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

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(based on joint work with Emily Fisher, Richard O'Neill, and Michael Ferris)

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Motivation

- 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

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Motivation (cont'd)

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- Optimal transmission switching does not necessarily indicate inefficient transmission planning but such an option may affect planning
- With appropriate Smart Grid switching technology, some backup transmission can be kept offline (just in time N-1)
- Currently operators change transmission assets' states on ad-hoc basis (per private communication with Andy Ott, VP, PJM)
- Economically motivated transmission switching is consistent with FERC order 890 (supports transmission for economics)

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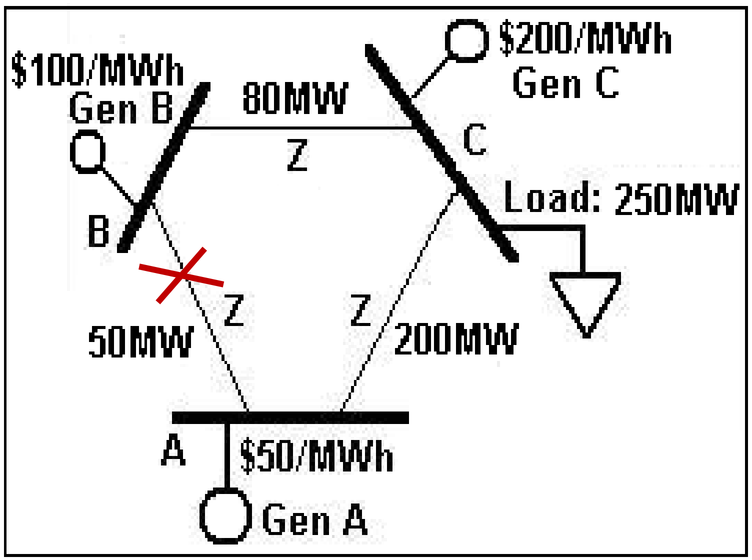
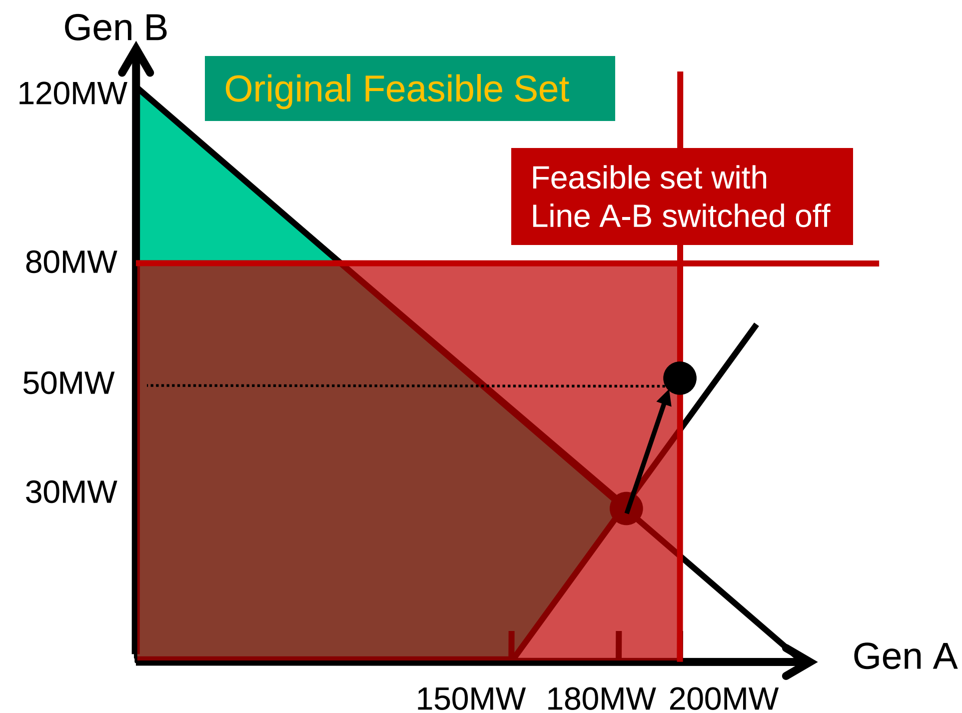
Transmission Switching Example

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





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

Technical Approach

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Traditional DCOPF

- Minimize: Total generation cost

  Subject to:
  - Bus angle constraints
  - Generator min & max operating constraints
  - Node balance constraints
  - Line flow constraints
  - Line min & max operating (thermal) constraint
- Initially we do not consider generation unit commitment (do not consider startup, no load cost or minimum load)
- We do not use PTDFs but rather: $B_k(\theta_n - \theta_m) - P_k^{nm} = 0$

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: $P_k^{\min} \le P_k^{nm} \le P_k^{\max}$
  - New: $P_k^{\min} z_k \le P_k^{nm} \le P_k^{\max} z_k$
- Update line flow constraints:
  - Original: $B_k(\theta_n - \theta_m) - P_k^{nm} = 0$
  - New:

$$B_k(\theta_n - \theta_m) - P_k^{nm} + (1 - z_k)M_k \ge 0$$

$$B_k(\theta_n - \theta_m) - P_k^{nm} - (1 - z_k)M_k \le 0$$

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Optimal Transmission Switching DCOPF

Minimize: $\sum_g c_g P_g^n$

$s.t.$

Bus Angle Constraints:

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

Generator Constraints

$$0 \le P_g^n \le P_g^{\max}, \; \forall g$$

Node Balance Constraints:

$$\sum_k P_k^{nm} - \sum_k P_k^{mn} + \sum_g P_g^n = d_n, \forall n$$

Transmission Constraints:

$$P_k^{\min} z_k \le P_k^{nm} \le P_k^{\max} z_k, \forall k$$

$$B_k(\theta_n - \theta_m) - P_k^{nm} + (1 - z_k) M_k \ge 0, \forall k$$

$$B_k(\theta_n - \theta_m) - P_k^{nm} - (1 - z_k) M_k \le 0, \forall k$$

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Optimal Transmission Switching with N-1 DCOPF

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- Add contingency constraints to DCOPF transmission switching problem
- Any new topology solution must satisfy all contingencies
- Determine modified N-1 contingency list for test cases
- IEEE 118 bus test case is not N-1 compliant with original topology
  - Modified N-1 contingency list includes all contingencies that can be met for the IEEE 118 test case with its original network topology
- RTS 96 test case is N-1 compliant with original topology
  - All N-1 contingencies are included
- Load shedding not allowed

Optimal Transmission Switching with Gen. Unit Commitment N-1 DCOPF

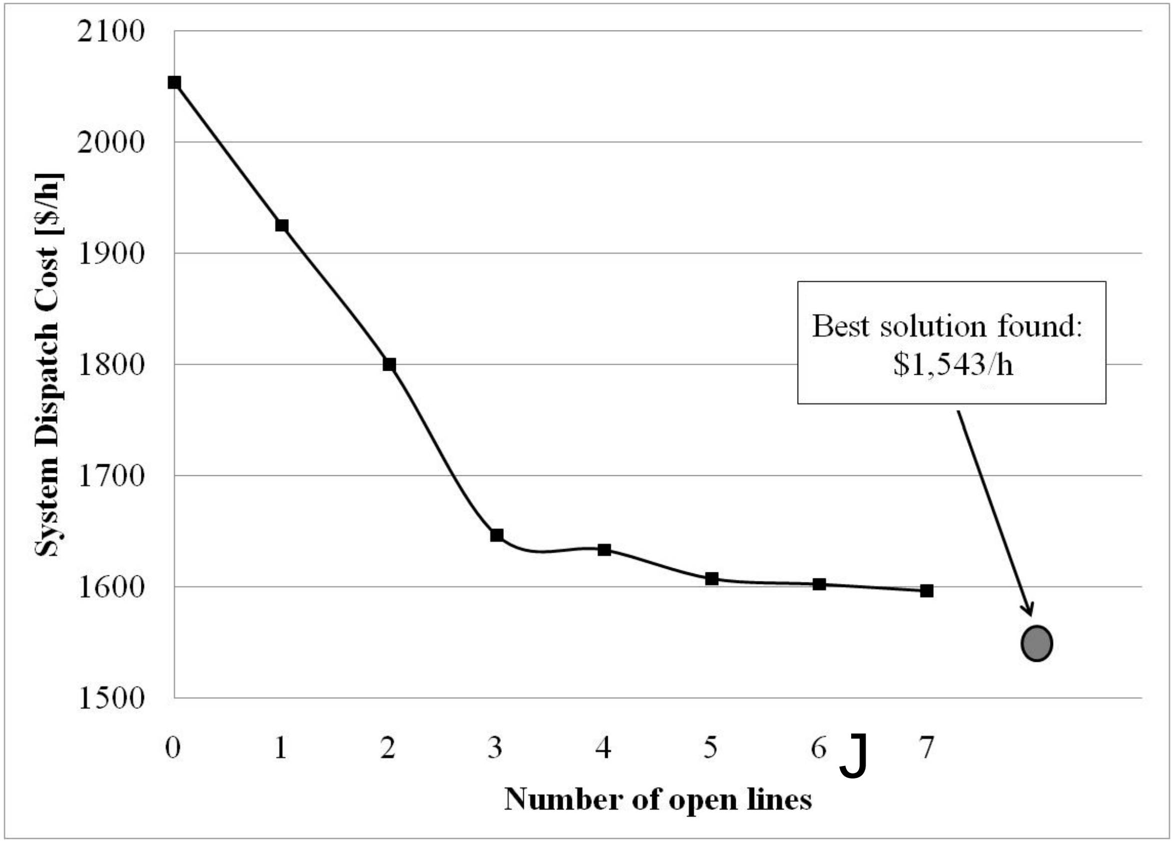
- Generation Unit Commitment Multi-Period Model
  - Startup costs
  - Shutdown costs
  - Minimum up and down time constraints
    - Facet defining valid inequalities
  - Ramp rate constraints
- Transmission Switching
- N-1 Contingency Constraints

Results

- 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)
- ISONE 5000 bus model (includes NEPOOL, NYISO, NB, NS – costs for NEPOOL only)
  - 5% to 13% savings of $600k total cost for NEPOOL for 1hr (for feasible solutions) - DCOPF

Results – DCOPF – IEEE 118

- Transmission switching solution saves 25% of total generation cost



Results – DCOPF – IEEE 118

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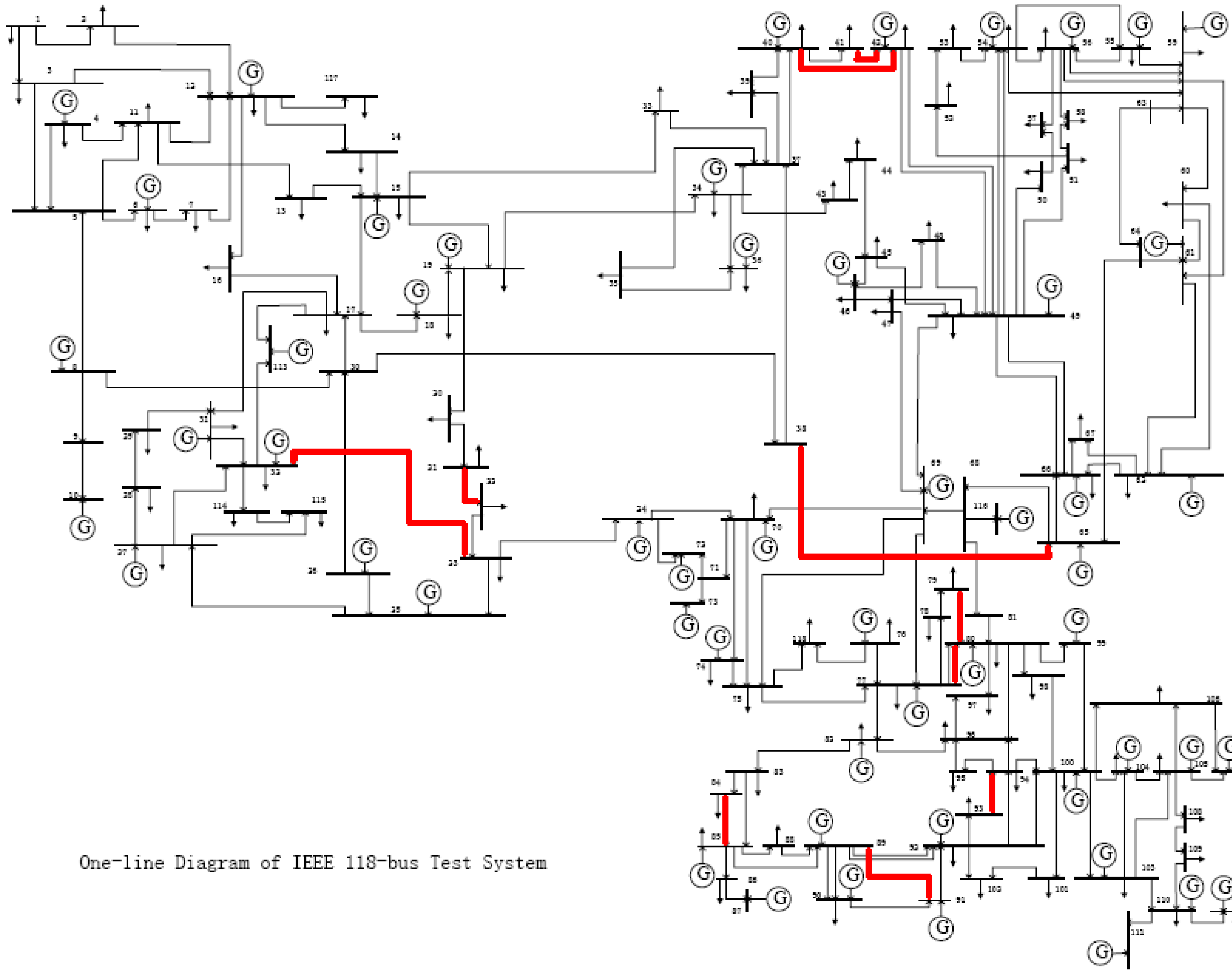
- IEEE 118 opened lines for J=10
- Note: this diagram has additional gens than our model



One-line Diagram of IEEE 118-bus Test System

Results – DCOPF – IEEE 118

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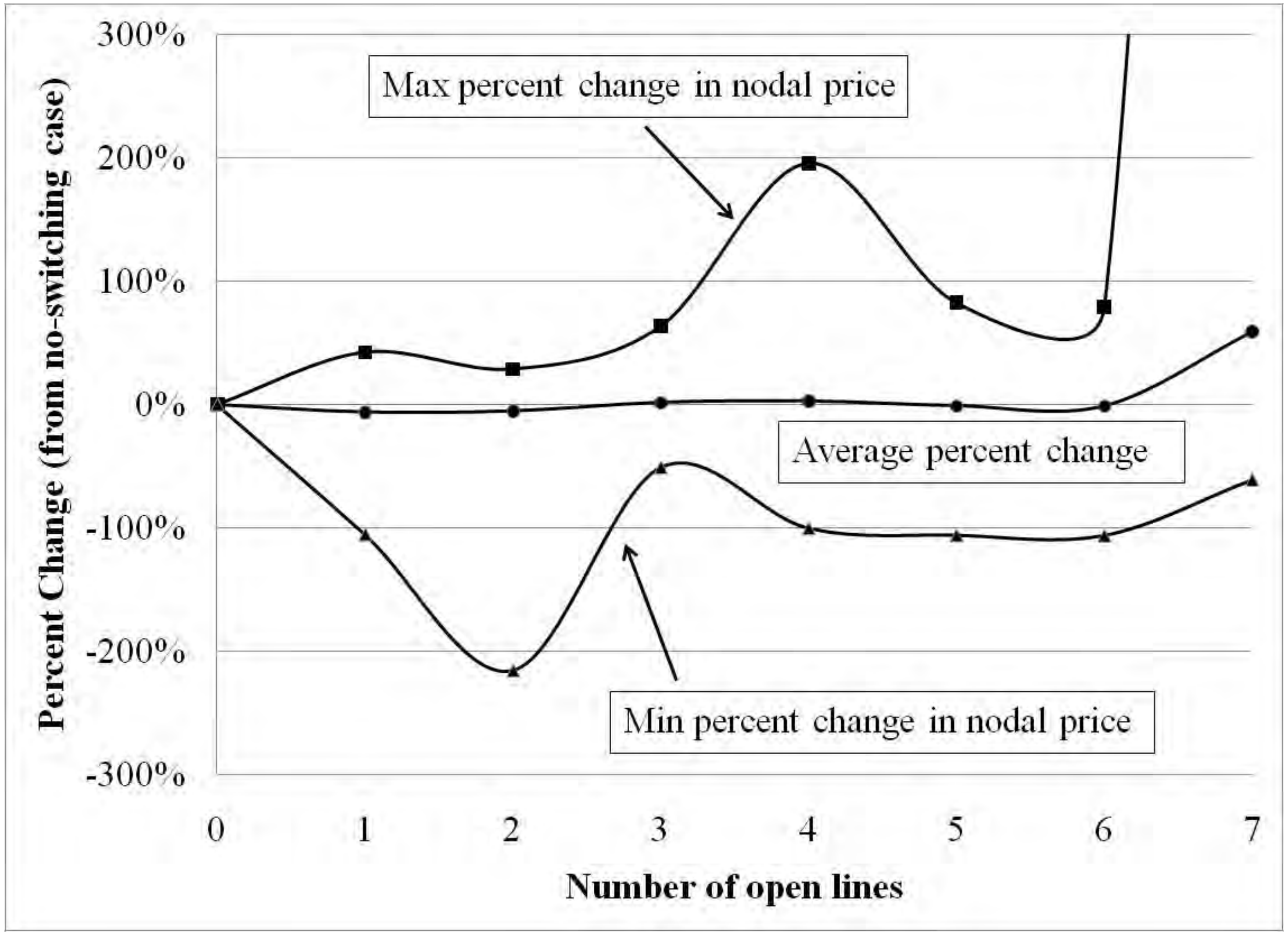

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Results – DCOPF – IEEE 118

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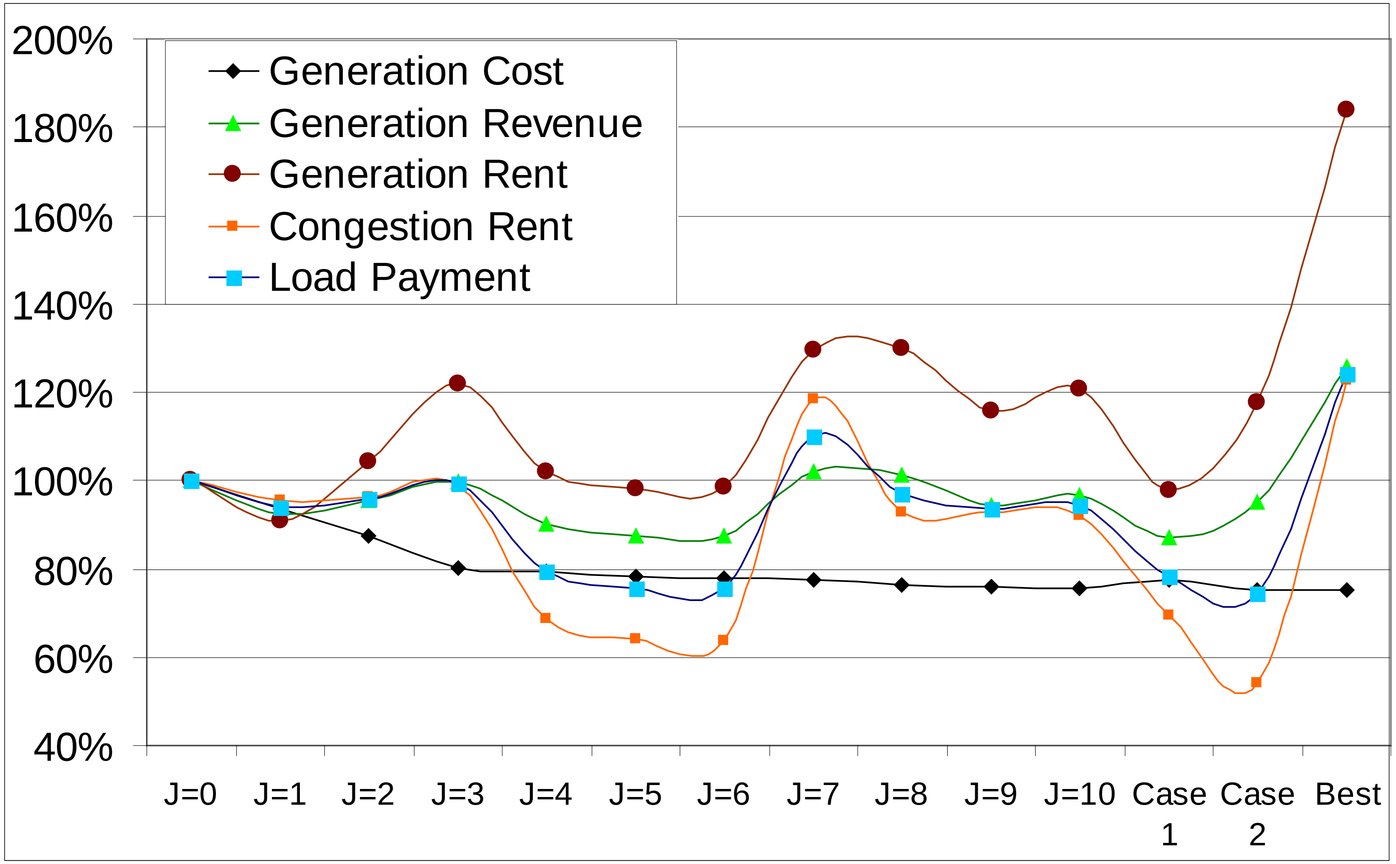
- Results are % of static network's DCOPF solution



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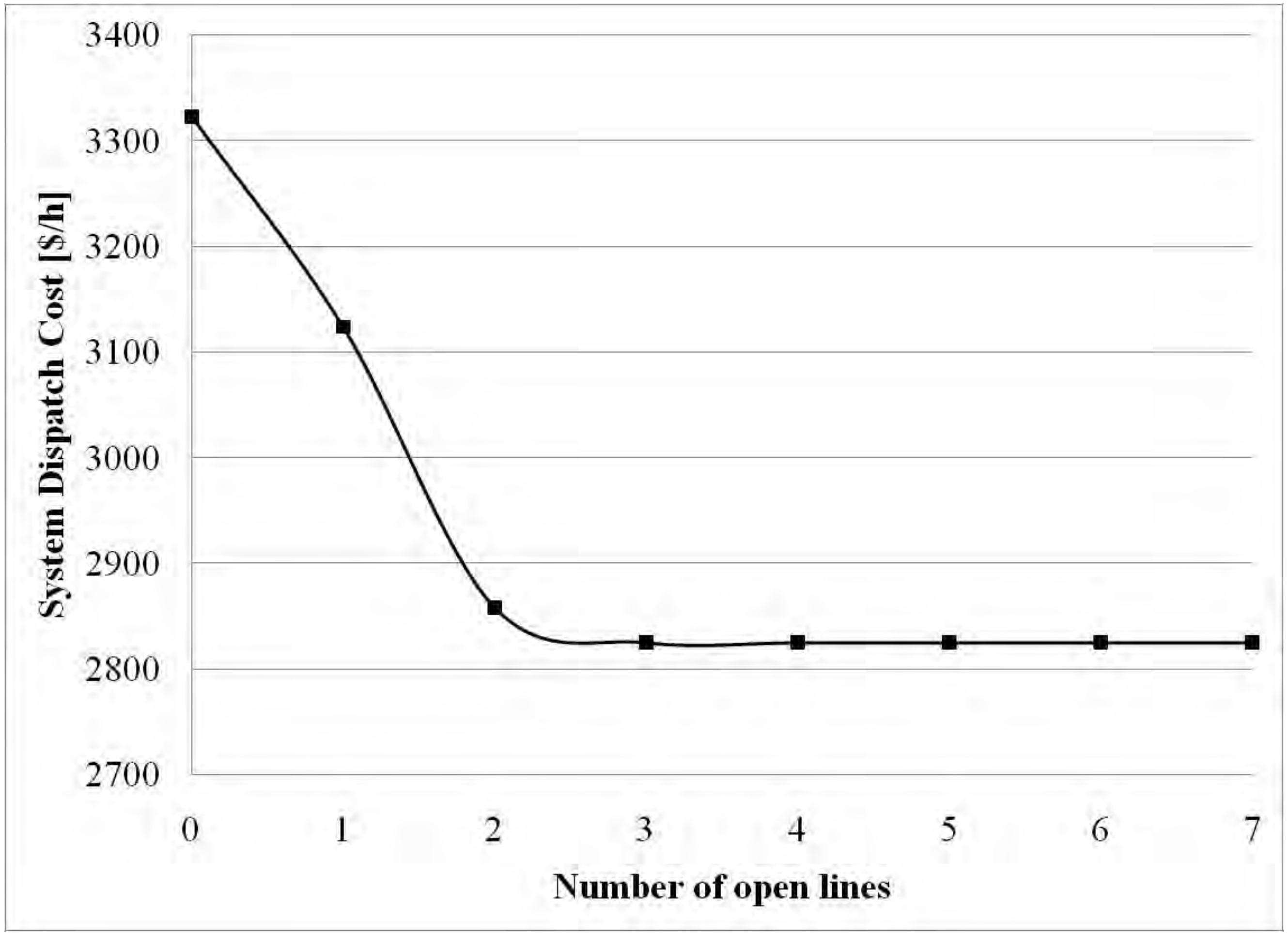
Results – N-1 DCOPF IEEE 118



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Results – N-1 DCOPF IEEE 118

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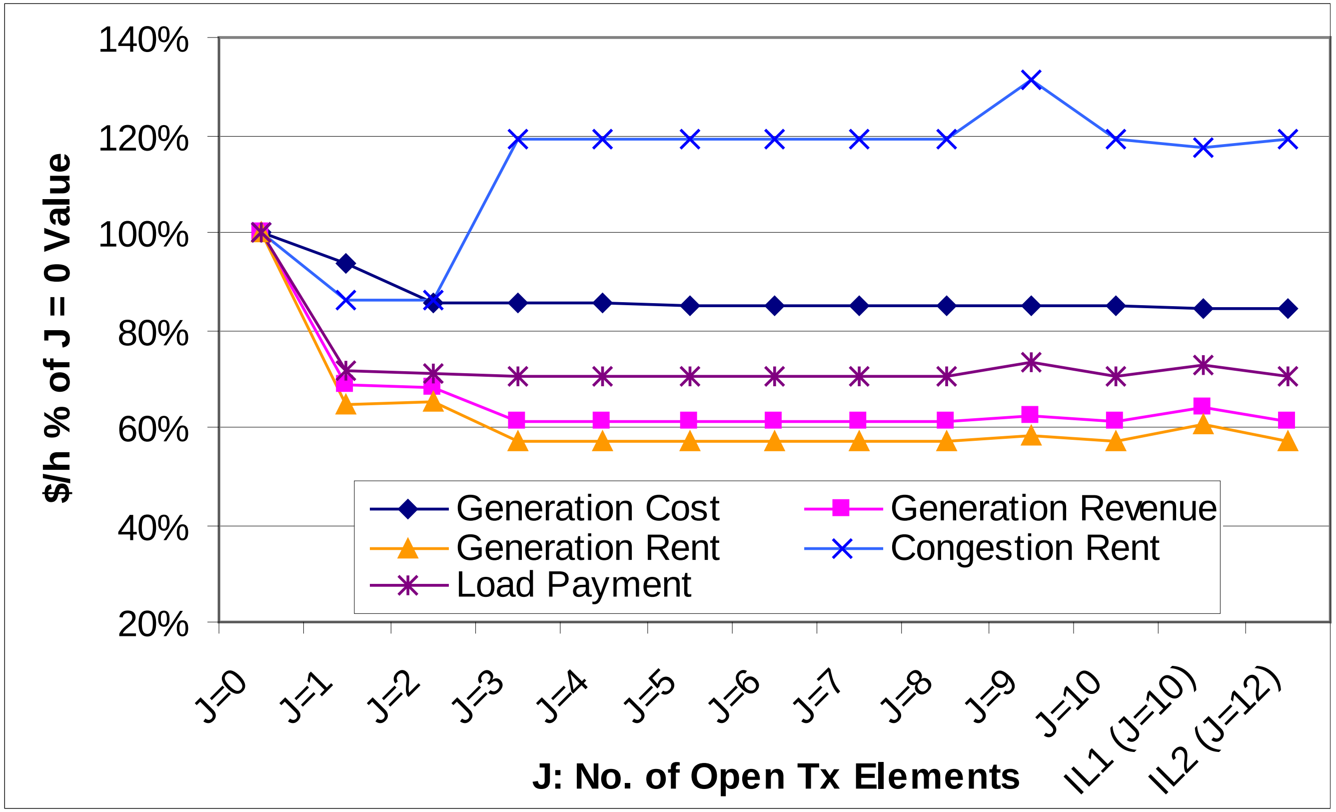
- Results are % of static network's N-1 DCOPF solution



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

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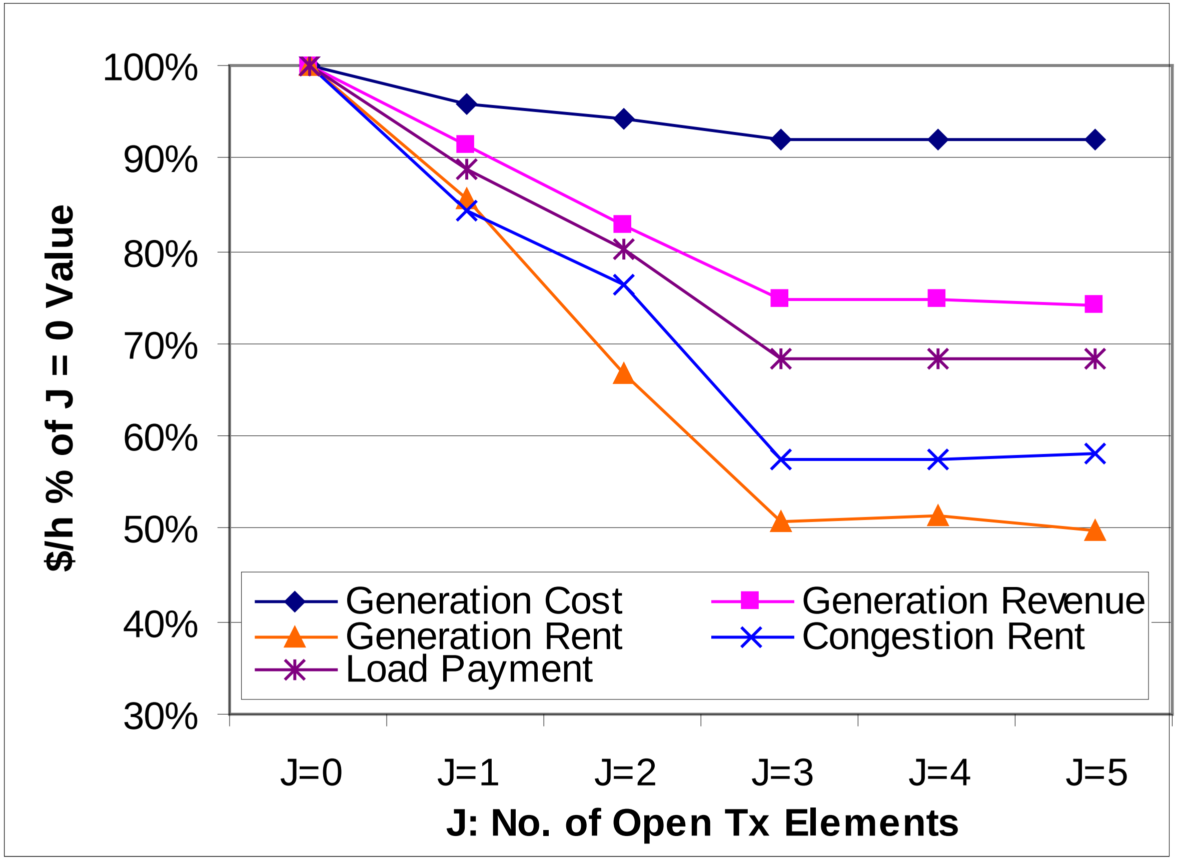
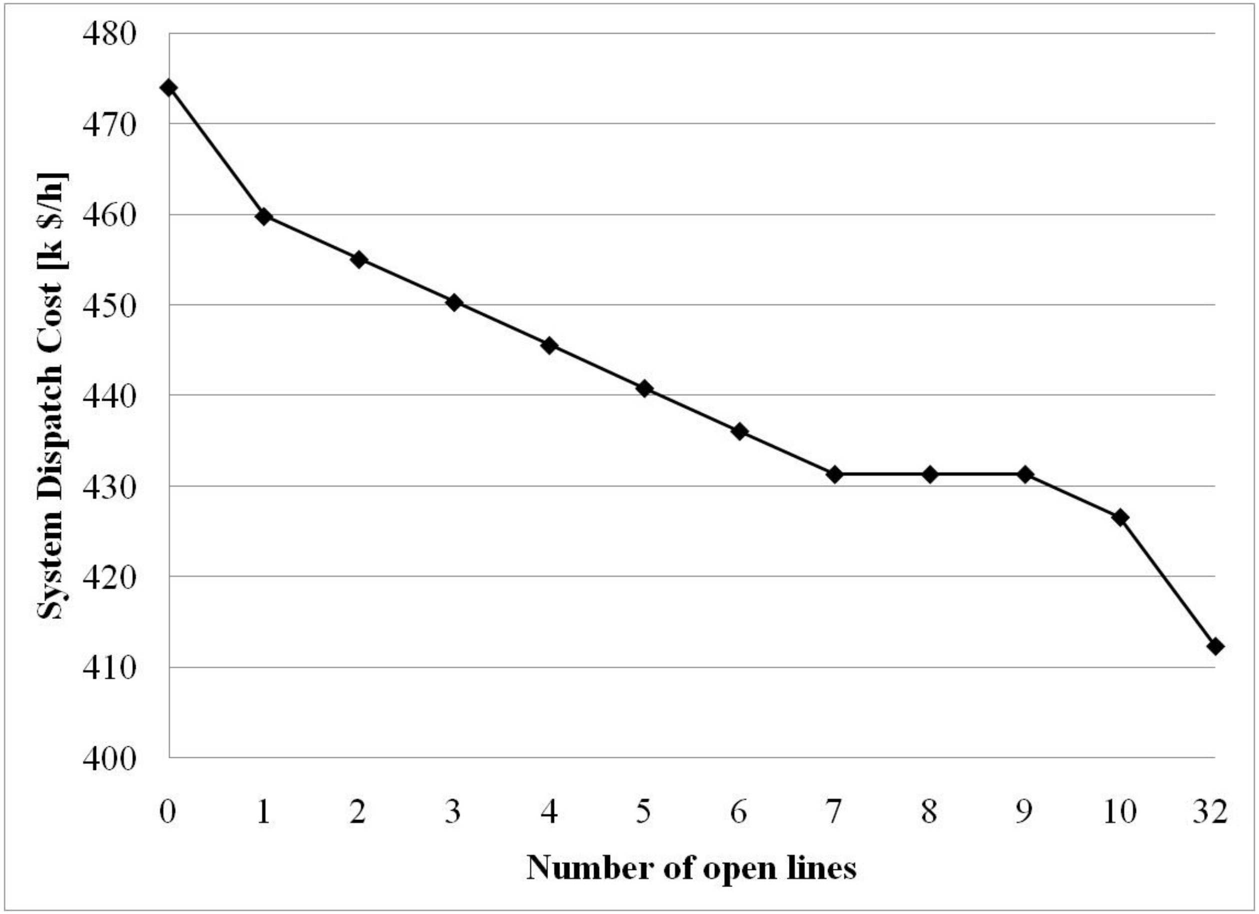
- Results are % of static network's N-1 DCOPF solution



Results – DCOPF – ISONE

- ISONE – Summer Peak Model (5000 bus network)



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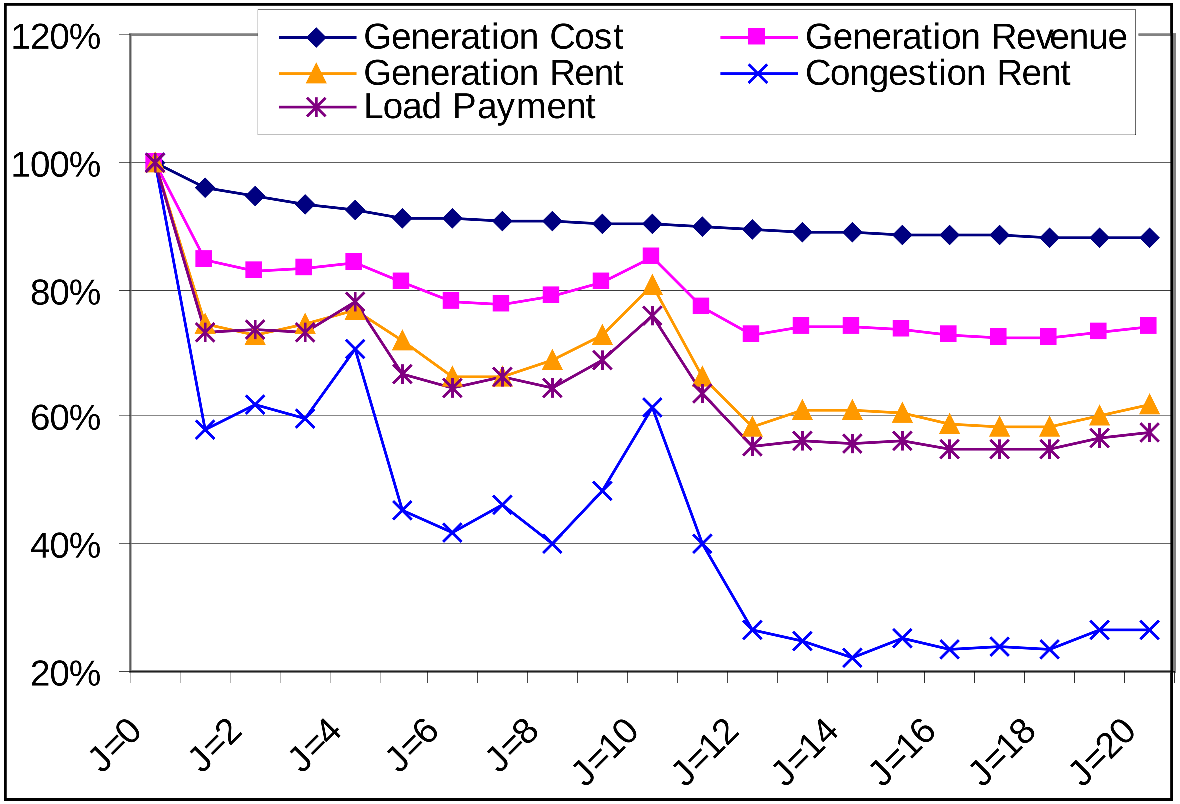
Results – DCOPF – ISONE

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



Results – DCOPF – ISONE (cont'd)

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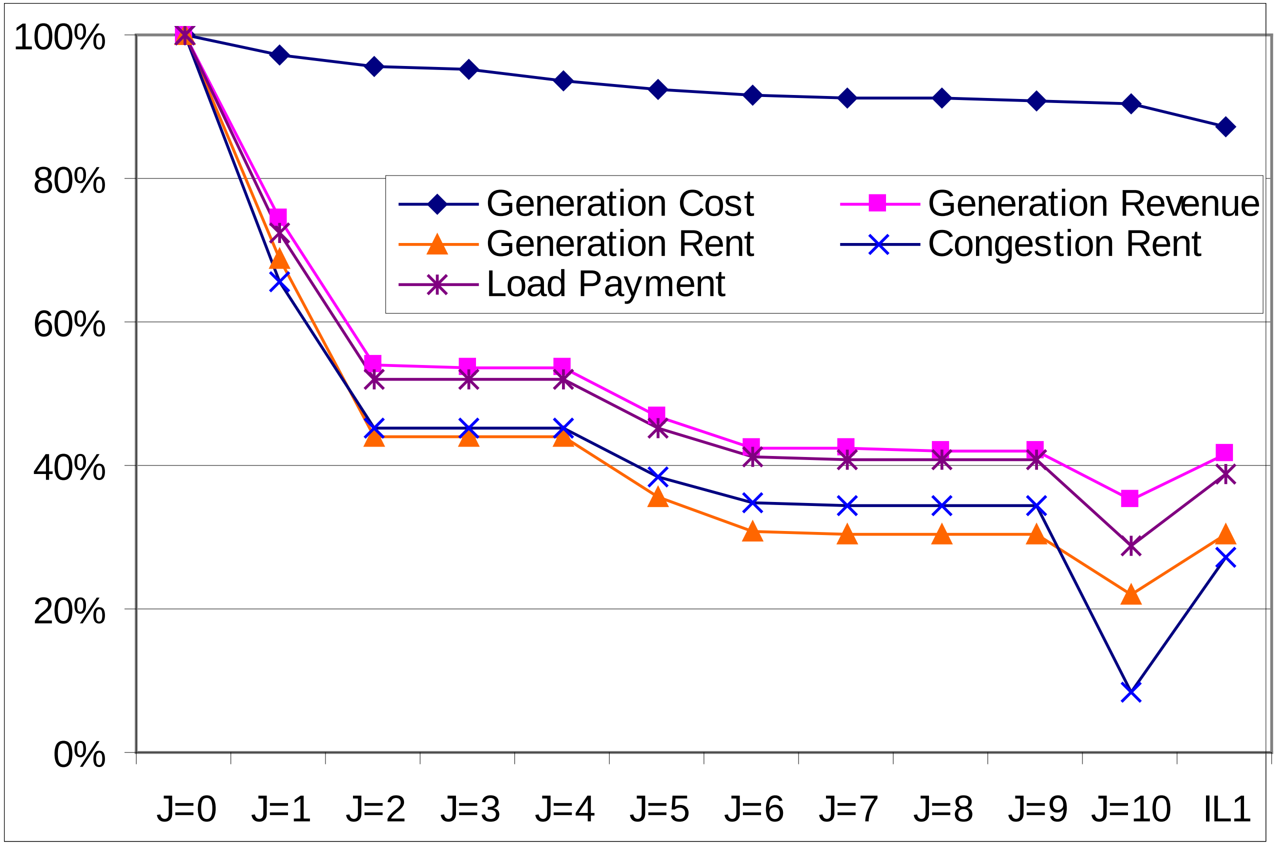
- Results are % of static network's DCOPF solution
- ISONE – Connecticut Import Study Model



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

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- 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

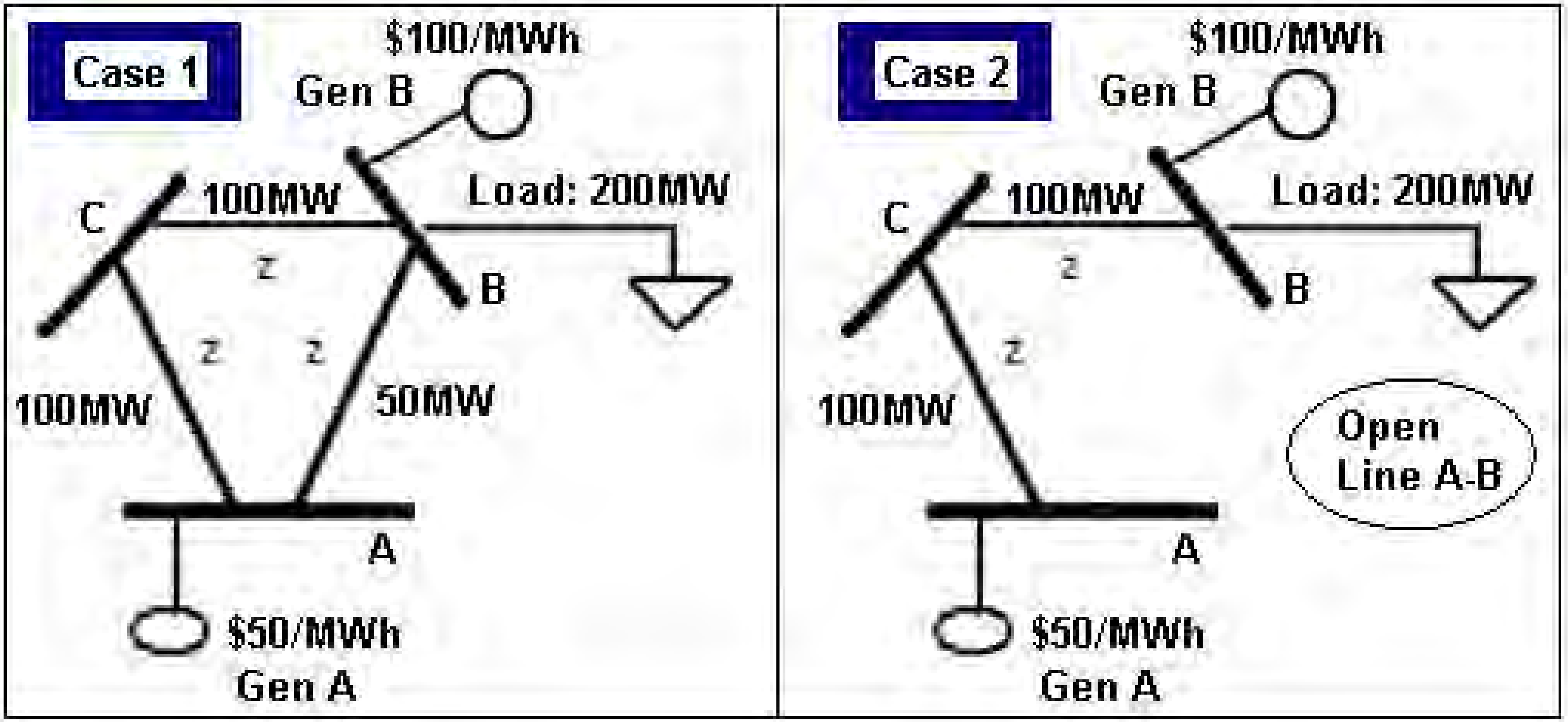
- ISONE (DCOPF)
  - Heuristics required to solve ISONE dataset
  - 6.6k binary vars, 19k vars, 37k linear constraints
- IEEE 118 DCOPF & N-1 DCOPF variables & constraints:

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

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
- Following example illustrates potential congestion revenue shortfall due to transmission switching

Revenue Adequacy of FTRs: Example



Revenue Adequacy of FTRs Cont'd

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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)**

- Transmission switching solution increases social welfare
- No switching solution (case 1) is revenue adequate
- Switching solution (case 2) is not revenue adequate
- Possible to have FTR holdings that will be revenue inadequate for specific network topology solutions that improve social welfare

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Further Research

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- 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

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Documentation and Publications

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[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