Study of Co-optimization Stochastic SuperOPF Application in the CAISO System

(Theme: Co-optimization Stochastic SuperOPF-renewables)

Technical Report

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Prof. Hsiao-Dong Chiang

School of Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853

Dr. Bin Wang
Mr. Patrick Causgrove

Bigwood Systems, Inc.
35 Thornwood Drive Suite #400
Cornell Business and Technology Park
Ithaca, NY 14850, U.S.A.

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1. BSI SuperOPF for Multi-Scenario Co-Optimization

Existing solvers and programs for optimal power flow (OPF) computation are mostly focused on achieving an optimal solution to the study objective for a single scenario, namely, the base case system, without considering any uncertainties that might arise during the planning horizon. In fact, with increasing penetration of renewable energy, where the output is stochastic in nature, in power networks and requests for regulatory compliance (such as compliance with FERC regulations), these uncertainties can be neglected no longer. It is crucial for the OPF solutions to be economic for the base-case system and also maintain economic and secure operation for the whole planning horizon even if one or more uncertain scenarios occur. This motivates the development of the multi-scenario SuperOPF (SuperOPF-MS) solver and program, to address the need of computing OPF solutions involving uncertain scenarios for power networks in today's more and more dynamic environment.

An overall structure of the SuperOPF solution framework is presented in Figure A-1. The solver takes several types of input data, the base case power flow data, the contingency list, and the renewable energy forecasts. Based on the input data, internal scenarios will be formatted in a tree-like structure. For each of these internal scenarios, an internal nonlinear optimization (NLP) model is constructed, along with the master optimization model associated with the co-optimization problem spanning the whole set of scenarios. All these internal optimization models are then fed to the SuperOPF-MS co-optimization solver for computing the optimal power flow solution that achieves the best expected objective value.

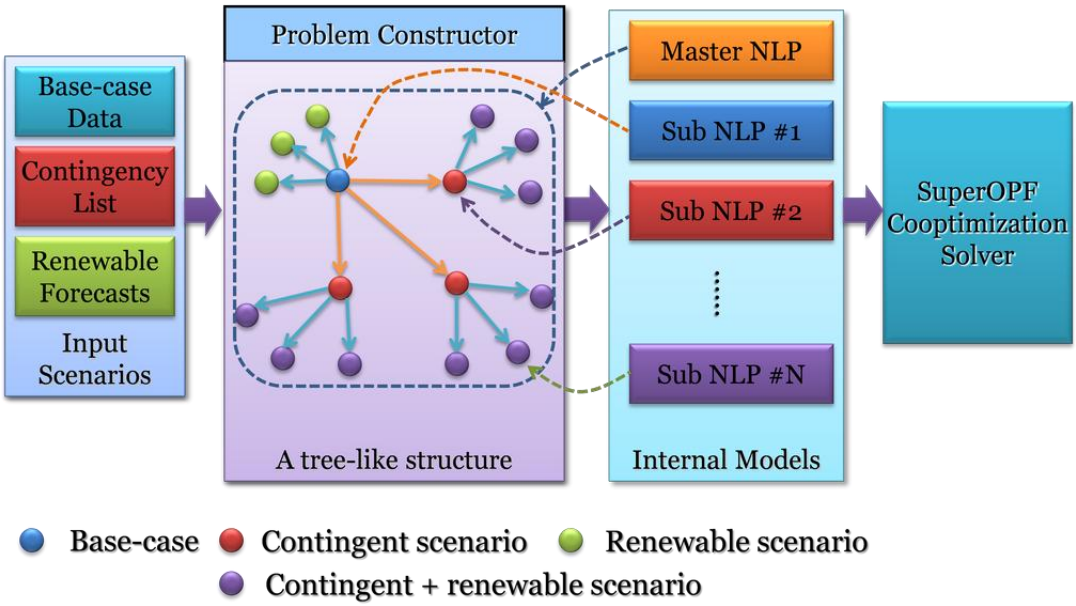

Figure 1. Illustration of the SuperOPF-MS procedure

The central task for the multi-scenario SuperOPF (SuperOPF-MS) solver is to solve the OPF problem which will result the best expected objective (such as the minimum system total power losses or generation costs) spanning the planning horizon. Therefore, the co-optimization that needs to be solved in order to get the desired OPF solution can be modeled as the optimization problem (1).

$$
\begin{array}{ll}
min & F(x) \\
s.t. & P_i(V_0,\theta_0,t_0,s_0,b_0) + P_D^i - P_G^i = 0 \\
 & Q_i(V_0,\theta_0,t_0,s_0,b_0) + Q_D^i - Q_{G0}^i = 0 \\
 & \underline{S_{ij}} \le S_{ij}(V_0,\theta_0,t_0,s_0,b_0) \le \overline{S_{ij}} \\
 & \left(\underline{V},\underline{\theta},\underline{t},\underline{s},\underline{b},\underline{Q_G}\right) \le (V_0,\theta_0,t_0,s_0,b_0,Q_{G0}) \le \left(\overline{V},\overline{\theta},\overline{t},\overline{s},\overline{b},\overline{Q_G}\right) \\
 & \cdots\cdots\cdots \\
 & P_i(V_k,\theta_k,t_k,s_k,b_k) + P_D^i - P_G^i = 0 \\
 & Q_i(V_k,\theta_k,t_k,s_k,b_k) + Q_D^i - Q_{Gk}^i = 0 \\
 & \underline{S_{ij}} \le S_{ij}(V_k,\theta_k,t_k,s_k,b_k) \le \overline{S_{ij}} \\
 & \left(\underline{V},\underline{\theta},\underline{t},\underline{s},\underline{b},\underline{Q_G}\right) \le (V_k,\theta_k,t_k,s_k,b_k,Q_{Gk}) \le \left(\overline{V},\overline{\theta},\overline{t},\overline{s},\overline{b},\overline{Q_G}\right) \\
 & \underline{P_G} \le P_G \le \overline{P_G}
\end{array}
\tag{1}
$$

where

- F(x): the objective function;
- $x = (P_G, V_0, \theta_0, t_0, s_0, b_0, Q_{G0}, \cdots, V_k, \theta_k, t_k, s_k, b_k, Q_{Gk})$: the vector of optimization variables;
- V, θ: bus voltage magnitudes and phase angles;
- t, s: transformers tap ratios, phase shifting angles, respectively;
- b: switchable shunt devices;
- P_G: real power generations (same for all scenarios);
- Q_G: reactive power generations;
- $(V_0, \theta_0, t_0, s_0, b_0, Q_{G0})$: base-case variables (excluding P_G);
- $(V_k, \theta_k, t_k, s_k, b_k, Q_{Gk})$: k-th scenario variables (excluding P_G);
- S_{ij}: line flow for the branch connecting i-th and j-th buses;
- $\underline{a}$ and $\overline{a}$: the lower and upper bounds for the variable a.

It can be seen from the problem model (1) that the optimization problem that needs to be solved is a very complicated nonlinear optimization problem. The problem size (the number of optimization variables and the number of equality and inequality constraints) will increase linearly as the number of contingent scenarios increases.

It is possible that a solution to the co-optimized OPF problem (1) is not achievable, especially for scenarios with:

- Severe contingencies, each of which considers dropping of a single or multiple important devices (transmission lines, generators, etc.) of the power network
- Large variations of renewable energy production
- The power network is undergoing a heavy loading condition
- Combinations of the above conditions

To accommodate these situations, extra corrective/preventive controls which are prepared for the post-contingency system are required and need to be involved in the problem formulation. One type of such corrective/preventive controls is the up-spinning reserve provided by generators. When these operational generation reserves are considered, the OPF problem to be solved can be updated to the corresponding reserve-constrained format (2).

$$
\begin{array}{ll}
min & F(x) + \sum r_i(R_{Gk}^i) \\
s.t. & P_i(V_0, \theta_0, t_0, s_0, b_0) + P_D^i - P_G^i = 0 \\
& Q_i(V_0, \theta_0, t_0, s_0, b_0) + Q_D^i - Q_{G0}^i = 0 \\
& \underline{S_{ij}} \le S_{ij}(V_0, \theta_0, t_0, s_0, b_0) \le \overline{S_{ij}} \\
& \left(\underline{V}, \underline{\theta}, \underline{t}, \underline{s}, \underline{b}, \underline{Q_G}\right) \le (V_0, \theta_0, t_0, s_0, b_0, Q_{G0}) \le \left(\overline{V}, \overline{\theta}, \overline{t}, \overline{s}, \overline{b}, \overline{Q_G}\right) \\
& \dots \dots \dots \\
& P_i(V_k, \theta_k, t_k, s_k, b_k) + P_D^i - P_G^i - a_{ik} R_{Gk}^i = 0 \\
& Q_i(V_k, \theta_k, t_k, s_k, b_k) + Q_D^i - Q_{Gk}^i = 0 \\
& \underline{S_{ij}} \le S_{ij}(V_k, \theta_k, t_k, s_k, b_k) \le \overline{S_{ij}} \\
& \left(\underline{V}, \underline{\theta}, \underline{t}, \underline{s}, \underline{b}, \underline{Q_G}\right) \le (V_k, \theta_k, t_k, s_k, b_k, Q_{Gk}) \le \left(\overline{V}, \overline{\theta}, \overline{t}, \overline{s}, \overline{b}, \overline{Q_G}\right) \\
& \underline{P_G} \le P_G \le \overline{P_G} \\
& P_G + a_k R_{Gk} \le \overline{P_G} \\
& 0 \le R_{Gk} \le \overline{R_{Gk}}
\end{array}
\tag{2}
$$

where, compared to the formulation (1), the newly introduced variables are

- a_{ik}: the status (0 or 1 binary constant value) for the availability of reserve of i-th generator for k-th contingency;
- R_{Gk}^i: the up-spinning reserve provided by i-th generator;
- $r_i(R_{Gk}^i)$: the auxiliary term in the objective function for the reserve offered by i-th generator.

2. Simulation Environment and Settings

2.1. Simulation Targets

The simulation in this report is targeted for the following tasks:

- SuperOPF version which can co-optimize the objective function and the updated worst scenario for voltage stability (requested by CAISO)
- Demonstrate Deliverable 1 on CAISO system data
- SuperOPF version which can co-optimize the objective function, operational reserve and the renewable energies. In addition, the ramp rate of renewable energy is included
- Demonstrate Deliverable 3 on CAISO system data

The test system is a CAISO 6534-bus EMS state estimation case, of the following dimensions:

- Number of buses: 6534
- Number of loads: 2901
- Number of generators: 1903
- Number of branches: 8295
- Number of transformers: 294
- Number of switched shunts: 520
- System load: 96907.09MW + j 10126.65MVar

The objective function of the simulation is to minimize the base case system real power losses. Two types of scenarios are considered in the simulation, including

- Worst N-1 transmission line contingencies, and
- Wind power generation forecast scenarios.

In this simulation, for co-optimization with reserves, the generator(s) at the slack bus(es) is treated as the reserve source. In other words, the remained generation capability of the slack generator(s) will be considered as available up-spinning reserve for contingency and renewable energy forecast scenarios.

2.2. Hardware and Software

All the simulations in this report have been carried out on a personal computer of the following configurations:

- CPU: Intel Core i7-3820QM Quad 2.70GHz (Turbo Boost up to 3.7 GHz) with 8MB shared L3 cache
- Memory: 16GB 1600MHz DDR3L SDRAM
- Storage: 512GB Flash Storage Drive
- OS: Ubuntu Linux 14.10 AMD64, Linux Kernel 3.16.0, GCC4.9.1
- Software: BSI SuperOPF v3.80

2.3. Optimization Variables

In the simulations, the following categories of optimization variables are adjusted by BSI SuperOPF in the OPF computations:

- *Vm*: Bus voltage magnitudes.
- *Va*: Bus voltage phase angles.
- *Pg*: Generator real power outputs.
- *Qg*: Generator reactive power outputs.
- *t:* ULTC transformer tap ratios.
- *s*: phase shifters.
- *b*: switchable shunts.

2.4. Stopping Criteria

For the involved simulations, the stopping criteria for the OPF computation by BSI SuperOPF are specified as follows:

- The maximum allowable iterations: 500.
- The convergence tolerance for P-mismatches is 0.01MW.
- The convergence tolerance for Q-mismatches is 0.1MVar.
- The convergence tolerance for thermal limits is 0.01MVA.
- The convergence tolerance for voltage magnitude bounds is 1e-4 p.u.
- The convergence tolerance for shunt device bounds is 0.01MVar.
- The convergence tolerance for transformer tap ratio bounds is 1e-4 p.u.
- The convergence tolerance for phase shifter phase angle bounds is 1e-4 rad.

3. Results of Contingency Co-optimization

The first simulation is to use SuperOPF to co-optimize the objective function and the worst scenarios for voltage stability. In this simulation, all N-1 transmission line contingencies in area #9 are generated and BSI voltage stability analysis (VSA) program is used to calculate load margins for the post-contingency systems. Contingencies are ranked in terms of their margins and worst contingencies are identified as those ones with the smallest load margins.

Table 1. Identified worst contingencies

Ctg ID	Contingency Details
8	DISCONNECT BRANCH FROM BUS 99982 TO BUS 10025 CKT 1 /* SNJUAN-B-A 345.0 KV Line
21	DISCONNECT BRANCH FROM BUS 99982 TO BUS 10292 CKT 1 /* SNJUAN-SNJUAN 345.0 KV Line
24	DISCONNECT BRANCH FROM BUS 10369 TO BUS 99986 CKT 1 /* WMESA-FCORNR 345.0 KV Line
28	DISCONNECT BRANCH FROM BUS 11111 TO BUS 11017 CKT 1 /* NEWMN-ARROYO 345.0 KV Line
34	DISCONNECT BRANCH FROM BUS 11093 TO BUS 11213 CKT 1 /* LUNA-LUNA 345.0 KV Line
35	DISCONNECT BRANCH FROM BUS 11217 TO BUS 11093 CKT 1 /* AFTON-LUNA 345.0 KV Line
36	DISCONNECT BRANCH FROM BUS 16104 TO BUS 11093 CKT 1 /* SPRNGR-LUNA 345.0 KV Line

There are seven N-1 transmission line contingencies identified by BSI VSA which have zero load margins; in other words, these contingencies are insecure in that the system cannot support the system load demands should any of these contingences happen. The details of these worst contingencies are summarized in Table 1.

3.1 Base-case + Individual Contingency Co-optimization

In this test, BSI SuperOPF is used to co-optimize the base case system and individual worst contingency scenarios. Results of the BSI SuperOPF multi-scenario co-optimization carried over these contingency cases are summarized in Table 2 and Table 3. More specifically, the co-optimization results without considering operational reserves are summarized in Table 2, while the results with operational reserves are summarized in Table 3.

Table 2. BSI SuperOPF co-optimization results, without reserve

Scenario	Real Losses (MW)	% of System Load	Iterations	CPU Time (sec)
Base case before OPF	2793.42	2.883%	-	-
Base case only OPF	1624.55	1.676%	43	4.88
Base case + Ctg.8	1693.85	1.748%	50	13.10
Base case + Ctg.21	1687.92	1.742%	56	26.58
Base case + Ctg.24	1692.73	1.747%	80	27.42
Base case + Ctg.28	1642.20	1.695%	70	18.33
Base case + Ctg.34	1745.98	1.802%	57	15.28
Base case + Ctg.35	1639.96	1.692%	62	19.71
Base case + Ctg.36	Unsolvable, OPF solution not achievable			

Table 3. BSI SuperOPF co-optimization results, with reserve

Scenario	Real Losses (MW)	% of System Load	Iterations	CPU Time (sec)
Base case before OPF	2793.42	2.883%	-	-
Base case only OPF	1624.55	1.676%	43	4.88
Base case + Ctg.8	1624.32	1.676%	68	17.66
Base case + Ctg.21	1624.55	1.676%	54	17.08
Base case + Ctg.24	1624.56	1.676%	69	22.67
Base case + Ctg.28	1623.57	1.675%	131	36.19
Base case + Ctg.34	1633.94	1.686%	70	18.47
Base case + Ctg.35	1624.36	1.676%	65	17.14
Base case + Ctg.36	Unsolvable, OPF solution not achievable			

It can be observed that, SuperOPF contingency-constrained co-optimization can achieve the OPF solution for six out of seven worst contingencies. It can also be observed that the objective values, i.e., (base case) system real power losses can be reduced if operational reserves are available as corrective/preventive controls for the post-contingency operation.

3.2 Base-case + All Contingency Co-optimization

In this simulation, BSI SuperOPF is used to co-optimize the base case system with all the identified worst contingencies (excluding the unsolvable contingencies). The co-optimization results are summarized in Table 4, including both co-optimization without considering generation reserves and that with generation servers. A condensed summary of the results of both co-optimizations with individual and all worst contingencies is provide in Figure 2.

Table 4. All-contingency-constrained co-optimization results

Scenario	Real Losses (MW)	% of System Load	Iterations	CPU Time (sec)
Base case before OPF	2793.42	2.883%	-	-
Base case only OPF	1624.55	1.676%	43	4.88
Base case + All Ctgs (No reserve)	1746.80	1.803%	173	430.25
Base case + All Ctgs (With reserve)	1633.69	1.686%	134	314.83

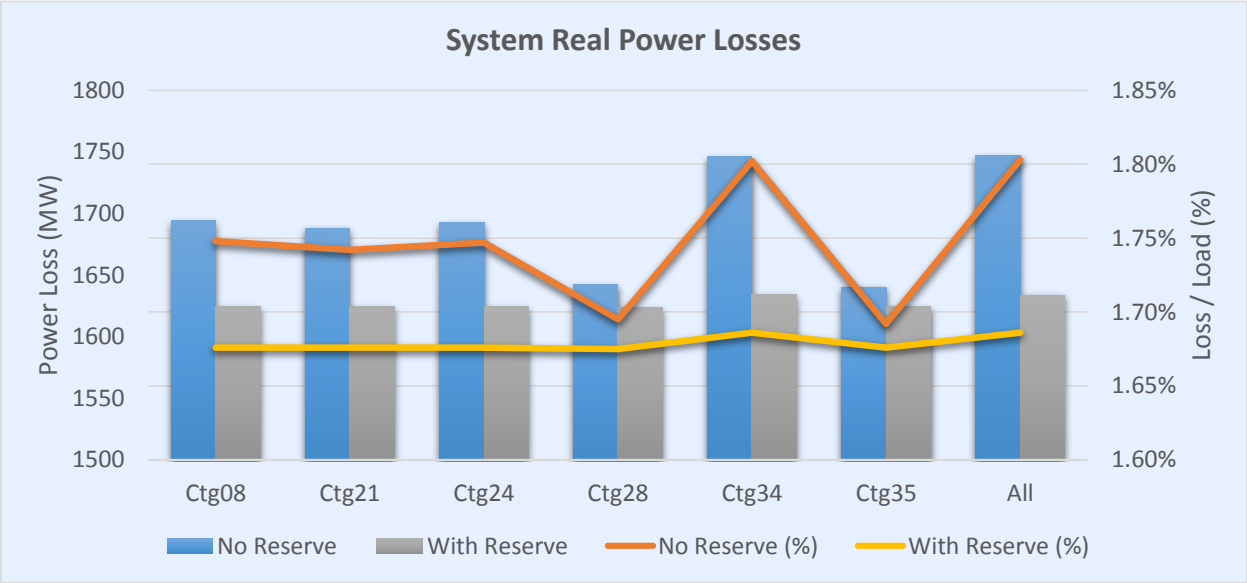

Figure 2. Contingency-constrained co-optimization

4. Results of Renewable Energy Co-optimization

In this simulation, renewable energy-constrained OPF computation is carried out using BSI SuperOPF. To simulate the effects of renewable energy penetration to the system, 20% system generators are randomly selected as wind generators. Therefore, 232 wind power generators are attached to the system.

Seven forecast scenarios of the wind power generations are produced for the simulation. Forecasts of real and reactive power generations for the wind generators are specified in the scenario file, where each forecast scenario is associated with a set of varied wind power outputs. Each forecast consists of random outputs of the generators varying uniformly in the range of $\pm 25\%$ of the initial outputs. For real-life applications, a scenario reduction procedure is indispensable in order to get a reduced list of credible renewable forecasts.

4.1 Base-case + Single Forecast Co-optimization

In this test, BSI SuperOPF is used to co-optimize the base case system and individual renewable energy forecast scenarios. Results of the BSI SuperOPF multi-scenario co-optimization carried over these renewable energy forecast cases are summarized in Table 5 and Table 6. More specifically, the co-optimization results without considering operational reserves are summarized in Table 2, while the results with operational reserves are summarized in Table 3.

Table 5. Single-forecast-constrained co-optimization results, without reserve

Scenario	Real Losses (MW)	% of System Load	Iterations	CPU Time (sec)
Base case before OPF	2793.42	2.883%	-	-
Base case only OPF	1624.55	1.676%	43	4.88
Base case + Scn.1	1703.15	1.758%	61	18.67
Base case + Scn.2	1623.60	1.675%	148	47.97
Base case + Scn.3	1794.48	1.852%	129	37.59
Base case + Scn.4	1624.43	1.676%	74	23.05
Base case + Scn.5	1681.97	1.736%	79	26.05
Base case + Scn.6	1662.83	1.716%	115	33.03
Base case + Scn.7	1623.90	1.676%	156	74.12

It can be observed that, results similar to that SuperOPF contingency-constrained co-optimization are obtained. It can also be observed that the objective values, i.e., (base case) system real power losses can be reduced if operational reserves are available as corrective/preventive controls for the post-forecast operation.

Table 6. Single-forecast-constrained co-optimization results, with reserve

Scenario	Real Losses (MW)	% of System Load	Iterations	CPU Time (sec)
Base case before OPF	2793.42	2.883%	-	-
Base case only OPF	1624.55	1.676%	43	4.88
Base case + Scn.1	1624.31	1.676%	68	24.46
Base case + Scn.2	1624.43	1.676%	91	35.92
Base case + Scn.3	1624.31	1.676%	62	20.07
Base case + Scn.4	1624.18	1.676%	76	29.07
Base case + Scn.5	1624.34	1.676%	101	29.00
Base case + Scn.6	1622.54	1.674%	78	23.49
Base case + Scn.7	1622.65	1.674%	65	20.09

4.2 Base-case + All Forecasts Co-optimization

In this simulation, BSI SuperOPF is used to co-optimize the base case system with all the renewable energy forecasts. The co-optimization results are summarized in Table 7, including both co-optimization without considering generation reserves and that with generation servers. A condensed summary of the results of both co-optimizations with individual and all renewable energy forecasts is provide in Figure 3.

Table 7. All-forecast-constrained co-optimization results

Scenario	Real Losses (MW)	% of System Load	Iterations	CPU Time (sec)
Base case before OPF	2793.42	2.883%	-	-
Base case only OPF	1624.55	1.676%	43	4.88
Base case + All Ctgs (No reserve)	1796.17	1.853%	330	1212.42
Base case + All Ctgs (With reserve)	1622.66	1.674%	380	1646.38

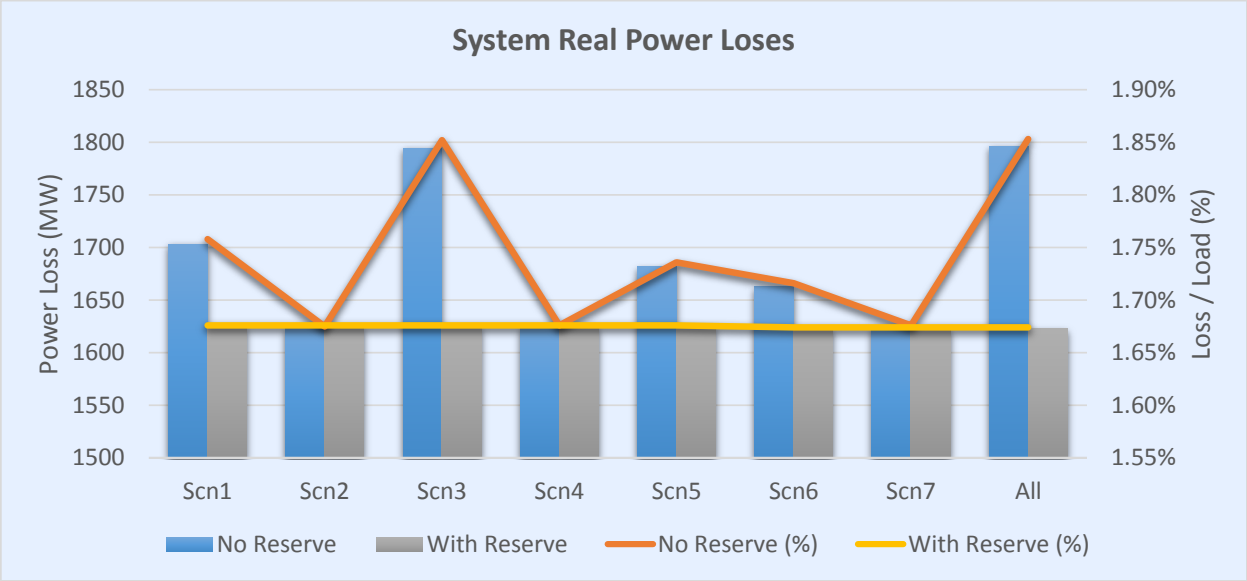

Figure 3. Renewable-energy-constrained co-optimization

5. Summary

In this report, simulations have been carried out using BSI SuperOPF to perform contingency-constrained and renewable-energy-constrained co-optimized OPF computation on CAISO system EMS data. The results suggest that BSI SuperOPF is an effective tool for multi-scenario cooptimized OPF analysis, which is applicable to handle a diversity of scenarios for large-scale power systems.