STOCHASTIC INTERCHANGE SCHEDULING
AN APPLICATION OF PROBABILISTIC REAL-TIME LMP FORECAST

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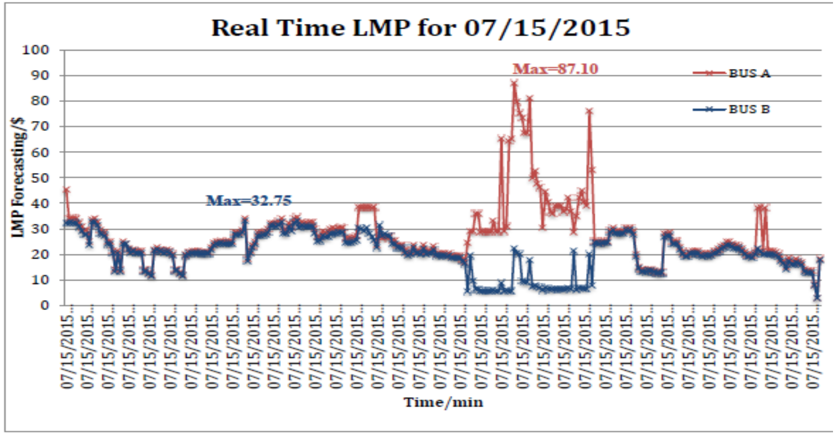
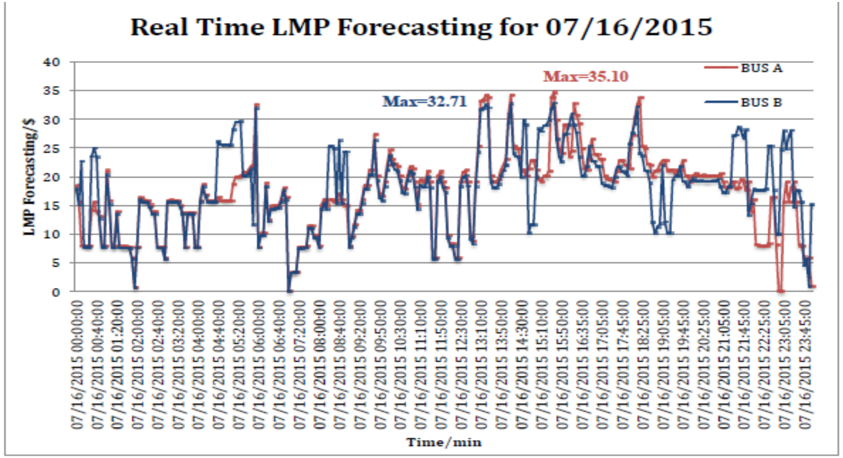
Overview

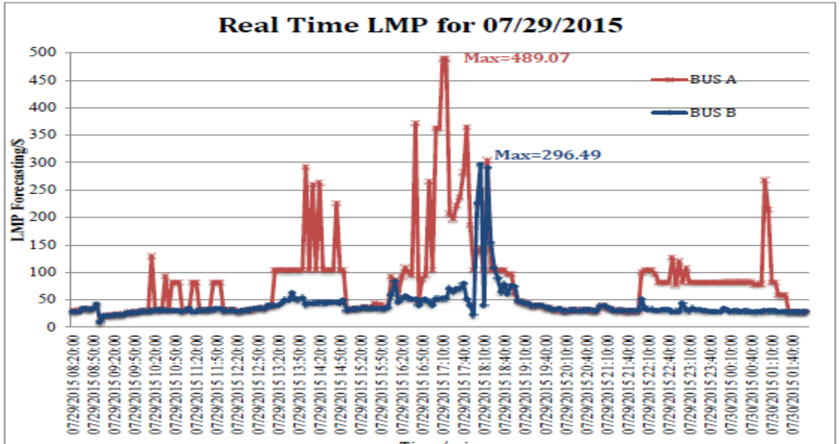
- Objectives
  - Investigate the real-time LMP forecast problem by an operator
  - Develop probabilistic forecasting techniques and applications

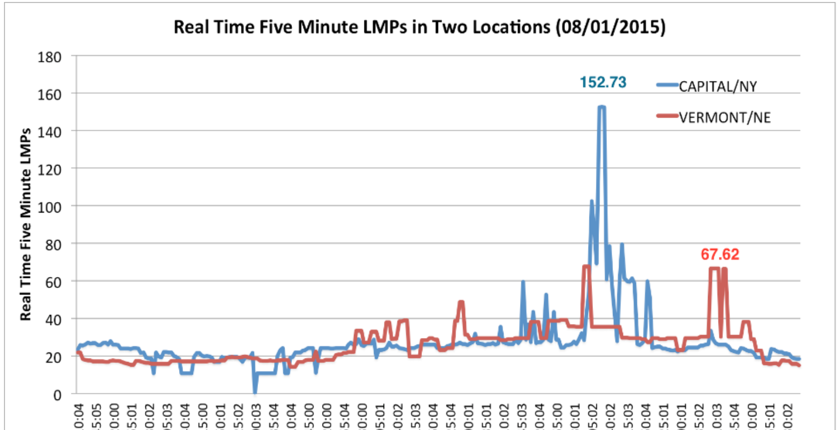
- Summary of results
  - Real-time LMP models
    - Including energy only and energy-reserve markets
    - Deterministic, probabilistic, and time varying contingencies
  - Forecast methods and applications
    - A multiparametric program approach for ex ante LMP
    - A Markov chain approach for ex ante and ex post LMPs
    - Multi-area interchange scheduling under uncertainties

Short-term LMP forecast









Probabilistic forecast of real-time LMP

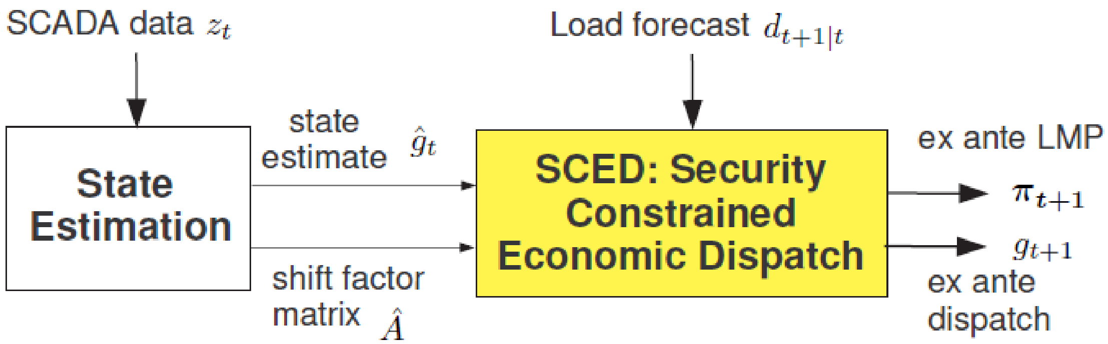
- Benefits
  - Valuable for generation and demand response decisions
  - Risk management
  - Congestion relief and operating cost reduction
  - Multi-area interchange scheduling under uncertainties
  - Examples: ERCOT, AEMO, ….

- Short term LMP forecast by an operator
  - Access to real-time data and network operating conditions
  - Access to internal LMP computation state
  - Ability to incorporate load/variable generation forecast models.

Outline

- Introduction
- Real-time LMP forecast model and techniques
  - LMP forecast models for energy and reserve markets
  - Forecast with probabilistic contingencies
  - Numerical results
- Stochastic inter-regional interchange scheduling
  - The interchange scheduling problem and solutions
    - Joint optimization, tie optimization, and coordinated transaction scheduling
  - Stochastic interchange scheduling via probabilistic forecast
  - Simulation results
- Conclusions and future work

Ex ante real time LMP model



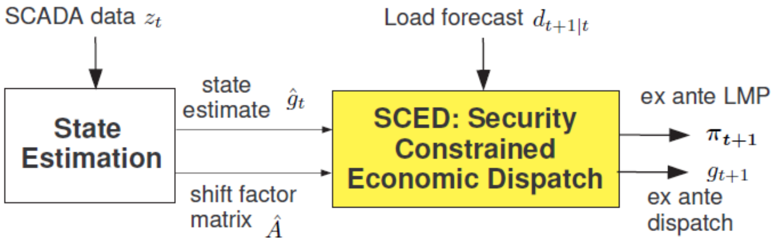
minimize $\quad c^T g$

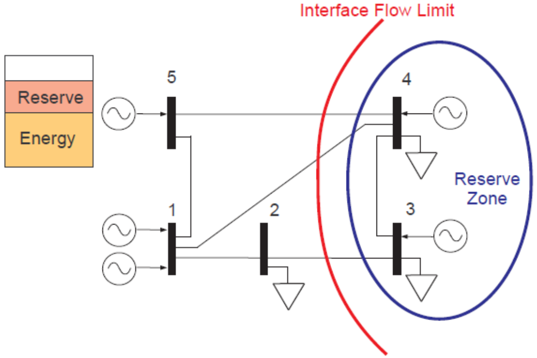
subject to

(λ) :	$\mathbf{1}^T(g - d_{t+1\|t}) = 0,$	power balance,
$(\mu^{+/-})$:	$-F^+ \leq \hat{A}(g - d_{t+1\|t}) \leq F^+,$	transmission constraint,
$(\gamma^{+/-})$:	$g^- \leq g \leq g^+,$	generation capacity,
$(\eta^{+/-})$:	$\hat{g}_t - \Delta^- \leq g \leq \hat{g}_t + \Delta^+,$	ramp limit.

$$\pi_{t+1} = \lambda \mathbf{1} + \hat{A}\mu^+ - \hat{A}\mu^-.$$

Ex ante real time LMP model with co-optimization





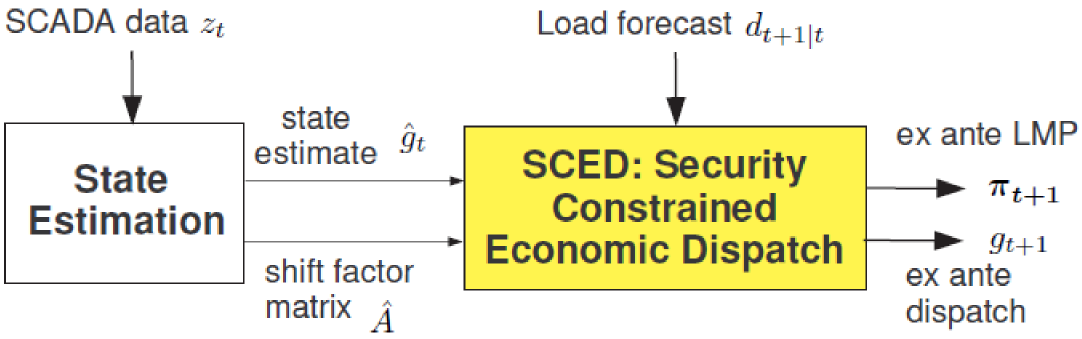
P0: $\min_{g,r,s} c_g^T g + c_r^T r + c_p^T s_l + c_p^T s_s$

subject to:

(λ) :	$1^T(g - d_{t+1\|t}) = 0,$	energy balance,
$(\mu^{+/-})$:	$-F^+ \leq \hat{A}(g - d_{t+1\|t}) \leq F^+,$	transmission,
(α) :	$\delta_{\text{local}}^T r + (I^+ - I) + s_l \geq Q_l,$	local reserve,
	$I = \hat{A}_I(g - d_{t+1\|t}),$	interface flow,
(β) :	$\delta_{\text{system}}^T r + s_s \geq Q_s,$	system reserve,
(γ^+) :	$g + r \leq g^+,$	generator capacity,
(ν) :	$\hat{g}_t - \Delta^- \leq g \leq g_t + \Delta^+,$	generation ramp,
(η) :	$0 \leq r_i, \leq r^+,$	reserve ramp,
(γ^-) :	$g \geq g^-,$	generation capacity,
	$s_l, s_s \geq 0.$	

$$\pi_{t+1} = \lambda 1 + \hat{A}\mu^+ - \hat{A}\mu^- + \hat{A}_I\alpha$$

LMP forecast via MPLP

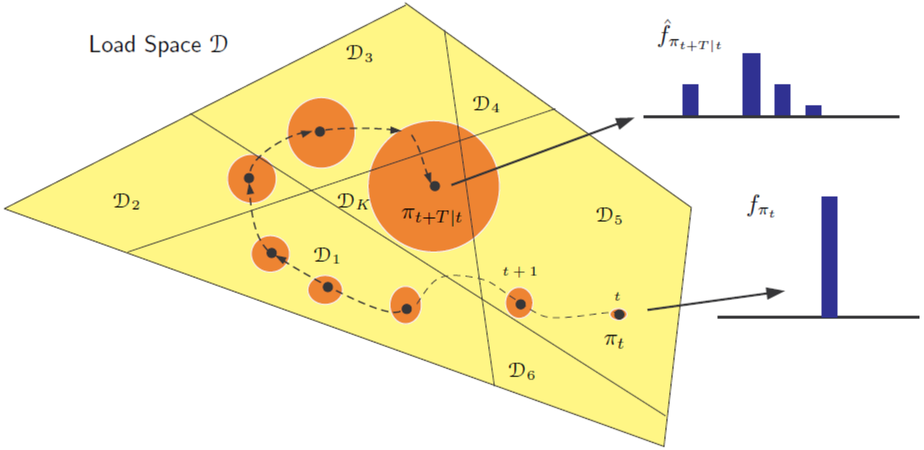


minimize $\quad c^T g$

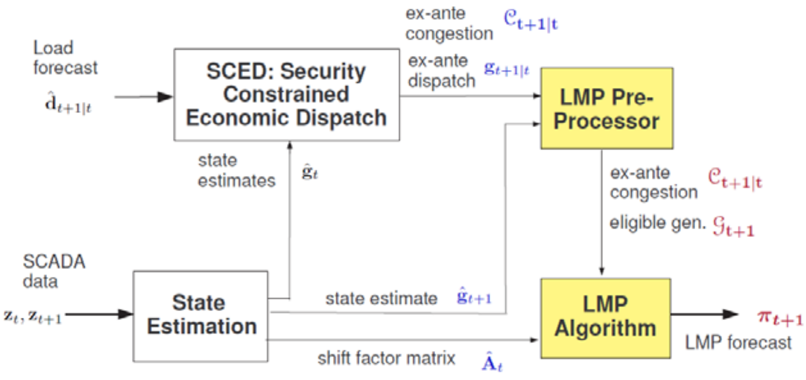
subject to

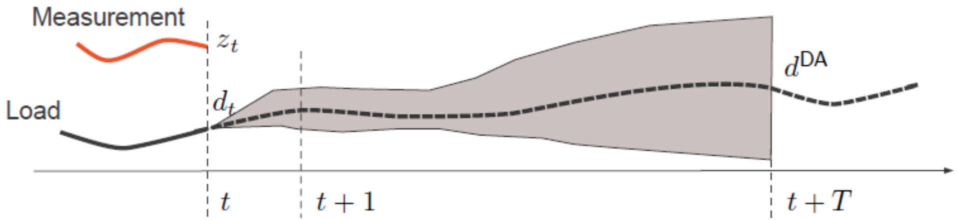
$$
\begin{aligned}
(\lambda): &\quad \mathbf{1}^T(g - d_{t+1}) = 0,\\
(\mu^{+/-}): &\quad -F^+ \leq \hat{A}(g - d_{t+1}) \leq F^+,\\
(\gamma^{+/-}): &\quad g^- \leq g \leq g^+,\\
(\eta^{+/-}): &\quad Bd_t - \Delta^- \leq g \leq Bd_t + \Delta^+,
\end{aligned}
$$

$$\pi_{t+1} = \lambda \mathbf{1} + \hat{A}\mu^+ - \hat{A}\mu^-.$$

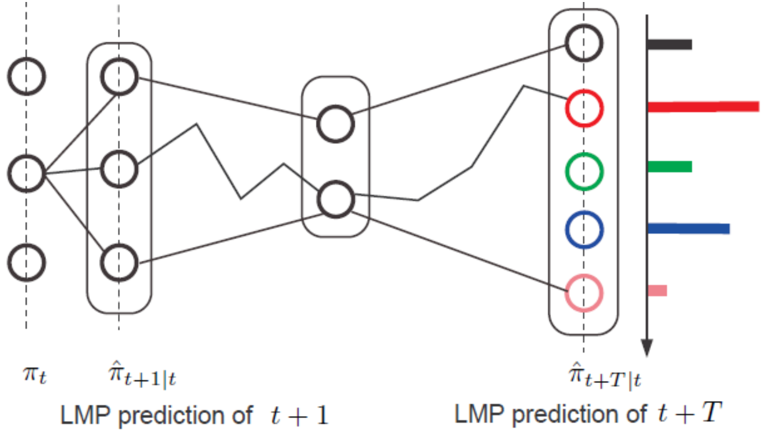


Forecast of ex post LMP via Markov chain

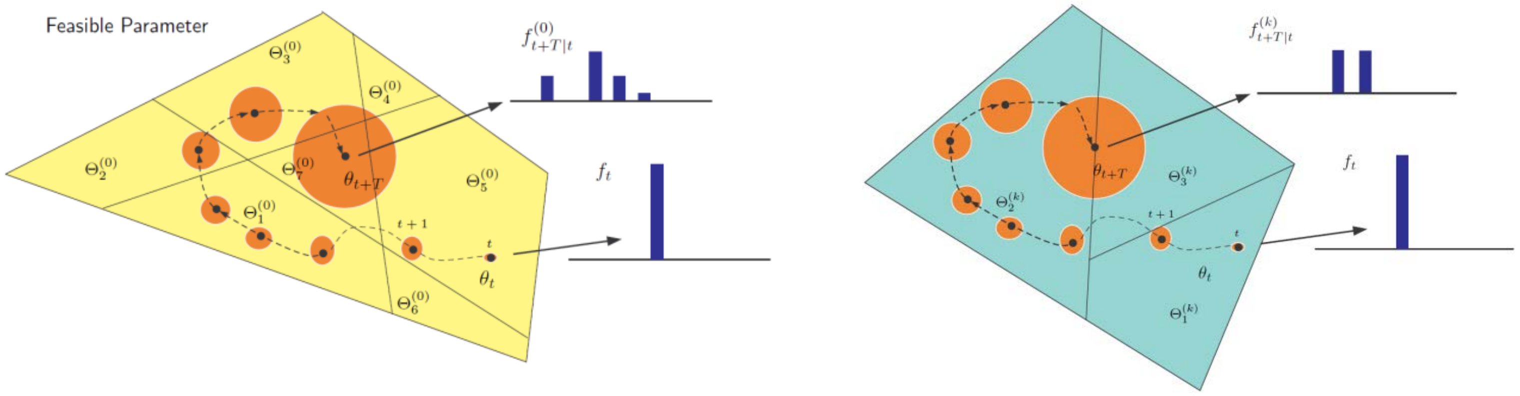




$$\begin{pmatrix} \mathcal{G}_{t+1} \\ \mathcal{C}_{t+1|t} \end{pmatrix} \xrightarrow{\text{LMPA}} \pi_{t+1} = \begin{bmatrix} \pi_{t+1}^{(1)} \\ \vdots \\ \pi_{t+1}^{(n)} \end{bmatrix}$$



LMP forecast with probabilistic contingencies

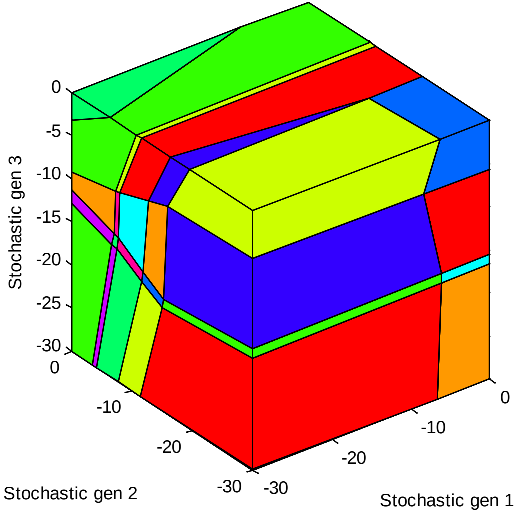


$$f_{t+T|t} = \begin{cases} f_{t+T|t}^{(k)}, & \text{if contingency } k \text{ occurs,} \\ \sum_{k=0}^{K} p_k f_{t+T|t}^{(k)}, & \text{otherwise,} \end{cases}$$

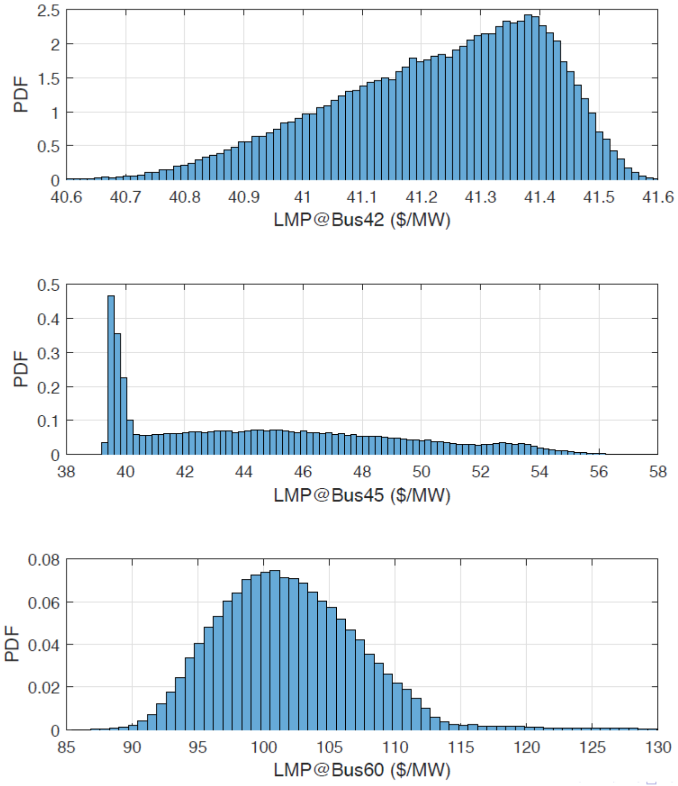
Numerical results: IEEE 118 bus system

- Quadratic cost function.
- Deterministic load.
- 3 stochastic generators (bus 42, 45 and 60).
- 5 transmission lines have limits (67, 68, 69, 89 and 90).
- 25 critical regions.
- 3 unique congestion patterns.

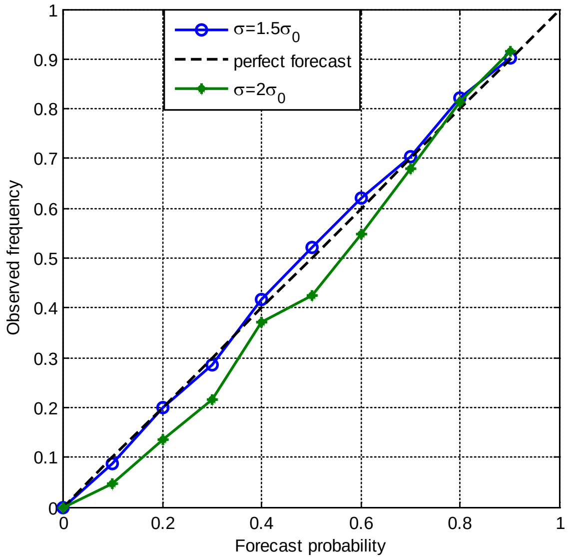
	Critical Region	Congestion Pattern
1	1,2,4,6,8,11,13,17	(-1,0,0,0,-1)
2	3,5,7,9,10,12,14,15,16,18-24	(-1,-1,0,0,-1)
3	25	(0,-1,0,0,-1)



Sample forecast distribution



	Critical Region	Congestion Pattern	Probability
1	1,2,4,6,8,11,13,17	(-1,0,0,0,-1)	0.33
2	3,5,7,9,10,12,14,15,16,18-24	(-1,-1,0,0,-1)	0.67
3	25	(0,-1,0,0,-1)	0



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  - The inter-regional interchange problem
    - The ideal, the practical, the practically optimal, and coordinated transaction scheduling
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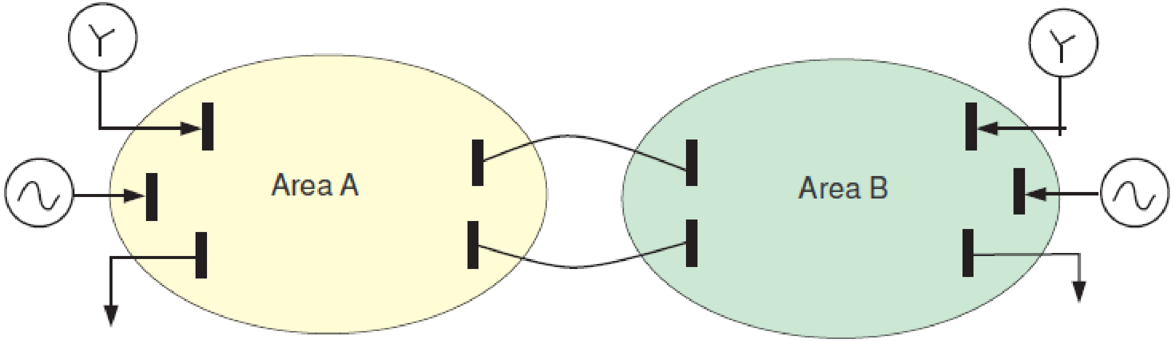
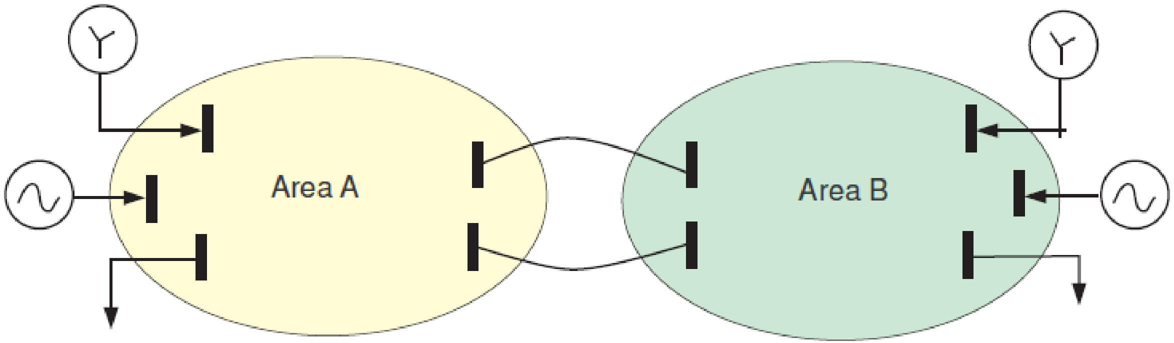
Inter-regional interchange & the seams problem



ISOs schedule operations independently, trading power across seams:

- Stochastic and time varying price disparities between regions.
- Under utilization of tie lines
- Counter-intuitive flows
- Estimated economic loss of $784 millions between NY & NE from 2006-2010.

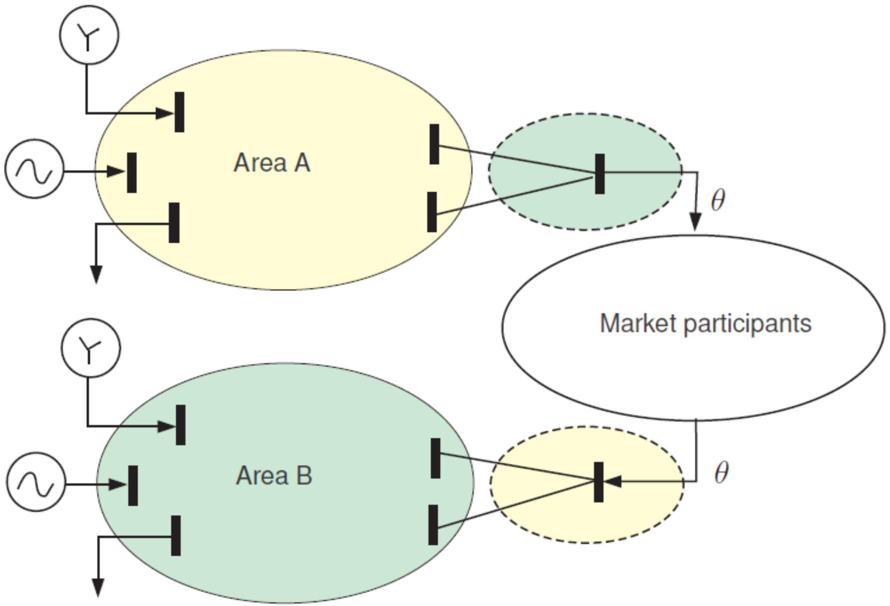
The ideal: joint optimization



Jointly optimal scheduling via decentralized optimization

- Extensively studied: Lagrange relaxation; decomposition techniques
- Advantages and challenges:
  - achieve globally economic solution
  - rate of convergence, required information sharing, dealing with uncertainties, and the role of market participants.

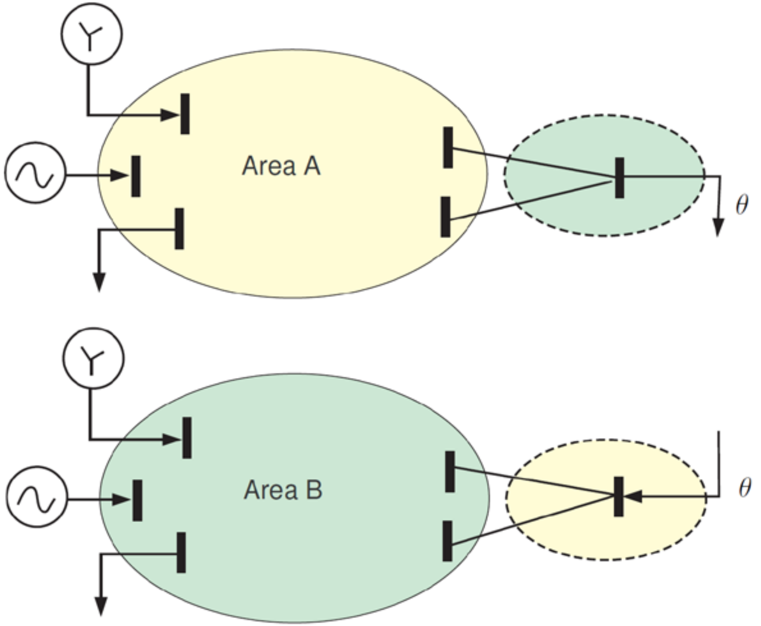
The practical: decoupled optimization



- Each ISO has a simplified model of the neighboring area with a proxy bus
- Market participants submit offers/bids for external transactions at proxy buses
- Export/import quantity is scheduled ahead of time.
- Each ISO schedules its own operations with fixed interchange.

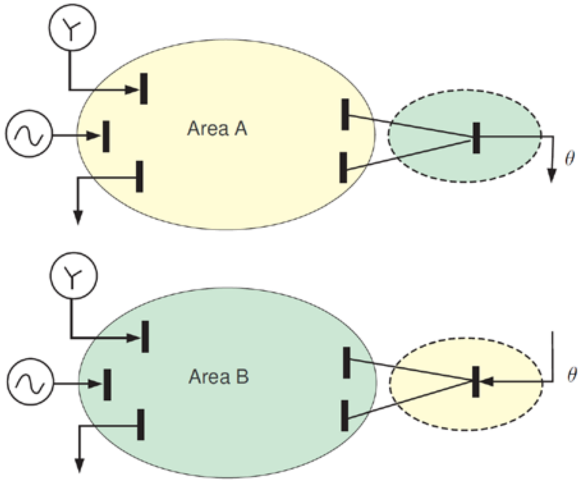
- FERC approves coordinated transaction scheduling (CTS) for PJM & NYISO, March 2014.
- Estimated cost saving: 9M~26M per year.
- Versions of CTS are being implemented for MISO-PJM, NYISO-ISONE

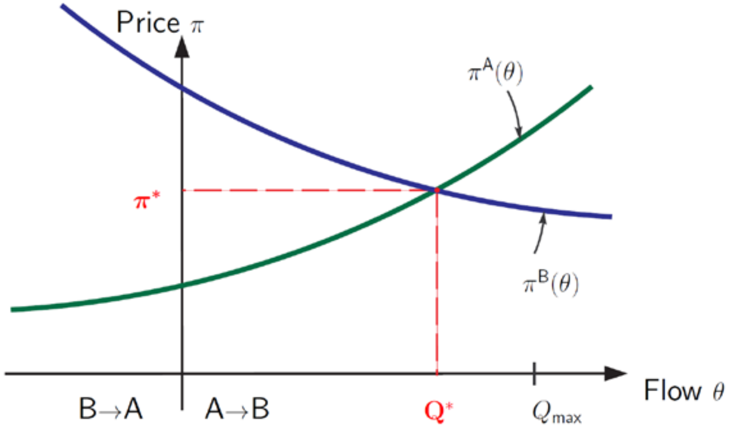
(Deterministic) tie optimization (TO)



$$
\begin{array}{lll}
\text{minimize} & c_A(g_A, \theta) + c_B(g_B, \theta) & \\
\text{subject to} & 1^\intercal(d_A - g_A) + \theta = 0, & (\lambda_A) \\
& S_A(d_A - g_A) \leq F_A - \tilde{S}_B\theta, & (\mu_A) \\
& 1^\intercal(d_B - g_B) - \theta = 0, & (\lambda_B) \\
& S_B(d_B - g_B) \leq F_B + \tilde{S}_A\theta. & (\mu_B) \\
& g_A \in \mathcal{G}_A, g_B \in \mathcal{G}_B &
\end{array}
$$

A market perspective





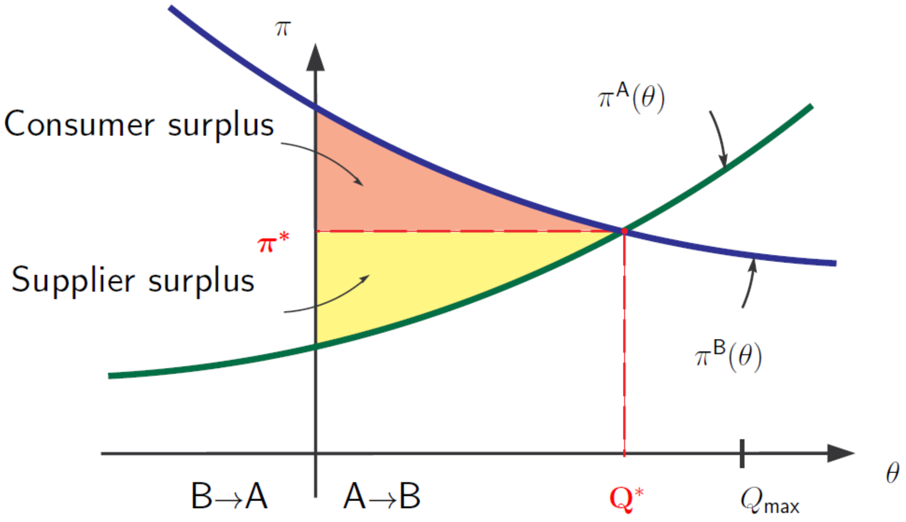
$$\mathcal{P}_A: \quad \text{minimize}_{g_A \in \mathcal{G}_A} \quad c_A(g_A)$$
$$\text{subject to} \quad \mathbf{1}^\mathsf{T}(d_A - g_A) + \theta = 0, \quad (\lambda_A)$$
$$S_A(d_A - g_A) \leq F_A - \tilde{S}_B\theta, \quad (\mu_A)$$

$$\pi^A(\theta) = \lambda_A + \tilde{S}_B^\mathsf{T}\mu_A$$

$$\mathcal{P}_B: \quad \text{minimize}_{g_B \in \mathcal{G}_B} \quad c_B(g_B)$$
$$\text{subject to} \quad \mathbf{1}^\mathsf{T}(d_B - g_B) - \theta = 0, \quad (\lambda_B)$$
$$S_B(d_B - g_B) \leq F_B + \tilde{S}_A\theta. \quad (\mu_B)$$

$$\pi^B(\theta) = \lambda_B + \tilde{S}_A^\mathsf{T}\mu_B$$

Tie optimization (TO) and equivalence



Cost minimization

$$
\begin{aligned}
\text{minimize} \quad & c_A(g_A,\theta) + c_B(g_B,\theta) \\
\text{subject to} \quad & 1^\intercal(d_A - g_A) + \theta = 0, && (\lambda_A) \\
& S_A(d_A - g_A) \le F_A - \tilde{S}_B\theta, && (\mu_A) \\
& 1^\intercal(d_B - g_B) - \theta = 0, && (\lambda_B) \\
& S_B(d_B - g_B) \le F_B + \tilde{S}_A\theta. && (\mu_B) \\
& g_A \in \mathcal{G}_A, g_B \in \mathcal{G}_B
\end{aligned}
$$

Surplus maximization

$$\max_Q \int_0^Q \left(\pi^{\mathsf{B}}(\theta) - \pi^{\mathsf{A}}(\theta)\right) d\theta \text{ subject to } Q \le Q_{\max}.$$

Stochastic tie optimization (STO)

STO as a two stage stochastic program

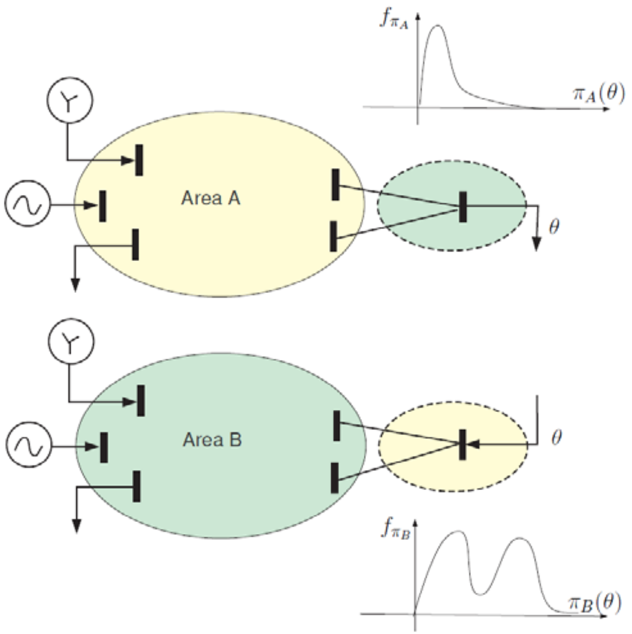
1st stage: $\min_{\theta} \mathbb{E}_{d_A,d_B}[c_{\mathsf{A}}(g^*_{\mathsf{A}}(\theta, d_A)) + c_b(g^*_b(\theta, d_B))]$ subject to $\theta \leq Q_{\text{max}}$

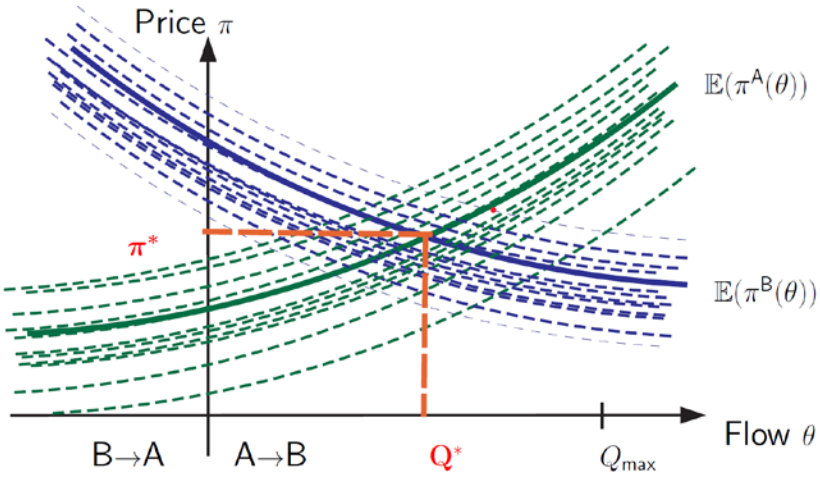
2nd stage:

$$
\begin{aligned}
\mathcal{P}_A: \quad & \min_{g_A \in \mathcal{G}_A} \quad c_A(g_A) \\
& \text{subject to} \quad \mathbf{1}^\intercal(d_A - g_A) + \theta = 0, && (\lambda_A) \\
& \qquad S_A(d_A - g_A) \leq F_A - \tilde{S}_B\theta, && (\mu_A)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{P}_B: \quad & \min_{g_B \in \mathcal{G}_B} \quad c_B(g_B) \\
& \text{subject to} \quad \mathbf{1}^\intercal(d_B - g_B) - \theta = 0, && (\lambda_B) \\
& \qquad S_B(d_B - g_B) \leq F_B + \tilde{S}_A\theta. && (\mu_B)
\end{aligned}
$$

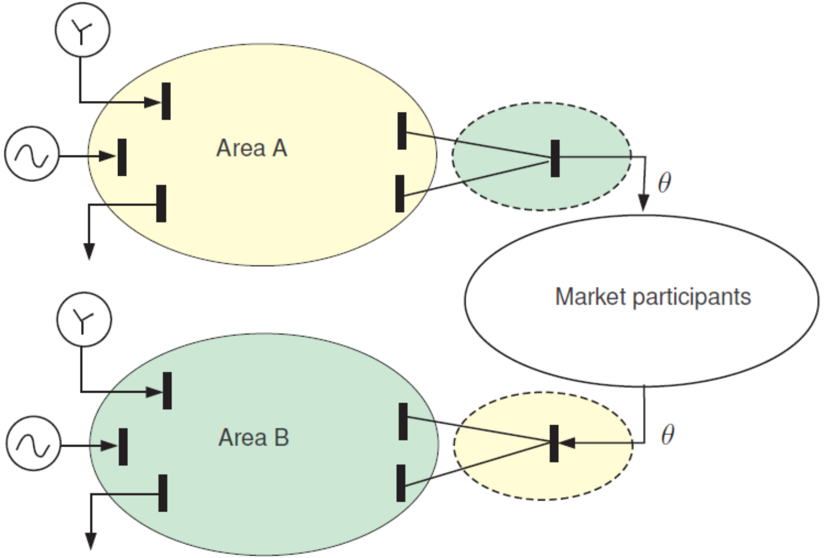
Stochastic tie optimization (STO)

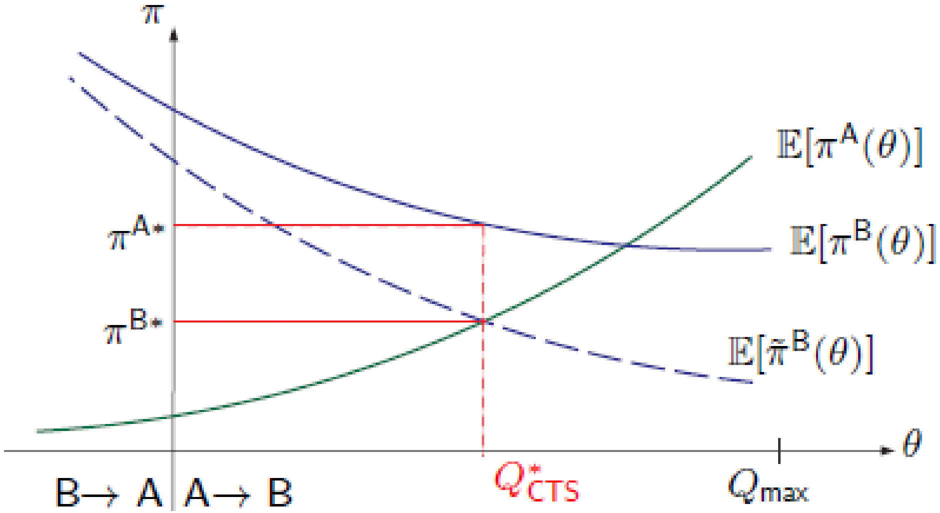




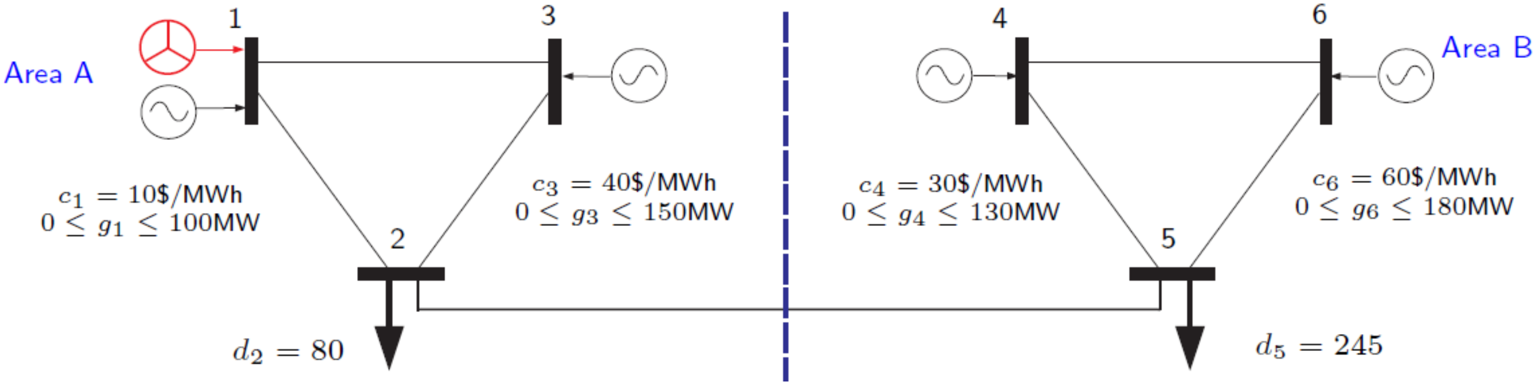
$$\mathsf{STO} = \max_{Q} \int_0^Q \left[\mathbb{E}(\pi^{\mathsf{B}}(\theta)) - \mathbb{E}(\pi^{\mathsf{A}}(\theta))\right] d\theta \text{ subject to } Q \leq Q_{\mathsf{max}}.$$

Stochastic coordinated transaction scheduling (SCTS)





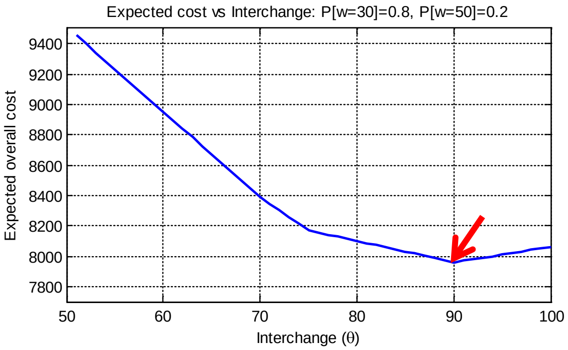
Numerical results: 2 area 6 bus system

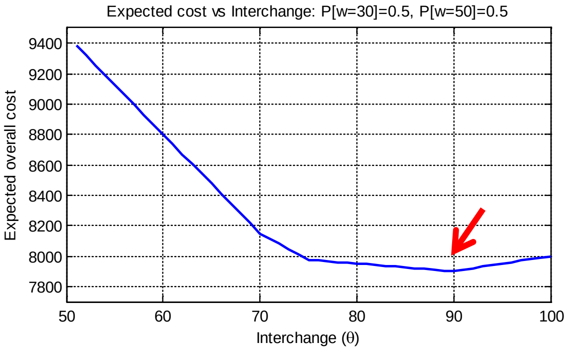


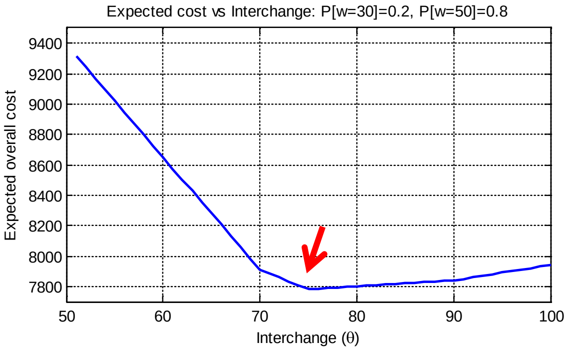
- Deterministic load.
- All lines are identical with limit 100MW.
- A single wind generator.

Discrete randomness

Case	Wind Forecast	Q^*_{TO}	Q^*_{STO}	$\mathbb{E}[C_{\text{TO}}]$	$\mathbb{E}[C_{\text{STO}}]$
1	Pr[$w = 30$]=0.8, Pr[$w = 50$]=0.2	86	90	8016	7960
2	Pr[$w = 30$]=0.5, Pr[$w = 50$]=0.5	80	90	7950	7900
3	Pr[$w = 30$]=0.2, Pr[$w = 50$]=0.8	75	75	7780	7780

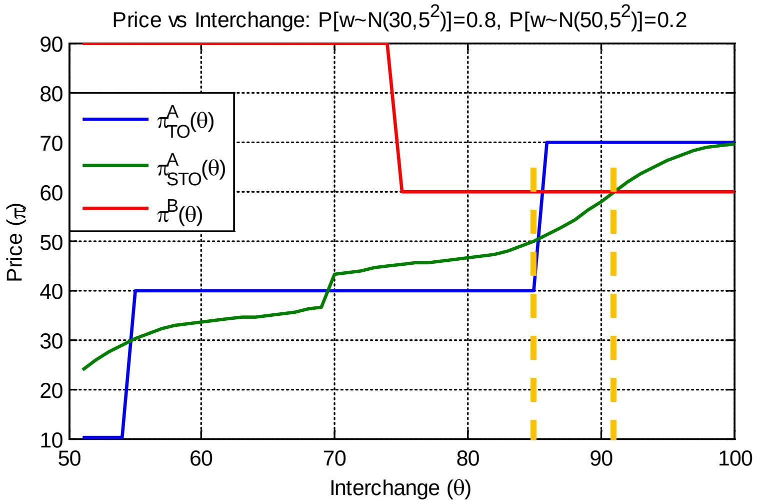






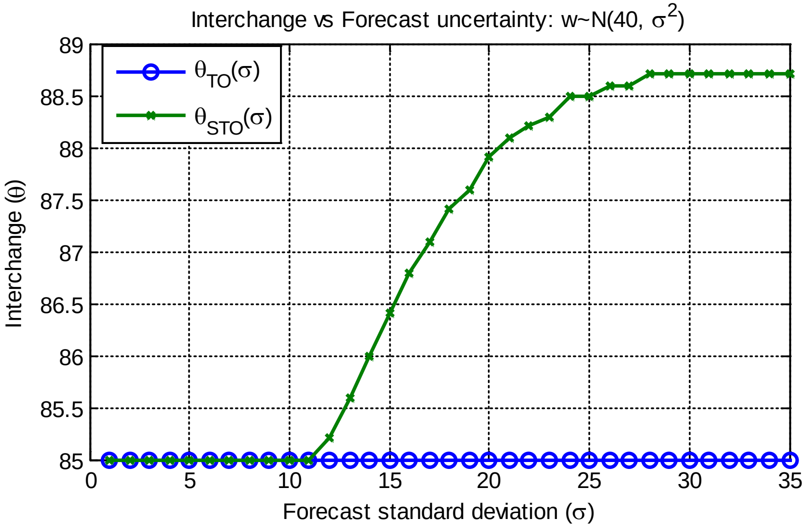
Continuous randomness

Case	Wind Forecast	Q^*_{TO}	Q^*_{STO}	$\mathbb{E}[C_{\mathsf{TO}}]$	$\mathbb{E}[C_{\mathsf{STO}}]$	$\mathbb{E}[\Delta\pi_{\mathsf{TO}}]$	$\mathbb{E}[\Delta\pi_{\mathsf{STO}}]$
4	$\Pr[w \sim \mathcal{N}(30,5^2)]=0.8$, $\Pr[w \sim \mathcal{N}(50,5^2)]=0.2$	86	92	8031.9	8009	10.53	-0.08
5	$\Pr[w \sim \mathcal{N}(30,5^2)]=0.5$, $\Pr[w \sim \mathcal{N}(50,5^2)]=0.5$	80	88	7952.3	7928.2	4.99	-0.02
6	$\Pr[w \sim \mathcal{N}(30,5^2)]=0.2$, $\Pr[w \sim \mathcal{N}(50,5^2)]=0.8$	75	75	7798	7798	-0.04	-0.04

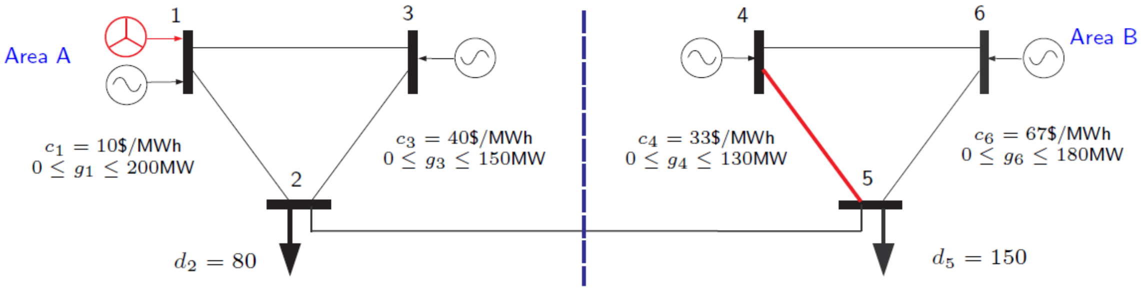


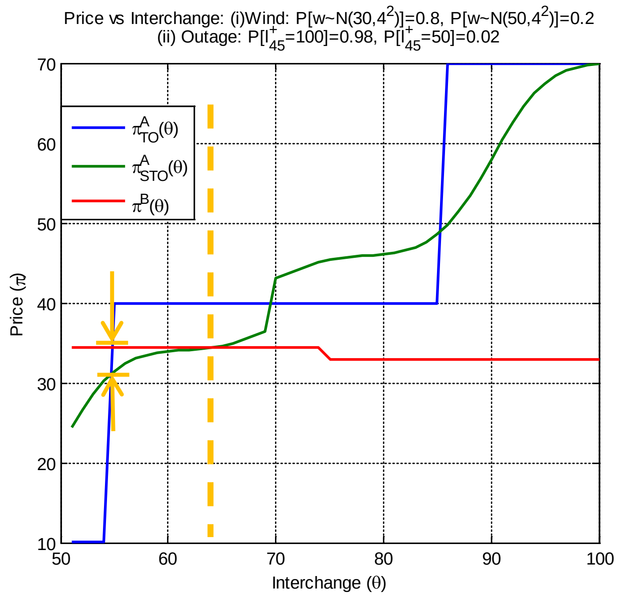
Impact of uncertainty

- Assume that wind $w \sim N(40, \sigma^2)$.
- STO: capability to capture the uncertainty level σ.



Contingency: transmission outage





$\Pr[l^+_{45} = 100]$=0.98, $\Pr[l^+_{45} = 50]$=0.02

$\Pr[w \sim \mathcal{N}(30, 4^2)]$=0.8, $\Pr[w \sim \mathcal{N}(50, 4^2)]$=0.2

$$Q^*_{\text{TO}} = 55,\ Q^*_{\text{STO}} = 64$$

$$\mathbb{E}[C_{\text{TO}}] = 8700,\ \mathbb{E}[C_{\text{STO}}] = 7801.5$$

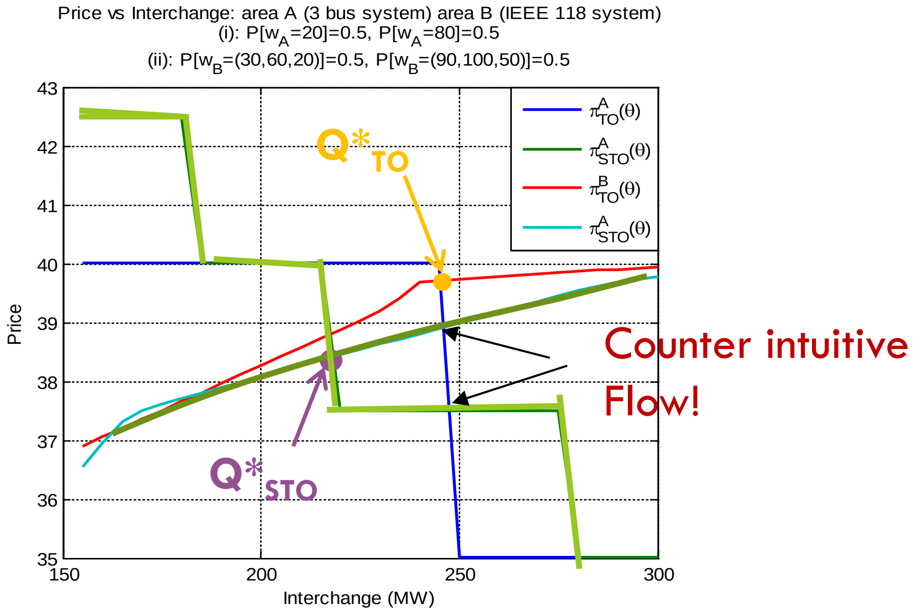
$$\Delta\pi_{\text{TO}} = 2.9,\ \Delta\pi_{\text{STO}} = -0.04$$

Example: 3+118 bus system

- Area A: 3 bus system with constant cost
  - 1 wind generator
  - Pr[high wind]=Pr[low wind]=0.5
- Area B: 118 bus system with quadratic cost
  - 3 wind generators
  - Pr[high wind]=Pr[low wind]=0.5
- Two systems are connected with a single tie line.

$$Q^*_{\text{TO}} = 245,\ Q^*_{\text{STO}} = 215$$

$$\mathbb{E}[C_{\text{TO}}] = 136007.5,\ \mathbb{E}[C_{\text{STO}}] = 135985$$



Summary and future work

- Summary of results
  - Real-time LMP models
    - Including energy only, energy-reserve markets & inter-regional interchange
    - Deterministic, probabilistic, and time varying contingencies
  - Forecast methods and applications
    - A multiparametric program approach for ex ante LMP
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- Future work
  - Addressing scalability issues of forecast
  - Characterization of performance loss of decoupled optimization
  - Performance evaluation in the presence of market participants