Stochastic Unit Commitment with Topology Control Recourse for Renewables Integration

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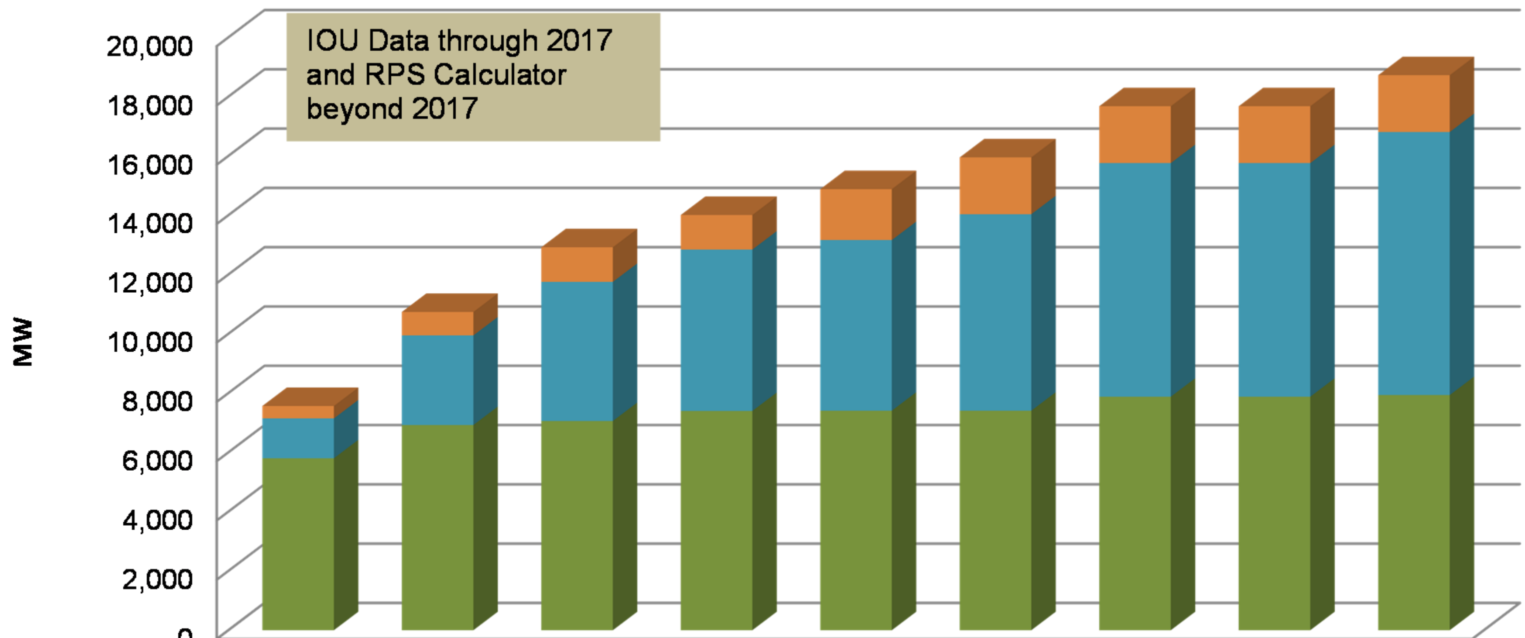
33% RPS - Cumulative expected VERs build-out through 2020

33% RPS --- Variable Resources Expected Build-out Through 2020

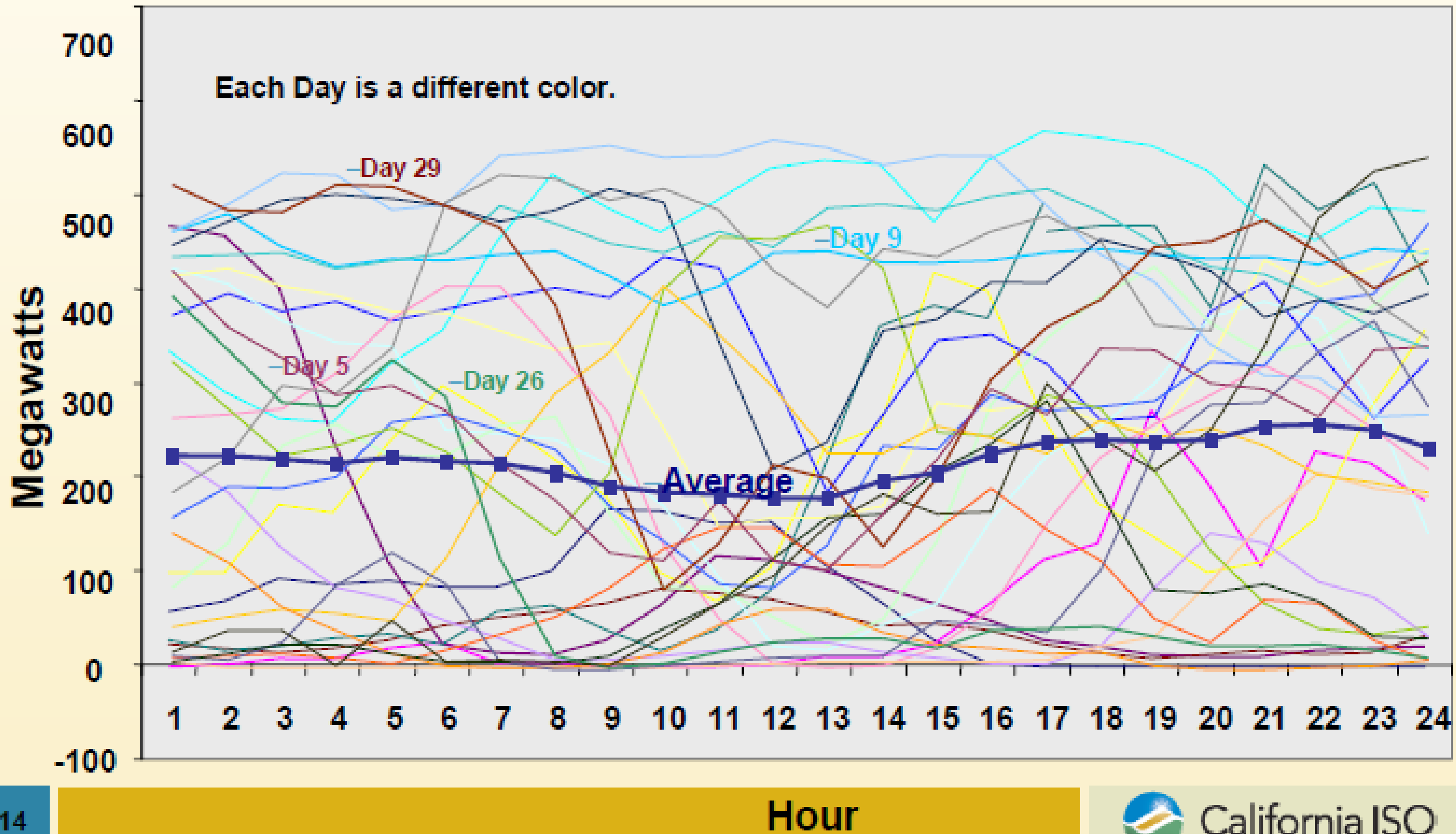


	2012 Existing	2013	2014	2015	2016	2017	2018	2019	2020
Solar Thermal	419	792	1,167	1,167	1,717	1,917	1,917	1,917	1,917
Solar PV	1,345	3,022	4,693	5,445	5,756	6,628	7,881	7,881	8,872
Wind	5,800	6,922	7,058	7,396	7,406	7,406	7,877	7,877	7,934

Source: CAISO

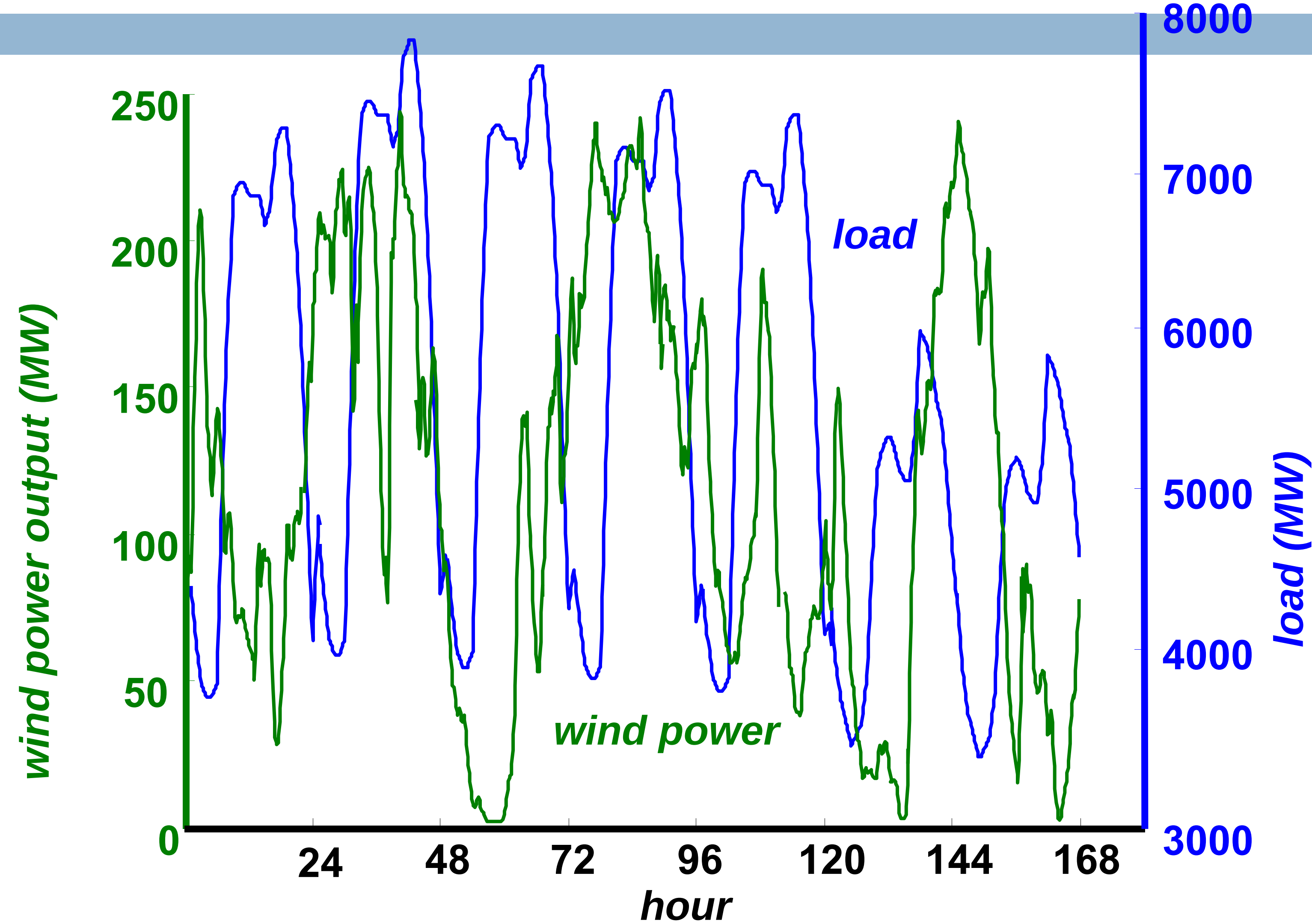
Tehachapi Wind Generation in April – 2005

Could you predict the energy production for this wind park
either day-ahead or 5 hours in advance?



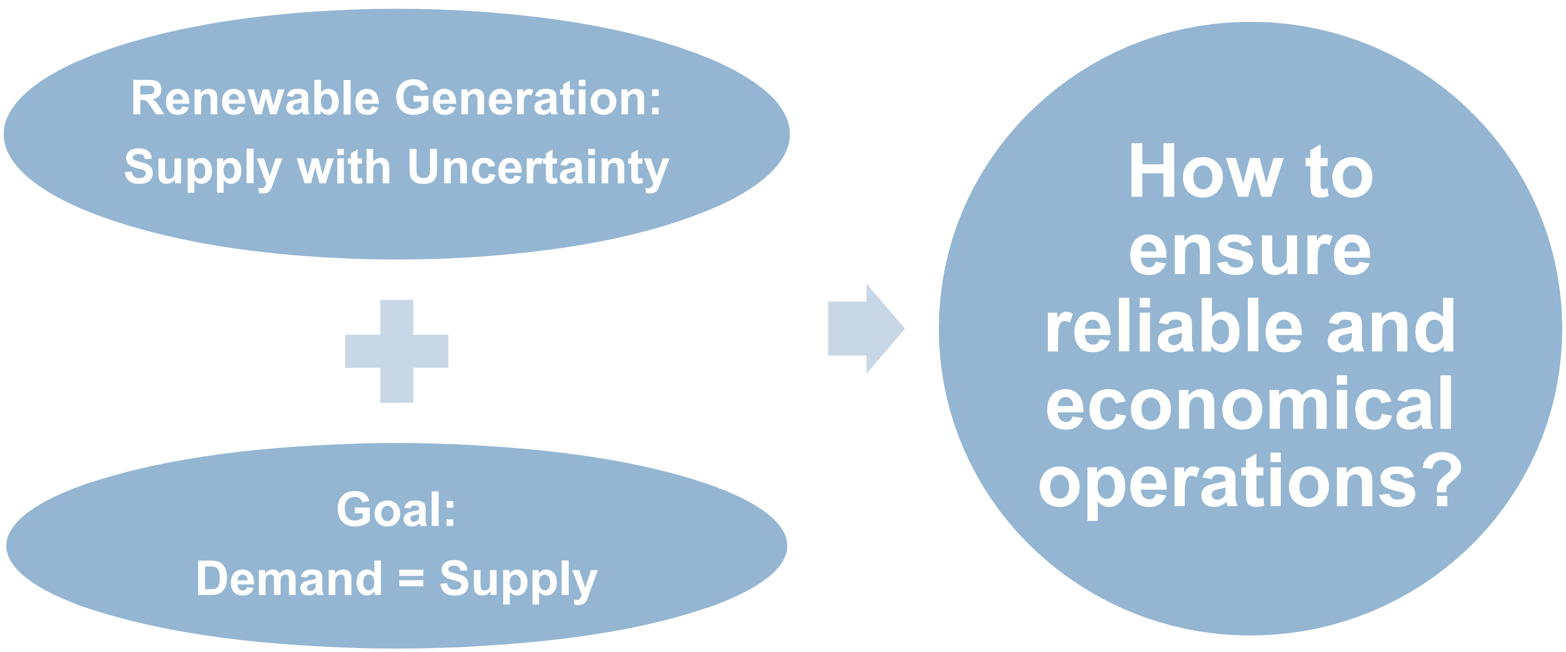
California ISO
Your Link to Power

Negative Correlation with Load



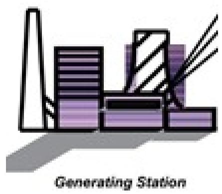
Introduction

- Integration of Renewable Generation
  - Challenge for energy system operations

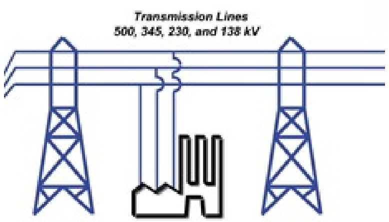


Integration of Renewable Generation

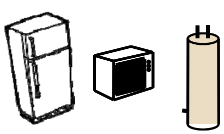
Flexibility



Flexible Generation



Flexible Transmission (Topology Control)



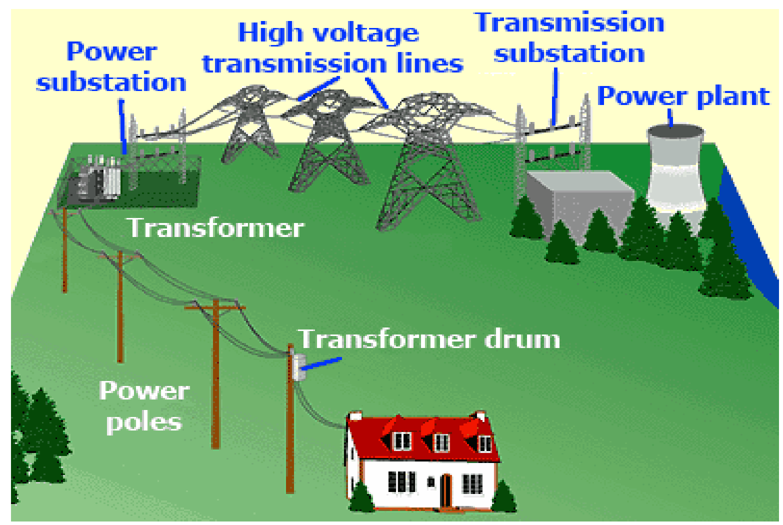
Demand Response

Storage

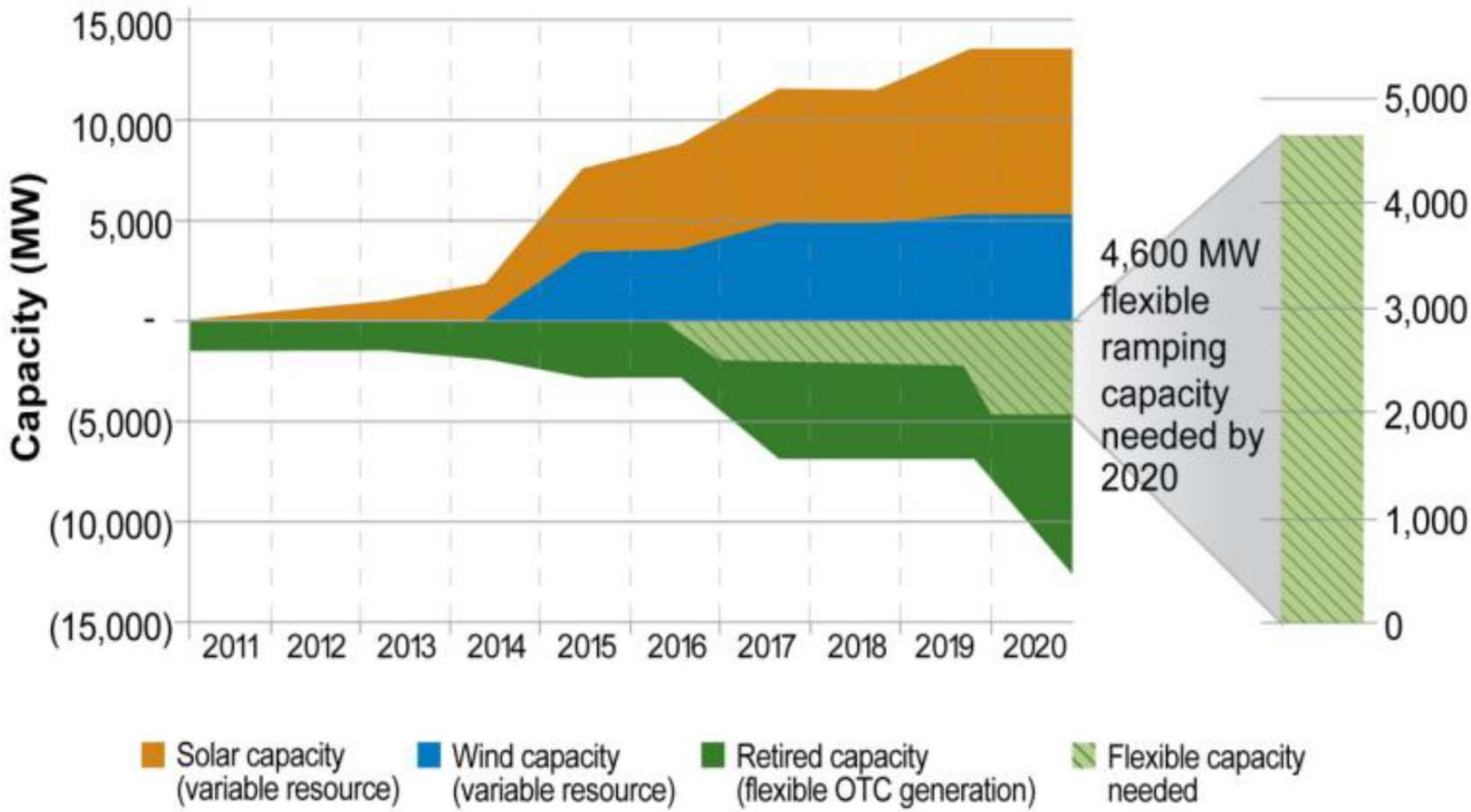
Goal:

Demand = Supply with Uncertainty

$$D_n(t) = S_n(t)$$



Conventional Solution



Source: CAISO

Background

- Topology Control
  - Topology control has been studied to:
    - Relieve abnormal conditions[1]
    - Reduce system loss[2]
    - Reduce operating cost (Optimal Transmission Switching)[3]
  - Utilize existing assets required by normal operating conditions. No additional cost other than the wear of breakers is incurred.

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[1] A. G. Bakirtzis and A. P. Sakis Meliopoulos, “Incorporation of switching operations in power system corrective control computations,” *IEEE Transactions on Power Systems*, vol. PWRS-2, no. 3, pp. 669–675, 1987.
[2] R. Bacher and H. Glavitsch, “Loss reduction by network switching,” *IEEE Transactions on Power Systems*, vol. 3, no. 2, pp. 447–454, 1988.
[3] E. Fisher, R. O’Neill, and M. Ferris, “Optimal transmission switching,” IEEE Transactions on Power Systems, pp. 1–10, 2008.

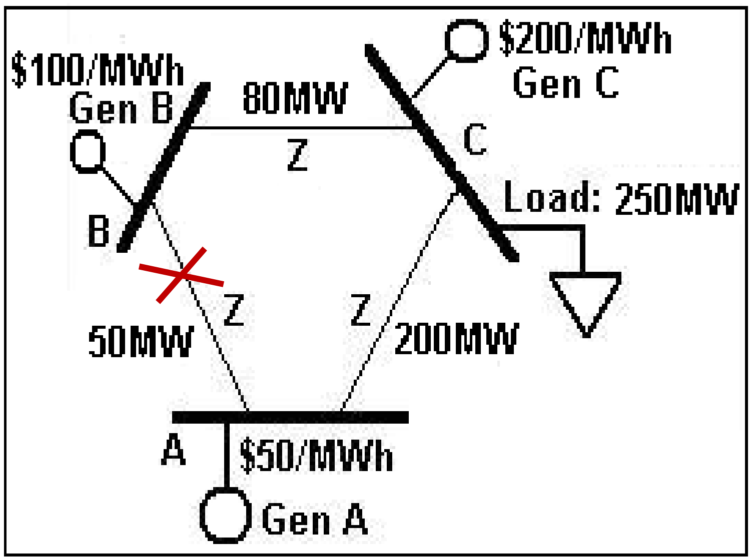
National Directives

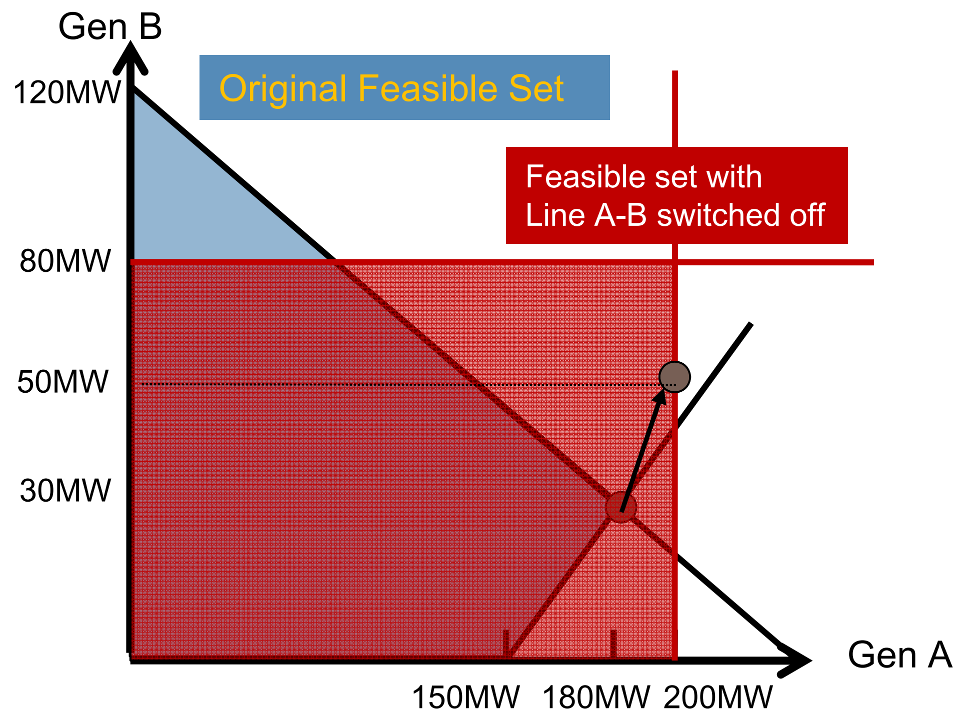
- Federal Energy Regulatory Commission (FERC) Order 890
  - Improve the economic operations of the electric transmission grid
- Energy Policy Act of 2005
  - Sec.1223.a.5 of the US Energy Policy Act of 2005
  - “encourage… deployment of advanced transmission technologies”
  - “optimized transmission line configuration”
- Energy Independence and Security Act of 2007
  - Title 13, Smart Grid:
  - “increased use of … controls technology to improve reliability, stability, and efficiency of the grid”
  - “dynamic optimization of grid operations and resources”

How?

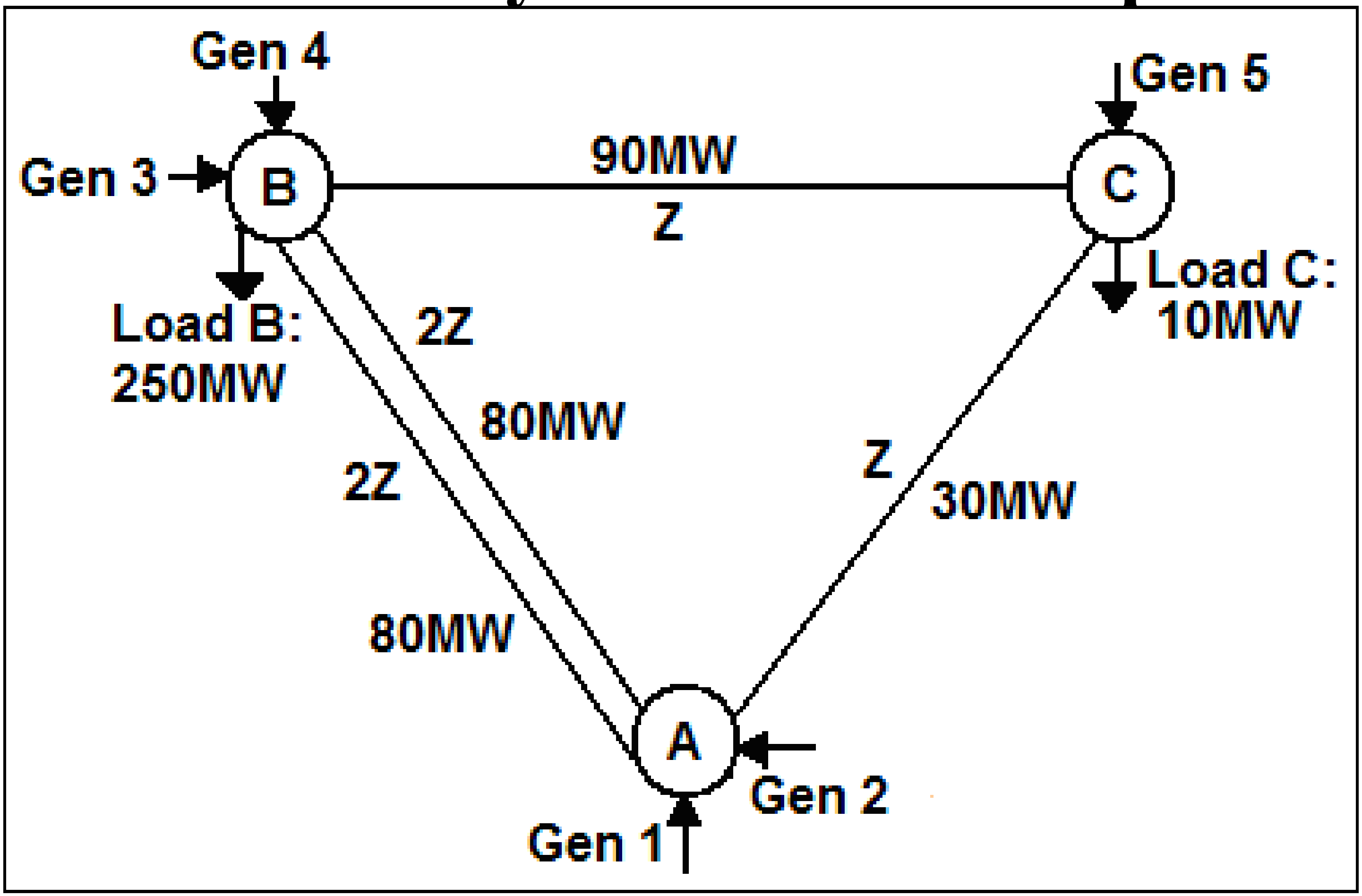
Original Optimal Cost: $20,000 (A=180MW,B=30MW, C=40MW)

Open Line A-B, Optimal Cost: $15,000 (A=200MW, B=50MW)





(Does Topology Control Always Degrade Reliability: Counter Example



Generator Info

- Operational costs, startup costs, shutdown costs, min & max operating levels, ramp rates
- N-1 is enforced
  - System must have adequate 10 minute spinning reserve online to respond to any contingency (line or generator)

Table 1 Generator Information

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
Cost $/MWh	25	20	80	80	100
Startup Cost $	100	100	300	500	400
Gen Min MW	50	50	10	50	10
Gen Max MW	400	100	250	100	150
Ramp Rate MW/10 min	200	100	50	50	150

Optimal Solutions & Impact on Reliability

- Optimal N-1 compliant solution with static topology:
  - Solution cannot handle loss of generators 3 and 4

Table 2 Case 1: Optimal Solution without Transmission Switching

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	**Total Cost:**
Optimal Dispatch	Offline	100	40	100	20	**$16,900**

- Optimal N-1 compliant solution with smart switching (line A-C open)
  - Solution can handle loss of generators 3 and 4

Table 3 Case 2: Optimal Solution with Transmission Switching (line A-C open)

	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	**Total Cost:**
Optimal Dispatch	160	Offline	10	80	10	**$13,700**

Superstorm Sandy

- PJM lost 82 bulk electric facilities
  - 6 500kV transmission assets; 3 345kV transmission assets ; 39 230kV transmission assets; 25 138kV transmission assets
- Caused extremely high voltage on the system during low load levels
- "We were dealing with extremely high voltage on the system but a switching plan was developed to help alleviate these conditions."
- Per Andy Ott, VP of PJM: several 500kV lines were switched out to mitigate over voltage concerns during these low load level periods

Topology Control as Recourse

- Topology Control
  - In deterministic unit commitment, topology control can reduce the generation cost[4] and mitigate post contingency violations
  - In stochastic unit commitment, topology control as a recourse action may leverage the grid controllability and mitigate the variability of renewable generation.

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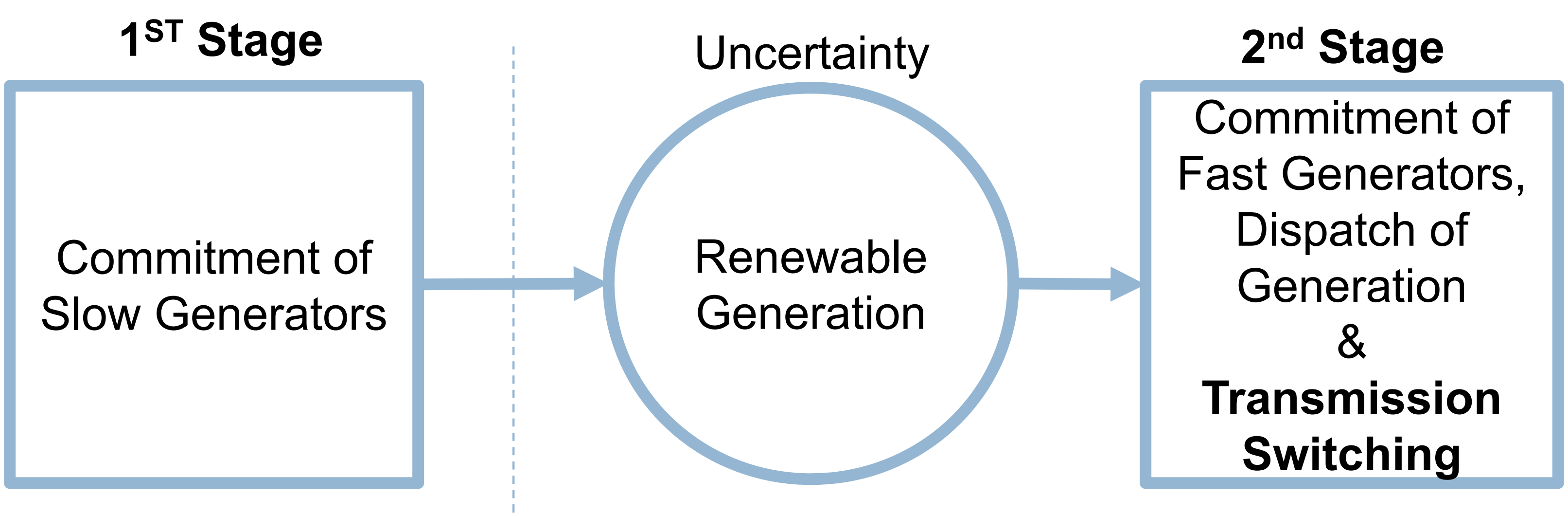
[4] K. Hedman and M. Ferris, and et al. "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," *IEEE Transactions on Power Systems* vol. 25, no. 2, pp. 1052–1063, 2010.

Scope

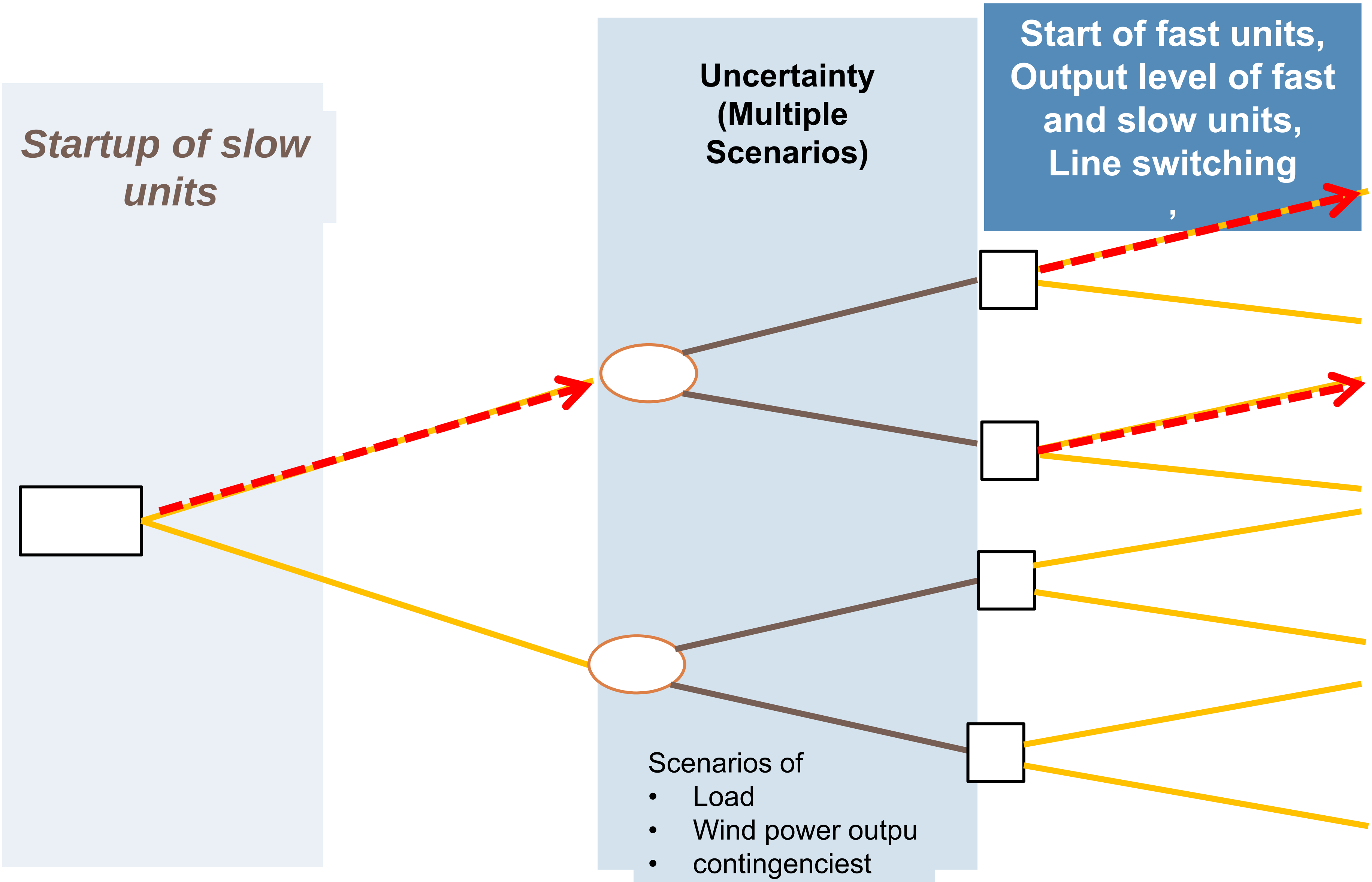
- Include the uncertainty of wind generation in the model of power system day-ahead scheduling.
- Examine whether the operation cost can be reduced in stochastic unit commitment when topology control is introduced in the recourse.

Formulation

- Two-stage Stochastic Programming
  - Objective : minimize the operating cost
  - Decision variables:



Decision Structure



Formulation

- Constraints
  - System-wide constraints
    - Market clearing
    - DC power flow
    - Line capacity
    - Number of lines that can be switched off
  - Generator constraints
    - Generation capacity
    - Ramping up/down
    - Min up/down time
    - On/off transition

DC power flow and Line capacity:

$$-\mathrm{M}_{ij}\left(1-r_{ij,t,s}\right)\leq F_{ij,t,s}-B_{ij}\left(\theta_{i,t,s}-\theta_{j,t,s}\right)\leq \mathrm{M}_{ij}\left(1-r_{ij,t,s}\right)$$

$$-r_{ij,t,s}F_{ij}^{\max}\leq F_{ij,t,s}\leq r_{ij,t,s}F_{ij}^{\max}$$

Formulation

$$\min \sum_{t\in T}\left(\sum_{g\in GS}\left(\alpha_g s_{g,t}+\beta_g u_{g,t}\right)+\sum_{s\in S}\pi_s\left(\sum_{g\in GF}\left(\alpha_g s_{g,t,s}+\beta_g u_{g,t,s}+c_g P_{g,t,s}\right)+\sum_{g\in GS} c_g P_{g,t,s}+\sum_{i\in N}\rho_i L_{i,t,s}\right)\right)$$

$$s.t. \sum_{\substack{i\in N\\ j\in N}} F_{ij,t,s}-\sum_{\substack{k\in N\\ i\in N}} F_{ki,t,s}+\sum_{\substack{g\in GF\\ g \text{ on bus } i}} P_{g,t,s}+\sum_{\substack{g\in GS\\ g \text{ on bus } i}} P_{g,t}+\sum_{\substack{g\in W\\ g \text{ on bus } i}} W_{g,t,s}-D_{i,t}+L_{i,t,s}=0, \forall i\in N, t\in T, s\in S$$

$$P_g^{\min}u_{g,t,s}\le P_{g,t,s}\le P_g^{\max}u_{g,t,s}, \forall g\in GF, t\in T, s\in S$$

$$P_g^{\min}u_{g,t}\le P_{g,t}\le P_g^{\max}u_{g,t}, \forall g\in GS, t\in T$$

$$P_{g,t,s}-P_{g,t-1,s}\le R_g^u, \forall g\in GF, t\in T, t\ge 1, s\in S$$

$$P_{g,t-1,s}-P_{g,t,s}\le R_g^d, \forall g\in GF, t\in T, t\ge 1, s\in S$$

$$P_{g,t,s}-P_{g,t-1,s}\le R_g^u, \forall g\in GS, t\in T, t\ge 1$$

$$P_{g,t-1,s}-P_{g,t,s}\le R_g^d, \forall g\in GS, t\in T, t\ge 1$$

$$s_{g,t,s}\ge u_{g,t,s}-u_{g,t-1,s}, \forall g\in GF, t\in T, t\ge 1, s\in S$$

$$s_{g,t}\ge u_{g,t}-u_{g,t-1}, \forall g\in GS, t\in T, t\ge 1$$

$$-\mathrm{M}_{ij}\left(1-r_{ij,t,s}\right)\le F_{ij,t,s}-B_{ij}\left(\theta_{i,t,s}-\theta_{j,t,s}\right)\le \mathrm{M}_{ij}\left(1-r_{ij,t,s}\right), \forall i,j\in N, t\in T, s\in S$$

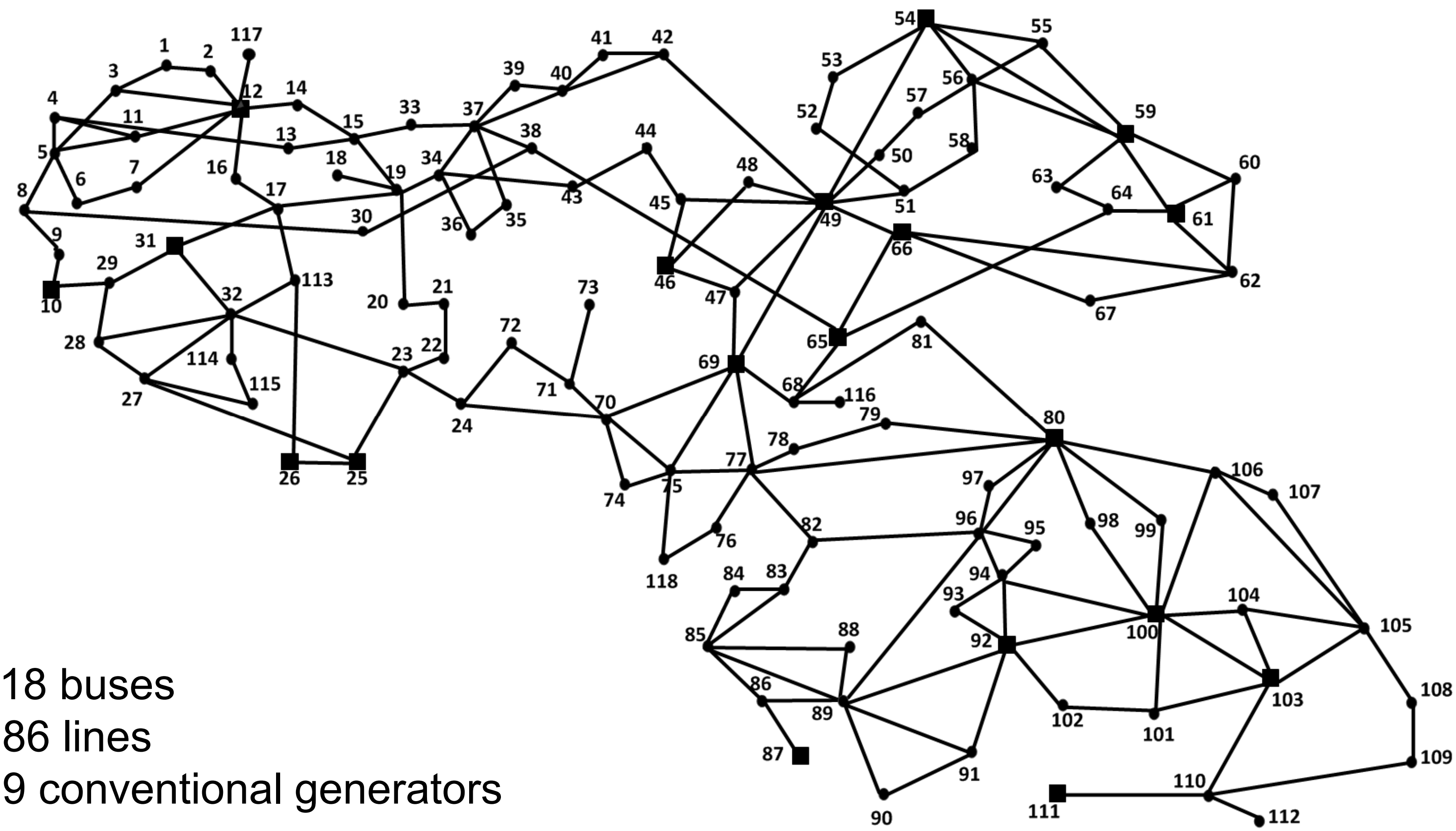
$$-r_{ij,t,s}F_{ij}^{\max}\le F_{ij,t,s}\le r_{ij,t,s}F_{ij}^{\max}, \forall i,j\in N, t\in T, s\in S$$

$$(r_{ij,t,s}\in\{0,1\}\ \forall i,j\in N, u_{g,t,s}\in\{0,1\}\ for\ g\in GF, u_{g,t}\in\{0,1\}\ \text{for } g\in GS), t\in T, s\in S$$

$$(s_{g,t,s}\in\{0,1\}\ for\ g\in GF, s_{g,t}\in\{0,1\}\ \text{for } g\in GS), t\in T, s\in S$$

Test Case

- IEEE 118 system



118 buses
186 lines
19 conventional generators

Wind Modeling

- Wind Generation Simulation
  - In our test, wind speed and wind power data of three locations in Wyoming are obtained from NREL Western Wind Resources Dataset .
  - 1000 wind generation scenarios are generated using the method described in [5].
  - To reduce the computational complexity, we adopt the scenario reduction technique introduced in [6].

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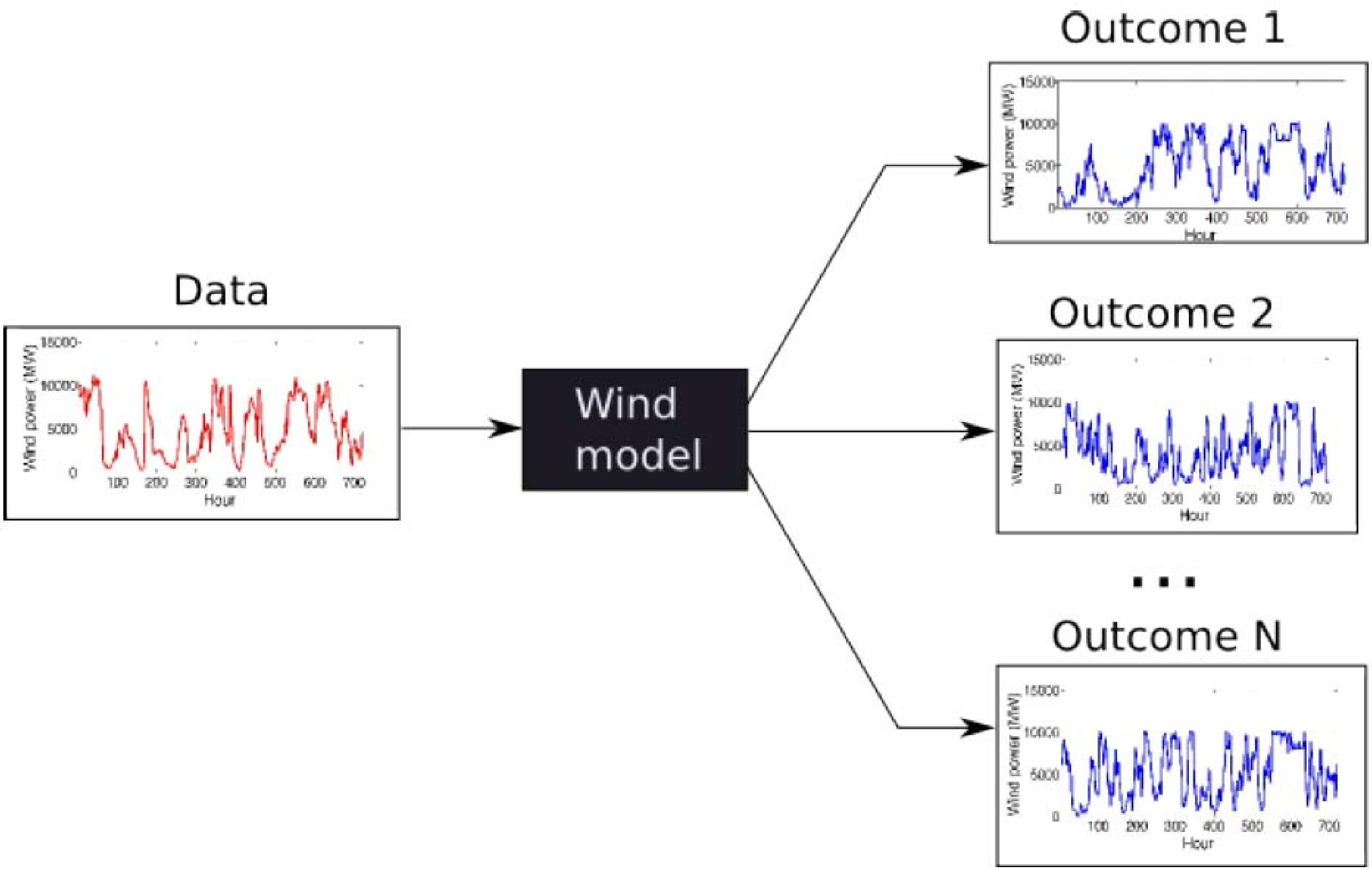
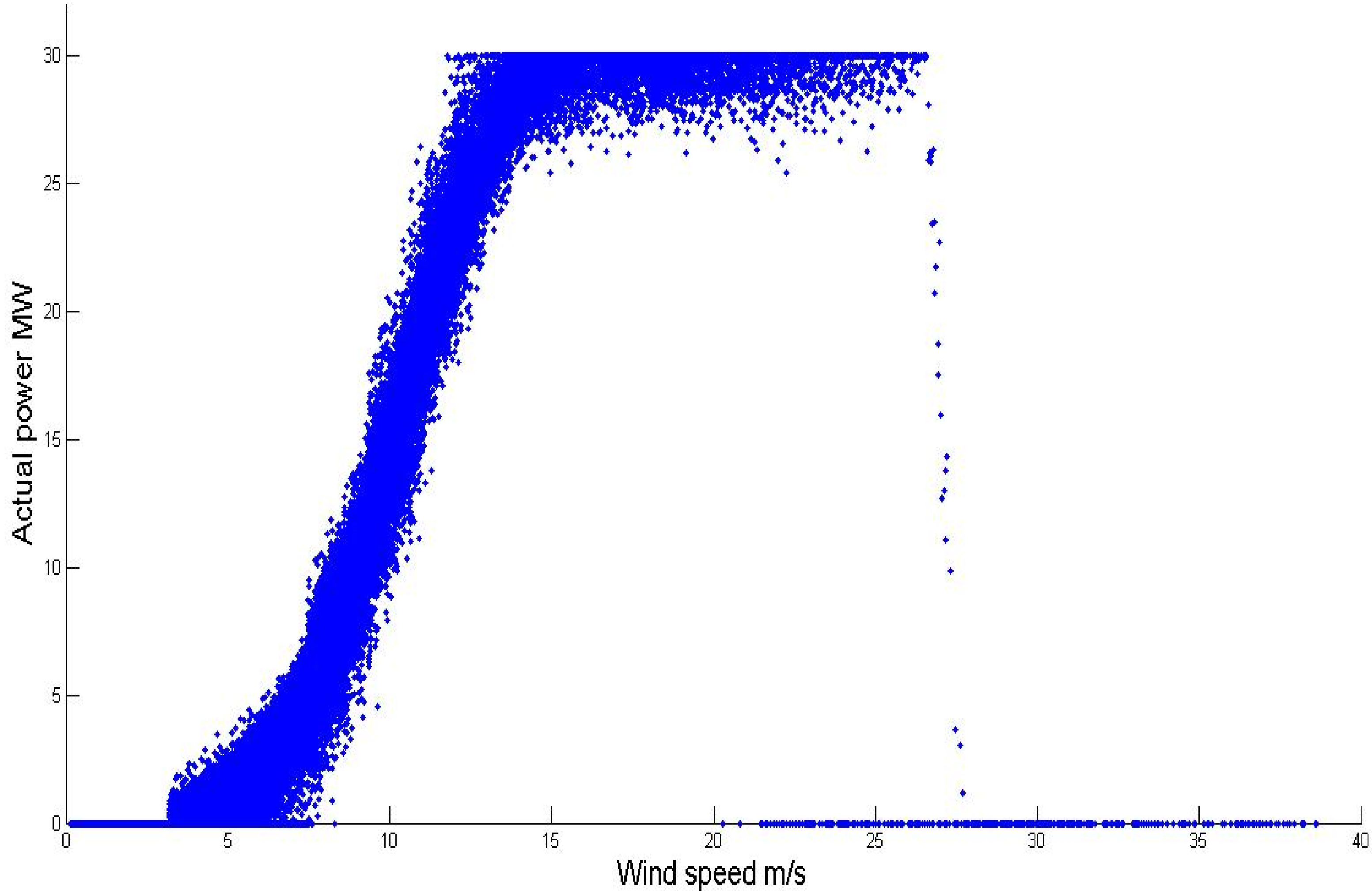
[5] A. Papavasiliou and S. S. Oren, "Multiarea stochastic unit commitment for high wind penetration in a transmission constrained network," Operations Research, vol. 61, no. 3, pp. 578–592, 2013.
[6] N Growe-Kuska, H Heitsch and W Romisch, "Scenario Reduction and Scenario Tree Construction for Power Management Problems". IEEE Power Tech Conference, Bologna 2003.

Wind Speed Scenario Generation



Power Curve



Wind Speed Modeling and Calibration

- Relevant literature: (Brown et al, 1984), (Torres et al., 2005), (Morales et al, 2010)
- Calibration steps
  1. Remove systematic effects:

$$y_{kt}^{S} = \frac{y_{kt} - \hat{\mu}_{kmt}}{\hat{\sigma}_{kmt}}.$$

  2. Transform data to obtain a Gaussian distribution:

$$y_{kt}^{GS} = N^{-1}(\hat{F}_k(y_{kt}^{S})).$$

  3. Estimate the autoregressive parameters $\hat{\phi}_{kj}$ and covariance matrix $\hat{\Sigma}$ using Yule-Walker equations.

Autoregressive Model

- Mathematical model:

$$Y_{k,t+1} = \sum_{j=0}^{p} \phi_{kj} Y_{k,t-j} + \omega_{kt},$$

  where $\Phi = (\phi_{kj})$ is the matrix of autoregressive parameters and $(\omega_{kt}), k \in \{1, \cdots, K\}$, are iid, multivariate Gaussian random variables with mean 0 and covariance matrix Σ
- No diagonal terms assumed in autoregressive parameter matrix
- Spatial correlations are captured by noise vector ω_{kt}

Scenario Generation

- Generate autoregressive noise of order p:

$$Y_{k,t+1}^{GS} = \sum_{j=0}^{p} \hat{\phi}_{kj} Y_{k,t-j}^{GS} + \omega_{kt}$$

- Transform to non-Gaussian distribution:

$$Y_{kt}^{S} = \hat{F}_{k}^{-1}(N(Y_{kt}^{GS}))$$

- Add seasonal and hourly mean and variance:

$$Y_{kt} = \hat{\sigma}_{kmt} Y_{kt}^{S} + \hat{\mu}_{kmt}$$

- Simulate power using approximate power curve:

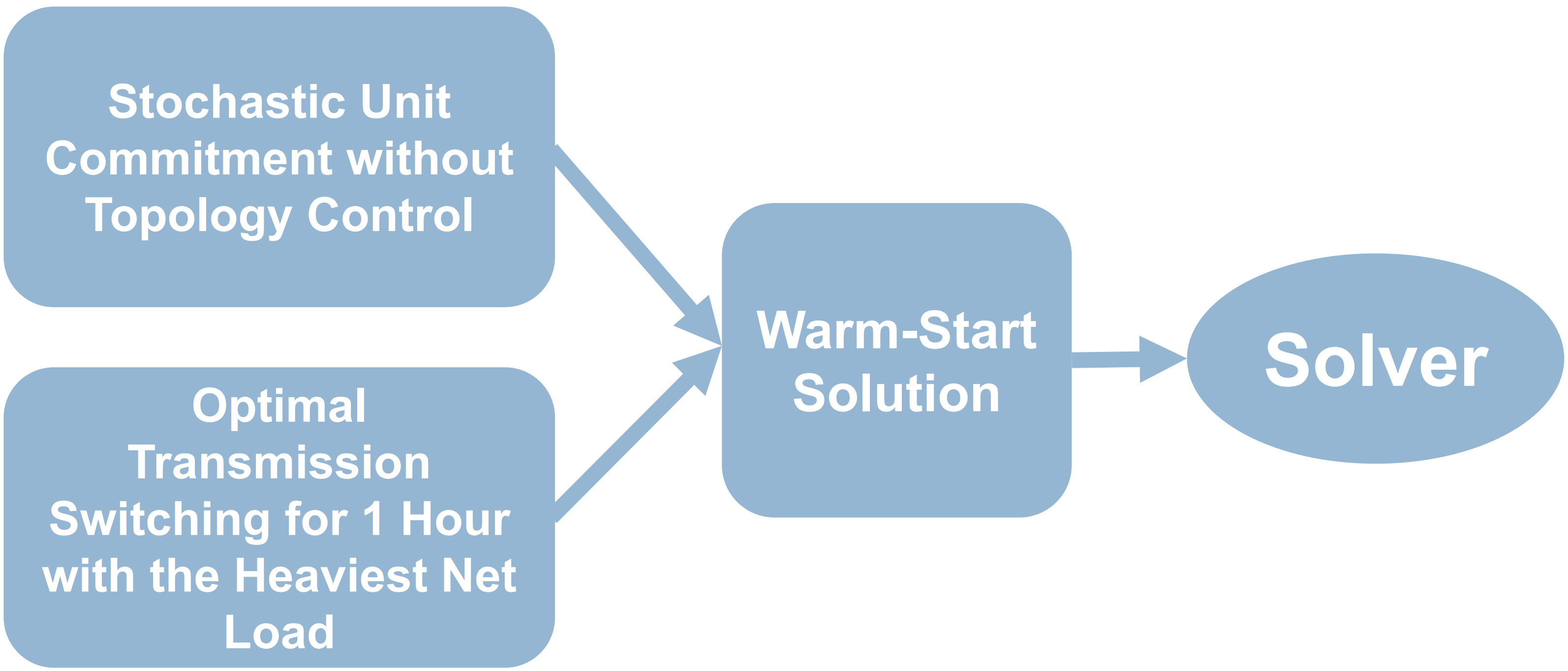
$$P_{kt} = \hat{P}_{k}(Y_{kt})$$

Preliminary Test Results

- Solving the problem—Branch and Bound
  - 48,336 binary variables, 80,352 continuous variables.
  - The problem is solved on a laptop: 2.6GHz CPU, 12G RAM.
  - When the MIP gap tolerance is 5%, using the default setting of CPLEX the program does not terminate after 8 hours.
  - The automatic tuning tool of CPLEX does not work for this problem. Appropriate parameters are not found after over 8 hours.

Warm Starts

- Solving the problem—Branch and Bound
  - Using CPLEX MIP warm-start



Warm Start Heuristic

- Solving the problem—Branch and Bound Using CPLEX MIP
  - Unit Commitment Decisions
    - The warm-start values for unit commitment decisions are obtained from solving a stochastic unit commitment problem with no topology control recourse.
    - In practice, system operators can use the commitment decisions of previous days with similar loading conditions to construct warm-up values for commitment decisions.

Warm Start Heuristic

- Solving the problem—Branch and Bound Using CPLEX MIP
  - Topology Control Decisions
    - Topology control warm-up values are obtained from solving an optimal transmission switching problem for the highest load hour (no wind).
    - The warm-start values for switching decisions are the same for different hours and scenarios.

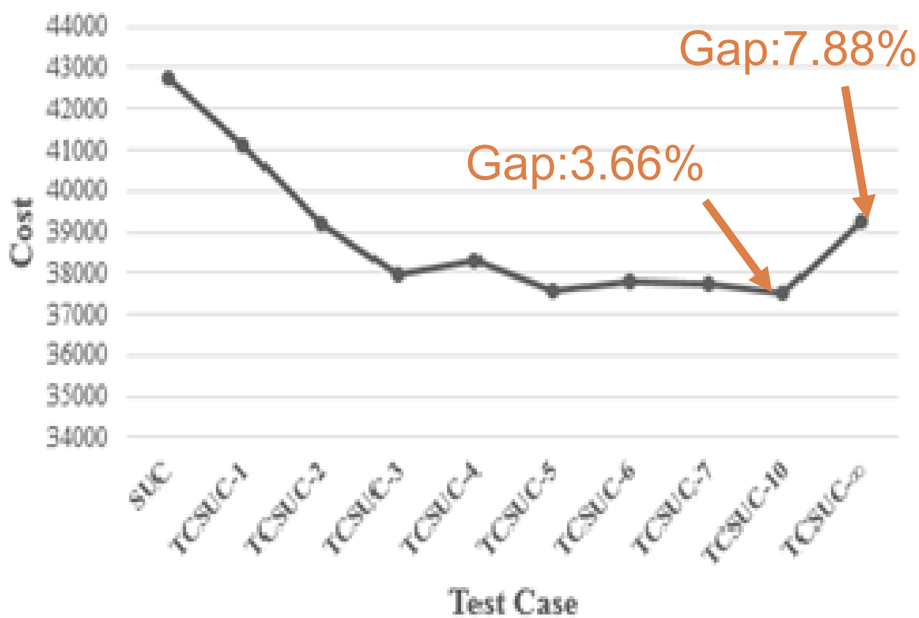
Test Results

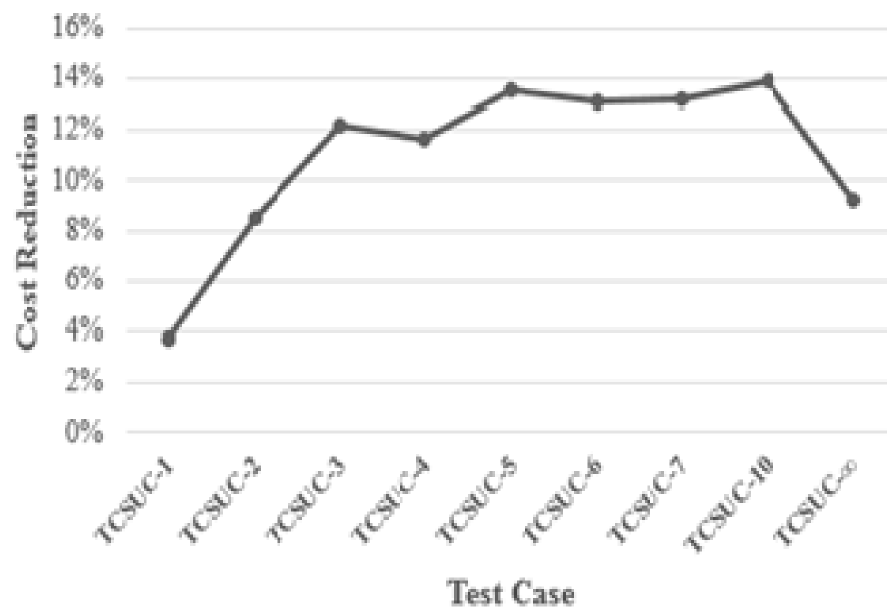
- Start Switching Solutions
  - We conducted 9 numerical tests
  - "x" in "TCSUC-x" stands for the maximum number of lines that can be switched off. $(J = x)$

Case	**Start switching solution**
TCSUC-1	132
TCSUC-2	132,136
TCSUC-3	132,136,153
TCSUC-4	132,136,153,162
TCSUC-5	132,136,151,153,163
TCSUC-6	132,136,148,153,161,162
TCSUC-7	63,132,136,148,153,161,162
TCSUC-10	126, 132, 136, 146, 151, 153, 157, 165
TCSUC-∞	1, 10, 14, 25, 28, 31, 57, 63, 66, 77, 79, 86, 96, 103, 110, 111, 132, 136, 146, 151, 153, 161, 165, 184

Test Results

Improvement over SUC with no switching





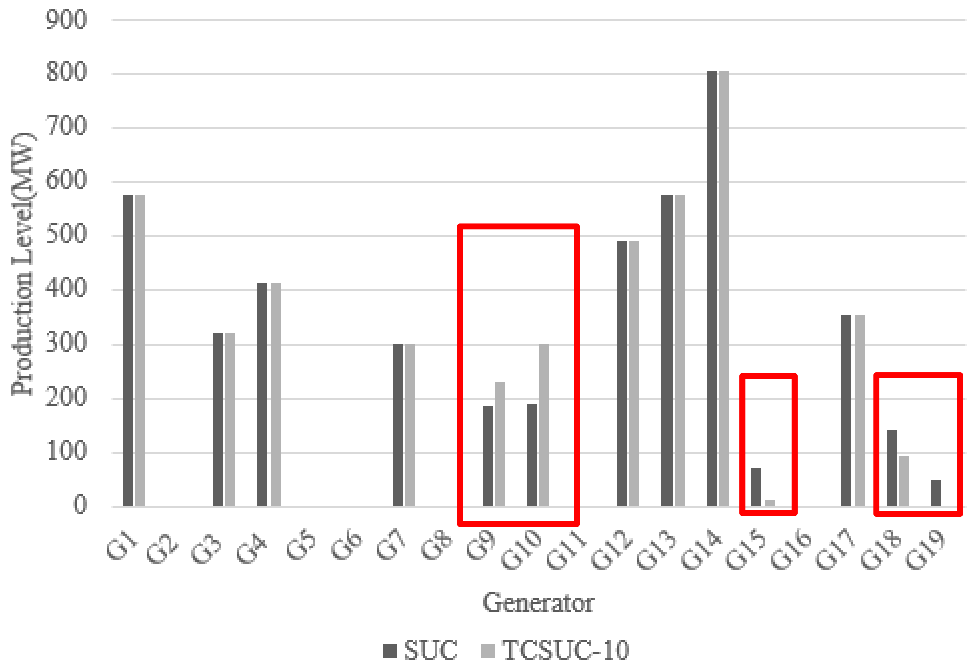
Cost Reduction: percentage of saving
Time limit: 30min
Maximum value of optimality gap: 7.88%

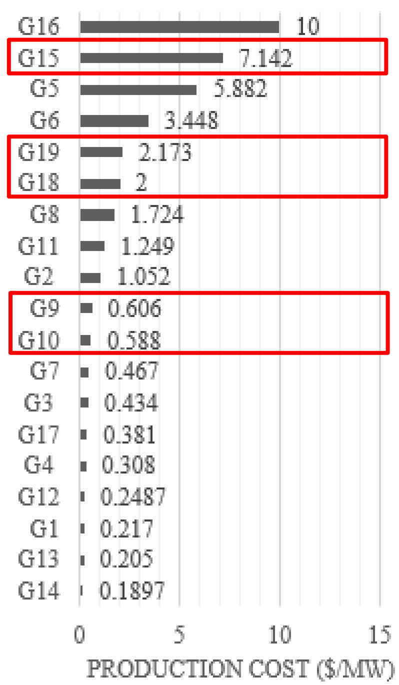
Test Results

- Results analysis
  - Why cost can be reduced with transmission switching in the recourse?
    - Reduction of production cost
    - Reduction of start-up cost
    - Reduction of no-load cost
    - Reduction of load shedding

Test Results

- Why cost can be reduced with transmission switching in the recourse?
  - Reduction of production cost

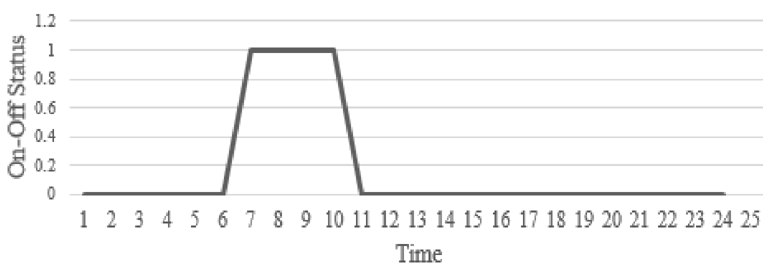




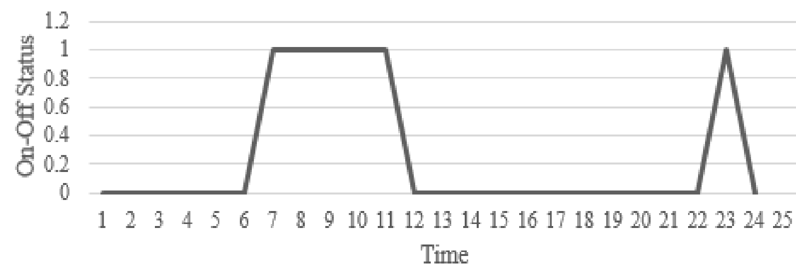
Test Results

- Why cost can be reduced with transmission switching in the recourse?
  - Reduction of start-up cost (STC6<STC8)

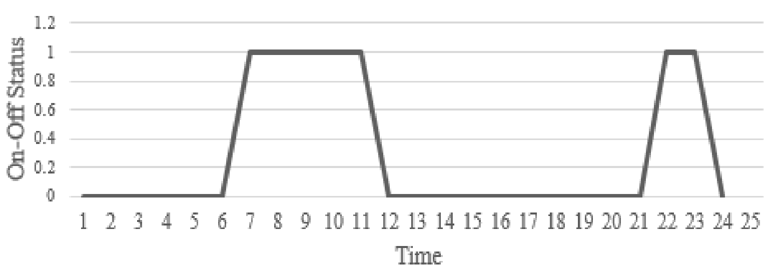
G6(SUC):



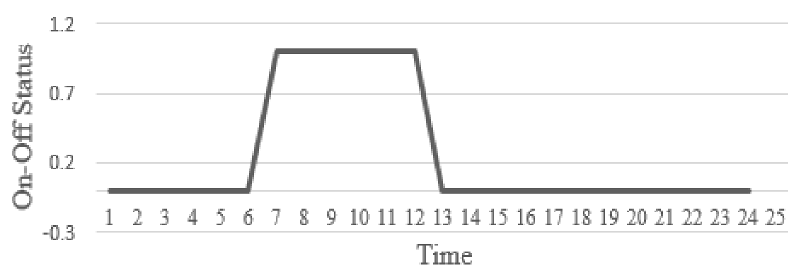
G6(TCSUC-10):



G8(SUC):

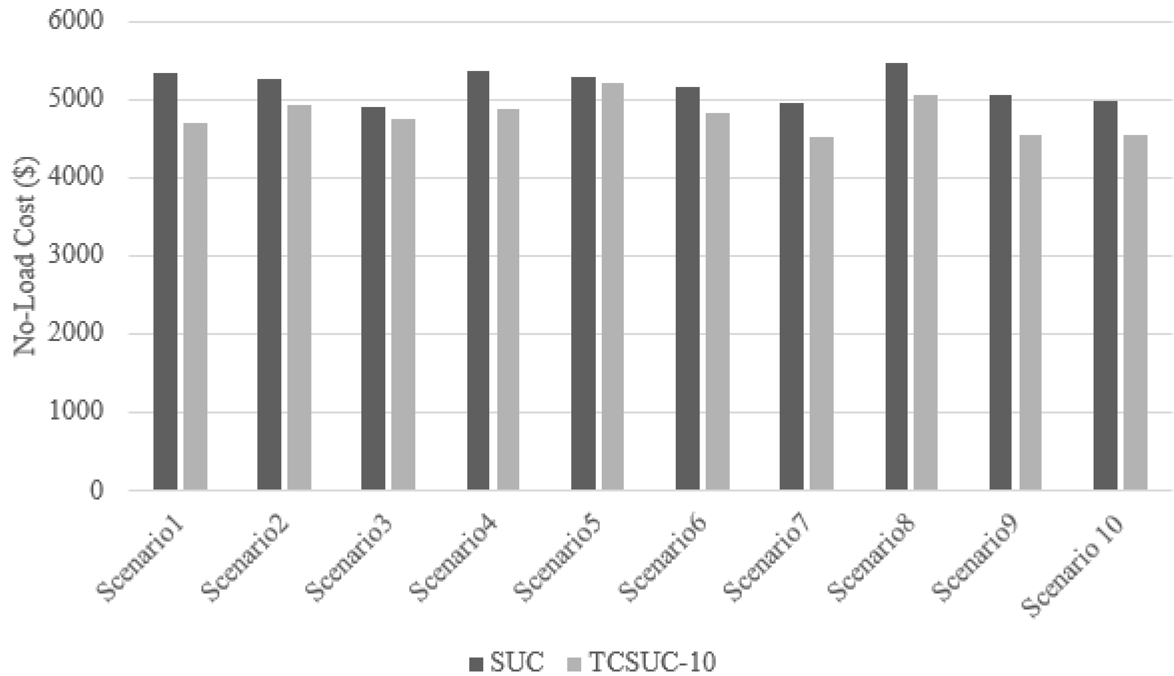


G8(TCSUC-10):



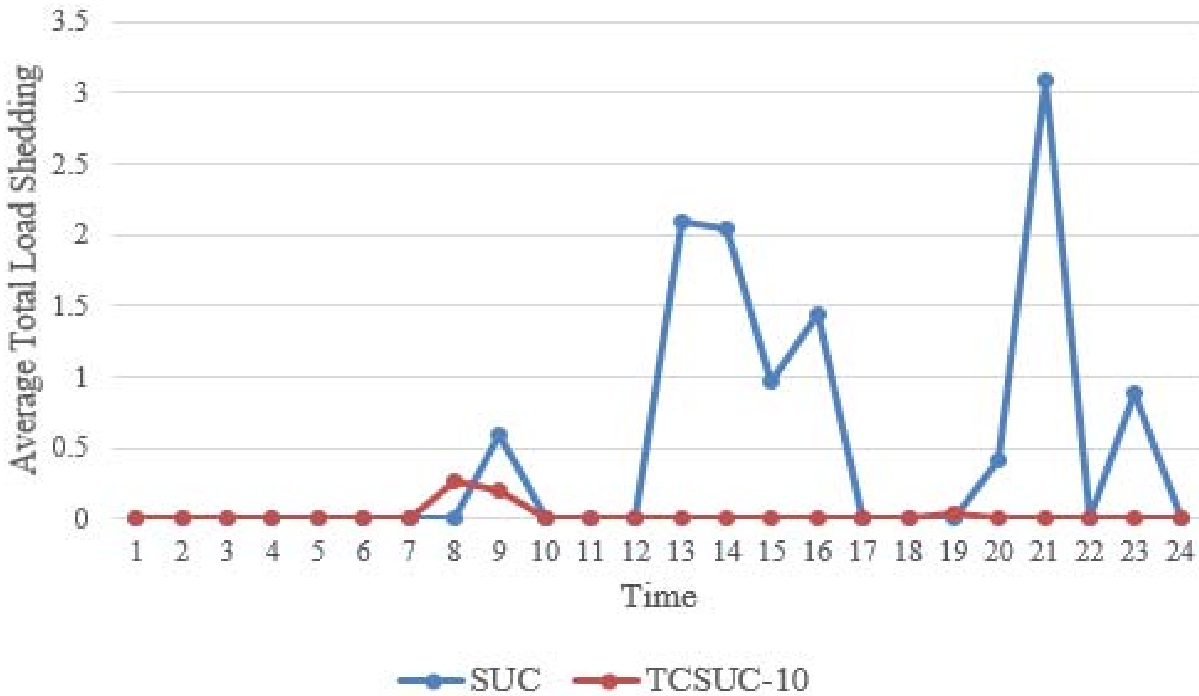
Test Results

- Why cost can be reduced with transmission switching in the recourse?
  - Reduction of no-load cost



Preliminary Test Results

- Why cost can be reduced with transmission switching in the recourse?
  - Reduction of load shedding



Solving the problem

- Progressive Hedging
  - For problem

$$\min f(x) + \sum_{s \in S} p_s g(x, y_s) : x, y_s \in Q_s$$

The algorithm proceeds as follows:

Step-0: $k = 0, \mathbf{w}^{(k)} = 0,\ x_s^{(k)} = \arg\min_{x,y} f(x) + g_s(x,y) : x, y \in Q_s$

Step-1: $\mu = \sum_{s \in S} p_s x_s;\ k = k+1;\ w_s^{(k)} = w_s^{(k)} + \rho\left(x_s^{(k-1)} - \mu\right)$

Step-2: For each s: $x_s^{(k)} = \arg\min_{x,y} f(x) + g_s(x,y) + w_s^{(k)} x$

$$+ \frac{1}{2}\rho \|x - \mu\|^2 : x, y \in Q_s$$

Step-3: If x has not converged, go to **Step-1**.

Solving the problem

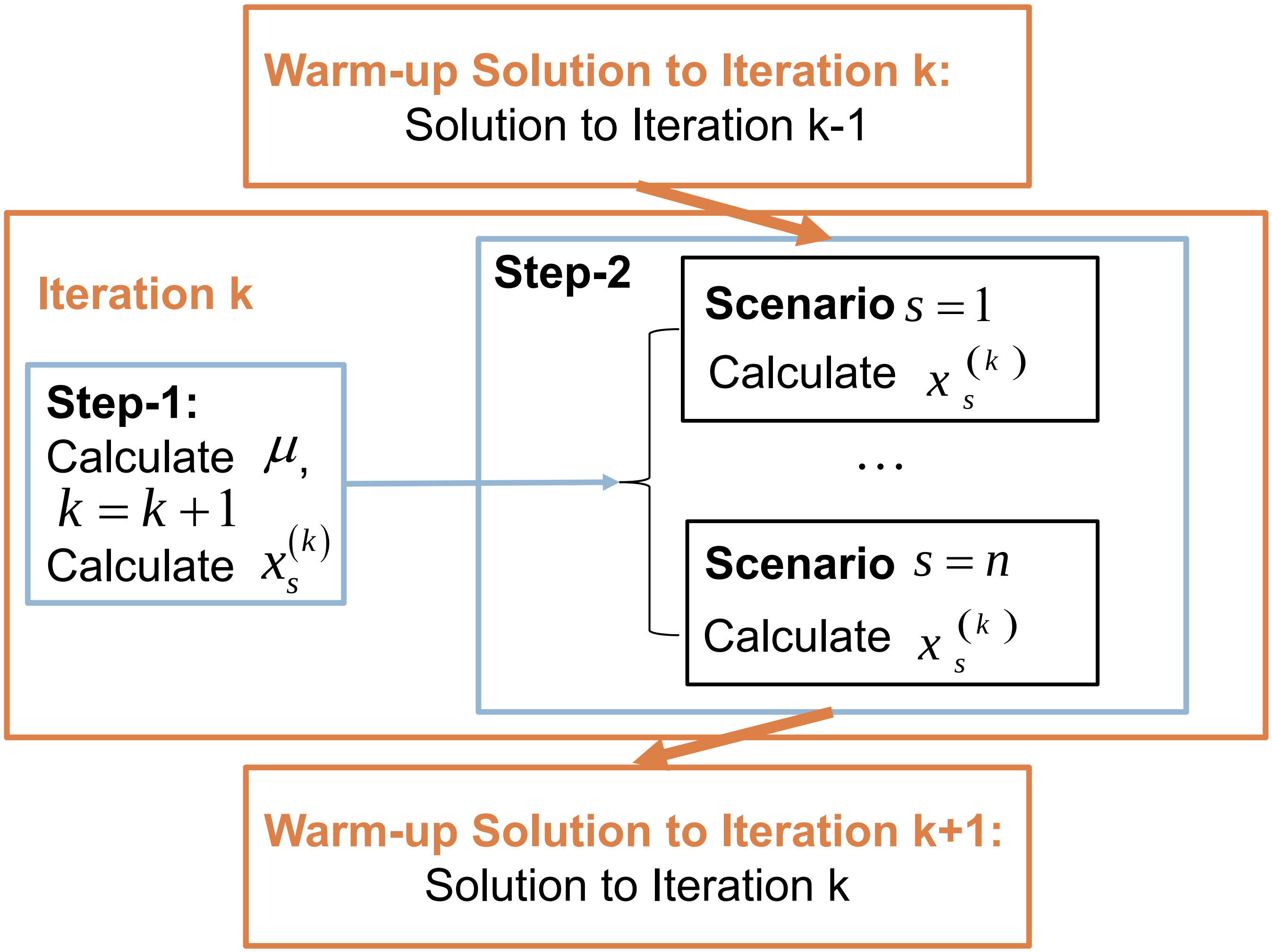
- Progressive Hedging
  - For stochastic unit commitment with topology control, all first stage variables are 0-1 variables. Quadratic terms in **Step-2** can be expressed as :

$$\frac{1}{2}\rho\|x-\mu\|^2 = \frac{1}{2}\rho x - \rho\mu^T x + \frac{1}{2}\rho\mu^T\mu$$

since $x^T x = x$.

  - **Step-2** can be implemented in parallel.

Solving the problem

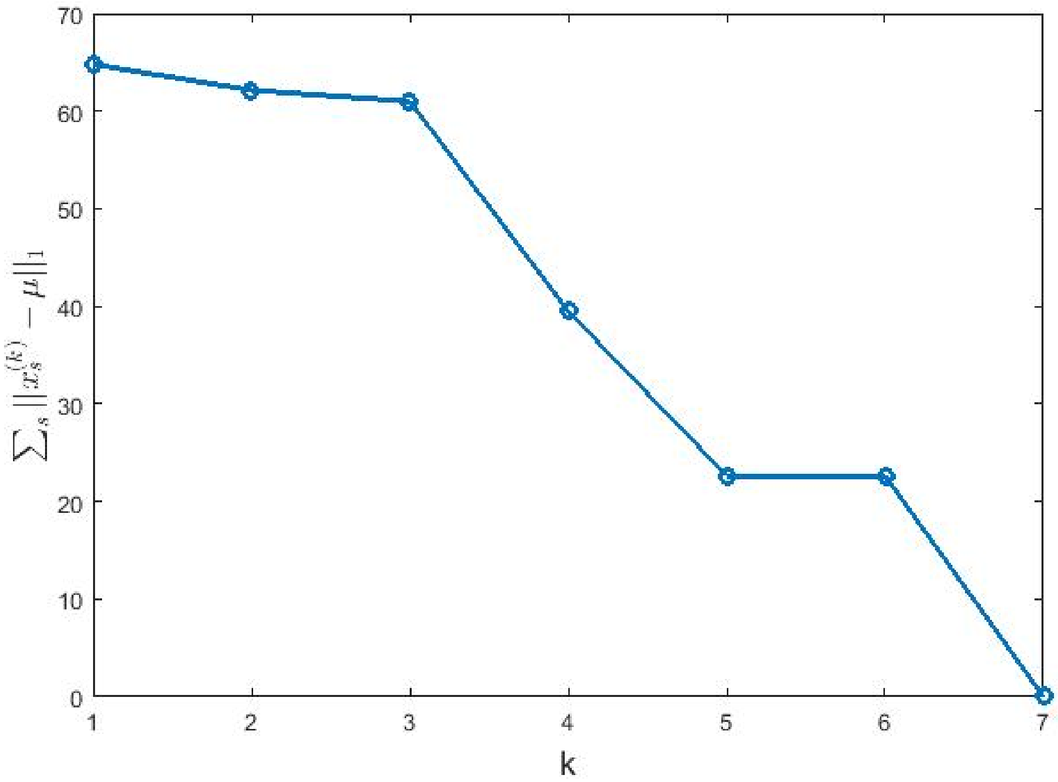


Solving the Problem

- The optimality gap for each sub-problem is set to be 4% and the time limit for each sub-problem is set to be 6 minutes.
- The algorithm converges after 7 iterations. The estimated time for solving the problem in parallel is 42 minutes.
- The cost is reduced by 10.1% with topology control recourse.

Progressive Hedging Results

- L1-norm error of first-stage decisions in each iteration:



Switching Results

- Switching solution for different scenario

Scenario	Switching solution of Hour 18 (Lines are off)
1	40, 94,109, 132, 136, 146, 151, 153, 157, 165
2	48, 88, 126, 132, 136, 146, 151, 153, 157, 165
3	116, 126, 132, 136, 153, 165
4	94, 96, 124, 132, 136, 146, 151, 153, 157, 165
5	39, 40, 63, 84, 122, 132, 136, 151, 153, 165
6	1, 83, 126, 132, 16. 146, 151, 153, 157, 165
7	45, 118, 126, 132, 136, 146, 151, 153, 157, 165
8	63, 96, 109, 124, 127, 132, 153, 163, 168
9	21, 42, 79, 132, 136, 146, 151, 153, 157, 162
10	37, 42, 59. 103, 132, 136, 146, 151, 153, 157

Evaluation

- Evaluate the robustness of the solution that was based on a reduced scenario set, under a richer uncertainty representation.
- The **commitment of slow generators are fixed as the slow generators commitment solution** of TCSUC-10.
- The **line switching decisions are optimized for each of the simulation scenarios bot constrained to the union of lines switched in** TCSUC-10 for the 10 optimization scenarios.
- 1000 wind generation scenarios produced using Monte Carlo simulation are used in the evaluation.
- Both unit commitment and unit commitment with transmission switching are implemented to compare the cost.

Test Results

- Line switching solution for scenario 1(12.8%)

line \ t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
126	1	0	1	0	1	1	1	1	1	0	1	1	0	0	1	0	0	0	1	0	0	0	1	1
132	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
136	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
146	1	0	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	1	1	1
151	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	1	0	0	0	0	1	1
153	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
157	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	0	0	1	0	0	1	1	1	1
165	0	1	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Test Results

- Line switching solution for scenario 2 (13.6%)

line \ t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
126	1	0	1	1	1	1	1	1	1	0	1	1	0	1	1	1	0	0	0	0	1	0	1	1
132	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
136	1	1	0	1	1	1	1	1	1	0	1	0	0	0	1	1	0	0	0	0	1	1	0	1
146	1	1	1	0	0	0	1	1	1	0	0	1	0	0	0	1	0	0	0	0	1	1	1	0
151	1	0	1	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	1	0	1	0
153	0	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
157	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	0	0	0	0	1	1	1	1
165	0	0	0	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	0	0	0

Evaluation

- In all 1000 tests, when there is transmission switching in the recourse, the total cost is less than when there is no transmission switching.
- The average total cost is reduced by 12.9% with transmission switching in the recourse.
- The simulation provides a **lower bound** of the cost reduction for the case where there is no restriction on the lines that can be switched.

Conclusion

- We have developed a two-stage stochastic programming model with topology control recourse for power systems with wind generation.
- We proposed a method to find a warm-start for the problem which helps reduce the solution time significantly.
- Numerical test results shown for the IEEE 118 system demonstrate that with topology control recourse, the operation cost will be reduced.
- To achieve good cost reduction, only a small fraction of lines need be switched off.
- For future research directions, we will study efficient algorithms that solve the problem for commercial-scale systems.

Future Work

- Conduct test on European system with over 600 buses and over 1000 transmission lines.
- Find a scalable method that can solve stochastic unit commitment with topology recourse efficiently.

Thank You!

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