Improving Economic Dispatch through Transmission Switching: New Opportunities for a Smart Grid

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POWER INDUSTRY RESTRUCTURING

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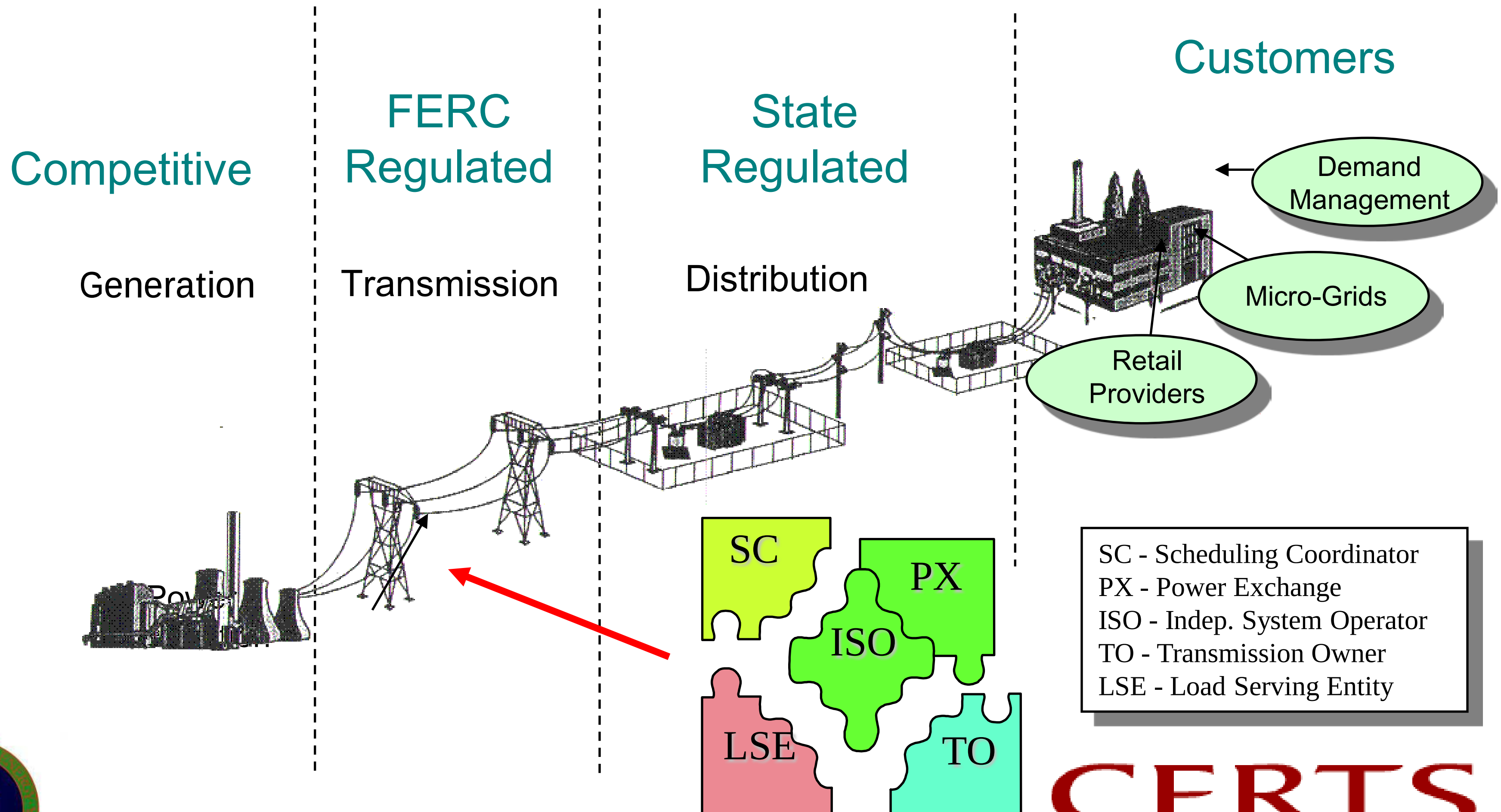

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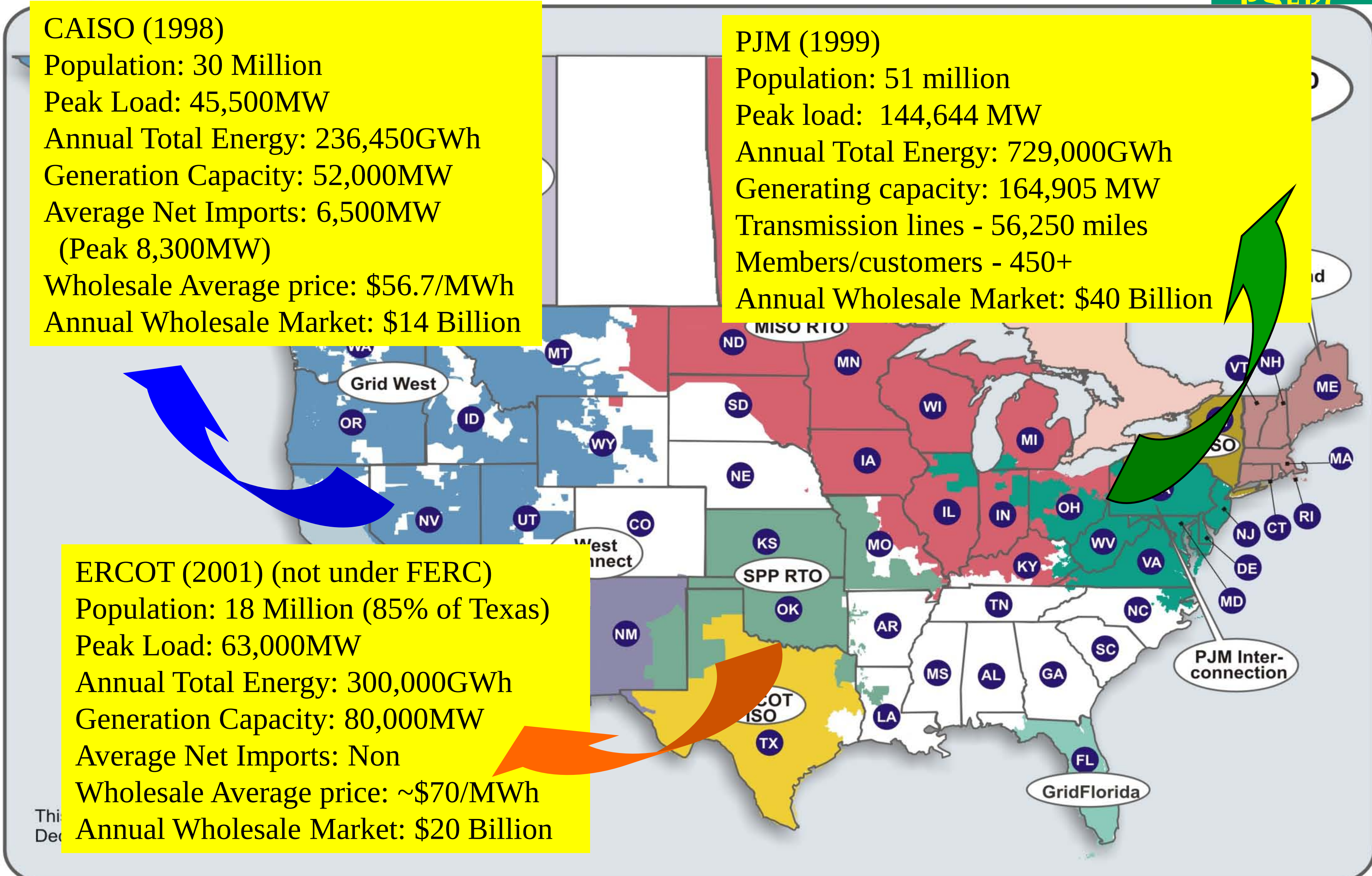
Scale of Regional Transmission Organizations (Cover half the states and 70% of load)

CAISO (1998)
Population: 30 Million
Peak Load: 45,500MW
Annual Total Energy: 236,450GWh
Generation Capacity: 52,000MW
Average Net Imports: 6,500MW
(Peak 8,300MW)
Wholesale Average price: $56.7/MWh
Annual Wholesale Market: $14 Billion

PJM (1999)
Population: 51 million
Peak load: 144,644 MW
Annual Total Energy: 729,000GWh
Generating capacity: 164,905 MW
Transmission lines - 56,250 miles
Members/customers - 450+
Annual Wholesale Market: $40 Billion



ERCOT (2001) (not under FERC)
Population: 18 Million (85% of Texas)
Peak Load: 63,000MW
Annual Total Energy: 300,000GWh
Generation Capacity: 80,000MW
Average Net Imports: Non
Wholesale Average price: ~$70/MWh
Annual Wholesale Market: $20 Billion

Market Mechanics at PJM

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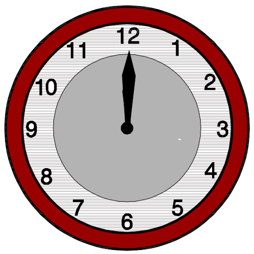
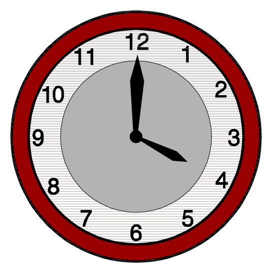
Day-Ahead Market closes



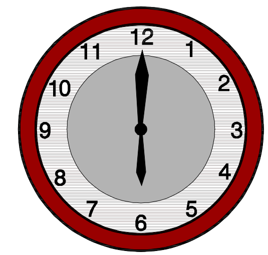
Day-ahead Market

- determines commitment profile that satisfies fixed demand, price sensitive demand bids, virtual bids and PJM Operating Reserve Objectives
- minimizes total production cost

Day-ahead Results Posted & Balancing Market Bid period opens



Balancing (RT) Market Bid period closes



Reserve Adequacy Assessment

- focus is reliability
- updated unit offers and availability
- Based on PJM load forecast
- minimizes startup and cost to run units at minimum

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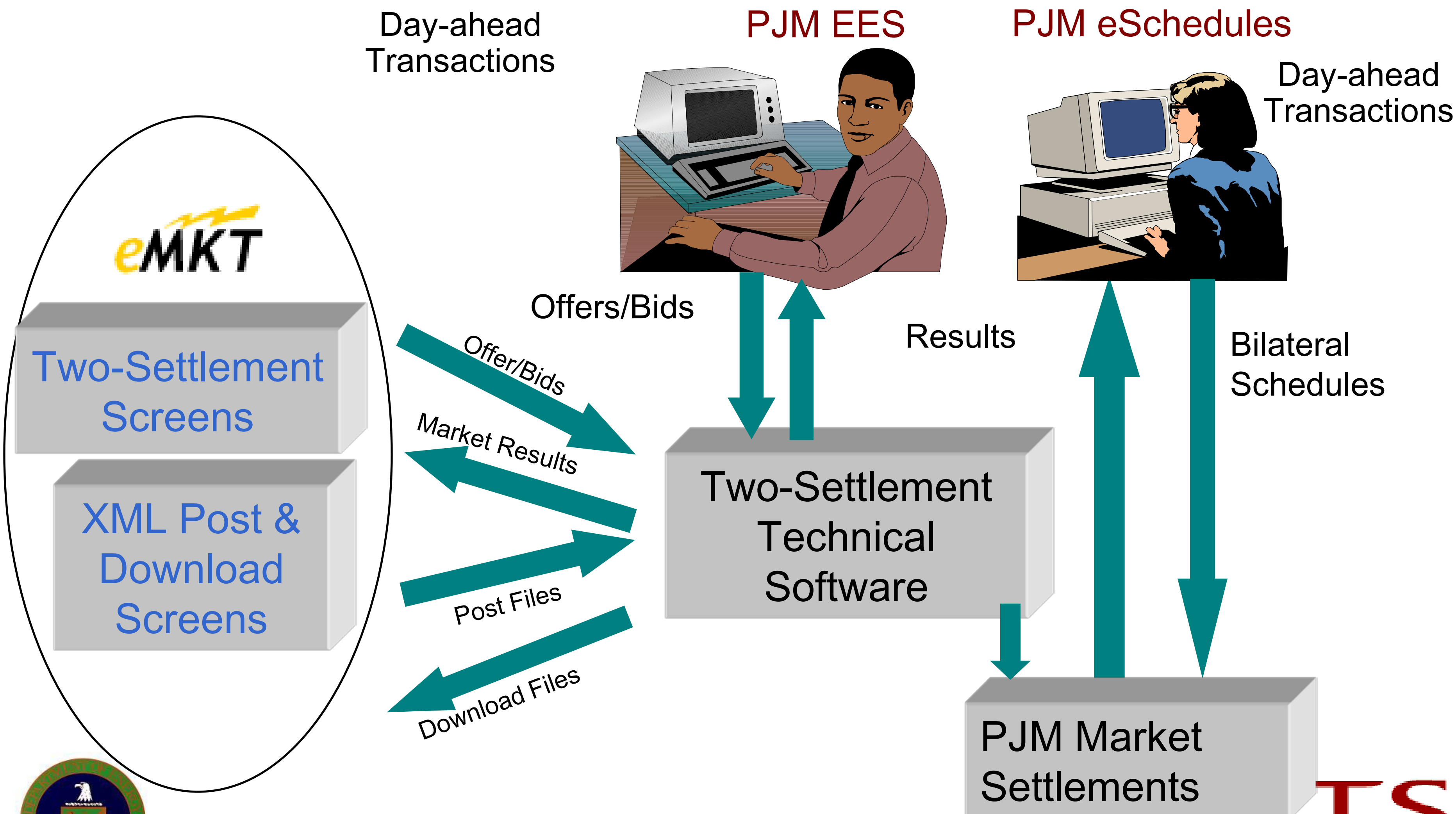
Day-ahead Market External Interfaces



Resource Dispatch Optimization Problems in Electric Power Systems

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- Generation Unit Commitment
- Optimal Power Flow (OPF) Problems
  - Alternating Current Optimal Power Flow (ACOPF)
  - Direct Current OPF (DCOPF) – Linearization of the ACOPF
- Reliability (Contingency) Requirements – N-1 Standards
  - N-1 DCOPF, Security Constrained ACOPF

Power Flow Optimization (every five minutes) and Locational Marginal Pricing (LMP)

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- *General Statement of OPF*
  - *Objective* f*:*
    - Vertical demand: *MIN Cost = Σ Generator Costs*
    - Elastic demand: *MAX Net Benefits*
      = Σ (Consumer Value - Generator Cost)
  - *Decision variables* X*:*
    - *Generation*
    - *Accepted demand bids*
    - *Operating reserves*
    - *Real and reactive power flows*
  - *Constraints*
    - *Generator limits (including dynamic limits such as ramp rates)*
    - *Demand (net supply = load* L *at each bus for P,Q)*
    - *Load flow constraints (e.g., KCL, KVL)*
    - *Transmission limits*
    - *Reserve requirements*
- *Price of energy (LMP) at bus i = Marginal cost of energy at bus*
  - *Most readily calculated as dual variable to energy balance (KCL) constraint for the bus in an Optimal Power Flow (OPF)*

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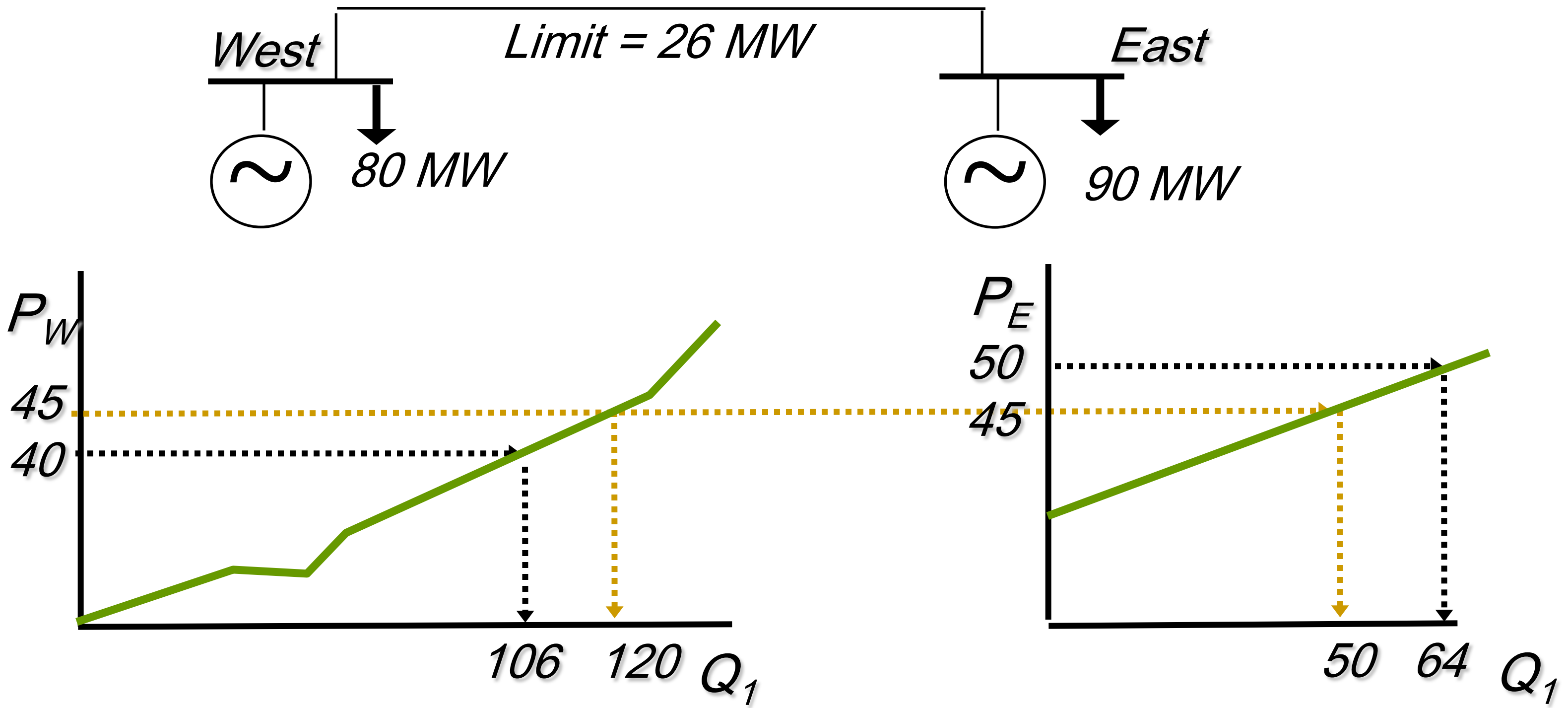
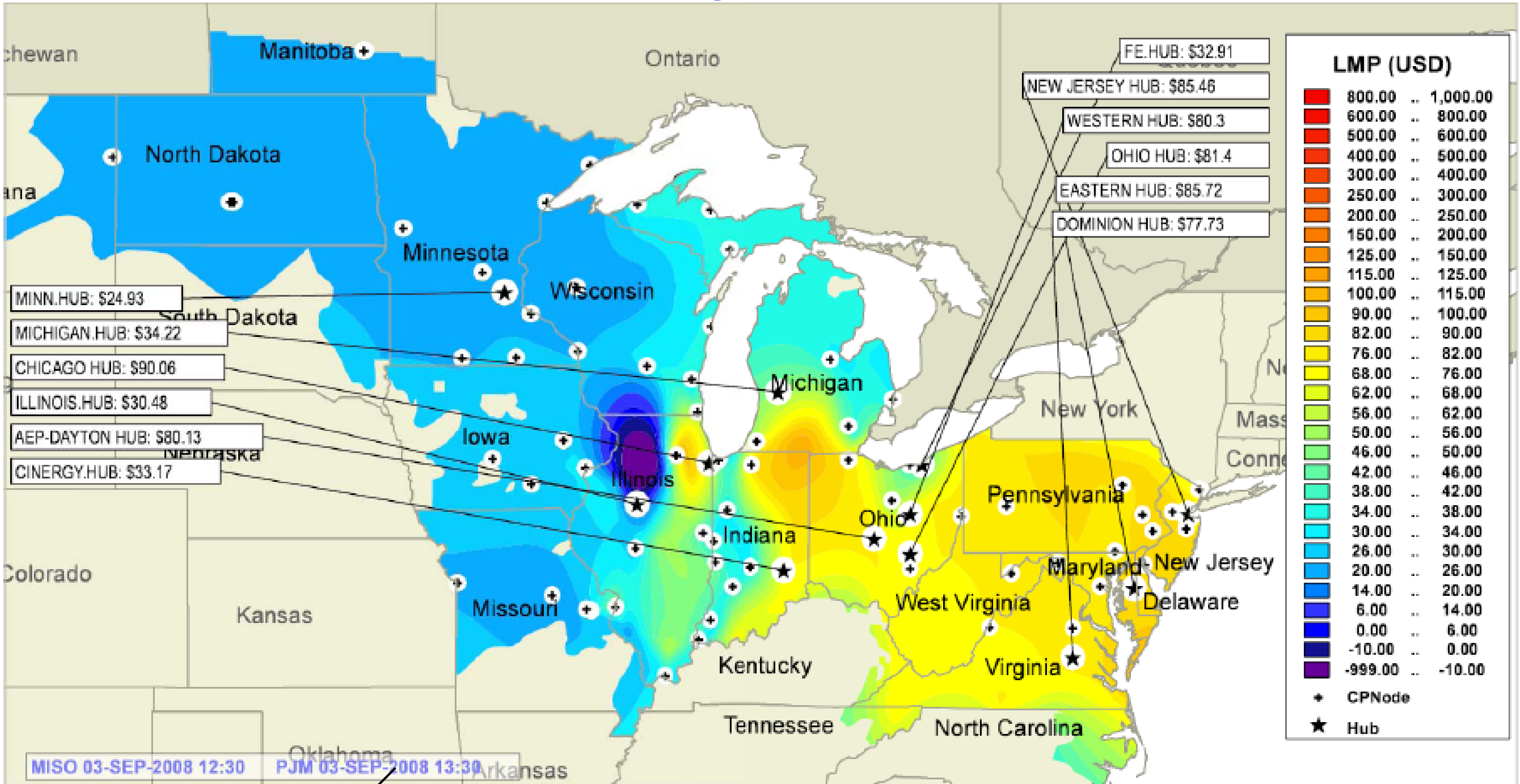
LMP / Congestion Example



Marginal value of transmission = \$10/MWh (=\$50 – \$40)
*Total congestion revenue = \$10*26 = \$260/hr*
Total redispatch cost = \$130/hr
*Congestion cost to consumers: (40*106+50*64) – (45*170) = 7440 – 7650 = –\$210/hr*

Locational Real Time Marginal Prices at PJM and MISO



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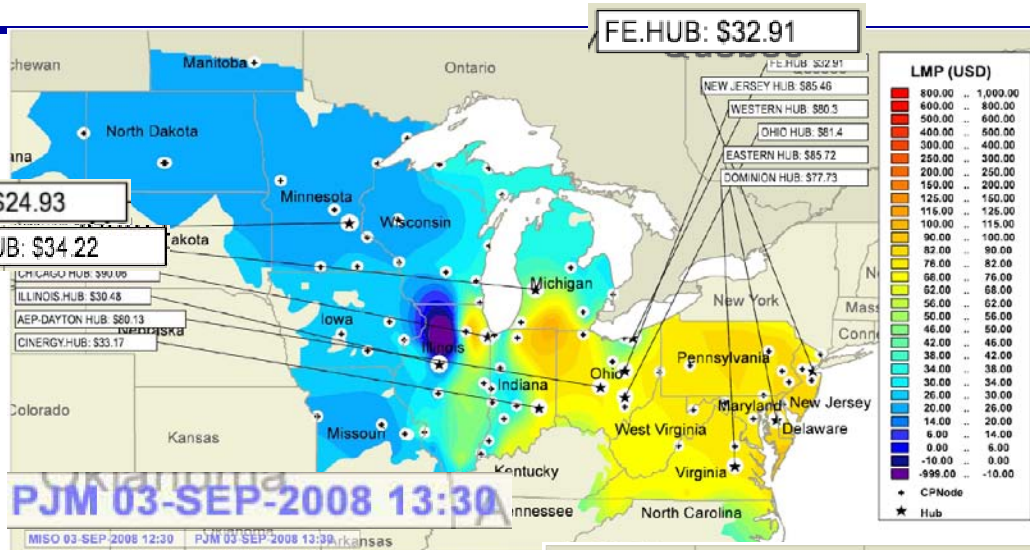
Midwest ISO Market data is based on Eastern Standard Time (EST) while PJM Market data is based on Eastern Prevailing Time.

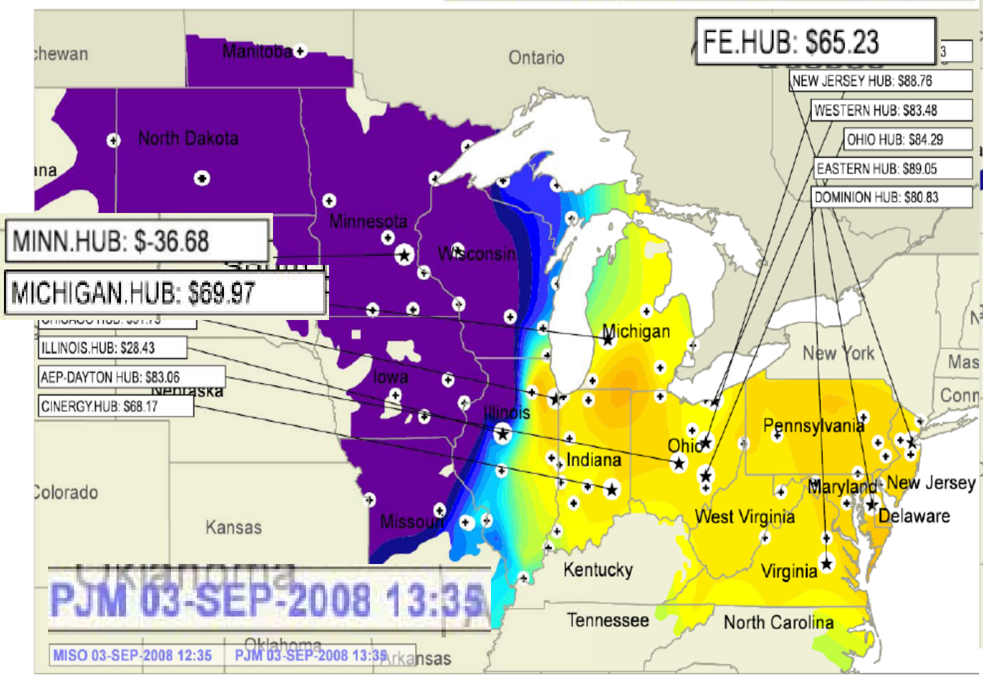
PJM 03-SEP-2008 13:30

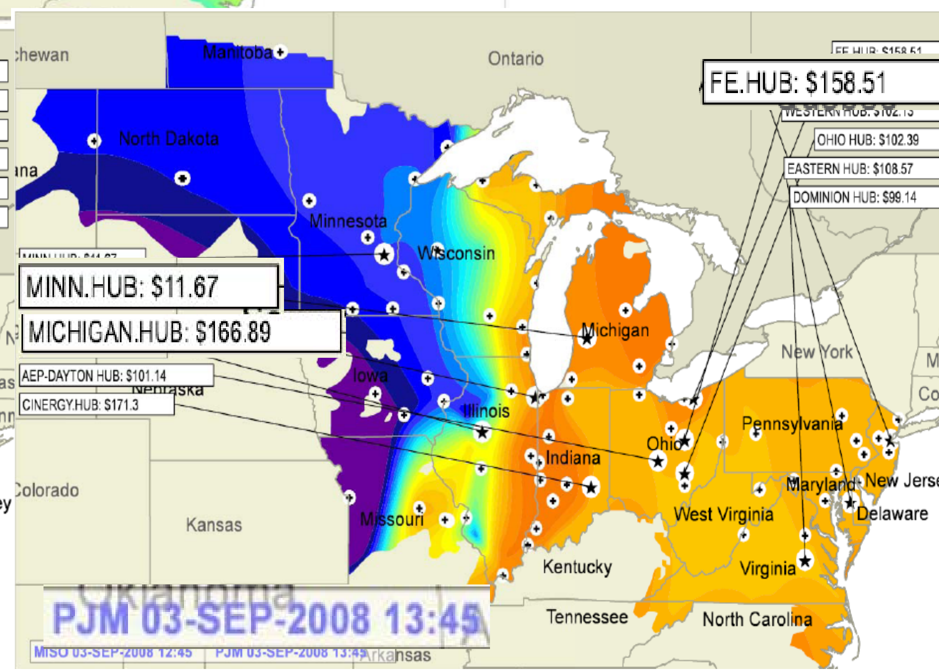
Midwest ISO We manage power.

pjm

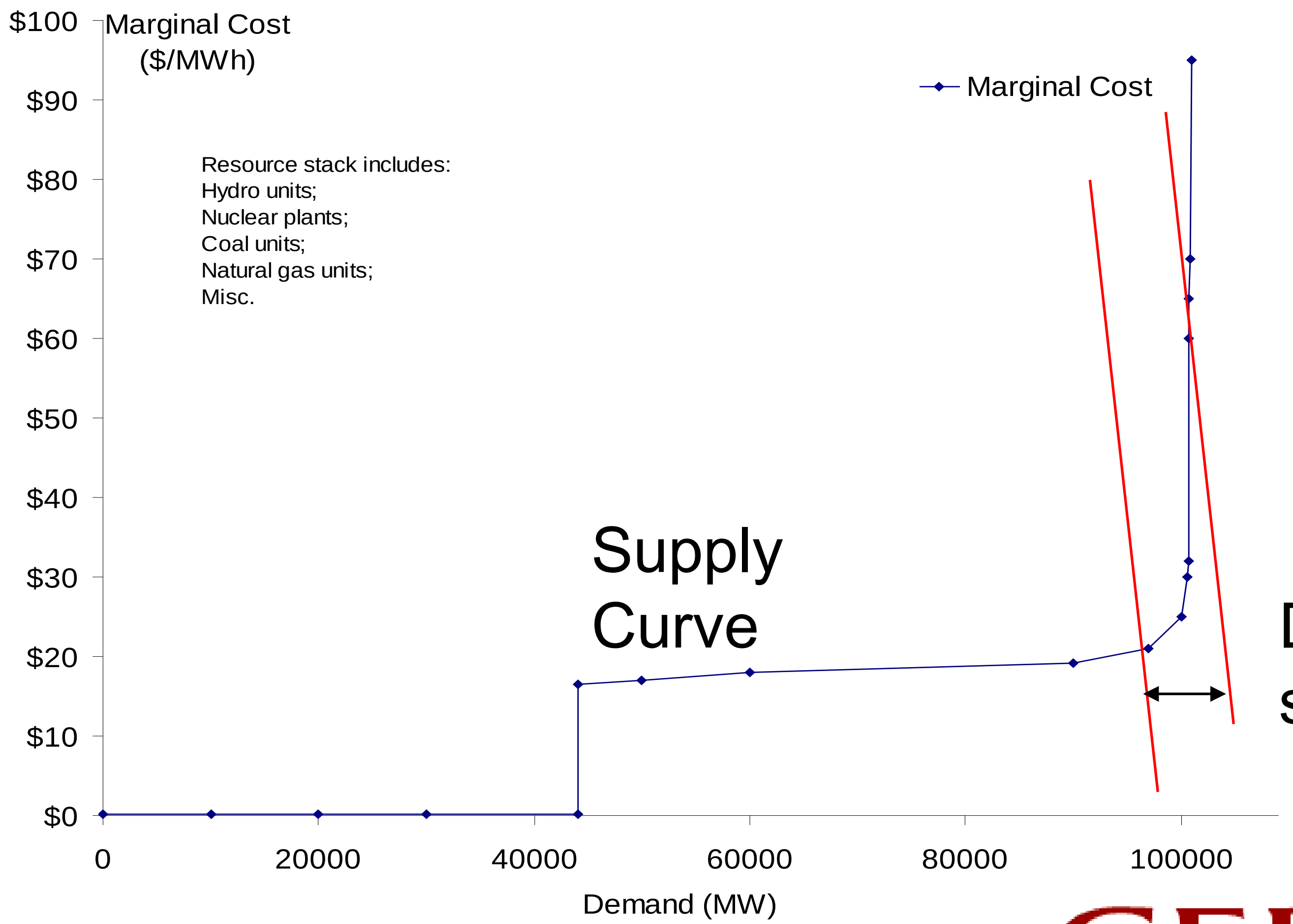
Dispatch is reoptimized every five minutes and LMP updated to reflect shadow prices on transmission constraints







Generation Resource Stack in WECC



3-Bus Example

- Line A-B:

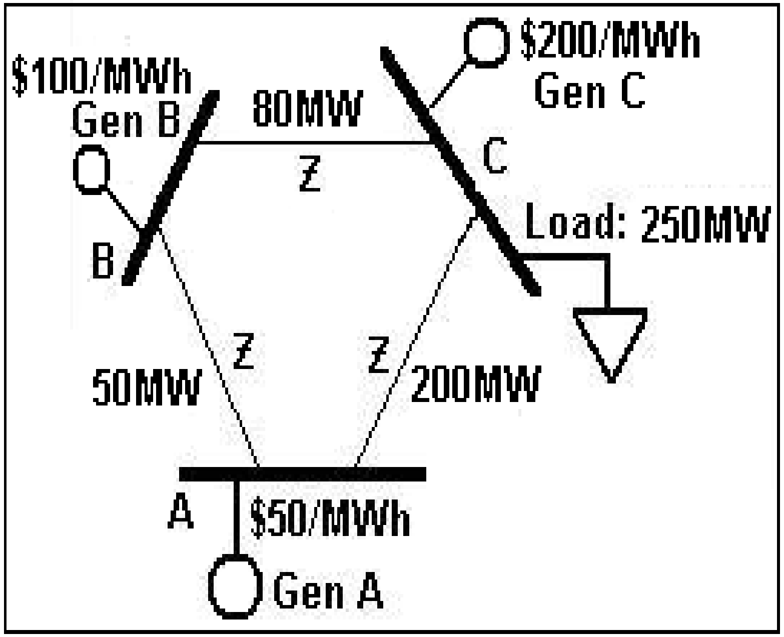
$$-50 \leq \frac{1}{3}Gen\_A - \frac{1}{3}Gen\_B \leq 50$$

- Line B-C:

$$-80 \leq \frac{1}{3}Gen\_A + \frac{2}{3}Gen\_B \leq 80$$

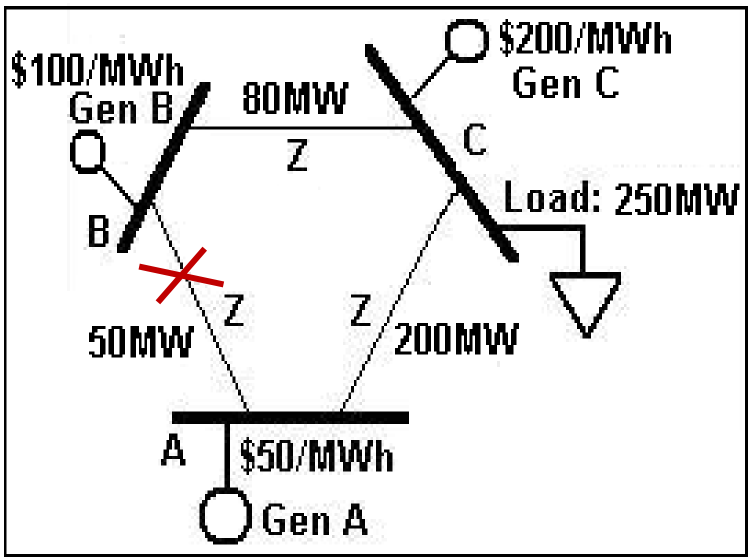
- Line A-C:

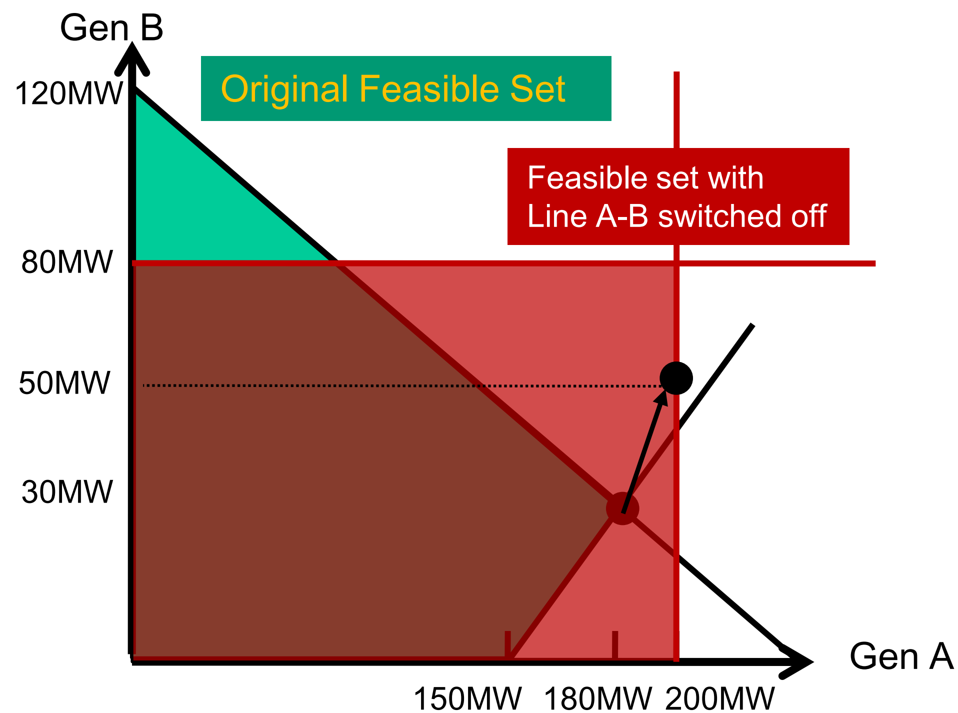
$$-200 \leq \frac{2}{3}Gen\_A + \frac{1}{3}Gen\_B \leq 200$$



Transmission Switching Example

- Original Optimal Cost: $20,000 (A=180MW,B=30MW, C=40MW)
- Open Line A-B, Optimal Cost: $15,000 (A=200MW, B=50MW)





Motivation

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- Transmission planning addresses long term problem and a broad range of contingencies so the grid is built with redundancies that may not be needed in every state of the system
- Network redundancies motivated by reliability requirements may constrain generation dispatch create congestion and reduce economic efficiency
- Transmission assets are currently seen as static in the short term and control of transmission assets for economic reasons is underutilized
- Security constrained economic dispatch can be improved and congestion reduced through co-optimization of generation dispatch and the network active topology while ensuring reliability
- With appropriate Smart Grid switching technology, some backup transmission can be kept offline (just in time N-1)

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Motivation (cont'd)

- Currently operators change transmission assets' states on ad-hoc basis (e.g. PJM)
- National Directives:
  - 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"

Objectives and Scope

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- Co-optimize transmission topology and generation dispatch
- Efficiency improvements with no reliability degradation
- Smart grid application by exploiting short term reconfiguration flexibility
- Asses cost of achieving reliability through network redundancy (e.g. N-1 criterion)
- Explore options and lay foundation for new reliability concepts (just in time N-1)
- Explore market implications of dynamic transmission switching and impact on transmission rights
- Proof of concept: IEEE 118, IEEE 73 (RTS 96), ISO-NE 5000 bus model

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Relevant Literature

- "Corrective Switching"
  - Changes the topology after the network optimization problem is complete to relieve constraints violations
  - Feasibility, search problems
- ***[Mazi, Wollenberg, Hesse 1986]:*** *Corrective control of power systems flows (line overloads)*
- ***[Schnyder, Glavitsch 1990]:*** *Security enhancement using an optimal switching power flow*
- ***[Glavitsch 1993]:*** *Power system security enhanced by post-contingency switching and rescheduling*
- ***[Shao, Vittal 2006]:*** *Corrective switching algorithm for relieving overloads and voltage violations*

Literature Review cont'd

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- **"After the fact" switching to reduce losses**
  - Does not incorporate transmission switching into the overall OPF problem
  - Changes topology to reduce losses after dispatch solution is known
- ***[Bacher, Glavitsch 1988]:*** *Loss reduction by network switching*
- ***[Fliscounakis, Zaoui, et al. 2007]:*** *Topology influence on loss reduction as a mixed integer linear program*

Literature Review cont'd

- **Optimal Switching to Relieve Congestion**
  - Similar MIP formulation
  - Aims at relieving congestion rather than co-optimizing network topology and generation
- ***[Granelli, Montagna, et al. 2006]:*** *Optimal network reconfiguration for congestion management by deterministic and genetic algorithms*

OPF Nomenclature

- **Variables:**

P_{nmk} (Q_{nmk}): real (reactive) power flow through transmission line *k* connecting buses *m* and *n*

P_{ng}: Generator *g* supply at bus *n*

V_n: Voltage magnitude at bus *n*

θ_n: Bus voltage angle at bus *n*

z_k: Transmission line status (1 closed, 0 open)

- **Parameters:**

B_k: Susceptance of transmission line *k*

P_{nd}: Real power load at bus *n*

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Power Flow Overview

- AC Line Flow Equations (Kirchhoff's laws):

$$P_{nmk} = G_k V_n V_m \cos(\theta_n - \theta_m) + B_k V_n V_m \sin(\theta_n - \theta_m)$$
$$Q_{nmk} = G_k V_n V_m \sin(\theta_n - \theta_m) - B_k V_n V_m \cos(\theta_n - \theta_m).$$

- Non-convex constraints
- Linearization of the ACOPF to get DCOPF
- DCOPF used in Academia & Industry
- DC Line Flow Equation:

$$B_k(\theta_n - \theta_m) - P_{nmk} = 0$$

- (Alternative representation uses PTDFs)

Optimal Transmission Switching with DCOPF

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- Z_k: Binary variable
  - State of transmission line (0 open, 1 closed)
- Update line min/max thermal constraints:
  - Original: $$P_k^{\min} \le P_{nmk} \le P_k^{\max}$$
  - New:

$$P_k^{\min} z_k \le P_{nmk} \le P_k^{\max} z_k$$

- Update line flow constraints:
  - Original: $$B_k(\theta_n - \theta_m) - P_{nmk} = 0$$
  - New:

$$B_k(\theta_n - \theta_m) - P_{nmk} + (1 - z_k)M_k \ge 0$$

$$B_k(\theta_n - \theta_m) - P_{nmk} - (1 - z_k)M_k \le 0$$

Optimal Transmission Switching DCOPF

Minimize: $TC = \sum_g c_{ng} P_{ng}$

$s.t.:$

Bus angle constraints

$$\theta_n^{\min} \le \theta_n \le \theta_n^{\max}, \quad \forall n$$

Generator constraints

$$0 \le P_{ng} \le P_g^{\max}, \quad \forall g$$

Node balance constraints

$$\sum_{\forall k|i=n} P_{ijk} - \sum_{\forall k|j=n} P_{ijk} + \sum_{\forall g|s=n} P_{sg} - P_{nd} = 0, \forall n$$

Transmission constraints

$$P_k^{\min} z_k \le P_{nmk} \le P_k^{\max} z_k, \quad \forall k$$

$$B_k(\theta_n - \theta_m) - P_{nmk} + (1 - z_k)M_k \ge 0, \quad \forall k$$

$$B_k(\theta_n - \theta_m) - P_{nmk} - (1 - z_k)M_k \le 0, \quad \forall k$$

$$z_k \in \{0,1\}, \quad \forall k \in K$$

Results - Summary

- IEEE 118 Bus Model:
  - DCOPF transmission switching solution with no contingencies saves 25% of total generation cost (10 lines switched off)
  - Up to 16% savings with N-1 DCOPF transmission switching (for feasible solutions)
- IEEE 73 (RTS 96) Bus Model
  - Up to **8%** savings with N-1 DCOPF transmission switching (for feasible solutions)

Results – DCOPF – IEEE 118

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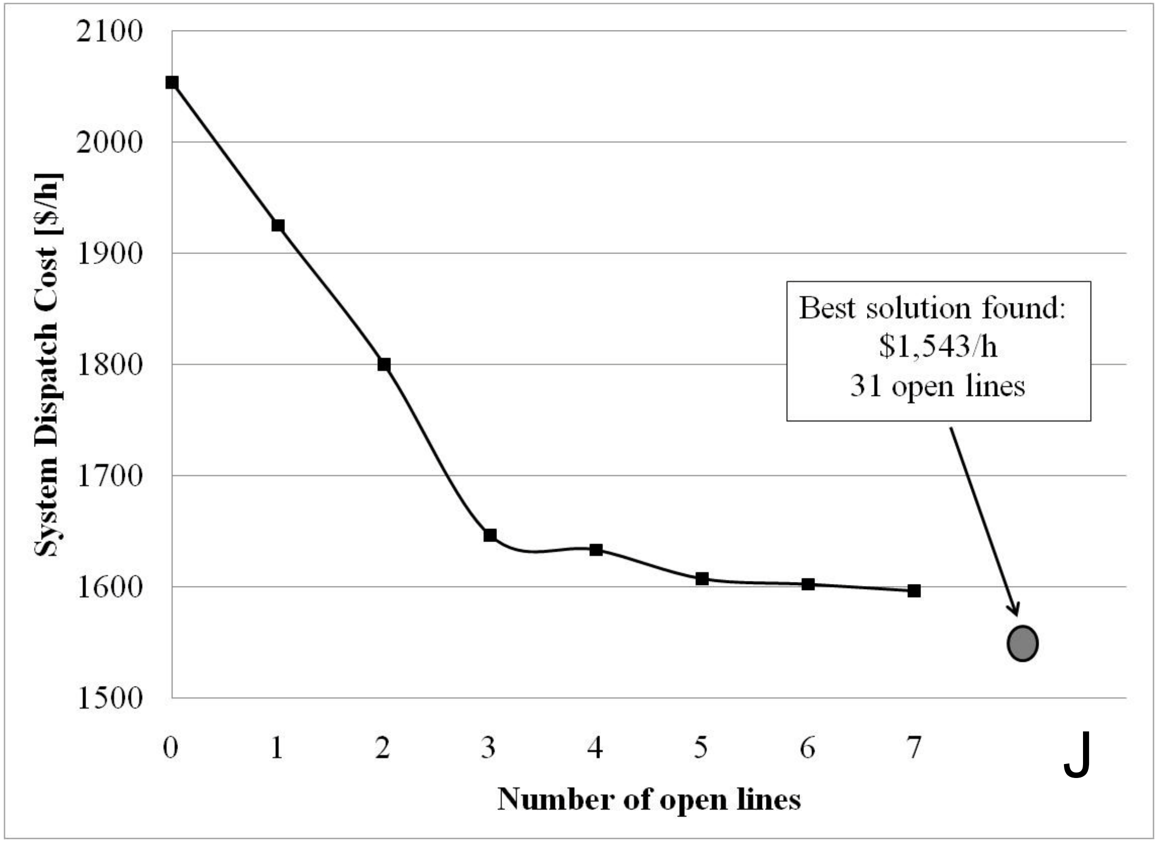
- Transmission switching solution saves 25% of total generation cost



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Results – DCOPF – IEEE 118

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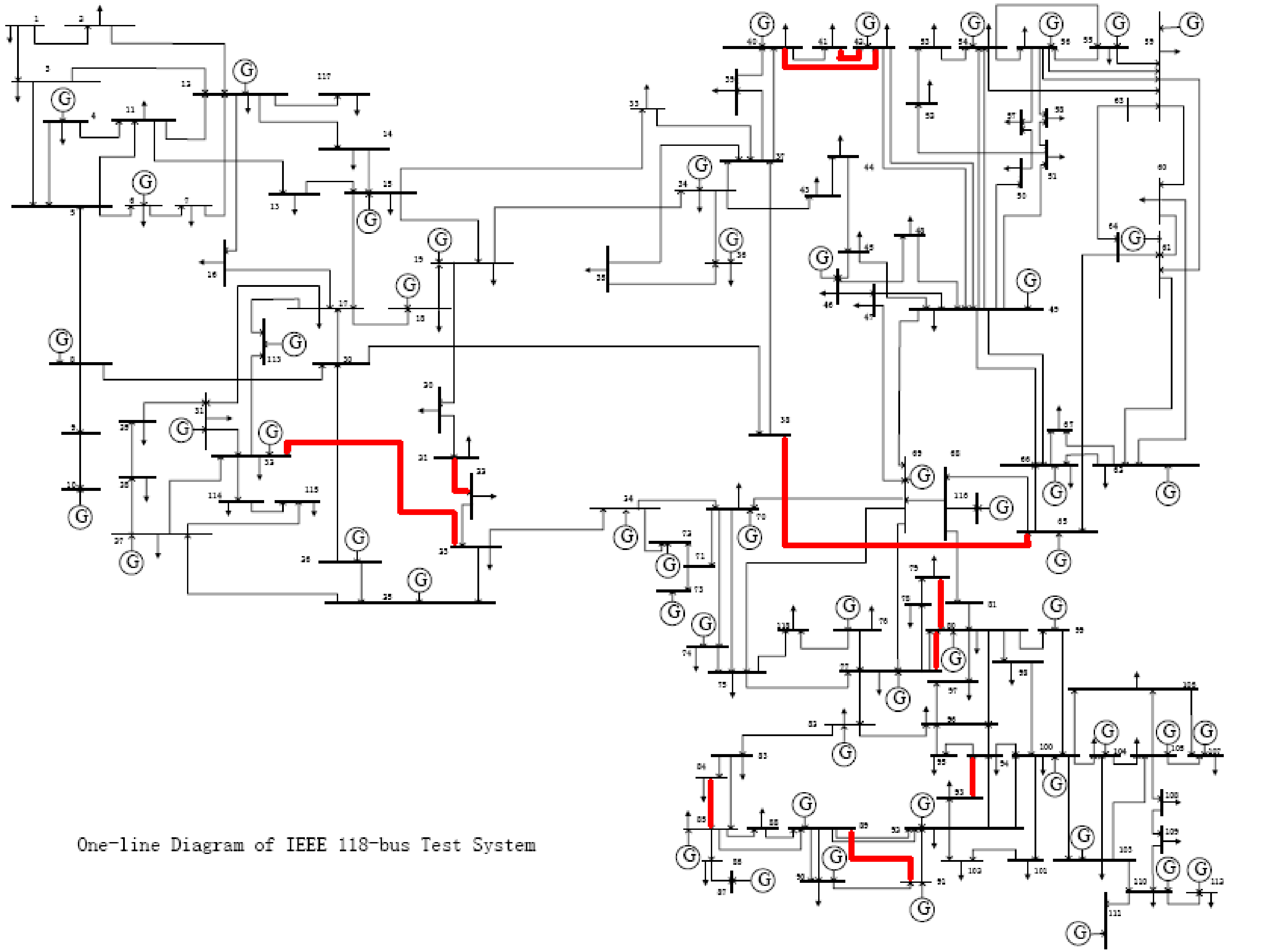
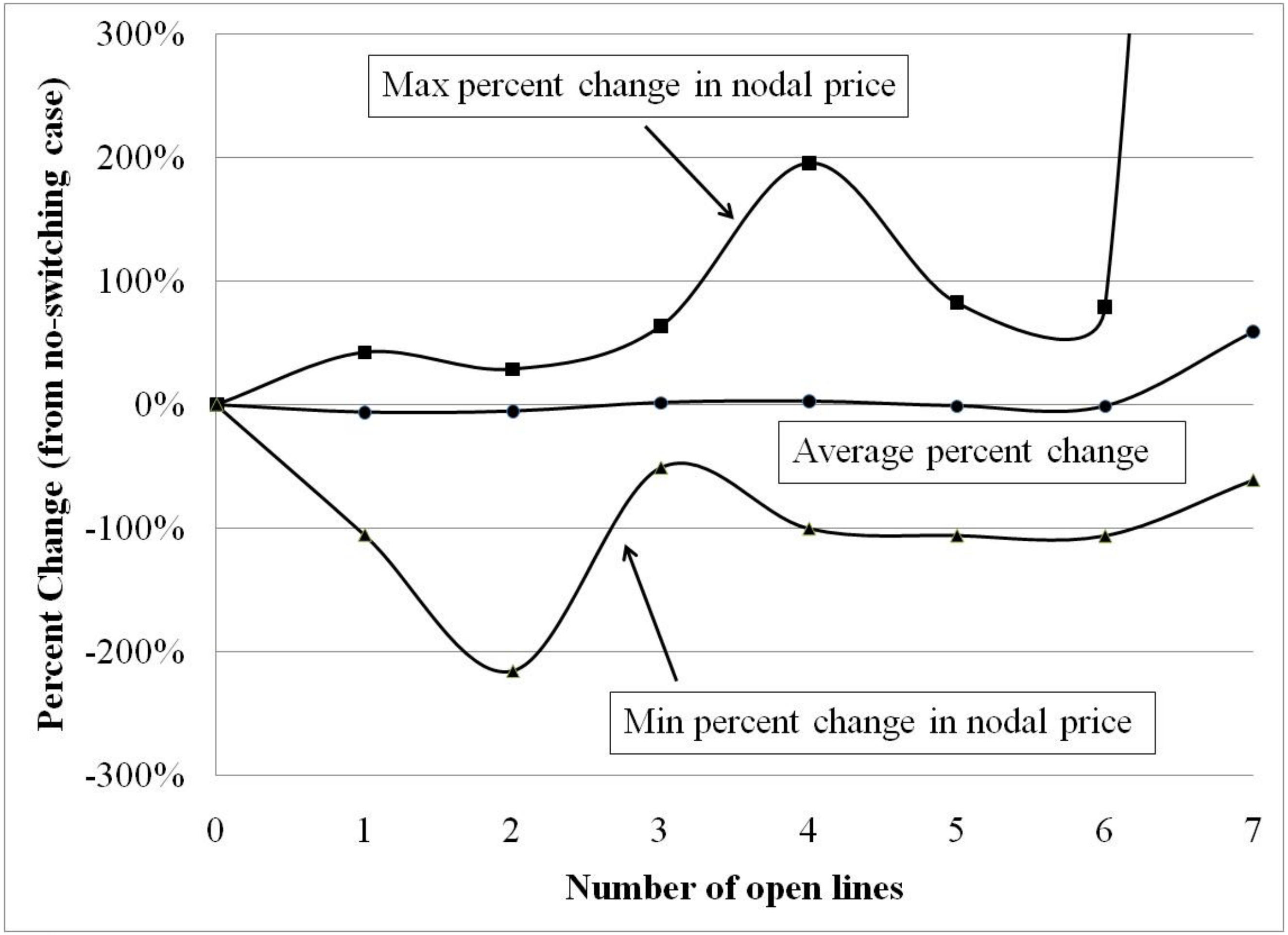
- IEEE 118 opened lines for J=10
- Note: this diagram has additional gens than our model



One-line Diagram of IEEE 118-bus Test System

Results – DCOPF – IEEE 118



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Results – DCOPF – IEEE 118

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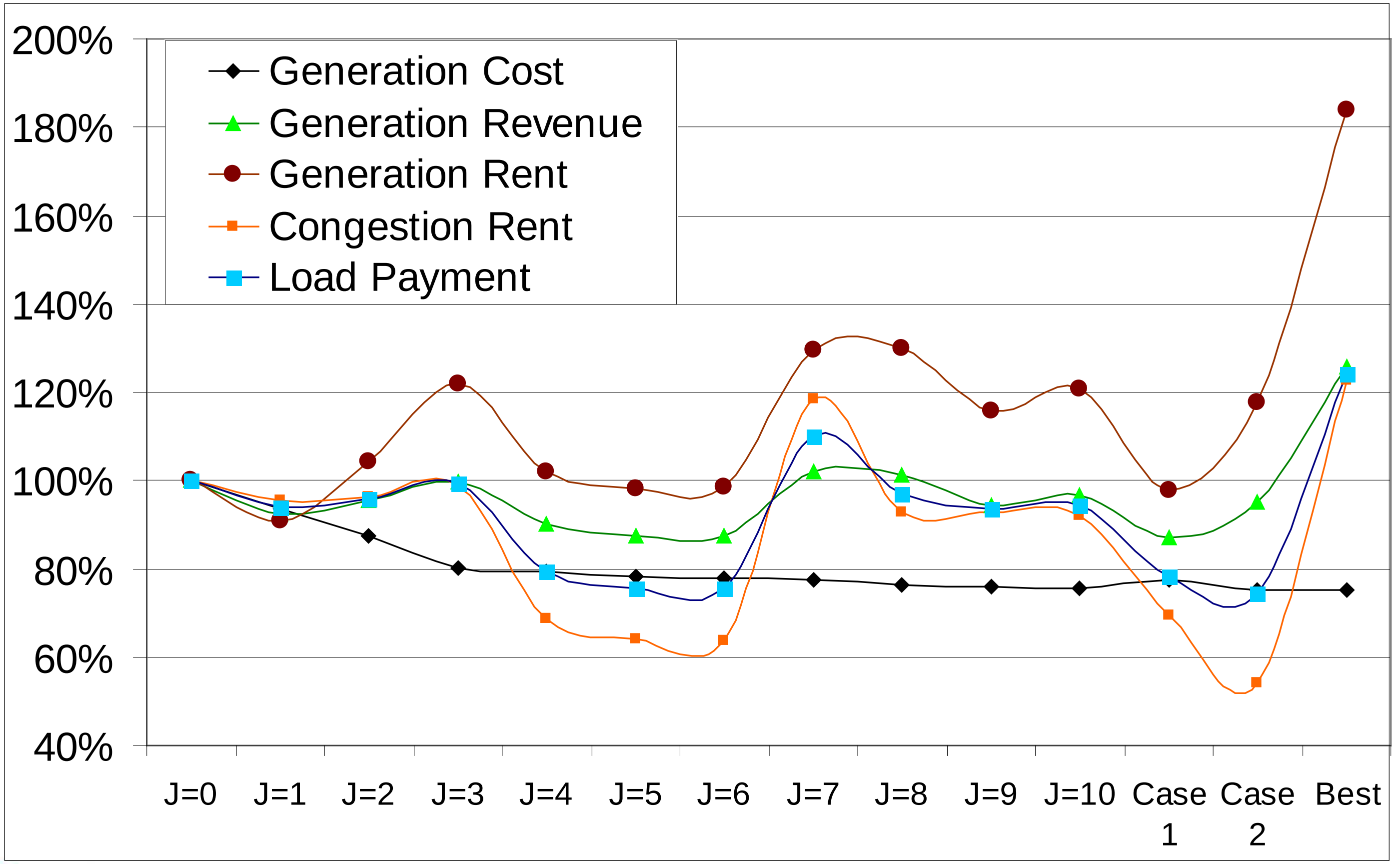
- Results are % of static network's DCOPF solution



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Optimal Transmission Switching with N-1 DCOPF

Minimize: $\mathrm{TC} = \sum_g c_{ng0} P_{ng0}$

s.t.:

Bus angle constraints

$$\theta_{n0}^{\min} \le \theta_{nc} \le \theta_{n0}^{\max}, \ \forall n, c$$

Generator constraints for each state

$$0 \le P_{ngc} \le P_{g0}^{\max} N1_{gc}, \ \forall g, c.$$

Node balance constraints

$$\sum_{\forall k|i=n} P_{ijkc} - \sum_{\forall k|j=n} P_{ijkc} + \sum_{\forall g|s=n} P_{sg0} - P_{nd} = 0,$$ $\forall n, c = 0,$ transmission contingency states c

$$\sum_{\forall k|i=n} P_{ijkc} - \sum_{\forall k|j=n} P_{ijkc} + \sum_{\forall g|s=n} P_{sgc} - P_{nd} = 0,$$ $\forall n,$ generator contingency states c

Transmission constraints for each state

$$P_{kc}^{\min} z_k N1_{kc} \le P_{nmkc} \le P_{kc}^{\max} z_k N1_{kc}, \ \forall k, c$$

$$B_k(\theta_{nc} - \theta_{mc}) - P_{nmkc} + (2 - z_k - N1_{kc}) M_{kc} \ge 0, \quad \forall k, c$$

$$B_k(\theta_{nc} - \theta_{mc}) - P_{nmkc} - (2 - z_k - N1_{kc}) M_{kc} \le 0, \quad \forall k, c$$

$$z_k \in \{0,1\}, \ \forall k \in K$$

$$N1_{ec} = \begin{Bmatrix} 0, \text{if } c = e \\ 1, \text{otherwise} \end{Bmatrix}, \ \forall c > 0, e$$

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N1 Binary Parameter

- Incorporation of N-1 reliability constraints:
- $N1_{ec}$: N-1 binary *parameter* specifying what element e (transmission or generator) in the network is offline for state c

- c=0 steady-state operations
- c>0 contingency state

$$N1_{ec} = \begin{Bmatrix} 0, \text{ if } c = e \\ 1, \text{ otherwise} \end{Bmatrix}, \ \forall c > 0, e \quad (13)$$

$$\sum_{\forall e} N1_{ec} = N - 1, \ \forall c > 0 \quad (14)$$

$$\sum_{\forall c > 0} N1_{ec} = N - 1, \ \forall e. \quad (15)$$

Optimal Transmission Switching with N-1 DCOPF (cont'd)

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- Transmission contingencies:
  - Thermal ratings are set at emergency ratings
  - Generator dispatch is unchanged
- Generation contingencies:
  - No ramp rate modeling of generators
  - Assume possible full redispatch of online generators
  - Thermal ratings are set at emergency ratings
- Determine modified N-1 contingency lists for test cases

Results – N-1 DCOPF IEEE 118

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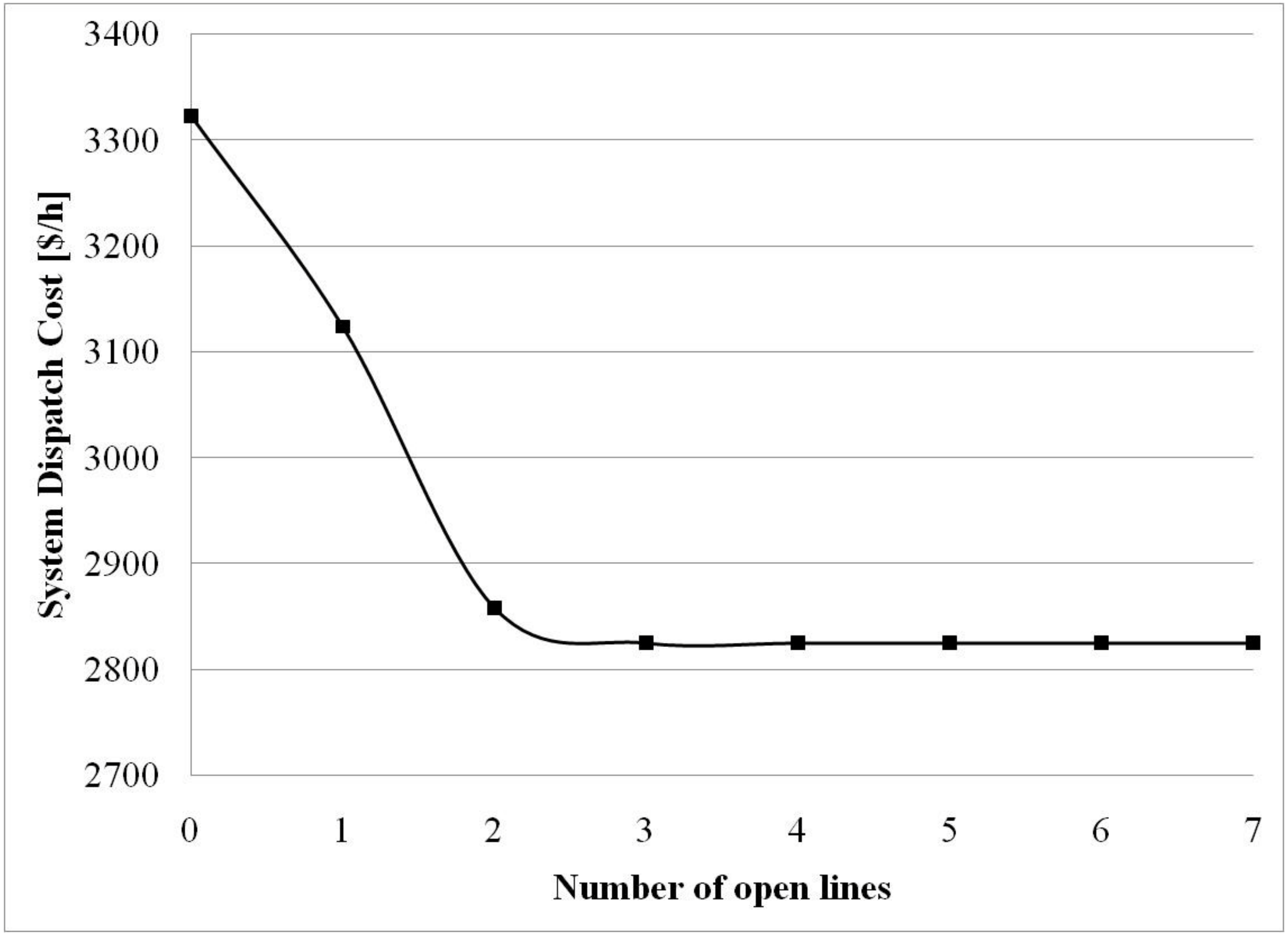

Results – N-1 DCOPF IEEE 118

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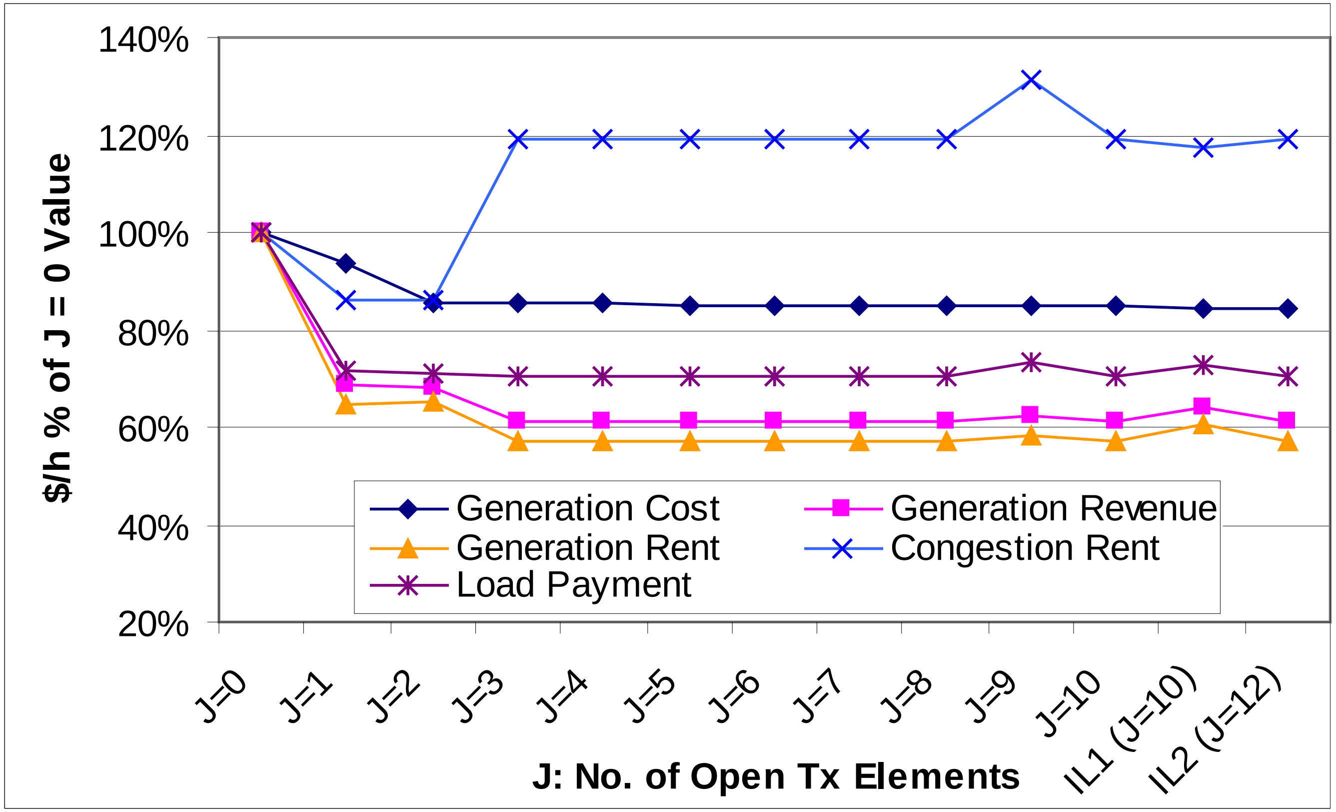
- Results are % of static network's N-1 DCOPF solution



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Results – N-1 DCOPF – IEEE 73 (RTS 96)

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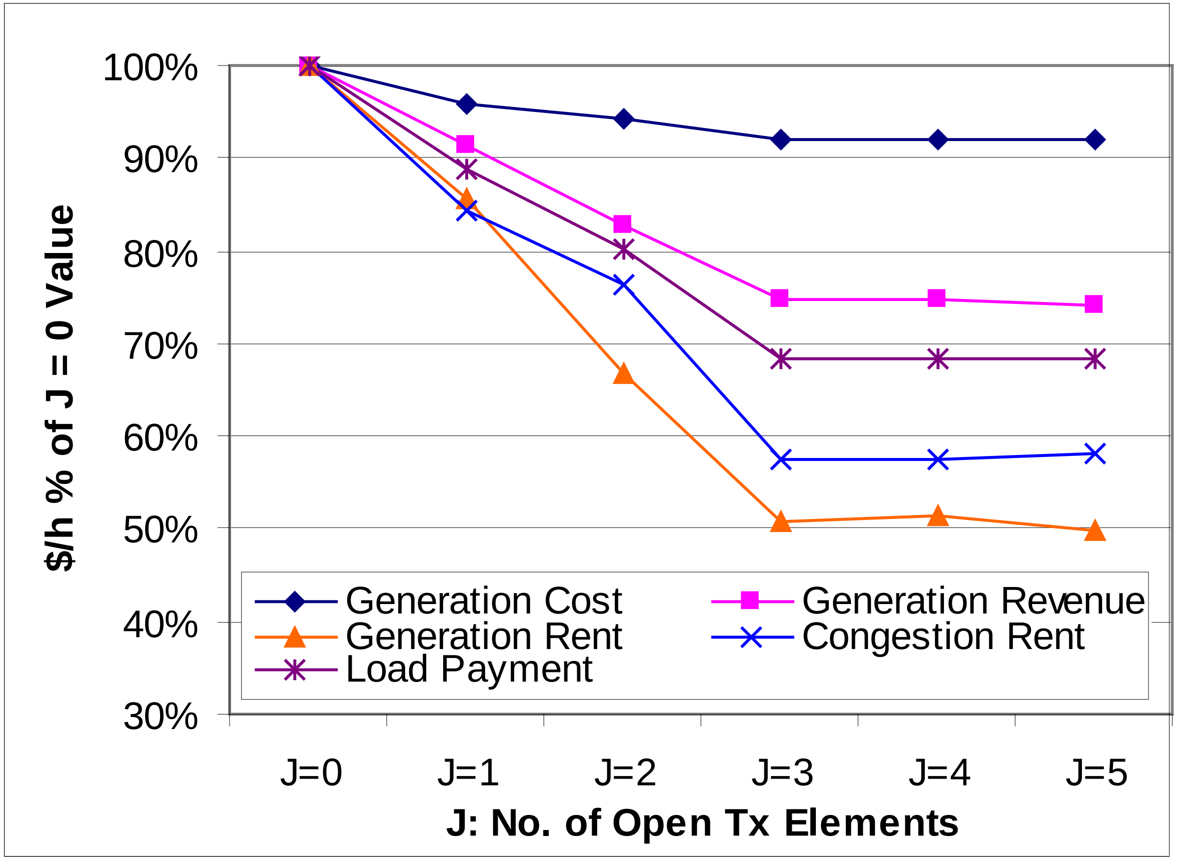
- Results are % of static network's N-1 DCOPF solution



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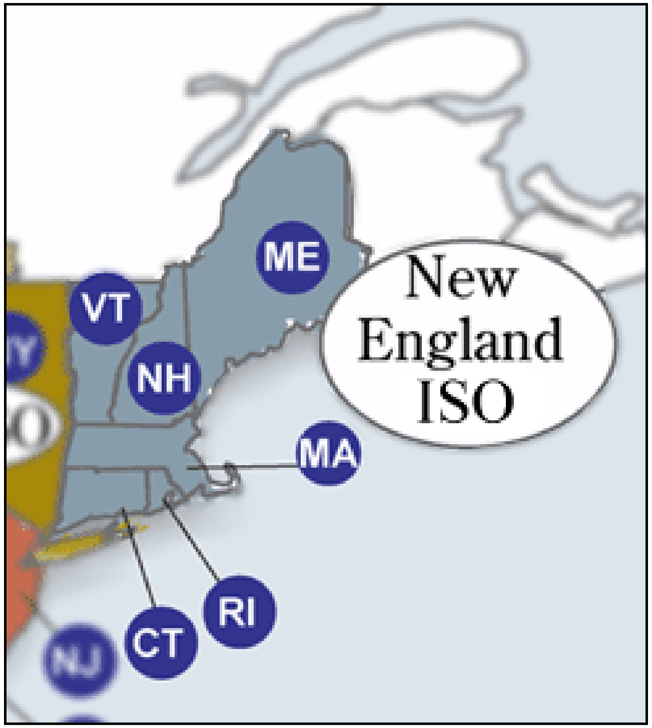
Results - Summary

- ISO-NE 5000 bus model
  - **5% to 13% savings of $600,000 total cost for NEPOOL for one hour** (feasible solutions)
- Does not include reliability constraints



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Results – DCOPF – ISONE

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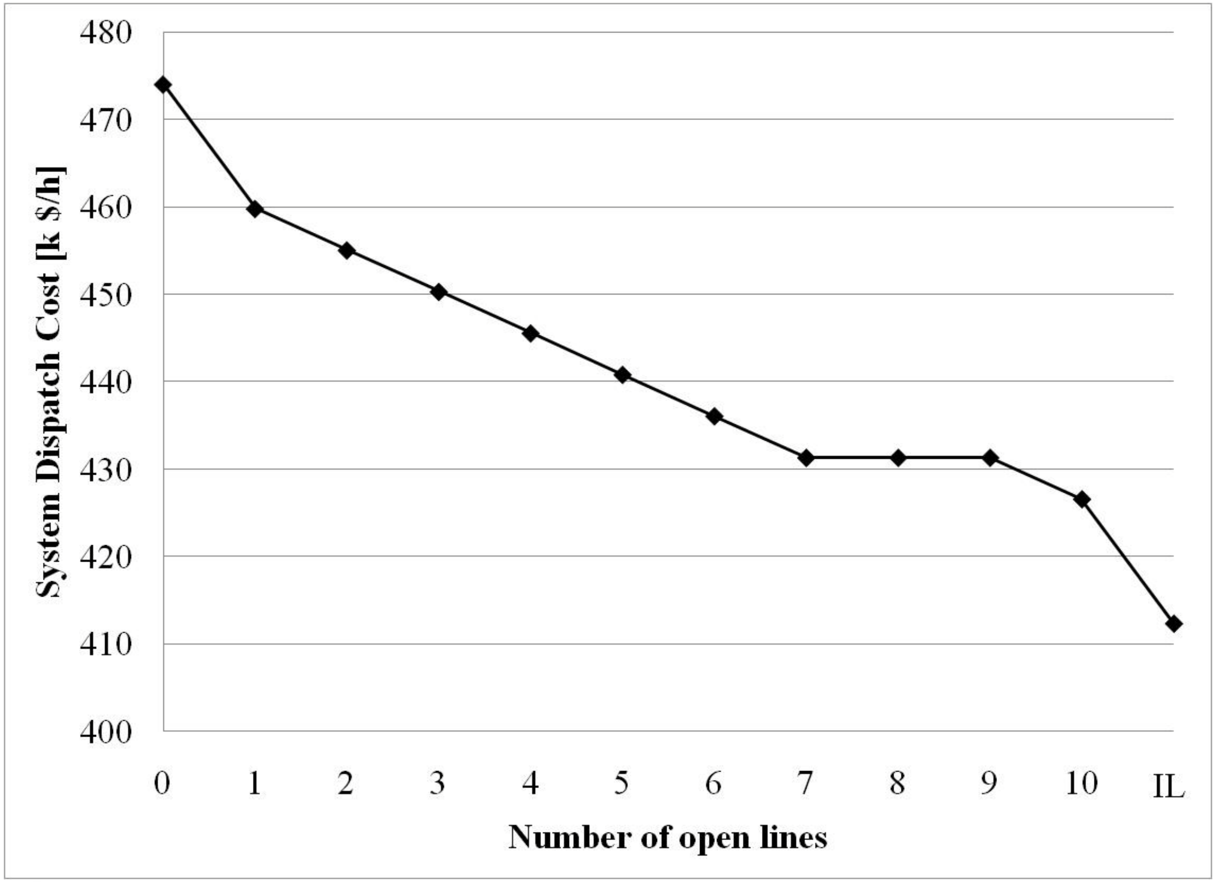
- ISONE – Summer Peak Model (5000 bus network)



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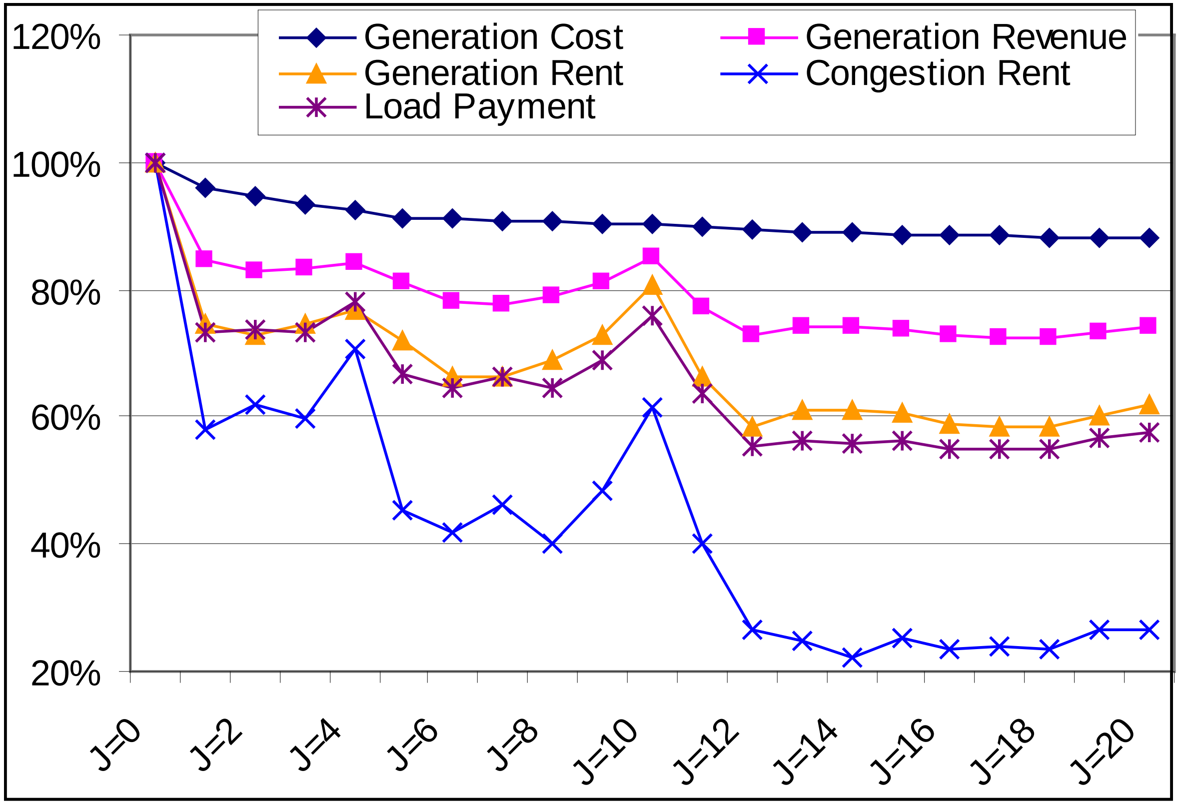
Results – DCOPF – ISONE

- Results are % of static network's DCOPF solution
- ISONE – Summer Peak Model



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Results – DCOPF – ISONE (cont'd)

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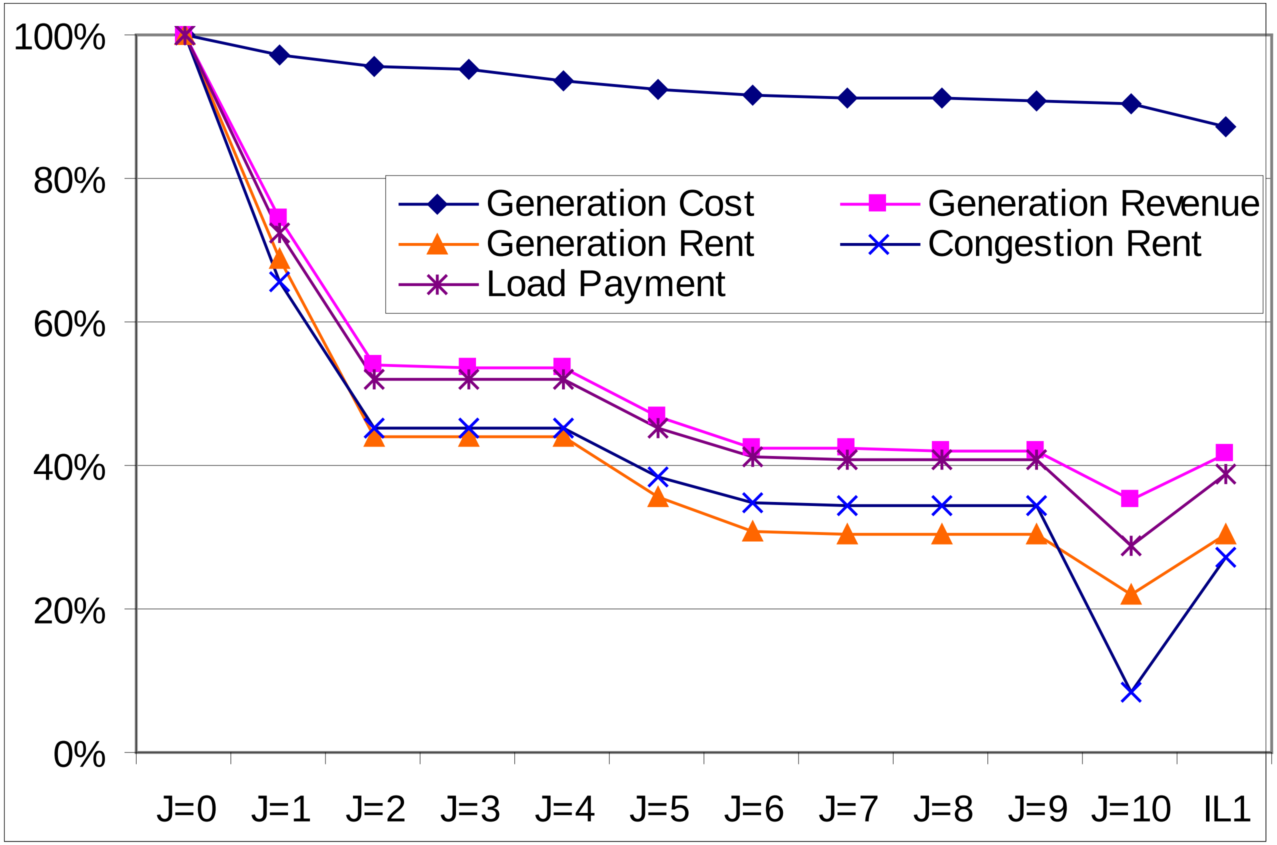
- Results are % of static network's DCOPF solution
- ISONE – Connecticut Import Study Model



Multi-Period Model with Reliability Constraints

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- Generation Unit Commitment Multi-Period Model
  - Startup costs
  - Shutdown costs
  - Minimum up and down time constraints
    - Facet defining valid inequalities
  - No ramp rate constraints
- Transmission Switching
- N-1 Contingency Constraints

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Generation Unit Commitment Nomenclature

- **Variables:**
- u_{gt}: Unit commitment variable (1 generator online, 0 generator offline)
- v_{gt}: Startup variable (1 generator turned on in period t, 0 otherwise)
- w_{gt}: Shutdown variable (1 generator turned off in period t, 0 otherwise)
- **Parameters:**
- SU_g: Startup cost, generator g
- SD_g: Shutdown cost, generator g
- UT_g: Minimum up time, generator g
- DT_g: Minimum down time, generator g

Multi-Period Formulation

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- Objective & Power Flow Constraints:

$$\text{Minimize: } \sum_t \sum_g \left(c_g P_{ng0t} + SU_g v_{gt} + SD_g w_{gt} \right) \quad (1)$$

s.t.

$$\theta^{\min} \le \theta_{nct} \le \theta^{\max}, \quad \forall n, c, t \quad (2)$$

$$\sum_{\forall k|i=n} P_{ijkct} - \sum_{\forall k|j=n} P_{ijkct} + \sum_{\forall g|s=n} P_{sg0t} - P_{ndt} = 0,$$
$$\forall n, c = 0, \text{ transmission contingency states } c,\ t \quad (3a)$$

$$\sum_{\forall k|i=n} P_{ijkct} - \sum_{\forall k|j=n} P_{ijkct} + \sum_{\forall g|s=n} P_{sgct} - P_{ndt} = 0,$$
$$\forall n, \text{ generator contingency states } c,\ t \quad (3b)$$

$$P_{kc}^{\min} z_{kt} N1_{kc} \le P_{nmkct} \le P_{kc}^{\max} z_{kt} N1_{kc}, \forall k, c, t \quad (4)$$

$$B_k(\theta_{nct} - \theta_{mct}) - P_{nmkct} + (2 - z_{kt} - N1_{kc})M_k \ge 0,$$
$$\forall k, c, t \quad (5a)$$

$$B_k(\theta_{nct} - \theta_{mct}) - P_{nmkct} - (2 - z_{kt} - N1_{kc})M_k \le 0,$$
$$\forall k, c, t \quad (5b)$$

Multi-Period Formulation cont'd

- Generation Unit Commitment Constraints:

$$P_g^{\min} N1_{gc} u_{gt} \le P_{ngct} \le P_g^{\max} N1_{gc} u_{gt}, \quad \forall g, c, t \tag{6}$$

$$v_{g,t} - w_{g,t} = u_{g,t} - u_{g,t-1}, \quad \forall g, t \tag{7}$$

$$\sum_{q=t-UT_g+1}^{t} v_{g,q} \le u_{g,t}, \quad \forall g, t \in \{UT_g, \ldots, T\} \tag{8}$$

$$\sum_{q=t-DT_g+1}^{t} w_{g,q} \le 1 - u_{g,t}, \quad \forall g, t \in \{DT_g, \ldots, T\} \tag{9}$$

$$0 \le v_{g,t} \le 1, \quad \forall g, t \tag{10}$$

$$0 \le w_{g,t} \le 1, \quad \forall g, t \tag{11}$$

$$u_{g,t} \in \{0,1\}, \quad \forall g, t. \tag{12}$$

Results – 24HR Gen UC & Optimal Transmission Switching N-1 DCOPF

- Model: IEEE RTS-96 system
- Results show:
  - Optimal network topology varies from hour to hour
  - Changing the network topology can change the optimal generation unit commitment solution
  - Total startup costs may be reduced
  - Peaker units initially required with original topology were not required once transmission switching was incorporated into the problem
- 3.7% overall savings or over $120,000 (24hr) for this medium sized IEEE test case – can translate into millions for large scale networks for entire year

Results – Computational Statistics

- IEEE 118 DCOPF & N-1 DCOPF variables & constraints:

IEEE 118	DCOPF		N-1 DCOPF	
	LP	MIP	LP	MIP
Total Variables:	323	509	63k	63k
Binary Variables:	0	186	0	186
Total Linear Constraints:	628	1000	126k	202k
Total Variables (Post Presolve):	315	492	60k	61k
Binary Variables (Post Presolve):	0	177	0	97
Linear Constraints (Post Presolve):	482	833	98k	137k

Computational Statistics cont'd

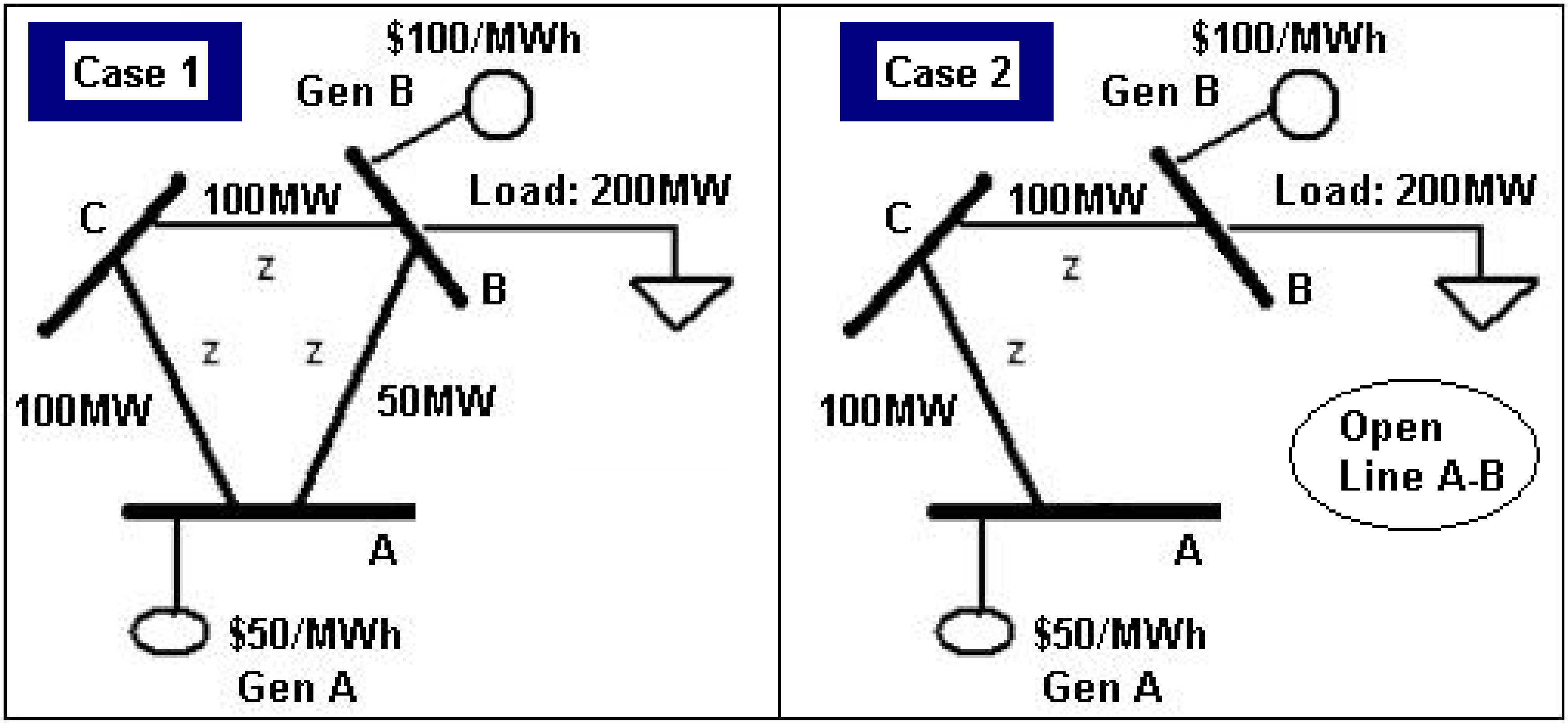
- ISONE (DCOPF)
  - To solve for best 2 lines to open, optimality not reached after 50 hours
  - Used heuristic of finding next best line to open

ISONE Summer Peak Model	LP	MIP
Total Variables:	12,237	18,889
Binary Variables:	0	6,652
Total Linear Constraints:	23,786	37,090
Upper or Lower Bound Constraints:	12,237	18,889
Total Variables (Post Presolve):	11,101	16,701
Binary Variables (Post Presolve):	0	5,600
Linear Constraints (Post Presolve):	17,063	27,441

Revenue Adequacy in Financial Transmission Rights Market

- FTRs: Hedging mechanism
- Market operator compensates FTR owners with congestion rent (surplus)
- Revenue adequacy not guaranteed if topology changes *[Alsac, Bright, et al. 2004]*
- Following example illustrate potential congestion revenue shortfall due to tran.smission switching

Revenue Adequacy of FTR s: Example



Revenue Adequacy of FTRs Cont'd

PSERC

Without Switching Line A-B In (Case 1):

BUS:	Gen Pg:	LMP:	Gen Cost:		BRANCH:	Line Flow:	Congestion Rent:
A	75MW	$50/MWh	$3,750		From A to B	50MW	$2,500
B	125MW	$100/MWh	$12,500		From A to C	25MW	$625
C	0MW	$75/MWh	$0		From B to C	-25MW	$625
		Total Gen Cost:	$16,250			Total Congestion Rent:	$3750

With Switching Line A-B Out (Case 2):

BUS	Gen Pg:	LMP:	Gen Cost:		BRANCH:	Line Flow:	Congestion Rent:
A	100MW	$50/MWh	$5,000		From A to B	0MW	$0
B	100MW	$100/MWh	$10,000		From A to C	100MW	$5,000
C	0MW	$100/MWh	$0		From B to C	-100MW	$0
		Total Gen Cost:	$15,000			Total Congestion Rent:	$5,000

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Revenue Adequacy of FTRs Cont'd

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Lines:	FTR Quantity:	FTR Payment Without Switching (Case 1)	FTR Payment With Switching (Case 2)
From A to B	50MW	$2,500 (LMP gap: $50/MWh)	$2,500 (LMP gap: $50/MWh)
From A to C	100MW	$2,500 (LMP gap: $25/MWh)	$5,000 (LMP gap: $50/MWh)
From B to C	50MW	-$1,250 (LMP gap: -$25/MWh)	$0 (LMP gap: $0/MWh)
Total FTR Payments:		**$3,750**	**$7,500 (>$5,000)**

Total generation cost decreases but we can create FTR holdings that result in revenue inadequacy for the switching solution.
We have revenue adequacy with the no switching solution (case 1) but we do not have it with the switching solution (case 2) even though it increases social welfare.

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Further Research

- Revenue adequacy and FTR settlement
  - Incorporate revenue adequacy feasibility test within transmission switching formulation
  - Do we need a compensation scheme to offset the impact on FTR settlements?
- Benders' decomposition
  - Analyze various sub-problem formats
  - Research techniques to improve solution time
    - Combinatorial cuts
    - Local branching
- Use AC OPF for short term (e.g. hourly) switching problem
  - MINLP very difficult
  - Research heuristic techniques

Documentation and Publications

PSERC

[1] **K. W. Hedman**, R. P. O'Neill, E. B. Fisher, **S. S. Oren**, "Optimal transmission switching – sensitivity analysis and extensions," *IEEE Trans. Power Syst.,* vol. 23, no. 3, pp. 1469-1479, Aug. 2008.

[2] **K. W. Hedman**, R. P. O'Neill, E. B. Fisher, S. S. Oren, "Optimal transmission switching with contingency analysis," *IEEE Trans. Power Syst.,* vol. 24, no. 3, Aug. 2009.

[3] **K. W. Hedman**, R. P. O'Neill, **S. S. Oren**, "Analyzing valid inequalities of the generation unit commitment problem," in *Proc. Power Syst. Conf. and Expo. (PSCE)*, March 2009.

[4] E. B. Fisher, **K. W. Hedman**, R. P. O'Neill, M. C. Ferris, **S. S. Oren**, "Optimal transmission switching in electric networks for improved economic operations," in *INFRADAY Conference* 2008.

[5] **K. W. Hedman**, M. C. Ferris, R. P. O'Neill, E. B. Fisher, **S. S. Oren**, "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," *IEEE Trans. Power Syst.*, submitted for publication.

[6] **K. W. Hedman**, R. P. O'Neill, E. B. Fisher, **S. S. Oren**, "Smart flexible just-in-time transmission and flowgate bidding," *IEEE Trans. Power Syst.*, submitted for publication.

[7] **K. W. Hedman**, R. P. O'Neill, **S. S. Oren**, "Ensuring revenue adequacy of FTRs with transmission switching," working paper.

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QUESTIONS?
Thank you!

http://www.ieor.berkeley.edu/~oren/index.htm