PFNET Python Documentation

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Welcome! This is the documentation for the Python wrapper of PFNET, last updated January 06, 2016.

What is PFNET?

PFNET is a library for modeling and analyzing electric power networks. It provides data parsers, network visualization routines, and fast and customizable constraint and objective function evaluators for modeling network optimization problems.

License

Citing

If you use PFNET in your work, please cite the software as follows:

```
@misc{pfnet,
   author={Tinoco De Rubira, Tomas},
   title={{PFNET}: A library for modeling and analyzing electric power networks},
   howpublished={\url{https://github.com/ttinoco/PFNET}},
   month={July},
   year={2015}
}
```

Contact

If you have any questions about PFNET or if you are interested in collaborating, send me an email:

- Tomas Tinoco De Rubira (ttinoco5687@gmail.com).

Documentation Contents

CHAPTER ONE

GETTING STARTED

This section describes how to get started with PFNET in Python. In particular, it covers required packages, installation, and provides a quick example showing how to use this package.

1.1 Dependencies

PFNET for Python has the following dependencies:

- Numpy (>=1.8.2): the fundamental package for scientific computing in Python.
- Scipy (>=0.13.3): a collection of mathematical algorithms and functions built on top of Numpy.
- PFNET: underlying C routines wrapped by this package (`libpfnet`).
- Graphviz (>= 2.38): graph visualization library (`libgvc`) (Optional).
- Raw parser (>=1.0): library for parsing power flow files in PSSE raw format version 32 (`libraw_parser`) (Optional).

1.2 Download

The latest version of PFNET can be downloaded from https://github.com/ttinoco/PFNET.

1.3 Installation

After building the C library `libpfnet`, the PFNET Python module can be installed using:

```
> sudo python setup.py install
```

from the `python` directory of the PFNET package.

If `libpfnet` was built without visualization capabilities, the argument `--no_graphviz` should be passed to `setup.py`. Similarly, if `libpfnet` was build without raw parsing capabilities, the argument `--no_raw_parser` should be passed to `setup.py`.

The installation can be tested using nose as follows:

```
> nosetests -v
```

1.4 Example

As a quick example of how to use the PFNET Python module, consider the task of constructing a power network from a MATPOWER-converted power flow file and computing the average bus degree. This can be done as follows:

```
>>> import numpy as np
>>> from pfnet import Network

>>> net = Network()
>>> net.load('ieee14.mat')

>>> print np.average([b.degree for b in net.buses])
2.86
```

CHAPTER

TWO

POWER NETWORKS

This section describes how to load and analyze power networks using PFNET.

2.1 Overview

Power networks in PFNET are represented by objects of type `Network`. These objects are initially empty and need to be loaded with data contained in specific types of files. Once the data is loaded, the network and its components can be analyzed, visualized, and used to construct network optimization problems. After a network optimization problem is solved, the network object can be updated with the solution to perform further analysis.

An important attribute of the `Network` class is `base_power`. This quantity, which has units of MVA, is useful for converting power quantities in per unit system base power to MW or MVAr.

2.2 Loading Data

Power networks can be loaded with data using the `load()` class method. This method takes as input the filename of a supported power flow file. Information about the data parsers available in PFNET and the supported file formats can be found in Section *Data Parsers*. The following simple example shows how to load data from a power flow `mat` file:

```
>>> from pfnet import Network

>>> net = Network()
>>> print net.num_buses
0

>>> net.load('ieee14.mat')
>>> print net.num_buses
14
```

2.3 Components

Power networks have several components. These are *buses*, *branches*, *generators*, *shunt devices*, *loads*, and *variable generators* (*i.e.*, non-dispatchable). For obtaining an overview of the components that form a network, the class method `show_components()` can be used:

```
>>> net.show_components()

Network Components
------------------
```

```
buses             : 14
  slack           : 1
  reg by gen      : 5
  reg by tran     : 0
  reg by shunt    : 0
shunts            : 1
  fixed           : 1
  switched v      : 0
branches          : 20
  lines           : 17
  fixed trans     : 3
  phase shifters  : 0
  tap changers v  : 0
  tap changers Q  : 0
generators        : 5
  slack           : 1
  reg             : 5
loads             : 11
vargens           : 0
```

2.3.1 Buses

Buses in a power network are objects of type `Bus`. Each bus has an `index`, a `number`, and a `name` attribute that can be used to identify this bus in a network. The `index` is associated with the location of the bus in the underlying C array of bus structures, while the `number` and `name` attributes are specified in the input data. An `index`, a `number`, or a `name` can be used to extract a specific bus from a network using the `Network` class methods `get_bus()`, `get_bus_by_number()`, and `get_bus_by_name()`, respectively:

```
>>> bus = net.get_bus(10)

>>> print bus.index == 10
True

>>> other_bus = net.get_bus_by_number(bus.number)

>>> print bus == other_bus
True
```

For convenience, a list of all the buses in the network is contained in the `buses` attribute of the `Network` class.

Buses in a network can have different properties. For example, some buses can be slack buses and others can have their voltage magnitudes regulated by generators, tap-changing transformers, or switched shunt devices. The `Bus` class provides methods for checking whether a bus has specific properties. The following example shows how to get a list of all the buses whose voltage magnitudes are regulated by generators:

```
>>> reg_buses = [b for b in net.buses if b.is_regulated_by_gen()]

>>> print len(reg_buses), net.get_num_buses_reg_by_gen()
5 5
```

A bus also has information about the devices that are connected to it or that are regulating its voltage magnitude. For example, the attributes `gens` and `reg_trans` contain a list of generators connected to the bus and a list of tap-changing transformers regulating its voltage magnitude, respectively.

2.3.2 Branches

Branches in a power network are objects of type `Branch` and are represented mathematically by the model described in Section 2.1.2 of [TTR2015]. Each branch has an `index` attribute that can be used to identify this branch in a network. The `Network` class method `get_branch()` can be used to extract a branch of a given `index`:

```
>>> branch = net.get_branch(5)

>>> print branch.index == 5
True
```

For convenience, a list of all the branches in the network is contained in the `branches` attribute of the `Network` class.

Branches in a power network can have different properties. Fore example, some branches can be transmission lines, fixed transformers, tap-changing transformers, or phase-shifting transformers. Tap-changing transformers in turn can control the reactive power flowing through the branch or the voltage magnitude of a bus. The `Branch` class provides methods for checking whether a branch has specific properties. The following example shows how to get a list of all the branches that are transmission lines:

```
>>> lines = [br for br in net.branches if br.is_line()]

>>> print len(lines), net.get_num_lines()
17 17
```

For branches that are transformers, the `Branch` class attributes `ratio` and `phase` correspond to the transformer's tap ratio and phase shift, respectively. These attributes correspond to the quantities a_{km} and ϕ_{km} of the branch model described in Section 2.1.2 of [TTR2015]. The quantity a_{mk} in this model is always one.

2.3.3 Generators

Generators in a power network are objects of type `Generator`. Each generator has an `index` attribute that can be used to identify this generator in a network. The `Network` class method `get_gen()` can be used to extract a generator of a given `index`:

```
>>> gen = net.get_gen(2)

>>> print gen.index == 2
True
```

For convenience, a list of all the generators in the network is contained in the `generators` attribute of the `Network` class.

Generators in a power network can have different properties. Fore example, some generators can be slack generators and others can provide bus voltage magnitude regulation. The `Generator` class provides methods for checking whether a generator has specific properties. The following example shows how to get a list of all the slack generators:

```
>>> slack_gens = [g for g in net.generators if g.is_slack()]

>>> print len(slack_gens), net.get_num_slack_gens()
1 1
```

The active and reactive powers that a generator injects into the bus to which it is connected are obtained from the `P` and `Q` attributes of the `Generator` class. These quantities are given in units of per unit `system base power`. The following example computes the total active power injected into the network by generators in units of MW:

```
>>> print sum([g.P for g in net.generators])*net.base_power
272.4
```

2.3.4 Shunt Devices

Shunt devices in a power network are objects of type `Shunt`. Each shunt has an `index` attribute that can be used to identify this shunt in a network. The `Network` class method `get_shunt()` can be used to extract a shunt of a given `index`:

```
>>> shunt = net.get_shunt(0)

>>> print shunt.index == 0
True
```

For convenience, a list of all the shunt devices in the network is contained in the `shunts` attribute of the `Network` class.

As other network components, shunt devices can have different properties. Some shunt devices can be fixed while others can be switchable and configured to regulate a bus voltage magnitude.

2.3.5 Loads

Loads in a power network are objects of type `Load`. As other components, the `index` attribute is used to identify a load in the network. A list of all the loads in the network is contained in the `loads` attribute of the `Network` class.

Similar to generators, the active and reactive powers that a load consumes from the bus to which it is connected are obtained from the `P` and `Q` attributes of the `Load` class. They are also given in units of per unit `system base power`.

2.3.6 Variable Generators

Variable generators in a power network are objects of type `VarGenerator`. They represent non-dispatchable energy sources such as wind generators or farms and photovoltaic power plants. As with other components, the `index` attribute is used to identify a variable generator in the network. In addition to the `index` attribute, a `name` attribute is also available, which can be used to extract a specific variable generator from the network using the `Network` class method `get_vargen_by_name()`. A list of all the variable generators in the network is also contained in the `var_generators` attribute of the `Network` class.

Similar to generators, the active and reactive powers produced by a variable generator are obtained from the `P` and `Q` attributes of the `VarGenerator` class in units of per unit `system base power`. This is the output of the device in the absence of uncertainty. When there is uncertainty, the output of the device is subject to variations about `P` that have a standard deviation given by the attribute `P_std`. Output limits of a variable generator are given by the `P_min`, `P_max`, `Q_min`, and `Q_max` attributes.

The output of variable generators in a network are subject to random variations that can be correlated, especially for devices that are "nearby". The method `create_vargen_P_sigma()` of the `Network` class allows constructing a covariance matrix for these variations based on a "correlation distance" `N` and a given correlation coefficient. The cross-covariance between the variation of two devices that are connected to buses that are less than `N` branches away from each other are set such that they have the given correlation coefficient.

Lastly, since many power network input files do not have variable generator information, these devices can be added to the network by using the `add_vargens()` method of the `Network` class.

2.4 Properties

A `Network` object has several quantities or `properties` that provide important information about the state of the network. The following table provides a description of each of these properties.

Names	Description	Units
bus_v_max	Maximum bus voltage magnitude	per unit
bus_v_min	Minimum bus voltage magnitude	per unit
bus_v_vio	Maximum bus voltage magnitude limit violation	per unit
bus_P_mis	Maximum absolute bus active power mismatch	MW
bus_Q_mis	Maximum absolute bus reactive power mismatch	MVAr
gen_v_dev	Maximum set point deviation of generator-regulated voltage	per unit
gen_Q_vio	Maximum generator reactive power limit violation	MVAr
gen_P_vio	Maximum generator active power limit violation	MW
tran_v_vio	Maximum band violation of transformer-regulated voltage	per unit
tran_r_vio	Maximum tap ratio limit violation of tap-changing transformer	unitless
tran_p_vio	Maximum phase shift limit violation of phase-shifting transformer	radians
shunt_v_vio	Maximum band violation of shunt-regulated voltage	per unit
shunt_b_vio	Maximum susceptance limit violation of switched shunt device	per unit
num_actions	Number of control adjustments (greater than 2% of control range)	unitless

All of these properties are attributes of the `Network` class. If there is a change in the network, the class method `update_properties()` needs to be called in order for the network properties to reflect the change. The following example shows how to update and extract properties:

```
>>> print net.bus_v_max
1.09

>>> for bus in net.buses:
...     bus.v_mag = bus.v_mag + 0.1
...

>>> print net.bus_v_max
1.09

>>> net.update_properties()

>>> print net.bus_v_max
1.19
```

For convenience, all the network properties can be extracted at once in a dictionary using the `get_properties()` class method:

```
>>> properties = net.get_properties()

>>> print properties['bus_v_max']
1.19
```

2.5 Variables

Network quantities can be specified to be `variables`. This is useful to represent network quantities with vectors and turn the network properties described above as functions of these vectors.

To set network quantities as variables, the `Network` class method `set_flags()` is used. This method takes as arguments a *component type*, a *flag mask* for specifying which flags types to set, a `property mask` for targeting objects with specific properties, and a `variable mask` for specifying which component quantities should be affected.

Property masks are component-specific. They can be combined using `logical OR` to make properties more complex. More information can be found in the following sections:

- *Bus Property Masks*
- *Branch Property Masks*
- *Generator Property Masks*
- *Shunt Property Masks*
- *Variable Generator Property Masks*

Variable masks are also component-specific. They can be combined using `logical OR` to target more than one component quantity. More information can be found in the following sections:

- *Bus Variable Masks*
- *Branch Variable Masks*
- *Generator Variable Masks*
- *Shunt Variable Masks*
- *Variable Generator Variable Masks*

The following example shows how to set as variables all the voltage magnitudes and angles of buses regulated by generators:

```
>>> import pfnet as pf

>>> net = pf.Network()
>>> net.load('ieee14.mat')

>>> print net.num_vars
0

>>> net.set_flags(pf.OBJ_BUS,
...               pf.FLAG_VARS,
...               pf.BUS_PROP_REG_BY_GEN,
...               pf.BUS_VAR_VMAG|pf.BUS_VAR_VANG)

>>> print net.num_vars, 2*net.get_num_buses_reg_by_gen()
10 10
```

Network components have a `has_flags()` method that allows checking whether flags of a certain type associated with specific quantities are set.

Once variables have been set, the *vector* containing all the current variable values can be extracted using `get_var_values()`:

```
>>> values = net.get_var_values()

>>> print type(values)
<type 'numpy.ndarray'>

>>> print values.shape
(10,)
```

The components that have quantities set as variables have indices that can be used to locate these quantities in the vector of all variable values:

```
>>> bus = [b for b in net.buses if b.is_reg_by_gen()][0]

>>> print bus.has_flags(pf.FLAG_VARS,pf.BUS_VAR_VMAG)
True
```

```
>>> bus.has_flags(pf.FLAG_VARS,pf.BUS_VAR_VANG)
True

>>> print bus.v_mag, net.get_var_values()[bus.index_v_mag]
1.09 1.09

>>> print bus.v_ang, net.get_var_values()[bus.index_v_ang]
-0.23 -0.23
```

A vector of variable values can be used to update the corresponding network quantities. This is done with the `Network` class method `set_var_values()`:

```
>>> bus.has_flags(pf.FLAG_VARS,pf.BUS_VAR_VANG)
True

>>> values = net.get_var_values()

>>> print bus.v_mag
1.09

>>> values[bus.index_v_mag] = 1.20
>>> net.set_var_values(values)

>>> print bus.v_mag
1.20
```

As we will see in later, variables are also useful for constructing network optimization problems.

Lastly, the class method `get_var_values()` can also be used to get upper or lower limits of the variables. To do this, a valid *variable value code* must be passed to this method.

2.6 Projections

As explained above, once the network variables have been set, a vector with the current values of the selected variables is obtained with the class method `get_var_values()`. To extract subvectors that contain values of specific variables, projection matrices can be used. These *matrices* can be obtained using the class method `get_var_projection()`, which take as arguments a *component type* and a `variable mask`, *e.g.*, *bus variable masks*. The next example sets the variables of the network to be the bus voltage magnitudes and angles of all the buses, extracts the vector of values of all variables, and then extracts two subvectors having only voltage magnitudes and only voltage angles, respectively:

```
>>> import numpy as np
>>> import pfnet as pf

>>> net = pf.Network()
>>> net.load('ieee14.mat')

>>> net.set_flags(pf.OBJ_BUS,
...               pf.FLAG_VARS,
...               pf.BUS_PROP_ANY,
...               pf.BUS_VAR_VMAG|pf.BUS_VAR_VANG)

>>> print net.num_vars, 2*net.num_buses
28 28

>>> P1 = net.get_var_projection(pf.OBJ_BUS,pf.BUS_VAR_VMAG)
```

```
>>> P2 = net.get_var_projection(pf.OBJ_BUS,pf.BUS_VAR_VANG)

>>> print type(P1)
<class 'scipy.sparse.coo.coo_matrix'>

>>> x = net.get_var_values()
>>> v_mags = P1*x
>>> v_angs = P2*x

>>> print v_mags
[ 1.036  1.05   1.055  1.057  1.051  1.056  1.09   1.062  1.07   1.02
  1.019  1.01   1.045  1.06 ]

>>> print v_angs
[-0.27995081 -0.26459191 -0.26302112 -0.2581342  -0.26354472 -0.26075219
 -0.23317599 -0.23335052 -0.24818582 -0.15323991 -0.18029251 -0.22200588
 -0.0869174   0. ]

>>> print np.linalg.norm(x - (P1.T*v_mags+P2.T*v_angs))
0.0
```

CHAPTER THREE

DATA PARSERS

This section describes the different data parsers available in PFNET and the supported file types.

3.1 MATPOWER case files

MATPOWER is a MATLAB package for solving power flow and optimal power flow problems. It contains several power flow and optimal power flow cases defined in MATLAB files. These "M" files can be converted to CSV files using the script `mpc2mat.m`. These MATPOWER-converted CSV files have extension `.mat` and can be used to load power networks in PFNET.

3.2 ARTERE case files

PFNET can load networks from case files used by ARTERE, which is a software for performing power flow computations using the Newton-Raphson method. These files should have extension `.art`. Details about these data files can be found in the document "ARTERE: description of data files".

Currently, PFNET has limited support of these files. More specifically:

- Components with open breakers are ignored.
- For LTC-V devices, tap positions are treated as continuous and the optional fields are ignored.
- The SWITCH, TRFO, PSHIFT-P, TURLIM, SVC, LFRESV, BUSPART and BRAPART records are not supported.
- Computation control parameters are ignored.

3.3 RAW case files

If built with raw parsing capabilities, which requires linking PFNET with `libraw_parser`, PFNET can load power networks from files with extension `.raw`. These files are used by the software PSS ® E and are widely used by North American power system operators.

CHAPTER

FOUR

VISUALIZATION

This section describes how to visualize power networks using PFNET. To have this capability, PFNET needs the Graphviz library `libgvc`.

4.1 Overview

To visualize a power network, a `Graph` objects needs to be created. To do this, one needs to specify the power `Network` that is to be associated with the graph:

```
>>> import pfnet as pf

>>> net = pf.Network()
>>> net.load('ieee14.mat')

>>> g = pf.Graph(net)
```

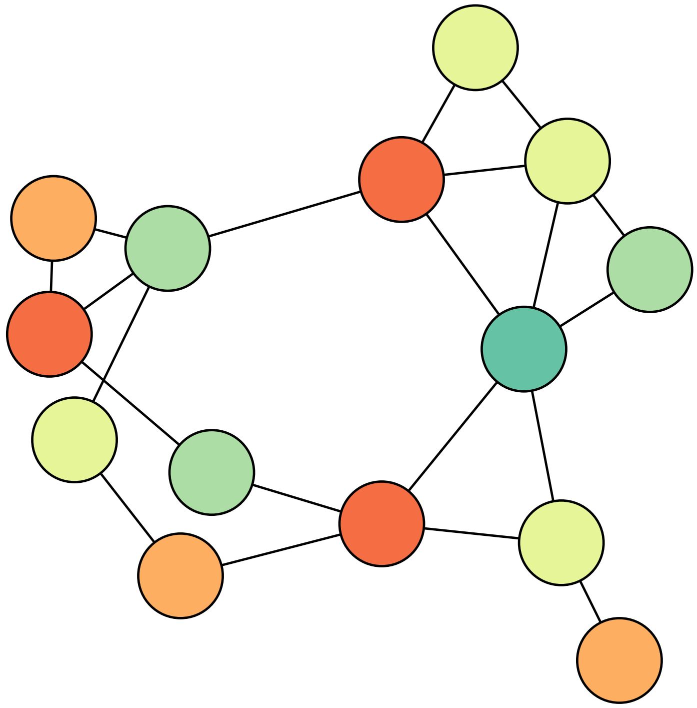
Then, a layout must be created for graph. This can be done using the `Graph` class method `set_layout`. This method uses the sfdp algorithm of Graphviz.

The `Graph` class provides routines for coloring nodes (network buses) according to different criteria. For example, buses can be colored according to reactive power mismatches:

```
>>> g.set_layout()

>>> g.color_nodes_by_mismatch(pf.BUS_MIS_REACTIVE)

>>> g.view()
```



CHAPTER

FIVE

OPTIMIZATION PROBLEMS

This section describes how to formulate power network optimization problems using PFNET.

5.1 Objective Function

The objective function ϕ for a network optimization problem created using PFNET is of the form

$$\varphi(x) = \sum_i w_i \varphi_i(x),$$

where w_i are weights, φ_i are general linear or nonlinear functions, and x is a vector of values of network quantities that have been set as variables. Each weight-function pair in the summation is represented by an object of type `Function`. To instantiate an object of this type, the function type and weight need to be specified as well as the `Network` object that is to be associated with the function. The following example sets all bus voltage magnitudes as variables and constructs a function that penalizes voltage magnitude deviations from ideal values:

```
>>> import pfnet as pf

>>> net = pf.Network()
>>> net.load('ieee14.mat')

>>> net.set_flags(pf.OBJ_BUS,
...               pf.FLAG_VARS,
...               pf.BUS_PROP_ANY,
...               pf.BUS_VAR_VMAG)

>>> func = pf.Function(pf.FUNC_TYPE_REG_VMAG,0.3,net)

>>> print func.type == pf.FUNC_TYPE_REG_VMAG
True

>>> print func.weight
0.3
```

After a `Function` object is created, its value, gradient and Hessian are zero, an empty vector, and an empty matrix, respectively. Before evaluating the function at a specific vector of values, it must be analyzed using the `Function` class method `analyze`. This routine analyzes the function and allocated the required vectors and matrices for storing its gradient and Hessian. After this, the function can be evaluated using the method `eval`:

```
>>> x = net.get_var_values()

>>> func.analyze()
```

```
>>> func.eval(x + 0.01)
>>> func.eval(x)
```

The value $\varphi_i(x)$, gradient $\nabla\varphi_i(x)$ and Hessian $\nabla^2\varphi_i(x)$ of a function can then be extracted from the `phi`, `gphi` and `Hphi` attributes, respectively:

```
>>> print x.shape
14

>>> print func.phi
0.255

>>> print type(func.gphi), func.gphi.shape
<type 'numpy.ndarray'> (14,)

>>> print type(func.Hphi), func.Hphi.shape
<class 'scipy.sparse.coo.coo_matrix'> (14, 14)
```

For the Hessian matrix, only the lower triangular part is stored.

Details about each of the different function types available in PFNET are provided below.

5.1.1 Voltage magnitude regularization

This function is of type `FUNC_TYPE_REG_VMAG`. It penalizes deviations of bus voltage magnitudes from ideal values. It is defined by the expression

$$\varphi(x) := \frac{1}{2}\sum_k \left(\frac{v_k - v_k^t}{\Delta v}\right)^2 + \frac{1}{2}\sum_k \left(\frac{v_k^y}{\Delta v}\right)^2 + \frac{1}{2}\sum_k \left(\frac{v_k^z}{\Delta v}\right)^2 + \frac{1}{2}\sum_k \left(\frac{v_k^h}{\Delta v}\right)^2 + \frac{1}{2}\sum_k \left(\frac{v_k^l}{\Delta v}\right)^2,$$

where v are bus voltage magnitudes, v^t are voltage magnitude set points (one for buses not regulated by generators), v^y and v^z are positive and negative deviations of v from v^t, v^h and v^l are voltage band upper and lower limit violations, and Δv is a normalization factor. Only terms that include optimization variables are included in the summation.

5.1.2 Voltage magnitude soft limit penalty

This function is of type `FUNC_TYPE_SLIM_VMAG`. It reduces voltage (soft) limit violations by penalizing deviations of bus voltage magnitudes from the mid point of their ranges. It is defined by the expression

$$\varphi(x) := \frac{1}{2}\sum_k \left(\frac{v_k - \bar{v}_k}{\Delta v}\right)^2,$$

where v are bus voltage magnitudes, $\bar{v}$ are the mid points of their ranges, and Δv is a normalization factor. Only terms that include optimization variables are included in the summation.

5.1.3 Voltage angle regularization

This function is of type `FUNC_TYPE_REG_VANG`. It penalizes large bus voltage angles and voltage angle differences across branches. It is defined by the expression

$$\varphi(x) := \frac{1}{2}\sum_k \left(\frac{\theta_k}{\Delta\theta}\right)^2 + \frac{1}{2}\sum_{(k,m)} \left(\frac{\theta_k - \theta_m - \phi_{km}}{\Delta\theta}\right)^2,$$

where θ are bus voltage angles, ϕ are branch phase shifts, and $\Delta\theta$ is a normalization factor. Only terms that include optimization variables are included in the summation.

5.1.4 Generator powers regularization

This function is of type `FUNC_TYPE_REG_PQ`. It penalizes deviations of generator powers from the midpoint of their ranges. It is defined by the expression

$$varphi(x) := \frac{1}{2}\sum_k \left(\frac{P_k^g - \bar{P}_k}{\Delta P}\right)^2 + \frac{1}{2}\sum_k \left(\frac{Q_k^g - \bar{Q}_k}{\Delta Q}\right)^2,$$

where P^g and Q^g are generator active and reactive powers, $\bar{P}$ and $\bar{Q}$ are midpoints of generator active and reactive power ranges, and $\Delta P = \Delta Q$ are normalization factors. Only terms that include optimization variables are included in the summation.

5.1.5 Active power generation cost

This function is of type `FUNC_TYPE_GEN_COST`. It measures active power generation cost by the expression

$$\varphi(x) := \sum_k q_{k0} + q_{k1}P_k^g + q_{k2}\big(P_k^g\big)^2,$$

where P^g are generator active powers in per unit base system power, and q^0, q^1, and q^2 are constant coefficients. These coefficients are attributes of each `Generator` object.

5.1.6 Transformer tap ratio regularization

This function is of type `FUNC_TYPE_REG_RATIO`. It penalizes deviations of tap ratios of tap-changing transformers from their initial value. It is defined by the expression

$$\varphi(x) := \frac{1}{2}\sum_k \left(\frac{t_k - t_k^0}{\Delta t}\right)^2 + \frac{1}{2}\sum_k \left(\frac{t_k^y}{\Delta t}\right)^2 + \frac{1}{2}\sum_k \left(\frac{t_k^z}{\Delta t}\right)^2,$$

where t are tap ratios of tap-changing transformers, t^0 are their initial values, t^y and t^z are positive and negative deviations of t from t^0, and Δt is a normalization factor. Only terms that include optimization variables are included in the summation.

5.1.7 Transformer phase shift regularization

This function is of type `FUNC_TYPE_REG_PHASE`. It penalizes deviations of phase shifts of phase shifting transformers from their initial value. It is defined by the expression

$$\varphi(x) := \frac{1}{2}\sum_k \left(\frac{\phi_k - \phi_k^0}{\Delta \phi}\right)^2$$

where ϕ are phase shifts of phase-shifting transformers, ϕ^0 are their initial values, and $\Delta\phi$ is a normalization factor. Only terms that include optimization variables are included in the summation.

5.1.8 Switched shunt susceptance regularization

This function is of type `FUNC_TYPE_REG_SUSC`. It penalizes deviations of susceptances of switched shunt devices from their initial value. It is defined by the expression

$$\varphi(x) := \frac{1}{2}\sum_k \left(\frac{b_k - b_k^0}{\Delta b}\right)^2 + \frac{1}{2}\sum_k \left(\frac{b_k^y}{\Delta b}\right)^2 + \frac{1}{2}\sum_k \left(\frac{b_k^z}{\Delta b}\right)^2,$$

where b are susceptances of switched shunt devices, b^0 are their initial values, b^y and b^z are positive and negative deviations of b from b^0, and Δb is a normalization factor. Only terms that include optimization variables are included in the summation.

5.1.9 Sparsity inducing penalty for controls

This function is of type FUNC_TYPE_SP_CONTROLS. It encourages sparse control adjustments with the expression

$$\varphi(x) := \sum_k \sqrt{\left(\frac{u_k - u_k^0}{\Delta u_k}\right)^2 + \epsilon},$$

where u are control quantities, u^0 are their current values, and ϵ is a small positive scalar. The normalization factors Δu_k are given by

$$\Delta u_k := \max\{u_k^{\max} - u_k^{\min}, \delta\},$$

where $u^{\max}$ and $u^{\min}$ are control limits, and δ is a small positive scalar. The control quantities that are considered by this function are specified using the Network class method set_flags using the flag type FLAG_SPARSE.

5.2 Constraints

Constraints in PFNET are of the form

$$Ax = b$$
$$f(x) = 0,$$

where A is a matrix, b is a vector, f is a vector-valued function, and x is a vector of values of network quantities that have been set as variables. They are represented by objects of type Constraint. To create an object of this type, the constraint type and the network to be associated with the constraint need to be specified. The following example sets all bus voltage magnitudes and angles as variables and constructs the power flow constraints:

```
>>> import pfnet as pf

>>> net = pf.Network()
>>> net.load('ieee14.mat')

>>> net.set_flags(pf.OBJ_BUS,
...               pf.FLAG_VARS,
...               pf.BUS_PROP_ANY,
...               pf.BUS_VAR_VMAG|pf.BUS_VAR_VANG)

>>> print net.num_vars == 2*net.num_buses
True

>>> constr = pf.Constraint(pf.CONSTR_TYPE_PF,net)

>>> print constr.type == pf.CONSTR_TYPE_PF
True
```

Before a Constraint object can be used, it must be initialized using the Constraint class method analyze. This routine analyzes the constraint and allocates the required vectors and matrices. After this, the constraint can be evaluated using the method eval:

```
>>> x = net.get_var_values()

>>> constr.analyze()

>>> constr.eval(x + 0.01)
>>> constr.eval(x)
```

The linear constraint matrix and right-hand side can be extracted from the `A` and `b` attributes of the `Constraint` object. The constraint violations vector and Jacobian matrix of the nonlinear constraints can be extracted from the attributes `f` and `J`, respectively. Also, the Hessian matrix of any individual nonlinear constraint $f_i(x) = 0$ can be extracted using the class method `get_H_single`. The following example shows how to extract the largest power flow mismatch in per unit `system base power` and the Hessian matrix corresponding to the active power balance constraint of a bus:

```
>>> import numpy as np

>>> f = constr.f

>>> print type(f), f.shape
<type 'numpy.ndarray'>  (28,)

>>> print np.linalg.norm(f,np.inf)
0.042

>>> bus = net.get_bus(5)
>>> Hi = constr.get_H_single(bus.index_P)

>>> print type(Hi), Hi.shape, Hi.nnz
<class 'scipy.sparse.coo.coo_matrix'> (28, 28) 27
```

As before, all Hessian matrices have stored only the lower triangular part. In addition to being possible to extract Hessian matrices of individual nonlinear constraints, it is also possible to construct any linear combination of these individual Hessian matrices. This can be done using the `Constraint` class method `combine_H`. After this, the resulting matrix can be extracted from the `H_combined` attribute:

```
>>> coefficients = np.random.randn(f.size)

>>> constr.combine_H(coefficients)
>>> H = constr.H_combined

>>> print type(H), H.shape, H.nnz
<class 'scipy.sparse.coo.coo_matrix'> (28, 28) 564
```

Lastly, Lagrange multiplier estimates of the nonlinear constraints $f(x) = 0$ can be used to store sensitivity information in the network components associated with the constraints. This is done using the class method `store_sensitivities`.

Details about each of the different constraint types available in PFNET are provided below.

5.2.1 Power balance

This constraint is of type `CONSTR_TYPE_PF`. It enforces active and reactive power balance at every bus of the network. It is given by

$$(P^g_k + jQ^g_k) - (P^l_k + jQ^l_k) - S^{sh}_k - \sum_{m \in [n]} S_{km} = 0, \; \forall \, k \in [n],$$

where P^g and Q^g are generator active and reactive powers, P^l and Q^l are load active and reactive powers, S^{sh} are apparent powers flowing out of buses through shunt devices, S are apparent powers flowing out of buses through branches, n is the number of buses, and $[n] := \{1, \dots, n\}$.

5.2.2 Variable fixing

This constraint is of type `CONSTR_TYPE_FIX`. It constrains specific variables to be fixed at their current value. The variables to be fixed are specified using the `Network` class method `set_flags` with the flag type `FLAG_FIXED`.

5.2.3 Variable bounding

This constraint is of type `CONSTR_TYPE_BOUND`. It constrains specific variables to be inside their bounds. The variables to be bounded are specified using the `Network` class method `set_flags` with the flag type `FLAG_BOUNDED`. These constraints are expressed as nonlinear equality constraints using the techniques described in Section 4.3.3 of [TTR2015].

5.2.4 Generator participation

This constraint is of type `CONSTR_TYPE_PAR_GEN`. It enforces specific active power participations among slack generators, and reactive power participations among generators regulating the same bus voltage magnitude. For slack generators, all participate with equal active powers. For voltage regulating generators, each one participates with the same fraction of its total resources. More specifically, this constraint enforces

$$P_k^g = P_m^g,$$

for all slack generators k and m connected to the same bus, and

$$\frac{Q_k^g - Q_k^{\min}}{Q_k^{\max} - Q_k^{\min}} = \frac{Q_m^g - Q_m^{\min}}{Q_m^{\max} - Q_m^{\min}},$$

for all generators k and m regulating the same bus voltage magnitude, where $Q^{\min}$ and $Q^{\max}$ are generator reactive power limits.

5.2.5 Voltage set-point regulation by generators

This constraint is of type `CONSTR_TYPE_REG_GEN`. It enforces voltage set-point regulation by generators. It approximates the constraints

$$\begin{aligned} v_k &= v_k^t + v_k^y - v_k^z \\ 0 &\leq (Q_k - Q_k^{\min}) \perp v_k^y \geq 0 \\ 0 &\leq (Q_k^{\max} - Q_k) \perp v_k^z \geq 0, \end{aligned}$$

for each bus k whose voltage is regulated by generators, where v are bus voltage magnitudes, v^t are their set points, v^y and v^z are positive and negative deviations of v from v^t, and Q, $Q^{\max}$ and $Q^{\min}$ are aggregate reactive powers and limits of the generators regulating the same bus voltage magnitude.

5.2.6 Voltage band regulation by transformers

This constraint is of type CONSTR_TYPE_REG_TRAN. It enforces voltage band regulation by tap-changing transformers. It approximates the constraints

$$\begin{aligned}
&t_k = t_k^0 + t_k^y - t_k^z \\
&0 \leq (v_k + v_k^l - v_k^{\min}) \perp t_k^y \geq 0 \\
&0 \leq (v_k^{\max} - v_k + v_k^h) \perp t_k^z \geq 0 \\
&0 \leq (t_k^{\max} - t_k) \perp v_k^l \geq 0 \\
&0 \leq (t_k - t_k^{\min}) \perp v_k^h \geq 0,
\end{aligned}$$

for each bus k whose voltage is regulated by tap-changing transformers, where v are bus voltage magnitudes, $v^{\max}$ and $v^{\min}$ are their band limits, v^l and v^h are voltage violations of band lower and upper limits, t are transformer tap ratios, t^0, $t^{\max}$ and $t^{\min}$ are their current values and limits, and t^y and t^z are positive and negative deviations of t from t^0. The above equations assume that the sensitivity between voltage magnitude and transformer tap ratio is positive. If it is negative, t^y and t^z are interchanged in the first two complementarity constraints, and v^l and v^h are interchanged in the bottom two complementarity constraints.

5.2.7 Voltage band regulation by switched shunts

This constraint is of type CONSTR_TYPE_REG_SHUNT. It enforces voltage band regulation by switched shunt devices. It approximates the constraints

$$\begin{aligned}
&b_k = b_k^0 + b_k^y - b_k^z \\
&0 \leq (v_k + v_k^l - v_k^{\min}) \perp b_k^y \geq 0 \\
&0 \leq (v_k^{\max} - v_k + v_k^h) \perp b_k^z \geq 0 \\
&0 \leq (b_k^{\max} - b_k) \perp v_k^l \geq 0 \\
&0 \leq (b_k - b_k^{\min}) \perp v_k^h \geq 0,
\end{aligned}$$

for each bus k whose voltage is regulated by switched shunt devices, where v are bus voltage magnitudes, $v^{\max}$ and $v^{\min}$ are their band limits, v^l and v^h are voltage violations of band lower and upper limits, b are switched shunt susceptances, b^0, $b^{\max}$ and $b^{\min}$ are their current values and limits, and b^y and b^z are positive and negative deviations of b from b^0 .

5.3 Problems

Optimization problems constructed with PFNET are of the form

$$\begin{aligned}
\text{minimize} \quad & \varphi(x) \\
\text{subject to} \quad & Ax = b \\
& f(x) = 0.
\end{aligned}$$

As already noted, the objective function φ is a weighted sum of functions φ_i. The linear and nonlinear equality constraints $Ax = b$ and $f(x) = 0$, respectively, correspond to one or more of the constraints described above. An optimization problem in PFNET is represented by an object of type Problem.

After instantiation, a Problem is empty and one needs to specify the Network that is to be associated with the problem, the Constraints to include, and the Functions that form the objective function. This can be done using the Problem class methods set_network, add_constraint, and add_function. The following example shows how to construct a simple power flow problem and solve it using the Newton-Raphson method:

```
#***************************************************#
# This file is part of PFNET.                       #
#                                                   #
# Copyright (c) 2015, Tomas Tinoco De Rubira.       #
#                                                   #
# PFNET is released under the BSD 2-clause license. #
#***************************************************#

import pfnet as pf
from numpy import hstack
from numpy.linalg import norm
from scipy.sparse import bmat
from scipy.sparse.linalg import spsolve

def NRsolve(net):

    net.clear_flags()

    # bus voltage angles
    net.set_flags(pf.OBJ_BUS,
                  pf.FLAG_VARS,
                  pf.BUS_PROP_NOT_SLACK,
                  pf.BUS_VAR_VANG)

    # bus voltage magnitudes
    net.set_flags(pf.OBJ_BUS,
                  pf.FLAG_VARS,
                  pf.BUS_PROP_NOT_REG_BY_GEN,
                  pf.BUS_VAR_VMAG)

    # slack gens active powers
    net.set_flags(pf.OBJ_GEN,
                  pf.FLAG_VARS,
                  pf.GEN_PROP_SLACK,
                  pf.GEN_VAR_P)

    # regulator gens reactive powers
    net.set_flags(pf.OBJ_GEN,
                  pf.FLAG_VARS,
                  pf.GEN_PROP_REG,
                  pf.GEN_VAR_Q)

    p = pf.Problem()
    p.set_network(net)
    p.add_constraint(pf.CONSTR_TYPE_PF)       # power flow
    p.add_constraint(pf.CONSTR_TYPE_PAR_GEN)  # generator participation
    p.analyze()

    x = p.get_init_point()
    p.eval(x)

    residual = lambda x: hstack((p.A*x-p.b,p.f))

    while norm(residual(x)) > 1e-4:
        x = x + spsolve(bmat([[p.A],[p.J]],format='csr'),-residual(x))
        p.eval(x)

    net.set_var_values(x)
```

```
    net.update_properties()
```

The above routine can then be used as follows:

```
>>> net = Network()
>>> net.load('case3012wp.mat')

>>> print net.bus_P_mis, net.bus_Q_mis
2.79e+0 1.56e+1

>>> NRsolve(net)

>>> print net.bus_P_mis, net.bus_Q_mis
2.37e-6 3.58e-6
```

As shown in the example, the `Problem` class method `analyze` needs to be called before the vectors and matrices associated with the problem constraints and functions can be used. The method `eval` can then be used for evaluating the problem objective and constraint functions at different points. As is the case for `Constraints`, a `Problem` has a method `combine_H` for forming linear combinations of individual constraint Hessians, and a method `store_sensitivities` for storing sensitivity information in the network components associated with the nonlinear equality constraints. Lastly, a useful attribute of the `Problem` class is `Z`, which is a sparse matrix whose columns are a basis for the null space of `A`.

CHAPTER

SIX

API REFERENCE

6.1 Vector

class numpy.**ndarray**
See numpy documentation.

6.2 Matrix

class scipy.sparse.**coo_matrix**
See scipy documentation.

6.3 Bus

6.3.1 Bus Property Masks

pfnet.**BUS_PROP_ANY**
Any bus.

pfnet.**BUS_PROP_SLACK**
Slack bus.

pfnet.**BUS_PROP_REG_BY_GEN**
Bus voltage magnitude is regulated by generators.

pfnet.**BUS_PROP_REG_BY_TRAN**
Bus voltage magnitude is regulated by tap-changing transformers.

pfnet.**BUS_PROP_REG_BY_SHUNT**
Bus voltage magnitude is regulated by switched shunt devices.

pfnet.**BUS_PROP_NOT_REG_BY_GEN**
Bus voltage magnitude is not regulated by generators.

pfnet.**BUS_PROP_NOT_SLACK**
Bus is not slack.

6.3.2 Bus Variable Masks

pfnet.**BUS_VAR_VMAG**
Voltage magnitude.

pfnet.**BUS_VAR_VANG**
Voltage angle.

pfnet.**BUS_VAR_VDEV**
Voltage magnitude positive and negative set point deviations.

pfnet.**BUS_VAR_VVIO**
Voltage magnitude upper and lower bound violations.

6.3.3 Bus Sensitivities

pfnet.**BUS_SENS_LARGEST**
Largest objective function sensitivity with respect to nonlinear equality constraints involving this bus.

pfnet.**BUS_SENS_P_BALANCE**
Objective function sensitivity with respect to bus active power balance.

pfnet.**BUS_SENS_Q_BALANCE**
Objective function sensitivity with respect to bus reactive power balance.

pfnet.**BUS_SENS_V_MAG_U_BOUND**
Objective function sensitivity with respect to bus upper voltage bound.

pfnet.**BUS_SENS_V_MAG_L_BOUND**
Objective function sensitivity with respect to bus lower voltage bound.

pfnet.**BUS_SENS_V_REG_BY_GEN**
Objective function sensitivity with respect to bus voltage magnitude regulation by generators.

pfnet.**BUS_SENS_V_REG_BY_TRAN**
Objective function sensitivity with respect to bus voltage magnitude regulation by tap-changing transformers.

pfnet.**BUS_SENS_V_REG_BY_SHUNT**
Objective function sensitivity with respect to bus voltage magnitude regulation by switched shunt devices.

6.3.4 Bus Power Mismatches

pfnet.**BUS_MIS_LARGEST**
Largest bus power mismatch.

pfnet.**BUS_MIS_ACTIVE**
Bus active power mismatch.

pfnet.**BUS_MIS_REACTIVE**
Bus reactive power mismatch.

6.3.5 Bus Class

class pfnet.**Bus** (*alloc=True*)
Bus class.

Parameters **alloc** : {True, False}

P_mis
Bus active power mismatch (p.u. system base MVA) (float).

Q_mis
Bus reactive power mismatch (p.u. system base MVA) (float).

branches
List of `branches` incident on this bus (list).

branches_from
List of `branches` that have this bus on the "from" side (list).

branches_to
List of `branches` that have this bus on the "to" side (list).

degree
Bus degree (number of incident branches) (float).

gens
List of `generators` connected to this bus (list).

get_largest_mis (*self*)
Gets the bus power mismatch of largest absolute value.

Returns mis : float

get_largest_mis_type (*self*)
Gets the type of bus power mismatch of largest absolute value.

Returns type : int

get_largest_sens (*self*)
Gets the bus sensitivity of largest absolute value.

Returns sens : float

get_largest_sens_type (*self*)
Gets the type of bus sensitivity of largest absolute value.

Returns type : int

get_quantity (*self*, *type*)
Gets the bus quantity of the given type.

Parameters type : int (*Bus Sensitivities*:, *Bus Power Mismatches*)

Returns value : float

get_total_gen_P (*self*)
Gets the total active power injected by generators connected to this bus.

Returns P : float

get_total_gen_Q (*self*)
Gets the total reactive power injected by generators connected to this bus.

Returns Q : float

get_total_gen_Q_max (*self*)
Gets the largest total reactive power that can be injected by generators connected to this bus.

Returns Q_max : float

get_total_gen_Q_min (*self*)
Gets the smallest total reactive power that can be injected by generators connected to this bus.

Returns Q_min : float

get_total_load_P (*self*)
Gets the total active power consumed by loads connected to this bus.

Returns P : float

get_total_load_Q (*self*)
Gets the total reactive power consumed by loads connected to this bus.

Returns Q : float

get_total_shunt_b (*self*)
Gets the combined susceptance of shunt devices connected to this bus.

Returns b : float

get_total_shunt_g (*self*)
Gets the combined conductance of shunt devices connected to this bus.

Returns g : float

has_flags (*self*, *fmask*, *vmask*)
Determines whether the bus has the flags associated with certain quantities set.

Parameters fmask : int (*Flag Masks*)

vmask : int (*Bus Variable Masks*)

Returns flag : {`True`, `False`}

index
Bus index (int).

index_P
Index of bus active power mismatch (int).

index_Q
Index for bus reactive power mismatch (int).

index_v_ang
Index of voltage angle variable (int).

index_v_mag
Index of voltage magnitude variable (int).

index_vh
Index of voltage high limit violation variable (int).

index_vl
Index of voltage low limit violation variable (int).

index_y
Index of voltage magnitude positive deviation variable (int).

index_z
Index of voltage magnitude negative deviation variable (int).

is_regulated_by_gen (*self*)
Determines whether the bus is regulated by a generator.

Returns flag : {`True`, `False`}

is_regulated_by_shunt (*self*)
Determines whether the bus is regulated by a shunt device.

Returns flag : {`True`, `False`}

is_regulated_by_tran (*self*)
Determines whether the bus is regulated by a transformer.

Returns flag : {`True`, `False`}

is_slack (*self*)
Determines whether the bus is a slack bus.

Returns flag : {True, False}

loads
List of `loads` connected to this bus (list).

name
Bus name (sting).

number
Bus number (int).

reg_gens
List of `generators` regulating the voltage magnitude of this bus (list).

reg_shunts
List of `switched shunt devices` regulating the voltage magnitude of this bus (list).

reg_trans
List of `tap-changing transformers` regulating the voltage magnitude of this bus (list).

sens_P_balance
Objective function sensitivity with respect to bus active power balance (float).

sens_Q_balance
Objective function sensitivity with respect to bus reactive power balance (float).

sens_v_mag_l_bound
Objective function sensitivity with respect to bus lower voltage limit (float).

sens_v_mag_u_bound
Objective function sensitivity with respect to bus upper voltage limit (float).

sens_v_reg_by_gen
Objective function sensitivity with respect to bus voltage regulation by generators (float).

sens_v_reg_by_shunt
Objective function sensitivity with respect to bus voltage regulation by shunts (float).

sens_v_reg_by_tran
Objective function sensitivity with respect to bus voltage regulation by transformers (float).

show (*self*)
Shows bus properties.

v_ang
Bus voltage angle (radians) (float).

v_mag
Bus volatge magnitude (p.u. bus base kv) (float).

v_max
Bus volatge upper bound (p.u. bus base kv) (float).

v_min
Bus voltage lower bound (p.u. bus base kv) (float).

v_set
Bus voltage set point (p.u. bus base kv) (float). Equals one if bus is not regulated by a generator.

vargens
List of `variable generators` connected to this bus (list).

6.4 Branch

6.4.1 Branch Property Masks

pfnet.**BRANCH_PROP_ANY**
Any branch.

pfnet.**BRANCH_PROP_TAP_CHANGER**
Branch is tap-changing transformer.

pfnet.**BRANCH_PROP_TAP_CHANGER_V**
Branch is tap-changing transformer regulating bus voltage magnitude.

pfnet.**BRANCH_PROP_TAP_CHANGER_Q**
Branch is tap-changing transformer regulating reactive power flow.

pfnet.**BRANCH_PROP_PHASE_SHIFTER**
Branch is phase-shifting transformer regulating active power flow.

6.4.2 Branch Variable Masks

pfnet.**BRANCH_VAR_RATIO**
Transformer tap ratio.

pfnet.**BRANCH_VAR_RATIO_DEV**
Transformer tap ratio deviations from current value.

pfnet.**BRANCH_VAR_PHASE**
Transformer phase shift.

6.4.3 Branch Class

class pfnet.**Branch**(*alloc=True*)
Branch class.

Parameters alloc : {True, False}

b
Branch series susceptance (p.u.) (float).

b_from
Branch shunt susceptance at the "from" side (p.u.) (float).

b_to
Branch shunt susceptance at the "to" side (p.u.) (float).

bus_from
Bus connected to the "from" side.

bus_to
Bus connected to the "to" side.

g
Branch series conductance (p.u.) (float).

g_from
Branch shunt conductance at the "from" side (p.u.) (float).

g_to
Branch shunt conductance at the "to" side (p.u.) (float).

has_flags (*self*, *fmask*, *vmask*)
Determines whether the branch has the flags associated with specific quantities set.

Parameters **fmask** : int (*Flag Masks*)

vmask : int (*Branch Variable Masks*)

Returns **flag** : {`True`, `False`}

has_pos_ratio_v_sens (*self*)
Determines whether tap-changing transformer has positive sensitivity between tap ratio and controlled bus voltage magnitude.

Returns **flag** : {`True`, `False`}

index
Branch index (int).

index_phase
Index of transformer phase shift variable (int).

index_ratio
Index of transformer tap ratio variable (int).

index_ratio_y
Index of transformer tap ratio positive deviation variable (int).

index_ratio_z
Index of transformer tap ratio negative deviation variable (int).

is_fixed_tran (*self*)
Determines whether branch is fixed transformer.

Returns **flag** : {`True`, `False`}

is_line (*self*)
Determines whether branch is transmission line.

Returns **flag** : {`True`, `False`}

is_phase_shifter (*self*)
Determines whether branch is phase shifter.

Returns **flag** : {`True`, `False`}

is_tap_changer (*self*)
Determines whether branch is tap-changing transformer.

Returns **flag** : {`True`, `False`}

is_tap_changer_Q (*self*)
Determines whether branch is tap-changing transformer that regulates reactive power flow.

Returns **flag** : {`True`, `False`}

is_tap_changer_v (*self*)
Determines whether branch is tap-changing transformer that regulates bus voltage magnitude.

Returns **flag** : {`True`, `False`}

phase
Transformer phase shift (radians) (float).

phase_max
Transformer phase shift upper limit (radians) (float).

phase_min
Transformer phase shift lower limit (radians) (float).

ratingA
Branch thermal rating A (p.u. system base power) (float).

ratio
Transformer tap ratio (float).

ratio_max
Transformer tap ratio upper limit (float).

ratio_min
Transformer tap ratio lower limit (float).

reg_bus
`Bus` whose voltage is regulated by this tap-changing transformer.

6.5 Generator

6.5.1 Generator Property Masks

pfnet.**GEN_PROP_ANY**
Any generator.

pfnet.**GEN_PROP_SLACK**
Slack generator.

pfnet.**GEN_PROP_REG**
Generator that regulates bus voltage magnitude.

pfnet.**GEN_PROP_NOT_REG**
Generator that does not regulate bus voltage magnitude.

pfnet.**GEN_PROP_NOT_SLACK**
Generator that is not slack.

pfnet.**GEN_PROP_P_ADJUST**
Generator that can adjust its active power (P_min < P_max).

6.5.2 Generator Variable Masks

pfnet.**GEN_VAR_P**
Generator active power.

pfnet.**GEN_VAR_Q**
Generator reactive power.

6.5.3 Generator Class

class pfnet.**Generator**(*alloc=True*)
Generator class.

Parameters **alloc** : {`True`, `False`}

P
Generator active power (p.u. system base MVA) (float).

P_max
Generator active power upper limit (p.u. system base MVA) (float).

P_min
Generator active power lower limit (p.u. system base MVA) (float).

Q
Generator reactive power (p.u. system base MVA) (float).

Q_max
Generator reactive power upper limit (p.u. system base MVA) (float).

Q_min
Generator reactive power lower limit (p.u. system base MVA) (float).

bus
`Bus` to which generator is connected.

cost_coeff_Q0
Coefficient for quadratic genertion cost (constant term).

cost_coeff_Q1
Coefficient for quadratic genertion cost (linear term).

cost_coeff_Q2
Coefficient for quadratic genertion cost (quadratic term).

has_flags (*self*, *fmask*, *vmask*)
Determines whether the generator has the flags associated with certain quantities set.

Parameters **fmask** : int (*Flag Masks*)

vmask : int (*Generator Variable Masks*)

Returns **flag** : {`True`, `False`}

index
Generator index (int).

index_P
Index of generator active power variable (int).

index_Q
Index of generator reactive power variable (int).

is_P_adjustable (*self*)
Determines whether generator has adjustable active power.

Returns **flag** : {`True`, `False`}

is_regulator (*self*)
Determines whether generator provides voltage regulation.

Returns **flag** : {`True`, `False`}

is_slack (*self*)
Determines whether generator is slack.

Returns **flag** : {`True`, `False`}

reg_bus
`Bus` whose voltage is regulated by this generator.

6.6 Shunt

6.6.1 Shunt Property Masks

pfnet.**SHUNT_PROP_ANY**
Any shunt.

pfnet.**SHUNT_PROP_SWITCHED_V**
Switched shunt devices that regulates bus voltage magnitude.

6.6.2 Shunt Variable Masks

pfnet.**SHUNT_VAR_SUSC**
Switched shunt susceptance.

pfnet.**SHUNT_VAR_SUSC_DEV**
Switched shunt susceptance deviations from current point.

6.6.3 Shunt Class

class pfnet.**Shunt**(*alloc=True*)
Shunt class.

Parameters alloc : {True, False}

b
Shunt susceptance (p.u.) (float).

b_max
Shunt susceptance upper limit (p.u.) (float).

b_min
Shunt susceptance lower limit (p.u.) (float).

bus
Bus to which the shunt devices is connected.

g
Shunt conductance (p.u.) (float).

has_flags(*self*, *fmask*, *vmask*)
Determines whether the shunt devices has flags associated with certain quantities set.

Parameters fmask : int (*Flag Masks*)

vmask : int (*Bus Variable Masks*)

Returns flag : {True, False}

index
Shunt index (int).

index_b
Index of shunt susceptance variable (int).

index_y
Index of shunt susceptance positive deviation variable (int).

index_z
Index of shunt susceptance negative deviation variable (int).

is_fixed(*self*)
Determines whether the shunt device is fixed (as opposed to switched).

Returns flag : {True, False}

is_switched_v(*self*)
Determines whether the shunt is switchable and regulates bus voltage magnitude.

Returns flag : {True, False}

reg_bus
Bus whose voltage magnitude is regulated by this shunt device.

6.7 Load

6.7.1 Load Class

class pfnet.**Load**(*alloc=True*)
Load class.

Parameters alloc : {True, False}

P
Load active power (p.u. system base MVA) (float).

Q
Load reactive power (p.u. system base MVA) (float).

bus
Bus to which load is connected.

index
Load index (int).

6.8 Variable Generator

6.8.1 Variable Generator Property Masks

pfnet.**VARGEN_PROP_ANY**
Any variable generator.

6.8.2 Variable Generator Variable Masks

pfnet.**VARGEN_VAR_P**
Variable generator active power.

pfnet.**VARGEN_VAR_Q**
Variable generator reactive power.

6.8.3 Variable Generator Class

class pfnet.**VarGenerator**(*alloc=True*)

Variable generator class.

Parameters alloc : {True, False}

P

Variable generator active power (p.u. system base MVA) (float).

P_max

Variable generator active power upper limit (p.u. system base MVA) (float).

P_min

Variable generator active power lower limit (p.u. system base MVA) (float).

P_std

Variable generator active power standard deviation (p.u. system base MVA) (float).

Q

Variable generator reactive power (p.u. system base MVA) (float).

Q_max

Variable generator maximum reactive power (p.u. system base MVA) (float).

Q_min

Variable generator minimum reactive power (p.u. system base MVA) (float).

bus

Bus to which variable generator is connected.

has_flags(*self*, *fmask*, *vmask*)

Determines whether the variable generator has the flags associated with certain quantities set.

Parameters fmask : int (*Flag Masks*)

vmask : int (*Variable Generator Variable Masks*)

Returns flag : {True, False}

index

Variable generator index (int).

index_P

Index of variable generator active power variable (int).

index_Q

Index of variable generator reactive power variable (int).

name

Variable generator name (string).

6.9 Network

6.9.1 Component Types

pfnet.**OBJ_BUS**

Bus.

pfnet.**OBJ_GEN**

Generator.

`pfnet.OBJ_BRANCH`
Branch.

`pfnet.OBJ_SHUNT`
Shunt device.

`pfnet.OBJ_LOAD`
Load.

`pfnet.OBJ_VARGEN`
Variable generator.

6.9.2 Flag Masks

`pfnet.FLAG_VARS`
For specifying quantities as variable.

`pfnet.FLAG_FIXED`
For specifying variables that should be fixed.

`pfnet.FLAG_BOUNDED`
For specifying variables that should be bounded.

`pfnet.FLAG_SPARSE`
For specifying control adjustments that should be sparse.

6.9.3 Variable Value Codes

`pfnet.CURRENT`
Current variable value.

`pfnet.UPPER_LIMIT`
Upper limit of variable.

`pfnet.LOWER_LIMIT`
Lower limit of variable.

6.9.4 Network Class

class `pfnet.Network`(*alloc=True*)
Network class.

Parameters **alloc** : {`True`, `False`}

`add_vargens`(*self*, *buses*, *penetration*, *uncertainty*, *corr_radius*, *corr_value*)
Adds variable generators to the network.

Parameters **buses** : list of `Buses`

penetration : float

percentage

uncertainty : float

percentage

corr_radius : int

number of branches

corr_value : float

correlation coefficient

adjust_generators (*self*)
Adjusts powers of slack and regulator generators connected to or regulating the same bus to correct generator participations without modifying the total power injected.

base_power
System base power (MVA) (float).

branches
List of network `branches` (list).

bus_P_mis
Largest bus active power mismatch in the network (MW) (float).

bus_Q_mis
Largest bus reactive power mismatch in the network (MVAr) (float).

bus_v_max
Maximum bus voltage magnitude (p.u.) (float).

bus_v_min
Minimum bus voltage magnitude (p.u.) (float).

bus_v_vio
Maximum bus voltage magnitude limit violation (p.u.) (float).

buses
List of network `buses` (list).

clear_error (*self*)
Clear error flag and message string.

clear_flags (*self*)
Clears all the flags of all the network components.

clear_properties (*self*)
Clears all the network properties.

clear_sensitivities (*self*)
Clears all sensitivity information.

create_sorted_bus_list (*self*, *sort_by*)
Creates list of buses sorted in descending order according to a specific quantity.

Parameters **sort_by** : int (*Bus Sensitivities*, *Bus Power Mismatches*).

Returns **buses** : list of `Buses`

create_vargen_P_sigma (*self*, *spread*, *corr*)
Creates covariance matrix (lower triangular part) for variable vargen active powers.

Parameters **spead** : int

Determines correlation neighborhood in terms of number of edges.

corr : float

Desired correlation coefficient for neighboring vargens.

Returns **sigma** : `coo_matrix`

gen_P_vio
Largest generator active power limit violation (MW) (float).

gen_Q_vio
Largest generator reactive power limit violation (MVAr) (float).

gen_v_dev
Largest voltage magnitude deviation from set point of bus regulated by generator (p.u.) (float).

generators
List of network `generators` (list).

get_branch (*self*, *index*)
Gets branch with the given index.

Parameters index : int

Returns branch : `Branch`

get_bus (*self*, *index*)
Gets bus with the given index.

Parameters index : int

Returns bus : `Bus`

get_bus_by_name (*self*, *name*)
Gets bus with the given name.

Parameters name : string

Returns bus : `Bus`

get_bus_by_number (*self*, *number*)
Gets bus with the given number.

Parameters number : int

Returns bus : `Bus`

get_gen (*self*, *index*)
Gets generator with the given index.

Parameters index : int

Returns gen : `Generator`

get_gen_buses (*self*)
Gets list of buses where generators are connected.

Returns buses : list

get_load (*self*, *index*)
Gets load with the given index.

Parameters index : int

Returns gen : `Load`

get_load_buses (*self*)
Gets list of buses where loads are connected.

Returns buses : list

get_num_P_adjust_gens (*self*)
Gets number of generators in the network that have adjustable active powers.

Returns num : int

get_num_branches (*self*)
Gets number of branches in the network.

Returns **num** : int

get_num_buses (*self*)
Gets number of buses in the network.

Returns **num** : int

get_num_buses_reg_by_gen (*self*)
Gets number of buses whose voltage magnitudes are regulated by generators.

Returns **num** : int

get_num_buses_reg_by_shunt (*self*, *only=False*)
Gets number of buses whose voltage magnitudes are regulated by switched shunt devices.

Returns **num** : int

get_num_buses_reg_by_tran (*self*, *only=False*)
Gets number of buses whose voltage magnitudes are regulated by tap-changing transformers.

Returns **num** : int

get_num_fixed_shunts (*self*)
Gets number of fixed shunts in the network.

Returns **num** : int

get_num_fixed_trans (*self*)
Gets number of fixed transformers in the network.

Returns **num** : int

get_num_gens (*self*)
Gets number of generators in the network.

Returns **num** : int

get_num_lines (*self*)
Gets number of transmission lines in the network.

Returns **num** : int

get_num_loads (*self*)
Gets number of loads in the network.

Returns **num** : int

get_num_phase_shifters (*self*)
Gets number of phase-shifting transformers in the network.

Returns **num** : int

get_num_reg_gens (*self*)
Gets number generators in the network that provide voltage regulation.

Returns **num** : int

get_num_shunts (*self*)
Gets number of shunts in the network.

Returns **num** : int

get_num_slack_buses (*self*)
Gets number of slack buses in the network.

Returns **num** : int

get_num_slack_gens (*self*)
Gets number of slack generators in the network.

Returns **num** : int

get_num_switched_shunts (*self*)
Gets number of switched shunts in the network.

Returns **num** : int

get_num_tap_changers (*self*)
Gets number of tap-changing transformers in the network.

Returns **num** : int

get_num_tap_changers_Q (*self*)
Gets number of tap-changing transformers in the network that regulate reactive flows.

Returns **num** : int

get_num_tap_changers_v (*self*)
Gets number of tap-changing transformers in the network that regulate voltage magnitudes.

Returns **num** : int

get_num_vargens (*self*)
Gets number of variable generators in the network.

Returns **num** : int

get_properties (*self*)
Gets network properties.

Returns **properties** : dict

get_shunt (*self*, *index*)
Gets shunt with the given index.

Parameters **index** : int

Returns **gen** : `Shunt`

get_var_projection (*self*, *obj_type*, *var*)
Gets projection matrix for specific object variables.

Parameters **obj_type** : int (*Component Types*)

var : int (*Bus Variable Masks*, *Branch Variable Masks*, *Generator Variable Masks*, *Shunt Variable Masks*)

get_var_values (*self*, *code=CURRENT*)
Gets network variable values.

Parameters **code** : int (See var values)

Returns **values** : `ndarray`

get_vargen (*self*, *index*)
Gets variable generator with the given index.

Parameters **index** : int

Returns **vargen** : `VarGenerator`

get_vargen_by_name (*self*, *name*)
Gets vargen with the given name.

Parameters **name** : string

Returns **vargen** : `VarGenerator`

has_error (*self*)
Indicates whether the network has the error flag set due to an invalid operation.

load (*self*, *filename*)
Loads a network data contained in a specific file.

Parameters **filename** : string

loads
List of network `loads` (list).

num_actions
Number of control adjustments (int).

num_bounded
Number of network quantities that have been set to bounded (int).

num_branches
Number of branches in the network (int).

num_buses
Number of buses in the network (int).

num_fixed
Number of network quantities that have been set to fixed (int).

num_gens
Number of generators in the network (int).

num_loads
Number of loads in the network (int).

num_shunts
Number of shunt devices in the network (int).

num_sparse
Number of network control quantities that have been set to sparse (int).

num_vargens
Number of variable generators in the network (int).

num_vars
Number of network quantities that have been set to variable (int).

set_flags (*self*, *obj_type*, *flags*, *props*, *vals*)
Sets flags of network components with specific properties.

Parameters **obj_type** : int (*Component Types*)

flags : int or list (*Flag Masks*)

props : int or list (*Bus Property Masks*, *Branch Property Masks*, *Generator Property Masks*, *Shunt Property Masks*)

vals : int or list (*Bus Variable Masks*, *Branch Variable Masks*, *Generator Variable Masks*, *Shunt Variable Masks*)

set_var_values (*self*, *values*)
Sets network variable values.

Parameters **values** : ndarray

show_buses (*self*, *number*, *sort_by*)
Shows information about the most relevant network buses sorted by a specific quantity.

Parameters **number** : int

sort_by : int (*Bus Sensitivities*, *Bus Power Mismatches*)

show_components (*self*)
Shows information about the number of network components of each type.

show_properties (*self*)
Shows information about the state of the network component quantities.

shunt_b_vio
Largest switched shunt susceptance limit violation (p.u.) (float).

shunt_v_vio
Largest voltage magnitude band violation of voltage regulated by switched shunt device (p.u.) (float).

shunts
List of network shunts (list).

tran_p_vio
Largest transformer phase shift limit violation (float).

tran_r_vio
Largest transformer tap ratio limit violation (float).

tran_v_vio
Largest voltage magnitude band violation of voltage regulated by transformer (p.u.) (float).

update_properties (*self*, *values=None*)
Re-computes the network properties using the given values of the network variables. If no values are given, then the current values of the network variables are used.

Parameters **values** : ndarray

update_set_points (*self*)
Updates voltage magnitude set points of gen-regulated buses to be equal to the bus voltage magnitudes.

var_generators
List of network variable generators (list).

vargen_corr_radius
Correlation radius of variable generators (number of edges).

vargen_corr_value
Correlation value (coefficient) of variable generators.

6.10 Graph

class pfnet.**Graph** (*net*, *alloc=True*)
Graph class.

Parameters **net** : Network

alloc : {True, False}

color_nodes_by_mismatch (*self*, *mis_type*)
Colors the graphs nodes according to their power mismatch.

Parameters **mis_type** : int (*Bus Power Mismatches*)

color_nodes_by_sensitivity (*self*, *sens_type*)
Colors the graphs nodes according to their sensitivity.

Parameters **sens_type** : int (*Bus Sensitivities*)

set_edges_property (*self*, *prop*, *value*)
Sets property of edges. See Graphviz documentation.

Parameters **prop** : string

value : string

set_layout (*self*)
Determines and saves a layout for the graph nodes.

set_nodes_property (*self*, *prop*, *value*)
Sets property of nodes. See Graphviz documentation.

Parameters **prop** : string

value : string

view (*self*)
Displays the graph.

write (*self*, *format*, *filename*)
Writes the graph to a file.

Parameters **format** : string (Graphviz output formats)

filename : string

6.11 Function

6.11.1 Function Types

pfnet.**FUNC_TYPE_UNKNOWN**
Unknown function.

pfnet.**FUNC_TYPE_REG_VMAG**
Bus voltage magnitude regularization.

pfnet.**FUNC_TYPE_SLIM_VMAG**
Bus voltage magnitude soft limits penalty.

pfnet.**FUNC_TYPE_REG_VANG**
Bus voltage angle regularization.

pfnet.**FUNC_TYPE_REG_PQ**
Generator active and reactive power regularization.

pfnet.**FUNC_TYPE_GEN_COST**
Active power generation cost.

pfnet.**FUNC_TYPE_REG_RATIO**
Transformer tap ratio regularization.

pfnet.**FUNC_TYPE_REG_PHASE**
Transformer phase shift regularization.

pfnet.**FUNC_TYPE_REG_SUSC**
Switched shunt susceptance regularization.

pfnet.**FUNC_TYPE_SP_CONTROLS**
Sparsity-inducing penalty for control adjustments.

6.11.2 Function Class

class pfnet.**Function**(*int type*, *float weight*, *Network net*, *alloc=True*)
Function class.

Parameters **type** : int (*Function Types*)

weight : float

net : Network

alloc : {True, False}

Hcounter
Number of nonzero entries in Hessian matrix (int).

Hphi
Function Hessian matrix (only the lower triangular part) (coo_matrix).

analyze(*self*)
Analyzes function and allocates required vectors and matrices.

clear_error(*self*)
Clears internal error flag.

eval(*self*, *var_values*)
Evaluates function value, gradient, and Hessian using the given variable values.

Parameters **var_values** : ndarray

gphi
Function gradient vector (ndarray).

phi
Function value (float).

type
Function type (int).

update_network(*self*)
Updates internal arrays to be compatible with any network changes.

weight
Function weight (float).

6.12 Constraint

6.12.1 Constraint Types

pfnet.**CONSTR_TYPE_PF**
Constraint for enforcing power balance at every bus of the network.

pfnet.**CONSTR_TYPE_FIX**
Constraint for fixing a subset of variables to their current value.

pfnet.**CONSTR_TYPE_BOUND**
Constraint for forcing a subset of variables to be within their bounds.

pfnet.**CONSTR_TYPE_PAR_GEN**
Constraint for enforcing generator participations.

pfnet.**CONSTR_TYPE_REG_GEN**
Constraint for enforcing voltage set point regulation by generators.

pfnet.**CONSTR_TYPE_REG_TRAN**
Constraint for enforcing voltage band regulation by tap-changing transformers.

pfnet.**CONSTR_TYPE_REG_SHUNT**
Constraint for enforcing voltage band regulation by switched shunt devices.

6.12.2 Constraint Class

class pfnet.**Constraint**(*int type*, *Network net*, *alloc=True*)
Constraint class.

Parameters **type** : int (*Constraint Types*)

net : Network

alloc : {True, False}

A
Matrix for linear equality constraints (coo_matrix).

Aconstr_index
Index of linear equality constraint (int).

Acounter
Number of nonzero entries in the matrix of linear equality constraints (int).

G
Matrix for linear inequality constraints (coo_matrix).

Gconstr_index
Index of linear ineqquality constraint (int).

Gcounter
Number of nonzero entries in the matrix of linear inequality constraints (int).

H_combined
Linear combination of Hessian matrices of individual nonlinear equality constraints (only the lower triangular part) (coo_matrix).

J
Jacobian matrix of nonlinear equality constraints (coo_matrix).

Jconstr_index
Index of nonlinear equality constraint (int).

Jcounter
Number of nonzero entries in the Jacobian matrix of the nonlinear equality constraints (int).

analyze(*self*)
Analyzes constraint and allocates required vectors and matrices.

b
Right-hand side vector of linear equality constraints (ndarray).

clear_error (*self*)
Clears internal error flag.

combine_H (*self*, *coeff*, *ensure_psd=False*)
Forms and saves a linear combination of the individual constraint Hessians.

Parameters **coeff** : ndarray

ensure_psd : {True, False}

eval (*self*, *var_values*)
Evaluates constraint violations, Jacobian, and individual Hessian matrices.

Parameters **var_values** : ndarray

f
Vector of nonlinear equality constraint violations (ndarray).

get_H_single (*self*, *i*)
Gets the Hessian matrix (only lower triangular part) of an individual constraint.

Parameters **i** : int

Returns **H** : coo_matrix

hl
Lower bound vector of linear inequality constraints (ndarray).

hu
Upper bound vector of linear inequality constraints (ndarray).

store_sensitivities (*self*, *sens*)
Stores Lagrange multiplier estimates of the nonlinear equality constraint in the power network components.

Parameters **sens** : ndarray

type
Constraint type (*Constraint Types*) (int).

update_network (*self*)
Updates internal arrays to be compatible with any network changes.

6.13 Optimization Problem

6.13.1 Problem Class

class pfnet.**Problem**
Class constructor.

A
Constraint matrix of linear equality constraints (coo_matrix).

H_combined
Linear combination of Hessian matrices of individual nonlinear equality constraints (only the lower triangular part) (coo_matrix).

Hphi
Objective function Hessian matrix (only the lower triangular part) (coo_matrix).

J
Jacobian matrix of the nonlinear equality constraints (`coo_matrix`).

add_constraint (*self*, *ctype*)
Adds constraint to optimization problem.

Parameters ctype : int (*Constraint Types*)

add_function (*self*, *ftype*, *weight*)
Adds function to optimization problem objective.

Parameters ftype : int (*Function Types*)

weight : float

analyze (*self*)
Analyzes function and constraint structures and allocates required vectors and matrices.

b
Right hand side vectors of the linear equality constraints (`ndarray`).

clear (*self*)
Resets optimization problem data.

combine_H (*self*, *coeff*, *ensure_psd*)
Forms and saves a linear combination of the individual constraint Hessians.

Parameters coeff : `ndarray`

ensure_psd : {`True`, `False`}

constraints
List of `constraints` of this optimization problem (list).

eval (*self*, *var_values*)
Evaluates objective function and constraints as well as their first and second derivatives using the given variable values.

Parameters var_values : `ndarray`

f
Vector of nonlinear equality constraints violations (`ndarray`).

find_constraint (*self*, *type*)
Finds constraint of give type among the constraints of this optimization problem.

Parameters type : int (*Constraint Types*)

functions
List of `functions` that form the objective function of this optimization problem (list).

get_init_point (*self*)
Gets initial solution estimate from the current value of the network variables.

Returns point : `ndarray`

get_lower_limits (*self*)
Gets vector of lower limits for the network variables.

Returns limits : `ndarray`

get_network (*self*)
Gets the power network associated with this optimization problem.

get_upper_limits (*self*)
Gets vector of upper limits for the network variables.

Returns limits : `ndarray`

`gphi`
Objective function gradient vector (`ndarray`).

`lam`
Initial dual point (`ndarray`).

`network`
Power network associated with this optimization problem (`Network`).

`nu`
Initial dual point (`ndarray`).

`phi`
Objective function value (float).

`set_network` (*self*, *net*)
Sets the power network associated with this optimization problem.

`show` (*self*)
Shows information about this optimization problem.

`store_sensitivities` (*self*, *sens*)
Stores Lagrange multiplier estimates of the nonlinear equality constraint in the power network components.

Parameters sens : `ndarray`

`update_lin` (*self*)
Updates linear equality constraints.

`x`
Initial primal point (`ndarray`).

6.14 References

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- *search*

[TTR2015] T. Tinoco De Rubira, *Numerical Optimization and Modeling Techniques for Power System Operations and Planning*. PhD thesis, Stanford University, March 2015.

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