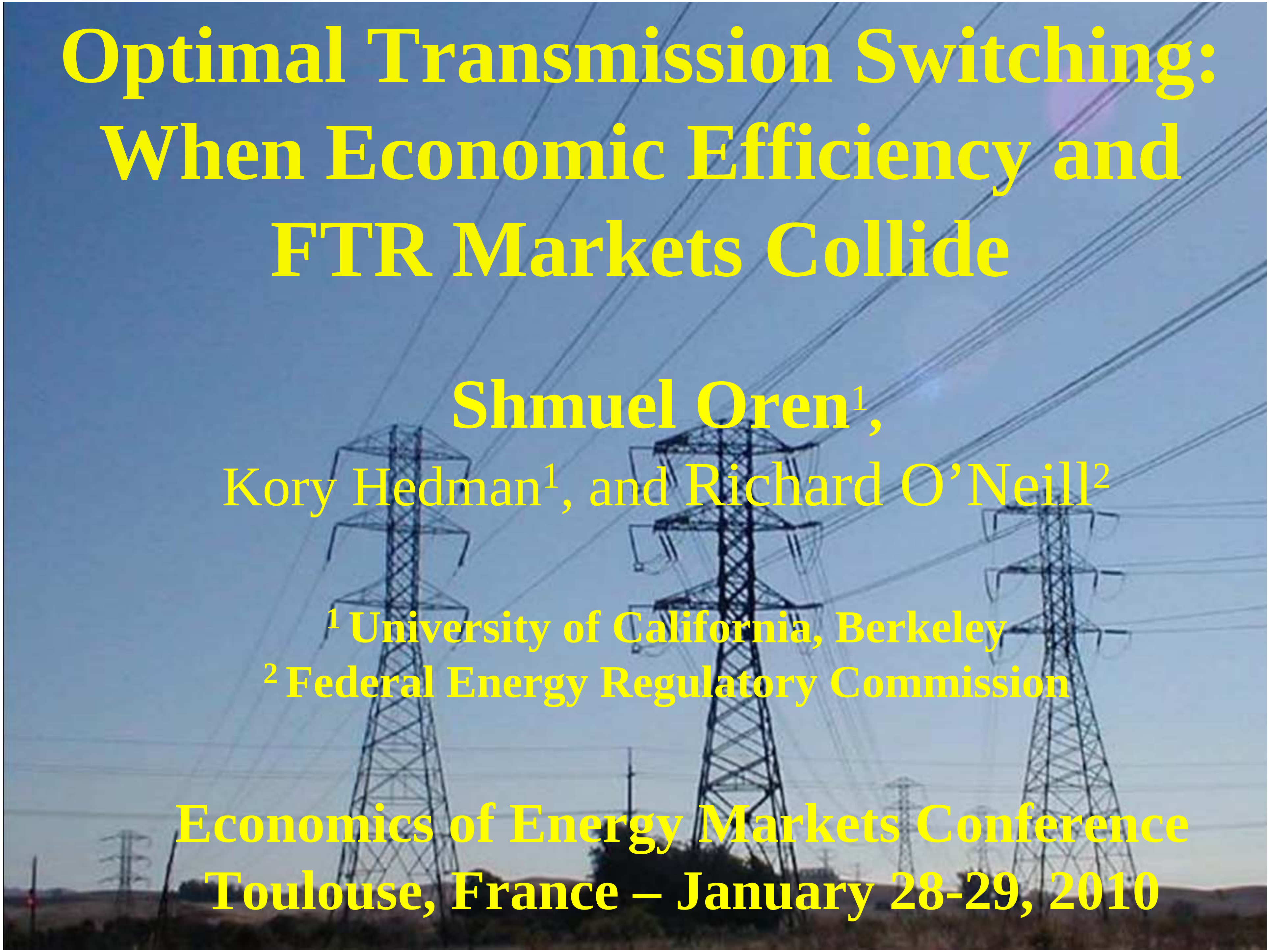

# Optimal Transmission Switching: When Economic Efficiency and FTR Markets Collide

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# Overview

- Motivation for transmission switching
  - Economic efficiency through topology improvements with no reliability degradation
  - Smart grid application by exploiting short term network reconfiguration flexibility
- Analyze market implications of optimal transmission switching
  - May undermine prevailing market mechanisms – cause revenue inadequacy in the FTR market
  - Unpredictable distributional impacts on LMPs, generation rent, congestion rent, etc.

# Overview of Optimal Transmission Switching Concept

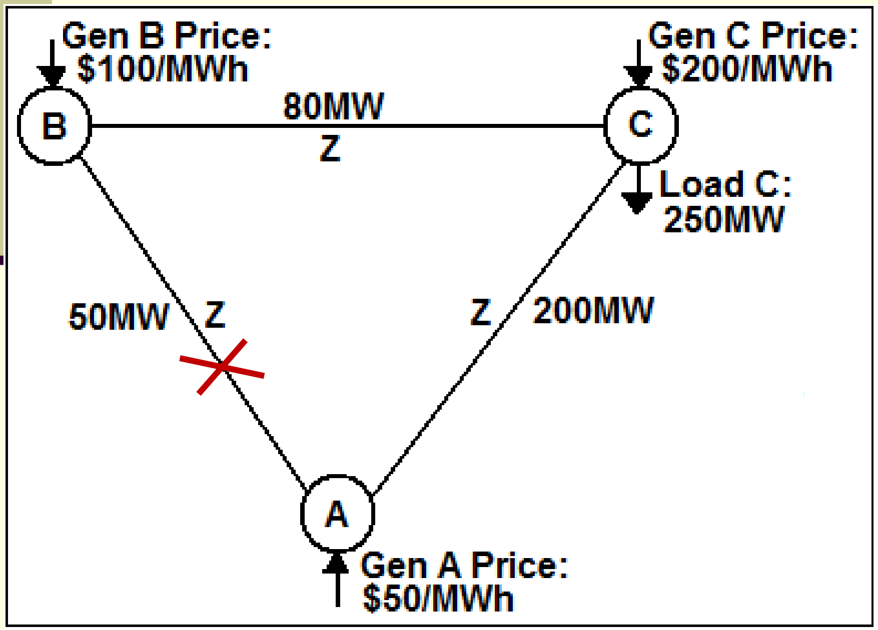
- Control of transmission not fully utilized today
  - Transmission assets are seen as static in the short term
  - Currently operators change transmission assets' states on ad-hoc basis (per private communication with Andy Ott, VP, PJM)

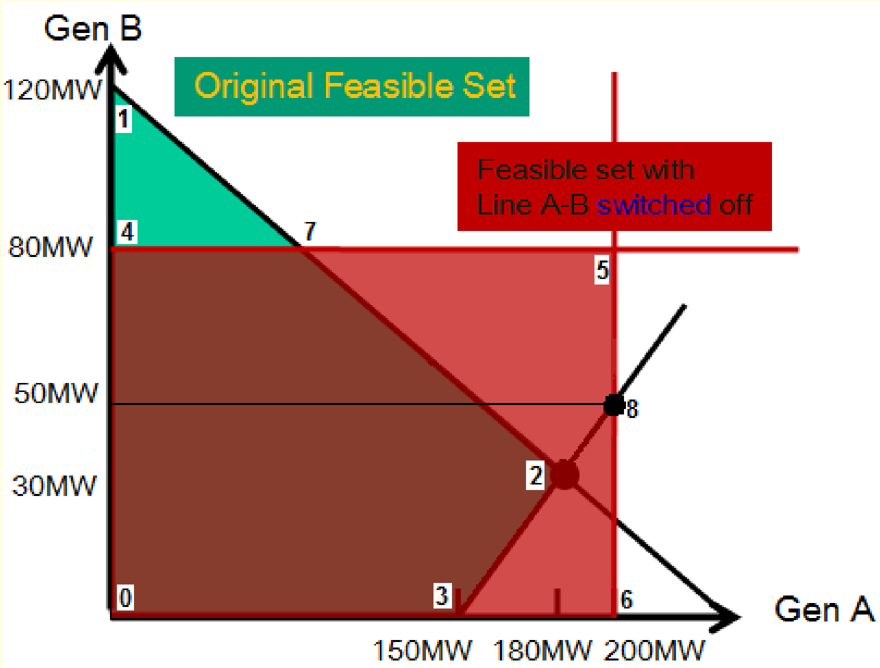
- Network redundancies
  - Required for reliability, not required for every market realization
  - Redundancies may cause dispatch inefficiency

- Optimal transmission switching: co-optimize network topology with generation dispatch

# Transmission Switching Example

- Original optimal cost: $20,000 (A=180MW,B=30MW,C=40MW) at {2}
  - Original feasible set: {0,1,2,3}
- Open Line A-B, optimal cost: $15,000 (A=200MW, B=50MW) at {8}
  - Feasible set with Line A-B open {0, 4, 5, 6}
- Feasible set with optimal transmission switching: {0, 1, 7, 5, 6} (non-convex)



# Literature Review

## Corrective switching

- ***[Mazi, Wollenberg, Hesse 1986]:*** *Corrective control of power systems flows*
- ***[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*

## Switching to reduce losses

- ***[Bacher, Glavitsch 1988]:*** *Loss reduction by network switching*
- ***[Fliscounakis, Zaoui, et al. 2007]:*** *Topology influence on loss reduction as a mixed integer linear program*

## Switching to relieve congestion

- ***[Granelli, Montagna, et al. 2006]:*** *Optimal network reconfiguration for congestion management by deterministic and genetic algorithms*

# Traditional DCOPF

- Minimize: Total generation cost

  Subject to:

  - Generator min & max operating constraints
  - Node balance constraints
  - Line flow constraints

$$B_k(\theta_n - \theta_m) - P_k = 0$$

  - Line capacity constraint

- **Variables:**

$P_k$: real power flow from bus $m$ to bus $n$ for line $k$

$P_g$: Gen $g$ supply at bus $n$

$\theta_n$: Bus n voltage angle

$z_k$: Transmission line status (1 closed/in service, 0 open/out of service)

- **Parameters:**

$B_k$: Susceptance of line $k$

$d_n$: Real power load at bus $n$

# Incorporating Transmission Switching into DCOPF

- $z_k$: State of transmission line (Binary: 0 open/offline, 1 closed/operational)
- Update line thermal (capacity) constraints:
  - Original: $P_k^{\min} \le P_k \le P_k^{\max}$
  - New: $P_k^{\min} z_k \le P_k \le P_k^{\max} z_k$
- Update line flow constraints:
  - Original: $B_k(\theta_n - \theta_m) - P_k = 0$
  - New: $$B_k(\theta_n - \theta_m) - P_k + (1 - z_k)M_k \ge 0$$ $$B_k(\theta_n - \theta_m) - P_k - (1 - z_k)M_k \le 0$$

# Optimal Transmission Switching DCOPF

Minimize: $\sum_{g}(c_g P_g)$

*s.t.*

Node Balance Constraints:

$$\sum_{\forall k(n,.)} P_k - \sum_{\forall k(.,n)} P_k + \sum_{\forall g(n)} P_g = d_n, \forall n$$

Generator Constraints:

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

Transmission Constraints:

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

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

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

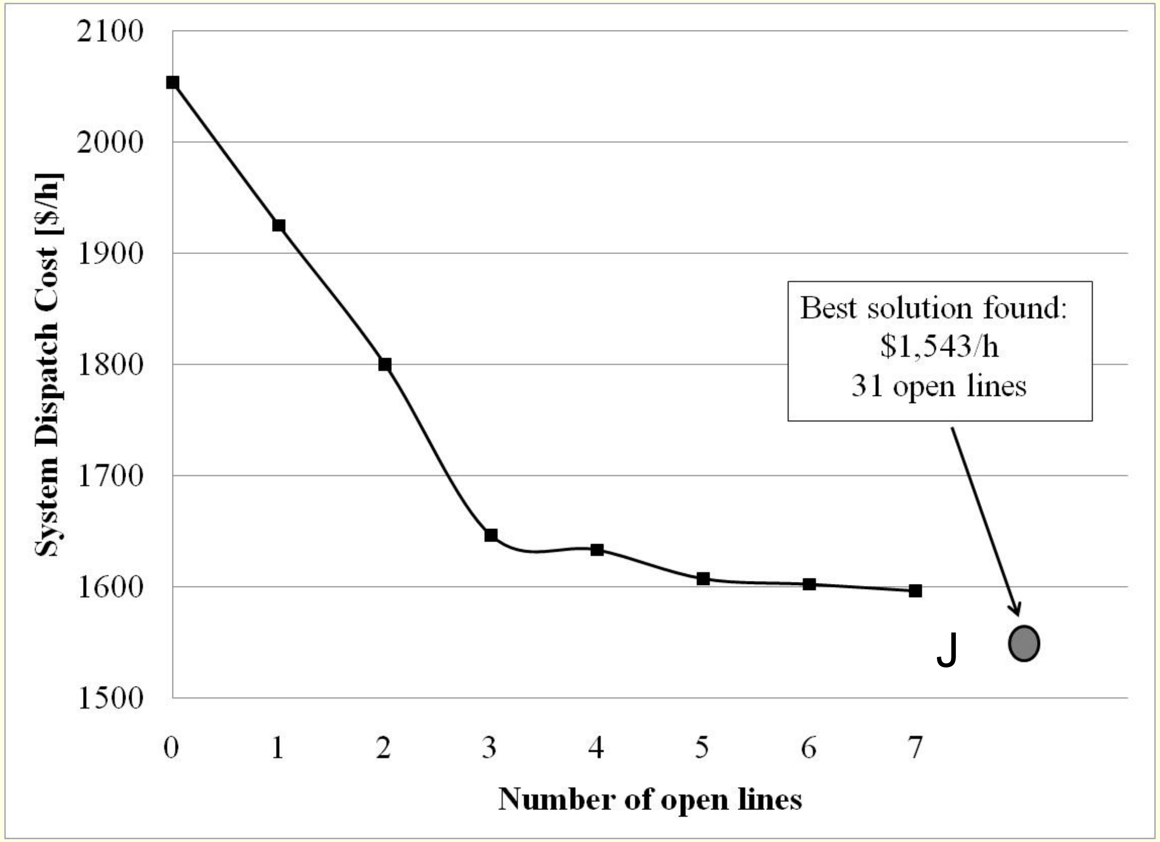
$$z_k \in \{0,1\}.$$

# Economic Savings for DCOPF and N-1 DCOPF Models

- DCOPF Transmission Switching Model (one hour):
  - IEEE 118 Bus Model: saves **25%** saving (10 lines off)
  - ISONE 5000 Bus Model: **5%-13% savings ($70,000 savings)**
  - With advanced smart grid technology, switch lines back into service for a contingency to meet N-1 (just-in-time transmission)
- N-1 DCOPF Transmission Switching Model (one hour):
  - IEEE 73-Bus Model: **up to 8% savings**
  - IEEE 118-Bus Model: **up to 16% savings**
  - Ensures N-1 within transmission switching model
  - Improves efficiency of grid while ensuring N-1 Reliability

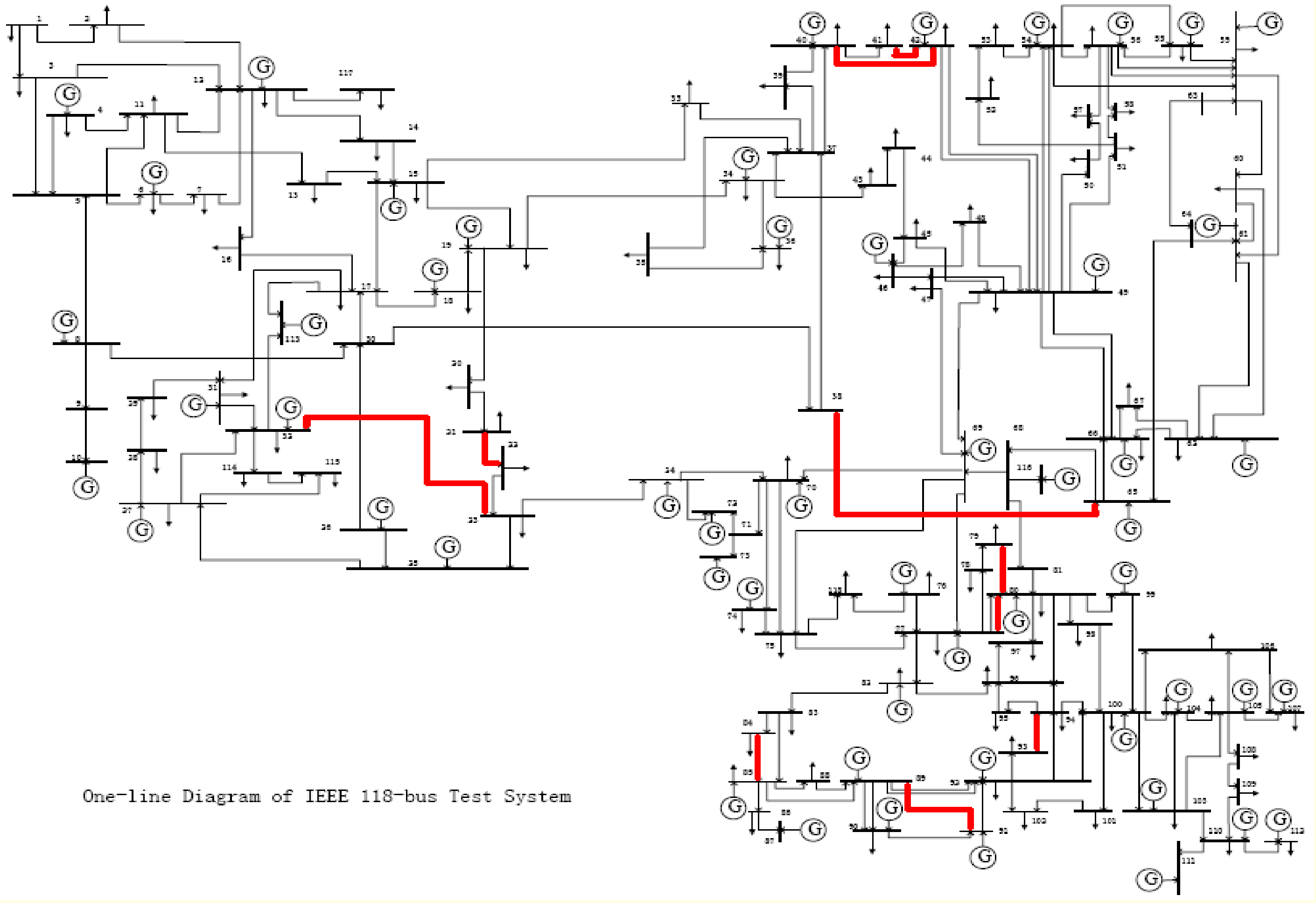
# Results – DCOPF – IEEE 118

- Transmission switching solution saves 25% of total generation cost



# Results – DCOPF – IEEE 118

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

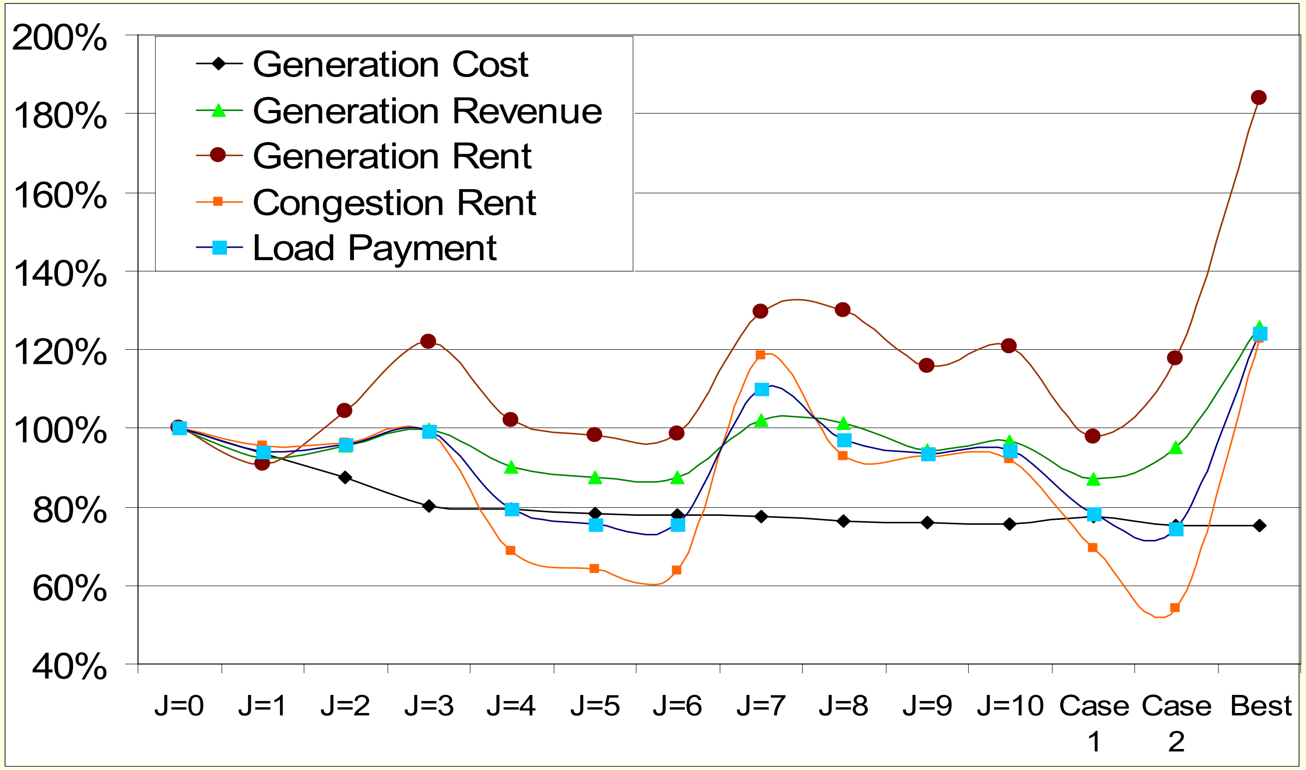


# Economic Savings for UC with Transmission Switching

- Generation Unit Commitment N-1 DCOPF Transmission Switching Model:
  - IEEE 73-Bus Model: **3.7% savings ($120,000 savings for 24-hour model)**
  - Unit commitment solution changes when topology changes
  - Peaker units committed with original topology - not committed under co-optimization of network topology and unit commitment
  - Optimal topology varies hour to hour

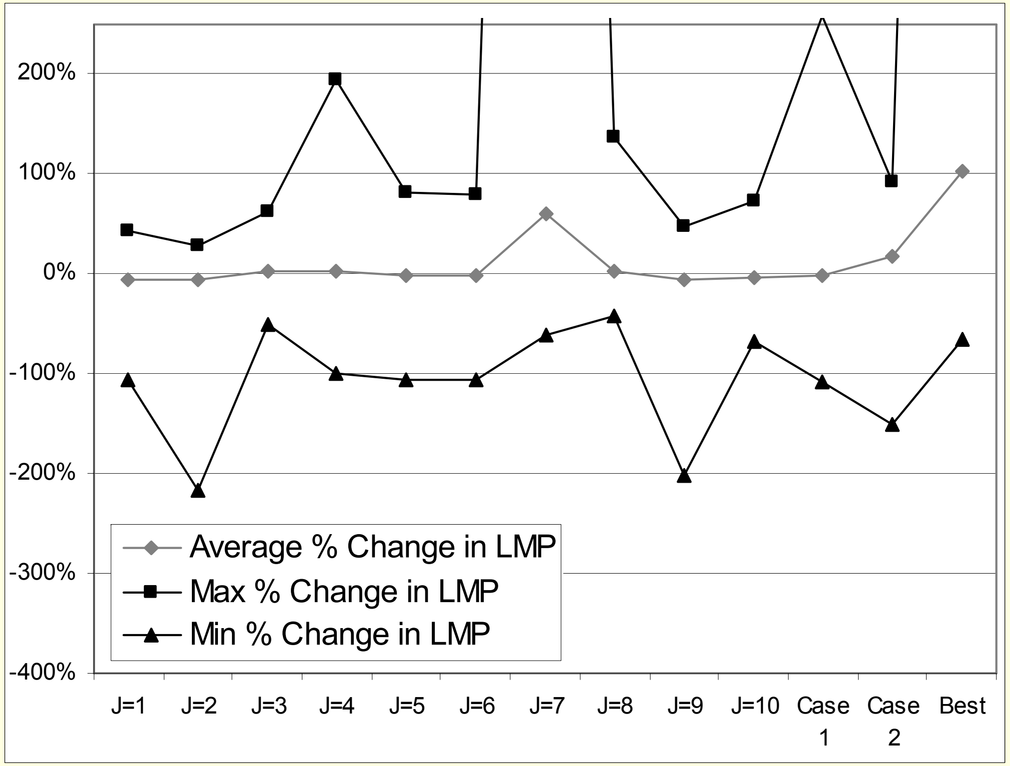
# Impact on Market Participants

- Results are % of static network's DCOPF solution
- Unpredictable distributional effects for market participants



# Impact on LMPs

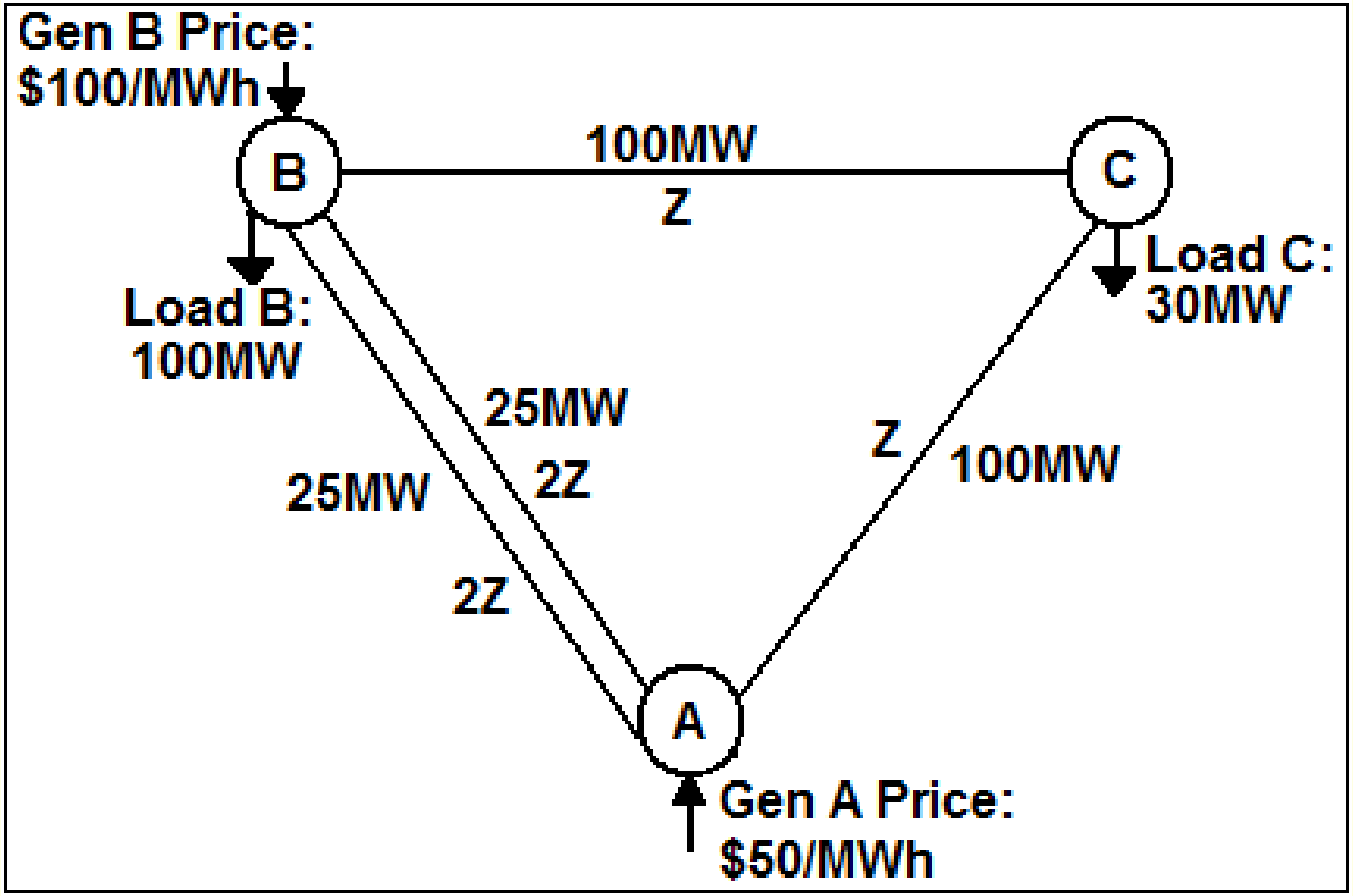
- Max and min percent change in LMP
  - IEEE 118 bus test case – DCOPF optimal transmission switching problem



# Overview of Financial Transmission Rights

- FTRs are used to hedge price risk
- FTR settlements are financed by congestion rents
- Revenue inadequacy occurs when ISO does not collect enough congestion rent to fulfill its obligation to FTR holders
  - ISO may then allocate shortfall to participants or carry it forward and try to recover it from surplus at other times
- Revenue adequacy of FTRs is guaranteed for the static DC topology (since the simultaneous FTR feasible solution corresponds to a suboptimal feasible power flow)
- Revenue adequacy is not guaranteed if the network topology changes
  - Optimal transmission switching undermines the assumption of a static topology

# 3-Bus FTR Revenue Adequacy Example



# Revenue Inadequacy due to Transmission Switching

3-bus example C optimal dispatch results (no switching)

| Bus: | Gen Pg: | LMP: | Gen Cost: | | Transaction: | MW: | Cong. Rent: |
|---|---|---|---|---|---|---|---|
| A | 90MW | $50/MWh | $4,500 | | A – B | 60MW | $3,000 |
| B | 40MW | $100/MWh | $4,000 | | A – C | 30MW | $750 |
| C | 0MW | $75/MWh | $0 | | **Total Congestion Rent:** | | **$3,750** |
| | **Total Generation Cost:** | | **$8,500** | | | | |

3-bus example C optimal dispatch results (lines A-B1 and A-B2 open)

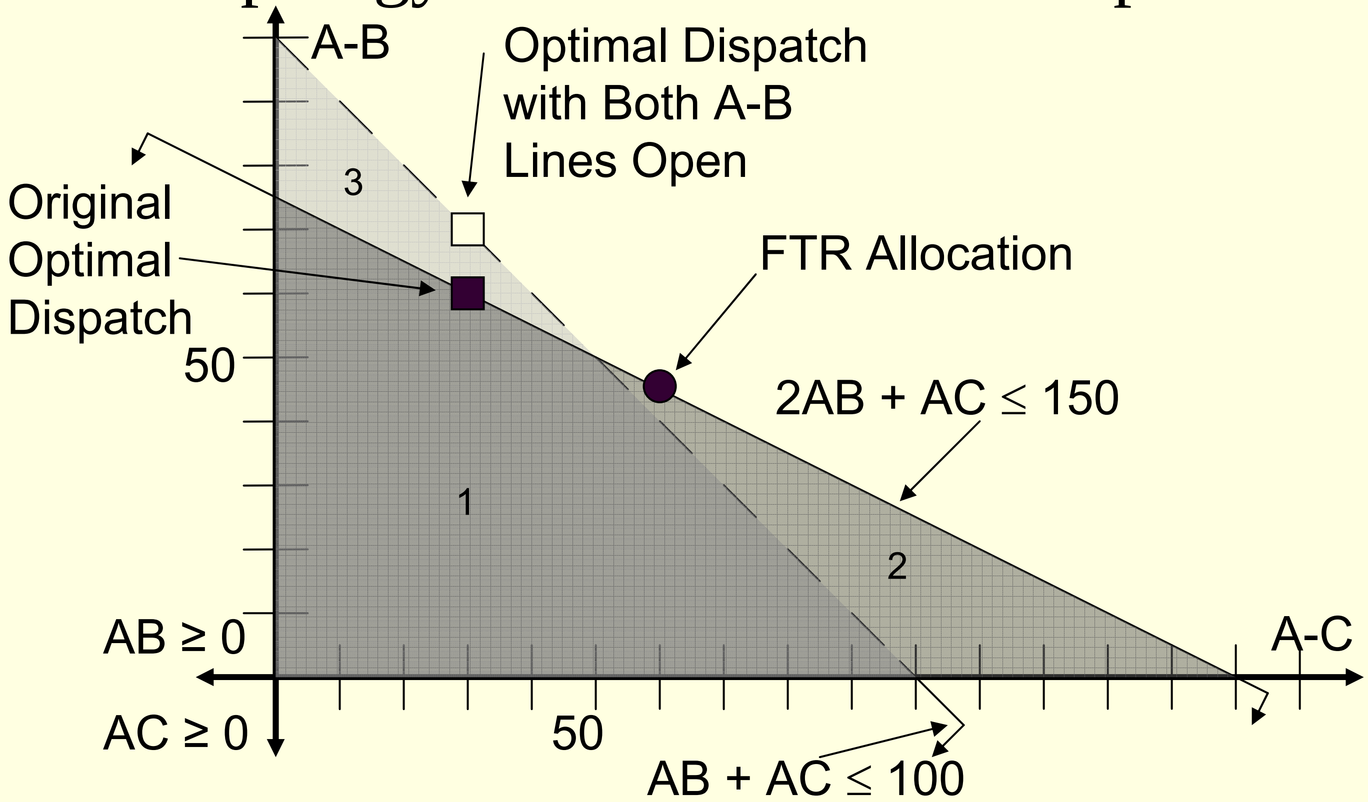
| Bus: | Gen Pg: | LMP: | Gen Cost: | | Transaction: | MW: | Cong. Rent: |
|---|---|---|---|---|---|---|---|
| A | 100MW | $50/MWh | $5,000 | | A – B | 70MW | $3,500 |
| B | 30MW | $100/MWh | $3,000 | | A – C | 30MW | $1,500 |
| C | 0MW | $100/MWh | $0 | | **Total Congestion Rent:** | | **$5,000** |
| | **Total Generation Cost:** | | **$8,000** | | | | |

3-bus example C results – FTR settlements

| Source to Sink: | FTR Quantity: | FTR Settlements (No Switching): | FTR Settlements (Lines A-B1 and A-B2 Open): |
|---|---|---|---|
| A to B | 45MW | $2,250 (LMP gap: $50/MWh) | $2,250 (LMP gap: $50/MWh) |
| A to C | 60MW | $1,500 (LMP gap: $25/MWh) | $3,000 (LMP gap: $50/MWh) |
| **Total FTR Settlements:** | | **$3,750** | **$5,250** |

# Revenue Inadequacy due to Transmission Switching

- FTR allocation is revenue adequate for initial topology but revenue inadequate for optimal network topology with both A-B lines open



# Transmission Switching Can Help Regain Revenue Adequacy

3-bus example C results (line A-B1 failed)

| Bus: | Gen Pg: | LMP: | Gen Cost: | | Transaction: | MW: | Cong. Rent: |
|---|---|---|---|---|---|---|---|
| A | 65MW | $50/MWh | $3,250 | | A – B | 35MW | $1,750 |
| B | 65MW | $100/MWh | $6,500 | | A – C | 30MW | $750 |
| C | 0MW | $75/MWh | $0 | | **Total Congestion Rent:** | | **$2,500** |
| | **Total Generation Cost:** | | **$9,750** | | | | |

3-bus example C optimal dispatch results (lines A-B1 failed A-B2 open)

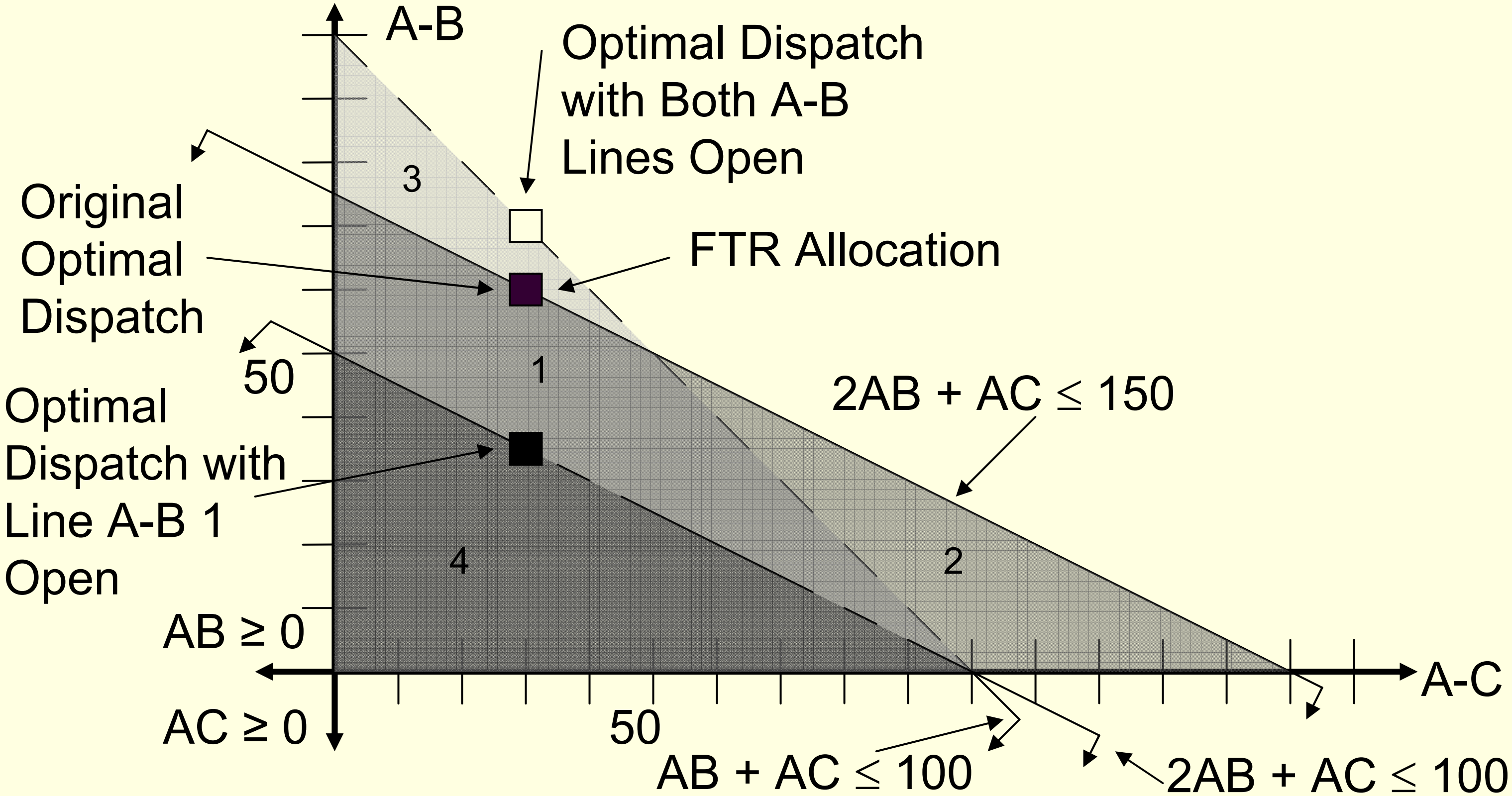
| Bus: | Gen Pg: | LMP: | Gen Cost: | | Transaction: | MW: | Cong. Rent: |
|---|---|---|---|---|---|---|---|
| A | 100MW | $50/MWh | $5,000 | | A – B | 70MW | $3,500 |
| B | 30MW | $100/MWh | $3,000 | | A – C | 30MW | $1,500 |
| C | 0MW | $100/MWh | $0 | | **Total Congestion Rent:** | | **$5,000** |
| | **Total Generation Cost:** | | **$8,000** | | | | |

3-bus example C results – FTR settlements (line A-B1 failed)

| Source to Sink: | FTR Quantity: | FTR Settlement (No Switching): | FTR Settlement (Line A-B2 Opened): |
|---|---|---|---|
| A to B | 60MW | $3,000 (LMP gap: $50/MWh) | $3,000 (LMP gap: $50/MWh) |
| A to C | 30MW | $750 (LMP gap: $25/MWh) | $750 (LMP gap: $25/MWh) |
| **Total FTR Settlements:** | | **$3,750** | **$3,750** |

# Transmission Switching Can Help Regain Revenue Adequacy

- Line outage causes revenue inadequacy (loss of A-B 1)
- Further grid modifications may regain revenue adequacy and improve market surplus (open line A-B 2)



# Policy Implications

- Optimal transmission switching improves social welfare
  - Yet market participants may object since it can cause revenue inadequacy, affects LMPs, generation rents, congestion rents, etc.
- How to deal with revenue inadequacy?
  - Implement side payments and who pays?
  - De-rate FTR payments?
- Emerging "smart grid" technologies may make certain market mechanisms obsolete
  - Rethink market design principles?
- How would optimal transmission switching affect FTR auctions?

# Summary

- FTRs are important as they are used to hedge price risk
- Revenue adequacy of FTRs is vulnerable to grid topology changes
- Co-optimizing generation and network topology improves market surplus even while maintaining reliability criteria
  - Unfortunately, it undermines prevailing market mechanisms
  - Can cause revenue inadequacy in FTR markets
  - It has unpredictable distributional effects on market participants

# QUESTIONS?
# Thank you!

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

# Publications

## Journal Papers:

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

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

[4] R. P. O'Neill, K. W. Hedman, E. A. Krall, A. Papavasiliou, M. C. Ferris, E. B. Fisher, and S. S. Oren, "Economic analysis of the N-1 reliable unit commitment and transmission switching problem using duality concepts," *Energy Systems*, accepted for publication.

# Publications cont'd

## Under Review:

[5] K. W. Hedman, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Smart flexible just-in-time transmission and flowgate bidding," *IEEE Trans. Power Syst.*, Submitted June 1, 2009; Revised November 15, 2009.

## Peer-Reviewed Conference Publications:

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

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