.2 R

Group *DCLink*

Resistive dc line

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
R		DC line resistance	0.010	<i>p.u.</i>	NumParam	non_zero,r

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
Idc	I_{dc}	$\frac{u(-v_1+v_2)}{R}$	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

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}

5.5.3 L

Group *DCLink*

Inductive dc line

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
L		DC line inductance	0.001	<i>p.u.</i>	NumParam	non_zero,r

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
IL	I_L	0	Inductance current	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$-\frac{u(v_1-v_2)}{L}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
v1	v_1	ExtAlgeb	$-I_L$
v2	v_2	ExtAlgeb	I_L

5.5.4 C

Group *DCLink*

Capacitive dc branch

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
C		DC capacitance	0.001	<i>p.u.</i>	NumParam	non_zero,g

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
vC	v_C	0	Capacitor current	<i>p.u.</i>	v_str
Idc	I_{dc}	0	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vC	v_C	State	$-\frac{I_{dc}u}{C}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}(1 - u) + u(-v_1 + v_2 + v_C)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

5.5.5 RCp

Group *DCLink*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
R	R	DC line resistance	0.010	<i>p.u.</i>	NumParam	non_zero,r
C	C	DC capacitance	0.001	<i>p.u.</i>	NumParam	non_zero,g

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
vC	v_C	$v_1 - v_2$	Capacitor current	<i>p.u.</i>	v_str
Idc	I_{dc}	$\frac{-v_1 + v_2}{R}$	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vC	v_C	State	$-\frac{u(I_{dc} - \frac{v_C}{R})}{C}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}(1 - u) + u(-v_1 + v_2 + v_C)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

5.5.6 RCs

Group *DCLink*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
R	R	DC line resistance	0.010	<i>p.u.</i>	NumParam	non_zero,r
C	C	DC capacitance	0.001	<i>p.u.</i>	NumParam	non_zero,g

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
vC	v_C	$v_1 - v_2$	Capacitor current	<i>p.u.</i>	v_str
Idc	I_{dc}	$\frac{-v_1 + v_2}{R}$	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vC	v_C	State	$-\frac{I_{dc}u}{C}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}(1 - u) + u(-I_{dc}R - v_1 + v_2 + v_C)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

5.5.7 RLs

Group *DCLink*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
R	R	DC line resistance	0.010	<i>p.u.</i>	NumParam	non_zero,r
L	L	DC line inductance	0.001	<i>p.u.</i>	NumParam	non_zero,r

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
IL	I_L	$\frac{v_1 - v_2}{R}$	Inductance current	<i>p.u.</i>	v_str
Idc	I_{dc}	$-\frac{u(v_1 - v_2)}{R}$	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$\frac{u(-I_L R + v_1 - v_2)}{L}$	

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}

5.5.8 RLCs

Group *DCLink*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
R	R	DC line resistance	0.010	<i>p.u.</i>	NumParam	non_zero,r
L	L	DC line inductance	0.001	<i>p.u.</i>	NumParam	non_zero,r
C	C	DC capacitance	0.001	<i>p.u.</i>	NumParam	non_zero,g

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
IL	I_L	0	Inductance current	<i>p.u.</i>	v_str
vC	v_C	$v_1 - v_2$	Capacitor current	<i>p.u.</i>	v_str
Idc	I_{dc}	0	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$\frac{u(-I_L R + v_1 - v_2 - v_C)}{L}$	
vC	v_C	State	$\frac{I_L u}{C}$	

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}

5.5.9 RLCp

Group *DCLink*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
node1		Node 1 index			IdxParam	mandatory
node2		Node 2 index			IdxParam	mandatory
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
R	R	DC line resistance	0.010	<i>p.u.</i>	NumParam	non_zero,r
L	L	DC line inductance	0.001	<i>p.u.</i>	NumParam	non_zero,r
C	C	DC capacitance	0.001	<i>p.u.</i>	NumParam	non_zero,g

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
IL	I_L	0	Inductance current	<i>p.u.</i>	v_str
vC	v_C	$v_1 - v_2$	Capacitor current	<i>p.u.</i>	v_str
Idc	I_{dc}	$\frac{-v_1 + v_2}{R}$	Current from node 2 to 1	<i>p.u.</i>	v_str
v1	v_1		DC voltage on node 1		
v2	v_2		DC voltage on node 2		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
IL	I_L	State	$\frac{uv_C}{L}$	
vC	v_C	State	$-\frac{u(-I_L + I_{dc} - \frac{v_C}{R})}{C}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Idc	I_{dc}	Algeb	$I_{dc}(1 - u) + u(-v_1 + v_2 + v_C)$
v1	v_1	ExtAlgeb	$-I_{dc}$
v2	v_2	ExtAlgeb	I_{dc}

5.6 DCTopology

Common Parameters: u, name

Common Variables: v

Available models: *Node*

5.6.1 Node

Group *DCTopology*

DC Node model.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
Vdcn	V_{dcn}	DC voltage rating	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
v0	V_{dc0}	initial voltage magnitude	1	<i>p.u.</i>	NumParam	
xcoord		x coordinate (longitude)	0		DataParam	
ycoord		y coordinate (latitude)	0		DataParam	
area		Area code			IdxParam	
zone		Zone code			IdxParam	
owner		Owner code			IdxParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
v	V_{dc}	$V_{dc0} (1 - z_{flat}) + z_{flat}$	voltage magnitude	<i>p.u.</i>	v_str

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
flat_start	z_{flat}	0	flat start for voltages	(0, 1)

5.7 Exciter

Exciter group for synchronous generators.

Common Parameters: u, name, syn

Common Variables: vout, vi

Available models: *EXDC2*, *IEEEEX1*, *ESDC2A*, *EXST1*, *ESST3A*, *SEXS*

5.7.1 EXDC2

Group *Exciter*

EXDC2 model.

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
syn		Synchronous generator idx			IdxParam	mandatory
TR	T_R	Sensing time constant	0.010	<i>p.u.</i>	NumParam	
TA	T_A	Lag time constant in anti-windup lag	0.040	<i>p.u.</i>	NumParam	
TC	T_C	Lead time constant in lead-lag	1	<i>p.u.</i>	NumParam	
TB	T_B	Lag time constant in lead-lag	1	<i>p.u.</i>	NumParam	
TE	T_E	Exciter integrator time constant	0.800	<i>p.u.</i>	NumParam	
TF1	T_{F1}	Feedback washout time constant	1	<i>p.u.</i>	NumParam	non_zero
KF1	K_{F1}	Feedback washout gain	0.030	<i>p.u.</i>	NumParam	
KA	K_A	Gain in anti-windup lag TF	40	<i>p.u.</i>	NumParam	
KE	K_E	Gain added to saturation	1	<i>p.u.</i>	NumParam	
VR-MAX	V_{RMAX}	Maximum excitation limit	7.300	<i>p.u.</i>	NumParam	
VRMIN	V_{RMIN}	Minimum excitation limit	-7.300	<i>p.u.</i>	NumParam	
E1	E_1	First saturation point	0	<i>p.u.</i>	NumParam	
SE1	S_{E1}	Value at first saturation point	0	<i>p.u.</i>	NumParam	
E2	E_2	Second saturation point	1	<i>p.u.</i>	NumParam	
SE2	S_{E2}	Value at second saturation point	1	<i>p.u.</i>	NumParam	
Sn	S_m	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_m	Rated voltage from generator	0	<i>kV</i>	ExtParam	
bus	bus	Bus idx of the generators	0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
vp	V_p	v_{f0}	Voltage after saturation feedback, before speed term	$p.u.$	v_str
LS_y	y_{LS}	$1.0V$	State in lag transfer function		v_str
LL_x	x'_{LL}	V_i	State in lead-lag		v_str
LA_y	y_{LA}	$K_A y_{LL}$	State in lag TF		v_str
W_x	x'_W	V_p	State in washout filter		v_str
omega	ω		Generator speed		
vout	v_{out}	v_{f0}	Exciter final output voltage		v_str
vref	V_{ref}	V_{ref0}	Reference voltage input	$p.u.$	v_str
Se	$S_e(V_{out})$	S_{e0}	saturation output		v_str
vi	V_i	V_{b0}	Total input voltages	$p.u.$	v_str
LL_y	y_{LL}	V_i	Output of lead-lag		v_str
W_y	y_W	0	Output of washout filter		v_str
vf	v_f		Excitation field voltage to generator		
Xad-Ifd	$X_{ad}I_{fd}$		Armature excitation current		
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation " $\dot{x} = f(x, y)$ "	T (LHS)
vp	V_p	State	$-K_E V_p - S_e(V_{out}) V_p + y_{LA}$	T_E
LS_y	y_{LS}	State	$1.0V - y_{LS}$	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)"
vout	v_{out}	Algeb	$V_p \omega - v_{out}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
Se	$S_e(V_{out})$	Algeb	$\frac{B_{SAT}^q z_0^{SL} (-A_{SAT}^q + V_p)^2}{V_p} - S_e(V_{out})$
vi	V_i	Algeb	$-V_i + V_{ref} - y_{LS} - y_W$
LL_y	y_{LL}	Algeb	$LL_{LT1z1} LL_{LT2z1} (-x'_{LL} + y_{LL}) + T_B x'_{LL} - T_B y_{LL} + T_C (V_i - x'_{LL})$
W_y	y_W	Algeb	$K_{F1} (V_p - x'_W) - T_{F1} y_W$
vf	v_f	ExtAl- geb	$u(-v_{f0} + v_{out})$
Xad- Ifd	$X_{ad} I_{fd}$	ExtAl- geb	0
a	θ	ExtAl- geb	0
v	V	ExtAl- geb	0

Services

Name	Symbol	Equation	Type
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	E_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}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}} ((SE_{SAT}^{2c} > 0) + (SE_{SAT}^{2c} < 0))$	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	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 ((a_{SAT} > 0) + (a_{SAT} < 0))}{(E_{SAT}^{1c} - E_{SAT}^{2c})^2}$	ConstService
Se0	S_{e0}	$\frac{B_{SAT}^q (A_{SAT}^q - v_{f0})^2 (v_{f0} > A_{SAT}^q)}{v_{f0}}$	ConstService
vr0	V_{r0}	$v_{f0} (K_E + S_{e0})$	ConstService
vb0	V_{b0}	$\frac{V_{r0}}{K_A}$	ConstService
vref0	V_{ref0}	$V + V_{b0}$	ConstService

Discrete

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

5.7.2 IEEEEX1

Group *Exciter*

IEEEEX1 Type 1 exciter (DC)

Derived from EXDC2 by varying the limiter bounds.

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
syn		Synchronous generator idx			IdxParam	mandatory
TR	T_R	Sensing time constant	0.010	<i>p.u.</i>	NumParam	
TA	T_A	Lag time constant in anti-windup lag	0.040	<i>p.u.</i>	NumParam	
TC	T_C	Lead time constant in lead-lag	1	<i>p.u.</i>	NumParam	
TB	T_B	Lag time constant in lead-lag	1	<i>p.u.</i>	NumParam	
TE	T_E	Exciter integrator time constant	0.800	<i>p.u.</i>	NumParam	
TF1	T_{F1}	Feedback washout time constant	1	<i>p.u.</i>	NumParam	non_zero
KF1	K_{F1}	Feedback washout gain	0.030	<i>p.u.</i>	NumParam	
KA	K_A	Gain in anti-windup lag TF	40	<i>p.u.</i>	NumParam	
KE	K_E	Gain added to saturation	1	<i>p.u.</i>	NumParam	
VR-MAX	V_{RMAX}	Maximum excitation limit	7.300	<i>p.u.</i>	NumParam	
VRMIN	V_{RMIN}	Minimum excitation limit	-7.300	<i>p.u.</i>	NumParam	
E1	E_1	First saturation point	0	<i>p.u.</i>	NumParam	
SE1	S_{E1}	Value at first saturation point	0	<i>p.u.</i>	NumParam	
E2	E_2	Second saturation point	1	<i>p.u.</i>	NumParam	
SE2	S_{E2}	Value at second saturation point	1	<i>p.u.</i>	NumParam	
Sn	S_m	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_m	Rated voltage from generator	0	<i>kV</i>	ExtParam	
bus	bus	Bus idx of the generators	0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
vp	V_p	v_{f0}	Voltage after saturation feedback, before speed term	<i>p.u.</i>	v_str
LS_y	y_{LS}	$1.0V$	State in lag transfer function		v_str
LL_x	x'_{LL}	V_i	State in lead-lag		v_str
LA_y	y_{LA}	$K_A y_{LL}$	State in lag TF		v_str
W_x	x'_W	V_p	State in washout filter		v_str
omega	ω		Generator speed		
vout	v_{out}	v_{f0}	Exciter final output voltage		v_str
vref	V_{ref}	V_{ref0}	Reference voltage input	<i>p.u.</i>	v_str
Se	$S_e(V_{out})$	S_{e0}	saturation output		v_str
vi	V_i	V_{b0}	Total input voltages	<i>p.u.</i>	v_str
LL_y	y_{LL}	V_i	Output of lead-lag		v_str
W_y	y_W	0	Output of washout filter		v_str
vf	v_f		Excitation field voltage to generator		
Xad-Ifd	$X_{ad}I_{fd}$		Armature excitation current		
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
vp	V_p	State	$-K_E V_p - S_e(V_{out}) V_p + y_{LA}$	T_E
LS_y	y_{LS}	State	$1.0V - y_{LS}$	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)"
vout	v_{out}	Algeb	$V_p - v_{out}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
Se	$S_e(V_{out})$	Algeb	$\frac{B_{SAT}^q z_0^{SL} (-A_{SAT}^q + V_p)^2}{V_p} - S_e(V_{out})$
vi	V_i	Algeb	$-V_i + V_{ref} - y_{LS} - y_W$
LL_y	y_{LL}	Algeb	$LL_{LT1z1} LL_{LT2z1} (-x'_{LL} + y_{LL}) + T_B x'_{LL} - T_B y_{LL} + T_C (V_i - x'_{LL})$
W_y	y_W	Algeb	$K_{F1} (V_p - x'_W) - T_{F1} y_W$
vf	v_f	ExtAl-geb	$u(-v_{f0} + v_{out})$
Xad-Ifd	$X_{ad} I_{fd}$	ExtAl-geb	0
a	θ	ExtAl-geb	0
v	V	ExtAl-geb	0

Services

Name	Symbol	Equation	Type
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	E_2	ConstService
SAT_SE1	SE_{SAT}^{1c}	S_{E1}	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{E2} - 2z_{SAT}^{SE_2^2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}} ((SE_{SAT}^{2c} > 0) + (SE_{SAT}^{2c} < 0))$	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	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 ((a_{SAT} > 0) + (a_{SAT} < 0))}{(E_{SAT}^{1c} - E_{SAT}^{2c})^2}$	ConstService
Se0	S_{e0}	$\frac{B_{SAT}^q (A_{SAT}^q - v_{f0})^2 (v_{f0} > A_{SAT}^q)}{v_{f0}}$	ConstService
vr0	V_{r0}	$v_{f0} (K_E + S_{e0})$	ConstService
vb0	V_{b0}	$\frac{V_{r0}}{K_A}$	ConstService
vref0	V_{ref0}	$V + V_{b0}$	ConstService
VRTMAX	$V_{RMAX} V_T$	$V V_{RMAX}$	VarService
VRTMIN	$V_{RMIN} V_T$	$V V_{RMIN}$	VarService

Discrete

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	<i>SAT</i>	ExcQuadSat	Field voltage saturation
LS	<i>LS</i>	Lag	Sensing lag TF
LL	<i>LL</i>	LeadLag	Lead-lag for internal delays
LA	<i>LA</i>	LagAntiWindup	Anti-windup lag
W	<i>W</i>	Washout	Signal conditioner

5.7.3 ESDC2A

Group *Exciter*

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	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
syn		Synchronous generator idx			IdxParam	mandatory
TR	T_R	Sensing time constant	0.010	<i>p.u.</i>	NumParam	
KA	K_A	Regulator gain	80		NumParam	
TA	T_A	Lag time constant in regulator	0.040	<i>p.u.</i>	NumParam	
TB	T_B	Lag time constant in lead-lag	1	<i>p.u.</i>	NumParam	
TC	T_C	Lead time constant in lead-lag	1	<i>p.u.</i>	NumParam	
VR- MAX	V_{RMAX}	Max. exc. limit (0-unlimited)	7.300	<i>p.u.</i>	NumParam	
VRMIN	V_{RMIN}	Min. excitation limit	-7.300	<i>p.u.</i>	NumParam	
KE	K_E	Saturation feedback gain	1	<i>p.u.</i>	NumParam	
TE	T_E	Integrator time constant	0.800	<i>p.u.</i>	NumParam	
KF	K_F	Feedback gain	0.100		NumParam	
TF1	T_{F1}	Feedback washout time constant	1	<i>p.u.</i>	NumParam	positive
Switch	S_w	Switch that PSS/E did not imple- ment	0	<i>bool</i>	NumParam	
E1	E_1	First saturation point	0	<i>p.u.</i>	NumParam	
SE1	S_{E1}	Value at first saturation point	0	<i>p.u.</i>	NumParam	
E2	E_2	Second saturation point	0	<i>p.u.</i>	NumParam	
SE2	S_{E2}	Value at second saturation point	0	<i>p.u.</i>	NumParam	
Sn	S_m	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_m	Rated voltage from generator	0	<i>kV</i>	ExtParam	
bus	bus	Bus idx of the generators	0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
LG_y	y_{LG}	V	State in lag transfer function		v_str
LL_x	x'_{LL}	V_i	State in lead-lag		v_str
LA_y	y_{LA}	K_{AYLL}	State in lag TF		v_str
INT_y	y_{INT}	v_{f0}	Integrator output		v_str
WF_x	x'_{WF}	y_{INT}	State in washout filter		v_str
omega	ω		Generator speed		
vout	v_{out}	v_{f0}	Exciter final output voltage		v_str
vref	V_{ref}	V_{ref0}	Reference voltage input	<i>p.u.</i>	v_str
vi	V_i	$-V + V_{ref0}$	Total input voltages	<i>p.u.</i>	v_str
LL_y	y_{LL}	V_i	Output of lead-lag		v_str
UEL	U_{EL}	0	Interface var for under exc. limiter		v_str
HG_y	y_{HG}	$HG_{sls0}U_{EL} + HG_{sls1}y_{LL}$	HVGate output		v_str
Se	$S_e(V_{out})$	S_{e0}	saturation output		v_str
VFE	V_{FE}	V_{FE0}	Combined saturation feedback	<i>p.u.</i>	v_str
WF_y	y_{WF}	0	Output of washout filter		v_str
vf	v_f		Excitation field voltage to generator		
Xad-Ifd	$X_{ad}I_{fd}$		Armature excitation current		
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$V - y_{LG}$	T_R
LL_x	x'_{LL}	State	$V_i - x'_{LL}$	T_B
LA_y	y_{LA}	State	$K_{AYLL} - y_{LA}$	T_A
INT_y	y_{INT}	State	$-V_{FE} + y_{LA}$	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)"
vout	v_{out}	Algeb	$-v_{out} + y_{INT}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-V - V_i + V_{ref} - y_{WF}$
LL_y	y_{LL}	Algeb	$LL_{LT1z1}LL_{LT2z1}(-x'_{LL} + y_{LL}) + T_Bx'_{LL} - T_By_{LL} + T_C(V_i - x'_{LL})$
UEL	U_{EL}	Algeb	$-U_{EL}$
HG_y	y_{HG}	Algeb	$HG_{sls0}U_{EL} + HG_{sls1}y_{LL} - y_{HG}$
Se	$S_e(V_{out})$	Algeb	$\frac{B_{SAT}^q z_0^{SL} (-A_{SAT}^q + y_{INT})^2}{y_{INT}} - S_e(V_{out})$
VFE	V_{FE}	Algeb	$-V_{FE} + y_{INT}(K_E + S_e(V_{out}))$
WF_y	y_{WF}	Algeb	$K_F(-x'_{WF} + y_{INT}) - T_{F1}y_{WF}$
vf	v_f	ExtAl- geb	$u(-v_{f0} + v_{out})$
Xad- Ifd	$X_{ad}I_{fd}$	ExtAl- geb	0
a	θ	ExtAl- geb	0
v	V	ExtAl- geb	0

Services

Name	Symbol	Equation	Type
VRMAXc	$VRMAXc$	$VRMAX - 999z_{VRMAX} + 999$	ConstService
SAT_E1	E_{SAT}^{1c}	E_1	ConstService
SAT_E2	E_{SAT}^{2c}	E_2	ConstService
SAT_SE1	SE_{SAT}^{1c}	SE_1	ConstService
SAT_SE2	SE_{SAT}^{2c}	$SE_2 - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}} ((SE_{SAT}^{2c} > 0) + (SE_{SAT}^{2c} < 0))$	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	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 ((a_{SAT} > 0) + (a_{SAT} < 0))}{(E_{SAT}^{1c} - E_{SAT}^{2c})^2}$	ConstService
Se0	S_{e0}	$\frac{B_{SAT}^q (A_{SAT}^q - v_{f0})^2 (v_{f0} > A_{SAT}^q)}{v_{f0}}$	ConstService
vfe0	V_{FE0}	$v_{f0}(K_E + S_{e0})$	ConstService
vref0	V_{ref0}	$V + \frac{V_{FE0}}{K_A}$	ConstService
VRU	$V_T V_{RMAX}$	$V V_{RMAXc}$	VarService
VRL	$V_T V_{RMIN}$	$V V_{RMIN}$	VarService

Discrete

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HG_sl	$None_{HG}$	Selector	HVGate Selector
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

5.7.4 EXST1

Group *Exciter*

EXST1-type static excitation system.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
syn		Synchronous generator idx			IdxParam	mandatory
TR	T_R	Measurement delay	0.010		NumParam	
VIMAX	V_{IMAX}	Max. input voltage	0.200		NumParam	
VIMIN	V_{IMIN}	Min. input voltage	0		NumParam	
TC	T_C	LL numerator	1		NumParam	
TB	T_B	LL denominator	1		NumParam	
KA	K_A	Regulator gain	80		NumParam	
TA	T_A	Regulator delay	0.050		NumParam	
VRMAX	V_{RMAX}	Max. regulator output	8		NumParam	
VRMIN	V_{RMIN}	Min. regulator output	-3		NumParam	
KC	K_C	Coef. for Ifd	0.200		NumParam	
KF	K_F	Feedback gain	0.100		NumParam	
TF	T_F	Feedback delay	1		NumParam	positive
Sn	S_m	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_m	Rated voltage from generator	0	<i>kV</i>	ExtParam	
bus	bus	Bus idx of the generators	0		ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Proper- ties
LG_y	y_{LG}	V	State in lag transfer function		v_str
LL_x	x'_{LL}	V_l	State in lead-lag		v_str
LR_y	y_{LR}	$K_A y_{LL}$	State in lag transfer function		v_str
WF_x	x'_{WF}	y_{LR}	State in washout filter		v_str
omega	ω		Generator speed		
vout	v_{out}	v_{f0}	Exciter final output voltage		v_str
vref	V_{ref}	V_{ref0}	Reference voltage input	<i>p.u.</i>	v_str
vi	V_i	$\frac{v_{f0}}{K_A}$	Total input voltages	<i>p.u.</i>	v_str
vl	V_l	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$	Input after limiter		v_str
LL_y	y_{LL}	V_l	Output of lead-lag		v_str
WF_y	y_{WF}	0	Output of washout filter		v_str
vf-max	V_{fmax}	$-K_C X_{ad} I_{fd} + V_{RMAX}$	Upper bound of output limiter		v_str
vfmin	V_{fmin}	$-K_C X_{ad} I_{fd} + V_{RMIN}$	Lower bound of output limiter		v_str
vf	v_f		Excitation field voltage to generator		
Xad-Ifd	$X_{ad} I_{fd}$		Armature excitation current		
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$V - y_{LG}$	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)"
vout	v_{out}	Algeb	$V_{fmax}z_u^{HLR} + V_{fmin}z_l^{HLR} - v_{out} + y_{LR}z_i^{HLR}$
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	$LL_{LT1z1}LL_{LT2z1}(-x'_{LL} + y_{LL}) + T_Bx'_{LL} - T_By_{LL} + T_C(V_l - x'_{LL})$
WF_y	y_{WF}	Algeb	$K_F(-x'_{WF} + y_{LR}) - T_Fy_{WF}$
vfmax	V_{fmax}	Algeb	$-K_CX_{ad}I_{fd} + V_{RMAX} - V_{fmax}$
vfmin	V_{fmin}	Algeb	$-K_CX_{ad}I_{fd} + V_{RMIN} - V_{fmin}$
vf	v_f	ExtAlgeb	$u(-v_{f0} + v_{out})$
Xad-Ifd	$X_{ad}I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
v	V	ExtAlgeb	0

Services

Name	Symbol	Equation	Type
vref0	V_{ref0}	$V + \frac{v_{f0}}{K_A}$	ConstService

Discrete

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

5.7.5 ESST3A

Group *Exciter*

Static exciter type 3A model

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
syn		Synchronous generator idx			Idx- Param	manda- tory
TR	T_R	Sensing time constant	0.010	<i>p.u.</i>	NumParam	
VI- MAX	V_{IMAX}	Max. input voltage	0.800		NumParam	
VIMIN	V_{IMIN}	Min. input voltage	- 0.100		NumParam	
KM	K_M	Forward gain constant	500		NumParam	
TC	T_C	Lead time constant in lead-lag	3		NumParam	
TB	T_B	Lag time constant in lead-lag	15		NumParam	
KA	K_A	Gain in anti-windup lag TF	50		NumParam	
TA	T_A	Lag time constant in anti-windup lag	0.100		NumParam	
VR- MAX	V_{RMAX}	Maximum excitation limit	8	<i>p.u.</i>	NumParam	
VR- MIN	V_{RMIN}	Minimum excitation limit	0	<i>p.u.</i>	NumParam	
KG	K_G	Feedback gain of inner field regulator	1		NumParam	
KP	K_P	Potential circuit gain coeff.	4		NumParam	
KI	K_I	Potential circuit gain coeff.	0.100		NumParam	
VB- MAX	V_{BMAX}	VB upper limit	18	<i>p.u.</i>	NumParam	
KC	K_C	Rectifier loading factor proportional to com- mutating reactance	0.100		NumParam	
XL	X_L	Potential source reactance	0.010		NumParam	
VG- MAX	V_{GMAX}	VG upper limit	4	<i>p.u.</i>	NumParam	
THETAP	θ_P	Rectifier firing angle	0	<i>de- gree</i>	NumParam	
TM	K_C	Inner field regulator forward time constant	0.100		NumParam	
VM- MAX	V_{MMAX}	Maximum VM limit	1	<i>p.u.</i>	NumParam	
VM- MIN	V_{RMIN}	Minimum VM limit	0.100	<i>p.u.</i>	NumParam	
Sn	S_m	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_m	Rated voltage from generator	0	<i>kV</i>	ExtParam	
bus	<i>bus</i>	Bus idx of the generators	0		ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Prop- erties
LG_y	y_{LG}	V	State in lag transfer function		v_str
LL_x	x'_{LL}	y_{HG}	State in lead-lag		v_str
LAW1_y	y_{LAW1}	K_{AYLL}	State in lag TF		v_str
LAW2_y	y_{LAW2}	$K_M V_{RS}$	State in lag TF		v_str
omega	ω		Generator speed		
vout	v_{out}	v_{f0}	Exciter final output voltage		v_str
UEL	U_{EL}	0	Interface var for under exc. limiter		v_str
IN	I_N	$\frac{K_C X_{ad} I_{fd}}{V_E}$	Input to FEX		v_str
FEX_y	y_{FEX}	$\begin{cases} 1 & \text{for } I_N \leq 0 \\ 1 - 0.577 I_N & \text{for } I_N \leq 0.433 \\ \sqrt{0.75 - I_N^2} & \text{for } I_N \leq 0.707 \\ 1.732 - 1.732 I_N & \text{for } I_N \leq 1 \\ 0 & \text{otherwise} \end{cases}$	Output of piecewise		v_str
VB_x	x_{VB}	$V_E y_{FEX}$	Gain output before limiter		v_str
VB_y	y_{VB}	$\frac{V_{Blimzi} x_{VB}}{V_{Blimzu} V_{BMAX}}$	Gain output after limiter		v_str
VG_x	x_{VG}	$K_G v_{out}$	Gain output before limiter		v_str
VG_y	y_{VG}	$\frac{V_{Glimzi} x_{VG}}{V_{Glimzu} V_{GMAX}}$	Gain output after limiter		v_str
vrs	V_{RS}	$\frac{v_{f0}}{K_M y_{VB}}$	VR subtract feedback VG		v_str
vref	V_{ref}	$V + \frac{V_{RS} + y_{VG}}{K_A}$	Reference voltage input	p.u.	v_str
vi	V_i	$-V + V_{ref}$	Total input voltages	p.u.	v_str
vil	V_{il}	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI}$	Input voltage after limit		v_str
HG_y	y_{HG}	$HG_{sls0} U_{EL} + HG_{sls1} V_{il}$	HVGate output		v_str
LL_y	y_{LL}	y_{HG}	Output of lead-lag		v_str
vf	v_f		Excitation field voltage to generator		
XadIfd	$X_{ad} I_{fd}$		Armature excitation current		
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		
vd	V_d		d-axis machine voltage		
vq	V_q		q-axis machine voltage		
Id	I_d		d-axis machine current		
Iq	I_q		q-axis machine current		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
LG_y	y_{LG}	State	$V - y_{LG}$	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

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
vout	v_{out}	Algeb	$-v_{out} + y_{LAW2}y_{VB}$
UEL	U_{EL}	Algeb	$-U_{EL}$
IN	I_N	Algeb	$-I_N + \frac{K_C X_{ad} I_{fd}}{V_E}$
FEX_y	y_{FEX}	Algeb	$-y_{FEX} + \begin{cases} 1 & \text{for } I_N \leq 0 \\ 1 - 0.577 I_N & \text{for } I_N \leq 0.433 \\ \sqrt{0.75 - I_N^2} & \text{for } I_N \leq 0.75 \\ 1.732 - 1.732 I_N & \text{for } I_N \leq 1 \\ 0 & \text{otherwise} \end{cases}$
VB_x	x_{VB}	Algeb	$V_E y_{FEX} - x_{VB}$
VB_y	y_{VB}	Algeb	$V B_{limzi} x_{VB} + V B_{limzu} V_{BMAX} - y_{VB}$
VG_x	x_{VG}	Algeb	$K_G v_{out} - x_{VG}$
VG_y	y_{VG}	Algeb	$V G_{limzi} x_{VG} + V G_{limzu} V_{GMAX} - y_{VG}$
vrs	V_{RS}	Algeb	$-V_{RS} + y_{LAW1} - y_{VG}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-V_i + V_{ref} - y_{LG}$
vil	V_{il}	Algeb	$V_i z_i^{HLI} + V_{IMAX} z_u^{HLI} + V_{IMIN} z_l^{HLI} - V_{il}$
HG_y	y_{HG}	Algeb	$HG_{sls0} U_{EL} + HG_{sls1} V_{il} - y_{HG}$
LL_y	y_{LL}	Algeb	$LL_{LT1z1} LL_{LT2z1} (-x'_{LL} + y_{LL}) + T_B x'_{LL} - T_B y_{LL} + T_C (-x'_{LL} + y_{HG})$
vf	v_f	ExtAlgeb	$u(-v_{f0} + v_{out})$
Xad-Ifd	$X_{ad} I_{fd}$	ExtAlgeb	0
a	θ	ExtAlgeb	0
v	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
KPC	K_{PC}	$K_P e^{i \text{radians}(\theta_P)}$	ConstService
VE	V_E	$ K_{PC}(V_d + iV_q) + i(I_d + iI_q)(K_I + K_{PC}X_L) $	VarService
vref0	V_{ref0}	V_{ref}	PostInitService

Discrete

Name	Symbol	Type	Info
VB_lim	lim_{VB}	HardLimiter	
VG_lim	lim_{VG}	HardLimiter	
HG_sl	$None_{HG}$	Selector	HVGate Selector
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

5.7.6 SEXS

Group *Exciter*

Simplified Excitation System Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
syn		Synchronous generator idx			IdxParam	mandatory
TATB	T_A/T_B	Time constant TA/TB	0.400		NumParam	
TB	T_B	Time constant TB in LL	5		NumParam	
K	K	Gain	20		NumParam	non_zero
TE	T_E	AW Lag time constant	1		NumParam	
EMIN	E_{MIN}	lower limit	-99		NumParam	
EMAX	E_{MAX}	upper limit	99		NumParam	
Sn	S_m	Rated power from generator	0	MVA	ExtParam	
Vn	V_m	Rated voltage from generator	0	kV	ExtParam	
bus	bus	Bus idx of the generators	0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
LL_x	x'_{LL}	V_i	State in lead-lag		v_str
LAW_y	y_{LAW}	Ky_{LL}	State in lag TF		v_str
omega	ω		Generator speed		
vout	v_{out}	v_{f0}	Exciter final output voltage		v_str
vref	V_{ref}	V_{ref0}	Reference voltage input	<i>p.u.</i>	v_str
vi	V_i	$-V + V_{ref0}$	Total input voltages	<i>p.u.</i>	v_str
LL_y	y_{LL}	V_i	Output of lead-lag		v_str
vf	v_f		Excitation field voltage to generator		
XadIfd	$X_{ad}I_{fd}$		Armature excitation current		
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

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	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
vout	v_{out}	Algeb	$-v_{out} + y_{LAW}$
vref	V_{ref}	Algeb	$V_{ref0} - V_{ref}$
vi	V_i	Algeb	$-V - V_i + V_{ref}$
LL_y	y_{LL}	Algeb	$LL_{LT1z1}LL_{LT2z1}(-x'_{LL} + y_{LL}) + TA(V_i - x'_{LL}) + T_Bx'_{LL} - T_By_{LL}$
vf	v_f	ExtAl- geb	$u(-v_{f0} + v_{out})$
Xad- Ifd	$X_{ad}I_{fd}$	ExtAl- geb	0
a	θ	ExtAl- geb	0
v	V	ExtAl- geb	0

Services

Name	Symbol	Equation	Type
TA	TA	$T_A/T_B T_B$	ConstService
vref0	V_{ref0}	$V + \frac{v_{f0}}{K}$	ConstService

Discrete

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	

5.8 Experimental

Experimental group

Common Parameters: u , name

Available models: *PI2*, *TestDB1*, *TestPI*

5.8.1 PI2

Group *Experimental*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
Kp					NumParam	
Ki					NumParam	
Wmax					NumParam	
Wmin					NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
u_{in}	u_{in}	0			v_str
x	x	0.05			v_str
y	y	0.05			v_str
w	w	0.05			v_str

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
uin	u_{in}	State	$\begin{cases} 0 & \text{for } t_{dae} \leq 0 \\ 1 & \text{for } t_{dae} \leq 2 \\ -1 & \text{for } t_{dae} < 6 \\ 1 & \text{otherwise} \end{cases}$	
x	x	State	$K i u_{in} z_i^{HL}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
y	y	Algeb	$K p u_{in} + x - y$
w	w	Algeb	$W max z_u^{HL} + W min z_l^{HL} - w + y z_i^{HL}$

Discrete

Name	Symbol	Type	Info
HL	HL	HardLimiter	

5.8.2 TestDB1

Group *Experimental*

Test model for *DeadBand1*.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Proper- ties
uin	u_{in}	-10			v_str
DB_y	y_{DB}	$DB_{dbzl}(u_{in} + 5)$ $DB_{dbzu}(u_{in} - 5)$	+ Deadband type 1 out- put		v_str

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
uin	u_{in}	Algeb	$t_{dae} - u_{in} - 10$
DB_y	y_{DB}	Algeb	$DB_{dbzl}(u_{in} + 5) + DB_{dbzu}(u_{in} - 5) - y_{DB}$

Discrete

Name	Symbol	Type	Info
DB_db	db_{DB}	DeadBand	

Blocks

Name	Symbol	Type	Info
DB	DB	DeadBand1	

5.8.3 TestPI

Group *Experimental*

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
PI_xi	xi_{PI}	0.0	Integrator output		v_str
PIAW_xi	xi_{PIAW}	0.0	Integrator output		v_str
PIF_xi	xi_{PIF}	0	Integrator output		v_str
uin	u_{in}	0			v_str
zf	z_f	0			v_str
PI_y	y_{PI}	u_{in}	PI output		v_str
PIAW_ys	ys_{PIAW}	$0.5u_{in}$	PI summation before limit		v_str
PIAW_y	y_{PIAW}	$PIAW_{limzi}ys_{PIAW} - 0.5PIAW_{limzl} + 0.5PIAW_{limzu}$	PI output		v_str
PIF_y	y_{PIF}	$0.5u_{in}$	PI output		v_str

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
PI_xi	xi_{PI}	State	$0.1u_{in}$	
PIAW_xi	xi_{PIAW}	State	$0.5u_{in} + 1.0y_{PIAW} - 1.0ys_{PIAW}$	
PIF_xi	xi_{PIF}	State	$u_{in} (0.5 - 0.5z_f)$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
uin	u_{in}	Algeb	$-u_{in} + \sin(t_{dae})$
zf	z_f	Algeb	$-z_f + \begin{cases} 0 & \text{for } t_{dae} \leq 2 \\ 1 & \text{for } t_{dae} \leq 6 \\ 0 & \text{otherwise} \end{cases}$
PI_y	y_{PI}	Algeb	$u_{in} + x_{iPI} - y_{PI}$
PIAW_ys	y_{SPIAW}	Algeb	$0.5u_{in} + x_{iPIAW} - y_{SPIAW}$
PIAW_y	y_{PIAW}	Algeb	$PIAW_{limzi}y_{SPIAW} - 0.5PIAW_{limzl} + 0.5PIAW_{limzu} - y_{PIAW}$
PIF_y	y_{PIF}	Algeb	$(1 - z_f)(0.5u_{in} + x_{iPIF} - y_{PIF})$

Discrete

Name	Symbol	Type	Info
PIAW_lim	lim_{PIAW}	HardLimiter	

Blocks

Name	Symbol	Type	Info
PI	PI	PIController	
PIAW	$PIAW$	PITrackAW	
PIF	PIF	PIFreeze	

5.9 FreqMeasurement

Frequency measurements.

Common Parameters: u, name

Common Variables: f

Available models: *BusFreq*, *BusROCOF*

5.9.1 BusFreq

Group *FreqMeasurement*

Bus frequency measurement.

Bus frequency output variable is f .

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
bus		bus idx			IdxParam	mandatory
Tf	T_f	input digital filter time const	0.020	<i>sec</i>	NumParam	
Tw	T_w	washout time const	0.020	<i>sec</i>	NumParam	
fn	f_n	nominal frequency	60	<i>Hz</i>	NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
L_y	y_L	$\theta - \theta_0$	State in lag transfer function		v_str
WO_x	x'_{WO}	y_L	State in washout filter		v_str
WO_y	y_{WO}	0	Output of washout filter		v_str
f	f	1	frequency output	<i>p.u. (Hz)</i>	v_str
a	θ				
v	V				

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	$1/\omega_n (-x'_{WO} + y_L) - T_w y_{WO}$
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

5.9.2 BusROCOF

Group *FreqMeasurement*

Bus frequency and ROCOF measurement.

The ROCOF output variable is Wf_y .

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
bus		bus idx			IdxParam	mandatory
Tf	T_f	input digital filter time const	0.020	<i>sec</i>	NumParam	
Tw	T_w	washout time const	0.020	<i>sec</i>	NumParam	
fn	f_n	nominal frequency	60	<i>Hz</i>	NumParam	
Tr	T_r	frequency washout time constant	0.100		NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
L_y	y_L	$\theta - \theta_0$	State in lag transfer function		v_str
WO_x	x'_{WO}	y_L	State in washout filter		v_str
Wf_x	x'_{Wf}	f	State in washout filter		v_str
WO_y	y_{WO}	0	Output of washout filter		v_str
f	f	1	frequency output	<i>p.u. (Hz)</i>	v_str
Wf_y	y_{Wf}	0	Output of washout filter		v_str
a	θ				
v	V				

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	$1/\omega_n (-x'_{WO} + y_L) - T_w y_{WO}$
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
iw _n	$1/\omega_n$	$\frac{u}{2\pi f_n}$	ConstService

Blocks

Name	Symbol	Type	Info
L	L	Lag	digital filter
WO	WO	Washout	angle washout
Wf	Wf	Washout	frequency washout yielding ROCOF

5.10 PSS

Power system stabilizer group.

Common Parameters: u, name

Common Variables: vsout

Available models: *IEEEST*, *ST2CUT*

5.10.1 IEEEST

Group *PSS*

IEEEST stabilizer model. Automatically adds frequency measurement devices if not provided.

Input signals (MODE):

1 (s0) - Rotor speed deviation (p.u.), 2 (s1) - Bus frequency deviation (*) (p.u.), 3 (s2) - Generator P electrical in Gen MVABase (p.u.), 4 (s3) - Generator accelerating power (p.u.), 5 (s4) - Bus voltage (p.u.), 6 (s5) - 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 *F1*, *F2*, *LL1*, *LL2* and *WO* in sequence. Two limiters are named *VLIM* and *OLIM* in sequence.

Parameters

Name	Symbol	Description	Default	Unit	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
avr		Exciter idx			IdxParam	mandatory
MODE		Input signal			NumParam	mandatory
busr		Optional remote bus idx			IdxParam	
busf		BusFreq idx for mode 2			IdxParam	
A1	A_1	filter time const. (pole)	1		NumParam	
A2	A_2	filter time const. (pole)	1		NumParam	
A3	A_3	filter time const. (pole)	1		NumParam	
A4	A_4	filter time const. (pole)	1		NumParam	
A5	A_5	filter time const. (zero)	1		NumParam	
A6	A_6	filter time const. (zero)	1		NumParam	
T1	T_1	first leadlag time const. (zero)	1		NumParam	
T2	T_2	first leadlag time const. (pole)	1		NumParam	
T3	T_3	second leadlag time const. (pole)	1		NumParam	
T4	T_4	second leadlag time const. (pole)	1		NumParam	
T5	T_5	washout time const. (zero)	1		NumParam	
T6	T_6	washout time const. (pole)	1		NumParam	
KS	K_S	Gain before washout	1		NumParam	
LSMAX	L_{SMAX}	Max. output limit	0.300		NumParam	
LSMIN	L_{SMIN}	Min. output limit	-0.300		NumParam	
VCU	V_{CU}	Upper enabling bus voltage	999	<i>p.u.</i>	NumParam	
VCL	V_{CL}	Upper enabling bus voltage	-999	<i>p.u.</i>	NumParam	
syn		Retrieved generator idx	0		ExtParam	
bus		Retrieved bus idx			ExtParam	
Sn	S_n	Generator power base	0		ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Proper- ties
F1_x	x'_{F1}	0	State in 2nd order LPF		v_str
F1_y	y_{F1}	S_{ig}	Output of 2nd order LPF		v_str
F2_x1	x'_{F2}	0	State #1 in 2nd order lead-lag		v_str
F2_x2	x''_{F2}	y_{F1}	State #2 in 2nd order lead-lag		v_str
LL1_x	x'_{LL1}	y_{F2}	State in lead-lag		v_str
LL2_x	x'_{LL2}	y_{LL1}	State in lead-lag		v_str
WO_x	x'_{WO}	y_{Vks}	State in washout filter		v_str
omega	ω		Generator speed	<i>p.u.</i>	
vsout	v_{sout}		PSS output voltage to exciter		
sig	S_{ig}	$V s_4^{SW} + s_0^{SW}(\omega - 1) + s_3^{SW}(\tau_m - \tau_{m0}) + \frac{\tau_{m0} s_2^{SW}}{(Sb/\bar{S}n)}$	Input signal		v_str
F2_y	y_{F2}	y_{F1}	Output of 2nd order lead-lag		v_str
LL1_y	y_{LL1}	y_{F2}	Output of lead-lag		v_str
LL2_y	y_{LL2}	y_{LL1}	Output of lead-lag		v_str
Vks_y	y_{Vks}	K_{SYLL2}	Gain output		v_str
WO_y	y_{WO}	$WO_{LTz1} x'_{WO}$	Output of washout filter		v_str
Vss	V_{ss}		Voltage output before output limiter		
tm	τ_m		Generator mechanical input		
te	τ_e		Generator electrical output		
v	V		Bus (or busr, if given) terminal voltage		
f	f		Bus frequency		
vi	v_i		Exciter input voltage		

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	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
vsout	v_{sout}	Algeb	$V_{ss}z_i^{OLIM} - v_{sout}$
sig	S_{ig}	Algeb	$-S_{ig} + V s_4^{SW} + V^{dv} s_5^{SW} + s_0^{SW} (\omega - 1) + s_1^{SW} (f - 1) + s_3^{SW} (\tau_m - \tau_{m0}) + \frac{\tau_e s_2^{SW}}{(Sb/Sn)}$
F2_y	y_{F2}	Algeb	$A_4 A_5 x'_{F2} + A_4 x''_{F2} - A_4 y_{F2} + A_6 (-A_3 x'_{F2} - x''_{F2} + y_{F1}) + F_{2LT1z1} F_{2LT2z1} F_{2LT3z1} F_{2LT4z1} (-x''_{F2} + y_{F2})$
LL1_y	y_{LL1}	Algeb	$LL_{1LT1z1} LL_{1LT2z1} (-x'_{LL1} + y_{LL1}) + T_1 (-x'_{LL1} + y_{F2}) + T_2 x'_{LL1} - T_2 y_{LL1}$
LL2_y	y_{LL2}	Algeb	$LL_{2LT1z1} LL_{2LT2z1} (-x'_{LL2} + y_{LL2}) + T_3 (-x'_{LL2} + y_{LL1}) + T_4 x'_{LL2} - T_4 y_{LL2}$
Vks_y	y_{Vks}	Algeb	$K_S y_{LL2} - y_{Vks}$
WO_y	y_{WO}	Algeb	$T_5 WO_{LTz0} (-x'_{WO} + y_{Vks}) + T_6 WO_{LTz1} x'_{WO} - T_6 y_{WO}$
Vss	V_{ss}	Algeb	$L_{SMAX} z_u^{VLIM} + L_{SMIN} z_l^{VLIM} - V_{ss} + y_{WO} z_i^{VLIM}$
tm	τ_m	Ex- tAl- geb	0
te	τ_e	Ex- tAl- geb	0
v	V	Ex- tAl- geb	0
f	f	Ex- tAl- geb	0
vi	v_i	Ex- tAl- geb	$u v_{sout}$

Discrete

Name	Symbol	Type	Info
dv	dv	Derivative	
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 [IEEEEST]

Option	Symbol	Value	Info	Accepted values
freq_model		BusFreq	default freq. measurement model	('BusFreq',)

5.10.2 ST2CUT

Group *PSS*

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	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
avr		Exciter idx			IdxParam	mandatory
MODE		Input signal 1			NumParam	mandatory
busr		Remote bus 1			NumParam	
busf		BusFreq idx for signal 1 mode 2			IdxParam	
MODE2		Input signal 2			NumParam	
busr2		Remote bus 2			NumParam	
busf2		BusFreq idx for signal 2 mode 2			IdxParam	
K1	K_1	Transducer 1 gain	1		NumParam	
K2	K_2	Transducer 2 gain	1		NumParam	
T1	T_1	Transducer 1 time const.	1		NumParam	
T2	T_2	Transducer 2 time const.	1		NumParam	
T3	T_3	Washout int. time const.	1		NumParam	
T4	T_4	Washout delay time const.	0.200		NumParam	
T5	T_5	Leadlag 1 time const. (1)	1		NumParam	
T6	T_6	Leadlag 1 time const. (2)	0.500		NumParam	
T7	T_7	Leadlag 2 time const. (1)	1		NumParam	
T8	T_8	Leadlag 2 time const. (2)	1		NumParam	
T9	T_9	Leadlag 3 time const. (1)	1		NumParam	
T10	T_{10}	Leadlag 3 time const. (2)	0.200		NumParam	
LSMAX	L_{SMAX}	Max. output limit	0.300		NumParam	
LSMIN	L_{SMIN}	Min. output limit	-0.300		NumParam	
VCU	V_{CU}	Upper enabling bus voltage	999	<i>p.u.</i>	NumParam	
VCL	V_{CL}	Upper enabling bus voltage	-999	<i>p.u.</i>	NumParam	
syn		Retrieved generator idx	0		ExtParam	
bus		Retrieved bus idx			ExtParam	
Sn	S_n	Generator power base	0		ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Prop- erties
L1_y	y_{L1}	$K_1 S_{ig}$	State in lag transfer func- tion		v_str
L2_y	y_{L2}	$K_2 S_{ig2}$	State in lag transfer func- tion		v_str
WO_x	x'_{WO}	I_N	State in washout filter		v_str
LL1_x	x'_{LL1}	y_{WO}	State in lead-lag		v_str
LL2_x	x'_{LL2}	y_{LL1}	State in lead-lag		v_str
LL3_x	x'_{LL3}	y_{LL2}	State in lead-lag		v_str
omega	ω		Generator speed	<i>p.u.</i>	
vsout	v_{sout}		PSS output voltage to ex- citer		
sig	S_{ig}	$V s_5^{SW} + s_1^{SW} (\omega - 1) + s_4^{SW} (\tau_m - \tau_{m0}) + \frac{\tau_{m0} s_3^{SW}}{(Sb/Sn)}$	Input signal		v_str
sig2	S_{ig2}	$V s_5^{SW_2} + s_1^{SW_2} (\omega - 1) + s_4^{SW_2} (\tau_m - \tau_{m0}) + \frac{\tau_{m0} s_3^{SW_2}}{(Sb/Sn)}$	Input signal 2		v_str
IN	I_N	$y_{L1} + y_{L2}$	Sum of inputs		v_str
WO_y	y_{WO}	$WO_{LTz1} x'_{WO}$	Output of washout filter		v_str
LL1_y	y_{LL1}	y_{WO}	Output of lead-lag		v_str
LL2_y	y_{LL2}	y_{LL1}	Output of lead-lag		v_str
LL3_y	y_{LL3}	y_{LL2}	Output of lead-lag		v_str
VSS_x	x_{VSS}	y_{LL3}	Gain output before limiter		v_str
VSS_y	y_{VSS}	$L_{SMAX} VSS_{limzu} + L_{SMIN} VSS_{limzl} + VSS_{limzi} x_{VSS}$	Gain output after limiter		v_str
tm	τ_m		Generator mechanical input		
te	τ_e		Generator electrical output		
v	V		Bus (or busr, if given) ter- minal voltage		
f	f		Bus frequency		
vi	v_i		Exciter input voltage		
v2	V		Bus (or busr2, if given) ter- minal voltage		
f2	f_2		Bus frequency 2		

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	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
vsout	v_{sout}	Algeb	$-v_{sout} + y_{VSS} z_i^{OLIM}$
sig	S_{ig}	Algeb	$-S_{ig} + V s_5^{SW} + V^{dv} s_6^{SW} + s_1^{SW} (\omega - 1) + s_2^{SW} (f - 1) + s_4^{SW} (\tau_m - \tau_{m0}) + \frac{\tau_e s_3^{SW}}{(Sb/Sn)}$
sig2	S_{ig2}	Algeb	$-S_{ig2} + V s_5^{SW_2} + V^{dv_2} s_6^{SW_2} + s_1^{SW_2} (\omega - 1) + s_2^{SW_2} (f_2 - 1) + s_4^{SW_2} (\tau_m - \tau_{m0}) + \frac{\tau_e s_3^{SW_2}}{(Sb/Sn)}$
IN	I_N	Algeb	$-I_N + y_{L1} + y_{L2}$
WO_y	y_{WO}	Algeb	$T_3 WO_{LTz0} (I_N - x'_{WO}) + T_4 WO_{LTz1} x'_{WO} - T_4 y_{WO}$
LL1_y	y_{LL1}	Algeb	$LL_{1LT1z1} LL_{1LT2z1} (-x'_{LL1} + y_{LL1}) + T_5 (-x'_{LL1} + y_{WO}) + T_6 x'_{LL1} - T_6 y_{LL1}$
LL2_y	y_{LL2}	Algeb	$LL_{2LT1z1} LL_{2LT2z1} (-x'_{LL2} + y_{LL2}) + T_7 (-x'_{LL2} + y_{LL1}) + T_8 x'_{LL2} - T_8 y_{LL2}$
LL3_y	y_{LL3}	Algeb	$LL_{3LT1z1} LL_{3LT2z1} (-x'_{LL3} + y_{LL3}) + T_9 (-x'_{LL3} + y_{LL2}) + T_{10} x'_{LL3} - T_{10} y_{LL3}$
VSS_x	x_{VSS}	Algeb	$-x_{VSS} + y_{LL3}$
VSS_y	y_{VSS}	Algeb	$L_{SMAX} VSS_{limzu} + L_{SMIN} VSS_{limzl} + VSS_{limzi} x_{VSS} - y_{VSS}$
tm	τ_m	ExtAl- geb	0
te	τ_e	ExtAl- geb	0
v	V	ExtAl- geb	0
f	f	ExtAl- geb	0
vi	v_i	ExtAl- geb	uv_{sout}
v2	V	ExtAl- geb	0
f2	f_2	ExtAl- geb	0

Services

Name	Symbol	Equation	Type
VOU	VOU	$VCUr + V_0$	ConstService
VOL	VOL	$VCLr + V_0$	ConstService

Discrete

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
freq_model		BusFreq	default freq. measurement model	('BusFreq',)

5.11 PhasorMeasurement

Phasor measurements

Common Parameters: u, name

Common Variables: am, vm

Available models: *PMU*

5.11.1 PMU

Group *PhasorMeasurement*

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	Type	Properties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
bus		bus idx			IdxParam	mandatory
Ta	T_a	angle filter time constant	0.100		NumParam	
Tv	T_v	voltage filter time constant	0.100		NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
am	θ_m	θ	phase angle measurement	<i>rad.</i>	v_str
vm	V_m	V	voltage magnitude measurement	<i>p.u.(kV)</i>	v_str
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation " $\dot{x} = f(x, y)$ "	T (LHS)
am	θ_m	State	$\dot{\theta} - \theta_m$	T_a
vm	V_m	State	$\dot{V} - V_m$	T_v

Algebraic Equations

Name	Symbol	Type	RHS of Equation " $0 = g(x, y)$ "
a	θ	ExtAlgeb	0
v	V	ExtAlgeb	0

5.12 StaticACDC

AC DC device for power flow

Common Parameters: u, name

Available models: *VSCShunt*

5.12.1 VSCShunt

Group *StaticACDC*

Data for VSC Shunt in power flow Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
bus		idx of connected bus			Idx- Param	manda- tory
node1		Node 1 index			Idx- Param	manda- tory
node2		Node 2 index			Idx- Param	manda- tory
Vn	V_n	AC voltage rating	110		NumParam	non_zero
Vdcn1	V_{dcn1}	DC voltage rating on node 1	100	<i>kV</i>	NumParam	non_zero
Vdcn2	V_{dcn2}	DC voltage rating on node 2	100	<i>kV</i>	NumParam	non_zero
Idcn	I_{dcn}	DC current rating	1	<i>kA</i>	NumParam	non_zero
rsh	r_{sh}	AC interface resistance	0.003	<i>ohm</i>	NumParam	z
xsh	x_{sh}	AC interface reactance	0.060	<i>ohm</i>	NumParam	z
control		Control method: 0-PQ, 1-PV, 2-vQ or 3-vV			NumParam	manda- tory
v0		AC voltage setting (PV or vV) or initial guess (PQ or vQ)	1		NumParam	
p0		AC active power setting	0	<i>pu</i>	NumParam	
q0		AC reactive power setting	0	<i>pu</i>	NumParam	
vdc0	v_{dc0}	DC voltage setting	1	<i>pu</i>	NumParam	
k0		Loss coefficient - constant	0		NumParam	
k1		Loss coefficient - linear	0		NumParam	
k2		Loss coefficient - quadratic	0		NumParam	
droop		Enable dc voltage droop control	0	<i>boolean</i>	NumParam	
K		Droop coefficient	0		NumParam	
vhigh		Upper voltage threshold in droop control	9999	<i>pu</i>	NumParam	
vlow		Lower voltage threshold in droop control	0	<i>pu</i>	NumParam	
vsh-max		Maximum ac interface voltage	1.100	<i>pu</i>	NumParam	
vsh-min		Minimum ac interface voltage	0.900	<i>pu</i>	NumParam	
Ish-max		Maximum ac current	2	<i>pu</i>	NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
ash	θ_{sh}	a	voltage phase behind the transformer	rad	v_str
vsh	V_{sh}	v_0	voltage magnitude behind transformer	$p.u.$	v_str
psh	P_{sh}	$p_0 (s_0^{mode} + s_1^{mode})$	active power injection into VSC	$p.u.$	v_str
qsh	Q_{sh}	$q_0 (s_0^{mode} + s_2^{mode})$	reactive power injection into VSC		v_str
pdc	P_{dc}	0	DC power injection		v_str
a	a		AC bus voltage phase		
v	v		AC bus voltage magnitude		
v1	v_1		DC node 1 voltage		
v2	v_2		DC node 2 voltage		

Algebraic Equations

Name	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
ash	θ_{sh}	Algeb	$-P_{sh} + u (V_{sh} b_{sh} v \sin(\theta_{sh} - a) - V_{sh} g_{sh} v \cos(\theta_{sh} - a) + g_{sh} v^2)$
vsh	V_{sh}	Algeb	$-Q_{sh} + u (V_{sh} b_{sh} v \cos(\theta_{sh} - a) + V_{sh} g_{sh} v \sin(\theta_{sh} - a) - b_{sh} v^2)$
psh	P_{sh}	Algeb	$u (-P_{sh} + p_0) (s_0^{mode} + s_1^{mode}) + u (s_2^{mode} + s_3^{mode}) (v_1 - v_2 - v_{dc0})$
qsh	Q_{sh}	Algeb	$u (-Q_{sh} + q_0) (s_0^{mode} + s_2^{mode}) + u (s_1^{mode} + s_3^{mode}) (-v + v_0)$
pdc	P_{dc}	Algeb	$P_{dc} + u (V_{sh}^2 g_{sh} - V_{sh} b_{sh} v \sin(\theta_{sh} - a) - V_{sh} g_{sh} v \cos(\theta_{sh} - a))$
a	a	ExtAl- geb	$-P_{sh}$
v	v	ExtAl- geb	$-Q_{sh}$
v1	v_1	ExtAl- geb	$-\frac{P_{dc}}{v_1 - v_2}$
v2	v_2	ExtAl- geb	$\frac{P_{dc}}{v_1 - v_2}$

Services

Name	Symbol	Equation	Type
gsh	g_{sh}	$\frac{\text{re}(r_{sh}) - \text{im}(x_{sh})}{(\text{re}(r_{sh}) - \text{im}(x_{sh}))^2 + (\text{re}(x_{sh}) + \text{im}(r_{sh}))^2}$	ConstService
bsh	b_{sh}	$\frac{-\text{re}(x_{sh}) - \text{im}(r_{sh})}{(\text{re}(r_{sh}) - \text{im}(x_{sh}))^2 + (\text{re}(x_{sh}) + \text{im}(r_{sh}))^2}$	ConstService

Discrete

Name	Symbol	Type	Info
mode	$mode$	Switcher	

5.13 StaticGen

Static generator group for power flow calculation

Common Parameters: u, name, Sn, Vn, p0, q0, ra, xs, subidx

Common Variables: p, q, a, v

Available models: *PV*, *Slack*

5.13.1 PV

Group *StaticGen*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data-Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data-Param	
Sn	S_n	Power rating	100		NumParam	non_zero
Vn	V_n	AC voltage rating	110		NumParam	non_zero
subidx		index for generators on the same bus			Data-Param	
bus		idx of the installed bus			IdxParam	
busr		bus idx for remote voltage control			IdxParam	
p0	p_0	active power set point in system base	0	<i>p.u.</i>	NumParam	
q0	q_0	reactive power set point in system base	0	<i>p.u.</i>	NumParam	
pmax	p_{max}	maximum active power in system base	999	<i>p.u.</i>	NumParam	
pmin	p_{min}	minimum active power in system base	-1	<i>p.u.</i>	NumParam	
qmax	q_{max}	maximum reactive power in system base	999	<i>p.u.</i>	NumParam	
qmin	q_{min}	minimum reactive power in system base	-999	<i>p.u.</i>	NumParam	
v0	v_0	voltage set point	1		NumParam	
vmax	v_{max}	maximum voltage	1.400		NumParam	
vmin	v_{min}	minimum allowed voltage	0.600		NumParam	
ra	r_a	armature resistance	0.010		NumParam	
xs	x_s	armature reactance	0.300		NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
p	p	p_0	actual active power generation	<i>p.u.</i>	v_str
q	q	q_0	actual reactive power generation	<i>p.u.</i>	v_str
a	θ				
v	V	v_0			v_str, v_setter

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
p	p	Algeb	$u(-p + p_0)$
q	q	Algeb	$u\left(z_i^{qlim}(-V + v_0) + z_l^{qlim}(-q + q_{min}) + z_u^{qlim}(-q + q_{max})\right)$
a	θ	ExtAlgeb	$-pu$
v	V	ExtAlgeb	$-qu$

Discrete

Name	Symbol	Type	Info
qlim	$qlim$	SortedLimiter	

Config Fields in [PV]

Option	Symbol	Value	Info	Accepted values
pv2pq	z_{pv2pq}	0	convert PV to PQ in PFlow at Q limits	(0, 1)
npv2pq	n_{pv2pq}	1	max. # of pv2pq conversion in each iteration	≥ 0

5.13.2 SlackGroup *StaticGen*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
Sn	S_n	Power rating	100		NumParam	non_zero
Vn	V_n	AC voltage rating	110		NumParam	non_zero
subidx		index for generators on the same bus			Data- Param	
bus		idx of the installed bus			IdxParam	
busr		bus idx for remote voltage control			IdxParam	
p0	p_0	active power set point in system base	0	<i>p.u.</i>	NumParam	
q0	q_0	reactive power set point in system base	0	<i>p.u.</i>	NumParam	
pmax	p_{max}	maximum active power in system base	999	<i>p.u.</i>	NumParam	
pmin	p_{min}	minimum active power in system base	-1	<i>p.u.</i>	NumParam	
qmax	q_{max}	maximum reactive power in system base	999	<i>p.u.</i>	NumParam	
qmin	q_{min}	minimum reactive power in system base	-999	<i>p.u.</i>	NumParam	
v0	v_0	voltage set point	1		NumParam	
vmax	v_{max}	maximum voltage	1.400		NumParam	
vmin	v_{min}	minimum allowed voltage	0.600		NumParam	
ra	r_a	armature resistance	0.010		NumParam	
xs	x_s	armature reactance	0.300		NumParam	
a0	θ_0	reference angle set point	0		NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
p	p	p_0	actual active power generation	<i>p.u.</i>	v_str
q	q	q_0	actual reactive power generation	<i>p.u.</i>	v_str
a	θ	θ_0			v_str, v_setter
v	V	v_0			v_str, v_setter

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
p	p	Algeb	$u \left(z_i^{plim} (-\theta + \theta_0) + z_l^{plim} (-p + p_{min}) + z_u^{plim} (-p + p_{max}) \right)$
q	q	Algeb	$u \left(z_i^{qlim} (-V + v_0) + z_l^{qlim} (-q + q_{min}) + z_u^{qlim} (-q + q_{max}) \right)$
a	θ	ExtAlgeb	$-pu$
v	V	ExtAlgeb	$-qu$

Discrete

Name	Symbol	Type	Info
qlim	$qlim$	SortedLimiter	
plim	$plim$	SortedLimiter	

Config Fields in [Slack]

Option	Symbol	Value	Info	Accepted values
pv2pq	z_{pv2pq}	0	convert PV to PQ in PFlow at Q limits	(0, 1)
npv2pq	n_{pv2pq}	1	max. # of pv2pq conversion in each iteration	≥ 0
av2pv	z_{av2pv}	0	convert Slack to PV in PFlow at P limits	(0, 1)

5.14 StaticLoad

Static load group.

Common Parameters: u, name

Available models: *PQ*

5.14.1 PQ

Group *StaticLoad*

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).

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
bus		linked bus idx			IdxParam	mandatory
Vn	V_n	AC voltage rating	110	<i>kV</i>	NumParam	non_zero
p0	p_0	active power load in system base	0	<i>p.u.</i>	NumParam	
q0	q_0	reactive power load in system base	0	<i>p.u.</i>	NumParam	
vmax	v_{max}	max voltage before switching to impedance	1.200		NumParam	
vmin	v_{min}	min voltage before switching to impedance	0.800		NumParam	
owner		owner idx			IdxParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
a	θ				
v	V				

Algebraic Equations

Name	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAl- geb	$u \left(I_{peq} V \gamma_{p2i} + P_{pf} \gamma_{p2p} + R_{eq} V^2 \gamma_{p2z} \right) (t_{dae} > 0) +$ $u \left(R_{lb} V^2 z_l^{vcmp} + R_{ub} V^2 z_u^{vcmp} + p_0 z_i^{vcmp} \right) (t_{dae} \leq 0)$
v	V	ExtAl- geb	$u \left(I_{qeq} V \gamma_{q2i} + Q_{pf} \gamma_{q2q} + V^2 X_{eq} \gamma_{q2z} \right) (t_{dae} > 0) +$ $u \left(V^2 X_{lb} z_l^{vcmp} + V^2 X_{ub} z_u^{vcmp} + q_0 z_i^{vcmp} \right) (t_{dae} \leq 0)$

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

Discrete

Name	Symbol	Type	Info
vcmp	$vcmp$	Limiter	

Config Fields in [PQ]

Op-tion	Sym-bol	Value	Info	Accepted val-ues
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

5.15 StaticShunt

Static shunt compensator group.

Common Parameters: u, name

Available models: *Shunt*

5.15.1 Shunt

Group *StaticShunt*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
bus		idx of connected bus			IdxParam	mandatory
Sn	S_n	Power rating	100		NumParam	non_zero
Vn	V_n	AC voltage rating	110		NumParam	non_zero
g	g	shunt conductance (real part)	0		NumParam	y
b	b	shunt susceptance (positive as cap- atance)	0		NumParam	y
fn	f	rated frequency	60		NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
a	θ				
v	V				

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
a	θ	ExtAlgeb	$V^2 g u$
v	V	ExtAlgeb	$-V^2 b u$

5.16 SynGen

Synchronous generator group.

Common Parameters: u, name, Sn, Vn, fn, bus, M, D

Common Variables: omega, delta, tm, te, vf, XadIfd, vd, vq, Id, Iq, a, v

Available models: *GENCLS*, *GENROU*

5.16.1 GENCLS

Group *SynGen*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Properties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
bus		interface bus id			Idx- Param	mandatory
gen		static generator index			Idx- Param	mandatory
coi		center of inertia index			Idx- Param	
Sn	S_n	Power rating	100		NumParam	
Vn	V_n	AC voltage rating	110		NumParam	
fn	f	rated frequency	60		NumParam	
D	D	Damping coefficient	0		NumParam	power
M	M	machine start up time (2H)	6		NumParam	non_zero,power
ra	r_a	armature resistance	0		NumParam	z
xl	x_l	leakage reactance	0		NumParam	z
xd1	x'_d	d-axis transient reactance	0.302		NumParam	z
kp	k_p	active power feedback gain	0		NumParam	
kw	k_w	speed feedback gain	0		NumParam	
S10	$S_{1.0}$	first saturation factor	0		NumParam	
S12	$S_{1.2}$	second saturation factor	1		NumParam	
subidx		Generator idx in plant; only used by PSS/E data	0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
delta	δ	δ_0	rotor angle	<i>rad</i>	v_str
omega	ω	ω	rotor speed	<i>pu (Hz)</i>	v_str
Id	I_d	I_{d0}	d-axis current		v_str
Iq	I_q	I_{q0}	q-axis current		v_str
vd	V_d	V_{d0}	d-axis voltage		v_str
vq	V_q	V_{q0}	q-axis voltage		v_str
tm	τ_m	τ_{m0}	mechanical torque		v_str
te	τ_e	P_0	electric torque		v_str
vf	v_f	v_{f0}	excitation voltage	<i>pu</i>	v_str
XadIfd	$X_{ad}I_{fd}$	v_{f0}	d-axis armature excitation current	<i>p.u (kV)</i>	v_str
psid	ψ_d	ψ_{d0}	d-axis flux		v_str
psiq	ψ_q	ψ_{q0}	q-axis flux		v_str
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
delta	δ	State	$2\pi f u (\omega - 1)$	
omega	ω	State	$\frac{u(-D(\omega-1)-\tau_e+\tau_m)}{M}$	

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Id	I_d	Algeb	$I_d x q + \psi_d - v_f$
Iq	I_q	Algeb	$I_q x q + \psi_q$
vd	V_d	Algeb	$V \sin(\delta - \theta) - V_d$
vq	V_q	Algeb	$V \cos(\delta - \theta) - V_q$
tm	τ_m	Algeb	$-\tau_m + \tau_{m0}$
te	τ_e	Algeb	$-I_d \psi_q + I_q \psi_d - \tau_e$
vf	v_f	Algeb	$-v_f + v_{f0}$
XadIfd	$X_{ad} I_{fd}$	Algeb	$-X_{ad} I_{fd} + v_{f0}$
psid	ψ_d	Algeb	$-\psi_d + u(I_q r_a + V_q)$
psiq	ψ_q	Algeb	$\psi_q + u(I_d r_a + V_d)$
a	θ	ExtAlgeb	$-u(I_d V_d + I_q V_q)$
v	V	ExtAlgeb	$-u(I_d V_q - I_q V_d)$

Services

Name	Symbol	Equation	Type
_V	V_c	$V e^{i\theta}$	ConstService
_S	S	$P_0 - iQ_0$	ConstService
_I	I_c	$\frac{S}{\text{conj}(V_c)}$	ConstService
_E	E	$I_c(r_a + i x q) + V_c$	ConstService
_deltac	δ_c	$\log\left(\frac{E}{\text{abs}(E)}\right)$	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}	$I_{d0} x q + I_{q0} r_a + V_{q0}$	ConstService

Config Fields in [GENCLS]

Option	Symbol	Value	Info	Accepted values
vf_lower		1	lower limit for vf warning	
vf_upper		5	upper limit for vf warning	

5.16.2 GENROU

Group *SynGen*

Round rotor generator with quadratic saturation

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Properties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
bus		interface bus id			Idx- Param	mandatory
gen		static generator index			Idx- Param	mandatory
coi		center of inertia index			Idx- Param	
Sn	S_n	Power rating	100		NumParam	
Vn	V_n	AC voltage rating	110		NumParam	
fn	f	rated frequency	60		NumParam	
D	D	Damping coefficient	0		NumParam	power
M	M	machine start up time (2H)	6		NumParam	non_zero,power
ra	r_a	armature resistance	0		NumParam	z
xl	x_l	leakage reactance	0		NumParam	z
xd1	x'_d	d-axis transient reactance	0.302		NumParam	z
kp	k_p	active power feedback gain	0		NumParam	
kw	k_w	speed feedback gain	0		NumParam	
S10	$S_{1.0}$	first saturation factor	0		NumParam	
S12	$S_{1.2}$	second saturation factor	1		NumParam	
xd	x_d	d-axis synchronous reactance	1.900		NumParam	z
xq	x_q	q-axis synchronous reactance	1.700		NumParam	z
xd2	x''_d	d-axis sub-transient reactance	0.204		NumParam	z
xq1	x'_q	q-axis transient reactance	0.500		NumParam	z
xq2	x''_q	q-axis sub-transient reactance	0.300		NumParam	z
Td10	T'_{d0}	d-axis transient time constant	8		NumParam	
Td20	T''_{d0}	d-axis sub-transient time constant	0.040		NumParam	
Tq10	T'_{q0}	q-axis transient time constant	0.800		NumParam	
Tq20	T''_{q0}	q-axis sub-transient time constant	0.020		NumParam	
subidx		Generator idx in plant; only used by PSS/E data	0		ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
delta	δ	δ_0	rotor angle	<i>rad</i>	v_str
omega	ω	u	rotor speed	<i>pu (Hz)</i>	v_str
e1q	e'_q	e'_{q0}	q-axis transient voltage		v_str
e1d	e'_d	e'_{d0}	d-axis transient voltage		v_str
e2d	e''_d	e''_{d0}	d-axis sub-transient voltage		v_str
e2q	e''_q	e''_{q0}	q-axis sub-transient voltage		v_str
Id	I_d	I_{d0}	d-axis current		v_str
Iq	I_q	I_{q0}	q-axis current		v_str
vd	V_d	V_{d0}	d-axis voltage		v_str
vq	V_q	V_{q0}	q-axis voltage		v_str
tm	τ_m	τ_{m0}	mechanical torque		v_str
te	τ_e	P_0	electric torque		v_str
vf	v_f	v_{f0}	excitation voltage	<i>pu</i>	v_str
XadIfd	$X_{ad}I_{fd}$	v_{f0}	d-axis armature excitation current	<i>p.u (kV)</i>	v_str
psid	ψ_d	ψ_{d0}	d-axis flux		v_str
psiq	ψ_q	ψ_{q0}	q-axis flux		v_str
psi2q	ψ_{aq}	ψ_{aq0}	q-axis air gap flux		v_str
psi2d	ψ_{ad}	ψ_{ad0}	d-axis air gap flux		v_str
psi2	ψ_a	$\text{abs}(\psi''_{0,dq})$	air gap flux magnitude		v_str
Se	$S_e(\psi_a)$	S_{e0}	saturation output		v_str
XaqI1q	$X_{aq}I_{1q}$	0	q-axis reaction	<i>p.u (kV)</i>	v_str
a	θ		Bus voltage phase angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
delta	δ	State	$2\pi f u (\omega - 1)$	
omega	ω	State	$\frac{u(-D(\omega-1)-\tau_e+\tau_m)}{M}$	
e1q	e'_q	State	$\frac{-X_{ad}I_{fd}+v_f}{T'_{d0}}$	
e1d	e'_d	State	$-\frac{X_{aq}I_{1q}}{T'_{q0}}$	
e2d	e''_d	State	$\frac{-I_d(x'_d-x_l)-e'_d+e'_q}{T''_{d0}}$	
e2q	e''_q	State	$\frac{I_q(x'_q-x_l)-e'_q+e'_d}{T''_{q0}}$	

Algebraic Equations

Name	Sym- bol	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	$V \sin(\delta - \theta) - V_d$
vq	V_q	Algeb	$V \cos(\delta - \theta) - V_q$
tm	τ_m	Algeb	$-\tau_m + \tau_{m0}$
te	τ_e	Algeb	$-I_d \psi_q + I_q \psi_d - \tau_e$
vf	v_f	Algeb	$-v_f + v_{f0}$
XadIfd	$X_{ad} I_{fd}$	Algeb	$S_e(\psi_a) \psi_{ad} - X_{ad} I_{fd} + e_q' + (-x_d' + x_d) (I_d \gamma_{d1} - \gamma_{d2} e_d'' + \gamma_{d2} e_q')$
psid	ψ_d	Algeb	$-\psi_d + u (I_q r_a + V_q)$
psiq	ψ_q	Algeb	$\psi_q + u (I_d r_a + V_d)$
psi2q	ψ_{aq}	Algeb	$\gamma_{q1} e_d' - \psi_{aq} + e_q'' (1 - \gamma_{q1})$
psi2d	ψ_{ad}	Algeb	$\gamma_{d1} e_q' + \gamma_{d2} e_d'' (x_d' - x_l) - \psi_{ad}$
psi2	ψ_a	Algeb	$-\psi_a + \sqrt{\psi_{ad}^2 + \psi_{aq}^2}$
Se	$S_e(\psi_a)$	Algeb	$\frac{B_{SAT}^q z_0^{SL} (-A_{SAT}^q + \psi_a)^2}{\psi_a} - S_e(\psi_a)$
XaqI1q	$X_{aq} I_{1q}$	Algeb	$S_e(\psi_a) \gamma_{qd} \psi_{aq} - X_{aq} I_{1q} + e_d' + (-x_q' + x_q) (-I_q \gamma_{q1} - \gamma_{q2} e_q'' + \gamma_{q2} e_d')$
a	θ	ExtAl- geb	$-u (I_d V_d + I_q V_q)$
v	V	ExtAl- geb	$-u (I_d V_q - I_q V_d)$

Services

Name	Symbol	Equation	Type
gd1	γ_{d1}	$\frac{x_d'' - x_l}{x_d' - x_l}$	ConstService
gq1	γ_{q1}	$\frac{x_q'' - x_l}{x_q' - x_l}$	ConstService
gd2	γ_{d2}	$\frac{-x_d'' + x_d'}{(x_d' - x_l)^2}$	ConstService
gq2	γ_{q2}	$\frac{-x_q'' + x_q'}{(x_q' - x_l)^2}$	ConstService
gqd	γ_{qd}	$\frac{-x_l + x_q}{x_d - x_l}$	ConstService
S12	$S{1.2}$	$S_{1.2} - f S_{12} + 1$	ConstService
SAT_E1	E_{SAT}^{1c}	1.0	ConstService
SAT_E2	E_{SAT}^{2c}	1.2	ConstService
SAT_SE1	SE_{SAT}^{1c}	$S_{1.0}$	ConstService
SAT_SE2	SE_{SAT}^{2c}	$S_{1.2} - 2z_{SAT}^{SE2} + 2$	ConstService
SAT_a	a_{SAT}	$\sqrt{\frac{E_{SAT}^{1c} SE_{SAT}^{1c}}{E_{SAT}^{2c} SE_{SAT}^{2c}}} \left((SE_{SAT}^{2c} > 0) + (SE_{SAT}^{2c} < 0) \right)$	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	$\frac{E_{SAT}^{2c} SE_{SAT}^{2c} (a_{SAT} - 1)^2 ((a_{SAT} > 0) + (a_{SAT} < 0))}{(E_{SAT}^{1c} - E_{SAT}^{2c})^2}$	ConstService

Continued on next page

Table 1 – continued from previous page

Name	Symbol	Equation	Type
_V	V_c	$V e^{i\theta}$	ConstService
_S	S	$P_0 - iQ_0$	ConstService
_Zs	Z_s	$r_a + i x_d''$	ConstService
_It	I_t	$\frac{S}{\text{conj}(V_c)}$	ConstService
_Is	I_s	$I_t + \frac{V_c}{Z_s}$	ConstService
psi20	ψ_0''	$I_s Z_s$	ConstService
psi20_arg	$\theta_{\psi''0}$	$\arg(\psi_0'')$	ConstService
psi20_abs	$ \psi_0'' $	$\text{abs}(\psi_0'')$	ConstService
_It_arg	θ_{It0}	$\arg(I_t)$	ConstService
_psi20_It_arg	$\theta_{\psi a It}$	$-\theta_{It0} + \theta_{\psi''0}$	ConstService
Se0	S_{e0}	$\frac{B_{SAT}^q (-A_{SAT}^q + \psi_0'')^2 (\psi_0'' \geq A_{SAT}^q)}{ \psi_0'' }$	ConstService
_a	a	$ \psi_0'' (S_{e0} \gamma_{qd} + 1)$	ConstService
_b	b	$(x_q'' - x_q) \text{abs}(I_t)$	ConstService
delta0	δ_0	$\theta_{\psi''0} + \text{atan}\left(\frac{b \cos(\theta_{\psi a It})}{-\theta + b \sin(\theta_{\psi a It})}\right)$	ConstService
Tdq	T{dq}	$-i \sin(\delta_0) + \cos(\delta_0)$	ConstService
psi20_dq	$\psi_{0,dq}''$	$T_{dq} \psi_0''$	ConstService
It_dq	$I_{t,dq}$	$\text{conj}(I_t T_{dq})$	ConstService
psi2d0	ψ_{ad0}	$\text{re}(\psi_{0,dq}'')$	ConstService
psi2q0	ψ_{aq0}	$-\text{im}(\psi_{0,dq}'')$	ConstService
Id0	I_{d0}	$\text{im}(I_{t,dq})$	ConstService
Iq0	I_{q0}	$\text{re}(I_{t,dq})$	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}	$u(I_{d0}(I_{d0} r_a + V_{d0}) + I_{q0}(I_{q0} r_a + V_{q0}))$	ConstService
vf0	v_{f0}	$I_{d0}(-x_d'' + x_d) + \psi_{ad0}(S_{e0} + 1)$	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}	$I_{d0}(x_d' - x_d) - S_{e0} \psi_{ad0} + v_{f0}$	ConstService
e1d0	e'_{d0}	$I_{q0}(-x_q' + x_q) - S_{e0} \gamma_{qd} \psi_{aq0}$	ConstService
e2d0	e''_{d0}	$I_{d0}(-x_d + x_l) - S_{e0} \psi_{ad0} + v_{f0}$	ConstService
e2q0	e''_{q0}	$-I_{q0}(x_l - x_q) - S_{e0} \gamma_{qd} \psi_{aq0}$	ConstService

Discrete

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
vf_lower		1	lower limit for vf warning	
vf_upper		5	upper limit for vf warning	

5.17 TimedEvent

Timed event group

Common Parameters: u, name

Available models: *Toggler*, *Fault*

5.17.1 Toggler

Group *TimedEvent*

Time-based connectivity status toggler.

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			DataParam	
u	<i>u</i>	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
model		Model or Group of the device to control			DataParam	mandatory
dev		idx of the device to control			IdxParam	mandatory
t		switch time for connection status	-1		Timer- Param	mandatory

5.17.2 Fault

Group *TimedEvent*

Three-phase to ground fault.

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
bus		linked bus idx			IdxParam	mandatory
tf		Bus fault start time	-1	<i>second</i>	Timer- Param	mandatory
tc		Bus fault end time	-1	<i>second</i>	Timer- Param	
xf	x_f	Fault to ground impedance (posi- tive)	0.000	<i>p.u.(sys)</i>	NumParam	
rf	x_f	Fault to ground resistance (posi- tive)	0	<i>p.u.(sys)</i>	NumParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
a	θ		Bus voltage angle	<i>p.u.(kV)</i>	
v	V		Bus voltage magnitude	<i>p.u.(kV)</i>	

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	$\frac{\text{re}(x_f) - \text{im}(x_f)}{(\text{re}(x_f) - \text{im}(x_f))^2 + (\text{re}(x_f) + \text{im}(x_f))^2}$	ConstService
bf	b_f	$\frac{-\text{re}(x_f) - \text{im}(x_f)}{(\text{re}(x_f) - \text{im}(x_f))^2 + (\text{re}(x_f) + \text{im}(x_f))^2}$	ConstService
uf	u_f	0	ConstService

5.18 TurbineGov

Turbine governor group for synchronous generator.

Common Parameters: u, name

Common Variables: pout

Available models: *TG2*, *TGOV1*, *IEEEGI*

5.18.1 TG2

Group *TurbineGov*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Properties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
syn		Synchronous generator idx			Idx- Param	manda- tory,unique
Tn	T_n	Turbine power rating. Equal to Sn if not provided.		<i>MVA</i>	NumParam	
wref0	ω_{ref0}	Base speed reference	1	<i>p.u.</i>	NumParam	
R	R	Speed regulation gain (mach. base de- fault)	0.050	<i>p.u.</i>	NumParam	ipower
pmax	p_{max}	Maximum power output	999	<i>p.u.</i>	NumParam	power
pmin	p_{min}	Minimum power output	0	<i>p.u.</i>	NumParam	power
dbl	L_{db}	Deadband lower limit	- 0.000	<i>p.u.</i>	NumParam	
dbu	U_{db}	Deadband upper limit	0.000	<i>p.u.</i>	NumParam	
dbc	C_{db}	Deadband neutral value	0	<i>p.u.</i>	NumParam	
T1	T_1	Transient gain time	0.200		NumParam	
T2	T_2	Governor time constant	10		NumParam	
Sg	S_n	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_n	Rated voltage from generator	0	<i>kV</i>	ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Proper- ties
ll_x	x'_{ll}	ω_{dmG}	State in lead-lag		v_str
omega	ω		Generator speed	<i>p.u.</i>	
paux	P_{aux}	P_{aux0}	Auxiliary power input		v_str
pout	P_{out}	$\tau_{m0}u$	Turbine final output power		v_str
wref	ω_{ref}	ω_{ref0}	Speed reference variable		v_str
w_d	ω_{dev}	0	Generator speed deviation before dead band (positive for under speed)		v_str
w_dm	ω_{dm}	0	Measured speed deviation after dead band		v_str
w_dmg	ω_{dmG}	0	Speed deviation after dead band after gain		v_str
ll_y	y_{ll}	ω_{dmG}	Output of lead-lag		v_str
pnl	P_{nl}	τ_{m0}	Power output before hard limiter		v_str
tm	τ_m		Mechanical power interface to SynGen		

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	$-\omega_{dev} + u(-\omega + \omega_{ref})$
w_dm	ω_{dm}	Algeb	$L_{db}z_{lr}^{wdb} + U_{db}z_{ur}^{wdb} + \omega_{dev}(1 - z_i^{wdb}) - \omega_{dm}$
w_dmG	ω_{dmG}	Algeb	$G\omega_{dm} - \omega_{dmG}$
ll_y	y_{ll}	Algeb	$T_1(\omega_{dmG} - x'_{ll}) + T_2x'_{ll} - T_2y_{ll} + ll_{LT1z1}ll_{LT2z1}(-x'_{ll} + y_{ll})$
pnl	P_{nl}	Algeb	$-P_{nl} + \tau_{m0} + y_{ll}$
tm	τ_m	ExtAlgeb	$u(P_{out} - \tau_{m0})$

Services

Name	Symbol	Equation	Type
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u}{R}$	ConstService

Discrete

Name	Symbol	Type	Info
w_db	w_{db}	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
deadband	$z_{deadband}$	0	enable input dead band	(0, 1)
hardlimit	$z_{hardlimit}$	1	enable output hard limit	(0, 1)

5.18.2 TGOV1

Group *TurbineGov*

TGOV1 model.

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Properties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
syn		Synchronous generator idx			Idx- Param	manda- tory,unique
Tn	T_n	Turbine power rating. Equal to Sn if not provided.		<i>MVA</i>	NumParam	
wref0	ω_{ref0}	Base speed reference	1	<i>p.u.</i>	NumParam	
R	R	Speed regulation gain (mach. base de- fault)	0.050	<i>p.u.</i>	NumParam	ipower
VMAX	V_{max}	Maximum valve position	1.200	<i>p.u.</i>	NumParam	power
VMIN	V_{min}	Minimum valve position	0	<i>p.u.</i>	NumParam	power
T1	T_1	Valve time constant	0.100		NumParam	
T2	T_2	Lead-lag lead time constant	0.200		NumParam	
T3	T_3	Lead-lag lag time constant	10		NumParam	
Dt	D_t	Turbine damping coefficient	0		NumParam	power
Sg	S_n	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_n	Rated voltage from generator	0	<i>kV</i>	ExtParam	

Variables

Name	Symbol	Initial Value	Description	Unit	Properties
LAG_y	y_{LAG}	P_d	State in lag TF		v_str
LL_x	x'_{LL}	y_{LAG}	State in lead-lag		v_str
omega	ω		Generator speed	<i>p.u.</i>	
paux	P_{aux}	P_{aux0}	Auxiliary power input		v_str
pout	P_{out}	$\tau_{m0}u$	Turbine final output power		v_str
wref	ω_{ref}	ω_{ref0}	Speed reference variable		v_str
pref	P_{ref}	$R\tau_{m0}$	Reference power input		v_str
wd	ω_{dev}	0	Generator under speed	<i>p.u.</i>	v_str
pd	P_d	$\tau_{m0}u$	Pref plus under speed times gain	<i>p.u.</i>	v_str
LL_y	y_{LL}	y_{LAG}	Output of lead-lag		v_str
tm	τ_m		Mechanical power interface to SynGen		

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	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$D_t \omega_{dev} - P_{out} + y_{LL}$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
pref	P_{ref}	Algeb	$-P_{ref} + R\tau_{m0}$
wd	ω_{dev}	Algeb	$-\omega - \omega_{dev} + \omega_{ref}$
pd	P_d	Algeb	$G u (P_{aux} + P_{ref} + \omega_{dev}) - P_d$
LL_y	y_{LL}	Algeb	$LL_{LT1z1} LL_{LT2z1} (-x'_{LL} + y_{LL}) + T_2 (-x'_{LL} + y_{LAG}) + T_3 x'_{LL} - T_3 y_{LL}$
tm	τ_m	ExtAl- geb	$u (P_{out} - \tau_{m0})$

Services

Name	Symbol	Equation	Type
paux0	P_{aux0}	0	ConstService
gain	G	$\frac{u}{R}$	ConstService

Discrete

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	

5.18.3 IEEEG1

Group *TurbineGov*

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, $K_1 + K_2 + \dots + K_8 = 1.0$. If the second generator is not connected, $K_1 + K_3 + K_5 + K_7 = 1$, and $K_2 + K_4 + K_6 + K_8 = 0$.

Parameters

Name	Symbol	Description	Default	Unit	Type	Property
idx		unique device idx			DataParam	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			DataParam	
syn		Synchronous generator idx			IdxParam	mandatory
Tn	T_n	Turbine power rating. Equal to <i>Sn</i> if not provided.		<i>MVA</i>	NumParam	
wref0	ω_{ref0}	Base speed reference	1	<i>p.u.</i>	NumParam	
syn2		Optional SynGen idx			IdxParam	
K	K	Gain (1/R) in mach. base	20	<i>p.u. (power)</i>	NumParam	power
T1	T_1	Gov. lag time const.	1		NumParam	
T2	T_2	Gov. lead time const.	1		NumParam	
T3	T_3	Valve controller time const.	0.100		NumParam	
UO	U_o	Max. valve opening rate	0.100	<i>p.u./sec</i>	NumParam	
UC	U_c	Max. valve closing rate	-0.100	<i>p.u./sec</i>	NumParam	
PMAX	P_{MAX}	Max. turbine power	5		NumParam	power
PMIN	P_{MIN}	Min. turbine power	0		NumParam	power
T4	T_4	Inlet piping/steam bowl time constant	0.400		NumParam	
K1	K_1	Fraction of power from HP	0.500		NumParam	
K2	K_2	Fraction of power from LP	0		NumParam	
T5	T_5	Time constant of 2nd boiler pass	8		NumParam	
K3	K_3	Fraction of HP shaft power after 2nd boiler pass	0.500		NumParam	
K4	K_4	Fraction of LP shaft power after 2nd boiler pass	0		NumParam	
T6	T_6	Time constant of 3rd boiler pass	0.500		NumParam	
K5	K_5	Fraction of HP shaft power after 3rd boiler pass	0		NumParam	
K6	K_6	Fraction of LP shaft power after 3rd boiler pass	0		NumParam	
T7	T_7	Time constant of 4th boiler pass	0.050		NumParam	
K7	K_7	Fraction of HP shaft power after 4th boiler pass	0		NumParam	
K8	K_8	Fraction of LP shaft power after 4th boiler pass	0		NumParam	
Sg	S_n	Rated power from generator	0	<i>MVA</i>	ExtParam	
Vn	V_n	Rated voltage from generator	0	<i>kV</i>	ExtParam	
Sg2	S_{n2}	Rated power of Syn2	0	<i>MVA</i>	ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Proper- ties
LL_x	x'_{LL}	ω_{dev}	State in lead-lag		v_str
IAW_y	y_{IAW}	tm_{012}	AW Integrator output		v_str
L4_y	y_{L4}	y_{IAW}	State in lag transfer function		v_str
L5_y	y_{L5}	y_{L4}	State in lag transfer function		v_str
L6_y	y_{L6}	y_{L5}	State in lag transfer function		v_str
L7_y	y_{L7}	y_{L6}	State in lag transfer function		v_str
omega	ω		Generator speed	<i>p.u.</i>	
paux	P_{aux}	P_{aux0}	Auxiliary power input		v_str
pout	P_{out}	$\tau_{m0}u$	Turbine final output power		v_str
wref	ω_{ref}	ω_{ref0}	Speed reference variable		v_str
wd	ω_{dev}	0	Generator under speed	<i>p.u.</i>	v_str
LL_y	y_{LL}	ω_{dev}	Output of lead-lag		v_str
vs	V_s	0	Valve speed		v_str
vsl	V_{sl}	$U_c z_l^{HL} + U_o z_u^{HL} + V_s z_i^{HL}$	Valve move speed after limiter		v_str
PHP	P_{HP}	$K_1 y_{L4} + K_3 y_{L5} + K_5 y_{L6} + K_7 y_{L7}$	HP output		v_str
PLP	P_{LP}	$K_2 y_{L4} + K_4 y_{L5} + K_6 y_{L6} + K_8 y_{L7}$	LP output		v_str
tm	τ_m		Mechanical power interface to SynGen		
tm2	τ_{m2}		Mechanical power to syn2		

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	Sym- bol	Type	RHS of Equation "0 = g(x, y)"
paux	P_{aux}	Algeb	$P_{aux0} - P_{aux}$
pout	P_{out}	Algeb	$P_{HP} - P_{out}$
wref	ω_{ref}	Algeb	$\omega_{ref0} - \omega_{ref}$
wd	ω_{dev}	Algeb	$-\omega - \omega_{dev} + \omega_{ref}$
LL_y	y_{LL}	Algeb	$KT_1 x'_{LL} + KT_2 (\omega_{dev} - x'_{LL}) + LL_{LT1z1} LL_{LT2z1} (-K x'_{LL} + y_{LL}) - T_1 y_{LL}$
vs	V_s	Algeb	$-V_s + \frac{P_{aux} + tm_{012} - y_{IAW} + y_{LL}}{T_3}$
vsl	V_{sl}	Algeb	$U_c z_i^{HL} + U_o z_u^{HL} + V_s z_i^{HL} - V_{sl}$
PHP	P_{HP}	Algeb	$K_1 y_{L4} + K_3 y_{L5} + K_5 y_{L6} + K_7 y_{L7} - P_{HP}$
PLP	P_{LP}	Algeb	$K_2 y_{L4} + K_4 y_{L5} + K_6 y_{L6} + K_8 y_{L7} - P_{LP}$
tm	τ_m	ExtAl- geb	$u(P_{out} - \tau_{m0})$
tm2	τ_{m2}	ExtAl- geb	$u z_{syn2} (P_{LP} - \tau_{m02})$

Services

Name	Symbol	Equation	Type
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
tm0K2	tm{0K2}	$\tau_{m0} z_{syn2} (K_2 + K_4 + K_6 + K_8)$	PostInitService
tm02K1	tm{02K1}	$\tau_{m02} (K_1 + K_3 + K_5 + K_7)$	PostInitService
tm012	tm_{012}	$\tau_{m02} + \tau_{m0}$	ConstService

Discrete

Name	Symbol	Type	Info
LL_LT1	LT_{LL}	LessThan	
LL_LT2	LT_{LL}	LessThan	
HL	HL	HardLimiter	Limiter on valve acceleration
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

5.19 Undefined

Common Parameters: u, name

Available models: *REGCAU1*

5.19.1 REGCAU1

Group *Undefined*

Parameters

Name	Sym- bol	Description	De- fault	Unit	Type	Proper- ties
idx		unique device idx			Data- Param	
u	u	connection status	1	<i>bool</i>	NumParam	
name		device name			Data- Param	
bus		interface bus id			Idx- Param	manda- tory
gen		static generator index			Idx- Param	manda- tory
Tg	T_g	converter time const.	0.100	<i>s</i>	NumParam	
Rrpwr	R_{rpwr}	Low voltage power logic (LVPL) ramp limit	999	<i>p.u.</i>	NumParam	
Brkpt	B_{rkpt}	LVPL characteristic voltage 2	1	<i>p.u.</i>	NumParam	
Ze- rox	Z_{erox}	LVPL characteristic voltage 1	0.500	<i>p.u.</i>	NumParam	
Lvpl1	L_{vpl1}	LVPL gain	1	<i>p.u.</i>	NumParam	
Volim	V_{olim}	Voltage lim for high volt. reactive current mgnt.	1.200	<i>p.u.</i>	NumParam	
Lvpnt1	L_{vpnt1}	High volt. point for low volt. active current mgnt.	1	<i>p.u.</i>	NumParam	
Lvpnt0	L_{vpnt0}	Low volt. point for low volt. active current mgnt.	0.400	<i>p.u.</i>	NumParam	
Iolim	I_{olim}	current limit for high volt. reactive current mgnt.	999	<i>p.u.</i>	NumParam	
Tfltr	T_{fltr}	Voltage filter T const for low volt. active current mgnt.	0.100	<i>s</i>	NumParam	
Khv	K_{hv}	Overvolt. compensation gain in high volt. reac- tive current mgnt.	0.700		NumParam	
Iqr- max	I_{qrmax}	Upper limit on the ROC for reactive current	999	<i>p.u.</i>	NumParam	
Iqr- min	I_{qrmin}	Lower limit on the ROC for reactive current	-999	<i>p.u.</i>	NumParam	
Ac- cel	A_{ccel}	Acceleration factor	0		NumParam	
Iq- max	I_{qmax}	Upper limit for reactive current	999	<i>p.u.</i>	NumParam	
Iqmin	I_{qmin}	Lower limit for reactive current	-999	<i>p.u.</i>	NumParam	
ra	r_a		0		ExtParam	
xs	x_s		0		ExtParam	

Variables

Name	Sym- bol	Initial Value	Description	Unit	Prop- erties
S1_y	y_{S1}	$-I_{qcmd}$	State in lag TF		v_str
S2_y	y_{S2}	$1.0V$	State in lag transfer function		v_str
S0_y	y_{S0}	I_{pcmd}	State in lag TF		v_str
Ipcmd	I_{pcmd}	I_{pcmd0}	current component for active power		v_str
Iqcmd	I_{qcmd}	I_{qcmd0}	current component for reactive power		v_str
LVG_y	y_{LVG}	$\begin{cases} 0 & \text{for } L_{vpnt0} \geq V \\ k_{LVG}(-L_{vpnt0} + V) & \text{for } L_{vpnt1} \geq V \\ 1 & \text{otherwise} \end{cases}$	Output of piecewise		v_str
LVPL_y	y_{LVPL}	$\begin{cases} 9999 - 9999z_{Lvplsw} & \text{for } Z_{erox} \geq y_{S2} \\ k_{LVPL}(-Z_{erox} + y_{S2}) - 9999z_{Lvplsw} + 9999 & \text{for } Z_{erox} < y_{S2} \\ 9999 & \text{otherwise} \end{cases}$	Output of piecewise		v_str
Ipout	I_{pout}	$I_{pcmd}y_{LVG}$	Output Ip current		v_str
HVG_x	x_{HVG}	$K_{hv}(V - V_{olim})$	Gain output before limiter		v_str
HVG_y	y_{HVG}	$HVG_{limzi}x_{HVG}$	Gain output after limiter		v_str
Iqout_x	x_{Iqout}	$-y_{HVG} + y_{S1}$	Gain output before limiter		v_str
Iqout_y	y_{Iqout}	$I_{olim}I_{qout_{limzl}} + I_{qout_{limzi}}x_{Iqout}$	Gain output after limiter		v_str
a	θ		Bus voltage angle		
v	V		Bus voltage magnitude		

Differential Equations

Name	Symbol	Type	RHS of Equation "T x' = f(x, y)"	T (LHS)
S1_y	y_{S1}	State	$-I_{qcmd} - y_{S1}$	T_g
S2_y	y_{S2}	State	$1.0V - y_{S2}$	T_{fltr}
S0_y	y_{S0}	State	$I_{pcmd} - y_{S0}$	T_g

Algebraic Equations

Name	Symbol	Type	RHS of Equation "0 = g(x, y)"
Ipcmd	I_{pcmd}	Al-geb	$-I_{pcmd} + I_{pcmd0}$
Iqcmd	I_{qcmd}	Al-geb	$-I_{qcmd} + I_{qcmd0}$
LVG_y	y_{LVG}	Al-geb	$-y_{LVG} + \begin{cases} 0 & \text{for } L_{vpnt0} \geq V \\ k_{LVG}(-L_{vpnt0} + V) & \text{for } L_{vpnt1} \geq V \\ 1 & \text{otherwise} \end{cases}$
LVPL_y	y_{LVPL}	Al-geb	$-y_{LVPL} + \begin{cases} 9999 - 9999z_{Lvplsw} & \text{for } Z_{erox} \geq y_{S2} \\ k_{LVPL}(-Z_{erox} + y_{S2}) - 9999z_{Lvplsw} + 9999 & \text{for } B_{rkpt} \geq y_{S2} \\ 9999 & \text{otherwise} \end{cases}$
Ipout	I_{pout}	Al-geb	$-I_{pout} + y_{LVG}y_{S0}$
HVG_xx	x_{HVG}	Al-geb	$K_{hv}(V - V_{olim}) - x_{HVG}$
HVG_yy	y_{HVG}	Al-geb	$HVG_{limzi}x_{HVG} - y_{HVG}$
Iqout_xx	x_{Iqout}	Al-geb	$-x_{Iqout} - y_{HVG} + y_{S1}$
Iqout_yy	y_{Iqout}	Al-geb	$I_{olim}I_{qoutlimzl} + I_{qoutlimzi}x_{Iqout} - y_{Iqout}$
a	θ	ExtAl-geb	$I_{pout}V$
v	V	ExtAl-geb	Vy_{Iqout}

Services

Name	Symbol	Equation	Type
Ipcmd0	I_{pcmd0}	$\frac{P_0}{V}$	ConstService
Iqcmd0	I_{qcmd0}	$-\frac{Q_0}{V}$	ConstService
kLVG	k_{LVG}	$\frac{1}{-L_{vpnt0} + L_{vpnt1}}$	ConstService
kLVPL	k_{LVPL}	$\frac{L_{vpl1}z_{Lvplsw}}{B_{rkpt} - Z_{erox}}$	ConstService

Discrete

Name	Symbol	Type	Info
S1_lim	$None_{S1}$	AntiWindupRate	
S0_lim	$None_{S0}$	AntiWindupRate	
HVG_lim	lim_{HVG}	HardLimiter	
Iqout_lim	lim_{Iqout}	HardLimiter	

Blocks

Name	Symbol	Type	Info
S1	S_1	LagAntiWindupRate	Iqcmd delay
LVG	LVG	Piecewise	Low voltage current gain
S2	S_2	Lag	Voltage filter with no anti-windup
LVPL	$LVPL$	Piecewise	Low voltage Ipcmd upper limit
S0	S_0	LagAntiWindupRate	
HVG	HVG	GainLimiter	High voltage gain block
Iqout	$Iqout$	GainLimiter	Iq output block

Config References

6.1 System

Option	Value	Info	Accepted values
freq	60	base frequency [Hz]	float
mva	100	system base MVA	float
store_z	0	store limiter status in TDS output	(0, 1)
ipadd	1	Use spmatrix.ipadd if available	(0, 1)
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_protocol	ipc		
dime_address	/tmp/dime2		

6.2 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')
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)

6.3 TDS

Op-tion	Value	Info	Accepted values
sparselib	klu	linear sparse solver name	('klu', 'umfpack', 'spsolve', 'cupy')
lin-solve	0	solve symbolic factorization each step (enable when KLU segfaults)	(0, 1)
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	the initial step step size	float
max_iter	15	maximum number of iterations	>=10

6.4 EIG

Option	Value	Info	Accepted values
sparselib	klu	linear sparse solver name	('klu', 'umfpack', 'spsolve', 'cupy')
lin-solve	0	solve symbolic factorization each step (enable when KLU segfaults)	(0, 1)
plot	0	show plot after computation	(0, 1)

7.1 Notes

7.1.1 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 is applicable to both state or 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 freed 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 complicate 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, 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 wrong results, since the residual is pegged at zero.

7.2 Per Unit System

The bases for AC system are

- S_b^{ac} : three-phase power in MVA. By default, $S_b^{ac} = 100 \text{ MVA}$ (in `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.

7.3 Profiling Import

To speed up the command-line program, import profiling is used to breakdown 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.

The APIs before v3.0.0 are in beta and may change without prior notice.

8.1 Since v1.0.0

8.1.1 v1.0.7

- 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.

8.1.2 v1.0.6 (2020-07-08)

- Patched step size adjustment algorithm.
- Added Area Control Error (ACE) model.

8.1.3 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`.

8.1.4 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.

8.1.5 v1.0.3 (2020-06-02)

- Patches *PQ* model equations where the "or" logic "I" 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.

8.1.6 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.

8.1.7 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.

8.2 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.

8.3 v0.9.4 (2020-05-20)

- Added exciter models EXST1, ESST3A, ESDC2A, SEXS, and IEEEEX1, 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.

8.4 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.

8.5 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*.

8.6 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.

8.7 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 IEEEEST stabilizer.
- Implemented COI for generator speed and angle measurement.

8.8 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 IEEEEST stabilizer with some fixes needed.

8.9 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.

8.10 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;

8.11 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.

8.12 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.

8.13 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.

9.1 GNU Public License v3

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10.1 andes.core package

10.1.1 Submodules

10.1.2 andes.core.block module

```
class andes.core.block.AlgebFreeze(u, freeze, name=None, tex_name=None,  
                                info=None)
```

Bases: *andes.core.block.Block*

Algebraic variable freezer implemented with *VarConst*.

For *freeze* elements equal to zero, the corresponding variables will remain at the pre-freeze values until *freeze* turns one.

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.Block(name: Optional[str] = None, tex_name: Optional[str] =
                             None, info: Optional[str] = None, namespace: str = 'local')
```

Bases: `object`

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
|
LeadLag A  exports (x, y)
|
Lag B      exports (x, y)
```

SomeModel instance M contains an instance of LeadLag block named A, which contains an instance of a Lag block named B. Both A and B exports two variables *x* and *y*.

In the code of Model, 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)
        self.vars = {..., 'A': self.A}
```

The `__setattr__` magic of LeadLag takes over the construction and assigns `A_B` to `B.name`, given A's name provided at run time. `self.A` is exported with the internal name A at the end.

Again, the LeadLag instance name (*A* in this example) **MUST** be provided in *SomeModel*'s constructor for the name prepending to work correctly. If there is more than one level of nesting, other than the leaf-level block, all parent blocks' names must be provided at instantiation.

When *A* is picked up by *SomeModel.__setattr__*, *B* is captured from *A*'s exports. 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*.

In this 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 *B* has gotten a new name *A_B*.

class_name

Return the class name.

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'
```

static enforce_tex_name (*fields*)

Enforce tex_name is not None

export ()

Method for exporting instances defined in this class in a dictionary. This method calls the define method first and returns `self.vars`.

Returns

dict Keys are the (last section of the) variable name, and the values are the attribute instance.

f_numeric (***kwargs*)

Function call to update differential equation values.

This function should modify the e value of block State and ExtState in place.

g_numeric (***kwargs*)

Function call to update algebraic equation values.

This function should modify the e value of block Algeb and ExtAlgeb in place.

j_numeric ()

This function stores the constant and variable jacobian information in corresponding lists.

Constant jacobians are stored by indices and values in, for example, *ifxc*, *jfxc* and *vfxc*. Value scalars or arrays are stored in *vfxc*.

Variable jacobians are stored by indices and functions. The function shall return the value of the corresponding jacobian elements.

j_reset ()

Helper function to clear the lists holding the numerical Jacobians.

This function should be only called once at the beginning of `j_numeric` in blocks.

class `andes.core.block.DeadBand1` (*u, center, lower, upper, enable=True, name=None, tex_name=None, info=None, namespace='local'*)

Bases: `andes.core.block.Block`

Deadband type 1.

Parameters

center Default value when within the deadband. If the input is an error signal, center should be set to zero.

Notes

Block diagram



define ()

Notes

Implemented equation:

$$0 = center + z_u * (u - upper) + z_l * (u - lower) - y$$

class `andes.core.block.Gain` (*u*, *K*, *name=None*, *tex_name=None*, *info=None*)

Bases: `andes.core.block.Block`

Gain block.



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*, *upper*, *lower*, *no_upper=False*, *no_lower=False*, *name=None*, *tex_name=None*, *info=None*)

Bases: `andes.core.block.Block`

Gain followed by a limiter.

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

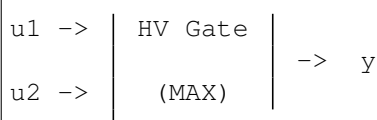
define()

TODO: write docstring

class `andes.core.block.HVGate(u1, u2, name=None, tex_name=None, info=None)`

Bases: `andes.core.block.Block`

High Value Gate. Outputs the maximum of two inputs.



define()

Implemented equations and initial conditions

$$0 = s_0^{sl} u_1 + s_1^{sl} u_2 - yy_0 = \text{maximum}(u_1, u_2)$$

Notes

In the implementation, one should not use

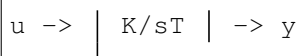
```
self.y.v_str = f'maximum({self.u1.name}, {self.u2.name})',
```

because SymPy processes this equation to `{self.u1.name}`. Not sure if this is a bug or intended.

class `andes.core.block.Integrator(u, T, K, y0, name=None, tex_name=None, info=None)`

Bases: `andes.core.block.Block`

Integrator block.



Exports a differential variable y . The initial output is specified by y_0 and default to zero.

define()

Implemented equation and the initial condition are

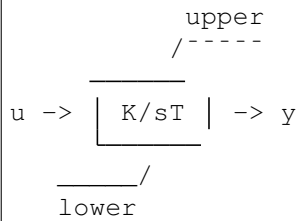
$$\dot{y} = Ku$$

$$y^{(0)} = 0$$

```
class andes.core.block.IntegratorAntiWindup(u, T, K, y0, lower, upper,
                                             name=None, tex_name=None,
                                             info=None)
```

Bases: `andes.core.block.Block`

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

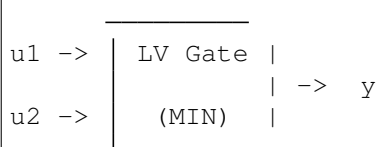
$$\dot{y} = Ku$$

$$y^{(0)} = 0$$

```
class andes.core.block.LVGate(u1, u2, name=None, tex_name=None, info=None)
```

Bases: `andes.core.block.Block`

Low Value Gate. Outputs the minimum of the two inputs.



define()

Implemented equations and initial conditions

$$0 = s_0^{sl}u_1 + s_1^{sl}u_2 - yy_0 = \text{minimum}(u_1, u_2)$$

Notes

Same problem as *HVGate* as *minimum* does not sympify correctly.

```
class andes.core.block.Lag(u, T, K, name=None, tex_name=None, info=None)
```

Bases: `andes.core.block.Block`

Lag (low pass filter) transfer function.



Exports one state variable y as the output.

Parameters

K Gain

T Time constant

u Input variable

define()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - y)$$

$$y^{(0)} = Ku$$

class `andes.core.block.Lag2ndOrd`(*u*, *K*, *T1*, *T2*, *name=None*, *tex_name=None*,
info=None)

Bases: `andes.core.block.Block`

Second order lag transfer function (low-pass filter)



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

$$T_2 \dot{x} = Ku - y - T_1 x$$

$$\dot{y} = x$$

$$x^{(0)} = 0$$

$$y^{(0)} = Ku$$

```
class andes.core.block.LagAWFreeze(u, T, K, lower, upper, freeze, name=None,
                                tex_name=None, info=None)
    Bases: andes.core.block.LagAntiWindup
```

Lag with anti-windup limiter and state freeze.

```
define ()
```

Notes

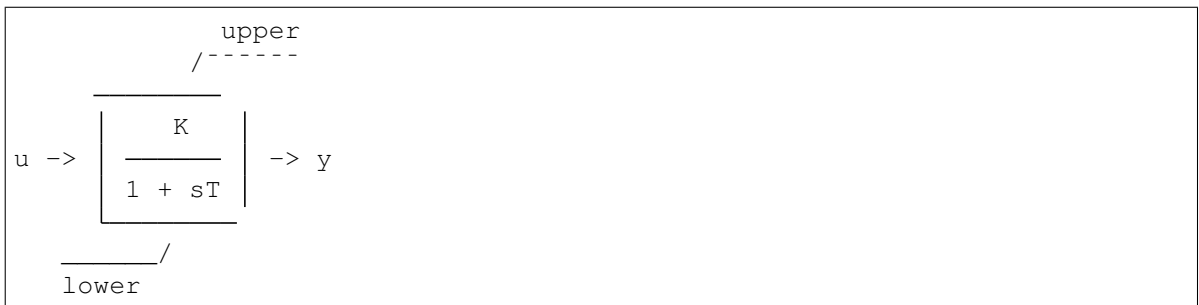
Equations and initial values are

$$T \dot{y} = (1 - freeze)(Ku - y)$$

$$y^{(0)} = Ku$$

```
class andes.core.block.LagAntiWindup(u, T, K, lower, upper, name=None,
                                     tex_name=None, info=None)
    Bases: andes.core.block.Block
```

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

u Input variable

```
define ()
```

Notes

Equations and initial values are

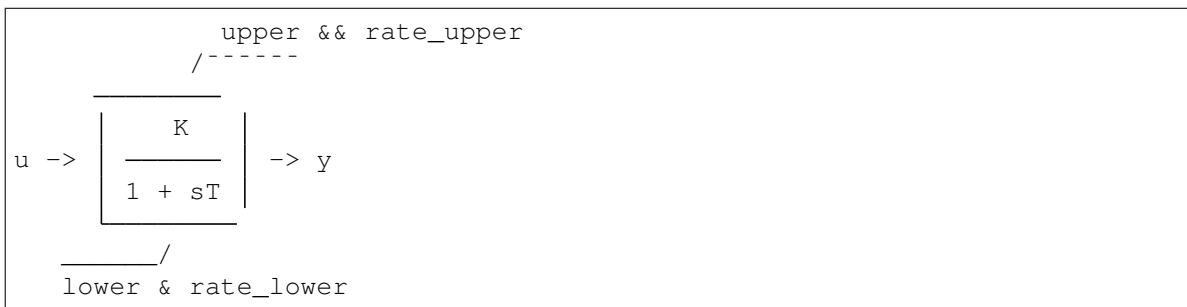
$$T\dot{y} = (Ku - y)$$

$$y^{(0)} = Ku$$

```
class andes.core.block.LagAntiWindupRate(u, T, K, lower, upper,
                                         rate_lower, rate_upper,
                                         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)
```

Bases: `andes.core.block.Block`

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

u Input variable

define ()

Notes

Equations and initial values are

$$T\dot{y} = (Ku - y)$$

$$y^{(0)} = Ku$$

```
class andes.core.block.LagFreeze(u, T, K, freeze, name=None, tex_name=None,
                                info=None)
```

Bases: `andes.core.block.Lag`

Lag with a state freeze input.

define()**Notes**

Equations and initial values are

$$T\dot{y} = (1 - freeze) * (Ku - y)$$

$$y^{(0)} = Ku$$

class `andes.core.block.LeadLag`(*u*, *T1*, *T2*, *K=1*, *zero_out=True*, *name=None*,
tex_name=None, *info=None*)
 Bases: `andes.core.block.Block`

Lead-Lag transfer function block in series implementation

$$u \rightarrow \left[\begin{array}{c} \frac{1 + sT_1}{1 + sT_2} \\ K \end{array} \right] \rightarrow y$$

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

$$T_2\dot{x}' = (u - x')$$

$$T_2y = KT_1(u - x') + KT_2x' + E_2, \text{ where}$$

$$E_2 = \begin{cases} (y - Kx') & \text{if } T_1 = T_2 = 0 \& zero_out = True \\ 0 & \text{otherwise} \end{cases}$$

$$x'^{(0)} = u$$

$$y^{(0)} = Ku$$

```
class andes.core.block.LeadLag2ndOrd(u, T1, T2, T3, T4, zero_out=False,
                                   name=None, tex_name=None, info=None)
```

Bases: `andes.core.block.Block`

Second-order lead-lag transfer function block

$$u \rightarrow \left[\frac{1 + sT_3 + s^2 T_4}{1 + sT_1 + s^2 T_2} \right] \rightarrow y$$

Exports two internal states (x_1 and x_2) and output algebraic variable y .

TODO: instead of implementing `zero_out` using `LessThan` and an additional term, consider correcting all parameters to 1 if all are 0.

```
define ()
```

Notes

Implemented equations and initial values are

$$\begin{aligned} T_2 \dot{x}_1 &= u - x_2 - T_1 x_1 \\ \dot{x}_2 &= x_1 \\ T_2 y &= T_2 x_2 + T_2 T_3 x_1 + T_4 (u - x_2 - T_1 x_1) + E_2, \text{ where} \\ E_2 &= \begin{cases} (y - x_2) & \text{if } T_1 = T_2 = T_3 = T_4 = 0 \& \text{zero_out} = \text{True} \\ 0 & \text{otherwise} \end{cases} \\ x_1^{(0)} &= 0 \\ x_2^{(0)} = y^{(0)} &= u \end{aligned}$$

```
class andes.core.block.LeadLagLimit(u, T1, T2, lower, upper, name=None,
                                   tex_name=None, info=None)
```

Bases: `andes.core.block.Block`

Lead-Lag transfer function block with hard limiter (series implementation)

$$u \rightarrow \left[\frac{1 + sT_1}{1 + sT_2} \right] \rightarrow y_{nl} \xrightarrow[\text{lower}]{\text{upper}} y$$

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

$$\begin{aligned}T_2\dot{x}' &= (u - x') \\T_2y &= T_1(u - x') + T_2x' \\x'^{(0)} &= y^{(0)} = u\end{aligned}$$

```
class andes.core.block.PIDController(u, kp, ki, ref=0.0, x0=0.0, name=None,  
                                     tex_name=None, info=None)
```

Bases: `andes.core.block.Block`

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.PIDControllerNumeric(u, kp, ki, ref=0.0, name=None,  
                                             tex_name=None, info=None)
```

Bases: `andes.core.block.Block`

A PI Controller implemented with numerical function calls.

ref must not be a variable.

define()

Skip the symbolic definition

f_numeric(kwargs)**

Function call to update differential equation values.

This function should modify the *e* value of block *State* and *ExtState* in place.

g_numeric (**kwargs)

Function call to update algebraic equation values.

This function should modify the `e` value of block `Algeb` and `ExtAlgeb` in place.

j_numeric ()

This function stores the constant and variable jacobian information in corresponding lists.

Constant jacobians are stored by indices and values in, for example, *ifxc*, *jfxc* and *vfxc*. Value scalars or arrays are stored in *vfxc*.

Variable jacobians are stored by indices and functions. The function shall return the value of the corresponding jacobian elements.

class `andes.core.block.PIFreeze` (*u, kp, ki, freeze, ref=0.0, x0=0.0, name=None, tex_name=None, info=None*)

Bases: `andes.core.block.PIController`

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

$$\begin{aligned} \dot{x}_i &= k_i * (u - ref) \\ y &= (1 - freeze) * (x_i + k_p * (u - ref)) + freeze * y \end{aligned}$$

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*)

Bases: `andes.core.block.Block`

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.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)
```

Bases: *`andes.core.block.PITrackAW`*

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.Piecewise(u, points: Union[List[T], Tuple], funs:
                                Union[List[T], Tuple], name=None,
                                tex_name=None, info=None)
    Bases: andes.core.block.Block
```

Piecewise block. Outputs an algebraic variable y .

This block takes a list of N points, $[x_0, x_1, \dots, x_{n-1}]$ to define $N+1$ ranges, namely $(-\infty, x_0)$, (x_0, x_1) , ..., $(x_{n-1}, +\infty)$. and a list of $N+1$ function strings $[fun_0, \dots, fun_n]$.

Inputs that fall within each range applies the corresponding function. The first range $(-\infty, x_0)$ applies fun_0 , and the last range $(x_{n-1}, +\infty)$ applies the last function fun_n .

Parameters

points [list, tuple] A list of piecewise points. Need to be provided in the constructor function.

funcs [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.funcs` needs to be provided with the function strings corresponding to each range.

class `andes.core.block.Washout` ($u, T, K, name=None, tex_name=None, info=None$)

Bases: `andes.core.block.Block`

Washout filter (high pass) block.

$$u \rightarrow \left[\frac{sK}{1 + sT} \right] \rightarrow y$$

Exports state x (symbol x') and output algebraic variable y .

define()

Notes

Equations and initial values:

$$\begin{aligned} T\dot{x}' &= (u - x') \\ Ty &= K(u - x') \\ x'^{(0)} &= u \\ y^{(0)} &= 0 \end{aligned}$$

class `andes.core.block.WashoutOrLag` ($u, T, K, name=None, zero_out=True, tex_name=None, info=None$)

Bases: `andes.core.block.Washout`

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:

$$\begin{aligned}Tx' &= (u - x') \\Ty &= z_0 K(u - x') + z_1 Tx \\x^{(0)} &= u \\y^{(0)} &= 0\end{aligned}$$

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.

10.1.3 andes.core.discrete module

```
class andes.core.discrete.AntiWindup(u,      lower,      upper,      enable=True,
                                     no_lower=False,      no_upper=False,
                                     name=None, tex_name=None, info=None,
                                     state=None)
```

Bases: *andes.core.discrete.Limiter*

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.

check_eq()

Check the variables and equations and set the limiter flags. Reset differential equation values based on limiter flags.

Notes

The current implementation reallocates memory for *self.x_set* in each call. Consider improving for speed. (TODO)

check_var (*args, **kwargs)

This function is empty. Defers *check_var* to *check_eq*.

```
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)
```

Bases: *andes.core.discrete.AntiWindup*, *andes.core.discrete.RateLimiter*

Anti-windup limiter with rate limits

check_eq()

Check the variables and equations and set the limiter flags. Reset differential equation values based on limiter flags.

Notes

The current implementation reallocates memory for *self.x_set* in each call. Consider improving for speed. (TODO)

```
class andes.core.discrete.Average(u,    mode='step',    delay=0,    name=None,
                                   tex_name=None, info=None)
```

Bases: *andes.core.discrete.Delay*

Compute the average of a BaseVar over a period of time or a number of samples.

check_var (dae_t, *args, **kwargs)

This function is called in *l_update_var* before evaluating equations.

It should update internal flags only.

```
class andes.core.discrete.DeadBand(u,    center,    lower,    upper,    enable=True,
                                   equal=True,    zu=0.0,    zl=0.0,    zi=0.0,
                                   name=None, tex_name=None, info=None)
```

Bases: *andes.core.discrete.Limiter*

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'
```

check_var (*args, **kwargs)

Notes

Updates three flags: **zi**, **zu**, **zl** based on the following rules:

zu: 1 if $u > \text{upper}$; 0 otherwise.

zl: 1 if $u < \text{lower}$; 0 otherwise.

zi: $\text{not}(\text{zu or zl})$;

class `andes.core.discrete.DeadBandRT` (*u*, *center*, *lower*, *upper*, *enable=True*)

Bases: `andes.core.discrete.DeadBand`

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) + \
                db_l * db_zlr + \
                db_u * db_zur - var_out'
```

check_var (*args, **kwargs)

Notes

Updates five flags: **zi**, **zu**, **zl**; **zur**, and **zlr** based on the following rules:

zu: 1 if $u > \text{upper}$; 0 otherwise.

zl: 1 if $u < \text{lower}$; 0 otherwise.

zi: $\text{not}(\text{zu or zl})$;

zur:

- set to 1 when $(\text{previous zu} + \text{present zi} == 2)$
- hold when $(\text{previous zi} == \text{zi})$
- clear otherwise

zlr:

- set to 1 when (previous zl + present zi == 2)
- hold when (previous zi == zi)
- clear otherwise

```
class andes.core.discrete.Delay (u,      mode='step',      delay=0,      name=None,
                                tex_name=None, info=None)
```

Bases: *andes.core.discrete.Discrete*

Delay class to memorize past variable values.

Delay allows to impose a predefined "delay" (in either steps or seconds) for an input variable. The amount of delay is a scalar and has to be fixed at model definition for now.

check_var (dae_t, *args, **kwargs)

This function is called in `l_update_var` before evaluating equations.

It should update internal flags only.

list2array (n)

Allocate memory for storage arrays.

```
class andes.core.discrete.Derivative (u,      name=None,      tex_name=None,
                                       info=None)
```

Bases: *andes.core.discrete.Delay*

Compute the derivative of an algebraic variable using numerical differentiation.

check_var (dae_t, *args, **kwargs)

This function is called in `l_update_var` before evaluating equations.

It should update internal flags only.

```
class andes.core.discrete.Discrete (name=None, tex_name=None, info=None)
```

Bases: `object`

Base discrete class.

Discrete classes export flag arrays (usually boolean) .

check_eq ()

This function is called in `l_check_eq` after updating equations.

It updates internal flags, set differential equations, and record pegged variables.

check_var (*args, **kwargs)

This function is called in `l_update_var` before evaluating equations.

It should update internal flags only.

class_name

get_names ()

Available symbols from this class

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.

get_values()

list2array(n)

warn_init_limit()

Warn if initialized at limits.

```
class andes.core.discrete.HardLimiter(u, lower, upper, enable=True,
                                     name=None, tex_name=None, info=None,
                                     no_upper=False, no_lower=False,
                                     equal=True, zu=0.0, zl=0.0, zi=1.0)
```

Bases: `andes.core.discrete.Limiter`

Hard limiter for algebraic or differential variable. This class is an alias of *Limiter*.

```
class andes.core.discrete.LessThan(u, bound, equal=False, enable=True,
                                   name=None, tex_name=None, cache=False,
                                   z0=0, z1=1)
```

Bases: `andes.core.discrete.Discrete`

Less than (<) comparison function.

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.

check_var(*args, **kwargs)

If enabled, set flags based on inputs. Use cached values if enabled.

```
class andes.core.discrete.Limiter(u, lower, upper, enable=True, name=None,
                                 tex_name=None, info=None, no_upper=False,
                                 no_lower=False, equal=True, zu=0.0, zl=0.0,
                                 zi=1.0)
```

Bases: `andes.core.discrete.Discrete`

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

equal: bool True to include equal signs in comparison (\geq or \leq).

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

check_var (*args, **kwargs)
Evaluate the flags.

```
class andes.core.discrete.RateLimiter(u,    lower,    upper,    enable=True,
                                     no_lower=False,    no_upper=False,
                                     lower_cond=None,    upper_cond=None,
                                     name=None, tex_name=None, info=None)
```

Bases: `andes.core.discrete.Discrete`

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 Anti-Windup limiter. Use *AntiWindupRate* for a rate-limited anti-windup limiter.

Notes

RateLimiter inherits from Discrete to avoid internal naming conflicts with *Limiter*.

check_eq()

This function is called in `l_check_eq` after updating equations.

It updates internal flags, set differential equations, and record pegged variables.

class `andes.core.discrete.Sampling`(*u*, *interval=1.0*, *offset=0.0*, *name=None*,
tex_name=None, *info=None*)

Bases: `andes.core.discrete.Discrete`

Sample an input variable repeatedly at a given time interval.

check_var(*dae_t*, **args*, ***kwargs*)

Check and update the output.

Notes

Present output stored in *v*. Output of the last step is stored in `_last_v`. Time for the last output is stored in `_last_t`.

Initially, store *v* and `_last_v`.

If time progresses and *dae_t* is a multiple of *period*, update `_last_v` and then *v*. Record `_last_t`.

If time does not progress, update *v*.

If time rewinds, restore `_last_v` to *v*.

list2array(*n*)

class `andes.core.discrete.Selector`(**args*, *fun*, *tex_name=None*, *info=None*)

Bases: `andes.core.discrete.Discrete`

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.

See also:

`numpy.ufunc.reduce` NumPy reduce function

`andes.core.block.HVGate`

`andes.core.block.LVGate`

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*.

check_var (*args, **kwargs)

Set the i-th variable's flags to 1 if the return of the reduce function equals the i-th input.

```
class andes.core.discrete.SortedLimiter(u, lower, upper, enable=True, n_select:
                                     Optional[int] = None, name=None,
                                     tex_name=None)
```

Bases: `andes.core.discrete.Limiter`

A comparer with the top value selection.

check_var (*args, **kwargs)

Evaluate the flags.

```
class andes.core.discrete.Switcher(u, options: Union[list, Tuple], name: str = None,
                                   tex_name: str = None, cache=True)
```

Bases: `andes.core.discrete.Discrete`

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 IEEEEST 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=[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([1, 0, 0, 0, 0]),
 'IC_s1': np.array([0, 1, 1, 0, 0]),
 'IC_s2': np.array([0, 0, 0, 0, 0]),
 'IC_s3': np.array([0, 0, 0, 1, 0]),
 'IC_s4': np.array([0, 0, 0, 0, 0]),
 'IC_s5': np.array([0, 0, 0, 0, 1])
}
```

check_var (*args, **kwargs)

Set the switcher flags based on inputs. Uses cached flags if cache is set to True.

list2array (n)

This forces to evaluate Switcher upon System setup

10.1.4 andes.core.model module

Base class for building ANDES models.

class andes.core.model.Cache

Bases: object

Class for caching the return value of callback functions.

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

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

```
class andes.core.model.Documenter (parent)
```

Bases: `object`

Helper class for documenting models.

Parameters

parent [Model] The *Model* instance to document

```
get (max_width=78, export='plain')
```

Return the model documentation in table-formatted string.

Parameters

max_width [int] Maximum table width. Automatically set to 0 if format is `rest`.

export [str, ('plain', 'rest')] Export format. Use fancy table if is `rest`.

Returns

str A string with the documentations.

```
class andes.core.model.Model (system=None, config=None)
```

Bases: `object`

Base class for power system DAE models.

After subclassing *ModelData*, subclass *Model* to complete a DAE model. Subclasses of *Model* defines 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`.

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 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. It 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 variables can be used in equation strings. An addition variable *dae_t* for the current simulation time can be used if the model has flag *tds*.

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 implements a piecewise 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

a_reset()

Reset addresses to empty and reset flags.address to `False`.

alter(src, idx, value)

Alter input parameter or service values.

If operates on a parameter, this function will convert the new value to per unit.

Parameters

src [str] The parameter name to alter

idx [str, float, int] The device to alter

value [float] The desired value

class_name

Return the class name

doc(max_width=78, export='plain')

Retrieve model documentation as a string.

e_clear()

Clear equation value arrays associated with all internal variables.

f_numeric(kwargs)**

Custom fcall functions. Modify equations directly.

f_update()

Evaluate differential equations.

Notes

In-place equations: added to the corresponding DAE array. Non-inplace equations: in-place set to internal array to overwrite old values (and avoid clearing).

g_numeric (**kwargs)

Custom gcall functions. Modify equations directly.

g_update ()

Evaluate algebraic equations.

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]`

get_init_order ()

Get variable initialization order and send to *logger.info*.

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 address of arrays changed. After initialization, all array assignments are inplace. 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.

get_md5 ()

Return the md5 hash of concatenated equation strings.

get_times()

Get event switch_times from *TimerParam*.

Returns

list A list containing all switching times defined in *TimerParams*

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

init()

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

init_iter()

Solve the initialization equation using the Newton-Krylov method.

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*.

j_update()

Update Jacobians and store the Jacobian values to *self.v<JName>*, where *<JName>* is the Jacobian name.

Returns

None

l_check_eq()

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

l_update_var(dae_t)

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

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 [:]).

post_init_check()

Post init checking. Warns if values of *InitChecker* is not True.

prepare(quick=False)

Symbolic processing and code generation.

refresh_inputs()

This is the helper function to refresh inputs.

The functions collects objects into OrderedDict and store to *self._input* and *self._input_z*.

Returns

None

refresh_inputs_arg()

Refresh inputs for each function with individual argument list.

s_numeric(kwargs)**

Custom service value functions. Modify *Service.v* directly.

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.

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.

s_update_post()

Update post-initialization services

s_update_var()

Update *VarService*.

set(src, idx, attr, value)

Set the value of an attribute of a model property.

Performs *self.<src>.<attr>[idx] = value*

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.

value [array-like] Values to be set

Returns**None****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 has 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.

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 *cvxopt.spmatrix*.

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.

v_numeric(kwargs)**

Custom variable initialization function.

class andes.core.model.ModelCall

Bases: `object`

Class for storing generated function calls and Jacobians.

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.

```
class andes.core.model.ModelData(*args, **kwargs)
```

Bases: `object`

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 *GENCLS* should be named *GENCLSData*.

Parameters should be defined in the `__init__` function of the derived class.

Refer to `andes.core.param` for available parameter types.

Notes

Two default parameters, *u* (connection status of type `andes.core.param.NumParam`), and *name* (device name of type `andes.core.param.DataParam`) are pre-defined in `ModelData`, and will be inherited by all models.

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.

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.

as_df ()

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.

as_df_in ()

Export all parameters from original input (*vin*) as a *pandas.DataFrame*. This function utilizes *as_dict* for preparing data.

Returns

DataFrame A *pandas.DataFrame* containing all model data. An *uid* column is prepended.

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)`.

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

find_param (*prop*)

Find params with the given property and return in an OrderedDict.

Parameters

prop [str] Property name

Returns

OrderedDict

class `andes.core.model.SymProcessor` (*parent*)

Bases: `object`

A helper class for symbolic processing and code generation.

Parameters

parent [Model] The *Model* instance to document

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.

non_vars_dict [OrderedDict] symbols in `input_syms` but not in `var_syms`.

generate_equations ()

generate_init ()

Generate lambda functions for initial values.

generate_jacobians()

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_pretty_print()

Generate pretty print variables and equations.

generate_py_files()

Create output source code file for generated code. NOT WORKING NOW.

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)

non_vars_dict [OrderedDict] name-symbol pair of all non-variables, namely, (inputs_dict - vars_dict)

10.1.5 andes.core.param module

```
class andes.core.param.BaseParam (default: Union[float, str, int, None] = None, name:
Optional[str] = None, tex_name: Optional[str]
= None, info: Optional[str] = None, unit: Op-
tional[str] = None, mandatory: bool = False, ex-
port: bool = True)
```

Bases: `object`

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`.

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.

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`.

class_name

Return the class name.

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

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.

n

Return the count of elements in the value array.

```

class andes.core.param.DataParam (default: Union[float, str, int, None] = None, name:
                                Optional[str] = None, tex_name: Optional[str]
                                = None, info: Optional[str] = None, unit: Op-
                                tional[str] = None, mandatory: bool = False, ex-
                                port: bool = True)

```

Bases: `andes.core.param.BaseParam`

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

```

class andes.core.param.ExtParam (model: str, src: str, indexer=None, dtype=<class
                                'float'>, allow_none=False, default=0.0, **kwargs)

```

Bases: `andes.core.param.NumParam`

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.

Attributes

parent_model [Model] The parent model providing the original parameter.

add (*value=None*)

ExtParam has an empty *add* method.

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.

restore()

ExtParam has an empty *restore* method

to_array()

Convert to array when *d_type* is not str

```
class andes.core.param.IdxParam (default: Union[float, str, int, None] = None, name:
                                Optional[str] = None, tex_name: Optional[str] =
                                None, info: Optional[str] = None, unit: Op-
                                tional[str] = None, mandatory: bool = False,
                                unique: bool = False, export: bool = True, model:
                                Optional[str] = None)
```

Bases: *andes.core.param.BaseParam*

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')
```

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.

```
class andes.core.param.NumParam(default: Union[float, str, Callable, None] = None,
                                name: Optional[str] = None, tex_name: Op-
                                tional[str] = None, info: Optional[str] = None, unit:
                                Optional[str] = None, vrange: Union[List[T], Tu-
                                ple, None] = None, non_zero: bool = False, posi-
                                tive: 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)
```

Bases: `andes.core.param.BaseParam`

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

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

positive: bool True if this parameter must be positive

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

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

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`

restore ()

Restore parameter to the original input by copying `self.vin` to `self.v`.

pu_coeff will not be overwritten.

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

to_array ()

Convert `v` to `np.ndarray` after adding elements. Store a copy if the input in *vin*. Set `pu_coeff` to all ones.

The conversion enables array-based calculation.

Warning: After this call, *add* will not be allowed, because data will not be copied over to *vin*.

```
class andes.core.param.TimerParam (callback: Optional[Callable] = None, default:
    Union[float, str, Callable, None] = None, name:
    Optional[str] = None, tex_name: Optional[str]
    = None, info: Optional[str] = None, unit: Op-
    tional[str] = None, non_zero: bool = False,
    mandatory: bool = False, export: bool = True)
```

Bases: `andes.core.param.NumParam`

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 toggler class `Toggler` takes a parameter `t` for the toggle time. Inside `Toggler.__init__`, one would have

```
self.t = TimerParam()
```

The `Toggler` class also needs to define a method for toggling 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 `Toggler.__init__`, assign the function as the callback for `self.t`

```
self.t.callback = self._u_switch
```

is_time (`dae_t`)

Element-wise check if the DAE time is the same as the parameter value. The current implementation uses `np.isclose`

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.

See also:

numpy.isclose See NumPy.isclose for the warning on absolute tolerance

10.1.6 andes.core.service module

class `andes.core.service.BackRef` (***kwargs*)

Bases: `andes.core.service.BaseService`

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.BaseService (name: str = None, tex_name: str = None,
                                     info: str = None, vtype: Type[CT_co] =
                                     None)
```

Bases: `object`

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

class_name

Return the class name

get_names ()

Return *name* in a list

Returns

list A list only containing the name of the service variable

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

```
class andes.core.service.ConstService (v_str: Optional[str] = None, v_numeric:
                                     Optional[Callable] = None, vtype: Op-
                                     tional[type] = None, name: Optional[str] =
                                     None, tex_name=None, info=None)
```

Bases: `andes.core.service.BaseService`

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`.

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

Attributes

v [array-like or a scalar] ConstService value

assign_memory (*n*)

Assign memory for `self.v` and set the array to zero.

```
class andes.core.service.DataSelect (optional, fallback, name: Optional[str] =  
                                     None, tex_name: Optional[str] = None, info:  
                                     Optional[str] = None)
```

Bases: `andes.core.service.BaseService`

Class for selecting values for optional DataParam or NumParam.

This service is a v-provider that uses optional DataParam if available with a fallback.

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)
```

v

```
class andes.core.service.DeviceFinder (u, link, idx_name, name=None,  
                                       tex_name=None, info=None)
```

Bases: `andes.core.service.BaseService`

Service for finding indices of optionally linked devices.

If not provided, *DeviceFinder* will add devices at the beginning of *System.setup*.

Examples

IEEEEST stabilizer takes an optional *busf* (IdxParam) for specifying the connected BusFreq, which is needed for mode 6. To avoid reimplementing *BusFreq* within IEEEEST, one can do

```
self.busfreq = DeviceFinder(self.busf, link=self.buss, idx_name='bus')
```

where *self.busf* is the optional input, *self.buss* is the bus indices that *busf* should measure, and *idx_name* is the name of a BusFreq parameter through which the measured bus indices are specified. For each *None* values in *self.busf*, a *BusFreq* is created to measure the corresponding bus in *self.buss*.

That is, `BusFreq[idx_name].v = [link].DeviceFinder` will find / create *BusFreq* devices so that the returned list of *BusFreq* indices are connected to *self.buss*, respectively.

find_or_add(system)

v

```
class andes.core.service.ExtService(model: str, src: str, indexer:
    Union[andes.core.param.BaseParam, andes.core.service.BaseService], attr: str =
    'v', allow_none: bool = False, default=0,
    name: str = None, tex_name: str = None,
    vtype=None, info: str = None)
```

Bases: `andes.core.service.BaseService`

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 GENCLSMModel(Model):
    def __init__(...):
        ...
        self.p0 = ExtService(src='p',
                             model='StaticGen',
                             indexer=self.gen,
                             tex_name='P_0')
```

assign_memory (*n*)

Assign memory for `self.v` and set the array to zero.

link_external (*ext_model*)

Method to be called by `System` for getting values from the external model or group.

Parameters

ext_model An instance of a model or group provided by `System`

class `andes.core.service.FlagValue` (*u*, *value*, *flag=0*, *name=None*, *tex_name=None*,
info=None, *cache=True*)

Bases: `andes.core.service.BaseService`

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).

v

class `andes.core.service.IdxRepeat` (*u*, *ref*, ***kwargs*)

Bases: `andes.core.service.OperationService`

Helper class to repeat `IdxParam`.

This class has the same functionality as `andes.core.service.NumRepeat` but only operates on `IdxParam`, `DataParam` or `NumParam`.

v

Return values stored in `self.v`. May be overloaded by subclasses.

class `andes.core.service.InitChecker` (*u*, *lower=None*, *upper=None*, *equal=None*,
not_equal=None, *enable=True*, *error_out=False*, ***kwargs*)

Bases: `andes.core.service.OperationService`

Class for checking init values against known typical values.

Instances will be stored in `Model.services_post` and `Model.services_ichack`, 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*.

check()

Check the bounds and equality conditions.

```
class andes.core.service.NumReduce(u, ref: andes.core.service.BackRef, fun:
                                   Callable, name=None, tex_name=None,
                                   info=None, cache=True)
```

Bases: *andes.core.service.OperationService*

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 *V_n* 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]`.

v

Return the reduced values from the reduction function in an array

Returns

The array `self._v` storing the reduced values

```
class andes.core.service.NumRepeat (u, ref, **kwargs)
```

Bases: `andes.core.service.OperationService`

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.

v

Return the values of the repeated values in a sequential 1-D array

Returns

The array, **self._v** storing the repeated values

```
class andes.core.service.NumSelect (optional, fallback, name: Optional[str] = None,
                                     tex_name: Optional[str] = None, info: Op-
                                     tional[str] = None)
```

Bases: *andes.core.service.OperationService*

Class for selecting values for optional NumParam.

Notes

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)
```

v

Return values stored in *self._v*. May be overloaded by subclasses.

```
class andes.core.service.OperationService (name=None,          tex_name=None,
                                           info=None)
```

Bases: *andes.core.service.BaseService*

Base class for a type of Service which performs specific operations

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

v

Return values stored in *self._v*. May be overloaded by subclasses.

```
class andes.core.service.ParamCalc (param1,   param2,   func,   name=None,
                                     tex_name=None, info=None, cache=True)
```

Bases: *andes.core.service.BaseService*

Parameter calculation service.

Useful to create parameters calculated instantly from existing ones.

v

```
class andes.core.service.PostInitService (v_str:   Optional[str] = None,
                                           v_numeric: Optional[Callable]
                                           = None, vtype: Optional[type] =
None, name: Optional[str] = None,
                                           tex_name=None, info=None)
```

Bases: *andes.core.service.ConstService*

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*.

class `andes.core.service.RandomService` (*func*=<built-in method *rand* of *numpy.random.mtrand.RandomState* object>, ***kwargs*)

Bases: `andes.core.service.BaseService`

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.

v

This class has *v* wrapped by a property decorator.

Returns

array-like Randomly generated service variables

class `andes.core.service.ReffFlatten` (*ref*, ***kwargs*)

Bases: `andes.core.service.OperationService`

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,
                  )

```

v

Return values stored in *self.v*. May be overloaded by subclasses.

class andes.core.service.**Replace**(old_val, flt, new_val, name=None, tex_name=None, info=None, cache=True)
 Bases: *andes.core.service.BaseService*

Replace parameters with new values if the function returns True

v

class andes.core.service.**VarService**(v_str: Optional[str] = None, v_numeric: Optional[Callable] = None, vtype: Optional[type] = None, name: Optional[str] = None, tex_name=None, info=None)
 Bases: *andes.core.service.ConstService*

Variable service that gets updated in each step/loop as variables change.

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.

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 ($v_d + jv_q$), ($I_d + jI_q$) 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))',
                    )

```


10.1.7 andes.core.solver module

class `andes.core.solver.CuPySolver`

Bases: `andes.core.solver.SciPySolver`

CuPy lsqr solver (GPU-based).

solve (A, b)

Solve linear systems.

Parameters

A [`scipy.csc_matrix`] Sparse N-by-N matrix

b [`numpy.ndarray`] Dense 1-dimensional array of size N

Returns

np.ndarray Solution x to $Ax = b$

class `andes.core.solver.KLUSolver`

Bases: `andes.core.solver.SuiteSparseSolver`

KLU solver.

Requires package `cvxoptklu`.

linsolve (A, b)

Solve linear equation set $Ax = b$ and returns the solutions in a 1-D array.

This function performs both symbolic and numeric factorizations every time, and can be slower than `Solver.solve`.

Parameters

A Sparse matrix

b RHS of the equation

Returns

The solution in a 1-D np array.

class `andes.core.solver.SciPySolver`

Bases: `object`

Base class for scipy family solvers.

clear ()

linsolve (A, b)

Exactly same functionality as `solve`.

solve (A, b)

Solve linear systems.

Parameters

A [`scipy.csc_matrix`] Sparse N-by-N matrix

b [numpy.ndarray] Dense 1-dimensional array of size N

Returns

np.ndarray Solution x to $Ax = b$

to_csc(A)

Convert A to scipy.sparse.csc_matrix.

Parameters

A [cvxopt.spmatrix] Sparse N-by-N matrix

Returns

scipy.sparse.csc_matrix Converted csc_matrix

class andes.core.solver.**Solver** (*sparselib='umfpack'*)

Bases: `object`

Sparse matrix solver class.

This class wraps UMFPACK, KLU, SciPy and CuPy solvers to provide an unified interface for solving sparse linear equations $Ax = b$.

Provides methods `solve`, `linsolve` and `clear`.

clear()

Remove all cached objects.

linsolve(A, b)

Solve linear equations without caching factorization. Performs full factorization each call.

Parameters

A [cvxopt.spmatrix] Sparse N-by-N matrix

b [cvxopt.matrix or numpy.ndarray] Dense N-by-1 matrix

Returns

numpy.ndarray Dense N-by-1 array

solve(A, b)

Solve linear equations and cache factorizations if possible.

Parameters

A [cvxopt.spmatrix] Sparse N-by-N matrix

b [cvxopt.matrix or numpy.ndarray] Dense N-by-1 matrix

Returns

numpy.ndarray Dense N-by-1 array

class andes.core.solver.**SpSolve**

Bases: `andes.core.solver.SciPySolver`

scipy.sparse.linalg.spsolve Solver.

solve (A, b)

Solve linear systems.

Parameters

A [scipy.csc_matrix] Sparse N-by-N matrix

b [numpy.ndarray] Dense 1-dimensional array of size N

Returns

np.ndarray Solution x to $Ax = b$

class andes.core.solver.SuiteSparseSolver

Bases: `object`

Base SuiteSparse solver interface.

Need to be derived by specific solvers such as UMFPACK or KLU.

clear ()

Remove all cached PyCapsule of C objects

linsolve (A, b)

Solve linear equation set $Ax = b$ and returns the solutions in a 1-D array.

This function performs both symbolic and numeric factorizations every time, and can be slower than `Solver.solve`.

Parameters

A Sparse matrix

b RHS of the equation

Returns

The solution in a 1-D np array.

solve (A, b)

Solve linear system $Ax = b$ using numeric factorization N and symbolic factorization F . Store the solution in b .

This function caches the symbolic factorization in `self.F` and is faster in general. Will attempt `Solver.linsolve` if the cached symbolic factorization is invalid.

Parameters

A Sparse matrix for the equation set coefficients.

F The symbolic factorization of A or a matrix with the same non-zero shape as A .

N Numeric factorization of A .

b RHS of the equation.

Returns

numpy.ndarray The solution in a 1-D ndarray

class `andes.core.solver.UMFPACKSolver`

Bases: `andes.core.solver.SuiteSparseSolver`

UMFPACK solver.

Utilizes `cvxopt.umfpack` for factorization.

linsolve (*A*, *b*)

Solve linear equation set $Ax = b$ and returns the solutions in a 1-D array.

This function performs both symbolic and numeric factorizations every time, and can be slower than `Solver.solve`.

Parameters

A Sparse matrix

b RHS of the equation

Returns

The solution in a 1-D np array.

10.1.8 andes.core.common module

class `andes.core.common.Config` (*name*, *dct=None*, ***kwargs*)

Bases: `object`

A class for storing system, model and routine configurations.

add (*dct=None*, ***kwargs*)

Add config fields from a dictionary or keyword args.

Existing configs will NOT be overwritten.

add_extra (*dest*, *dct=None*, ***kwargs*)

as_dict (*refresh=False*)

Return the config fields and values in an `OrderedDict`.

Values are cached in *self._dict* unless refreshed.

check ()

Check the validity of config values.

doc (*max_width=78*, *export='plain'*, *target=False*, *symbol=True*)

load (*config*)

Load from a `ConfigParser` object, *config*.

tex_names

class `andes.core.common.DummyValue` (*value*)

Bases: `object`

Class for converting a scalar value to a dummy parameter with *name* and *tex_name* fields.

A `DummyValue` object can be passed to `Block`, which utilizes the `name` field to dynamically generate equations.

Notes

Pass a numerical value to the constructor for most use cases, especially when passing as a v-provider.

class `andes.core.common.JacTriplet`

Bases: `object`

Storage class for Jacobian triplet lists.

append_ijv (*j_full_name*, *ii*, *jj*, *vv*)

Append triplets to the given sparse matrix triplets.

Parameters

j_full_name [str] Full name of the sparse Jacobian. If is a constant Jacobian, append 'c' to the Jacobian name.

ii [array-like] Row indices

jj [array-like] Column indices

vv [array-like] Value indices

clear_ijv ()

Clear stored triplets for all sparse Jacobian matrices

ijv (*j_full_name*)

Return triplet lists in a tuple in the order of (ii, jj, vv)

merge (*triplet*)

Merge another triplet into this one.

zip_ijv (*j_full_name*)

Return a zip iterator in the order of (ii, jj, vv)

class `andes.core.common.ModelFlags` (*collate=False*, *pflow=False*, *tds=False*, *series=False*, *nr_iter=False*, *f_num=False*, *g_num=False*, *j_num=False*, *s_num=False*, *sv_num=False*)

Bases: `object`

Model flags.

Parameters

collate [bool] True: collate variables by device; False: by variable. Non-collate (continuous memory) has faster computation speed.

pflow [bool] True: called during power flow

tds [bool] True if called during tds; if is False, `dae_t` cannot be used

series [bool] True if is series device

nr_iter [bool] True if is series device
f_num [bool] True if the model defines *f_numeric*
g_num [bool] True if the model defines *g_numeric*
j_num [bool] True if the model defines *j_numeric*
s_num [bool] True if the model defines *s_numeric*
sv_num [bool] True if the model defines *s_numeric_var*

update (*dct*)

`andes.core.common.dummyfy` (*param*)

Dummify scalar parameter and return a DummyValue object. Do nothing for BaseParam instances.

Parameters

param [float, int, str, BaseParam] parameter object or scalar value

Returns

DummyValue(param) if param is a scalar; param itself, otherwise.

10.1.9 andes.core.var module

class `andes.core.var.Algeb` (*name: Optional[str] = None, tex_name: Optional[str] = None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None, v_iter: Optional[str] = None, e_str: Optional[str] = None, discrete: Optional[andes.core.discrete.Discrete] = None, v_setter: Optional[bool] = False, e_setter: Optional[bool] = False, addressable: Optional[bool] = True, export: Optional[bool] = True, diag_eps: Optional[float] = 0.0*)

Bases: `andes.core.var.BaseVar`

Algebraic variable class, an alias of the *BaseVar*.

Attributes

e_code [str] Equation code string, equals string literal *g*

v_code [str] Variable code string, equals string literal *y*

e_code = 'g'

v_code = 'y'

```
class andes.core.var.BaseVar (name: Optional[str] = None, tex_name: Optional[str] =
                             None, info: Optional[str] = None, unit: Optional[str] =
                             None, v_str: Union[str, float, None] = None, v_iter: Op-
                             tional[str] = None, e_str: Optional[str] = None, discrete:
                             Optional[andes.core.discrete.Discrete] = None, v_setter:
                             Optional[bool] = False, e_setter: Optional[bool] =
                             False, addressable: Optional[bool] = True, export: Op-
                             tional[bool] = True, diag_eps: Optional[float] = 0.0)
```

Bases: `object`

Base variable class.

Derived classes *State* and *Algeb* should be used to build model variables.

Parameters

name [str, optional] Variable name

info [str, optional] Descriptive information

unit [str, optional] Unit

tex_name [str] LaTeX-formatted variable name. If is None, use *name* instead.

discrete [Discrete] Associated discrete component. Will call *check_var* on the discrete component.

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

class_name

get_names ()

reset ()

Reset the internal numpy arrays and flags.

set_address (addr: *numpy.ndarray*, *contiguous=False*)

Set the address of internal variables.

Parameters

addr [ndarray] The assigned address for this variable

contiguous [bool, optional] If the addresses are contiguous

set_arrays (dae)

Set the equation and values arrays.

It slicing into DAE (when contiguous) or allocating new memory (when not contiguous).

Parameters

dae [DAE] Reference to System.dae

```
class andes.core.var.ExtAlgeb(model: str, src: str, indexer: Union[List[T],
    numpy.ndarray, andes.core.param.BaseParam, andes.core.service.BaseService, None] = None, allow_none: Optional[bool] = False, name: Optional[str] = None, tex_name: Optional[str] = None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None, v_iter: Optional[str] = None, e_str: Optional[str] = None, v_setter: Optional[bool] = False, e_setter: Optional[bool] = False, addressable: Optional[bool] = True, export: Optional[bool] = True, diag_eps: Optional[float] = 0.0)
```

Bases: `andes.core.var.ExtVar`

External algebraic variable type.

```
e_code = 'g'
```

```
v_code = 'y'
```

```
class andes.core.var.ExtState(model: str, src: str, indexer: Union[List[T],
    numpy.ndarray, andes.core.param.BaseParam, andes.core.service.BaseService, None] = None, allow_none: Optional[bool] = False, name: Optional[str] = None, tex_name: Optional[str] = None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None, v_iter: Optional[str] = None, e_str: Optional[str] = None, v_setter: Optional[bool] = False, e_setter: Optional[bool] = False, addressable: Optional[bool] = True, export: Optional[bool] = True, diag_eps: Optional[float] = 0.0)
```

Bases: `andes.core.var.ExtVar`

External state variable type.

<p>Warning: <code>ExtState</code> is not allowed to set <code>t_const</code>, as it will conflict with the source <code>State</code> variable. In fact, one should not set <code>e_str</code> for <code>ExtState</code>.</p>

```
e_code = 'f'
```

```
t_const = None
```

```
v_code = 'x'
```



```
class andes.core.var.ExtVar(model: str, src: str, indexer: Union[List[T],
    numpy.ndarray, andes.core.param.BaseParam, andes.core.service.BaseService, None] = None, allow_none:
    Optional[bool] = False, name: Optional[str] = None,
    tex_name: Optional[str] = None, info: Optional[str]
    = None, unit: Optional[str] = None, v_str: Union[str,
    float, None] = None, v_iter: Optional[str] = None,
    e_str: Optional[str] = None, v_setter: Optional[bool]
    = False, e_setter: Optional[bool] = False, addressable:
    Optional[bool] = True, export: Optional[bool] = True,
    diag_eps: Optional[float] = 0.0)
```

Bases: `andes.core.var.BaseVar`

Externally defined algebraic variable

This class is used to retrieve the addresses of externally- defined variable. The *e* value of the *ExtVar* will be added to the corresponding address in the DAE equation.

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] True to allow None in indexer

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.

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.

set_address (*addr*, *contiguous=False*)

Empty function.

set_arrays (*dae*)

Empty function.

```
class andes.core.var.State (name: Optional[str] = None, tex_name: Optional[str]
    = None, info: Optional[str] = None, unit: Optional[str] = None, v_str: Union[str, float, None] = None,
    v_iter: Optional[str] = None, e_str: Optional[str] = None, discrete: Optional[andes.core.discrete.Discrete] =
    None, t_const: Union[andes.core.param.BaseParam, andes.core.common.DummyValue, None] = None, v_setter:
    Optional[bool] = False, e_setter: Optional[bool] = False, addressable: Optional[bool] = True, export: Optional[bool]
    = True, diag_eps: Optional[float] = 0.0)
```

Bases: *andes.core.var.BaseVar*

Differential variable class, an alias of the *BaseVar*.

Parameters

t_const [BaseParam, DummyValue] Left-hand time constant for the differential equation. Time constants will not be evaluated as part of the differential equation. They will be collected to array *dae.Tf* to multiply to the right-hand side *dae.f*.

Attributes

e_code [str] Equation code string, equals string literal *f*

v_code [str] Variable code string, equals string literal *x*

e_code = 'f'

v_code = 'x'

10.1.10 Module contents

Import subpackage classes

10.2 andes.io package

10.2.1 Submodules

10.2.2 andes.io.matpower module

Simple MATPOWER format parser

`andes.io.matpower.read(system, file)`

Read a MATPOWER data file into mpc and build andes device elements

`andes.io.matpower.testlines(fid)`

10.2.3 andes.io.psse module

PSS/E file parser.

Include a RAW parser and a DYR parser.

`andes.io.psse.get_block_lines(b, mdata)`

Return the number of lines based on data

`andes.io.psse.read(system, file)`

read PSS/E RAW file v32 format

`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

`andes.io.psse.sort_psse_models(dyr_yaml)`

Sort supported models so that model names are ordered by dependency.

`andes.io.psse.testlines(fid)`

Check the raw file for frequency base

10.2.4 andes.io.txt module

`andes.io.txt.dump_data(text, header, rowname, data, file, width=14, precision=5)`

10.2.5 andes.io.xlsx module

Excel reader and writer for ANDES power system parameters

This module utilizes `xlsxwriter` and `pandas.DataFrame`. While I like the simplicity of the dome format, spreadsheet data is easier to read and edit.

```
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] Path to the input file

Returns

System System instance after succeeded

```
andes.io.xlsx.testlines(fid)
```

```
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

10.2.6 Module contents

```
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.

`andes.io.get_output_ext(out_format)`

`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

`andes.io.parse(system)`

Parse input file with the given format in *system.files.input_format*.

Returns

bool True if successful; False otherwise.

10.3 andes.models package

10.3.1 Submodules

10.3.2 andes.models.area module

class `andes.models.area.ACE(system, config)`

Bases: *andes.models.area.ACEData*, *andes.core.model.Model*

Area Control Error model.

Note: area idx is automatically retrieved from *bus*.

class `andes.models.area.ACEData`

Bases: *andes.core.model.ModelData*

Area Control Error data

class `andes.models.area.Area(system, config)`

Bases: *andes.models.area.AreaData*, *andes.core.model.Model*

bus_table()

Return a formatted table with area idx and bus idx correspondence

Returns

str Formatted table

class `andes.models.area.AreaData`

Bases: *andes.core.model.ModelData*

10.3.3 andes.models.bus module

class andes.models.bus.**Bus** (*system=None, config=None*)

Bases: *andes.core.model.Model, andes.models.bus.BusData*

AC Bus model.

Power balance equation have the form of $\text{load} - \text{injection} = 0$. Namely, load is positively summed, while injections are negative.

class andes.models.bus.**BusData**

Bases: *andes.core.model.ModelData*

Class for Bus data

10.3.4 andes.models.governor module

class andes.models.governor.**IEEEG1** (*system, config*)

Bases: *andes.models.governor.IEEEG1Data, andes.models.governor.IEEEG1Model*

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, $K1 + K2 + \dots + K8 = 1.0$. If the second generator is not connected, $K1 + K3 + K5 + K7 = 1$, and $K2 + K4 + K6 + K8 = 0$.

class andes.models.governor.**IEEEG1Data**

Bases: *andes.models.governor.TGBaseData*

class andes.models.governor.**IEEEG1Model** (*system, config*)

Bases: *andes.models.governor.TGBase*

class andes.models.governor.**TG2** (*system, config*)

Bases: *andes.models.governor.TG2Data, andes.models.governor.TGBase*

class andes.models.governor.**TG2Data**

Bases: *andes.models.governor.TGBaseData*

class andes.models.governor.**TGBase** (*system, config, add_sn=True, add_tm0=True*)

Bases: *andes.core.model.Model*

Base Turbine Governor model.

Parameters

add_sn [bool] True to add *NumSelect* Sn; False to add later in custom models. This is useful when the governor connects to two generators.

class `andes.models.governor.TGBaseData`

Bases: `andes.core.model.ModelData`

class `andes.models.governor.TGOV1` (*system, config*)

Bases: `andes.models.governor.TGOV1Data`, `andes.models.governor.TGOV1Model`

TGOV1 model.

class `andes.models.governor.TGOV1Data`

Bases: `andes.models.governor.TGBaseData`

class `andes.models.governor.TGOV1Model` (*system, config*)

Bases: `andes.models.governor.TGBase`

class `andes.models.governor.TGOV1ModelAlt` (*system, config*)

Bases: `andes.models.governor.TGBase`

10.3.5 andes.models.group module

class `andes.models.group.ACLine`

Bases: `andes.models.group.GroupBase`

class `andes.models.group.ACTopology`

Bases: `andes.models.group.GroupBase`

class `andes.models.group.Calculation`

Bases: `andes.models.group.GroupBase`

Group of classes that calculates based on other models.

class `andes.models.group.Collection`

Bases: `andes.models.group.GroupBase`

Collection of topology models

class `andes.models.group.DCLink`

Bases: `andes.models.group.GroupBase`

Basic DC links

class `andes.models.group.DCTopology`

Bases: `andes.models.group.GroupBase`

class `andes.models.group.Exciter`

Bases: `andes.models.group.GroupBase`

Exciter group for synchronous generators.

class `andes.models.group.Experimental`

Bases: `andes.models.group.GroupBase`

Experimental group

class andes.models.group.FreqMeasurement

Bases: *andes.models.group.GroupBase*

Frequency measurements.

class andes.models.group.GroupBase

Bases: *object*

Base class for groups

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

add_model (*name, instance*)

class_name

doc (*export='plain'*)

doc_all (*export='plain'*)

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.

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

get_next_idx (*idx=None, model_name=None*)

Return the auto-generated next *idx*

Parameters

idx

model_name

idx2model (*idx*, *allow_none=False*)

Find model name for the given idx.

If *allow_none* is True, will return None at the corr. position.

n

Total number of devices

set (*src: str*, *idx*, *attr*, *value*)

class `andes.models.group.PSS`

Bases: `andes.models.group.GroupBase`

Power system stabilizer group.

class `andes.models.group.PhaseMeasurement`

Bases: `andes.models.group.GroupBase`

Phasor measurements

class `andes.models.group.StaticACDC`

Bases: `andes.models.group.GroupBase`

AC DC device for power flow

class `andes.models.group.StaticGen`

Bases: `andes.models.group.GroupBase`

Static generator group for power flow calculation

class `andes.models.group.StaticLoad`

Bases: `andes.models.group.GroupBase`

Static load group.

class `andes.models.group.StaticShunt`

Bases: `andes.models.group.GroupBase`

Static shunt compensator group.

class `andes.models.group.SynGen`

Bases: `andes.models.group.GroupBase`

Synchronous generator group.

class `andes.models.group.TimedEvent`

Bases: `andes.models.group.GroupBase`

Timed event group

class `andes.models.group.TurbineGov`

Bases: `andes.models.group.GroupBase`

Turbine governor group for synchronous generator.

class `andes.models.group.Undefined`

Bases: `andes.models.group.GroupBase`

10.3.6 andes.models.jit module

class `andes.models.jit.JIT` (*system, model, device, name*)

Bases: `object`

Dummy Just-in-Time initialization class

doc (***kwargs*)

elem_add (*idx=None, name=None, **kwargs*)

overloading `elem_add` function of a JIT class

jit_load ()

Import and instantiate this JIT object

10.3.7 andes.models.line module

class `andes.models.line.Line` (*system=None, config=None*)

Bases: `andes.models.line.LineData, andes.core.model.Model`

class `andes.models.line.LineData`

Bases: `andes.core.model.ModelData`

10.3.8 andes.models.pq module

class `andes.models.pq.PQ` (*system=None, config=None*)

Bases: `andes.models.pq.PQData, andes.core.model.Model`

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`).

class `andes.models.pq.PQData`

Bases: `andes.core.model.ModelData`

10.3.9 andes.models.pv module

class `andes.models.pv.PV` (*system=None, config=None*)

Bases: `andes.models.pv.PVData, andes.models.pv.PVModel`

class `andes.models.pv.PVData`

Bases: `andes.core.model.ModelData`

class `andes.models.pv.PVModel` (*system=None, config=None*)

Bases: `andes.core.model.Model`

PV generator model (power flow) with q limit and PV-PQ conversion.

class `andes.models.pv.Slack` (*system=None, config=None*)

Bases: `andes.models.pv.SlackData`, `andes.models.pv.PVModel`

class `andes.models.pv.SlackData`

Bases: `andes.models.pv.PVData`

10.3.10 andes.models.shunt module

class `andes.models.shunt.Shunt` (*system=None, config=None*)

Bases: `andes.models.shunt.ShuntData`, `andes.core.model.Model`

class `andes.models.shunt.ShuntData` (*system=None, name=None*)

Bases: `andes.core.model.ModelData`

10.3.11 andes.models.synchronous module

Synchronous generator classes

class `andes.models.synchronous.Flux0`

Bases: `object`

Flux model without electro-magnetic transients and ignore speed deviation

class `andes.models.synchronous.Flux1`

Bases: `object`

Flux model without electro-magnetic transients but considers speed deviation.

class `andes.models.synchronous.Flux2`

Bases: `object`

Flux model with electro-magnetic transients.

class `andes.models.synchronous.GENBase` (*system, config*)

Bases: `andes.core.model.Model`

v_numeric (***kwargs*)

Custom variable initialization function.

class `andes.models.synchronous.GENBaseData`

Bases: `andes.core.model.ModelData`

class `andes.models.synchronous.GENCLS` (*system, config*)

Bases: `andes.models.synchronous.GENBaseData`, `andes.models.synchronous.GENBase`, `andes.models.synchronous.GENCLSMModel`, `andes.models.synchronous.Flux0`

class `andes.models.synchronous.GENCLSMModel`

Bases: `object`

```
class andes.models.synchronous.GENROU(system, config)
    Bases: andes.models.synchronous.GENROUData, andes.models.synchronous.
            GENBase, andes.models.synchronous.GENROUModel, andes.models.
            synchronous.Flux0

    Round rotor generator with quadratic saturation

class andes.models.synchronous.GENROUData
    Bases: andes.models.synchronous.GENBaseData

class andes.models.synchronous.GENROUModel
    Bases: object
```

10.3.12 andes.models.timer module

```
class andes.models.timer.Fault(system, config)
    Bases: andes.core.model.ModelData, andes.core.model.Model

    Three-phase to ground fault.

    apply_fault (is_time: numpy.ndarray)
        Apply fault and store pre-fault algebraic variables (voltages and other algebs) to self._vstore.

    clear_fault (is_time: numpy.ndarray)
        Clear fault and restore pre-fault bus algebraic variables (voltages and others).

class andes.models.timer.Toggler(system, config)
    Bases: andes.models.timer.TogglerData, andes.core.model.Model

    Time-based connectivity status toggler.

class andes.models.timer.TogglerData
    Bases: andes.core.model.ModelData
```

10.3.13 Module contents

10.4 andes.routines package

10.4.1 Submodules

10.4.2 andes.routines.base module

```
class andes.routines.base.BaseRoutine(system=None, config=None)
    Bases: object

    Base routine class.

    Provides references to system, config, and solver.

    class_name

    doc (max_width=78, export='plain')
```

```

init()
report()
run(**kwargs)
summary()

```

10.4.3 andes.routines.eig module

```

class andes.routines.eig.EIG(system, config)
    Bases: andes.routines.base.BaseRoutine

```

Eigenvalue analysis routine

```

calc_eigvals()
    Solve eigenvalues of the state matrix self.As

```

Returns

None

```

calc_part_factor(As=None)
    Compute participation factor of states in eigenvalues

```

```

calc_state_matrix()
    Return state matrix and store to self.As.

```

Returns

cvxopt.matrix state matrix

Notes

For systems with the form

$$\begin{aligned}
 T\dot{x} &= f(x, y) \\
 0 &= g(x, y)
 \end{aligned}$$

The state matrix is calculated from

$$A_s = T^{-1}(f_x - f_y * g_y^{-1} * g_x)$$

```

export_state_matrix()
    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

```

plot(mu=None, fig=None, ax=None, left=-6, right=0.5, ymin=-8, ymax=8, damping=0.05,
     line_width=0.5, dpi=150, show=True, latex=True)

```

remove_singular_rc()

Remove rows and cols associated with zero time constant.

report (*x_name=None*)

Save eigenvalue analysis reports

Returns

None

run (***kwargs*)

summary ()

Print out a summary to `logger.info`.

10.4.4 andes.routines.pflow module

class andes.routines.pflow.**PFlow** (*system=None, config=None*)

Bases: [*andes.routines.base.BaseRoutine*](#)

Power flow calculation routine.

init ()

newton_krylov (*verbose=False*)

Full Newton-Krylov method from SciPy.

Parameters

verbose True if verbose.

Returns

np.array Solutions *dae.xy*.

Warning: The result might be wrong if discrete are in use!

nr_step ()

Single step using Newton-Raphson method.

Returns

float maximum absolute mismatch

report ()

Write power flow report to text file.

run (***kwargs*)

Full Newton-Raphson method.

Returns

bool convergence status

summary()

Output a summary for the PFlow routine.

10.4.5 andes.routines.tds module

class andes.routines.tds.**TDS** (*system=None, config=None*)

Bases: *andes.routines.base.BaseRoutine*

Time-domain simulation routine.

calc_h()

Calculate the time step size during the TDS.

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
```

do_switch()

Perform switch if is switch time

init()

Initialize the status, storage and values for TDS.

Returns

array-like The initial values of xy.

is_switch_time()

Return if the current time is a switching time for time domain simulation.

Time is approximated with a tolerance of 1e-8.

Returns

bool True if is a switching time; False otherwise.

load_plotter()

Manually load a plotter into `TDS.plotter`.

rewind(t)

TODO: rewind to a past time.

run (*no_pbar=False, no_summary=False, **kwargs*)

Run the implicit numerical integration for TDS.

Parameters

no_pbar [bool] True to disable progress bar

no_summary [bool, optional] True to disable the display of summary

save_output (*npz=True*)

Save the simulation data into two files: a 1st file and a npz file.

Parameters

npz [bool] True to save in npz format; False to save in npy format.

Returns

bool True if files are written. False otherwise.

summary ()

Print out a summary to logger.info.

test_init ()

Update f and g to see if initialization is successful.

10.4.6 Module contents

10.5 andes.utils package

10.5.1 Submodules

10.5.2 andes.utils.cached module

class andes.utils.cached.**cached** (*func, name=None, doc=None*)

Bases: `object`

A decorator that converts a function into a lazy property. The function wrapped is called the first time to retrieve the result and then that calculated result is used the next time you access the value:

```
class Foo(object):  
  
    @cached_property  
    def foo(self):  
        # calculate something important here  
        return 42
```

The class has to have a `__dict__` in order for this property to work. See for details: <http://stackoverflow.com/questions/17486104/python-lazy-loading-of-class-attributes>

10.5.3 andes.utils.paths module

Utility functions for loading andes stock test cases

class andes.utils.paths.**DisplayablePath** (*path, parent_path, is_last*)

Bases: `object`


```

display_filename_prefix_last = '└─'
display_filename_prefix_middle = '├─'
display_parent_prefix_last = '│'
display_parent_prefix_middle = ' '
displayable()
displayname
classmethod make_tree(root, parent=None, is_last=False, criteria=None)

```

`andes.utils.paths.cases_root()`

Return the root path to the stock cases

`andes.utils.paths.confirm_overwrite(outfile, overwrite=None)`

`andes.utils.paths.get_case(rpath)`

Return the path to the stock cases

`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.

`andes.utils.paths.get_dot_andes_path()`

Return the path to `<HomeDir>/ .andes`

`andes.utils.paths.get_log_dir()`

Get the directory for log file.

On Linux or macOS, `/tmp/andes` is the default. On Windows, `%APPDATA%/andes` is the default.

Returns

str The path to the temporary logging directory

`andes.utils.paths.get_pkl_path()`

Get the path to the picked/dilled function calls.

Returns

str Path to the calls.pkl file

`andes.utils.paths.list_cases(rpath='', no_print=False)`

List stock cases under a given folder relative to `cases`

`andes.utils.paths.tests_root()`

Return the root path to the stock cases

10.5.4 andes.utils.func module

`andes.utils.func.interp_n2(t, x, y)`

Interpolation function for $N * 2$ value arrays.

Parameters

t [float] Point for which the interpolation is calculated

x [1-d array with two values] x-axis values

y [2-d array with size N-by-2] Values corresponding to x

Returns

N-by-1 array interpolated values at *t*

`andes.utils.func.list_flatten(input_list)`

Flatten a multi-dimensional list into a flat 1-D list.

10.5.5 andes.utils.misc module

`andes.utils.misc.elapsed(t0=0.0)`

Get the elapsed time from the give time. If the start time is not given, returns the unix-time.

Returns

t [float] Elapsed time from the given time; Otherwise the epoch time.

s [str] The elapsed time in seconds in a string

`andes.utils.misc.is_interactive()`

`andes.utils.misc.is_notebook()`

`andes.utils.misc.to_number(s)`

Convert a string to a number. If unsuccessful, return the de-blanked string.

10.5.6 andes.utils.tab module

class `andes.utils.tab.Tab(title=None, header=None, descr=None, data=None, export='plain', max_width=78)`

Bases: `andes.utils.texttable.Texttable`

Use package `texttable` to create well-formatted tables for setting helps and device helps.

Parameters

export [(`'plain'`, `'rest'`)] Export format in plain text or restructuredText.

max_width [int] Maximum table width. If there are equations in cells, set to 0 to disable wrapping.

draw()

Draw the table and return it in a string.

header (*header_list*)

Set the header with a list.

set_title (*val*)

Set table title to *val*.

`andes.utils.tab.make_doc_table` (*title, max_width, export, plain_dict, rest_dict*)

Helper function to format documentation data into tables.

`andes.utils.tab.math_wrap` (*tex_str_list, export*)

Wrap each string item in a list with latex math environment \dots .

Parameters

tex_str_list [list] A list of equations to be wrapped

export [str, ('rest', 'plain')] Export format. Only wrap equations if export format is `rest`.

10.5.7 Module contents

10.6 andes.variables package

10.6.1 Submodules

10.6.2 andes.variables.dae module

class `andes.variables.dae.DAE` (*system*)

Bases: `object`

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 `cvxopt.spmatrix`. The defined arrays and descriptions are as follows:

DAE Array	Description
<code>x</code>	Array for state variable values
<code>y</code>	Array for algebraic variable values
<code>z</code>	Array for 0/1 limiter states (if enabled)
<code>f</code>	Array for differential equation derivatives
<code>Tf</code>	Left-hand side time constant array for <code>f</code>
<code>g</code>	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 `cvxopt.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

$$\begin{aligned}T\dot{x} &= f(x, y) \\ 0 &= g(x, y)\end{aligned}$$

DAE does not keep track of the association of variable and address. Only a variable instance keeps track of its addresses.

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

clear_arrays ()

Reset equation and variable arrays to empty.

clear_fg ()

Resets equation arrays to empty

clear_ijv ()

Clear stored triplets.

clear_ts ()

clear_xy ()

Reset variable arrays to empty.

clear_z ()

Reset status arrays to empty

fg

Return a concatenated array of [f, g].

get_name (*arr*)

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

print_array (*name*, *values=None*, *tol=None*)

reset ()

Reset array sizes to zero and clear all arrays.

resize_arrays ()

Resize arrays to the new sizes *m* and *n*, and *o*.

If $m > \text{len}(\text{self.y})$ or $n > \text{len}(\text{self.x})$, arrays will be extended. Otherwise, new empty arrays will be sliced, starting from 0 to the given size.

restore_sparse ()

Restore all sparse arrays to shape with non-zero constants

set_t (*t*)

Helper function for setting time in-place

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

write_lst (*lst_path*)

Dump the variable name lst file.

Parameters

lst_path Path to the lst file.

Returns

bool succeed flag

write_npy (*file_path*)

Write TDS data into NumPy uncompressed format.

write_npz (*file_path*)

Write TDS data into NumPy compressed format.

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.

class andes.variables.dae.**DAETimeSeries** (*dae=None*)

Bases: `object`

DAE time series data

store_txyz (*t, xy, z=None*)

Store t, xy, and z in internal storage, respectively.

Parameters

t [float] simulation time

xy [array-like] array data for states and algebraic variables

z [array-like or None] discrete flags data

txyz

Return the values of [t, x, y, z] in an array.

unpack (*df=False*)

Unpack stored data in `_xy` and `_z` into arrays *t*, *xy*, and *z*.

Parameters

df [bool] True to construct DataFrames *self.df* and *self.df_z* (time-consuming).

x**y**

10.6.3 andes.variables.fileman module

class andes.variables.fileman.**FileMan** (*case=None, **kwargs*)

Bases: `object`

Define a File Manager class for System

get_fullpath (*fullname=None*)

Return the original full path if full path is specified, otherwise search in the case file path.

set (*case=None, **kwargs*)

`andes.variables.fileman.add_suffix` (*fullname, suffix*)
Add suffix to a full file name.

10.6.4 `andes.variables.report` module

class `andes.variables.report.Report` (*system*)
Bases: `object`

Report class to store system static analysis reports

info

update ()

Update values based on the requested content

write ()

Write report to file.

`andes.variables.report.report_info` (*system*)

10.6.5 Module contents

11.1 andes.cli module

`andes.cli.create_parser()`

The main level of command-line interface.

`andes.cli.main()`

Main command-line interface

`andes.cli.preamble()`

Log the ANDES command-line preamble at the *logging.INFO* level

11.2 andes.main module

`andes.main.config_logger(stream=True, file=True, stream_level=20,
log_file='andes.log', log_path=None, file_level=10)`

Configure a logger for the andes package with options for a *FileHandler* and a *StreamHandler*. This function is called at the beginning of `andes.main.main()`.

Parameters

stream [bool, optional] Create a *StreamHandler* for *stdout* if *True*. If *False*, the handler will not be created.

file [bool, optional] *True* if logging to `log_file`.

log_file [str, optional] Log 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

`andes.main.doc (attribute=None, list_supported=False, init_seq=False, config=False, **kwargs)`
Quick documentation from command-line.

`andes.main.edit_conf (edit_config: Union[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` if a config file is found and an editor is opened. `False` if `edit_config` is `False`.

`andes.main.find_log_path (lg)`
Find the file paths of the *FileHandlers*.

`andes.main.load (case, codegen=False, setup=True, **kwargs)`
Load a case and set up without running. Return a system

Parameters

case: `str` Path to the test case

codegen [bool, optional] Call full *System.prepare* on the returned system. Set to `True` if one needs to inspect pretty-print equations and run simulations.

setup [bool, optional] Call *System.setup* after loading

Warnings

——

If one needs to add devices beside these from the case

file, do “setup=False” and manually invoke “setup()”

after adding all devices.

`andes.main.misc (edit_config=", save_config=", show_license=False, clean=True, recursive=False, overwrite=None, cli=False, **kwargs)`
Misc functions.

`andes.main.plot (**kwargs)`
Wrapper for the plot tool.

```
andes.main.prepare(quick=False, incremental=False, cli=False, **kwargs)
```

Run code generation.

Returns

System object

```
andes.main.print_license()
```

```
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.

```
andes.main.run(filename, input_path="", verbose=20, mp_verbose=30, ncpu=2, 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

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..

```
andes.main.run_case(case, routine='pflow', profile=False, convert="", convert_all="",
                   add_book=None, codegen=False, remove_pycapsule=False,
                   **kwargs)
```

Run a single simulation case.

`andes.main.save_conf (config_path=None, overwrite=None)`

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 empty 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.

`andes.main.selftest (**kwargs)`

Run unit tests.

`andes.main.set_logger_level (lg, type_to_set, level)`

Set logging level for the given type of handler.

11.3 andes.plot module

The Andes plotting tool.

class `andes.plot.TDSData (full_name=None, mode='file', dae=None, path=None)`

Bases: `object`

A data container for loading and plotting results from Andes time-domain simulation.

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, latex=True, dpi=150, line_width=1.0, greyscale=False, save_fig=None, save_format=None, show=True, **kwargs*)

Plot with `bqplot`. Experimental and incomplete.

data_to_df ()

Convert to `pandas.DataFrame`

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 1st 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

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)

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)

get_values (*idx*)

Return the variable values at the given indices.

Parameters

idx [list] The index of the variables to retrieve. *idx=0* is for Time. Variable indices start at 1.

Returns

np.ndarray Variable data

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*.

Returns

None

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

plot (*yidx*, *xidx*=(0,), *a*=None, *ycalc*=None, *left*=None, *right*=None, *ymin*=None, *ymax*=None, *ytimes*=None, *xlabel*=None, *ylabel*=None, *legend*=None, *grid*=False, *greyscale*=False, *latex*=True, *dpi*=150, *line_width*=1.0, *font_size*=12, *savefig*=None, *save_format*=None, *show*=True, *title*=None, *use_bqplot*=False, *hline1*=None, *hline2*=None, *vline1*=None, *vline2*=None, ***kwargs*)

Entry function for plot scripting. This function retrieves the x and y values based on the *xidx* and *yidx* inputs and then calls *plot_data()* to do the actual plotting.

Note that *ytimes* and *ycalc* are applied sequentially if apply.

Refer to *plot_data()* for the definition of arguments.

Parameters

xidx [list or int] The index for the x-axis variable

yidx [list or int] The indices for the y-axis variables

Returns

(**fig**, **ax**) Figure and axis handles

plot_data (*xdata*, *ydata*, *xheader*=None, *yheader*=None, *xlabel*=None, *ylabel*=None, *line_styles*=None, *left*=None, *right*=None, *ymin*=None, *ymax*=None, *legend*=None, *grid*=False, *fig*=None, *ax*=None, *latex*=True, *dpi*=150, *line_width*=1.0, *font_size*=12, *greyscale*=False, *savefig*=None, *save_format*=None, *show*=True, *title*=None, *hline1*=None, *hline2*=None, *vline1*=None, *vline2*=None, ***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()*.

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.

xheader [list] A list containing the variable names for the x-axis variable

yheader [list] A list containing the variable names for the y-axis variable

xlabel [str] Text label for the x axis

ylabel [str] Text label for the y axis
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
legend [bool] True to show legend and False otherwise
grid [bool] True to show grid and False otherwise
fig Matplotlib fig object to draw the axis on
ax Matplotlib axis object to draw the lines on
latex [bool] True to enable latex and False to disable
greyscale [bool] True to use greyscale, False otherwise
savefig [bool] True to save to png figure file
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)
show [bool] True to show the image
title [str] Title string to be shown at the top
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
kwargs Optional kwargs

Returns

(fig, ax) The figure and axis handles

`andes.plot.add_plot(x, y, xl, yl, fig, ax, LATEX=False, linestyle=None, **kwargs)`
 Add plots to an existing plot

`andes.plot.check_init(yval, yl)`
 " Check initialization by comparing t=0 and t=end values for a flat run.

Warning: This function is deprecated as the initialization check feature is built into TDS. See `TDS.test_initialization()`.

`andes.plot.eig_plot (name, args)`

`andes.plot.isfloat (value)`

`andes.plot.isint (value)`

`andes.plot.label_latexify (label)`

Convert a label to latex format by appending surrounding \$ and escaping spaces

Parameters

label [str] The label string to be converted to latex expression

Returns

str A string with \$ surrounding

`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] <= upper.

lower [int] Lower limit. In the return list y, y[i] >= lower.

`andes.plot.scale_func (k)`

Return a lambda function that scales its input by k

Parameters

k [float] The scaling factor of the returned lambda function

Returns

——

Lambda function

`andes.plot.set_latex (enable=True)`

Enables LaTeX for matplotlib based on the *with_latex* option and *dvipng* availability.

Parameters

enable [bool, optional] True for latex on and False for off

Returns

bool True for LaTeX on, False for off

`andes.plot.tdsplot (filename, y, x=(0,), tocsv=False, fnd=None, xargs=None, exclude=None, **kwargs)`

TDS plot main function based on the new TDSDData 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

tocsv [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

11.4 andes.shared module

Shared constants and delayed imports.

11.4.1 PAST NOTES

Known issues of LazyImport

```
1) The delayed import of pandas and newton_krylov will cause a
↳ ``RuntimeWarning``

RuntimeWarning: numpy.ufunc size changed, may indicate binary incompatibility.
↳ Expected 192 from C header,
got 216 from PyObject
    return f(*args, **kwds)

2) High overhead when called hundreds of thousands times. For example, NumPy_
↳ must not be imported with
LazyImport.

3) Prevents from serialization due to recursion depth.
```

11.5 andes.system module

System class for power system data and methods

class andes.system.**ExistingModels**

Bases: `object`

Storage class for existing models

```
class andes.system.System(case: Optional[str] = None, name: Optional[str] =  
                        None, config_path: Optional[str] = None, options: Op-  
                        tional[Dict[KT, VT]] = None, **kwargs)
```

Bases: `object`

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.

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

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.

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

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.

call_models (*method*: str, *models*: collections.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

collect_ref()

Collect indices into *BackRef* for all models.

dill()

Serialize generated numerical functions in *System.calls* with package *dill*.

The serialized file will be stored to `~/andes/calls.pkl`, where `~` is the home directory path.

Notes

This function sets `dill.settings['recurse'] = True` to serialize the function calls recursively.

e_clear (*models: collections.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.

f_update (*models: Union[str, List[T], collections.OrderedDict, None] = None*)

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.

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.

find_devices()

Add dependent devices for all model based on *DeviceFinder*.

find_models (*flag: Union[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.

g_update (*models: Union[str, List[T], collections.OrderedDict, None] = None*)
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.

get_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.

get_z (*models: Union[str, List[T], collections.OrderedDict, None] = None*)
Get all discrete status flags in a numpy array.

Returns

numpy.array

import_groups ()
Import all groups classes defined in `devices/group.py`.

Groups will be stored as instances with the name as class names. All groups will be stored to dictionary `System.groups`.

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`.

import_routines ()
Import routines as defined in `routines/__init__.py`.

Routines will be stored as instances with the name as class names. All groups will be stored to dictionary `System.groups`.

Examples

`System.PFlow` is the power flow routine instance, and `System.TDS` and `System.EIG` are time-domain analysis and eigenvalue analysis routines, respectively.

init (*models: collections.OrderedDict*)

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.

j_update (*models: collections.OrderedDict*)

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).

l_update_eq (*models: collections.OrderedDict*)

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.

l_update_var (*models: collections.OrderedDict*)

Update variable-based limiter discrete states by calling `l_update_var` of models.

This function is must be called before any equation evaluation.

link_ext_param (*model=None*)

Retrieve values for `ExtParam` for the given models.

static load_config (*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

prepare (*quick=False, incremental=False*)

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.

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()
```

remove_pycapsule()

Remove PyCapsule objects in solvers.

reset()

Reset to the state after reading data and setup (before power flow).

Warning: If TDS is initialized, reset will lead to unpredictable state.

s_update_post (*models: collections.OrderedDict*)

Update variable services by calling `s_update_post` of models.

This function is called at the end of `System.init()`.

s_update_var (*models: collections.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*.

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.

set_address (*models*)

Set addresses for differential and algebraic variables.

set_config (*config=None*)

Set configuration for the System object.

Config for models are routines are passed directly to their constructors.

set_dae_names (*models*)

Set variable names for differential and algebraic variables, and discrete flags.

setup ()

Set up system for studies.

This function is to be called after adding all device data.

store_adder_setter (*models*)

Store non-inplace adders and setters for variables and equations.

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.

store_sparse_pattern (*models: collections.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.

store_switch_times (*models*)

Store event switching time in a sorted Numpy array at *System.switch_times*.

Returns

array-like self.switch_times

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

switch_action (*models*)

Invoke the actions associated with switch times.

undill ()

Deserialize the function calls from `~/andes.calls.pkl` with dill.

If no change is made to models, future calls to `prepare()` can be replaced with `undill()` for acceleration.

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.

vars_to_models ()

Copy variable values from *System.dae* to models.

CHAPTER 12

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