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

August 5, 2015

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Agenda

- Project overview
- SuperOPF distinguished features and Co-optimization
- Commercialization activities and feedbacks
- New Developments and features
- Data preparation, and Simulation Results on the CAISO
- Summary

One key Goal of SuperOPF

SuperOPF commercialization:

- Develop an OPF solver which can handle large power systems with industry data formats ;
  - To develop a robust and efficient OPF solver which can converge well under all loading conditions;
  - To develop an OPF solver which can determine optimal values for discrete control variables.

One key Goal of SuperOPF

- To develop a co-optimization OPF solver over contingencies and renewable uncertainties
- Evaluate on a practical 15,000-bus system and a practical 6,500-bus for Co-optimization models with

more than 3 million matrix dimensions (considering renewable and contingency)

Practical OPF Solvers

- Modeling capability (support PSS/E model, and CIM-compliance model)
- Speed
- Robust
- Large-scale OPF problems
- Quality of OPF solutions (local or global OPF solutions)
- A large set of Contingencies
- Stability constraints
- Stochastic formulations of renewable energy
- OPF solutions are practically executable.

SuperOPF Solver (2)

- SuperOPF is a full-featured ACOPF solver with a comprehensive modeling capability
- SuperOPF is robust despite bad initialization

Solver	MIPS	FMINCON	KNITRO	IPOPT	TRALM	PSSE	SuperOPF
118-bus system	69/101	101/101	101/101	101/101	101/101	101/101	1001/1001
3120-bus system	1/101	1/101	36/101	1/101	1/101	0/101	1001/1001

- Solutions by SuperOPF are also of high quality, in terms of optimality compared with lower bounds computed by SDP convexification/relaxation methods.

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Conventional formulation of AC Optimal Power Flow

- The Conventional formulation
  - n_B: # of buses
  - n_G: # of generators
  - L: the set of lines
  - n_T: # of transformers
  - n_P: # of phase shifter
  - n_S: # of switchable shunts

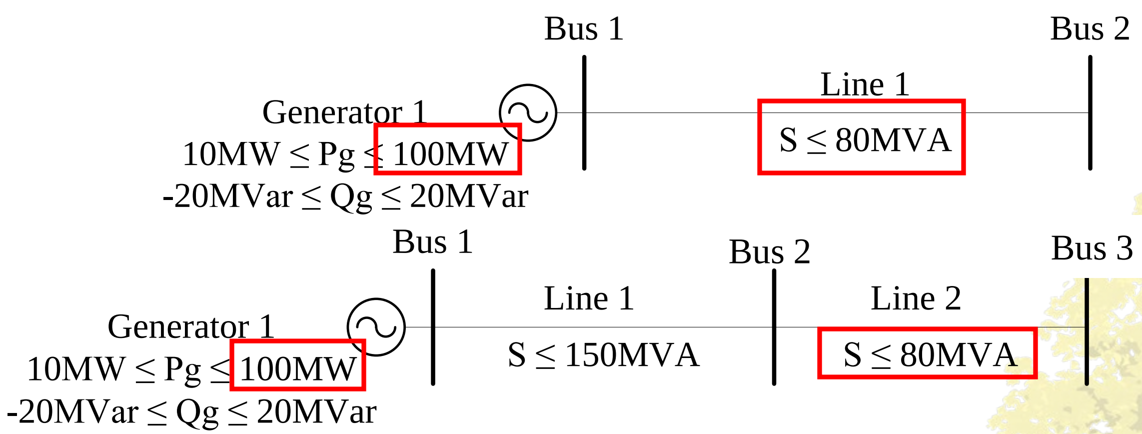
$$
\begin{aligned}
\min \quad & f(V,\theta,t,\phi,b,P^G,Q^G) \\
s.t. \quad & P_i(V,\theta,t,\phi,b) + P_i^L - P_i^G = 0, \; i = 1,\cdots,n_B \\
& Q_i(V,\theta,t,\phi,b) + Q_i^L - Q_i^G = 0, \; i = 1,\cdots,n_B \\
& S_{ij}(V,\theta,t,\phi,b) \le \overline{S}_{ij}, \; (i,j) \in \mathcal{L} \\
& S_{ji}(V,\theta,t,\phi,b) \le \overline{S}_{ij}, \; (i,j) \in \mathcal{L} \\
& \underline{V}_i \le V_i \le \overline{V}_i, \; i = 1,\cdots,n_B \\
& \underline{t}_i \le t_i \le \overline{t}_i, \; i = 1,\cdots,n_T \\
& \underline{\phi}_i \le \phi_i \le \overline{\phi}_i, \; i = 1,\cdots,n_P \\
& \underline{b}_i \le b_i \le \overline{b}_i, \; i = 1,\cdots,n_S \\
& \underline{P}_j^G \le P_j^G \le \overline{P}_j^G, \; j = 1,\cdots,n_G \\
& \underline{Q}_j^G \le Q_j^G \le \overline{Q}_j^G, \; j = 1,\cdots,n_G
\end{aligned}
$$

Multi-Stage, Multi-level adaptive Homotopy-enhanced Interior-Point-based Method

- A multi-Stage and Multi-level solver is developed:
- Why: speed and robust
  - Stage 1: Constraint analysis for improving convergence and detecting infeasibility.
  - Stage 2: OPF without thermal constraints and identify active thermal constraints.
  - Stage 3: OPF with active set of thermal constraints to eliminate all thermal violations (multi-level and homotopy-enhaced Stage).
  - Stage 4: Determine discrete control variables

Stage 1: OPF Constraint Analysis and Feasibiity Detection

- 1. Improper generation upper bounds
  - ***Issue***: The upper generation bound is larger than the thermal limit of Line 1 or Line 2.



Stage 1: detection of feasibility regions

- How to detect over-constrained OPF solutions (i.e. no solution exists due to over-constrained requirement)

- How to restore feasible regions

Stage 2: OPF w/o Thermal Limits

- The formulation: no thermal constraints

$$
\begin{aligned}
\min \quad & f(V,\theta,t,\phi,b,P^G,Q^G) \\
s.t. \quad & P_i(V,\theta,t,\phi,b) + P_i^L - P_i^G = 0, \; i=1,\cdots,n_B \\
& Q_i(V,\theta,t,\phi,b) + Q_i^L - Q_i^G = 0, \; i=1,\cdots,n_B \\
& \underline{V}_i \le V_i \le \overline{V}_i, \; i=1,\cdots,n_B \\
& \underline{t}_i \le t_i \le \overline{t}_i, \; i=1,\cdots,n_T \\
& \underline{\phi}_i \le \phi_i \le \overline{\phi}_i, \; i=1,\cdots,n_P \\
& \underline{b}_i \le b_i \le \overline{b}_i, \; i=1,\cdots,n_S \\
& \underline{P}_j^G \le P_j^G \le \overline{P}_j^G, \; j=1,\cdots,n_G \\
& \underline{Q}_j^G \le Q_j^G \le \overline{Q}_j^G, \; j=1,\cdots,n_G
\end{aligned}
$$

Stage 3: OPF with Thermal Constraints

- Only active thermal constraints are involved in stage 3 optimization.
- Active thermal constraints in the OPF solution at each iteration are added to the constraint set
- solved by our proposed adaptive homotopy-enhanced Interior Point Method.

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Test System- an on-line test system

Total buses	13183
loads	9691
generators	2304
Transmission branches	18168
transformers	1410
Switchable shunts	1404

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Super-OPF Dimensions

13183-Bus System

Stage I: OPF Constraint Analyzer → Stage II: Simple OPF w/o Thermal Limits → Stage III: Homotopy OPF w/ Active Thermal Limits → Stage IV: Sensitivity Analyzer for Discretization →

Input Data

OPF Result

System:
- Buses: 13183
- Loads: 9691
- Generators: 2304
- Branches: 18168
- Transformers: 1410
- Switched shunts: 1404

OPF Dimensions: (Stage II)
- Dimension of x: 31134
- Nonlinear equality constraints: 26366
- Nonlinear inequality constraints: 0
- Total equality constraints: 26367
- Total inequality constraints: 35902

OPF Dimensions: (Stage III)
- Dimension of x: 31134
- Nonlinear equality constraints: 26366
- Nonlinear inequality constraints: varying (<100)
- Total equality constraints: 26367
- Total inequality constraints: >35902 (varying)

PJM System:
- Continuous variables: 28320
- Discrete variables: 2814

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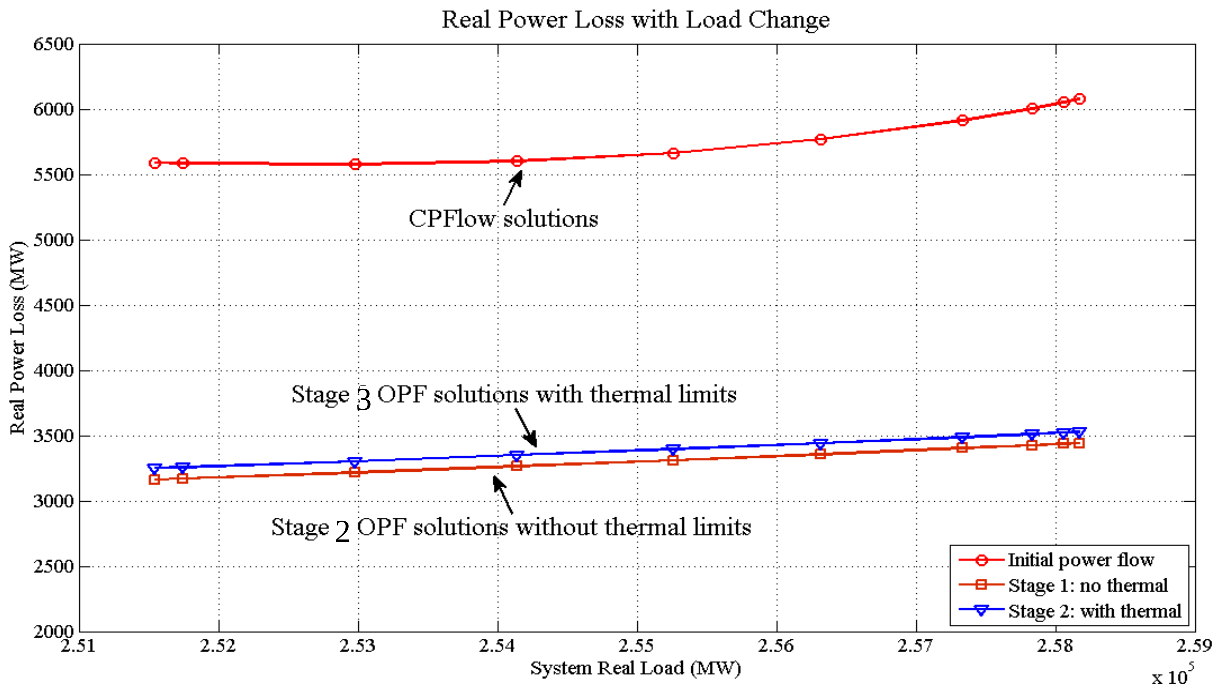
Results: Real Power Loss Reductions



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Results: Efficiency and Robustness (Analytical Jacobian matrices)

Effects of constraint analysis

Base case
Without constraint analysis
• Converged in 217 iterations • CPU time: 177 seconds • OPF loss: 3251.284MW
With constraint analysis
• Converged in 191 iterations • CPU time: 143 seconds • OPF loss: 3251.353MW

Robustness of our method

Loading Condition	One-Staged Scheme	Multi-Staged Scheme
1	Succeeded	Succeeded
2	Succeeded	Succeeded
3	Succeeded	Succeeded
4	Succeeded	Succeeded
5	Failed	Succeeded
6	Failed	Succeeded
7	Failed	Succeeded
8	Failed	Succeeded
9	Failed	Succeeded
10	Failed	Succeeded

On the Global Convergence of a Class of Homotopy Methods for Nonlinear Circuits and Systems

Tao Wang,Member, IEEE, and Hsiao-Dong Chiang,Fellow, IEEE

IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: EXPRESS BRIEFS, VOL. 61, NO. 11, NOVEMBER 2014

- Abstract—Homotopy methods are developed for robustly computing solutions of nonlinear equations, which is of fundamental importance in nonlinear circuit and system simulations. This brief develops theoretical results on the global convergence of a class of homotopy methods for solving nonlinear circuits and systems. A set of sufficient conditions that guarantee the global convergence of homotopy methods is derived. These analytical results are then illustrated on a small nonlinear circuit and a large (about 10 000-dimension) power grid.

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SuperOPF Solution Quality (2)

- SuperOPF solution is almost identical to the lower bounds of SDP relaxation, meaning the SuperOPF solution is mostly the global optimal solution.
- The lower bound of SDP relaxation provides a guide for finding better solutions.
- The lower bounds of SDP relaxation are not always reliable, especially for large-scale systems (as indicated in the pictures, SDP lower bounds are worse than SuperOPF solutions for large systems).
- SDP is also very slow, the problem complexity increases exponentially as system size increase.

Solver \ Systems / CPU Time (s)	39-Bus	118-Bus	300-Bus	2383-Bus	6470-Bus
SuperOPF	0.075	0.139	0.325	3.014	8.58
SDP	1.734	3.929	7.915	453.974	2424.50

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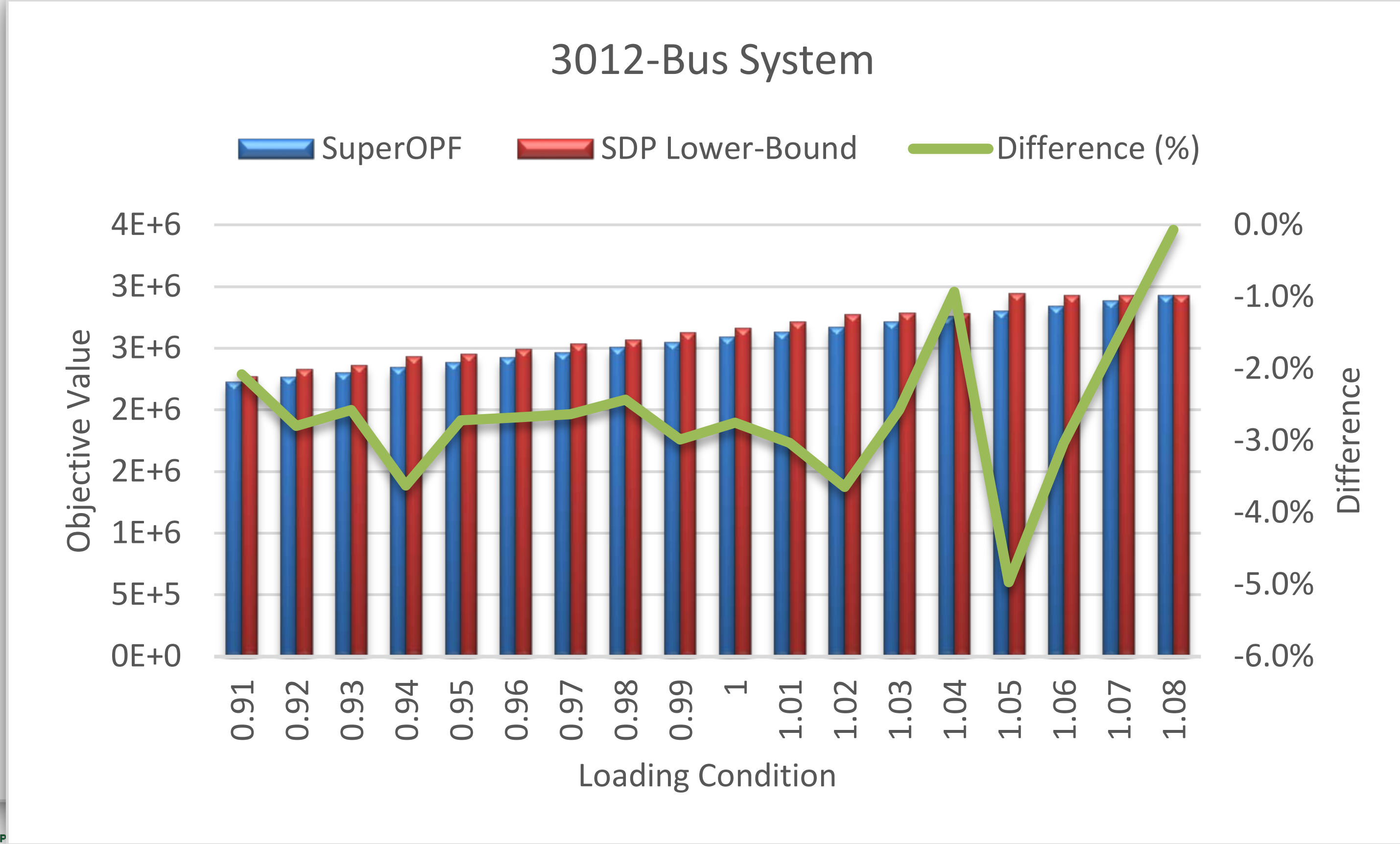
SuperOPF Solution Quality (1)



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Characterization of ACOPF Feasible Region

- Motivation
- ACOPF formulation
- ACOPF feasibility
- ACOPF feasible region
- Characterizing ACOPF feasible region

ACOPF Formulation (1)

- An ACOPF problem can be stated as the following nonlinear optimization problem

$$\min \quad f(V,\theta,t,\phi,b,P^G,Q^G)$$

$$s.t. \quad P_i(V,\theta,t,\phi,b) + P_i^L - P_i^G = 0, i = 1,\cdots,n_B$$

$$Q_i(V,\theta,t,\phi,b) + Q_i^L - Q_i^G = 0, i = 1,\cdots,n_B$$

$$S_{ij}(V,\theta,t,\phi,b) \le \bar{S}_{ij}, (i,j) \in L$$

$$S_{ji}(V,\theta,t,\phi,b) \le \bar{S}_{ij}, (i,j) \in L$$

$$\underline{V}_i \le V_i \le \bar{V}_i, i = 1,\cdots,n_B$$

$$\underline{t}_i \le t_i \le \bar{t}_i, i = 1,\cdots,n_T$$

$$\underline{\phi}_i \le \phi_i \le \bar{\phi}_i, i = 1,\cdots,n_P$$

$$\underline{b}_i \le b_i \le \bar{b}_i, i = 1,\cdots,n_S$$

$$\underline{P}_j^G \le P_j^G \le \bar{P}_j^G, j = 1,\cdots,n_G$$

$$\underline{Q}_j^G \le Q_j^G \le \bar{Q}_j^G, j = 1,\cdots,n_G$$

Equality constraints $C_E(x) = 0$

Inequality constraints $C_I(x) \le 0$

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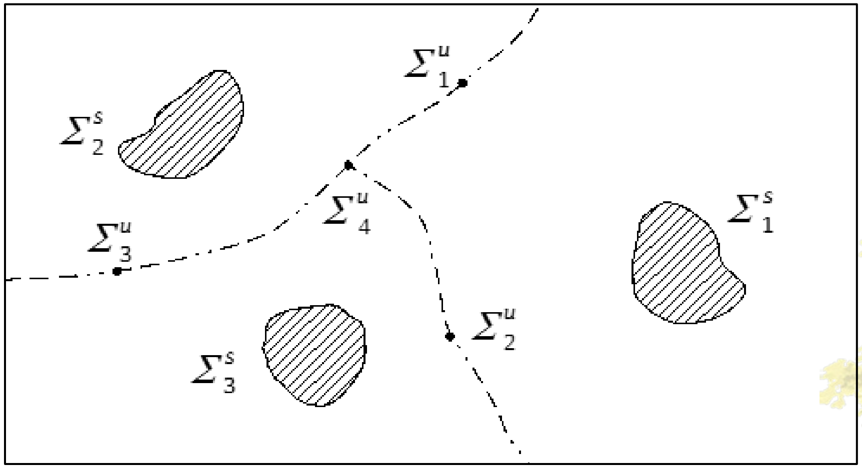
Characterizing ACOPF Feasibility Region (1)

- By transforming the feasibility problem into a tailored dynamical system, we can gain deep insight of the structure of the ACOPF feasible region.
- We build a quotient-gradient system (QGS)
- ***Theorem 1 (Feasible components and SEMs):*** Each ACOPF feasible component is a stable equilibrium manifold of the ACOPF corresponding QGS.



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Characterizing ACOPF Feasibility Region (2)

- ***Theorem 2 (Completely stable):*** Every trajectory of the QGS is bounded and converges to one of the equilibrium manifolds.

- ***Theorem 3 (SEMs and local optima):*** Each SEM of the QGS is a local optimum of the optimization problem:

$$\min_{x \in R^n} E(x) = \frac{1}{2} \|C_E(x)\|^2 + \frac{1}{2} \left\|C_I^B(x)\right\|^2$$

- E(x) is an energy function of the QGS.

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Simulation Settings

- Feasible regions for three test systems under different loading conditions
  - Test systems

Test System	Buses	Generators	Branches
30-Bus System	30	6	41
118-Bus System	118	54	186
300-Bus System	300	69	411

  - Loading conditions

Test System	30-Bus	118-Bus	300-Bus
Loading Conditions	$\lambda = 0.75, 1.0$	$\lambda = 1.0, 2.0$	$\lambda = 0.75, 1.0, 1.06$
λ is the loading parameter, i.e., the load multiplier w.r.t. to the basecase.			

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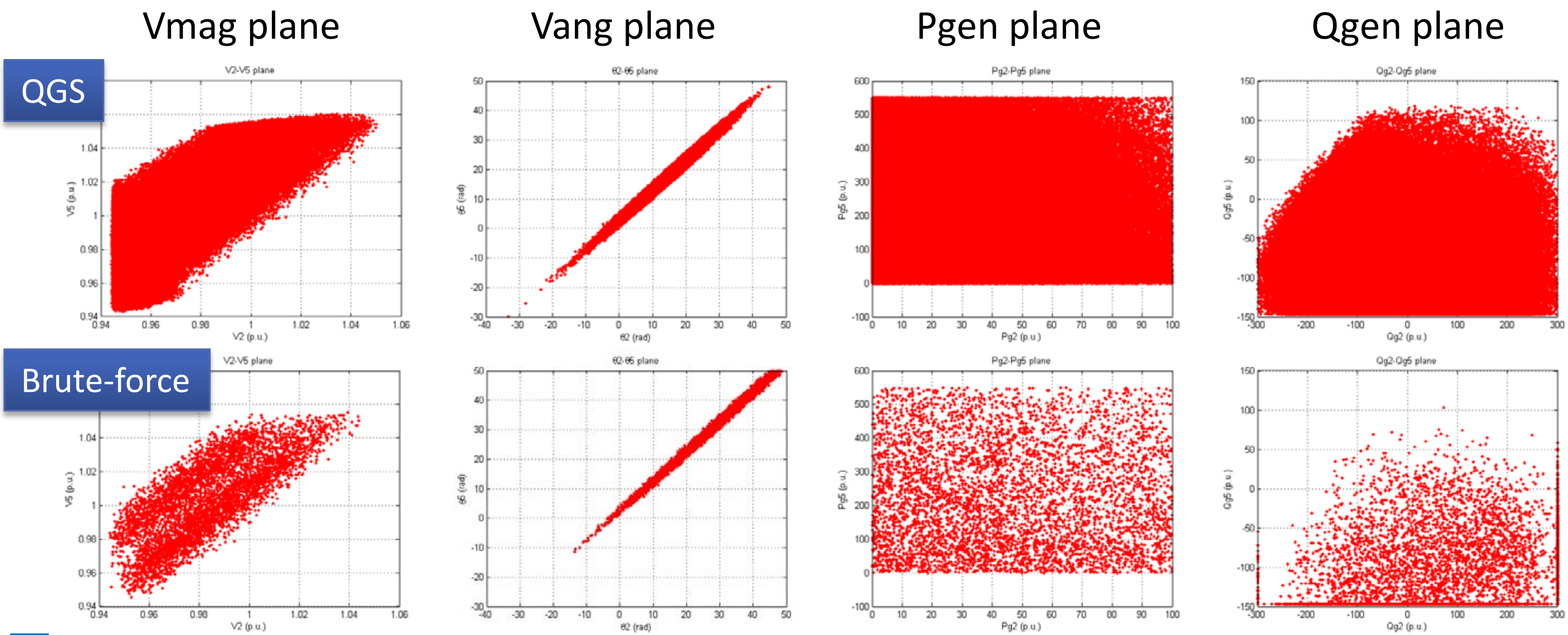
Results: QGS vs Brute-force (118-bus)

- Starting from random initial points within the variable bounds, a Newton power flow is carried out.
- Feasibility is checked for converged power flow solutions.
- Feasible regions are compared, validating QGS results.



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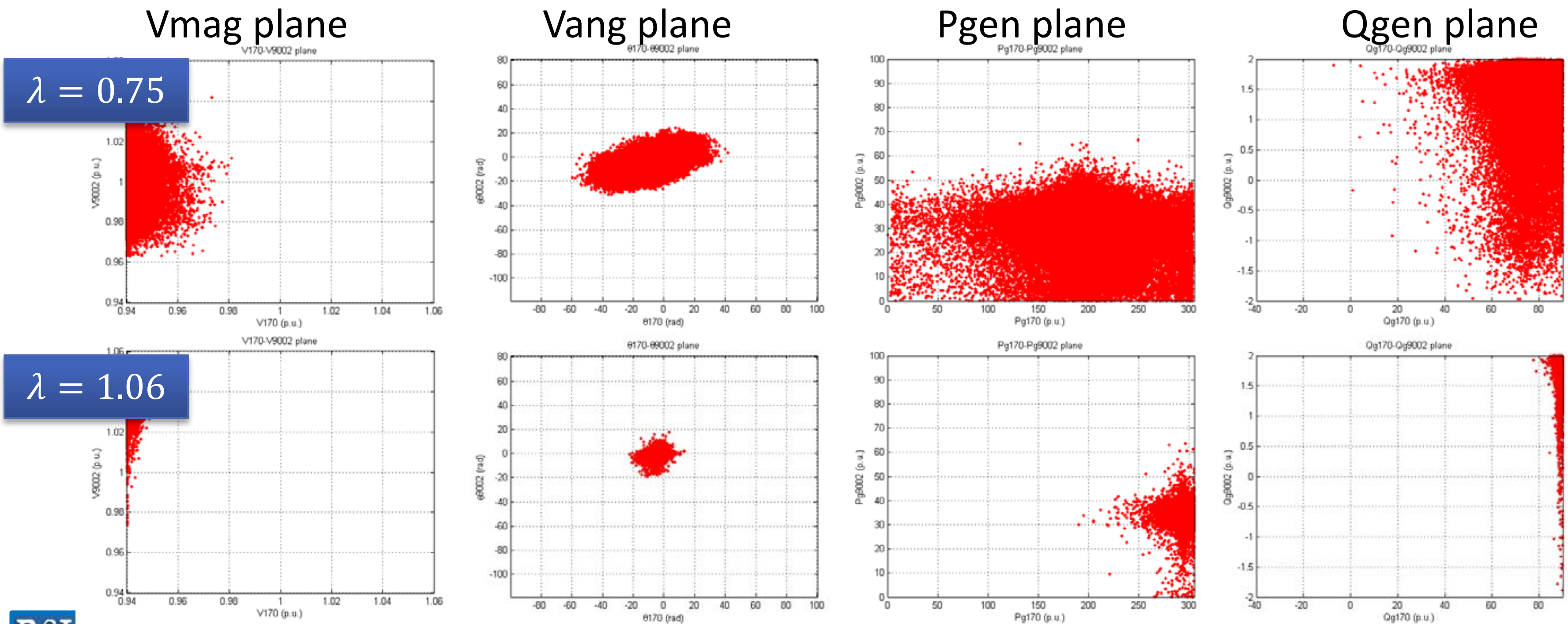
Results: Feasible Region - 300-Bus System

- Convergence more frequently to the middle and on the outer boundaries of the feasible region than to the inner boundaries.
- 2-dimensional projection does not well reveal the underlying structure of the complicated high-dimensional feasible region.



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SuperOPF Solver (1)

- A full-featured ACOPF program

Various Objectives

Market
- Generation cost
- Social Welfare

Operation
- Real/reactive power losses
- Real/reactive power generation
- Operation efficiency
- Stability & Security

Complete Modeling Capability

- AC power flow constraints
- Thermal-limit
- Interface-flow limit
- Transfer capability limit
- Static & dynamic stability

Full Range of Control Variables

- Voltage magnitude & phase angles
- Real/reactive generation
- Transformer tap ratio\Phase shifter\Switchable shunts

Multiple Scenarios

- Contingency scenarios
- Renewable forecast scenarios

Commercialization Activities

- Advanced Voltage Control System (EPRI & TPC, a 35GW company)
- ARPA-E (G-OPF)
- Hitachi Ltd. (Tokyo, Japan)
- CAISO:

2 short-term projects and 1 long-term project.

Advanced Voltage Control: A Novel System and Case Study

Dr. Hsiao-Dong Chiang
Prof, School of ECE, Cornell University, NY
President, Bigwood systems, Inc. Ithaca, NY

Robert Entriken
EPRI, Principal Technical Leader

System Information:

- 4 Areas
  - North, Central, South, East
-

Buses	1713
Loads	528
Generators	294
Branches	1331
Transformers	1333
Shunts	503

CASE 11

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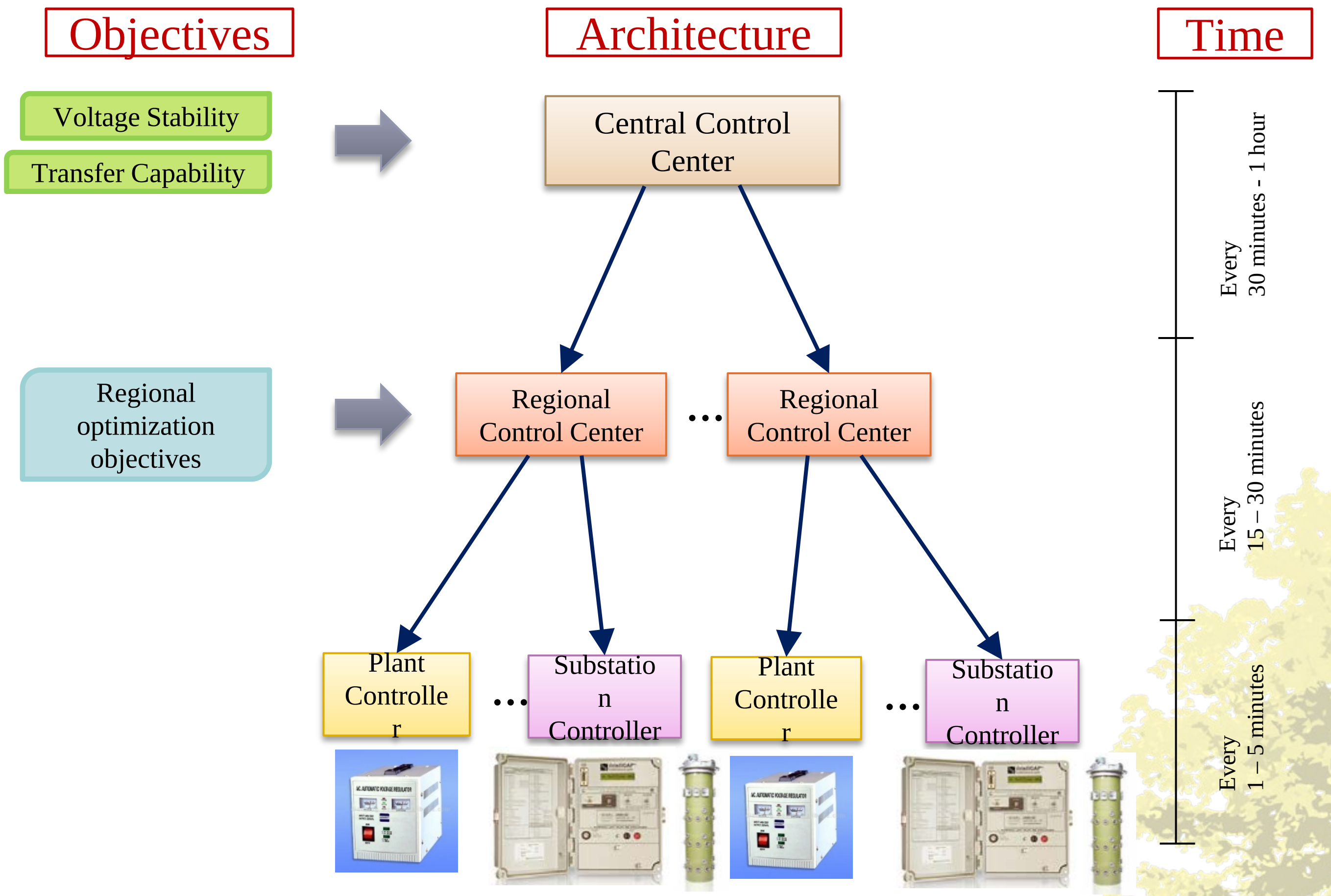
AVC project

- Objective
  - Design a real-time, closed-loop advanced voltage control system
  - Assess its feasibility for implementation
- Metrics
  - Power transfer capability increase
  - Power losses reduction
  - Voltage profile improvement

BSI-AVC Design



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AVC – Key Benefits

Central Control Center
- Enhanced transfer capability
- Ensured static security including voltage stability

Regional Control Center
- Improved system wide voltage profile
- Reduced power losses

System Wide
- Minimal system investment due to simple hierarchy

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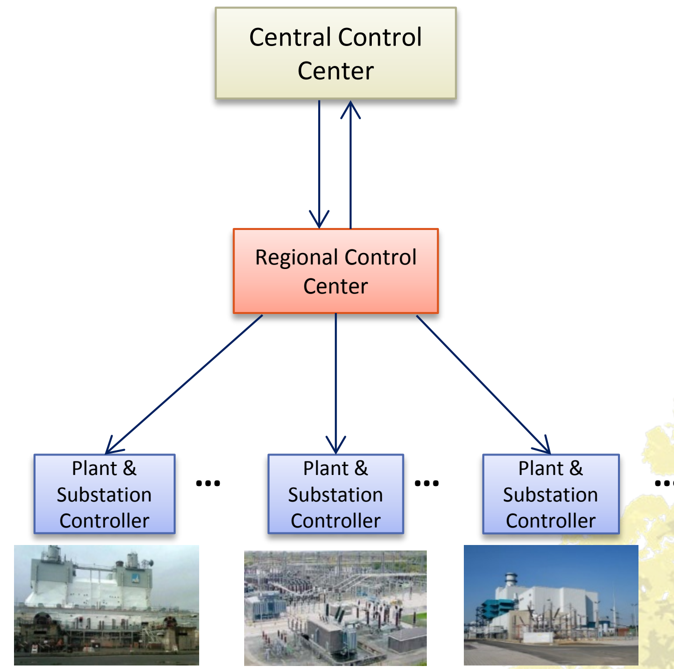
Three-layer Architecture



Source: 2012 Sustainability Report, TPC, August 2012

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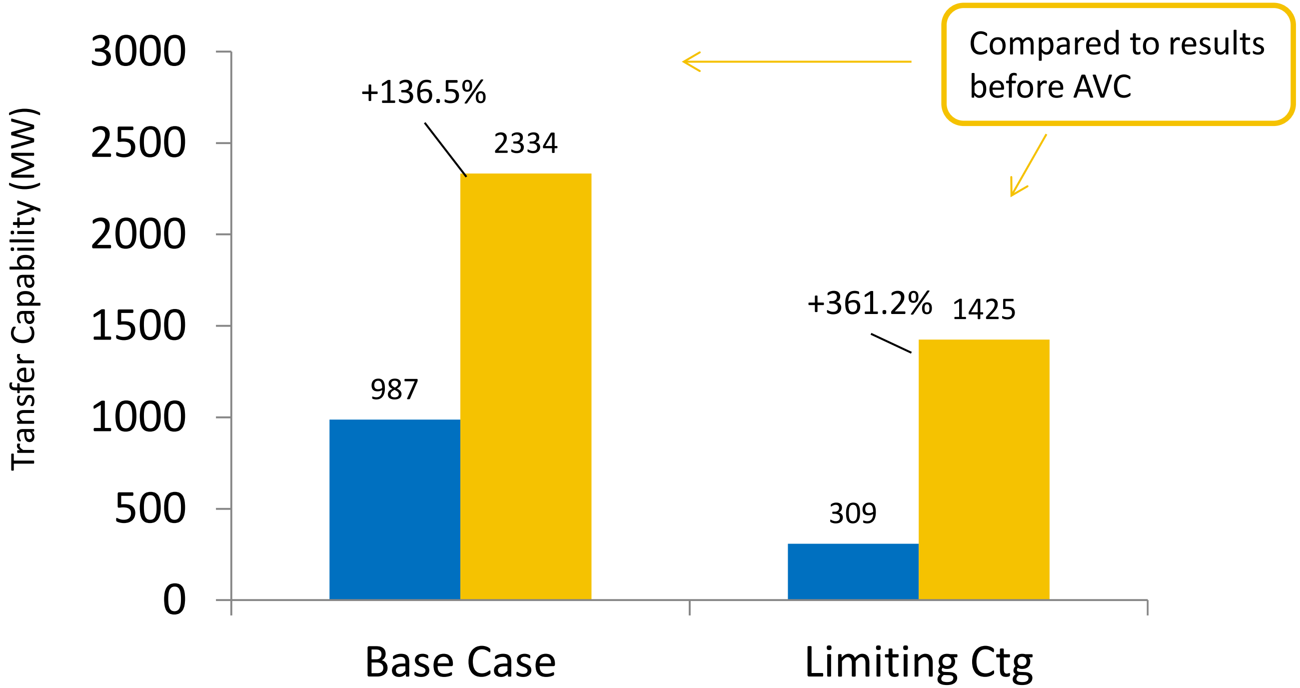
VSA/E Result

- Limiting contingency-No.35198
- Pilot buses selected

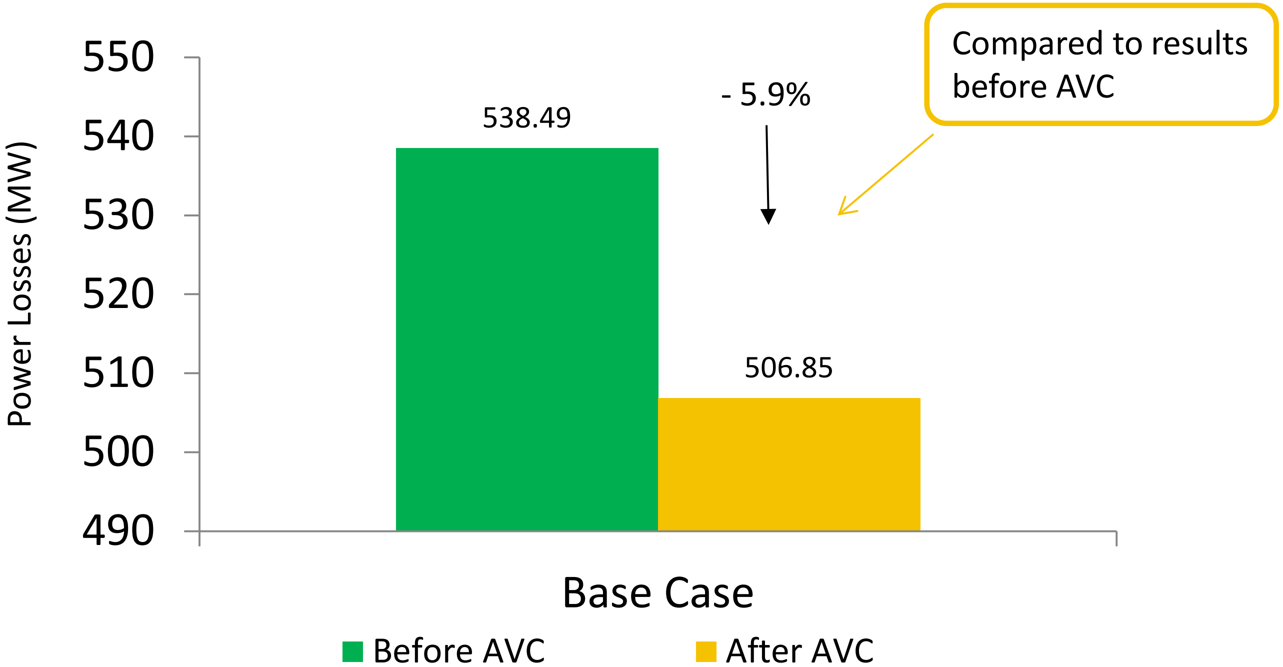
BUS	Name	vSet
BUS 210		1.028
BUS 1700		1.026

CASE 11

Transfer Capability Improvement

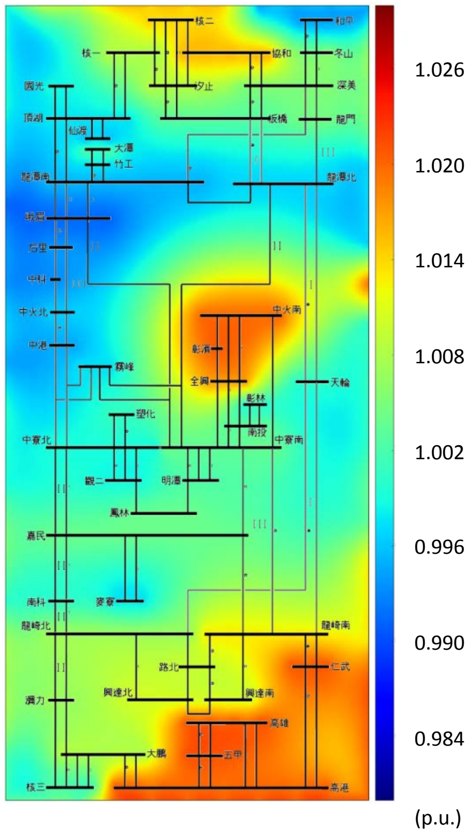


Power Losses Reduction

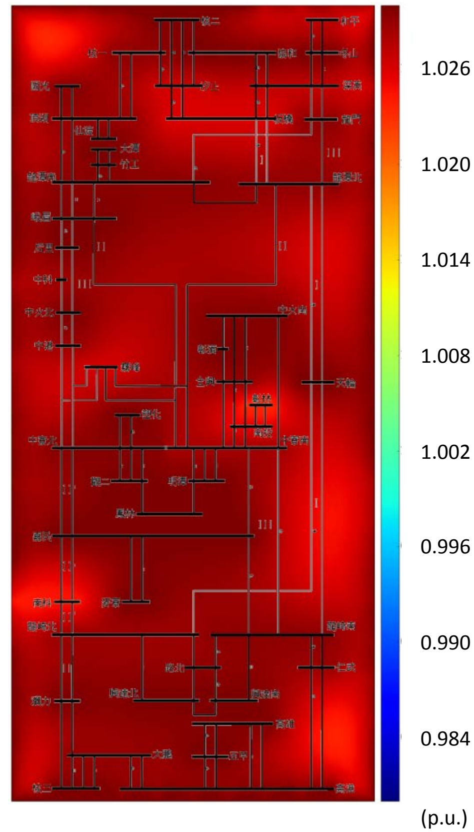


CASE 11

Voltage Profile Improvement



Before AVC

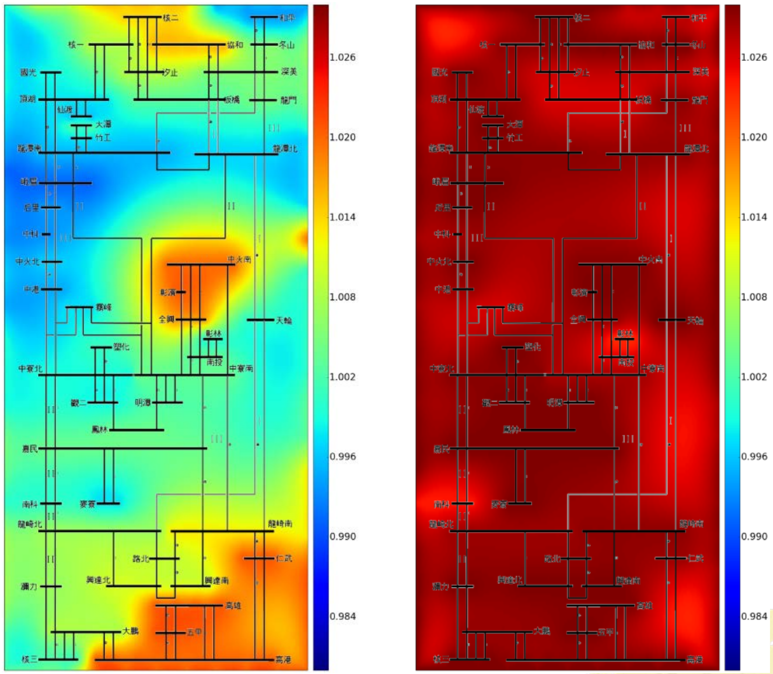


After AVC

CASE 11

Key Lessons
Most Promising Benefits

- Increased Transfer Capability
- Reduced Power Losses
- More uniform voltage profile
- Proactive voltage control based scheduling
- Reduced maintenance on shunt devices



Before AVC

After AVC

CASIO-Outage Scheduling

- **One key** ISO’s responsibility: scheduling and coordination of transmission equipment outages (periods when equipment is out of service). Outages can last from 15 minutes to several weeks or months, and can be continuous or intermittent.
- **A planned outage**
- **An unplanned outage**

CASIO-Advanced Voltage Control

- Real-time Power Market
- 5-minute ahead Power Market

- Project Idea: to apply advanced voltage control before 5-minute ahead power market to relief congestions.

CAISO – Long-term Project

- SuperOPF for power market application
- LMP calculation based on ACOPF model (instead of linearized OPF model) with comprehensive and accurate representation of static as well as dynamic constratints.

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Observations

- The numerical QGS-based scheme is effective for finding ACOPF feasible solutions or detecting the non-existence of feasible solutions.
- Based on characterization of ACOPF feasibility region, G-OPF package (version I and II) is under development.

Next Project Target

- To study the impact of co-optimization in improving key challenges in the CAISO system using the commercial-grade SuperOPF tool.

Co-Optimization

- Co-optimize the objective function and the updated worst scenario for voltage stability
- Co-optimize the objective function, operational reserve and the renewable energies.
- Handling ramp constraints of generation
- Handling constraints needed for LMP calculations and outputs needed for the power market.

Project Deliverables

D1. SuperOPF co-optimization of objective function and the worst scenario for voltage stability.	*D2. SuperOPF co-optimization of objective function, operational reserve and renewable energy.*
D3. SuperOPF co-optimization with ramping constraints of generations.	*D4. SuperOPF with constraints needed for LMP calculations and outputs needed for the power market.*
D5. Documents: user's manual, design manual, final reports.	**D6. Additional evaluations with power market data and piece-wise linear cost functions.**

Simulation Configuration

- Test system: CAISO 7199-bus system
  - Buses: 7199, Loads: 3004,
  - Generators: 2097, Shunts: 579
  - Branches: 9084 (Transformers: 2533),
  - System load: 76323.36MW

Simulation and SuperOPF version 3.9 (single threaded)

- Simulated scenarios
  - Two types of objective functions are considered in the simulation, including
    - To minimize the system real power losses, and
    - To minimize the system production costs.
  - Co-optimization is carried out for worst "N-1" contingencies. All computations were performed under different loading conditions
- Simulation environment:
  - 2.7GHz quad-core Intel i7-3820QM processor (Turbo boost to 3.7GHz), 16GB 1600MHz DDR3 RAM, Ubuntu Linux 15.04 AMD64, Linux Kernel 3.19.0, GCC 5.1.1.

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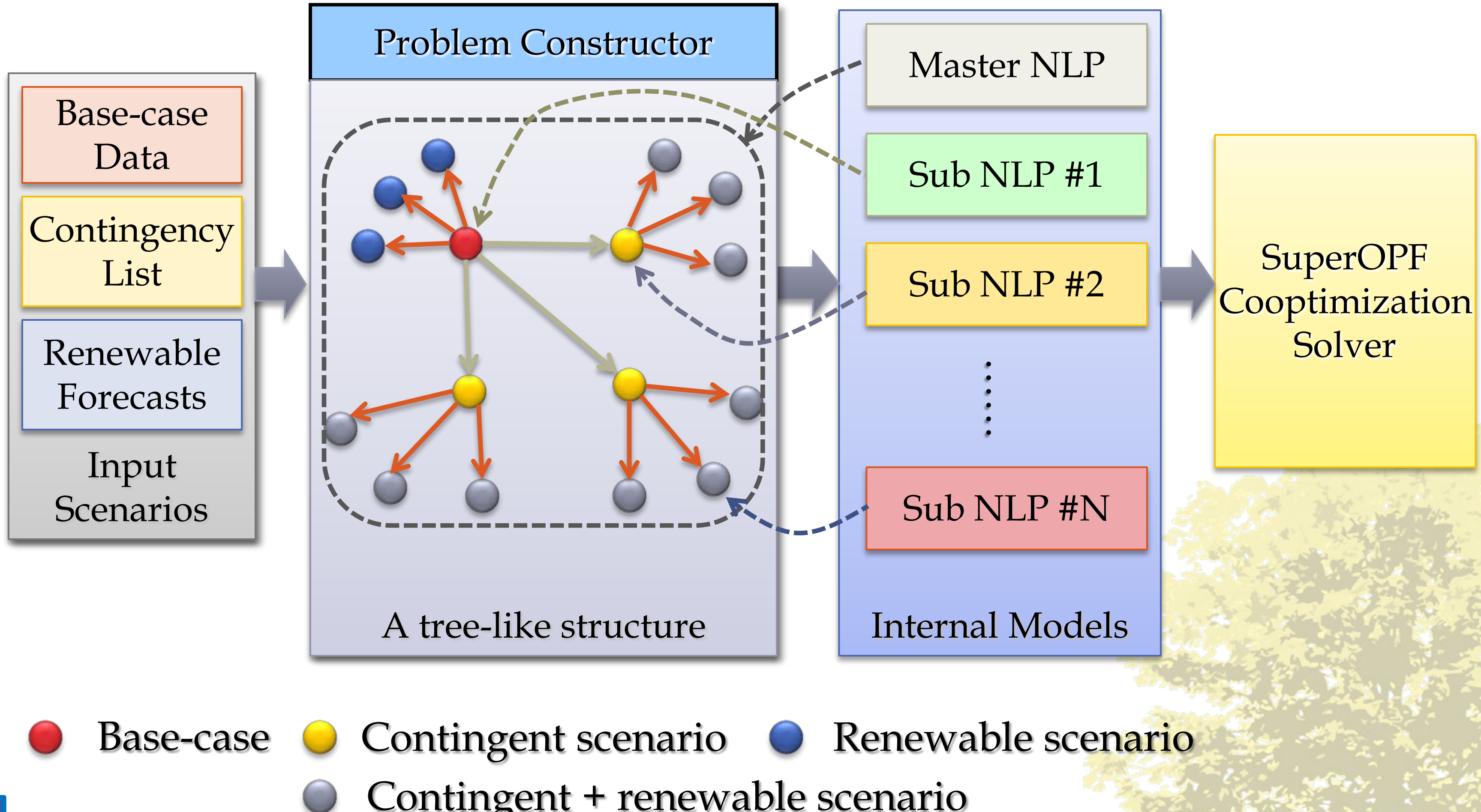
SuperOPF Co-optimization

- Solution methodology



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SuperOPF Co-optimization

- Four types of scenarios

Type-1 scenario: Base case

$$\begin{aligned} \min \quad & f(x) \\ s.t. \quad & P_i(x) + P_{Di} - P_{Gi} = 0 \qquad 1 \le i \le n_B \\ & Q_i(x) + Q_{Di} - Q_{Gi} = 0 \\ & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} \qquad (i,j) \in L \\ & x^{min} \le x \le x^{max} \end{aligned}$$

n_B: the number of buses L: the set of branches

Type-2 scenario: Base case + contingency

$$\begin{aligned} \min \quad & f(x) \\ s.t. \quad & P_i(x) + P_{Di} - P_{Gi} = 0 \qquad 1 \le i \le n_B \\ & Q_i(x) + Q_{Di} - Q_{Gi} = 0 \\ & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} \qquad (i,j) \in \hat{L} \\ & x^{min} \le x \le x^{max} \end{aligned}$$

$\hat{L}$: L excludes contingent branches

Type 3 scenario: Base case + renewable energy

$$\begin{aligned} \min \quad & f(x) \\ s.t. \quad & P_i(x) + \hat{P}_{Di} - P_{Gi} = 0 \qquad 1 \le i \le n_B \\ & Q_i(x) + \hat{Q}_{Di} - Q_{Gi} = 0 \\ & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} \qquad (i,j) \in L \\ & x^{min} \le x \le x^{max} \end{aligned}$$

$\hat{P}_D, \hat{Q}_D$: equivalent loads for renewable energy

Type 4 scenario: Base case + renewable energy + contingency

$$\begin{aligned} \min \quad & f(x) \\ s.t. \quad & P_i(x) + \hat{P}_{Di} - P_{Gi} = 0 \qquad 1 \le i \le n_B \\ & Q_i(x) + \hat{Q}_{Di} - Q_{Gi} = 0 \\ & S_k = \sqrt{P_{ij}^2(x) + Q_{ij}^2(x)} \le S_k^{max} \qquad (i,j) \in \hat{L} \\ & x^{min} \le x \le x^{max} \end{aligned}$$

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Supported Scenario Types and Variables

- Supported scenario types
  - Contingency scenarios
  - Renewable forecast scenarios (renewable uncertainties)
  - Combination of the contingent and renewable forecast scenarios
- Supported variable types:
  - Voltage magnitudes and phase angles
  - Real and reactive power generations
  - Transformer tap ratios (continuous or discrete)
  - Phase shifters (continuous or discrete)
  - Switchable shunts (continuous or discrete)

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Data Preparation & Program Changes

- Forward
- Network data
- Cost data
- Piece-wise linear costs
- Program changes

Forward

The Project Data Chase Story

- The plan was to evaluate the SuperOPF package as a power market application using a market case with sanitized data that would protect the privacy and integrity of the market, yet be realistic.
- Well, despite a method to make the data anonymous, ongoing efforts by the technical team at CAISO and plenty of lead time to negotiate the NDA process in the CIP era, the legal folk said NO.
- Thus, the motivation for this case preparation work

Data Preparation: Network Data

- Base case: a raw file from a recent BSI VSA study case for CAISO
- Loading pattern: the same loading pattern used in BSI VSA study is used to generate CPFLOW solutions under different loading conditions.
- Voltage limits:
  - the bus voltage ranges specified in the VSA monitor list file are used;
  - for buses not covered in the monitor list file, [0.9, 1.1] is used.
- Thermal limits: Thermal limit constraints for branches included in the monitor list file are enforced.

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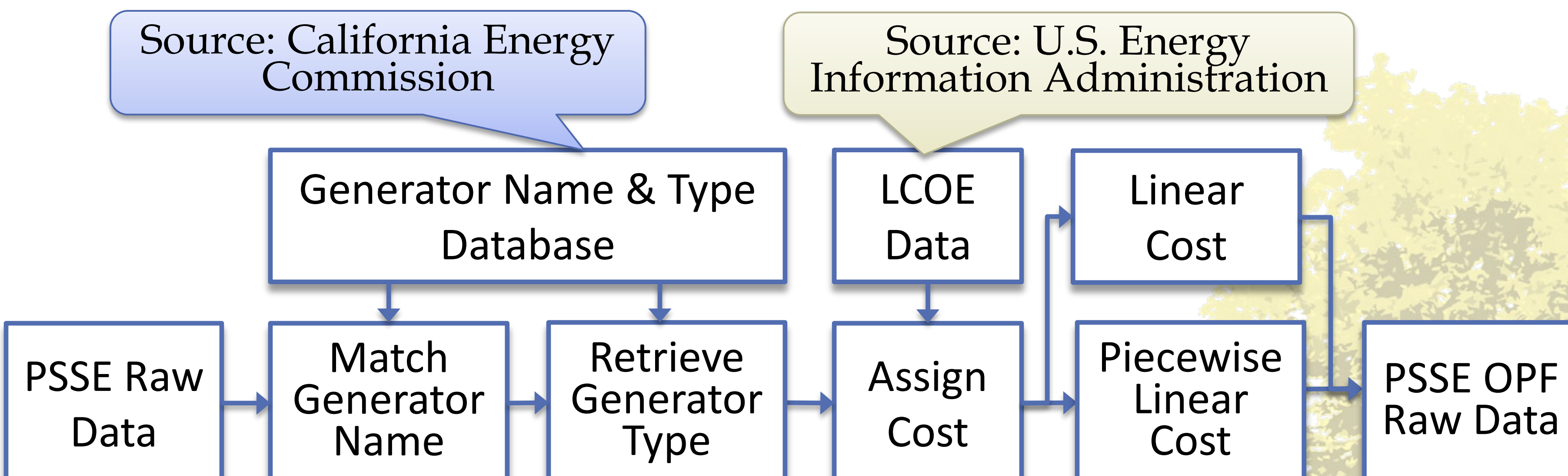
Data Preparation: Cost Data

- The flow of creating realistic cost data.
  - Public databases and statistics were used to determine the generator type and cost ranges;
  - The created cost data is stored in PSSE OPF raw data format, which supports piecewise linear, piecewise quadratic, and polynomial and exponential costs.



Data Preparation: Cost Data

- The generation cost data is created based on several online data sources.
  - The levelized cost of electricity (LCOE) for different generation resources from U.S. Energy Information Administration.
  - The generation types are retrieved from the Power Plant Owner Reporting Database published by California Energy Commission (QFER CEC-1304 .)
- Two types of costs are assigned to the generations: linear and piece-wise linear costs.
- The cost values are drawn randomly following uniform distribution from the range of the LCOE.

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Data Preparation: LCOE Table

Plant Type	Range for Total System LCOE (2012 $/MWh)			Range for Total LCOE with Subsidies[1] (2012 $/MWh)		
	Minimum	Average	Maximum	Minimum	Average	Maximum
Dispatchable Technologies						
Conventional Coal	87.0	95.6	114.4			
IGCC	106.4	115.9	131.5			
IGCC with CCS	137.3	147.4	163.3			
Natural Gas-fired						
Conventional Combined Cycle	61.1	66.3	75.8			
Advanced Combined Cycle	59.6	64.4	73.6			
Advanced CC with CCS	85.5	91.3	105.0			
Conventional Combustion Turbine	106.0	128.4	149.4			
Advanced Combustion Turbine	96.9	103.8	119.8			
Advanced Nuclear	92.6	96.1	102.0	82.6	86.1	92.0
Geothermal	46.2	47.9	50.3	43.1	44.5	46.4
Biomass	92.3	102.6	122.9			
Non-Dispatchable Technologies						
Wind	71.3	80.3	90.3			
Wind – Offshore	168.7	204.1	271.0			
Solar PV[2]	101.4	130.0	200.9	92.6	118.6	182.6
Solar Thermal	176.8	243.1	388.0	162.6	223.6	356.7
Hydroelectric[3]	61.6	84.5	137.7			

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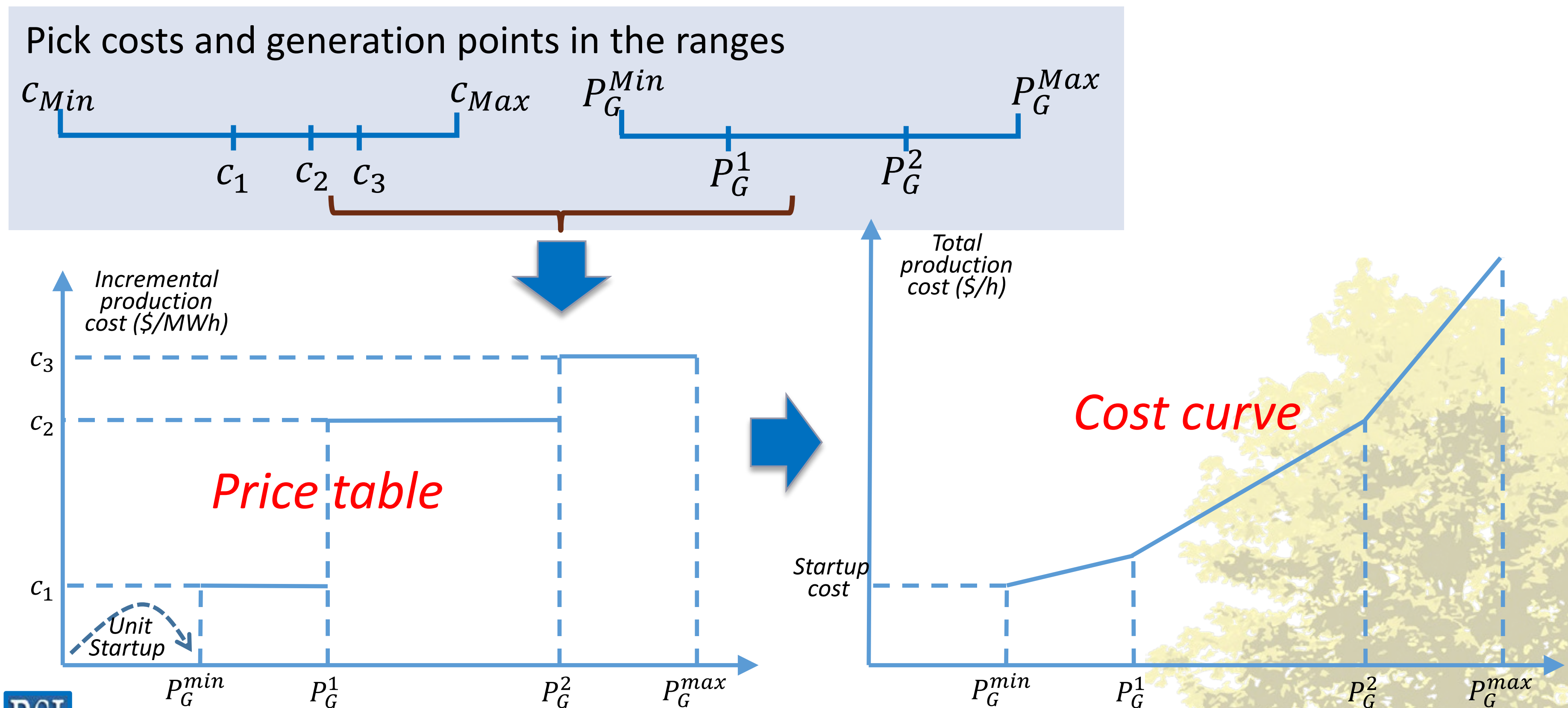
Data Preparation: Piece-wise Linear Costs

- Piece-wise linear costs are assigned to 10% of generators, each has 2 to 5 cost segments in the range of the minimal and maximal generations.

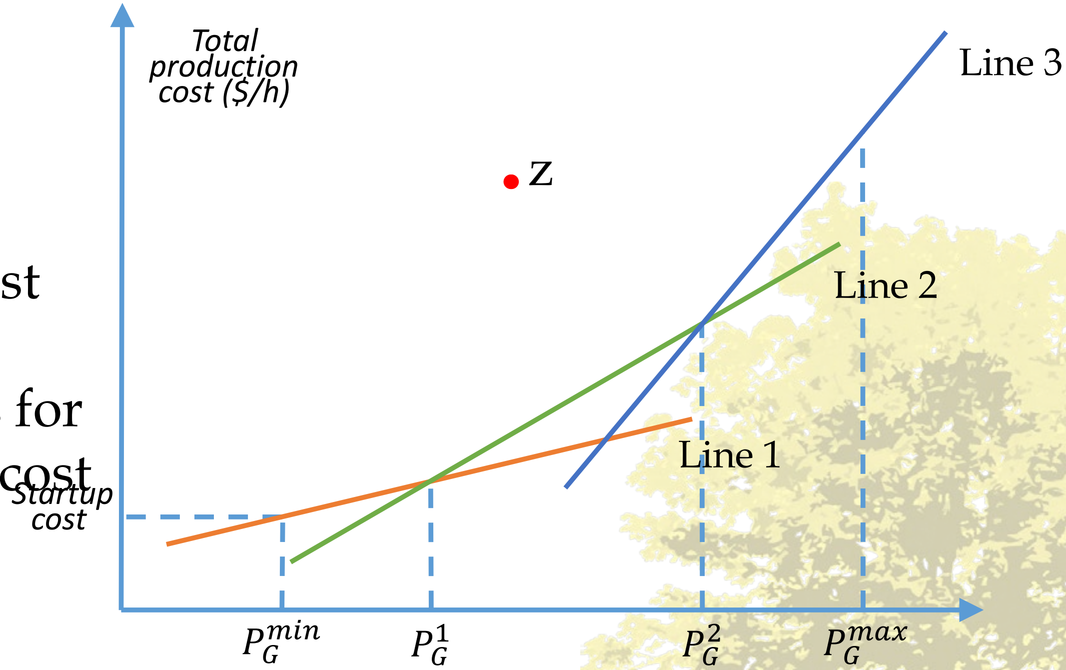


Program Changes

- To support piece-wise linear cost functions, program was upgraded to automatically build the new OPF formulation.
- A proxy cost variable, noted as z_i for i-th generator with piece-wise linear cost, is added to the OPF problem formulation, along with the following new set of proxy constraints:

$$z_i \geq a_{i1}P_i + b_{i1}$$
$$z_i \geq a_{i2}P_i + b_{i2},$$
$$\cdots\cdots$$
$$z_i \geq a_{iK}P_i + b_{iK}$$

where, K is the number of cost segments, $a_{1i}, \cdots, a_{Ki}$ and $b_{1i}, \ldots, b_{Ki}$ are the parameters for the lines associated with the cost segments



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Loading Conditions

- BSI's voltage stability analysis (VSA) program is used to perform a CPFLOW computation on the test system
- The "SDGE+CFE-BG-LOAD_INC" loading pattern is simulated: loads are increased in area 11 "SDGE-22"
- Power flow solutions are computed until the nose point of the P-V curves is reached, beyond which no power flow solutions exist.
- These power flow solutions are used as the initial conditions for OPF. These power flow solutions under different loading conditions can have violations and may not be feasible.

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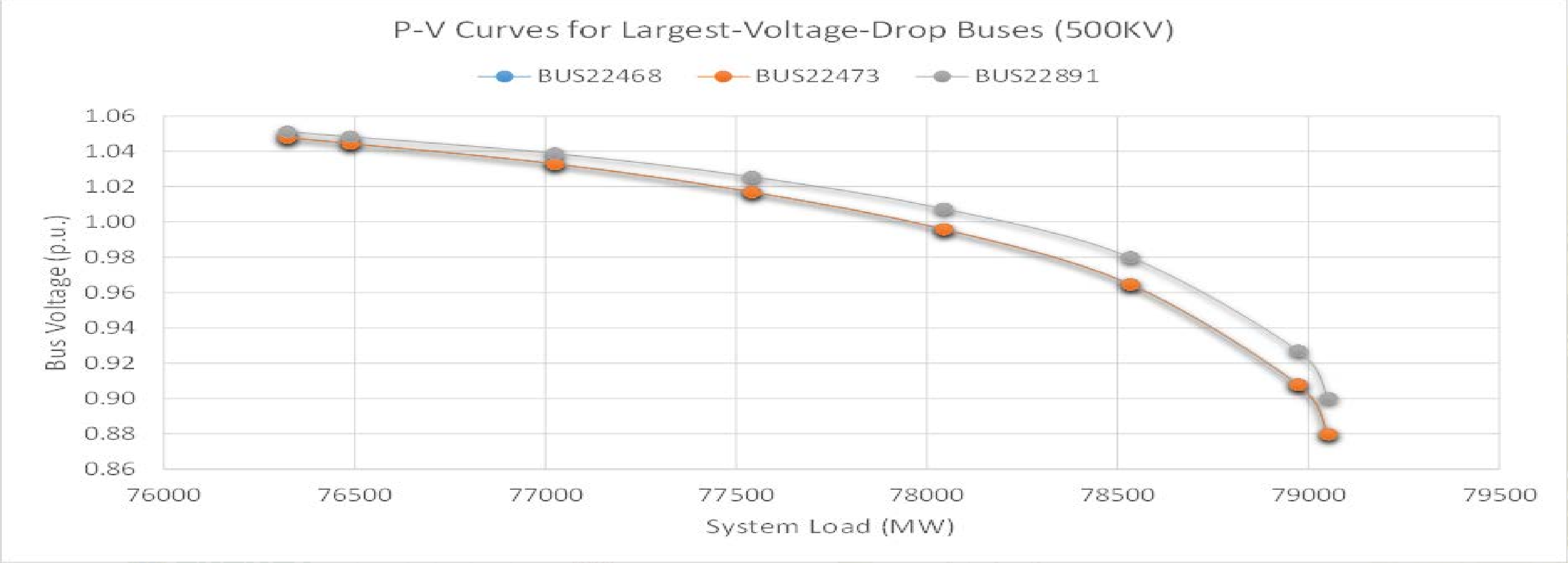
Loading Conditions

Case	1	2	3	4	5	6	7	8
Load (MW)	76323.36	76489.11	77024.66	77541.53	78044.94	78532.81	78972.60	79052.42
Violations	#V: 41	#V: 41	#V: 37	#V: 42	#V: 49	#V: 49	#V: 180 #T: 1	#V: 215 #T: 1

Basecase system load margin: 2738.8MW. ("#V" for the number of voltage magnitude violations, "#T" for the number of thermal limit violations)



Simulation Results

- Base-case Optimization
- Worst Contingencies and Post-Contingency Optimization
- Base-case + Individual Contingency Co-optimization
- Base-case + All Contingency Co-optimization

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Results: Basecase Optimization

- SuperOPF for system power loss and production cost minimization on the base-case system under different loading conditions.
- Infeasibility for the two heaviest loading conditions, validated using our feasibility tool.

Case	SEM	SEP	SEP Energy	Violations for SEP
7	None	1	2.92×10^{-4}	Six voltages with violations greater 0.001 p.u. ., which the largest being 0.0114 p.u.
8	None	1	3.91×10^{-4}	Seven voltages with violations greater 0.001 p.u., which the largest being 0.0124 p.u.

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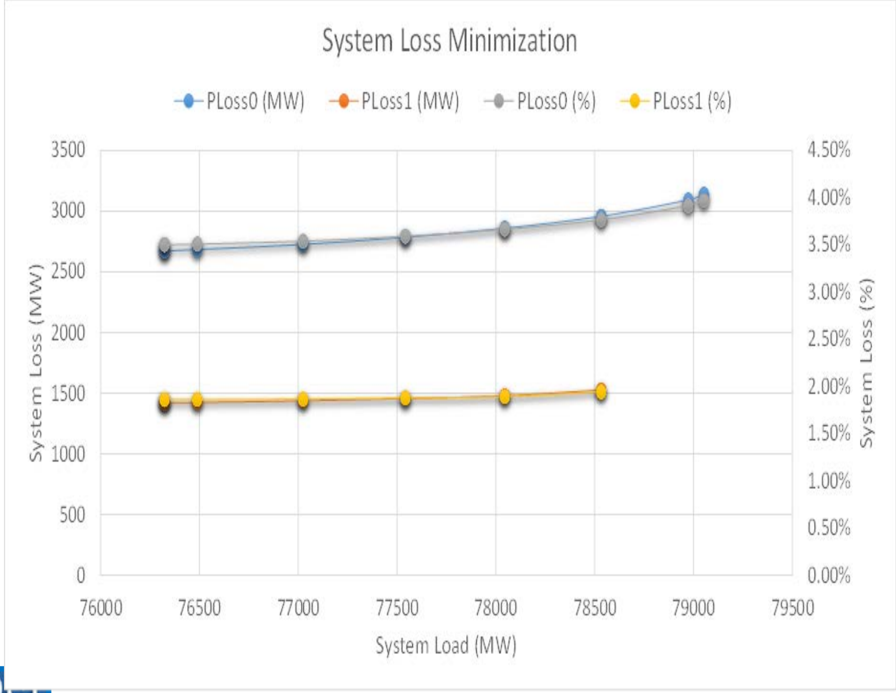
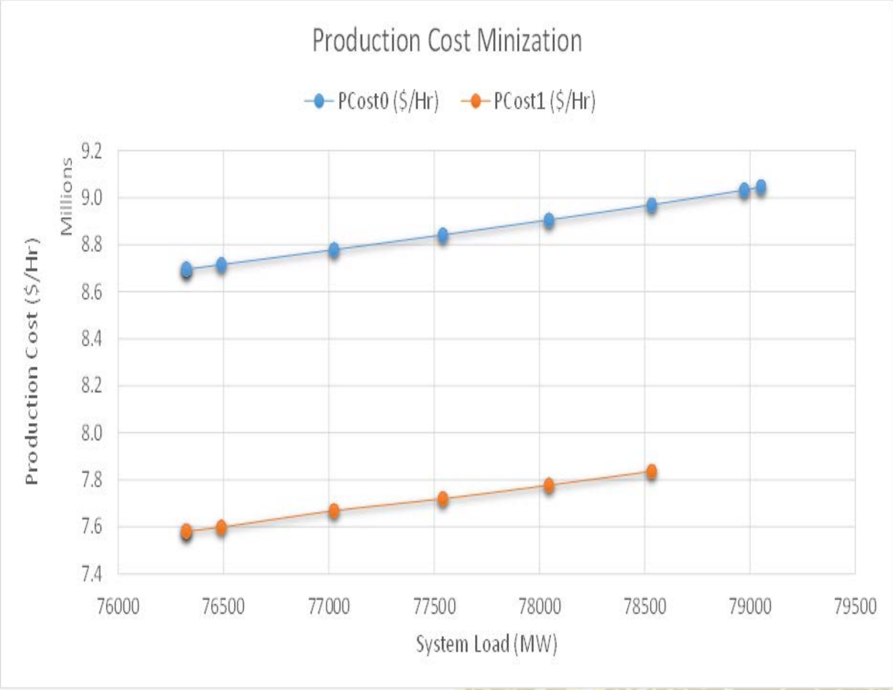
Results: Basecase Optimization

- SuperOPF solver can robustly compute the OPF solutions under all feasible loading conditions.
- SuperOPF can effectively reduce system losses (~48%) and production costs (~13%) under all loading conditions.





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Results: Base-case Optimization

- IPM failed to converge in four out of six feasible cases.
- In contrast, SuperOPF can still successfully converge on all loading conditions.

Case	Load (MW)	IPM	SuperOPF
1	76323.36	Failed	Converged
2	76489.11	Converged	Converged
3	77024.66	Failed	Converged
4	77541.53	Failed	Converged
5	78044.94	Converged	Converged
6	78532.81	Failed	Converged
7	78972.60	Problem infeasible	
8	79052.42	Problem infeasible	

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Results: Worst Contingencies

- "N-1" transmission line contingencies are generated.
- BSI VSA is used to estimate load margins for the post-contingency systems.
- Two insecure contingencies with zero load margins are identified.

Ctg ID	Details	Load Margin
0	Basecase	2738.8MW
558	DISCONNECT BRANCH FROM BUS 11217 TO BUS 11093 CKT 1 /* AFTON-LUNA 345.0 KV Line	0MW
2909	DISCONNECT BRANCH FROM BUS 34774 TO BUS 34776 CKT 1 /* MIDWAY-TAFT 115.0 KV Line	0MW

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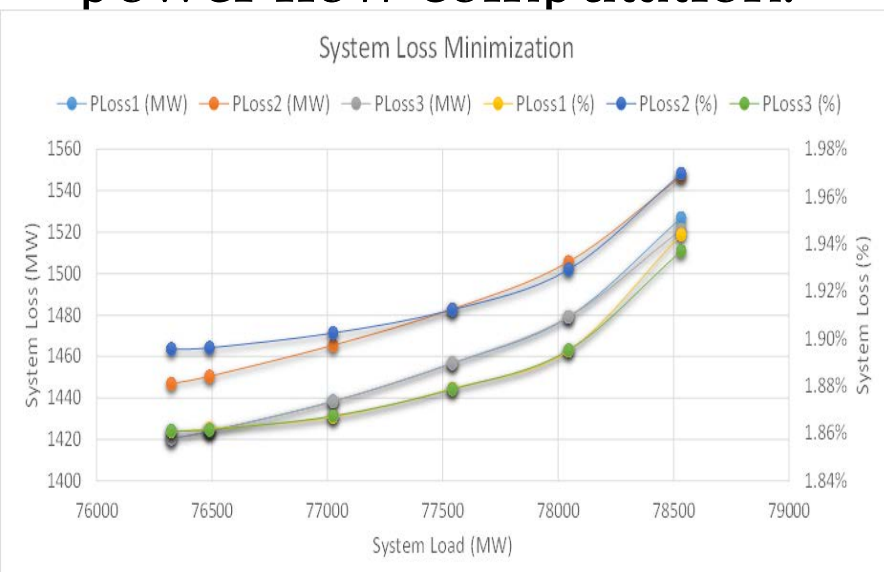
Results: Worst Contingencies

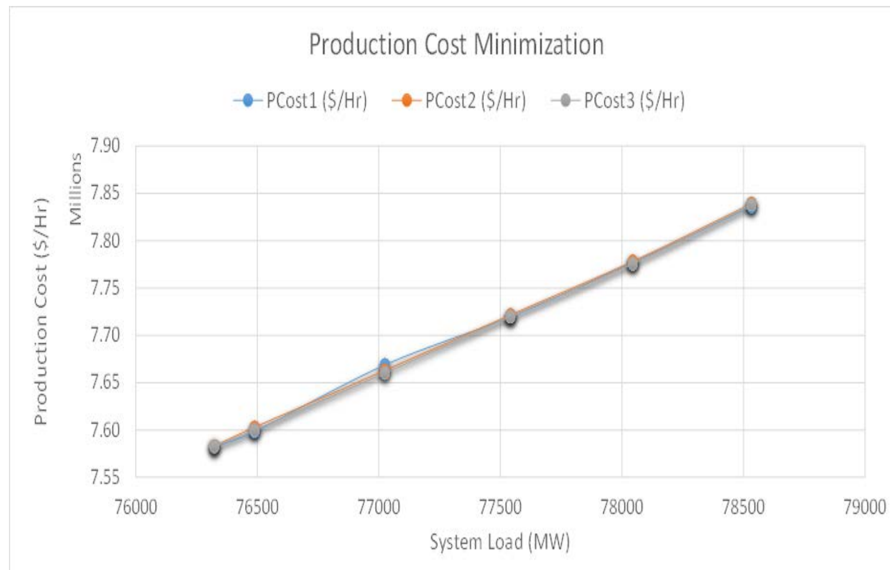
- OPF computation for post-contingency systems.
- IPM diverged for seven among 24 cases.
- SuperOPF solver converged for both post-contingency systems under all loading conditions.

Case	Load (MW)	IPM				SuperOPF
		Loss Minimization		Cost Minimization		
		Ctg_558	Ctg_2909	Ctg_558	Ctg_2909	
1	76323.36	Converged	Converged	Converged	Converged	Converged
2	76489.11	Converged	Failed	Converged	Converged	Converged
3	77024.66	Converged	Converged	Failed	Failed	Converged
4	77541.53	Converged	Converged	Converged	Converged	Converged
5	78044.94	Converged	Converged	Converged	Failed	Converged
6	78532.81	Failed	Failed	Failed	Converged	Converged

Results: Worst Contingencies

- SuperOPF can robustly compute OPF solutions under all feasible loading conditions, even though the post-contingency systems are insecure.
- This is due to more controllable generations available for OPF computation, instead of the single slack generator for power flow computation.





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Results: Worst Contingencies

- Since only one transmission line is taken out in the "N-1" contingencies, its impact on the resulted post-contingency system losses is not significant.
- Contingencies not necessary always increase the OPF losses. For the loading condition 6, contingency #558 in fact result better loss reduction compared to the basecase OPF (i.e. line switching).

Results: Basecase + Single Contingency

- Co-optimizing the basecase and single worst contingency.
- IPM diverged for 14 among 24 cases, more failure cases as problems become more complicated.
- SuperOPF solver converged for all cases.

Case	Load (MW)	IPM				SuperOPF
		Loss Minimization		Cost Minimization		
		Ctg_558	Ctg_2909	Ctg_558	Ctg_2909	
1	76323.36	Converged	Failed	Failed	Failed	Converged
2	76489.11	Converged	Failed	Failed	Failed	Converged
3	77024.66	Converged	Failed	Converged	Failed	Converged
4	77541.53	Converged	Failed	Failed	Failed	Converged
5	78044.94	Converged	Converged	Converged	Converged	Converged
6	78532.81	Failed	Converged	Failed	Failed	Converged

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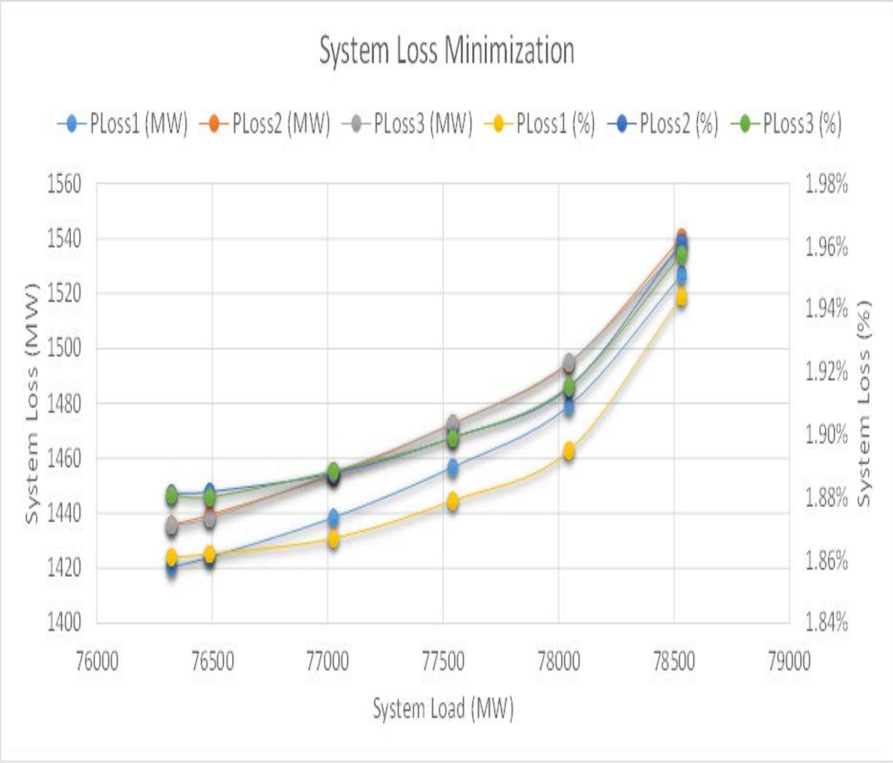
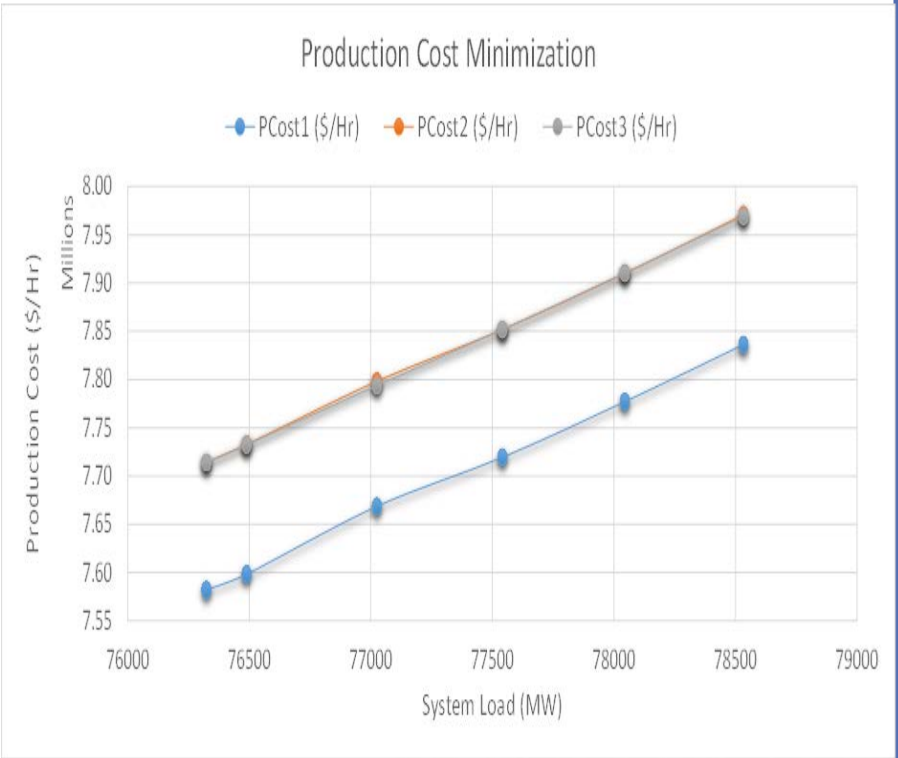
Results: Basecase + Single Contingency

- SuperOPF can robustly co-optimize the basecase system with worst contingency constraints under all feasible loading conditions.





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Results: Basecase + All Contingencies

- Co-optimizing the base-case and both worst contingencies.
- IPM diverged for 8 among 12 cases (fail with 66%), more failure cases as problems become more complicated.
- SuperOPF solver converged for all cases.

Case	Load (MW)	IPM		SuperOPF
		Loss Minimization	Cost Minimization	
1	76323.36	Failed	Failed	Converged
2	76489.11	Converged	Failed	Converged
3	77024.66	Failed	Failed	Converged
4	77541.53	Failed	Failed	Converged
5	78044.94	Converged	Converged	Converged
6	78532.81	Converged	Failed	Converged

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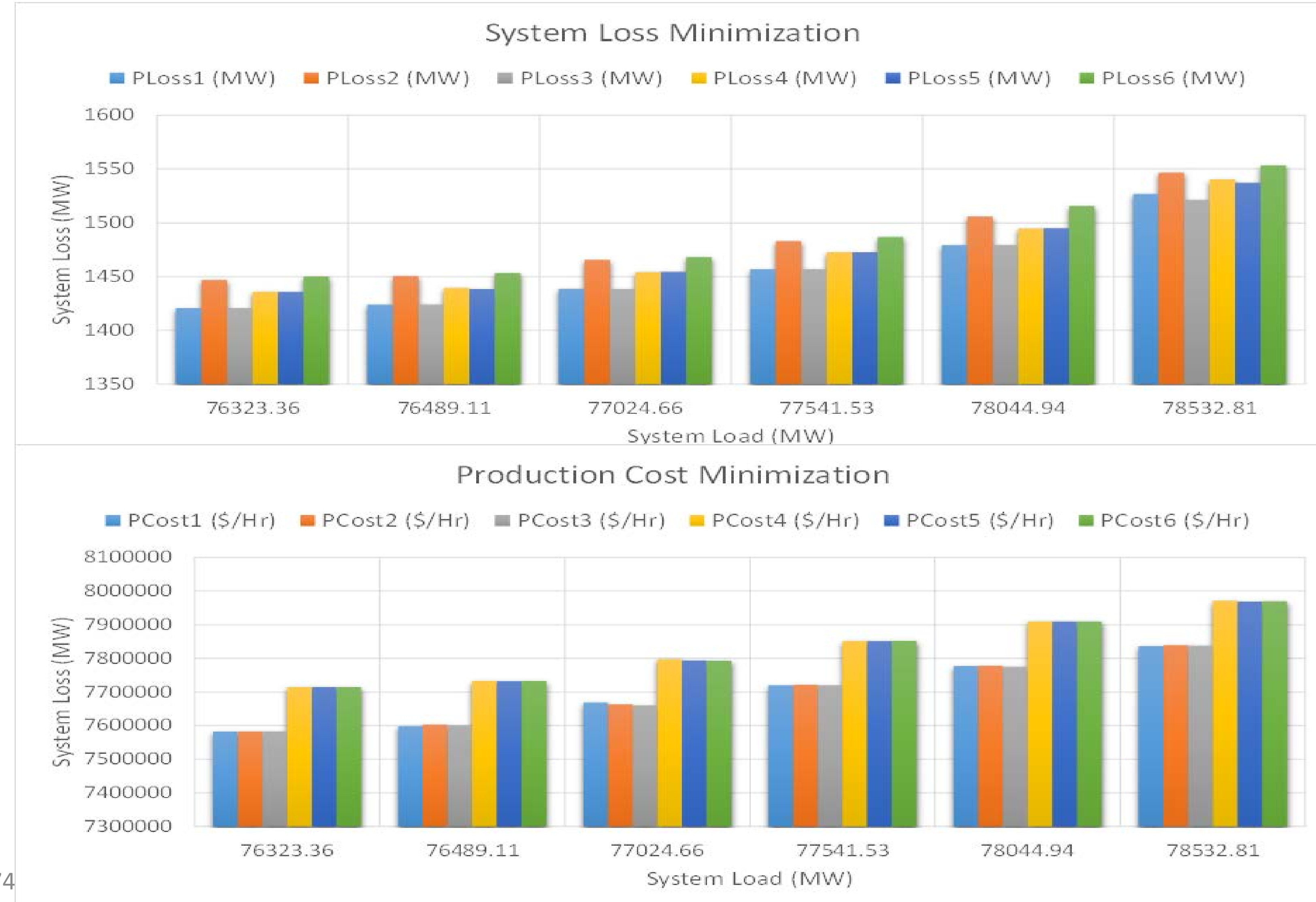
Results: Base-case + All Contingencies

- SuperOPF can still robustly co-optimize the basecase system with both worst contingency constraints under all feasible loading conditions.
- The computational time is roughly linear (per iteration) w.r.t. to the optimization problem size (the number of optimization variables and the number of constraints), which is doubled for “basecase+single contingency”, and tripled for “basecase+all contingencies”.

Results: Combined Objective Values



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Results: Combined Objective Values

- The result data tables
  - System loss minimization

Load (MW)	PLoss1 (MW)	PLoss2 (MW)	PLoss3 (MW)	PLoss4 (MW)	PLoss5 (MW)	PLoss6 (MW)
76323.4	1420.4	1446.84	1420.5	1435.87	1435.57	1449.96
76489.1	1423.96	1450.42	1423.95	1439.39	1438.14	1453.26
77024.7	1438.4	1465.40	1438.36	1454.05	1454.58	1468.05
77541.5	1456.76	1482.84	1456.8	1472.60	1472.51	1486.65
78044.9	1479.1	1505.67	1479.1	1494.63	1494.91	1515.52
78532.8	1526.84	1546.86	1521.26	1540.30	1537.25	1553.22

  - Production cost minimization

Load (MW)	PCost1 ($/Hr)	PCost2 ($/Hr)	PCost3 ($/Hr)	PCost4 ($/Hr)	PCost5 ($/Hr)	PCost6 ($/Hr)
76323.36	7582236.18	7582858.57	7582601.81	7714212.64	7714114.04	7714284.52
76489.11	7598383.37	7602631.16	7599915.84	7732790.7	7732559.2	7732869.31
77024.66	7668672.15	7662677.88	7659999.27	7798172.14	7793811.69	7793250.29
77541.53	7719517.58	7721382.9	7719793.49	7851769.17	7851824.31	7851992.34
78044.94	7777127.93	7777963.71	7775321.97	7910018.53	7910470.52	7910274.56
78532.81	7836365.4	7839068.25	7838036.41	7970888.42	7969248.91	7970107.54

1: Basecase, 2: Ctg558, 3: Ctg2909, 4: Base+Ctg558, 5: Base+Ctg2909, 6: Base+Ctg558+2909

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Results: Combined CPU Times and Iterations

- The result data tables
  - System loss minimization

Load (MW)	Iters1	Time1	Iters2	Time2	Iters3	Time3	Iters4	Time4	Iters5	Time5	Iters6	Time6
76323.4	77	7.95	168	17.57	80	8.4	63	14.86	123	37.63	215	134.73
76489.1	149	15.47	160	17.12	83	12.86	146	34.89	189	53.72	173	70.16
77024.7	96	10.07	176	18.26	138	14.55	225	52.94	145	44.62	133	64.52
77541.5	82	8.51	81	8.34	107	11.56	228	55.06	61	24.22	118	72.98
78044.9	45	4.67	169	17.45	84	8.75	123	28.71	111	22.32	237	123.66
78532.8	84	8.69	101	14.33	50	9.34	227	64.66	92	21.69	69	33.69

  - Production cost minimization

Load (MW)	Iters1	Time1	Iters2	Time2	Iters3	Time3	Iters4	Time4	Iters5	Time5	Iters6	Time6
76323.4	59	8.58	55	5.79	44	4.61	63	31.45	82	36.2	84	60.41
76489.1	45	7.2	66	6.95	42	4.4	61	20.7	105	42.17	89	43.8
77024.7	67	9.55	53	8.15	57	13.44	149	35.47	62	31.38	87	79.41
77541.5	43	7	40	4.25	55	5.92	51	29.49	71	33.91	186	134.71
78044.9	42	7.49	65	6.97	91	15.62	142	34.21	81	19.36	77	26.9
78532.8	76	10.55	55	8.36	78	8.4	264	81.39	181	60.2	303	169.59

1: Basecase, 2: Ctg558, 3: Ctg2909, 4: Base+Ctg558, 5: Base+Ctg2909, 6: Base+Ctg558+2909

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Summary

- Highlights of SuperOPF
  - Comprehensive and flexible AC OPF modeling capability.
  - Reliable and effective large-scale power networks (>80,000 buses) optimization.
  - Contingency- and renewable-constrained co-optimization for system security and power market.
  - Robustness to loading conditions and contingencies.
  - Comprehensive analysis result reporting and database bridging.
  - Support major power system data formats.

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Thank You!

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