Optimal Transmission Switching: A Practical Assessment

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

June 28-30 2011

Washington DC

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Outline

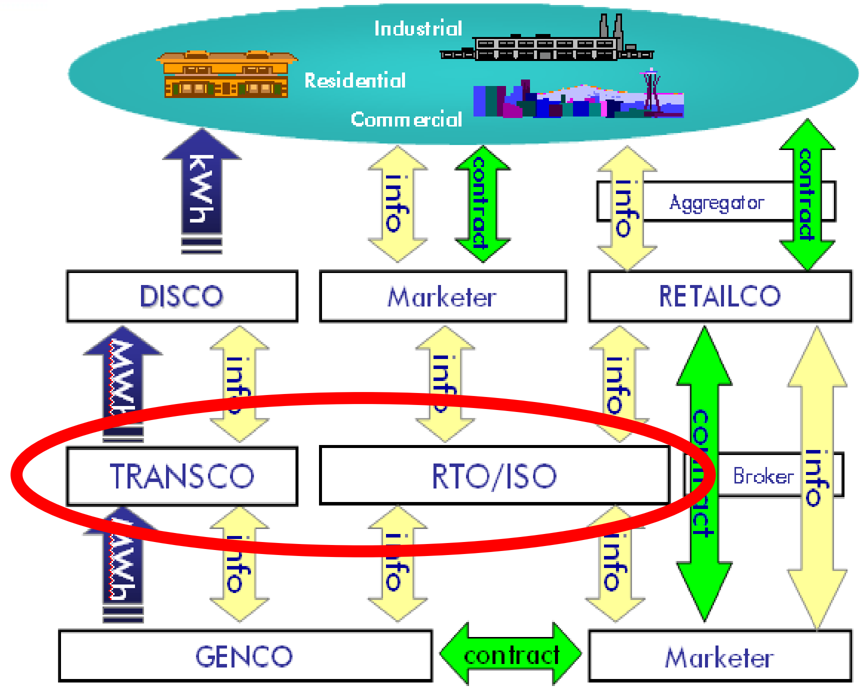
1. Introduction
2. Basic Dispatch Model for Market Clearing
3. Optimal Transmission Switching Modeling
4. Some Practical Consideration
5. Test Cases
6. Conclusions

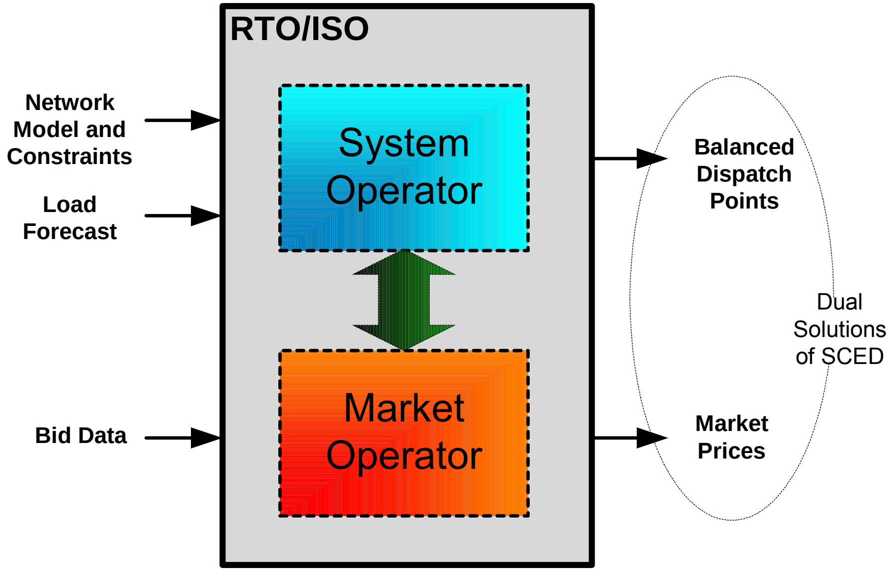
Introduction

- 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 could further maximize the market surplus and improve economic efficiency.
- Assess the benefit gain and computational performance impact of optimal transmission switching.

Basic Dispatch Model for Market Clearing

- Market and System Operation
  - Generation dispatch/Scheduling (cost-based and market-based)
  - Maintain system reliability
  - Transmission scheduling & congestion management
  - Market Pricing





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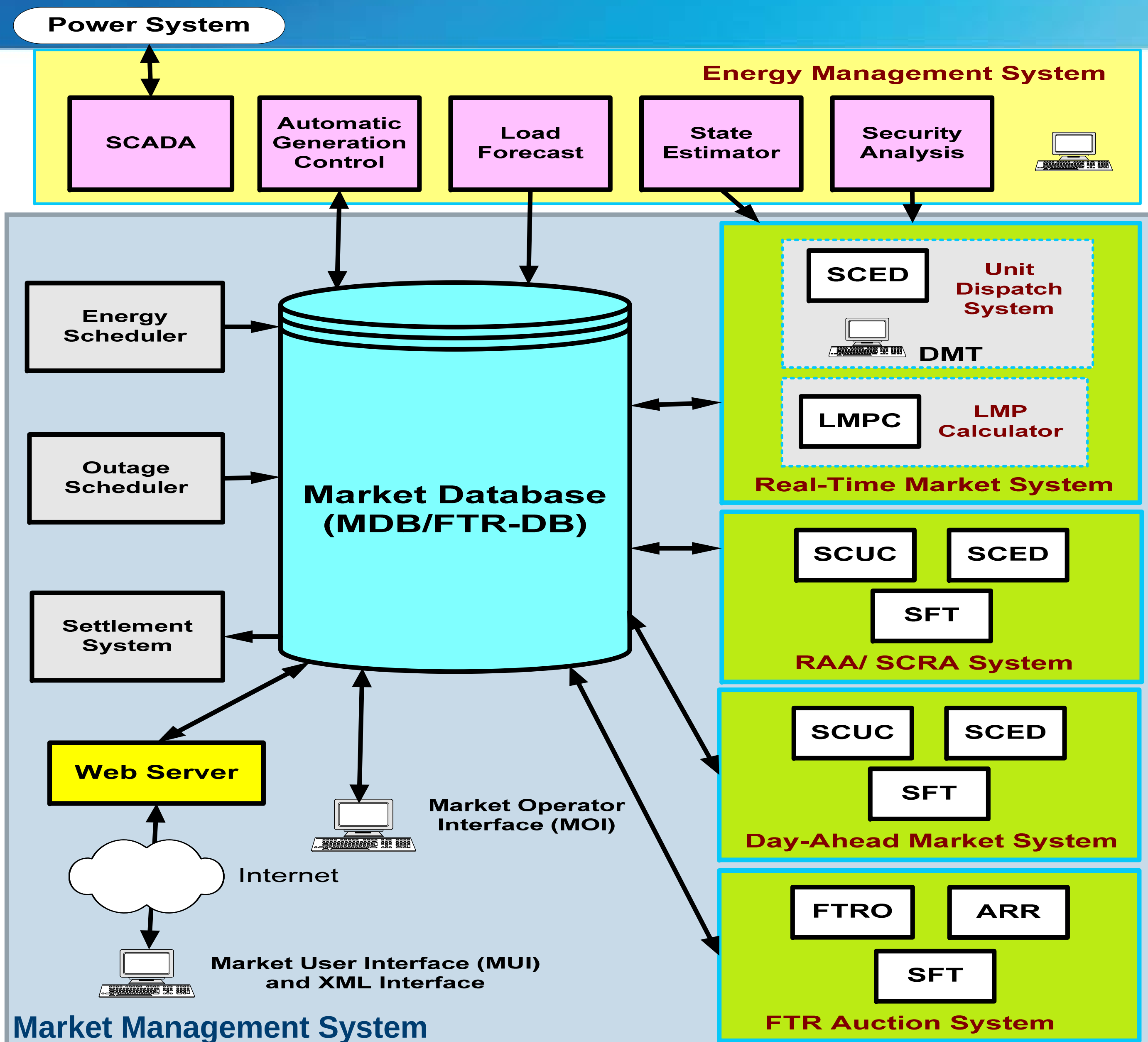
State-of-the-Art Market Management System



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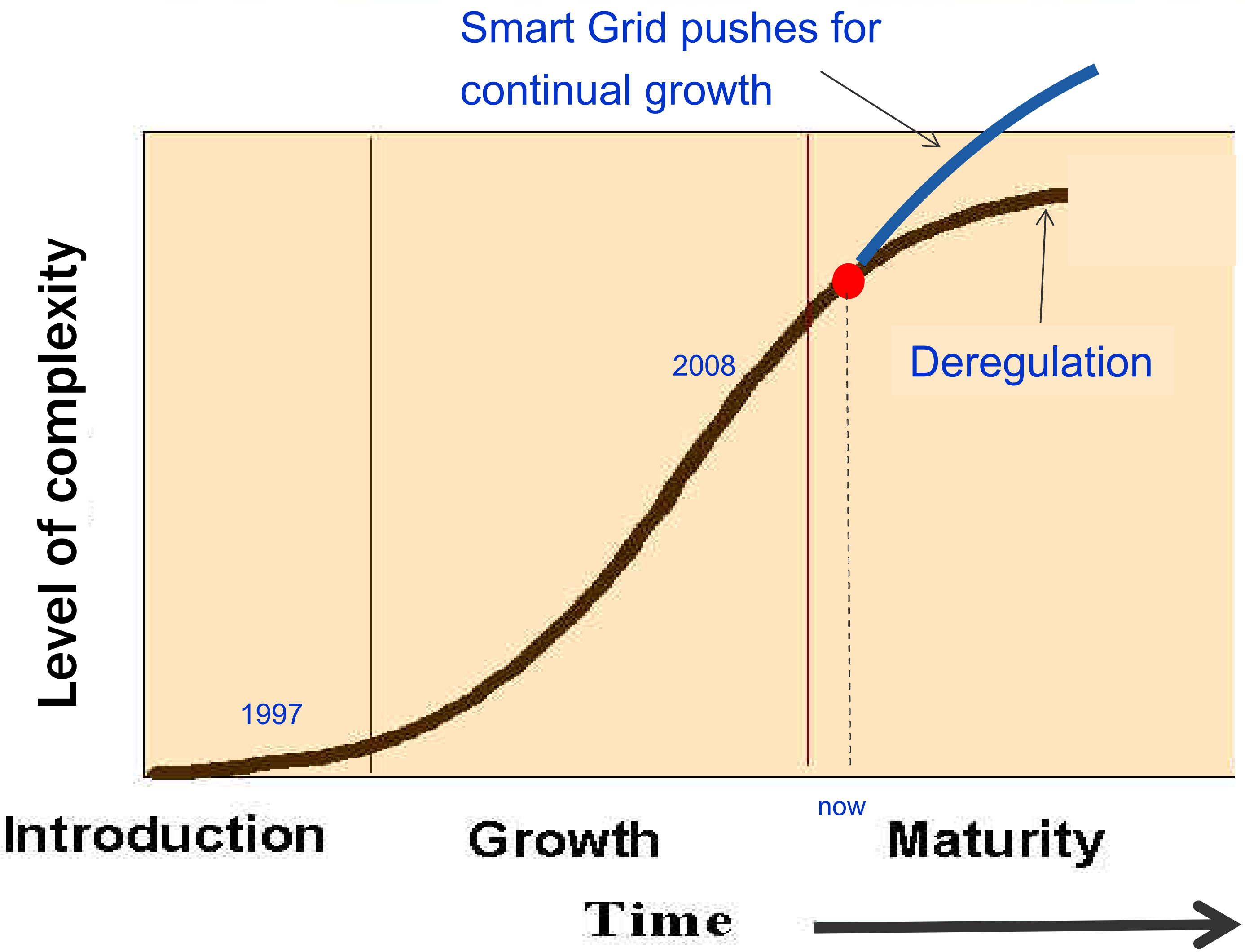
Maturity Curve of Worldwide Electricity Market



3 Eras of System Dispatch Evolution

Classical Dispatch (70's – mid 90's)

- Unit Commitment Scheduling, Economic Dispatch, AGC
- Grid security, scheduling, dispatch are Independent tasks

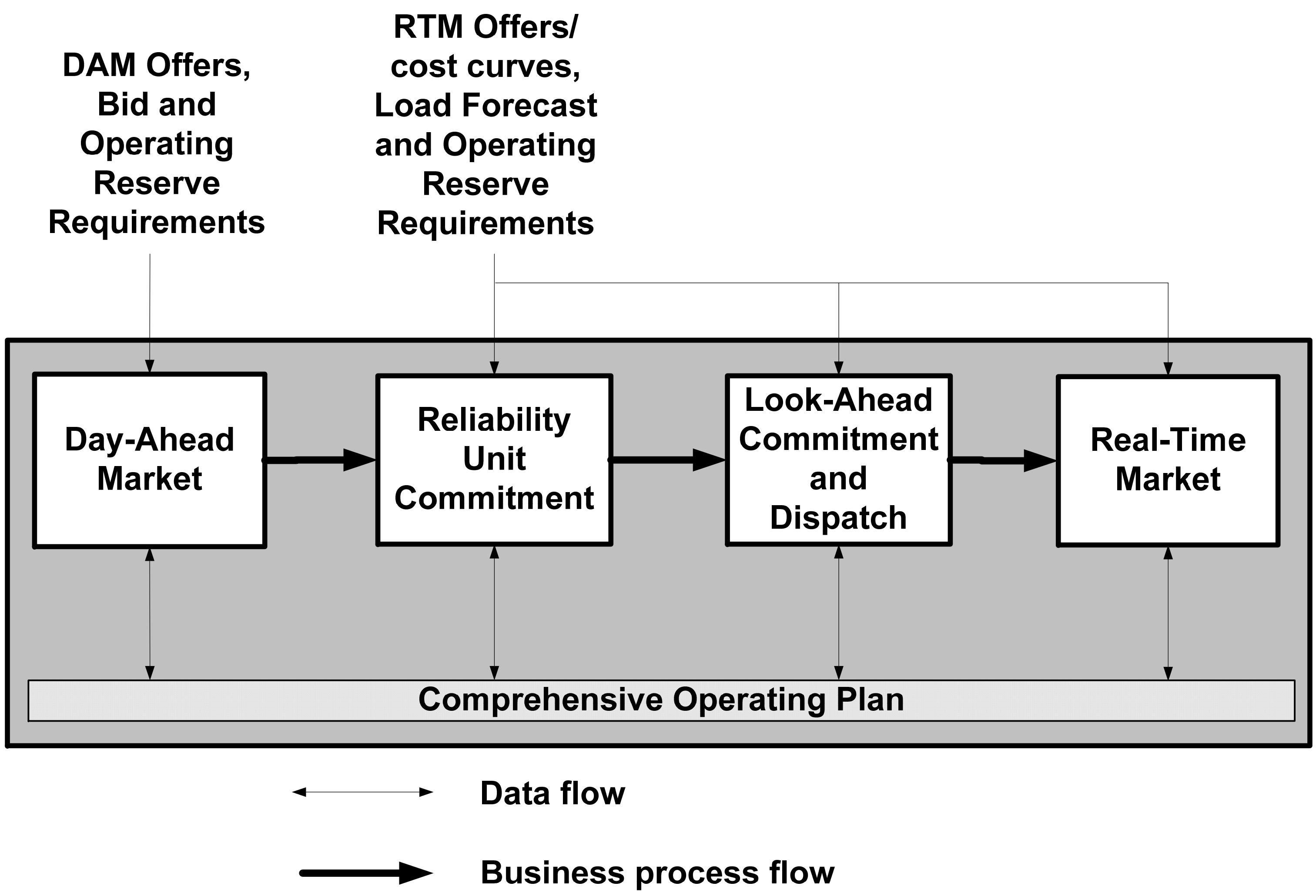
Market-Based Dispatch (mid 90's – 2009)

- UC/ED with explicit transmission security constraints
- Formal Day-Ahead and Real-time tasks
- Pricing - Dual of the MW signal
- Transparency & consistency
- Large-scale system dispatch

Smart Dispatch (2009 and beyond)

- Dispatch with explicit forward vision
- Better predictive inputs for dispatch (e.g. load forecast, resource characteristics, transmission constraint parameter)
- Modeling of price responsive demand
- Improve system resiliency against uncertainties (e.g. DER, Wind, DR)
- Mitigate root-causes for dispatch deficiencies
- Process re-engineering for business/economic analysis
- Dispatch generation and transmission simultaneously

Basic Dispatch Model for Market Clearing



Basic Unit Commitment & Economic Dispatch Model

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

Subject to

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

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

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

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

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

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

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

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

$$(\mathbf{u}, \mathbf{p}, \mathbf{r}) \in \Gamma.$$

DC power flow model

- PTDF transmission flow model

$$f_{kt} = \sum_g (a_{kgt} p_{gt} - d_{gt} l_t), \qquad \forall k, t$$

(Power Transfer Distribution Factor-PTDF model)

- Location marginal price

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

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Optimal Transmission Switching Model

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

Subject to

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

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

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

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

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

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

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

Integer decision variable representing the state of transmission element

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

A. Indices and Sets

g : generator; t : study period

k : transmission line Γ : set of feasible solutions

B. Unit Commitment Model Parameters

l_t : load forecast for study period t,

$\underline{p}_{gt}, \overline{p}_{gt}$: capacity limits of generator g for study period t,

$\underline{r}_t$: spinning reserve requirement for study period t,

$\overline{r}_{gt}$: spinning reserve limit of generator g for study period t,

d_{gt} : load distribution factor of generator g for study period t,

a_{kgt} : sensitivity of transmission line k with respect to generator g for study period t,

$\overline{f}_{gt}$: transmission line limit of generator g for study period t,

C. Variables

u_{gt} : commitment status (0/1) for generator g for study period;

p_{gt} : power output of generator g for study period t,

r_{gt} : spinning reserve contribution of generator g for study period t,

u : vector of all u_{gt}

p : vector of all p_{gt}

r : vector of all r_{gt}

D. Functions

$\chi_{gt}(\cdot)$: production and no-load costs for generator g for study period t,

$\varsigma_{gt}(\cdot)$: start-up costs for generator g for study period t.

$p_t^{loss}(\cdot)$: system loss for study period t.

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DC Power Flow Performance Comparison

- Optimal transmission switching requires an embedded power flow model.
- Most state-of-the-art real-time dispatch engines of large RTOs are based on PTDF (Power Transfer Distribution Factor) to model transmission constraints.
- For 37,000-bus 47,000-branch system, a single period dispatch has the following performance with various system conditions.

	Solver Solution Time (sec)	
	LP without DC model	LP with DC model
Condition 1	1.593	8.046
Condition 2	2.34	272.83
Condition 3	12.55	459.50
Condition 4	14.04	551.95

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 remedy: Reduction of problem space
  - Reduce the size of "switchable" transmission lines (OTSbr)
  - Limit the number of open lines

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

Maximum number of open lines

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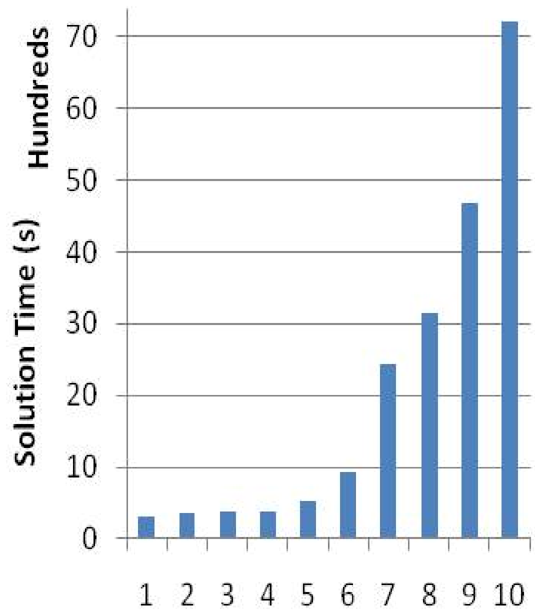
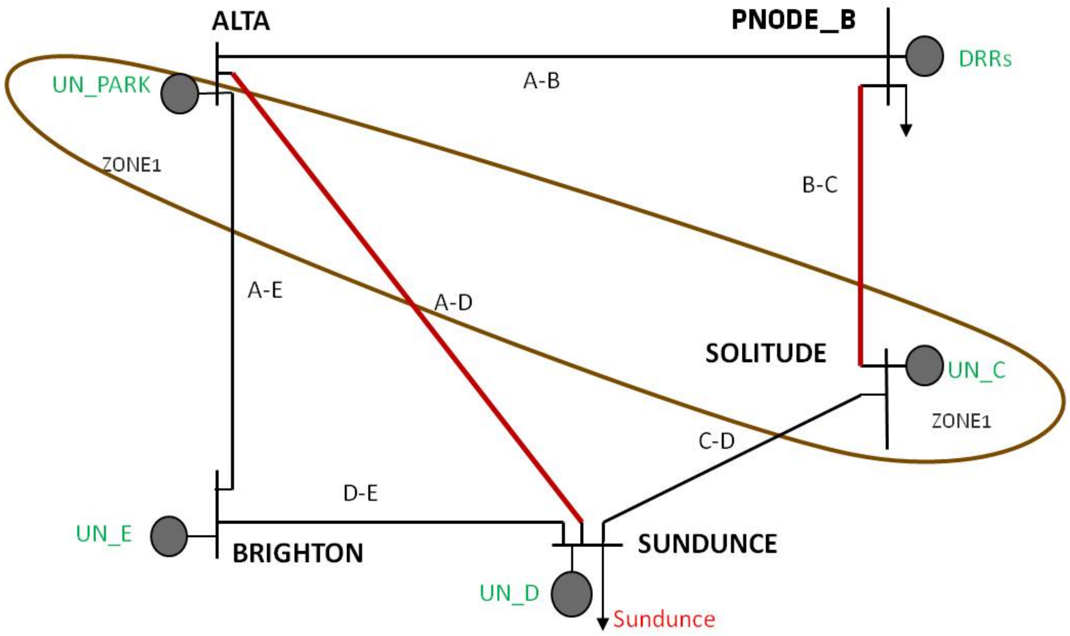
Some Practical Consideration

- Some ideas to reduce the size of switchable transmission lines (OTSbr)
  - Violation/binding transmission lines with the base case
  - Most heavily loaded transmission lines connecting to dispatchable generators.
  - Transmission lines that have large impact on dispatchable generations that have rooms to move up and down.
  - Transmission lines which are previously switched by OTS with great savings.
  - Operator’s experience

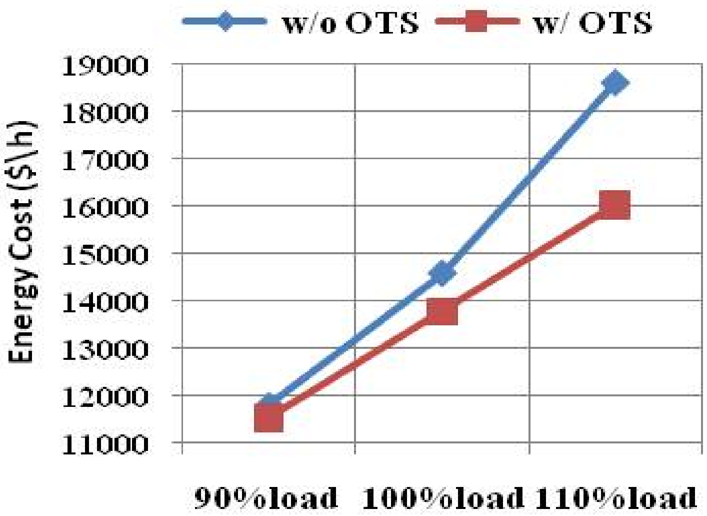


1	w/ DC model but w/o OTS			304s
2	OTSbr=14	j=10	1 line off	351s
3	OTSbr=18	j=8	4 lines off	378s
4	OTSbr=18	j=18	4 lines off	378s
5	OTSbr=27	j=5	4 lines off	516s
6	OTSbr=74	j=5	5 lines off	920s
7	OTSbr=340	j=5	1 line off	2444s
8	OTSbr=691	j=5	0 line off	3138s
9	OTSbr=1561	j=5	2 lines off	4686s
10	OTSbr=1647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

5-Bus Test System



Unit	BandMW (MW)	BandPrice ($/MWh)	Energy (MW) w/o OTS	Energy (MW) w/ OTS
UN_PARK	95	12	99	13
UN_PARK	120	15		
UN_C	300	18	446	416
UN_C	560	30		
UN_E	400	8	358	480
UN_E	660	10		



❖ Total energy saving w/OTS is $802/h (5.8% of total energy cost)

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5-Bus Test System

SEGMENT_ID	BREAKPOINT	PENALTY
ZONE1OR_1	28(MW)	2037($/MWh)
ZONE1OR_2	42(MW)	1100($/MWh)
ZONE1RR_1	10(MW)	1500($/MWh)

SEGMENT_ID	BREAKPOINT	PENALTY
SystemOR_1	70(MW)	2037($/MWh)
SystemOR_2	800(MW)	1100($/MWh)
SystemRR_1	70(MW)	1500($/MWh)

- Average LMP w/OTS is decreased from $25.1/MWh to $18.8/MWh

	Reg at 90%, 100%, 110% load		Spin at 90%, 100% load		Spin at 110% load	
Units	w/o OTS	w/ OTS	w/o OTS	w/ OTS	w/o OTS	w/ OTS
UN_PARK	10 (MW)	10 (MW)		20 (MW)		20 (MW)
UN_C			60 (MW)	40 (MW)		40 (MW)
UN_E	60 (MW)	60 (MW)	20 (MW)	20 (MW)	80 (MW)	20 (MW)
Total Cost	413($/h)	413($/h)	660 ($/h)	561($/h)	264($/h)	561 ($/h)

Penalty violation ($82,866/h) of zone 1 OR requirement not included.

Case		w/o OTS (MW)			w/OTS (MW)					
		.9Load	load	1.1load		.9Load		load		1.1load
Lines	Limit	Flow	Flow	Flow	on/off	Flow	on/off	Flow	on/off	Flow
A-B	200	65.3	88.3	119.2		158.6		159.5		192.8
A-D	200	55.2	46.5	35.4	off	0	off	0	off	
A-E	200	-31.5	-35.8	-55.6		-135.6		-90.5		-123.8
B-C	200	-51.5	-70.4	-73.1	off	0	off	0	off	
C-D	210	126.6	145.8	109.6		173.6		204.5		182.2
D-E	200	-200	-211.4	-292.3		-200		-200		-255.6

No violation or less violation with OTS

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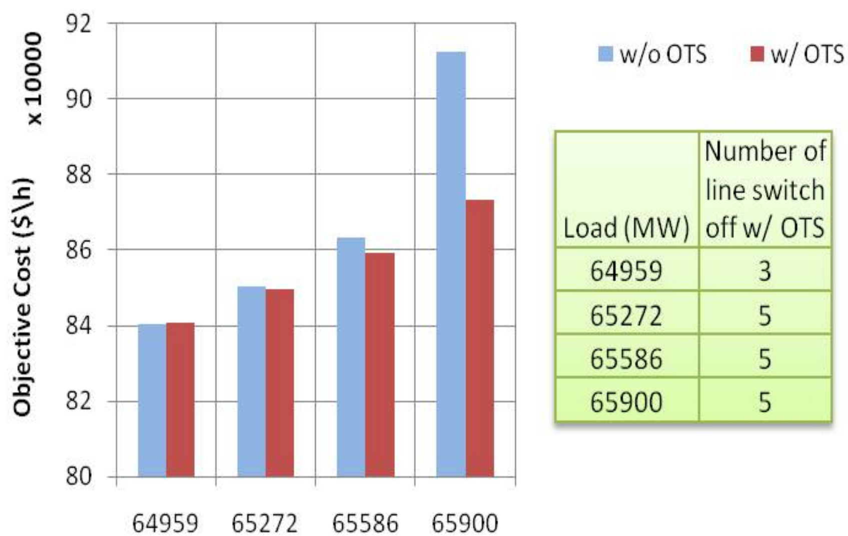
37,000-bus, 47,000-branch Test System

- Switchable transmission lines – 18 violation lines in the base case. 7 lines are switched off as a result. Objective saving due to penalty cost.

	w/o OTS	w/ OTS
Objective ($/h)	3384616	2749157
Solution Time(s)	404.81	401.141

- Switchable transmission lines – Transmission lines that have large impact on dispatchable generations that have rooms to move up and down.



Load (MW)	Number of line switch off w/ OTS
64959	3
65272	5
65586	5
65900	5

j = 10

OTSbr = 14

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Conclusions

- This presentation discussed transmission switching in power system operations.
- A basic dispatch model with co-optimization of energy, ancillary services and transmission switching is presented.
- The size of switchable 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 especially in more stress system condition.
- More research is desirable in the area of identifying the switchable set of transmission lines.
- 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.

References

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Kwok W. Cheung, Jun Wu, Ricardo Rios-Zalapa, "A Practical Implementation of Optimal Transmission Switching", to be presented at the *4th International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT 2011)*.

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