

**ExaGO™ Users Manual**  
*Version 1.0*

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# Chapter 1

## Introduction

The Exascale Grid Optimization (ExaGO<sup>TM</sup>) toolkit is an open source package for solving large-scale power grid optimization problems on parallel and distributed architectures, particularly targeted for exascale machines with heterogeneous architectures (GPU). ExaGO<sup>TM</sup> is written in C/C++ and makes heavy use of the functionality provided by the PETSc[1] library. It uses RAJA [3] and Umpire [4] libraries for execution on the GPU and can make use of several optimization solvers - Ipopt [7], HiOp [6, 5], and TAO [1]- for solving the optimization problems.

All ExaGO<sup>TM</sup> applications use a nonlinear formulation based on full AC optimal power flow. The different applications available with ExaGO are listed in Table 1.1

Table 1.1: ExaGO applications

Application	Description	Notes
OPFLOW	AC optimal power flow	
SCOPFLOW	Security-constrained AC optimal power flow	Uses TCOPFLOW for multi-period contingencies
TCOPFLOW	Multi-period AC optimal power flow	
SOPFLOW	Stochastic AC optimal power flow	Uses SCOPFLOW for multi-contingency scenarios

While ExaGO is targeted for making use of distributed computing environments and GPUs, its full support is still under development. Table 1.2 lists the architecture support for ExaGO applications.

Table 1.2: ExaGO application execution on different hardware

Application	CPU (serial)	CPU (parallel)	GPU
OPFLOW	Y	N	Y
SCOPFLOW	Y	Y (embarrassingly parallel)	N
SOPFLOW	Y	Y (embarrassingly parallel)	N
TCOPFLOW	Y	N	N

Together, these applications cater to problems spanning the dimensions of security (contingencies), stochasticity, and time as shown in Figure 1.1.

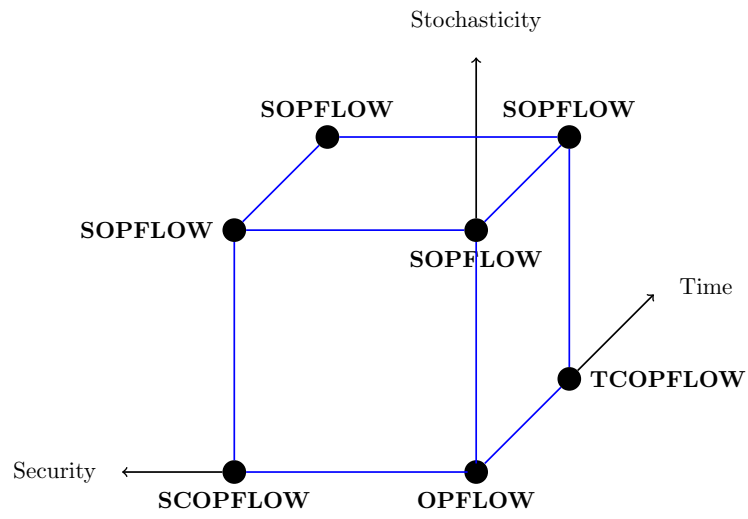


Figure 1.1: ExaGO provides applications along the dimensions of security (contingencies), time, and stochasticity. The label vertices denote different ExaGO applications available.

# Chapter 2

## Getting Started

### 2.1 System requirements

ExaGO is currently only built on 64b OSX and Linux machines, compiled with GCC  $\geq 7.3$ . We build ExaGO on Intel and IBM Power9 architectures.

### 2.2 Prerequisites

This section assumes that you already have the ExaGO source code, and that the environment variable EXAGODIR is the directory of the ExaGO source code. ExaGO may be acquired via [the PNNL git repository linked here](#), like so:

```
> git clone https://gitlab.pnnl.gov/exasgd/frameworks/exago.git exago
> export EXAGODIR=$PWD/exago
```

Paths to installations of third party software in examples are abbreviated with placeholder paths. For example, /path/to/cuda is a placeholder for a path to a valid CUDA Toolkit installation.

### 2.3 Dependencies

ExaGO has dependencies in [table 2.1](#).

Table 2.1: Dependency Table

Dependency	Version Constraints	Mandatory	Notes
<a href="#">PETSc [1]</a>	$\geq 3.13.0$	✓	Only needed for the setup stage
CMake	$\geq 3.10$	✓	Only a build dependency
MPI	$\geq 3.1.3$		Only tested with openmpi and spectrumpi
<a href="#">Ipopt [7]</a>	$\geq 3.12$		
<a href="#">HiOp [6, 5]</a>	$\geq 0.3.0$		Prefer dynamically linked
<a href="#">RAJA [3]</a>	$\geq 0.11.0$		
<a href="#">Umpire [2]</a>	$\geq 2.1.0$		Only when RAJA is enabled
<a href="#">MAGMA</a>	$\geq 2.5.2$		Only when GPU acceleration is enabled
<a href="#">CUDA Toolkit</a>	$\geq 10.2.89$		Only when GPU acceleration is enabled

These may all be toggled via CMake, which will be discussed in the section [Building and installation](#).



### 2.3.1 Notes on environment modules

Many of the dependencies are available via environment modules on institutional clusters. To get additional information on your institution's clusters, please ask your institution's system administrators. Some end-to-end examples in this document will use system-specific modules and are not expected to run on other clusters.

For example, the modules needed to build and run ExaGO on Newell, an IBM Power9 PNNL cluster, are as follows:

```
> module load gcc/7.4.0
> module load openmpi/3.1.5
> module load cuda/10.2
> module load magma/2.5.2_cuda10.2
> module load metis/5.1.0
> module load cmake/3.16.4
```

### 2.3.2 Additional Notes on GPU Accelerators

As of January 2021, CUDA is the only GPU accelerator platform ExaGO fully supports. We have preliminary support for HIP, however this is not in any of our main development branches yet. Full HIP support should arrive in early 2021.

### 2.3.3 Additional Notes on Umpire

Umpire is an implicit dependency of RAJA. If a user enables RAJA, they must also provide a valid installation of Umpire. Additionally, if a user would like to run ExaGO with RAJA and without CUDA, they must provide a CPU-only build of Umpire since an Umpire build with CUDA enabled will link against CUDA.

## 2.4 Building and installation

### 2.4.1 Default Build

ExaGO may be built with a standard CMake workflow:

Listing 2.1: Example CMake workflow

```
> cd $EXAGODIR
> export BUILDDIR=$PWD/build INSTALLDIR=$PWD/install
> mkdir $BUILDDIR $INSTALLDIR
> cd $BUILDDIR
> cmake .. -DCMAKE_INSTALL_PREFIX=$INSTALLDIR
> make install
```

The following sections will assume the user is following the basic workflow outlined above.

**Note:** For changes to the CMake configuration to take effect, the code will have to be rebuilt.

## 2.4.2 Additional Options

To enable additional options, CMake variables may be defined via CMake command line arguments, `ccmake`, or `cmake-gui`. CMake options specific to ExaGO have an `EXAGO_` prefix. For example, the following shell commands will build ExaGO with MPI:

```
> cmake .. -DCMAKE_INSTALL_PREFIX=$INSTALLDIR -DEXAGO_ENABLE_MPI=ON
```

ExaGO's CMake configuration will search the usual system locations for an MPI installation.

For dependencies not installed to a system-wide location, users may also directly specify the location of a dependency. For example, this will build ExaGO with IPOPT enabled and installed to a user directory:

```
> cmake .. \  
  -DCMAKE_INSTALL_PREFIX=$INSTALLDIR \  
  -DEXAGO_ENABLE_IPOPT=ON \  
  -DIPOPT_DIR=/path/to/ipopt
```

Notice that the CMake variable `IPOPT_DIR` does not have an `EXAGO_` prefix. This is because the variables specifying locations often belong to external CMake modules. CMake variables indicating installation directories do not have an `EXAGO_` prefix.

Some CMake options effect others. This is especially common when the user enables ExaGO's GPU options. For example, if the user enables `EXAGO_ENABLE_GPU` and `EXAGO_ENABLE_RAJA`, the user must provide a GPU-enabled RAJA installation. Umpire is also an implicit dependency of RAJA, so if the user enables `EXAGO_ENABLE_GPU` they must **also** provide a GPU-enabled Umpire installation.

Below is a complete shell session on PNNL's cluster Newell in which a more complicated ExaGO configuration is built, where each dependency installation is explicitly passed to CMake. Environment modules specific to Newell are provided to make the example thorough, even though they are not likely to work on another machine.

Listing 2.2: ExaGO build with all options enabled

```
> module load gcc/7.4.0  
> module load cmake/3.16.4  
> module load openmpi/3.1.5  
> module load magma/2.5.2_cuda10.2  
> module load metis/5.1.0  
> module load cuda/10.2  
> git clone https://gitlab.pnnl.gov/exasgd/frameworks/exago.git exago  
> export EXAGODIR=$PWD/exago  
> cd $EXAGODIR  
> export BUILDDIR=$PWD/build INSTALLDIR=$PWD/install  
> mkdir $BUILDDIR $INSTALLDIR  
> cd $BUILDDIR  
> cmake .. \  
  -DCMAKE_INSTALL_PREFIX=$INSTALLDIR \  
  -DCMAKE_BUILD_TYPE=Debug \  
  -DEXAGO_ENABLE_GPU=ON \  
  -DEXAGO_ENABLE_HIOP=ON \  
  -DEXAGO_ENABLE_IPOPT=ON \  
  -DEXAGO_ENABLE_MPI=ON
```

```

-DEXAGO_ENABLE_MPI=ON \
-DEXAGO_ENABLE_PETSC=ON \
-DEXAGO_RUN_TESTS=ON \
-DEXAGO_ENABLE_RAJA=ON \
-DEXAGO_ENABLE_IPOPT=ON \
-DIPOPT_DIR=/path/to/ipopt \
-DRAJA_DIR=/path/to/raja \
-Dumpire_DIR=/path/to/umpire \
-DHIOP_DIR=/path/to/hiop \
-DMAGMA_DIR=/path/to/magma \
-DPETSC_DIR=/path/to/petsc
> make -j 8 install
> # For the following commands, a job scheduler command may be needed.
> # Run test suite
> make test
> # Run an ExaGO application:
> $INSTALLDIR/bin/opflow

```

## 2.5 Usage

Each ExaGO application has the following format for execution

```
./app <app_options>
```

Here, `app_options` are the command line options for the application. Each application has many options through which the input files and the control options can be set for the application. All application options have the form `-app_option_name` followed by the `app_option_value`. For instance,

```
./opflow -netfile case9mod.m -opflow_model POWER_BALANCE_POLAR \
-opflow_solver IPOPT
```

will execute the **OPFLOW** application using `case9mod.m` input file with the model `POWER_BALANCE_POLAR` ↪ and **Ipo**pt [7]solver.

Options can also be passed to each application through `-options_file`, or through a combination of the command line and options file. The configuration specified last on the command line overrides any previous options. For example, if `-options_file opflowoptions` specified `-netfile case9mod.m` within its settings:

```
./opflow -netfile case118.m -options_file opflowoptions # Uses case9mod.m
./opflow -options_file opflowoptions -netfile case118.m # Uses case118.m
```

If no options file is specified through the command line, ExaGO applications will attempt to locate the default options file for a given application in `./`, `./options`, `<install_dir>/options`. Each solver that can be used within ExaGO also have their own unique options. Some of these options are specified internally within ExaGO, but any other options that are needed should either be passed through the command line, or additionally specified in the options file.

## Chapter 3

# Optimal power flow (OPFLOW)

OPFLOW solves the full AC optimal power flow problem and provides various flexible features that can be toggled via run-time options. It has interfaces to different optimization solvers and includes different representations of the underlying equations (power-balance-polar and power-balance-cartesian) that can be used. By selecting the appropriate solver, OPFLOW can be executed on CPUs (in serial or parallel) or on GPUs.

### 3.1 Formulation

Optimal power flow is a general nonlinear programming problem with the following form

$$\min. f(x) \tag{3.1}$$

s.t.

$$g(x) = 0 \tag{3.2}$$

$$h(x) \leq 0 \tag{3.3}$$

$$x^{\min} \leq x \leq x^{\max} \tag{3.4}$$

Here,  $x$  are the decision variables with lower and upper bounds  $x^{\min}$  and  $x^{\max}$ , respectively,  $f(x)$  is the objective function,  $g(x)$  and  $h(x)$  are the equality and inequality constraints, respectively. In the following sections we describe what constitutes these different terms as used by OPFLOW.

#### 3.1.1 Variables and bounds

The different variables used in **OPFLOW** formulation are described in Table 3.1.

Power imbalance variables are non-physical (slack) variables that measure the violation of power balance at buses. Having these variables (may) help in making the optimization problem easier to solve since they always ensure feasibility of the bus power balance constraints.

#### 3.1.2 Objective Function

The objective function for OPFLOW is given in (3.5)

$$\min. C(p^g) + C(\Delta p^g) + C(\Delta p^l, \Delta q^l) + C(\Delta p, \Delta q) \tag{3.5}$$

Table 3.1: Optimal power flow (OPFLOW) variables

Variable	Symbol	Bounds	Notes
Generator real power dispatch	$p_j^g$	$p_j^{gmin} \leq p_j^g \leq p_j^{gmax}$	
Generator reactive power dispatch	$q_j^g$	$q_j^{gmin} \leq q_j^g \leq q_j^{gmax}$	
Generator real power deviation	$\Delta p_j^g$	$-p_j^r \leq \Delta p_j^g \leq p_j^r$	<ul style="list-style-type: none"> <li>• Only used when <code>-opflow_has_gensetpoint</code> or <code>-opflow_use_agc</code> option is active</li> <li>• <math>\Delta p_j^g</math> is the deviation from real power generation set-point <math>p_j^{gset}</math>.</li> </ul>
Generator real power set-point	$p_j^{gset}$	$p_j^{gmin} \leq p_j^{gset} \leq p_j^{gmax}$	<ul style="list-style-type: none"> <li>• Only used when <code>-opflow_has_gensetpoint</code> or <code>-opflow_use_agc</code> option is active.</li> </ul>
System power excess/deficit	$\Delta P$	Unbounded	Only used when <code>-opflow_use_agc</code> is active
Bus voltage angle	$\theta_i$	$-\pi \leq \theta_i \leq \pi$	<ul style="list-style-type: none"> <li>• Used with power balance polar model (<code>-opflow_model POWER_BALANCE_POLAR</code>)</li> <li>• <math>\theta_i</math> is unbounded, except reference bus angle <math>\theta_i^{ref}</math> which is fixed to 0</li> </ul>
Bus voltage magnitude	$v_i$	$v_i^{min} \leq v_i \leq v_i^{max}$	<ul style="list-style-type: none"> <li>• Used with power balance polar model (<code>-opflow_model POWER_BALANCE_POLAR</code>)</li> <li>• <math>v_i^{min} = v_i^{max} = v_i^{set}</math> if fixed generator set point voltage option is active (<code>-opflow_has_gensetpoint</code>)</li> </ul>
Bus voltage real part	$e_i$	$-v_i^{max} \leq e_i \leq v_i^{max}$	Used with power balance cartesian model ( <code>-opflow_model POWER_BALANCE_CARTESIAN</code> )
Bus voltage imaginary part	$f_i$	$-v_i^{max} \leq f_i \leq v_i^{max}$	Used with power balance cartesian model ( <code>-opflow_model POWER_BALANCE_CARTESIAN</code> )
Bus real power mismatch	$\Delta p_i$	Unbounded	Used when power mismatch variable option is active ( <code>-opflow_include_powerimbalance_variables1</code> )
Bus reactive power mismatch	$\Delta q_i$	Unbounded	Used when power mismatch variable option is active ( <code>-opflow_include_powerimbalance_variables1</code> )
Real power load loss	$\Delta p_j^l$	$0 \leq \Delta p_j^l \leq p_j^l$	Used when load loss variable option is active ( <code>-opflow_include_loadloss_variables1</code> )
Reactive power load loss	$\Delta q_j^l$	$0 \leq \Delta q_j^l \leq q_j^l$	Used when load loss variable option is active ( <code>-opflow_include_loadloss_variables1</code> )

### Total generation cost $C(p^g)$

Needs option `-opflow_objective MIN_GEN_COST`

$$C(p^g) = \sum_{j \in J^{\text{gen}}} C_j^g(p_j^g) \quad (3.6)$$

Here,  $C_j^g$  is a quadratic function of the form  $C_j^g = a_j^g p_j^{g^2} + b_j^g p_j^g + c_j^g$ .

### Total generation setpoint deviation $C(\Delta p^g)$

Needs option `-opflow_objective MIN_GENSETPOINT_DEVIATION` option

$$C(\Delta p^g) = \sum_{j \in J^{\text{gen}}} (\Delta p_j^{g^2}) \quad (3.7)$$

### Load loss $C(\Delta p^l, \Delta q^l)$

This term gets added to the objective when `-opflow_include_loadloss_variables` option is active.

$$C(\Delta p^l, \Delta q^l) = \sum_{j \in J^{\text{ld}}} \sigma_j^l (\Delta p_j^{l^2} + \Delta q_j^{l^2}) \quad (3.8)$$

The load loss penalty  $\sigma_j^l$  can be set via the option `-opflow_loadloss_penalty`. The default is \$1000/MW for all loads.

### Power imbalance $C(\Delta p, \Delta q)$

This term gets added to the objective when `-opflow_include_powerimbalance_variables` option is active.

$$C(\Delta p, \Delta q) = \sum_{i \in J^{\text{bus}}} \sigma_i (\Delta p_i^2 + \Delta q_i^2) \quad (3.9)$$

The power imbalance cost  $\sigma_i$  can be set via the option `-opflow_powerimbalance_penalty`. The default is \$10,000/MW for all buses. Though the power imbalance variables  $\Delta p_i, \Delta q_i$  are slack or non-physical, they can help in solving infeasible cases and provide a measure of the infeasibility.

## 3.1.3 Equality constraints

### Nodal power balance

$$\sum_{\substack{j \in J^{\text{gen}} \\ A_{ij}^g \neq 0}} p_j^g = p_i^{\text{sh}} + \sum_{\substack{j \in J^{\text{ld}} \\ A_{ij}^l \neq 0}} p_j^l + \sum_{\substack{j \in J^{\text{br}} \\ A_{oi}^{\text{br}} \neq 0}} p_{jod}^{\text{br}} + \sum_{\substack{j \in J^{\text{br}} \\ A_{id}^{\text{br}} \neq 0}} p_{jdo}^{\text{br}} \quad (3.10)$$

$$\sum_{\substack{j \in J^{\text{gen}} \\ A_{ij}^g \neq 0}} q_j^g = q_i^{\text{sh}} + \sum_{\substack{j \in J^{\text{ld}} \\ A_{ij}^l \neq 0}} q_j^l + \sum_{\substack{j \in J^{\text{br}} \\ A_{oi}^{\text{br}} \neq 0}} q_{jod}^{\text{br}} + \sum_{\substack{j \in J^{\text{br}} \\ A_{id}^{\text{br}} \neq 0}} q_{jdo}^{\text{br}} \quad (3.11)$$

$$(3.12)$$

where, the real and reactive power shunt consumption is given by (3.19) and (3.20)

The real and reactive power flow  $p_{jod}^{br}, q_{jod}^{br}$  for line  $j$  from the origin bus  $o$  to destination bus  $d$  is given by (3.21) – (3.22) and from destination bus  $d$  to origin bus  $o$  is given by (3.23) – (3.24)

### Generator real power output

When using `-opflow_has_gensetpoint`, two extra variables  $p_j^{gset}$  and  $\Delta p_j^g$  are added for each generator. The generator real power output  $p_j^g$  is related to the power deviation  $\Delta p_j^g$  by the following relations

$$p_j^{gset} + \Delta p_j^g - p_j^g = 0 \quad (3.13)$$

$$p_j^{gset} - p_j^{g*} = 0 \quad (3.14)$$

The second equation here allows to fix the generator set point  $p_j^{gset}$  to a fixed value  $p_j^{g*}$ . Here,  $p_j^{g*}$  is the set-point for the generator real power output, which can be thought of as an operator set or contractual agreement set-point.

### 3.1.4 Inequality constraints

#### MVA flow on branches

MVA flow limits at origin and destination buses for each line.

$$p_{jod}^{br2} + q_{jod}^{br2} \leq s_j^{rateA^2}, \quad j \in J^{br} \quad (3.15)$$

$$p_{jdo}^{br2} + q_{jdo}^{br2} \leq s_j^{rateA^2}, \quad j \in J^{br} \quad (3.16)$$

To reduce the number of inequality constraints, only lines that are in service and having MVA A rating  $s_j^{rateA}$  less than 10000 MVA are considered.

#### Automatic generation control (AGC)

With `-opflow_use_agc`, two additional constraints are added for each participating generator to enforce the proportional generator redispatch participation as done in automatic generation control (AGC). These two equations are

$$\begin{aligned} (\alpha_j^g \Delta P - \Delta p_j^g) (p_j^g - p_j^{gmax}) &\geq 0 \\ ((\Delta p_j^g - \alpha_j^g \Delta P) (p_j^{gmin} - p_j^g) &\geq 0 \end{aligned} \quad (3.17)$$

Eq. 3.17 enforces the generator set-point deviation to be equal to the generation participation when the generator has head-room available  $p_j^{gmin} \leq p_j^g \leq p_j^{gmax}$ . Here,  $\alpha_j^g$  is the generator participation factor which is the proportion of the power deficit/excess  $\Delta P$  that the generator provides.

#### Generator bus voltage control

When the option `-opflow_genbusvoltage FIXED_WITHIN_QBOUNDS` is used, the generator bus voltage is fixed when the total reactive power generation available at the bus is within bounds. When

it reaches its bounds, the voltage varies with the generator reactive power fixed at its bound. To implement this behavior, two inequality constraints are added for each generator bus

$$\begin{aligned}(v_i^{\text{set}} - v_i)(q_i - q^{\text{max}_i}) &\geq 0 \\ (v_i - v_i^{\text{set}})(q^{\text{min}_i} - q_i) &\geq 0\end{aligned}\tag{3.18}$$

Here,  $q_i$ ,  $q^{\text{max}_i}$ , and  $q^{\text{min}_i}$  are the generated, maximum, and minimum reactive power at the bus, respectively.

## 3.2 Models

Table 3.2: OPFLOW models

Model type	OPFLOW option ( <code>-opflow.model1</code> )	Compatible solvers	CPU-GPU
Power balance with polar coordinates	POWER_BALANCE_POLAR	IPOPT	CPU
Power balance with cartesian coordinates	POWER_BALANCE_CARTESIAN	IPOPT, TAO	CPU
Power balance with polar coordinates used with HIOP	POWER_BALANCE_HIOP	HiOp [6, 5]	CPU/GPU
Power balance with polar coordinates used with HIOP on GPU	PBPOLRAJAHOP	HiOp [6, 5]	GPU

### 3.2.1 Power balance polar

#### Shunt power

$$p_i^{\text{sh}} = g_i^{\text{sh}} v_i^2 \tag{3.19}$$

$$q_i^{\text{sh}} = -b_i^{\text{sh}} v_i^2 \tag{3.20}$$

#### Branch flows

The real and reactive power flow  $p_{jod}^{\text{br}}$ ,  $q_{jod}^{\text{br}}$  from bus  $o$  to bus  $d$  on line  $j$  is given by (3.21) – (3.22)

$$p_{jod}^{\text{br}} = g_{oo} v_o^2 + v_o v_d (g_{od} \cos(\theta_o - \theta_d) + b_{od} \sin(\theta_o - \theta_d)) \tag{3.21}$$

$$q_{jod}^{\text{br}} = -b_{oo} v_o^2 + v_o v_d (-b_{od} \cos(\theta_o - \theta_d) + g_{od} \sin(\theta_o - \theta_d)) \tag{3.22}$$

and from bus  $d$  to bus  $o$  is given by (3.23) – (3.24)

$$p_{jdo}^{\text{br}} = g_{dd} v_d^2 + v_d v_o (g_{do} \cos(\theta_d - \theta_o) + b_{do} \sin(\theta_d - \theta_o)) \tag{3.23}$$

$$q_{jdo}^{\text{br}} = -b_{dd} v_d^2 + v_d v_o (-b_{do} \cos(\theta_d - \theta_o) + g_{do} \sin(\theta_d - \theta_o)) \tag{3.24}$$



Table 3.3: OPFLOW Model-solver compatibility

Model	<a href="#">Ipopt</a> [7]	<a href="#">HiOp</a> [6, 5]	<a href="#">TAO</a> [1]
POWER_BALANCE_POLAR	✓		
POWER_BALANCE_CARTESIAN	✓		✓
POWER_BALANCE_HIOP		✓	
PBPOLRAJAHOP		✓	

### 3.2.2 Power balance with HiOp

Power balance formulation with polar coordinates used with [HiOp](#) [6, 5][6] library. This model runs on CPU only, though the [HiOp](#) [6, 5] solver can run on GPU.

### 3.2.3 Power balance with HiOp,RAJA,and Umpire

Power balance formulation with polar coordinates used with [HiOp](#) [6, 5] and [RAJA](#) [3]. This model uses [RAJA](#) [3] [3] and Umpire [4] libraries to run **OPFLOW** calculations (objective, constraints, etc.) on the GPU.

## 3.3 Solvers

**OPFLOW** can be used with a few different solvers. All the three solvers solve the optimization problem via a nonlinear interior-point algorithm.

1. [Ipopt](#) [7] is a popular open-source package for solving nonlinear optimization problems. It is the most robust of the solvers implemented for solving **OPFLOW**. However, it can be run only on a single process and does not have GPU support. Option:

```
-opflow_solver IPOPT
```

2. The Toolkit for Applied Optimization ([TAO](#) [1]) is a toolkit available through [PETSc](#) [1] for solving optimization problems. TAO includes a interior-point algorithm that is used by **OPFLOW**. The TAO algorithm is fully parallel, but is less robust compared to IPOPT. Currently, the TAO solver can only be used with the power balance cartesian model. Option:

```
-opflow_solver TAO -opflow_model POWER_BALANCE_CARTESIAN
```

3. [HiOp](#) [6, 5] is a high-performance optimization library that implements an interior-point algorithm for solving nonlinear optimization problems. The library supports execution both on the CPU and the GPU. Options:

```
CPU: -opflow_solver HIOP -opflow_model POWER_BALANCE_HIOP
```

```
GPU: -opflow_solver HIOP -opflow_model PBPOLRAJAHOP
```

The option `-hiop_ipopt_debug` can be used with the CPU option in order to use an adapter that verifies the correctness of the first and second order derivatives when compared to [Ipopt](#) [7]. This may be useful when debugging experimental changes.

## 3.4 Input and Output

The current ExaGO version only supports reading network file in [MATPOWER](#) format and can (optionally) write the output back in [MATPOWER](#) data file format.

## 3.5 Usage

```
./opflow -netfile <netfilename> <opflowoptions>
```

## 3.6 Options

See table 3.4

Table 3.4: OPFLOW options

Option	Meaning	Values (Default value)
-netfile	Network file name	string < 4096 characters (case9mod.m)
-print_output	Print output to screen	0 or 1 (0)
-save_output	Save output to file	0 or 1 (0)
-opflow_model	Representation of network balance equations and bus voltages	See Table 3.2 (POWER_BALANCE_POLAR)
-opflow_solver	Optimization solver	See section 3.3
-opflow_initialization	Type of initialization	See Table 3.5 (MIDPOINT)
-opflow_has_gensetpoint	Uses generation set point and activates ramping variables	0 or 1 (0)
-opflow_use_agc	Uses AGC formulation in OPF	0 or 1 (0)
-opflow_objective	type of objective function	See table 3.7 (MIN_GEN_COST)
-opflow_genbusvoltage	Type of generator bus voltage control	See Table 3.6 (FIXED_WITHIN_QBOUNDS)
-opflow_ignore_lineflow_constraints	Ignore line flow constraints	0 or 1 (0)
-opflow_include_loadloss_variables	Include load loss	0 or 1 (0)
-opflow_include_powerimbalance_variables	Include power imbalance	0 or 1 (0)
-opflow_loadloss_penalty	\$ penalty for load loss	real (1000)
-opflow_powerimbalance_penalty	\$ penalty for power imbalance	real (10000)
-opflow_tolerance	Optimization solver tolerance	real (1e-6)

Table 3.5: OPFLOW initializations

Initialization type	Meaning
MIDPOINT	Use mid-point of bounds
FROMFILE	Use values from network file
ACPF	Run AC power flow for initialization
FLATSTART	Flat-start

Table 3.6: OPFLOW generator bus voltage control modes

Voltage control type	Meaning
FIXED_AT_SETPOINT	Fixed at given set-point. Reactive power limits are ignored
FIXED_WITHIN_QBOUNDS	Fixed within reactive power bounds
VARIABLE_WITHIN_BOUNDS	Variable within voltage bounds

Table 3.7: OPFLOW objective function types

Objective function	Meaning
MIN_GEN_COST	Minimize generation cost
MIN_GENSETPOINT_DEVIATION	Minimize deviation (ramp up-down) from generator set-point
NO_OBJ	No objective function

### 3.7 Examples

Some **OPFLOW** example runs are provided with some sample output. Options values are the default values in table 3.4 unless otherwise specified. `-print_output` is only used in the first example to save space. Sample output is generated by running examples from the installation directory.

Example using the **TAO** [1] solver:

```
$ ./bin/opflow -netfile case9mod.m -opflow_solver TAO -opflow_model \
POWER_BALANCE_CARTESIAN -print_output
[ExaGO INFO]: -- Checking ... -options_file not passed      exists: no
[ExaGO INFO]: Creating OPFlow
TAO solve converged due to CONVERGED_GRTOL iterations 12
=====
                Optimal Power Flow
=====
Model                POWER_BALANCE_CARTESIAN
Solver               TAO
Objective            MIN_GEN_COST
Initialization       MIDPOINT
Load loss allowed    NO
Power imbalance allowed NO
Ignore line flow constraints NO

Number of variables      24
Number of equality constraints 19
Number of inequality constraints 27

Convergence status      CONVERGED
Objective value          4144.46

-----
Bus      Pd      Qd      Vm      Va      mult_Pmis      mult_Qmis
-----
1         0.00     0.00    1.100   -0.000      2102.91         0.00
2         0.00     0.00    1.095    3.927      2059.18         0.00
3         0.00     0.00    1.087    2.120      2065.15        -0.00
4         0.00     0.00    1.097   -1.993      2103.16         0.08
5        75.00    50.00    1.079   -3.060      2113.46         7.29
6        90.00    30.00    1.087   -3.927      2129.85         1.62
7         0.00     0.00    1.100    0.535      2059.57        -0.04
8       100.00    35.00    1.089   -1.720      2079.34         2.99
```

9	0.00	0.00	1.100	-0.135	2065.43	-0.09		
<hr/>								
From	To	Status	Sft	Stf	Slim	mult_Sf	mult_St	
<hr/>								
1	4	1	73.17	72.98	380.00	0.00	0.00	
2	7	1	114.18	114.68	250.00	0.00	0.00	
3	9	1	83.57	84.60	300.00	0.00	0.00	
4	5	1	29.68	40.50	250.00	0.00	0.00	
4	6	1	44.86	46.03	250.00	0.00	0.00	
5	7	1	51.29	49.04	250.00	0.00	0.00	
6	9	1	48.94	51.43	150.00	0.00	0.00	
7	8	1	66.61	68.11	250.00	0.00	0.00	
8	9	1	38.87	34.15	150.00	0.00	0.00	
<hr/>								
Gen	Status	Fuel	Pg	Qg	Pmin	Pmax	Qmin	Qmax
<hr/>								
1	1	UNDEFINED	72.86	6.79	10.00	350.00	-300.00	300.00
2	1	UNDEFINED	114.07	-5.13	10.00	300.00	-300.00	300.00
3	1	UNDEFINED	80.21	-23.47	10.00	270.00	-300.00	300.00
[ExaGO INFO]: Finalizing opflow application.								

Example using the **Ipo**pt [7] solver:

```
$ ./bin/opflow -opflow_solver IPOPT -opflow_model POWER_BALANCE_POLAR \
-opflow_initialisation ACPF -opflow_objective MIN_GENSETPOINT_DEVIATION
[ExaGO INFO]: -- Checking ... -options_file not passed      exists: no
[ExaGO INFO]: Creating OPFlow

*****
This program contains Ipo
```

pt, a library for large-scale nonlinear optimization. Ipo

pt is released as open source code under the Eclipse Public License (EPL).

\*\*\*\*\*

This is Ipo

pt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...: 125

Number of nonzeros in inequality constraint Jacobian.: 106

Number of nonzeros in Lagrangian Hessian.....: 159

Total number of variables.....: 32

variables with only lower bounds: 0

variables with lower and upper bounds: 24

variables with only upper bounds: 0

Total number of equality constraints.....: 24

Total number of inequality constraints.....: 36

```

        inequality constraints with only lower bounds:      15
    inequality constraints with lower and upper bounds:    21
        inequality constraints with only upper bounds:      0

iter objective  inf_pr inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
0   5.9999880e-04  1.80e+00  2.60e-01 -1.0  0.00e+00 - 0.00e+00  0.00e+00  0
1   1.1156839e-02  1.31e+00  7.65e+01 -1.0  1.25e+00 - 9.33e-02  2.67e-01h 1
2   1.9076073e-02  1.26e+00  7.36e+01 -1.0  1.84e+00 - 3.08e-02  4.25e-02f 1
3   4.6334972e-02  1.17e+00  6.85e+01 -1.0  1.20e+00 - 1.51e-02  7.14e-02f 1
...
86   8.8262569e-02  3.01e-12  2.18e-03 -7.0  2.12e-05 - 1.00e+00  1.00e+00h 1
87   8.8262567e-02  3.55e-15  1.33e-10 -7.0  2.54e-09 - 1.00e+00  1.00e+00h 1

Number of Iterations.....: 87

                                (scaled)                                (unscaled)
Objective.....:      8.8262566709882084e-02      8.8262566709882084e-02
Dual infeasibility...:  1.3274141855146966e-10    1.3274141855146966e-10
Constraint violation:  3.5527136788005009e-15      3.5527136788005009e-15
Complementarity.....:  9.0929465340161350e-08      9.0929465340161350e-08
Overall NLP error....:  9.0929465340161350e-08      9.0929465340161350e-08

Number of objective function evaluations          = 120
Number of objective gradient evaluations          = 88
Number of equality constraint evaluations          = 120
Number of inequality constraint evaluations        = 120
Number of equality constraint Jacobian evaluations = 88
Number of inequality constraint Jacobian evaluations = 88
Number of Lagrangian Hessian evaluations          = 87
Total CPU secs in IPOPT (w/o function evaluations) =      0.039
Total CPU secs in NLP function evaluations        =      0.011

EXIT: Optimal Solution Found.
[ExaGO INFO]: Finalizing opflow application.

```

Example using the **HiOp** [6, 5] solver on the CPU:

```

$ ./bin/opflow -opflow_solver HIOP -opflow_model POWER_BALANCE_HIOP \
-opflow_initialisaition FLATSTART -hiop_compute_mode CPU \
-hiop_verbosity_level 3
[ExaGO INFO]: -- Checking ... -options_file not passed      exists: no
[ExaGO INFO]: Creating OPFlow
[Warning] Detected 1 fixed variables out of a total of 24.
[Warning] Fixed variables will be relaxed internally.
=====
Hiop SOLVER
=====

```

```

#
# Hiop options
#
...
# end of Hiop options

Using 1 MPI ranks.
-----
Problem Summary
-----
Total number of variables: 24
      lower/upper/lower_and_upper bounds: 16 / 16 / 16
Total number of equality constraints: 18
Total number of inequality constraints: 18
      lower/upper/lower_and_upper bounds: 18 / 18 / 18
iter  objective  inf_pr  inf_du  lg(mu)  alpha_du  alpha_pr  linesrch
0   1.0318125e+04  1.800e+00  4.460e+03  -1.00   0.000e+00  0.000e+00  -(-)
1   7.7139414e+03  1.167e+00  2.900e+03  -1.00   6.255e-01  3.496e-01  1(s)
2   7.3644945e+03  1.075e+00  2.654e+03  -1.00   9.785e-03  8.498e-02  1(s)
...
13  4.1444605e+03  3.989e-10  3.273e-08  -7.00   1.000e+00  1.000e+00  1(h)
Successfull termination.
Total time 0.003 sec
Hiop internal time:      total 0.001 sec      avg iter 0.000 sec
      internal total std dev across ranks 0.000 percent
Fcn/deriv time:total=0.001sec (obj=0.000 grad=0.000 cons=0.000 \
      Jac=0.000 Hess=0.001)
      Fcn/deriv total std dev across ranks 0.000 percent
Fcn/deriv #: obj 14 grad 14 eq cons 14 ineq cons 14 eq Jac 14 ineq Jac 14
Total KKT time 0.001 sec
      update init 0.000sec      update linsys 0.000 sec      fact 0.001 sec
      solve rhs-manip 0.000 sec      triangular solve 0.000 sec

[ExaGO INFO]: Finalizing opflow application.

```

Example using **HiOp** [6, 5] solver on the GPU:

```

$mpirun -n 1 ./bin/opflow -opflow_model PBPOLRAJAHIOp -opflow_solver HIOP\
-hiop_compute_mode GPU -hiop_verbosity_level 3 \
-opflow_initialisation ACPF -opflow_ignore_lineflow_constraints 1 \
-netfile datafiles/case_ACTIVSg200.m
[ExaGO INFO]: -- Checking ... -options_file not passed      exists: no
[ExaGO INFO]: Creating OPFlow
[Warning] Detected 1 fixed variables out of a total of 476.
[Warning] Fixed variables will be relaxed internally.
=====
Hiop SOLVER
=====

```

```

#
# Hiop options
#
...
# end of Hiop options

Using 1 MPI ranks.
-----
Problem Summary
-----
Total number of variables: 476
      lower/upper/lower_and_upper bounds: 277 / 277 / 277
Total number of equality constraints: 400
Total number of inequality constraints: 0
      lower/upper/lower_and_upper bounds: 0 / 0 / 0
iter  objective  inf_pr  inf_du  lg(mu)  alpha_du  alpha_pr  linesrch
0   2.6329021e+04  1.725e+00  2.321e+03  -1.00   0.000e+00  0.000e+00  -(-)
1   2.6227762e+04  1.723e+00  2.318e+03  -1.00   8.506e-04  1.026e-03  1(s)
2   2.6134620e+04  1.721e+00  2.314e+03  -1.00   1.697e-03  8.630e-04  1(s)
...
24  2.7557571e+04  3.921e-09  3.801e-07  -7.00   1.000e+00  1.000e+00  1(h)
Successfull termination.
Total time 4.555 sec
Hiop internal time:      total 4.538 sec      avg iter 0.189 sec
      internal total std dev across ranks 0.000 percent
Fcn/deriv time:      total=0.015 sec  ( obj=0.001 grad=0.001 cons=0.003 \
                                Jac=0.004 Hess=0.006)
      Fcn/deriv total std dev across ranks 0.000 percent
Fcn/deriv #: obj 27 grad 25 eq cons 27 ineq cons 27 eq Jac 25 ineq Jac 25
Total KKT time 4.464 sec
      update init 0.004sec  update linsys 0.046 sec      fact 4.327 sec
      solve rhs-manip 0.072 sec      triangular solve 0.015 sec

[ExaGO INFO]: Finalizing opflow application.

```

## Chapter 4

# Multi-period optimal power flow (TCOPFLOW)

TCOPFLOW solves a full AC multi-period optimal power flow problem with the objective of minimizing the total cost over the given time horizon while adhering to constraints for each period and between consecutive time-periods (ramping constraints).

### 4.1 Formulation

The multi-period optimal power flow problem is a series of optimal power flow problems coupled via temporal constraints. The generator real power deviation ( $p_{jt}^g - p_{jt-\Delta t}^g$ ) constrained within the ramp limits form the temporal constraints. An illustration of the temporal constraints is shown in Fig. 4.1 with four time steps. Each time-step  $t$  is coupled with its preceding time  $t - \Delta t$ , where  $\Delta t$  is the time-step where the objective is to find a least cost dispatch for the given time horizon.

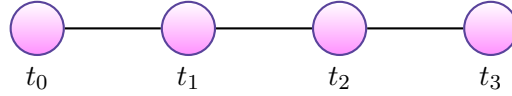


Figure 4.1: Multi-period optimal power flow example with four time-steps. The lines connecting the different time-periods denote the coupling between them.

In general form, the equations for multi-period optimal power flow are given by (4.1) – (4.5). TCOPFLOW solves to minimize the total generation cost  $\sum_{t=0}^{N_t-1} f(x_t)$  over the time horizon, where  $N_t$  is the number of time-steps. At each time-step, the equality constraints ( $g(x_t)$ ), inequality  $h(x_t)$ , and the lower/upper limit ( $x^-, x^+$ ) constraints need to be satisfied. Equation (4.5) represents the coupling between the consecutive time-steps. It is the most common form of coupling that limits the deviation of the real power generation at time  $t$  from its preceding time-step  $t - \Delta t$  to within its ramping capability  $\delta_t x$ .



$$\min \sum_{t=0}^{N_t-1} f(x_t) \quad (4.1)$$

s.t.

$$g(x_t) = 0, \quad t \in [0, N_t - 1] \quad (4.2)$$

$$h(x_t) \leq 0, \quad t \in [0, N_t - 1] \quad (4.3)$$

$$x^- \leq x_t \leq x^+, \quad t \in [0, N_t - 1] \quad (4.4)$$

$$-\delta_t x \leq x_t - x_{t-\Delta t} \leq \delta_t x, \quad t \in [1, N_t - 1] \quad (4.5)$$

## 4.2 Solvers

**TCOPFLOW** solves the coupled multi-period using the solver **Ipopt** [7]. Currently, ExaGO only supports solving **TCOPFLOW** using **Ipopt** [7], which is also the default solver. Solving **TCOPFLOW** is supported only on a single process.

## 4.3 Input and Output

- **Network file:** The network file describing the network details. Only **MATPOWER** format files are currently supported.
- **Load data:** One file for load real power and one for reactive power. The files need to be in CSV format. An example of the format for the 9-bus case is [here](#).
- **Wind generation:** The wind generation time-series described in CSV format. See an example of the format [here](#).

If the load data and/or wind generation profiles are not set then a flat profile is assumed, i.e., the load and wind generation for all hours is constant.

The **TCOPFLOW** output is saved to a directory named *tcopflowout*. This directory contains  $N_t$  files, one for each time-step, in **MATPOWER** data file format.

## 4.4 Usage

```
./tcopflow -netfile <netfilename> -tcopflow_pload_profile <ploadprofile> \
-tcopflow_windgen_profile <windgenprofile> <tcopflowoptions> \
-tcopflow_qload_profile <qloadprofile>
```

## 4.5 Options

See table 4.1. In addition, all **OPFLOW** options given in Table 3.4 can be used.

Table 4.1: TCOPFLOW options

Option	Meaning	Values (Default value)
-netfile	Network file name	string < 4096 characters ( <a href="#">case9mod_gen3_wind.m</a> )
-save_output	Save output to file	0 or 1 (0)
-tcopflow_pload_profile	Real power load profile	string < 4096 characters ( <a href="#">load_P.csv</a> )
-tcopflow_qload_profile	Reactive power load profile	string < 4096 characters ( <a href="#">load_Q.csv</a> )
-tcopflow_windgen_profile	Wind generation profile	string < 4096 characters ( <a href="#">case9/scenarios_9bus.csv</a> )
-tcopflow_dT	Length of time-step (minutes)	double (5.0)
-tcopflow_duration	Total duration (hours)	double (0.5)
-tcopflow_iscoupling	Coupling between time steps (ramp constraints)	0 or 1 (0)

## 4.6 Examples

Some **TCOPFLOW** example runs are provided with some sample output. Options are the default options provided in table 3.4 and 4.1 unless otherwise specified. Sample output is generated by running examples from the installation directory.

Example using [Ipopt](#) [7] solver:

```
$ ./bin/tcopflow -tcopflow_iscoupling 1 -print_output
[ExaGO INFO]: -- Checking ... -options_file not passed exists: no
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.500000 hours, timestep = 5.000000 minutes, \
              number of time-steps = 7

TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
Setting: "0" is not a valid setting for Option: tol.
Check the option documentation.

### tol (Real Number) ###
Category: Convergence
Description: Desired convergence tolerance (relative).
0 < (1e-08) <= +inf

*****
This program contains Ipopt...
*****

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...:      770
Number of nonzeros in inequality constraint Jacobian...:    610
Number of nonzeros in Lagrangian Hessian.....:          630
```

```

Total number of variables.....: 161
      variables with only lower bounds: 0
      variables with lower and upper bounds: 105
      variables with only upper bounds: 0
Total number of equality constraints.....: 126
Total number of inequality constraints.....: 186
      inequality constraints with only lower bounds: 42
      inequality constraints with lower and upper bounds: 144
      inequality constraints with only upper bounds: 0

iter  objective  inf_pr  inf_du lg(mu)  ||d||  lg(rg)  alpha_du  alpha_pr  ls
0  5.2094875e+04  1.80e+00  5.02e+01  -1.0  0.00e+00 - 0.00e+00  0.00e+00  0.00e+00  0
1  3.6277420e+04  1.40e+00  1.06e+02  -1.0  2.05e+00 - 1.88e-01  2.20e-01f  1
...
33  2.0843675e+04  1.13e-14  3.32e-09  -8.6  1.76e-08 - 1.00e+00  1.00e+00h  1

Number of Iterations.....: 33

                                (scaled)                                (unscaled)
Objective.....: 4.6734697780313832e+02  2.0843675210019970e+04
Dual infeasibility...: 3.3166774138882895e-09  1.4792381265941772e-07
Constraint violation: 1.1296519275560968e-14  1.1296519275560968e-14
Complementarity.....: 4.9900570925632554e-09  2.2255654632832121e-07
Overall NLP error....: 4.9900570925632554e-09  2.2255654632832121e-07

Number of objective function evaluations = 47
Number of objective gradient evaluations = 34
Number of equality constraint evaluations = 47
Number of inequality constraint evaluations = 47
Number of equality constraint Jacobian evaluations = 34
Number of inequality constraint Jacobian evaluations = 34
Number of Lagrangian Hessian evaluations = 33
Total CPU secs in IPOPT (w/o function evaluations) = 0.025
Total CPU secs in NLP function evaluations = 0.032

EXIT: Optimal Solution Found.
=====
      Multi-Period Optimal Power Flow
=====
OPFLOW Model                POWER_BALANCE_POLAR
Solver                      IPOPT
Duration (minutes)          30.00
Time-step (minutes)         5.00
Number of steps              7
Active power demand profile  datafiles/case9/load_P.csv

```

Rective power demand profile	datafiles/case9/load_Q.csv
Wind generation profile	datafiles/case9/scenarios_9bus.csv
Load loss allowed	NO
Power imbalance allowed	NO
Ignore line flow constraints	NO
Number of variables	168
Number of equality constraints	126
Number of inequality constraints	168
Number of coupling constraints	18
Convergence status	CONVERGED
Objective value	20843.68

Bus	Pd	Qd	Vm	Va	mult_Pmis	mult_Qmis
1	0.00	0.00	1.040	0.000	2063.35	-0.00
2	0.00	0.00	1.025	4.553	2013.40	0.00
3	0.00	0.00	1.025	2.955	2017.53	0.00
4	0.00	0.00	1.037	-2.174	2063.59	-0.74
5	75.00	30.00	1.025	-3.405	2074.28	2.68
6	90.00	30.00	1.023	-4.213	2092.22	4.26
7	0.00	0.00	1.033	0.783	2014.09	3.85
8	100.00	35.00	1.022	-1.667	2035.30	7.65
9	0.00	0.00	1.036	0.264	2018.00	3.11

From	To	Status	Sft	Stf	Slim	mult_Sf	mult_St
1	4	1	71.31	71.13	380.00	-0.00	-0.00
2	7	1	111.80	112.67	250.00	-0.00	-0.00
3	9	1	86.66	87.56	300.00	-0.00	-0.00
4	5	1	28.34	34.62	250.00	-0.00	-0.00
4	6	1	42.81	45.47	250.00	-0.00	-0.00
5	7	1	47.86	51.21	250.00	-0.00	-0.00
6	9	1	49.48	52.48	150.00	-0.00	-0.00
7	8	1	63.89	65.25	250.00	-0.00	-0.00
8	9	1	41.64	36.64	150.00	-0.00	-0.00

Gen	Status	Fuel	Pg	Qg	Pmin	Pmax	Qmin	Qmax
1	1	COAL	71.06	5.89	10.00	350.00	-300.00	300.00
2	1	COAL	111.38	-9.71	10.00	300.00	-300.00	300.00
3	1	WIND	85.00	-16.87	0.00	85.00	-300.00	300.00

[ExaGO INFO]: Finalizing tcopflow application.

## Chapter 5

# Security-constrained optimal power flow (SCOPFLOW)

SCOPFLOW solves a contingency-constrained optimal power flow problem. The problem is set up as a two-stage optimization problem where the first-stage (base-case) represents the normal operation of the grid and the second-stage comprises  $N_c$  contingency scenarios. Each contingency scenario can be single or multi-period.

### 5.1 Formulation

#### 5.1.1 Single-period

The contingency-constrained optimal power flow (popularly termed as security-constrained optimal power flow (SCOPF) in power system parlance) attempts to find a least cost dispatch for the base case (or no contingency) while ensuring that if any of contingencies do occur then the system will be secure. This is illustrated in Fig. 5.1 for a SCOPF with a base-case  $c_0$  and three contingencies.

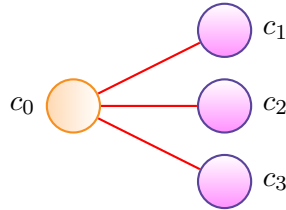


Figure 5.1: Contingency constrained optimal power flow example with three contingencies.  $c_0$  represents the base case (or no contingency case).  $c_1$ ,  $c_2$ ,  $c_3$  are the three contingency cases. Each of the contingency states is coupled with the base-case through ramping constraints (denoted by red lines)

In general form, the equations for contingency-constrained optimal power flow are given by (5.1) – (5.5). This is a two-stage stochastic optimization problem where the first stage is the base case  $c_0$  and each of the contingency states  $c_i, i \in [1, N_c - 1]$  are second-stage subproblems. SCOPFLOW aims to minimize the objective  $\sum_{c=0}^{N_c-1} f(x_c)$ , while adhering to the equality  $g(x_c)$ , inequality  $h(x_c)$ , and the lower/upper bound  $(x^-, x^+)$  constraints. Equation (5.5) represents the coupling between the base-case and each of the contingency states  $c_i$ . Equation (5.5) is the most typical form of coupling that limits the deviation of the contingency variables  $x_c$  from the base  $x_0$  to within  $\delta_c x$ . An example of this constraint could be the allowed real power output deviation for the generators constrained by their ramp limit.

$$\min f(x_0) \tag{5.1}$$

s.t.

$$g(x_c) = 0, \quad c \in [0, N_c - 1] \tag{5.2}$$

$$h(x_c) \leq 0, \quad c \in [0, N_c - 1] \tag{5.3}$$

$$x^- \leq x_c \leq x^+, \quad c \in [0, N_c - 1] \tag{5.4}$$

$$-\delta_c x \leq x_c - x_0 \leq \delta_c x, \quad c \in [1, N_c] \tag{5.5}$$

### 5.1.2 Multiperiod

In the multi-period version, each contingency is comprised of multiple time-periods. The multiple periods have variables and constraints as described in chapter 4. An example of multi-contingency multi-period optimal power flow is illustrated in Fig. 5.2 with two contingencies  $c_0$  and  $c_1$ . Here,  $c_0$  is the case with no contingencies, i.e., the base-case. Each contingency is multi-period with four time-periods. Each time-step is coupled with its adjacent one through ramping constraints. We assume that the contingency is incident at the first time-step, i.e. at  $t_0$ . This results in the coupling between the contingency cases  $c_i, i \in [1, N_c - 1]$  and the base-case  $c_0$  only at time-step  $t_0$  as shown in Fig. 5.2.

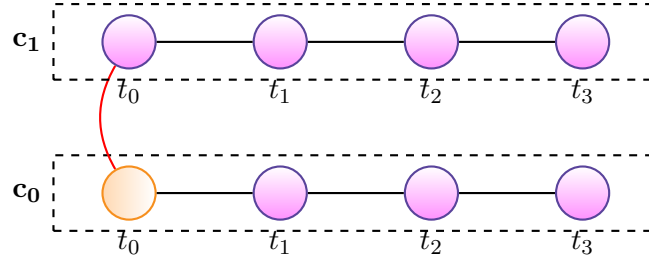


Figure 5.2: Multi-period contingency constrained optimal power flow example with two contingencies  $c_0$  and  $c_1$ , each with four time-periods  $t_0, t_1, t_2, t_3$ . State  $c_0, t_0$  represent the base case (no contingency) case. We assume that any contingency is incident at the first time-step, i.e., at  $t_0$ . The contingency states  $c_1, t_0$  is coupled with the no-contingency state  $c_0, t_0$  at time  $t_0$ . The red line denotes the coupling between the contingency.

The overall objective of this contingency-constrained multi-period optimal power flow is to find a secure dispatch for base-case  $c_0$  while adhering to contingency and temporal constraints. The general formulation of this problem is given in Eqs. (5.6) – (5.12).

$$\min \sum_{c=0}^{N_c-1} \sum_{t=0}^{N_t-1} f(x_{c,t}) \quad (5.6)$$

s.t.

$$g(x_{c,t}) = 0, \quad c \in [0, N_c - 1], t \in [0, N_t - 1] \quad (5.7)$$

$$h(x_{c,t}) \leq 0, \quad c \in [0, N_c - 1], t \in [0, N_t - 1] \quad (5.8)$$

$$x^- \leq x_{c,t} \leq x^+, \quad c \in [0, N_c - 1], t \in [0, N_t - 1] \quad (5.9)$$

$$-\delta_t x \leq x_{c,t} - x_{c,t-\Delta t} \leq \delta_t x, \quad c \in [0, N_c - 1], t \in [1, N_t - 1] \quad (5.10)$$

$$-\delta_c x \leq x_{c,0} - x_{0,0} \leq \delta_c x, \quad c \in [1, N_c - 1] \quad (5.11)$$

$$(5.12)$$

In this formulation, the objective is to reduce the cost for the base-case time horizon, where  $f(x_{0,t})$  is the objective cost for contingency  $c_0$  at time  $t$ . Equation (5.12) represents the coupling between the base case  $c_0$  and each contingency  $c_i$  at time-step  $t_0$ . We use a simple box constraint  $\delta_c x$  to restrict the deviation of decision variables  $x_{c,0}$  from the base-case  $x_{0,0}$ . The bound  $\delta_c x$  could represent here, for example, the allowable reserve for each generator.

## 5.2 Solvers

**SCOPFLOW** can be solved with **Ipopt** [7]. If one wants to solve each contingency independently, i.e., without any coupling constraints then use the **EMPAR** solver. **EMPAR** distributes the contingencies to different processes when executed in parallel.

## 5.3 Input and Output

To execute **SCOPFLOW**, the following files are required:

- **Network file:** The network file describing the network details. Only **MATPOWER** format files are currently supported.
- **Contingency file:** The file describing the contingencies. Contingencies can be single or multiple outages. The contingency file needs to be described in PTI format.

If the multi-period option is chosen, then additional files describing the load and wind generation can be (optionally) set.

- **Load data:** One file for load real power and one for reactive power. The files need to be in CSV format. An example of the format for the 9-bus case is [here](#).
- **Wind generation:** The wind generation time-series described in CSV format. See an example of the format [here](#).

The **SCOPFLOW** output is saved to a directory named *scopflowout*. This directory contains  $N_c$  files to save the solution for each contingency in MATPOWER datafile format. Each file has the name *cont.xx* where *xx* is the contingency number.

If the multi-period option is chosen then  $N_c$  subdirectories are created (one for each contingency), and each subdirectory contains  $N_t$  output files, one for each time-period. The subdirectories have the naming convention *cont.xx* and the output file are named as *t.yy* where *yy* is the time-step number.

## 5.4 Usage

```
./scopflow -netfile <netfilename> -ctgcfile <ctgcfilename> \
<scopflowoptions> [-scopflow_enable_multiperiod 1]
```

## 5.5 Options

See table 5.1. In addition, all **OPFLOW** options in Table 3.4 and **TCOPFLOW** options in Table 4.1 can be used.

Table 5.1: SCOPFLOW options

Option	Meaning	Values (Default value)
-netfile	Network file name	string < 4096 characters ( <a href="#">case9mod_gen3_wind.m</a> )
-ctgcfile	Contingency file name	string < 4096 characters ( <a href="#">case9.cont</a> )
-save_output	Save output to directory	0 or 1 (0)
-scopflow_solver	Set solver for scopflow	IPOPT or EMPAR
-scopflow_Nc	Number of contingencies	int (0. Passing -1 results in all contingencies in the file used)
-scopflow_mode	Operation mode: Preventive or corrective	0 or 1 (0)
-scopflow_iscoupling	Coupling between first and second stage	0 or 1 (0)
-scopflow_enable_multiperiod	Multi-period SCOPFLOW	0 or 1 (0)
-scopflow_pload_profile	Real power load profile	string ( <a href="#">load.P.csv</a> )
-scopflow_qload_profile	Reactive power load profile	string ( <a href="#">load.Q.csv</a> )
-scopflow_windgenprofile	Wind generation profile	string ( <a href="#">case9/scenarios_9bus.csv</a> )
-scopflow_dT	Length of time-step (minutes)	double (5.0)
-scopflow_duration	Total duration (hours)	double (0.5)

Depending on the *mode*, SCOPFLOW can either be *preventive* (mode = 0) or *corrective* (mode = 1). In the preventive mode, the PV and PQ generator real power is fixed to its corresponding base-case values. The generators at the reference bus pick up any make-up power required for the contingency. The corrective mode allows deviation of the PV and PQ generator real power from the base-case dispatch constrained by its 30-min. ramp rate capability.

-scopflow\_enable\_multiperiod 1 must be used in order to enable any of the options listed in table 5.1 that are below -scopflow\_enable\_multiperiod.

## 5.6 Examples

Some **SCOPFLOW** example runs are provided with some sample output. Options are the default options given in table 3.4, 4.1 and 5.1 unless otherwise specified. Sample output is generated by running examples in the installation directory.

Example using the [Ipsolt \[7\]](#) solver:

```
$ ./bin/scopflow -scopflow_solver IPOPT -tcopflow_iscoupling 1 \
```



```

-scopflow_iscoupling 1 -print_output
[ExaGO INFO]: -- Checking ... -options_file not passed          exists: no
SCOPFLOW: Application created
SCOPFLOW running with 2 contingencies (base case + 1 contingencies)
Rank 0 has 2 contingencies, range [0 -- 2]
SCOPFLOW: Using IPOPT solver
SCOPFLOW: Setup completed

*****
This program contains Ipopt, a library for large-scale nonlinear
optimization. Ipopt is released as open source code under the Eclipse
Public License (EPL).
*****

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...:      231
Number of nonzeros in inequality constraint Jacobian.:      182
Number of nonzeros in Lagrangian Hessian.....:      249

Total number of variables.....:      55
    variables with only lower bounds:          0
    variables with lower and upper bounds:      39
    variables with only upper bounds:          0
Total number of equality constraints.....:      44
Total number of inequality constraints.....:      59
    inequality constraints with only lower bounds:      21
    inequality constraints with lower and upper bounds:   38
    inequality constraints with only upper bounds:       0

iter  objective  inf_pr  inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
0   7.4421250e+03  1.80e+00  1.69e+01  -1.0  0.00e+00 - 0.00e+00  0.00e+00  0
1   6.9108233e+03  1.65e+00  1.56e+01  -1.0  1.24e+00 - 4.46e-02  8.38e-02f  1
2   5.9991119e+03  1.30e+00  5.10e+01  -1.0  7.41e-01 - 7.07e-02  2.08e-01f  1
...
43  3.0556401e+03  1.07e-14  3.95e-10  -8.6  2.79e-09 - 1.00e+00  1.00e+00f  1

Number of Iterations.....: 43

                                (scaled)                                (unscaled)
Objective.....:      6.8512110967619464e+01      3.0556401491558281e+03
Dual infeasibility...:      3.9453703519053556e-10      1.7596351769497887e-08
Constraint violation:      1.0658141036401503e-14      1.0658141036401503e-14
Complementarity.....:      5.0027986112663857e-09      2.2312481806248081e-07
Overall NLP error....:      5.0027986112663857e-09      2.2312481806248081e-07

```

```

Number of objective function evaluations      = 59
Number of objective gradient evaluations     = 44
Number of equality constraint evaluations    = 59
Number of inequality constraint evaluations  = 59
Number of equality constraint Jacobian evaluations = 44
Number of inequality constraint Jacobian evaluations = 44
Number of Lagrangian Hessian evaluations    = 43
Total CPU secs in IPOPT (w/o function evaluations) = 0.019
Total CPU secs in NLP function evaluations    = 0.009

```

EXIT: Optimal Solution Found.

=====

Security-Constrained Optimal Power Flow

=====

```

OPFLOW Formulation      POWER_BALANCE_POLAR
Solver                  IPOPT
Initialization          MIDPOINT
Number of contingencies 1
Load loss allowed       NO
Power imbalance allowed  NO
Ignore line flow constraints NO

Number of variables      57
Number of equality constraints 42
Number of inequality constraints 58
Number of coupling constraints 3

Convergence status      CONVERGED
Objective value          3055.64

```

Bus	Pd	Qd	Vm	Va	mult_Pmis	mult_Qmis
1	0.00	0.00	1.040	0.000	2158.80	-0.00
2	0.00	0.00	1.025	4.572	2108.44	0.00
3	0.00	0.00	1.025	1.912	2118.81	0.00
4	0.00	0.00	1.038	-2.306	2159.07	-0.61
5	75.00	30.00	1.026	-3.550	2170.87	2.93
6	90.00	30.00	1.023	-4.551	2191.34	4.30
7	0.00	0.00	1.033	0.613	2109.20	4.12
8	100.00	35.00	1.022	-2.070	2133.92	7.92
9	0.00	0.00	1.036	-0.462	2119.23	2.84

From	To	Status	Sft	Stf	Slim	mult_Sf	mult_St
1	4	1	75.61	75.44	380.00	-0.00	-0.00

2	7	1	117.34	118.26	250.00	-0.00	-0.00
3	9	1	76.90	77.68	300.00	-0.00	-0.00
4	5	1	28.64	34.88	250.00	-0.00	-0.00
4	6	1	46.84	48.91	250.00	-0.00	-0.00
5	7	1	47.56	50.96	250.00	-0.00	-0.00
6	9	1	45.96	48.57	150.00	-0.00	-0.00
7	8	1	69.77	70.78	250.00	-0.00	-0.00
8	9	1	37.09	30.76	150.00	-0.00	-0.00

Gen	Status	Fuel	Pg	Qg	Pmin	Pmax	Qmin	Qmax
1	1	COAL	75.40	5.62	10.00	350.00	-300.00	300.00
2	1	COAL	116.97	-9.31	10.00	300.00	-300.00	300.00
3	1	WIND	75.00	-16.97	0.00	75.00	-300.00	300.00

[ExaGO INFO]: Finalizing scopflow application

Example using the IPOPT solver with multiperiod enabled:

```

$./bin/scopflow -scopflow_solver IPOPT -scopflow_enable_multiperiod 1 \
-tcopflow_iscoupling 1 -scopflow_iscoupling 1
[ExaGO INFO]: -- Checking ... -options_file not passed          exists: no
SCOPFLOW: Application created
SCOPFLOW running with 2 contingencies (base case + 1 contingencies)
Rank 0 has 2 contingencies, range [0 -- 2]
SCOPFLOW: Using IPOPT solver
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.166667 hours, timestep = 5.000000 minutes, \
          number of time-steps = 3
TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.166667 hours, timestep = 5.000000 minutes, \
          number of time-steps = 3
TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
SCOPFLOW: Setup completed

*****
This program contains Ipopt, a library for large-scale nonlinear
optimization. Ipopt is released as open source code under the
Eclipse Public License (EPL).
*****

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...:      640
Number of nonzeros in inequality constraint Jacobian..:      494

```

```

Number of nonzeros in Lagrangian Hessian.....:      540

Total number of variables.....:      138
      variables with only lower bounds:          0
      variables with lower and upper bounds:      90
      variables with only upper bounds:          0
Total number of equality constraints.....:      110
Total number of inequality constraints.....:      151
      inequality constraints with only lower bounds:      36
      inequality constraints with lower and upper bounds:  115
      inequality constraints with only upper bounds:      0

iter objective inf_pr  inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
0  4.4652750e+04 1.80e+00 5.01e+01 -1.0 0.00e+00 - 0.00e+00 0.00e+00 0
1  3.1127309e+04 1.41e+00 1.01e+02 -1.0 1.97e+00 - 1.87e-01 2.18e-01f 1
...
55 1.7423413e+04 9.91e-15 8.48e-10 -8.6 9.66e-09 - 1.00e+00 1.00e+00h 1

Number of Iterations.....: 55

                                (scaled)                                (unscaled)
Objective.....:      3.9065947675497836e+02      1.7423412663272036e+04
Dual infeasibility...:      8.4833681960093011e-10      3.7835822154201486e-08
Constraint violation:      9.9087404947795221e-15      9.9087404947795221e-15
Complementarity.....:      3.3875752035319637e-09      1.5108585407752560e-07
Overall NLP error....:      3.3875752035319637e-09      1.5108585407752560e-07

Number of objective function evaluations          = 91
Number of objective gradient evaluations          = 56
Number of equality constraint evaluations          = 91
Number of inequality constraint evaluations        = 91
Number of equality constraint Jacobian evaluations = 56
Number of inequality constraint Jacobian evaluations = 56
Number of Lagrangian Hessian evaluations          = 55
Total CPU secs in IPOPT (w/o function evaluations) =      0.045
Total CPU secs in NLP function evaluations        =      0.052

EXIT: Optimal Solution Found.
[ExaGO INFO]: Finalizing scopflow application.

```

Example using the *EMPAR* solver with multiperiod enabled:

```

$ ./bin/scopflow -scopflow_solver EMPAR -scopflow_enable_multiperiod 1 \
-tcopflow_iscoupling 1 -scopflow_iscoupling 1
[ExaGO INFO]: -- Checking ... -options_file not passed      exists: no
SCOPFLOW: Application created
SCOPFLOW running with 2 contingencies (base case + 1 contingencies)

```

```

Rank 0 has 2 contingencies, range [0 -- 2]
SCOPFLOW: Using EMPAR solver
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.166667 hours, timestep = 5.000000 minutes,
          number of time-steps = 3
TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.166667 hours, timestep = 5.000000 minutes,
          number of time-steps = 3
TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
SCOPFLOW: Setup completed
Setting: "0" is not a valid setting for Option: tol.
Check the option documentation.

### tol (Real Number) ###
Category: Convergence
Description: Desired convergence tolerance (relative).
0 < (1e-08) <= +inf

*****
This program contains Ipopt, a library for large-scale nonlinear
optimization. Ipopt is released as open source code under
the Eclipse Public License (EPL).
*****

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...:      330
Number of nonzeros in inequality constraint Jacobian.:      258
Number of nonzeros in Lagrangian Hessian.....:            270

Total number of variables.....:          69
      variables with only lower bounds:          0
      variables with lower and upper bounds:       45
      variables with only upper bounds:            0
Total number of equality constraints.....:          54
Total number of inequality constraints.....:          78
      inequality constraints with only lower bounds:  18
      inequality constraints with lower and upper bounds: 60
      inequality constraints with only upper bounds:   0

iter  objective  inf_pr  inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
0   2.2326375e+04  1.80e+00  5.02e+01  -1.0  0.00e+00 - 0.00e+00  0.00e+00  0
1   1.5533385e+04  1.40e+00  1.02e+02  -1.0  1.95e+00 - 1.88e-01  2.20e-01f  1
...

```

```

32  8.6735595e+03 7.99e-15 3.70e-09  -8.6 1.93e-08 - 1.00e+00 1.00e+00h 1

Number of Iterations.....: 32

                                (scaled)                                (unscaled)
Objective.....: 1.9447442817603635e+02  8.6735594966512217e+03
Dual infeasibility...: 3.6983296779767669e-09  1.6494550363776382e-07
Constraint violation: 7.9936057773011271e-15  7.9936057773011271e-15
Complementarity.....: 4.9913149587308981e-09  2.2261264715939807e-07
Overall NLP error....: 4.9913149587308981e-09  2.2261264715939807e-07

Number of objective function evaluations          = 40
Number of objective gradient evaluations          = 33
Number of equality constraint evaluations          = 40
Number of inequality constraint evaluations        = 40
Number of equality constraint Jacobian evaluations = 33
Number of inequality constraint Jacobian evaluations = 33
Number of Lagrangian Hessian evaluations          = 32
Total CPU secs in IPOPT (w/o function evaluations) =      0.019
Total CPU secs in NLP function evaluations        =      0.014

EXIT: Optimal Solution Found.
Setting: "0" is not a valid setting for Option: tol.
Check the option documentation.

### tol (Real Number) ###
Category: Convergence
Description: Desired convergence tolerance (relative).
0 < (1e-08) <= +inf
This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...: 306
Number of nonzeros in inequality constraint Jacobian.: 234
Number of nonzeros in Lagrangian Hessian.....: 270

Total number of variables.....: 69
      variables with only lower bounds: 0
      variables with lower and upper bounds: 45
      variables with only upper bounds: 0
Total number of equality constraints.....: 54
Total number of inequality constraints.....: 72
      inequality constraints with only lower bounds: 18
      inequality constraints with lower and upper bounds: 54
      inequality constraints with only upper bounds: 0

iter objective  inf_pr  inf_du lg(mu) ||d|| lg(rg) alpha_du alpha_pr  ls

```

```

0  2.2326375e+04 1.80e+00 4.89e+01 -1.0 0.00e+00 - 0.00e+00 0.00e+00 0
1  1.5535979e+04 1.41e+00 1.01e+02 -1.0 1.97e+00 - 1.87e-01 2.18e-01f 1
...
51 8.7491131e+03 8.88e-15 4.80e-09 -8.6 1.07e-08 - 1.00e+00 1.00e+00h 1

Number of Iterations.....: 51

                                (scaled)                                (unscaled)
Objective.....: 1.9616845456090007e+02 8.7491130734161434e+03
Dual infeasibility...: 4.8019002633480731e-09 2.1416475174532407e-07
Constraint violation: 8.8817841970012523e-15 8.8817841970012523e-15
Complementarity.....: 4.9761717933322852e-09 2.2193726198261992e-07
Overall NLP error...: 4.9761717933322852e-09 2.2193726198261992e-07

Number of objective function evaluations = 54
Number of objective gradient evaluations = 52
Number of equality constraint evaluations = 54
Number of inequality constraint evaluations = 54
Number of equality constraint Jacobian evaluations = 52
Number of inequality constraint Jacobian evaluations = 52
Number of Lagrangian Hessian evaluations = 51
Total CPU secs in IPOPT (w/o function evaluations) = 0.024
Total CPU secs in NLP function evaluations = 0.016

EXIT: Optimal Solution Found.
[ExaGO INFO]: Finalizing scopflow application.

```

## Chapter 6

# Stochastic optimal power flow (SOPFLOW)

SOPFLOW solves a stochastic security-constrained multi-period optimal power flow problem. The problem is set up as a two-stage optimization problem where the first-stage (base-case) represents the normal operation of the grid (or the most likely forecast) and the second-stage comprises  $N_s$  scenarios of forecast deviation. Each scenario can have multiple contingencies and each contingency can be multi-period. Thus, depending on the options selected, each stochastic scenario can be

- Single-period, no contingencies
- Single-period, with contingencies
- Multi-period, with contingencies

### 6.1 Formulation

An illustration of **SOPFLOW** is shown in Fig. 6.1 for a case with two scenarios  $s_0$  and  $s_1$ . Each scenario has two contingencies  $c_0, c_1$ , and each contingency has four time-periods.

The formulation for the stochastic security-constrained multi-period optimal power flow is given in (6.1) – (6.7). In this formulation, the objective is to reduce the expected cost, where  $f(x_{s,c,t})$  is the cost for scenario  $s$  with contingency  $c$  at time  $t$ .  $\pi_s$  is the probability of scenario  $s$ .

$$\min \sum_{s=0}^{N_s-1} \pi_s \sum_{c=0}^{N_c-1} \sum_{t=0}^{N_t-1} f(x_{s,c,t}) \quad (6.1)$$

s.t.

$$g(x_{s,c,t}) = 0, \quad s \in [1, N_s - 1], c \in [0, N_c - 1], t \in [0, N_t - 1] \quad (6.2)$$

$$h(x_{s,c,t}) \leq 0, \quad s \in [1, N_s - 1], c \in [0, N_c - 1], t \in [0, N_t - 1] \quad (6.3)$$

$$x^- \leq x_{s,c,t} \leq x^+, \quad s \in [1, N_s - 1], c \in [0, N_c - 1], t \in [0, N_t - 1] \quad (6.4)$$

$$-\delta_t x \leq x_{s,c,t} - x_{s,c,t-\Delta t} \leq \delta_t x, \quad s \in [1, N_s - 1], c \in [0, N_c - 1], t \in [1, N_t - 1] \quad (6.5)$$

$$-\delta_c x \leq x_{s,c,0} - x_{s,0,0} \leq \delta_c x, \quad s \in [1, N_s - 1], c \in [1, N_c - 1] \quad (6.6)$$

$$-\delta_s x \leq x_{s,0,0} - x_{0,0,0} \leq \delta_s x, \quad s \in [1, N_s - 1] \quad (6.7)$$



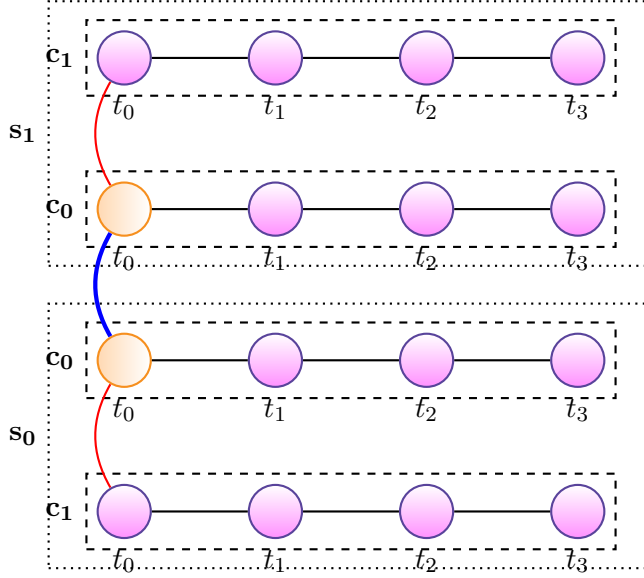


Figure 6.1: Stochastic multi-period contingency constrained example with two scenarios  $s_0$  and  $s_1$ . Each scenario has two contingencies  $c_0$  and  $c_1$  and each contingency consists of four time-periods  $t_0, t_1, t_2, t_3$ . State  $s_0, c_0, t_0$  represents the base case (no contingency) case for the two scenarios. We assume that any contingency is incident at the first time-step, i.e., at  $t_0$ . Thus, the contingency states  $c_1, t_0$  is coupled with the no-contingency state  $c_0, t_0$  at time  $t_0$  for both the scenarios. The red line denotes the coupling between the contingency and the no-contingency states. The blue line denotes the coupling between the scenarios

The modeling details used for an optimal power flow problem are also used for a **SOPFLOW** problem, i.e., each of the circles shown in Fig. 6.1 has the modeling details of an optimal power flow problem (**OPFLOW**). Incorporating the probabilities  $\pi_s$  for each scenario is not implemented yet which leads to each scenario having an equal probability.

Currently, **SOPFLOW** uses wind power generation as the stochastic variables and each scenario is a realization of the power output from wind generators. A zero fuel cost is used for wind power generation to ensure wind generation would be the dispatched to the given target level (upper limit).

For contingencies, **SOPFLOW** supports generation and/or transmission outages. A contingency can have multiple outages, but, it should not cause any islanding. The coupling between the no-contingency and the contingency case for each scenario is also the difference in real power output ( $p_{jsct}^g - p_{js0t}^g, j \in J^{\text{gen}}$ ) that must be within the 30 minute generator ramp rate.

For multi time-period, we use ramping constraints on the generator real power output between successive time steps.

**SOPFLOW** can be run in two modes: preventive and corrective. In the preventive mode, generator real power output is fixed to the base-case values for generators at PV bus(es). In this mode, the generators at the reference bus provide/absorb any deficit/surplus power. The corrective mode allows deviation of the PV and PQ generator real power from the base-case dispatch constrained by its 30-min. ramp rate capability. Note that the preventive/corrective mode is only applied at the first step  $t_0$ . In the successive time-steps, the generator dispatch is dictated by the previous step dispatch and the ramp limits.

## 6.2 Solvers

**SOPFLOW** can be solved with **Ipopt** [7]. If one wants to solve each scenario independently, i.e., without any coupling constraints then use the **EMPAR** solver. **EMPAR** distributes the contingencies to different processes when executed in parallel.

## 6.3 Input and Output

The following files are needed for executing SOPFLOW.

- **Network file:** The network file describing the network details. Only **MATPOWER** format files are currently supported.
- **Scenario file:** **SOPFLOW** only supports reading wind generation scenarios in a CSV format. An example of this format for the 9-bus case is [here](#).
- **Contingency file:** Contingencies can be specified via PTI format file as described in chapter 5. The option `-sopflow_enable_multicontingency` should be set for multi-contingency problems.
- **Load data:** One file for load real power and one for reactive power. The files need to be in CSV format. An example of the format for the 9-bus case is [here](#).

The **SOPFLOW** output is saved to a directory named *sopflowout*. This directory contains  $N_s$  subdirectories to save the solution for each scenario. Each of these subdirectories contain  $N_c$  subdirectories, one for each contingency. Each contingency subdirectory has  $N_t$  MATPOWER format files to store the output for each time-period for the given contingency and scenario. The subdirectories have the directory name format *scen\_x* where x is the scenario number, *cont\_y* where y is the contingency number, and the output files have the file name format *t.z* where z is the time-step number.

## 6.4 Usage

```
./sopflow -netfile <netfilename> -scenfile <scenfilename> \  
[-sopflow_enable_multicontingency 1] <sopflowoptions>
```

## 6.5 Options

See table 6.1. With multi-contingency SOPFLOW, all **SCOPFLOW** options given in Table 5.1 can be used to tune the contingencies. All **OPFLOW** options in Table 3.4, along with **TCOPFLOW** options in Table 4.1 can also be used. Multi-contingency SOPFLOW also allows the options listed after `-sopflow_enable_multicontingency` in Table 6.1 to be used.

Depending on the *mode*, SOPFLOW can either be *preventive* (mode = 0) or *corrective* (mode = 1). In the preventive mode, the PV and PQ generator real power is fixed to its corresponding base-case values. The generators at the reference bus pick up any make-up power required for the contingency. The corrective mode allows deviation of the PV and PQ generator real power from the base-case dispatch constrained by its 30-min. ramp rate capability.

Table 6.1: SOPFLOW options

Option	Meaning	Values (Default value)
-netfile	Network file name	string < 4096 characters ( <a href="#">case9mod_gen3_wind.m</a> )
-scenfile	Scenario file name	string < 4096 characters ( <a href="#">case9/scenarios_9bus.csv</a> )
-sopflow_mode	Operation mode: Preventive or corrective	0 or 1 (0)
-sopflow_solver	Set solver for sopflow	IPOPT or EMPAR
-sopflow_enable_multicontingency	Multi-contingency SOPFLOW	0 or 1 (0)
-ctgcfle	Contingency file name	string ( <a href="#">case9.cont</a> )
-sopflow_Ns	Number of scenarios	int (Default 0. Passing -1 results in all scenarios in the file being used)

## 6.6 Examples

Some **SOPFLOW** example runs are provided with some sample output. Options are the default options given in Tables 3.4, 4.1, 5.1 and 6.1 unless otherwise specified. Sample output is generated by running examples in the installation directory.

Example using the [Ipopt](#) [7] solver:

```
$ ./bin/sopflow -print_output -sopflow_solver IPOPT
[ExaGO INFO]: -- Checking ... -options_file not passed      exists: no
SOPFLOW: Application created
Rank[0]: color = 0, ns = 2, sstart= 0, send=2
SOPFLOW running with 2 scenarios (base case + 1 scenarios)
Rank 0 scenario range [0 -- 2]
SOPFLOW: Using IPOPT solver
SOPFLOW: Setup completed

*****
This program contains Ipopt, a library for large-scale nonlinear
optimization. Ipopt is released as open source code under the
Eclipse Public License (EPL).
*****

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...:      222
Number of nonzeros in inequality constraint Jacobian.:      168
Number of nonzeros in Lagrangian Hessian.....:      180

Total number of variables.....:      46
    variables with only lower bounds:              0
    variables with lower and upper bounds:          30
    variables with only upper bounds:               0
Total number of equality constraints.....:      37
```

```

Total number of inequality constraints.....:      50
      inequality constraints with only lower bounds:      12
      inequality constraints with lower and upper bounds:    38
      inequality constraints with only upper bounds:        0

iter  objective  inf_pr  inf_du lg(mu)  ||d||  lg(rg)  alpha_du  alpha_pr  ls
0   1.4884250e+04  1.80e+00  5.02e+01  -1.0  0.00e+00 - 0.00e+00  0.00e+00  0
1   1.0889088e+04  1.45e+00  7.87e+01  -1.0  1.92e+00 - 1.69e-01  1.93e-01f  1
2   1.0548318e+04  1.33e+00  7.28e+01  -1.0  6.01e-01 - 2.76e-02  8.30e-02f  1
...
29   5.9075224e+03  1.24e-14  2.96e-12  -7.0  4.91e-10 - 1.00e+00  1.00e+00h  1

Number of Iterations.....: 29

                                (scaled)                                (unscaled)
Objective.....:      1.3245566021454471e+02      5.9075224455686939e+03
Dual infeasibility...:      2.9592247352450450e-12      1.3198142319192901e-10
Constraint violation:      1.2434497875801753e-14      1.2434497875801753e-14
Complementarity.....:      9.0910764708133484e-08      4.0546201059827535e-06
Overall NLP error....:      9.0910764708133484e-08      4.0546201059827535e-06

Number of objective function evaluations      = 33
Number of objective gradient evaluations      = 30
Number of equality constraint evaluations      = 33
Number of inequality constraint evaluations    = 33
Number of equality constraint Jacobian evaluations = 30
Number of inequality constraint Jacobian evaluations = 30
Number of Lagrangian Hessian evaluations      = 29
Total CPU secs in IPOPT (w/o function evaluations) =      0.006
Total CPU secs in NLP function evaluations      =      0.003

EXIT: Optimal Solution Found.
=====
      Stochastic Optimal Power Flow
=====
OPFLOW Formulation      POWER_BALANCE_POLAR
Solver      IPOPT
Initialization      MIDPOINT
Number of scenarios      1
Load loss allowed      NO
Power imbalance allowed      NO
Ignore line flow constraints      NO

Number of variables      48
Number of equality constraints      0
Number of inequality constraints      0

```

Number of coupling constraints            0

Convergence status                        CONVERGED

Objective value                            5907.52

Bus	Pd	Qd	Vm	Va	mult_Pmis	mult_Qmis
1	0.00	0.00	1.040	0.000	2218.76	-0.00
2	0.00	0.00	1.025	4.156	2170.20	0.00
3	0.00	0.00	1.025	1.685	2180.00	0.00
4	0.00	0.00	1.038	-2.389	2219.06	-0.56
5	75.00	30.00	1.026	-3.714	2231.93	2.96
6	90.00	30.00	1.023	-4.683	2252.92	4.40
7	0.00	0.00	1.033	0.291	2170.95	4.07
8	100.00	35.00	1.022	-2.352	2196.02	8.01
9	0.00	0.00	1.036	-0.689	2180.43	2.83

From	To	Status	Sft	Stf	Slim	mult_Sf	mult_St
1	4	1	78.31	78.15	380.00	-0.00	-0.00
2	7	1	114.58	115.48	250.00	-0.00	-0.00
3	9	1	76.90	77.69	300.00	-0.00	-0.00
4	5	1	30.36	36.13	250.00	-0.00	-0.00
4	6	1	47.82	49.77	250.00	-0.00	-0.00
5	7	1	45.94	49.28	250.00	-0.00	-0.00
6	9	1	45.11	47.63	150.00	-0.00	-0.00
7	8	1	68.77	69.83	250.00	-0.00	-0.00
8	9	1	37.83	31.76	150.00	-0.00	-0.00

Gen	Status	Fuel	Pg	Qg	Pmin	Pmax	Qmin	Qmax
1	1	COAL	78.13	5.42	10.00	350.00	-300.00	300.00
2	1	COAL	114.18	-9.55	10.00	300.00	-300.00	300.00
3	1	WIND	75.00	-17.00	0.00	75.00	-300.00	300.00

[ExaGO INFO]: Finalizing sopflow application.

Example using the *EMPAR* solver with multicontingency enabled:

```
$ ./bin/sopflow -sopflow_solver EMPAR -sopflow_enable_multicontingency 1
[ExaGO INFO]: -- Checking ... -options_file not passed          exists: no
SOPFLOW: Application created
Rank[0]: color = 0, ns = 2, sstart= 0, send=2
SOPFLOW running with 2 scenarios (base case + 1 scenarios)
Rank 0 scenario range [0 -- 2]
SOPFLOW: Using EMPAR solver
```

```

SCOPFLOW: Application created
SCOPFLOW running with 2 contingencies (base case + 1 contingencies)
Rank 0 has 2 contingencies, range [0 -- 2]
SCOPFLOW: Using IPOPT solver
SCOPFLOW: Setup completed
SCOPFLOW: Application created
SCOPFLOW running with 2 contingencies (base case + 1 contingencies)
Rank 0 has 2 contingencies, range [0 -- 2]
SCOPFLOW: Using IPOPT solver
SCOPFLOW: Setup completed
SOPFLOW: Setup completed

*****
This program contains Ipopt, a library for large-scale nonlinear
optimization. Ipopt is released as open source code under the
Eclipse Public License (EPL).
*****

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...:      226
Number of nonzeros in inequality constraint Jacobian.:      168
Number of nonzeros in Lagrangian Hessian.....:      215

Total number of variables.....:      51
      variables with only lower bounds:      0
      variables with lower and upper bounds:      35
      variables with only upper bounds:      0
Total number of equality constraints.....:      42
Total number of inequality constraints.....:      58
      inequality constraints with only lower bounds:      21
      inequality constraints with lower and upper bounds:      37
      inequality constraints with only upper bounds:      0

iter  objective  inf_pr  inf_du lg(mu)  ||d||  lg(rg)  alpha_du  alpha_pr  ls
0   7.4421250e+03  1.80e+00  1.04e+01  -1.0  0.00e+00 - 0.00e+00  0.00e+00  0.00e+00  0
1   6.5388630e+03  1.51e+00  2.24e+01  -1.0  1.07e+00 - 5.38e-01  1.58e-01f  1
2   5.9394843e+03  1.28e+00  2.56e+02  -1.0  7.32e-01 - 3.31e-02  1.56e-01f  1
...
29   3.0556401e+03  1.07e-14  5.62e-10  -8.6  4.33e-09 - 1.00e+00  1.00e+00f  1

Number of Iterations.....: 29

                                (scaled)                                (unscaled)
Objective.....:      6.8512110964678271e+01      3.0556401490246512e+03
Dual infeasibility..:      5.6231688979129259e-10      2.5079333284691651e-08
Constraint violation:      1.0658141036401503e-14      1.0658141036401503e-14

```

Complementarity.....:	2.7880113972390153e-09	1.2434530831686009e-07
Overall NLP error....:	2.7880113972390153e-09	1.2434530831686009e-07

Number of objective function evaluations	=	48
Number of objective gradient evaluations	=	30
Number of equality constraint evaluations	=	48
Number of inequality constraint evaluations	=	48
Number of equality constraint Jacobian evaluations	=	30
Number of inequality constraint Jacobian evaluations	=	30
Number of Lagrangian Hessian evaluations	=	29
Total CPU secs in IPOPT (w/o function evaluations)	=	0.010
Total CPU secs in NLP function evaluations	=	0.006

EXIT: Optimal Solution Found.

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian....:	226
Number of nonzeros in inequality constraint Jacobian..:	168
Number of nonzeros in Lagrangian Hessian.....:	215
Total number of variables.....:	51
variables with only lower bounds:	0
variables with lower and upper bounds:	35
variables with only upper bounds:	0
Total number of equality constraints.....:	42
Total number of inequality constraints.....:	58
inequality constraints with only lower bounds:	21
inequality constraints with lower and upper bounds:	37
inequality constraints with only upper bounds:	0

iter	objective	inf_pr	inf_du	lg(mu)	d	lg(rg)	alpha_du	alpha_pr	ls
0	7.4421250e+03	1.80e+00	1.04e+01	-1.0	0.00e+00	-	0.00e+00	0.00e+00	0
1	6.2852600e+03	1.53e+00	2.73e+01	-1.0	1.34e+00	-	3.21e-01	1.50e-01f	1
...									
28	2.8488309e+03	1.07e-14	3.60e-09	-8.6	1.94e-08	-	1.00e+00	1.00e+00h	1

Number of Iterations.....: 28

	(scaled)	(unscaled)
Objective.....:	6.3875131478884526e+01	2.8488308639582501e+03
Dual infeasibility...:	3.5985088591418374e-09	1.6049349511772596e-07
Constraint violation:	1.0658141036401503e-14	1.0658141036401503e-14
Complementarity.....:	4.7446211848960068e-09	2.1161010484636192e-07
Overall NLP error....:	4.7446211848960068e-09	2.1161010484636192e-07

Number of objective function evaluations	=	43
--	---	----

Number of objective gradient evaluations	=	29
Number of equality constraint evaluations	=	43
Number of inequality constraint evaluations	=	43
Number of equality constraint Jacobian evaluations	=	29
Number of inequality constraint Jacobian evaluations	=	29
Number of Lagrangian Hessian evaluations	=	28
Total CPU secs in IPOPT (w/o function evaluations)	=	0.016
Total CPU secs in NLP function evaluations	=	0.009

EXIT: Optimal Solution Found.

Example using the **Ipopt** [7] solver with multicontingency and multiperiod enabled:

```
./bin/sopflow -sopflow_solver IPOPT -sopflow_enable_multicontingency 1\
-scopflow_enable_multiperiod 1 -sopflow_Ns -1 -scopflow_Nc -1
[ExaGO INFO]: -- Checking ... -options_file not passed          exists: no
SOPFLOW: Application created
Rank[0]: color = 0, ns = 4, sstart= 0, send=4
SOPFLOW running with 4 scenarios (base case + 3 scenarios)
Rank 0 scenario range [0 -- 4]
SOPFLOW: Using IPOPT solver
SCOPFLOW: Application created
SCOPFLOW running with 10 contingencies (base case + 9 contingencies)
Rank 0 has 10 contingencies, range [0 -- 10]
SCOPFLOW: Using IPOPT solver
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.166667 hours, timestep = 5.000000 minutes,
            number of time-steps = 3
TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
TCOPFLOW: Application created
TCOPFLOW: Duration = 0.166667 hours, timestep = 5.000000 minutes,
            number of time-steps = 3
TCOPFLOW: Using IPOPT solver
TCOPFLOW: Setup completed
...
SCOPFLOW running with 10 contingencies (base case + 9 contingencies)
Rank 0 has 10 contingencies, range [0 -- 10]
SCOPFLOW: Using IPOPT solver
...
TCOPFLOW: Setup completed
SCOPFLOW: Setup completed
SOPFLOW: Setup completed

*****
This program contains Ipopt, a library for large-scale nonlinear
optimization. Ipopt is released as open source code under the
Eclipse Public License (EPL).
```



\*\*\*\*\*

This is Ipopt version 3.12.10, running with linear solver ma27.

Number of nonzeros in equality constraint Jacobian...: 12678  
 Number of nonzeros in inequality constraint Jacobian.: 9636  
 Number of nonzeros in Lagrangian Hessian.....: 10404

Total number of variables.....: 2688  
     variables with only lower bounds: 0  
     variables with lower and upper bounds: 1728  
     variables with only upper bounds: 0  
 Total number of equality constraints.....: 2223  
 Total number of inequality constraints.....: 2922  
     inequality constraints with only lower bounds: 648  
     inequality constraints with lower and upper bounds: 2274  
     inequality constraints with only upper bounds: 0

iter	objective	inf_pr	inf_du	lg(mu)	d	lg(rg)	alpha_du	alpha_pr	ls
0	8.0374950e+05	2.59e+00	6.64e+01	-1.0	0.00e+00	-	0.00e+00	0.00e+00	0
1	7.8996010e+05	2.48e+00	6.98e+01	-1.0	1.43e+00	2.0	2.04e-02	3.97e-02f	1
2	7.7076082e+05	2.31e+00	9.50e+01	-1.0	1.16e+00	2.4	2.69e-02	6.75e-02f	1
...									
197	4.2506331e+05	1.42e-14	3.34e-10	-7.0	2.10e-09	-	1.00e+00	1.00e+00h	1

Number of Iterations.....: 197

	(scaled)	(unscaled)
Objective.....:	9.5305673828307717e+03	4.2506330527425243e+05
Dual infeasibility...:	3.3401254461705077e-10	1.4896959489920465e-08
Constraint violation:	1.4210854715202004e-14	1.4210854715202004e-14
Complementarity.....:	9.1353878464689626e-08	4.0743829795251576e-06
Overall NLP error....:	9.1353878464689626e-08	4.0743829795251576e-06

Number of objective function evaluations	=	283
Number of objective gradient evaluations	=	198
Number of equality constraint evaluations	=	283
Number of inequality constraint evaluations	=	283
Number of equality constraint Jacobian evaluations	=	198
Number of inequality constraint Jacobian evaluations	=	198
Number of Lagrangian Hessian evaluations	=	197
Total CPU secs in IPOPT (w/o function evaluations)	=	2.136
Total CPU secs in NLP function evaluations	=	4.421

EXIT: Optimal Solution Found.

[ExaGO INFO]: Finalizing sopflow application.

# Appendices

# Appendix A

## Symbol reference

Units of measurement are given in Table (A.1), indices and index sets in Table (A.2), subsets in Table (A.3), special set elements in Table (A.4), and real-valued parameters in Table (A.5).

Table A.1: Units of measurement

Symbol	Description
1	dimensionless. Dimensionless real number quantities are indicated by a unit of 1.
USD	US dollar. Cost, penalty, and objective values are expressed in USD.
h	hour. Time is expressed in h.
pu	per unit. Voltage magnitude is expressed in a per unit system under given base values, and the unit is denoted by pu
rad	radian. Voltage angles are expressed in rad.
MW	megawatt. Real power is expressed in MW.
MVar	megavolt-ampere-reactive. Reactive power is expressed in MVar.
MVA	megavolt-ampere. Apparent power is expressed in MVA.
MW at 1 pu	megawatt at unit voltage. Conductance is expressed in MW at 1 pu, meaning the conductance is such as to yield a real power flow equal to the indicated amount when the voltage is equal to 1 pu
MVar at 1 pu	megavolt-ampere-reactive at unit voltage. Susceptance is expressed in MVar at 1 pu, meaning the susceptance is such as to yield a reactive power flow equal to the indicated amount when the voltage is equal to 1 pu

Table A.2: Index sets

Symbol	Description
$a \in A$	areas
$i \in I$	buses

Table A.2: Continued

Symbol	Description
$j \in J$	bus-connected grid components, i.e. loads, shunts, generators, stochastic resources, branches
$k \in K$	security contingencies, i.e. NERC $(n - 1)$ - or $(n - k)$ -style contingencies, different from the severe event we are modeling
$s \in S$	stochastic scenarios
$t \in T$	time periods

Table A.3: Subsets

Symbol	Description
$J^{\text{gen}} \subset J$	generators
$J^{\text{ld}} \subset J$	loads
$J^{\text{br}} \subset J$	branches, i.e. lines, transformers
$J^{\text{sh}} \subset J$	shunts
$J_i^{\text{o}} \subset J$	branches with origin bus at bus $i$
$J_i^{\text{d}} \subset J$	branches with destination bus at bus $i$

Table A.4: Special set elements

Symbol	Description
$a_i \in A$	area of bus $i$
$i_j^{\text{d}} \in I$	destination bus of branch $j \in J$
$i_j^{\text{o}} \in I$	origin bus of branch $j \in J^{\text{br}}$

Table A.5: Real-valued parameters

Symbol	Description
$b_j^{\text{max}}$	maximum susceptance for shunt $j \in J^{\text{sh}}$ (MVar at 1 pu)

Table A.5: Continued

Symbol	Description
$b_j^{\min}$	minimum susceptance for shunt $j \in J^{\text{sh}}$ (MVar at 1 pu)
$b_j^{\text{ch}}$	charging susceptance for branch $j \in J^{\text{br}}$ (MVar at 1 pu)
$b_j^{\text{s}}$	series susceptance for branch $j \in J^{\text{br}}$ (MVar at 1 pu)
$p_j^{\text{gset}}$	real power set point of generator $j \in J^{\text{gen}}$ (MW)
$p_j^{\text{gmax}}$	maximum real power output for generator $j \in J^{\text{gen}}$ (MW)
$p_j^{\text{gmin}}$	minimum real power output for generator $j \in J^{\text{gen}}$ (MW)
$p_j^{\text{r}}$	maximum ramp rate for generator $j \in J^{\text{gen}}$ (MW/h)
$q_j^{\text{gmax}}$	maximum reactive power output for generator $j \in J^{\text{gen}}$ (MVar)
$q_j^{\text{gmin}}$	minimum reactive power output for generator $j \in J^{\text{gen}}$ (MVar)
$v_i^{\text{max}}$	maximum voltage magnitude for bus $i \in I$ (pu)
$v_i^{\text{min}}$	minimum voltage magnitude for bus $i \in I$ (pu)
$\pi_s$	probability of scenario $s$ (1)

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