Candidate Selection for Transmission Switching in Large Power Network

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Staff Technical Conference on Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software

June 24-26 2013

Washington DC

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Outline

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Introduction

- Regional transmission organizations are reliant on wholesale market mechanism to optimally dispatch energy and ancillary services.
- Transmission are traditionally treated as non-dispatchable asset in the network.
- Co-optimizing transmission topology and generation dispatch has the potential to further maximize the market surplus and improve economic efficiency.
- To solve the full problem, a significant number of additional integer variables are required to model the on/off status of transmission elements.
- Selection of a subset of transmission lines for potential switching for optimal transmission switching (OTS) is a way to make the problem more tractable.
- Further assess the practicality, benefit gain and computational performance impact of OTS.

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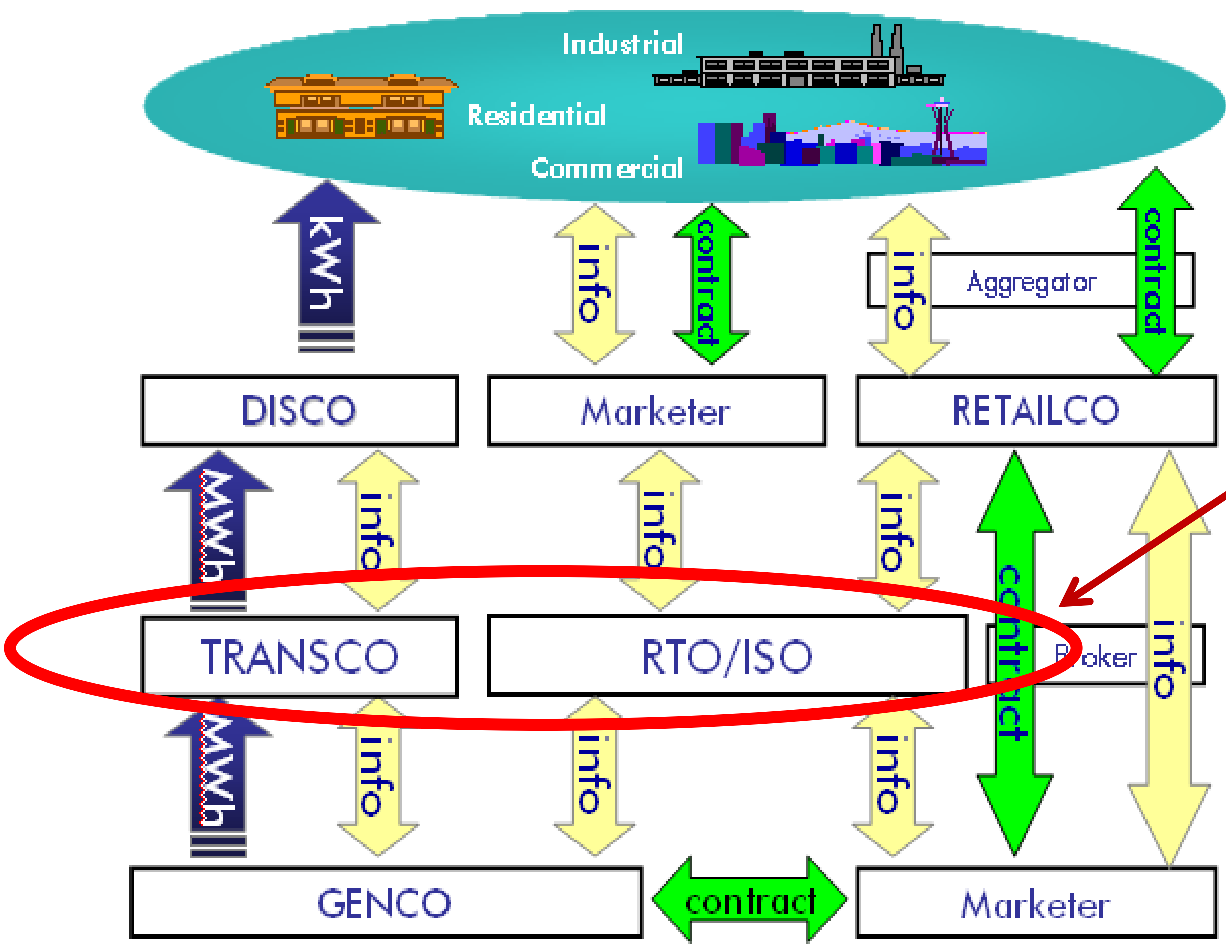
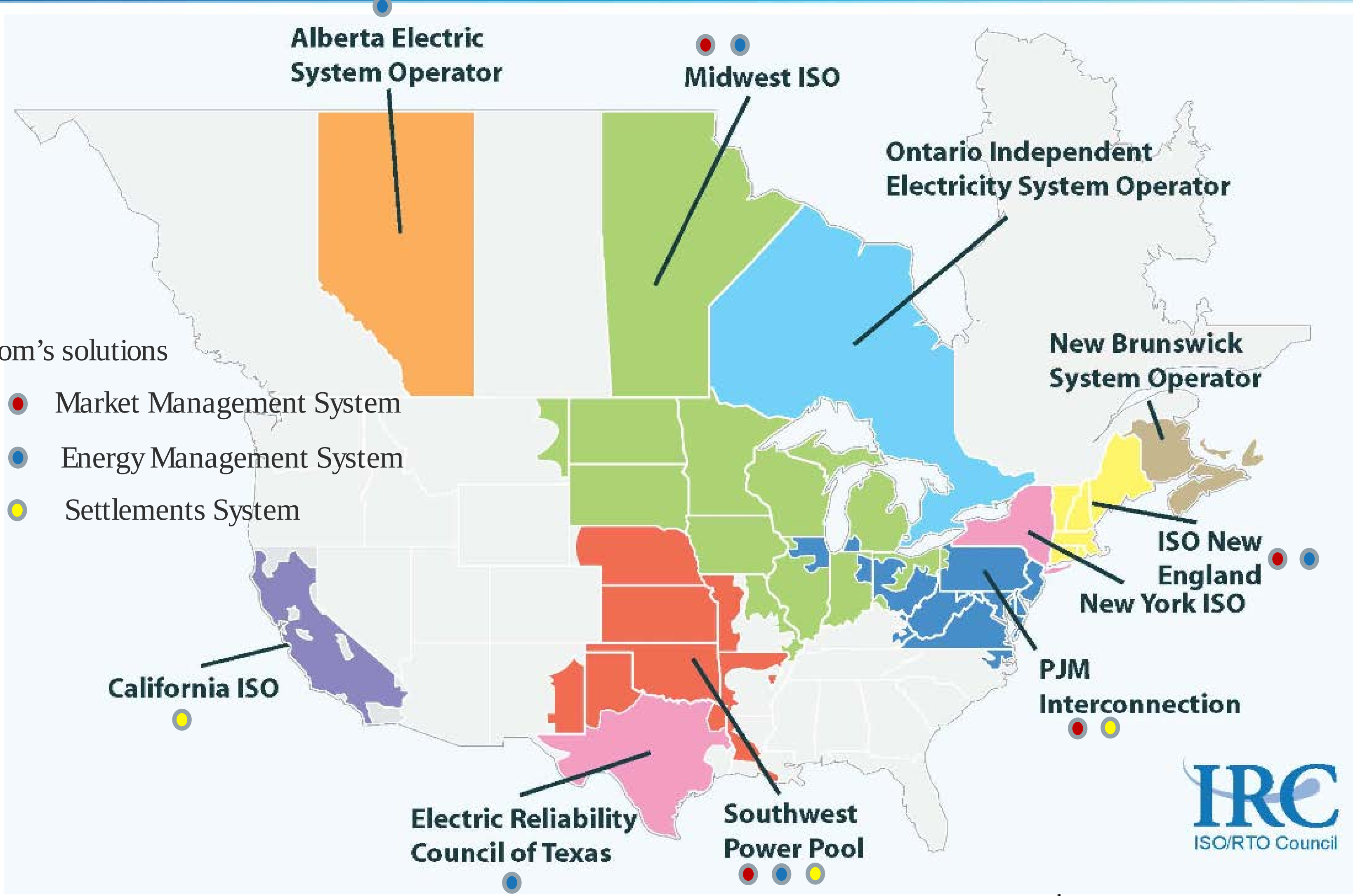
Restructured Power Industry



Alstom's Network Management Systems in NA

Alstom's solutions

- Market Management System
- Energy Management System
- Settlements System



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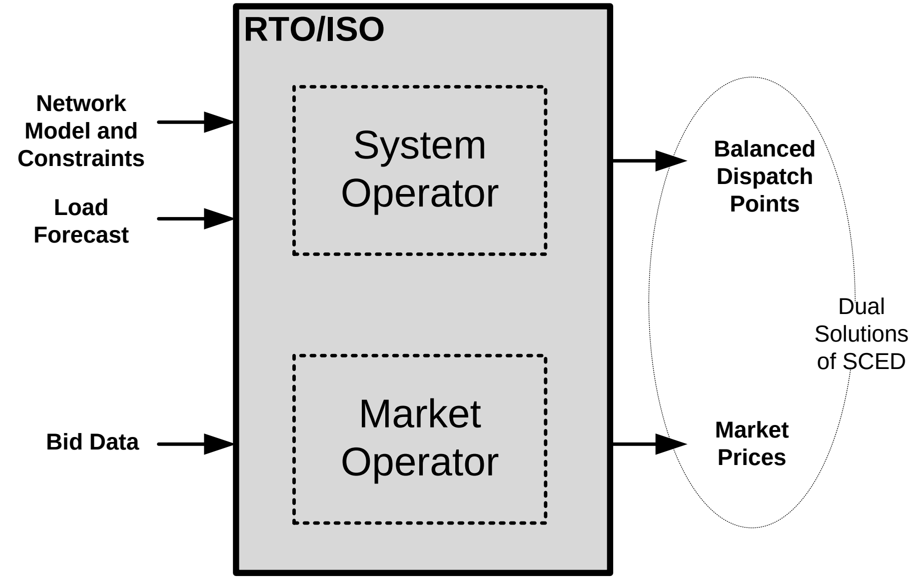
Optimization-based Integrated Approach

Consistent dispatch signals and price signals

- Security constrained economic dispatch (SCED)
- Locational Marginal Pricing (LMP)

Widely adopted in North America

- PJM
- Midwest ISO
- ISO New England
- New York ISO
- California ISO
- ERCOT (Texas)
- Southwest Power Pool (Under implementation)



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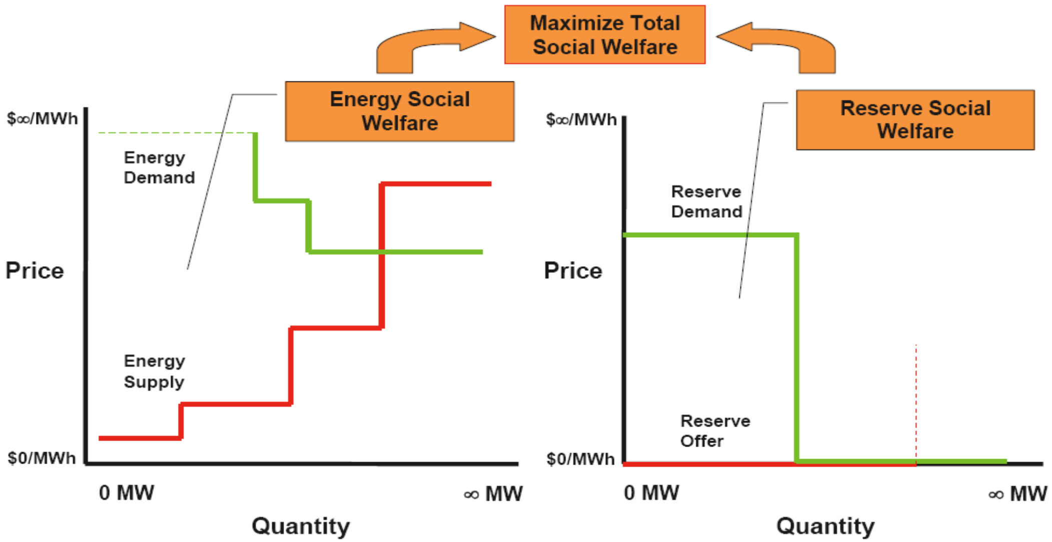
Wholesale Power Market Platform

- In the beginning of this century, FERC pushed for a common market design framework called Standard Market Design (Now called the Wholesale Power Market Platform). Variation of such a model (LMP-based two-settlement system) has been adopted by all RTOs in the United States.
- As energy-only markets approached maturity, RTOs one after another enhanced their energy markets to incorporate clearing of ancillary services.
- A co-optimized approach of clearing energy and ancillary services simultaneously has been extensively accepted by ***all*** restructured electricity markets in USA.



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Basic Unit Commitment & Economic Dispatch Model

$$\min \sum_{g,t} (u_{gt}\chi_{gt}(p_{gt}) + \varsigma_{gt}(u_{g(t-1)}, u_{gt}))$$

Subject to

$$(\lambda_t) \qquad \sum_g p_{gt} = l_t + p_t^{loss}, \qquad \forall t$$

$$(\alpha_t \geq 0) \qquad \sum_g r_{gt} \geq \underline{r}_t, \qquad \forall t$$

$$u_{gt}\underline{p}_{gt} \leq p_{gt} \leq u_{gt}\overline{p}_{gt}, \qquad \forall g,t$$

$$p_{gt} + r_{gt} \leq u_{gt}\overline{p}_{gt}, \qquad \forall g,t$$

$$0 \leq r_{gt} \leq u_{gt}\overline{r}_{gt}, \qquad \forall g,t$$

$$(\mu_{kt}) \qquad \underline{f}_{kt} \leq f_{kt} \leq \overline{f}_{kt}, \qquad \forall k,t$$

$$f_{kt} = B_k(\theta_{mt} - \theta_{nt}), \qquad \forall k,t$$

$$\theta \leq \theta_{mt} \leq \overline{\theta}, \qquad \forall m,t$$

$$(\lambda_{mt}) \qquad p_{gmt} - l_{mt} - p_{mt}^{loss} = \sum_{k \in line_m^{fr}} f_{kt} - \sum_{k \in line_m^{to}} f_{kt}, \qquad \forall m,t$$

- Alternative Transmission flow model

$$f_{kt} = \sum_g a_{kgt} p_{gt}, \qquad \forall k,t$$

(Power Transfer Distribution Factor-PTDF model)

- Location marginal price (LMP)

$$LMP_{gt} = \lambda_t - \lambda_t \frac{\partial p_t^{loss}}{\partial p_{gt}} - \sum_k a_{kgt}\mu_{kt}$$

- Promoted by FERC, LMP methodology is proven to be an effective mechanism to relieve transmission congestion and to achieve market efficiency.
- LMP is the foundation for market-based congestion management.

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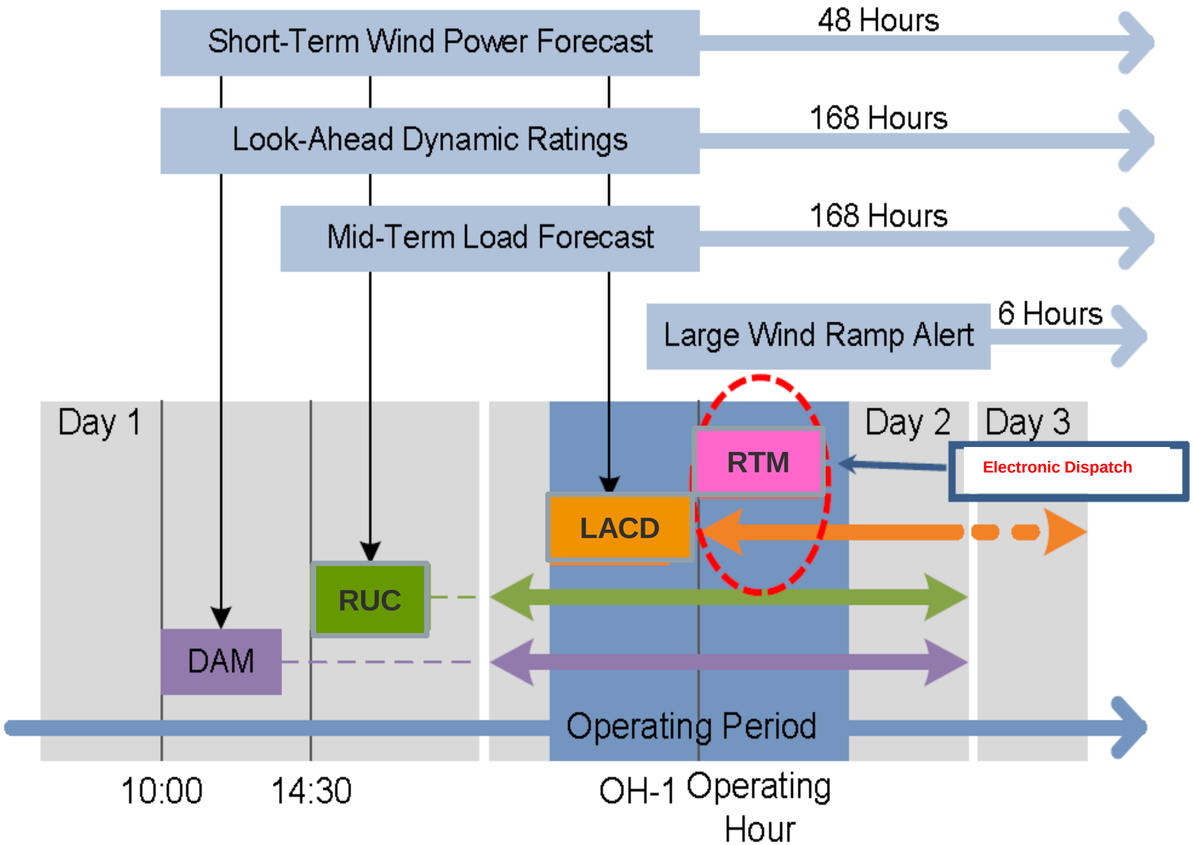
Market-Based Congestion Management

Transmission congestion leads to non-zero μ_k. The difference in nodal prices gives the Congestion Rent (*CR*)

$$CR = \sum_{i \neq j} (LMP_i - LMP_j) \quad f_{kt}$$

- RTO/ISO can either
  - o invests the rent into network reinforcement, or
  - o have the rent being shared among the market participants, where a common way of allocation is the use of financial transmission rights (FTRs).
- An FTR's economic value is based on the MW reservation level times the difference between the LMPs of the source and sink points.
- FTR can be treated as a financial instrument for market participants to hedge against the volatility of LMPs due to transmission congestion.
- The concept of FTR is based on the assumption that network topology is relatively static.

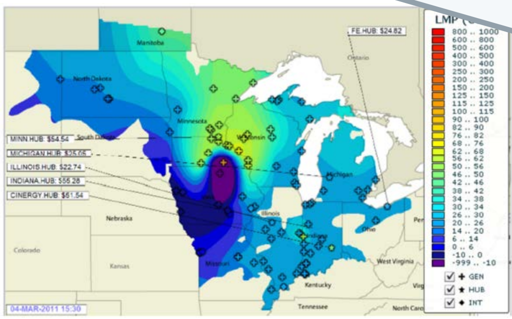
LMP-Based Two-Settlement System in North America



- Day-Ahead Market (DAM) process - provides functions for day-ahead bid data submission, market clearing, and market solution publishing.
- Reliability Unit Commitment (RUC) process - provides system operators a set of tools to revise the day-ahead unit commitment schedule as necessary in order to ensure that the forecasted load and operating reserve requirements will be met and the transmission system is reliable and secured.
- Look-Ahead Commitment and Dispatch (LACD) process – provides a forward-looking view of system operating conditions and recommend start-up/shut-down recommendation of fast-start resources to operators.
- Real-Time Market (RTM) process – provides market-clearing functions to balance generation and load, and meet reserve requirements based on actual real-time system operating conditions. The RTM process computes ex-ante pricing and provides the dispatch signals either MW or price back to the Market Participants.

Transmission Congestion Leads to High Production Cost

Real-Time LMPs vary spatially and in time



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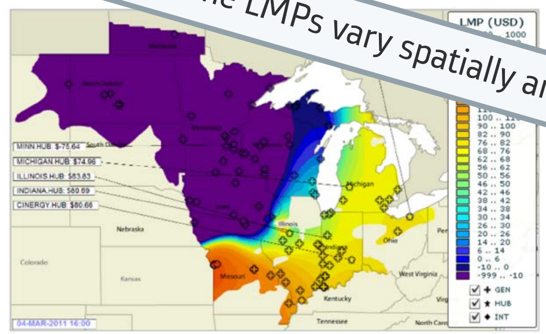

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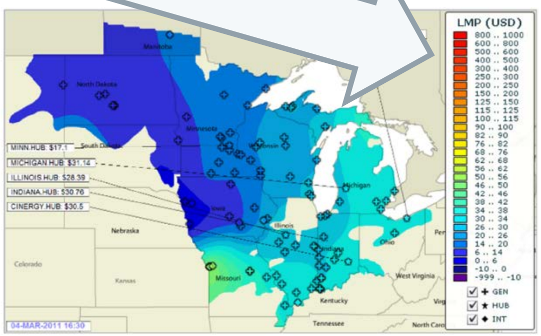

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- Due to transmission constraints, the economic merit order dispatch is not feasible.
- Some low-cost units have to decrease their production, while some high-cost units have to increase their generation.
- Production costs increase by the order of billions of dollars annually due to transmission congestion in USA.

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Concept of Optimal Transmission Switching

Motivation:

- Further improve social welfare in market clearing by changing topology.

Control of transmission not fully utilized today

- Transmission assets are treated as static in the short term
- Current control for reliability purposes:
  1. Operators change transmission assets' states on ad-hoc basis.
  2. Special Protection Schemes (SPSs)
- Can topology control practically be utilized for economic reasons?

Network redundancies

- Required only for reliability not for economics.
- Redundancies may cause dispatch inefficiency.
- More advanced control allows systems to be operated less conservatively.

Incorporate state of transmission assets into generation dispatch co-optimization.

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Optimal Transmission Switching Model

$$\min \sum_{g,t} (u_{gt}\chi_{gt}(p_{gt}) + \varsigma_{gt}(u_{g(t-1)}, u_{gt}))$$

Subject to

$$(\lambda_t) \qquad \sum_g p_{gt} = l_t + p_t^{loss}, \qquad \forall t$$

$$(\alpha_t \geq 0) \qquad \sum_g r_{gt} \geq \underline{r}_t, \qquad \forall t$$

Integer decision variable +representing the state of transmission element

$$u_{gt}\underline{p}_{gt} \leq p_{gt} \leq u_{gt}\overline{p}_{gt}, \qquad \forall g,t$$

$$p_{gt} + r_{gt} \leq u_{gt}\overline{p}_{gt}, \qquad \forall g,t$$

$$0 \leq r_{gt} \leq u_{gt}\overline{r}_{gt}, \qquad \forall g,t$$

A large value set to $B_k(\overline{\theta} - \underline{\theta})$

$$(\mu_{kt}) \qquad \underline{f}_{kt} z_{kt} \leq f_{kt} \leq \overline{f}_{kt} z_{kt}, \qquad \forall k,t$$

$$B_k(\theta_{mt} - \theta_{nt}) - f_{kt} + (1 - z_{kt})M_k \geq 0, \quad \forall k,t$$

$$B_k(\theta_{mt} - \theta_{nt}) - f_{kt} - (1 - z_{kt})M_k \leq 0, \quad \forall k,t$$

$$\sum_k (1 - z_{kt}) \leq j\_Open, \qquad \forall k,t$$

$$(\lambda_{mt}) \qquad p_{gmt} - l_{mt} - p_{mt}^{loss} = \sum_{k \in line_m^{fr}} f_{kt} - \sum_{k \in line_m^{to}} f_{kt}, \quad \forall m,t$$

$$\underline{\theta} \leq \theta_{mt} \leq \overline{\theta}, \qquad \forall m,t$$

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Some Practical Consideration

- Transmission line switching combination

  2^n n is # of transmission lines

- The number of integer variables representing the state of transmission elements are significant.
- The proposed OTS model is impractical to solve within typical market time frame.
- One remedial compromise: Reduction of problem space
  - Limit the number of "switchable" transmission lines (OTSbr)
  - Limit the number of open lines

Maximum number of open lines

$$\sum_k (1 - z_{kt}) \leq j\_Open, \qquad \forall k, t$$

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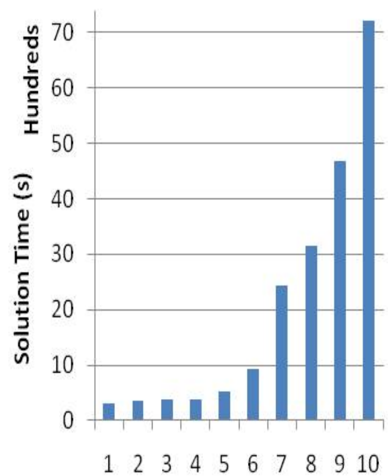
Selection of Candidate Lines for Switching

- General strategy is to limit the number of switchable line and open lines.
- Solution time grows with *OTSbr* , *j_ Open* and the size of the power network.
- For a given power network, proper sizes of *OTSbr* and *j_ Open* can be pre-determined via offline studies.



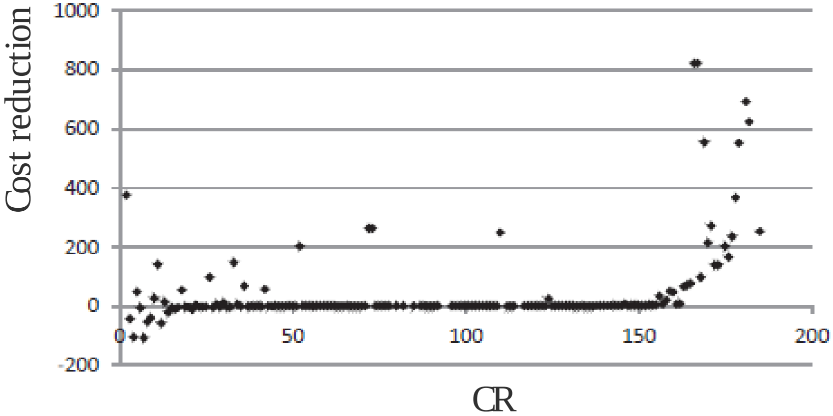
1	w/ DC model but w/o OTS			304s
2	OTSbr=14	j=10	1 line off	351s
3	OTSbr=18	j=8	4 lines off	378s
4	OTSbr=18	j=18	4 lines off	378s
5	OTSbr=27	j=5	4 lines off	516s
6	OTSbr=74	j=5	5 lines off	920s
7	OTSbr=340	j=5	1 line off	2444s
8	OTSbr=691	j=5	0 line off	3138s
9	OTSbr=1561	j=5	2 lines off	4686s
10	OTSbr=1647	j=5	0 line off	7201s

Selection Measures for Switching Candidate of Lines

- Limit violations of transmission lines [3]
  - To avoid violation penalties (amount of violation x penalty factor)
- Congestion Rents (CR) of transmission lines [4]

$$CR = f_{kt}(\lambda_{mt} - \lambda_{nt})$$

  - *CR* is an indication of transmission congestion.
  - By removing the line, its transmission congestion can not avoided.



- Production Costs associated with transmission lines
  - *A newly proposed method based on sensitivities of production cost (PC) w.r.t. line flow.*

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New Measure Based on Production Cost

Goal: Calculate $\frac{\partial PC}{\partial f_{kt}}$ and use that as a measure for candidate selection

- Transmission flow:

$$f_{k(m,n)t} = B_{mn,t}(\theta_{m,t} - \theta_{n,t})$$

$$\Delta F = A \Delta \theta$$

where ΔF is the vector of changes of transmission line flow $f_{k(m,n)t}$ and A has the following structure.

$$A = \begin{array}{c} \\ \\ \end{array} \begin{array}{ccccc} & \text{col. } m & & \text{col. } n & \\ \end{array}$$

$$A = \begin{bmatrix} .. & .. & .. & .. & ... \\ 0.. & B_{mn} & 0.. & -B_{mn} & 0.. \\ .. & .. & .. & .. & .. \end{bmatrix}$$

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New Measure Based on Production Cost (Cont'd)

- The sensitivities of the bus angle of w.r.t. line flow:

$$A'\Delta F = A'A\Delta\theta = \Pi\Delta\theta$$

$$\Pi_{ij} = \begin{cases} \sum B_{ii}^2, i = j \\ -\sum B_{ij}^2, i \neq j \end{cases}$$

$$A'\Delta F = \begin{array}{cc} \left[\begin{matrix} \cdots \\ \sum\limits_{\substack{j\neq i \\ k\in line_i^{fr}}} B_{ij}\Delta f_{k(i,j)t} - \sum\limits_{\substack{j\neq i \\ k\in line_i^{to}}} B_{ij}\Delta f_{k(j,i)t} \\ \cdot\cdot \\ \sum\limits_{\substack{j\neq n \\ k\in line_n^{fr}}} B_{nj}\Delta f_{k(n,j)t} - \sum\limits_{\substack{j\neq n \\ k\in line_n^{to}}} B_{nj}\Delta f_{k(j,n)t} \end{matrix}\right] & \begin{matrix} \\ Line.i \\ \\ Line.n \end{matrix} \end{array}$$

$$\Delta\theta_{it} = \sum_k B_{mn}(\Pi_{mi}^{-1} - \Pi_{ni}^{-1})\Delta f_{k(m,n)t} = \sum_k \beta_{ik}\Delta f_{k(m,n)t}$$

$$\partial\theta_{it} \Big/ \partial f_{kt} = \beta_{ik}$$

Interpreted as the sensitivities of the bus angle of bus *i* with respect to the flow of transmission line *k*.

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New Measure Based on Production Cost (Cont'd)

- The production costs associated with transmission lines:

$$PC = \sum_g c_{gt} p_{gt}$$

$$\frac{\partial PC}{\partial f_{kt}} = \sum_g \frac{\partial PC}{\partial p_{gt}} \frac{\partial p_{gt}}{\partial f_{kt}}.$$

where

$$\frac{\partial p_{gt}}{\partial f_{kt}} = \sum_i \frac{\partial p_{gt}}{\partial \theta_{it}} \frac{\partial \theta_{it}}{\partial f_{kt}} = B_{hh}\beta_{hk} - \sum_{i \neq h} B_{hi}\beta_{ik}$$

h denotes the bus to which generation *g* is connected.

Hence,

$$\frac{\partial PC}{\partial f_{kt}} = \sum_g \frac{\partial PC}{\partial p_{gt}} \frac{\partial p_{gt}}{\partial f_{kt}} = \sum_g c_{gt}(B_{hh}\beta_{hk} - \sum_{i \neq h} B_{hi}\beta_{ik})$$

The production costs associated with transmission lines:

$$PC_k = (\sum_g c_{gt}(B_{hh}\beta_{hk} - \sum_{i \neq h} B_{hi}\beta_{ik}))\, f_k$$

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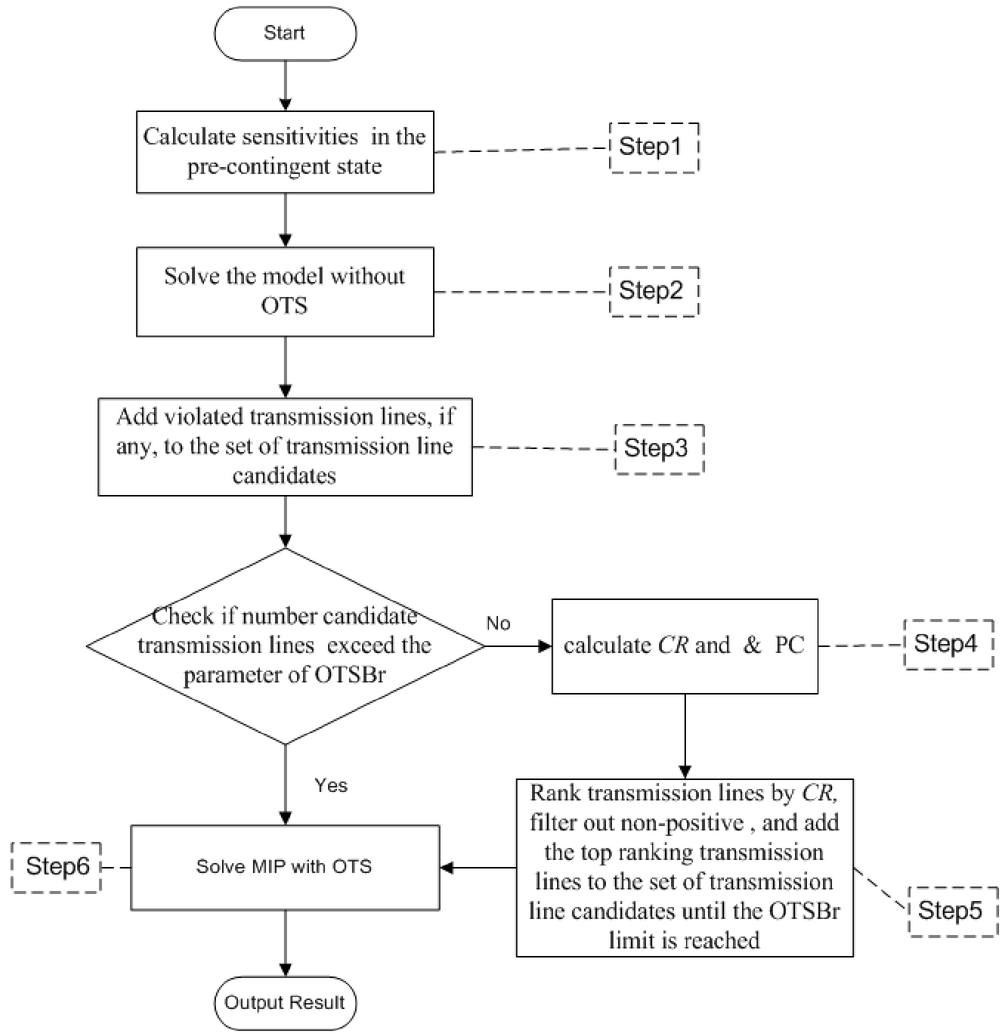
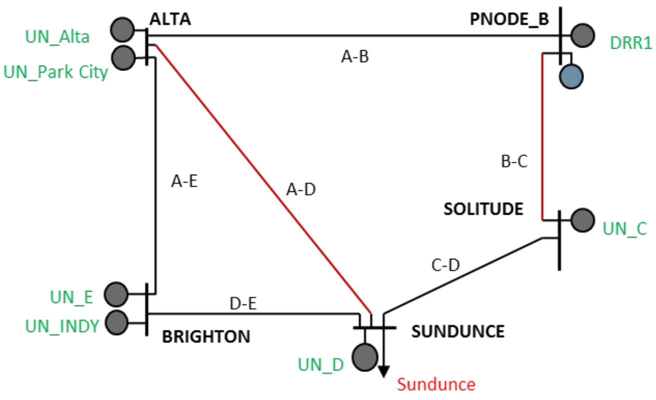
Selection Method

- The violated transmission lines, if any, will first be selected as switching candidates since they usually cause large penalty costs in the objective function.
- Calculate transmission line ranking based on *PCk* and *CR* (*PCCR*).



Test Cases - 5 Bus System

TRANSMISSION LINES	FROMBUS	TOBUS	ADMITTANCE	LIMIT
A-B	A	B	-28.1	170
A-D	A	D	-30.4	300
A-E	A	E	-6.4	300
B-C	B	C	-10.8	300
C-D	C	D	-29.7	35
D-E	D	E	-29.7	400



Transmission lines	Transmission flow
SUNDANCE_230 KV_D-E_LN	-373.86
ALTA_230 KV_A-B_LN	170
ALTA_230 KV_A-D_LN	68.49
ALTA_230 KV_A-E_LN	-66.14
PNODE_B_230 KV_B-C_LN	-31.67
SOLITUDE_230 KV_C-D_LN	-25.68

bus	Bus Angle
A	6.03497
C	2.9249
D	3.78749
E	16.34437

B Matrix :

	A	B	C	D	E
A	65.06	-28.169		-30.475	-6.416
B	-28.169	38.996	-10.827		
C		-10.827	40.6	-29.773	
D	-30.475		-29.773	90.021	-29.773
E	-6.416			-29.773	36.189

Π Matrix :

	A	B	C	D	E
A	1763.379	-793.502		-928.715	-41.162
B	-793.502	910.717	-117.215		
C		-117.215	1003.653	-886.438	
D	-928.715		-886.438	2701.591	-886.438
E	-41.162			-886.438	927.6

Test Cases - 5 Bus System (Cont'd)

❖ The sensitivities of the bus angle w.r.t. the line flow:

$$\beta_{ik} = B_{mn}(\Pi_{mi}^{-1} - \Pi_{ni}^{-1})$$

$$\theta_{it} = \sum_k \beta_{ik} f_{kt}$$

Transmission Lines	bus	β
SUNDANCE_230 KV_D-E_LN	A	-0.000143895
SUNDANCE_230 KV_D-E_LN	C	0.00097412
SUNDANCE_230 KV_D-E_LN	D	0.001102929
SUNDANCE_230 KV_D-E_LN	E	-0.03104933
ALTA_230 KV_A-B_LN	A	0.03175687
ALTA_230 KV_A-B_LN	C	0.025338301
ALTA_230 KV_A-B_LN	D	0.02868882
ALTA_230 KV_A-B_LN	E	0.028824964
ALTA_230 KV_A-D_LN	A	0.003319171
ALTA_230 KV_A-D_LN	C	-0.022469569
ALTA_230 KV_A-D_LN	D	-0.025440752
ALTA_230 KV_A-D_LN	E	-0.024164541
ALTA_230 KV_A-E_LN	A	0.000667765
ALTA_230 KV_A-E_LN	C	-0.004520524
ALTA_230 KV_A-E_LN	D	-0.00511828
ALTA_230 KV_A-E_LN	E	-0.011778037
PNODE_B_230 KV_B-C_LN	A	-0.009738564
PNODE_B_230 KV_B-C_LN	C	-0.026438729
PNODE_B_230 KV_B-C_LN	D	-0.017721174
PNODE_B_230 KV_B-C_LN	E	-0.017366949
SOLITUDE_230 KV_C-D_LN	A	-0.003541296
SOLITUDE_230 KV_C-D_LN	C	0.023973275
SOLITUDE_230 KV_C-D_LN	D	-0.006444063
SOLITUDE_230 KV_C-D_LN	E	-0.006315254

Test Cases - 5 Bus System (Cont'd)

- The sensitivity of generation w.r.t. line flow:

$$\frac{\partial p_{gt}}{\partial f_{kt}} = \sum_i \frac{\partial p_{gt}}{\partial \theta_{it}} \frac{\partial \theta_{it}}{\partial f_{kt}} = B_{hh}\beta_{hk} - \sum_{i \neq h} B_{hi}\beta_{ik}$$

$$p_{gt} = \sum_k (B_{hh}\beta_{hk} - \sum_{i \neq h} B_{hi}\beta_{ik}) f_{kt}$$

bus	Transmission Lines	$\frac{\partial p_{gt}}{\partial f_{kt}}$
A	SUNDANCE_ 230 KV_ D-E_ LN	0.1562
A	ALTA_ 230 KV_ A-B_ LN	1.0069
A	ALTA_ 230 KV_ A-D_ LN	1.1463
A	ALTA_ 230 KV_ A-E_ LN	0.275
A	PNODE_ B_ 230 KV_ B-C_ LN	0.0179
A	SOLITUDE_ 230 KV_ C-D_ LN	0.0065
B	SUNDANCE_ 230 KV_ D-E_ LN	-0.0065
B	ALTA_ 230 KV_ A-B_ LN	-1.1689
B	ALTA_ 230 KV_ A-D_ LN	0.1498
B	ALTA_ 230 KV_ A-E_ LN	0.0301
B	PNODE_ B_ 230 KV_ B-C_ LN	0.5606
B	SOLITUDE_ 230 KV_ C-D_ LN	-0.1598
C	SUNDANCE_ 230 KV_ D-E_ LN	0.0067
C	ALTA_ 230 KV_ A-B_ LN	0.1746
C	ALTA_ 230 KV_ A-D_ LN	-0.1548
C	ALTA_ 230 KV_ A-E_ LN	-0.0311
C	PNODE_ B_ 230 KV_ B-C_ LN	-0.5458
C	SOLITUDE_ 230 KV_ C-D_ LN	1.1652
D	SUNDANCE_ 230 KV_ D-E_ LN	0.9991
D	ALTA_ 230 KV_ A-B_ LN	0.0022
D	ALTA_ 230 KV_ A-D_ LN	-1.0029
D	ALTA_ 230 KV_ A-E_ LN	0.0042
D	PNODE_ B_ 230 KV_ B-C_ LN	0.0057
D	SOLITUDE_ 230 KV_ C-D_ LN	-0.9979
E	SUNDANCE_ 230 KV_ D-E_ LN	-1.1556
E	ALTA_ 230 KV_ A-B_ LN	-0.0148
E	ALTA_ 230 KV_ A-D_ LN	-0.1383
E	ALTA_ 230 KV_ A-E_ LN	-0.2781
E	PNODE_ B_ 230 KV_ B-C_ LN	-0.0384
E	SOLITUDE_ 230 KV_ C-D_ LN	-0.014

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Test Cases - 5 Bus System (Cont'd)

- The sensitivities of the production cost w.r.t. line flow:

$$\frac{\partial PC}{\partial f_{kt}} = \sum_{g} \frac{\partial PC}{\partial p_{gt}} \frac{\partial p_{gt}}{\partial f_{kt}}$$
$$= \sum_{g} c_{gt} (B_{hh} \beta_{hk} - \sum_{i \neq h} B_{hi} \beta_{ik}))$$

Transmission Lines	$\frac{\partial PC}{\partial f_{kt}}$
SUNDANCE_ 230 KV_ D-E_ LN	-7.3486
ALTA_ 230 KV_ A-B_ LN	22.6841
ALTA_ 230 KV_ A-D_ LN	16.2458
ALTA_ 230 KV_ A-E_ LN	1.8366
PNODE_ B_ 230 KV_ B-C_ LN	-13.1137
SOLITUDE_ 230 KV_ C-D_ LN	27.9587

- The production costs associated with transmission lines :

$$PC_k = (\sum_{g} c_{gt} (B_{hh} \beta_{hk} - \sum_{i \neq h} B_{hi} \beta_{ik}))\, f_k$$

Transmission Lines	PCk
SUNDANCE_ 230 KV_ D-E_ LN	2747.34
ALTA_ 230 KV_ A-B_ LN	3856.29
ALTA_ 230 KV_ A-D_ LN	1112.7
ALTA_ 230 KV_ A-E_ LN	-121.48
PNODE_ B_ 230 KV_ B-C_ LN	415.27
SOLITUDE_ 230 KV_ C-D_ LN	-718.04

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Test Cases - 37,000-bus, 47,000-branch Test System

- For a given case with 18 violation transmission lines, by choosing all of them as candidate transmission lines, as the result of OTS, 7 lines are switched off, and the objective cost has significant savings from $3,384,616/h to $2,749,157/h while solver solution times are almost the same.

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Test Cases - 37,000-bus, 47,000-branch Test System

❖ For another given case without violation but there are about 44 binding transmission constraints and 370 dispatchable generation units

CANDIDATES WITH *CR*

Transmission Lines	CR($/h)
BURR_OAK_34513_A_LN	305032.27
BURR_OAK_A_NO_2_XFMRAK_XF	239439.35
PLYMOUT2_13821_NIPS_P_LN	187571.80
EASTLAKE_11_EL_LM_1_LN	125764.79
EAU_CLA_EAU_CKING34_1_1_LN	109724.77
EWINAMAC_13832_A_LN	95546.81
EASTLAKE_EL61_TR61_XF	81929.61
EASTLAKE_EL62_TR62_XF	70459.46
ARGENTA_ARGENTWIN_34_1_1_LN	70111.24
ARGENTA_ARGENBATTL34_1_1_LN	65547.23
MANSFLD2_MANS_HOYT_1_LN	58850.29
AJ_MA_MO_AJ_MAMONRO34_1_1_LN	58639.49
LLOYD_11_LY_KI_1_LN	55949.56
PERRY_C_S_8_PY_EL_1_LN	49271.90
EWINAMAC_13882_A_LN	42393.93
LAMONT2_11_LM_LY_1_LN	37299.71
MILAN3_MILANMAJES34_1_1_LN	37116.47
SAMMIS_HIGHLND_SAMMIS_1_LN	36696.69
HIGHLNDD_HGHLN_S_SPNG_1_LN	35232.15

19 candidates

4 lines are open

CANDIDATES WITH *PCCR*

Transmission Lines	PC($/h)	CR($/h)
BURR_OAK_34513_A_LN	35722.98	305032.27
DUMONT_DUMONSTILL34_1_1_LN	173.68	19994.85
M_TOWN_M_TOWBLRST11_1_1_LN	102.89	13215.91
RANCESC_FRANCHANNA34_1_1_LN	35.65	18346.87
BUNGE_BUNGEHASTI16_1_1_LN	35.30	25242.07
EWINAMAC_13882_A_LN	21.09	42393.93
EWINAMAC_13832_A_LN	15.68	95546.81
CLARNDA_CLARNHASTI16_1_1_LN	14.80	18626.53
EAU_CLA_EAU_CKING34_1_1_LN	9.26	109724.77
ARGENTA_ARGENPALIS34_1_1_LN	2.71	24366.57
ARGENTA_ARGENPALIS34_2_1_LN	2.71	24366.57
J_MA_MO_AJ_MAMONRO34_1_1_LN	2.17	58639.49
ARGENTA_ARGENTWIN_34_1_1_LN	1.71	70111.24
ITCHLCO_MITCHHAZLT34_1_1_LN	1.30	14351.31

14 candidates

7 lines are open

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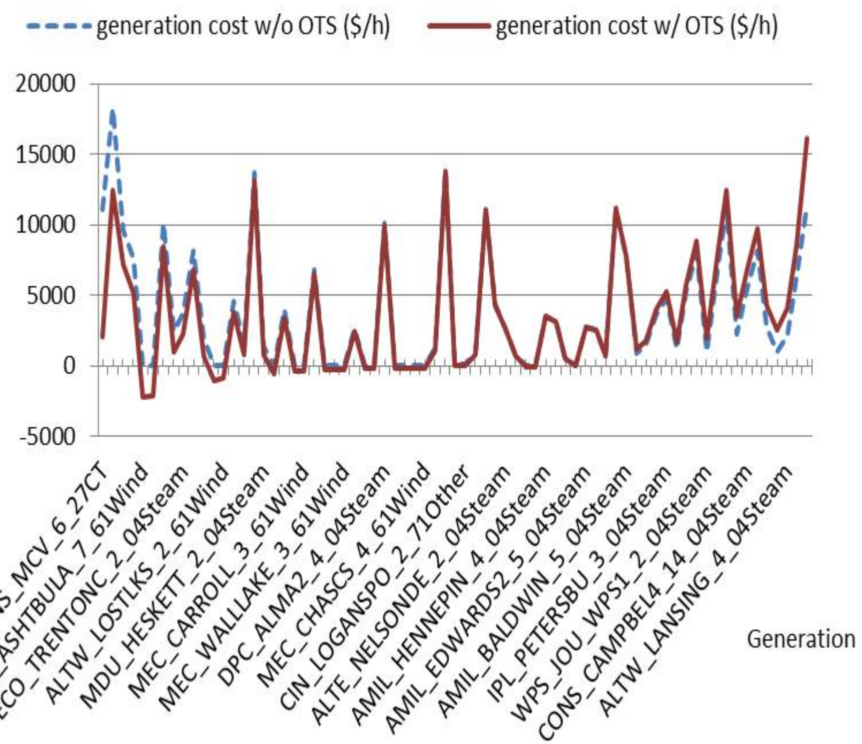
37,000-bus, 47,000-branch Test System (Cont'd)

Comparison of Objectives with and without OTS for *CR* and *PCCR*

	w/o OTS ($/h)	w/ OTS($/h)	
		CR	*PCCR*
Objective	888471	876997	864197

- The objective savings of *CR* is about $11,474/h.
- The objective savings of *PCCR* is about $24,274/h which is about $12,800/h more savings than that of *CR*.



Generation cost w/o and w/ OTS

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37,000-bus, 47,000-branch Test System (Cont'd)

Hardware:

2 cores: Intel(R) Core (TM) i7-2620M
CPU@ 2.70GHz
RAM:8.00GB

Runtime for one single period dispatch

		OTSBr	Solver Time	Total time	Objective
w/ o OTS		0	10s	1m	888471.7
w/ OTS	PCCR	14	104s	2m22s	864197.7
		11	56s	1m34s	870672.7
	CR	22	226s	4m26s	874427.8
		11	56s	1m34s	881893.1

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Conclusions

- This presentation discussed transmission switching for power system operations.
- A basic dispatch model with co-optimization of energy, ancillary services and transmission switching is presented.
- The size of candidate transmission lines needs to be limited in order to solve the MIP model for all practical purposes.
- Optimal transmission switching is verified to improve market efficiency.
- A couple of criteria are presented and a heuristic method is proposed to select candidates for transmission-line switching to achieve better market surplus within a reasonable time frame.
- Further studies and evaluation of impact of reserve costs to the selection of transmission line candidates are desirable in energy and ancillary services co-optimization markets.
- More studies are needed to investigate its impact of day-ahead market, reliability unit commitment, reliability assessment, system stability and revenue adequacy of FTR market.

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4. J. David Fuller et al, "Fast Heuristics for Transmission Line Switching", *IEEE Trans. on Pwr Sys. Vol 27, Issue 3, pp. 1377-1386. (2012)*

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