DOE/OE Transmission Reliability Program

Probabilistic Forecasting for Power System Operations

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Overview

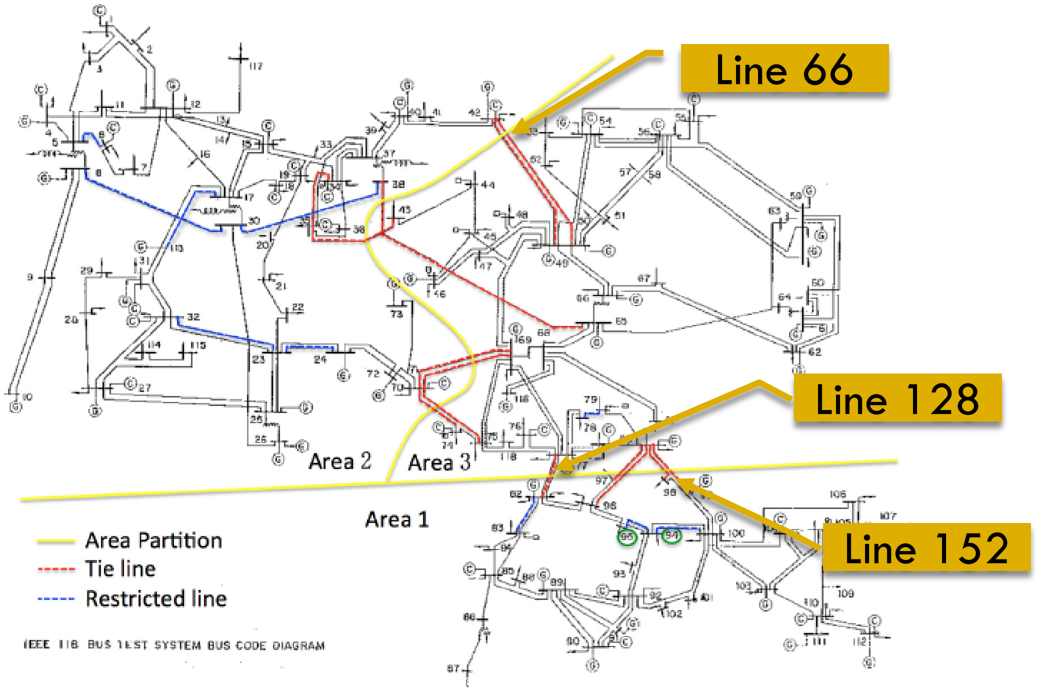
- Overall Project Objectives
  - Develop scalable probabilistic forecasting and system simulation tools for real-time operations. Specifically,
    - Forecasts of marginal and joint distributions of LMP, power flow, and reserve;
    - Forecasts of probability mass functions of discrete events such as congestions and contingencies.
- Why is probabilistic forecasting important?
  - For operators, probabilistic forecasting is essential to achieve economic efficiency under uncertainty.
  - For market participants, probabilistic forecasting is essential for integrating flexible demand and distributed energy resources.

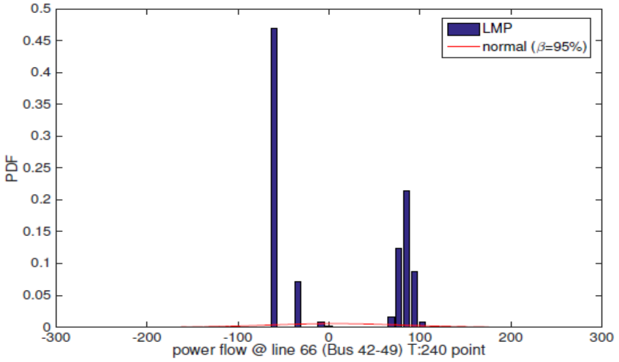
Outline

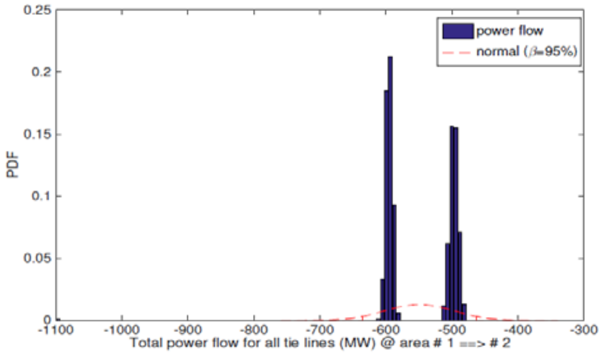
- Major accomplishments and technical contributions
  - Probabilistic forecasting of power system operation.
  - Multi-area economic dispatch and interchange scheduling
    - Stochastic and robust interchange scheduling
    - Generalized Coordinated Transmission Scheduling (CTS)
- Deliverables and remaining schedule
  - Publications and software
  - Industrial collaborations
- Looking forward

Probabilistic Forecasting of Real-time Operations

- Summary of major contributions
  - Functionality: a probabilistic simulation and forecasting tool.



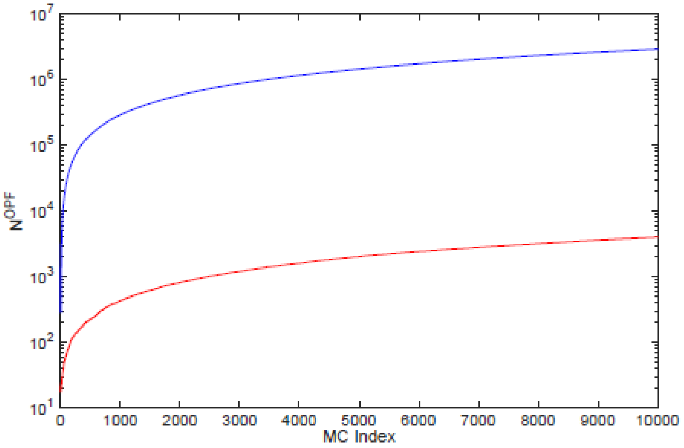


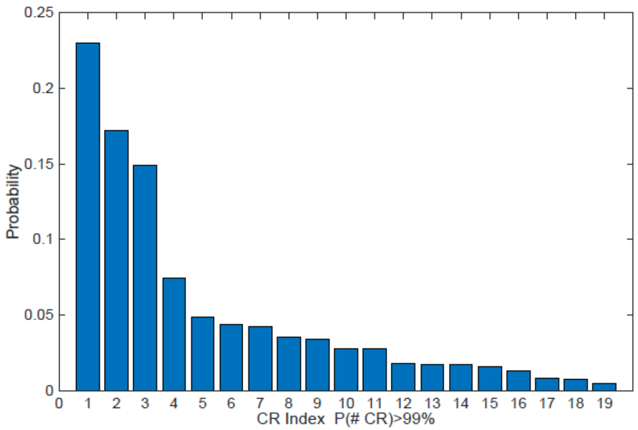


- Y. Ji, R. J. Thomas, L. Tong, "Probabilistic forecasting of real-time LMP and network congestion," *IEEE Trans.*

Probabilistic Forecasting of Real-time Operations

- Summary of major contributions
  - Functionality: a probabilistic simulation and forecasting tool.
  - Scalability: achieving several orders of magnitude reduction in computation costs. (over 0.1% of the computation cost of the state of the art on the 3120 bus 3963 branch Polish network.)



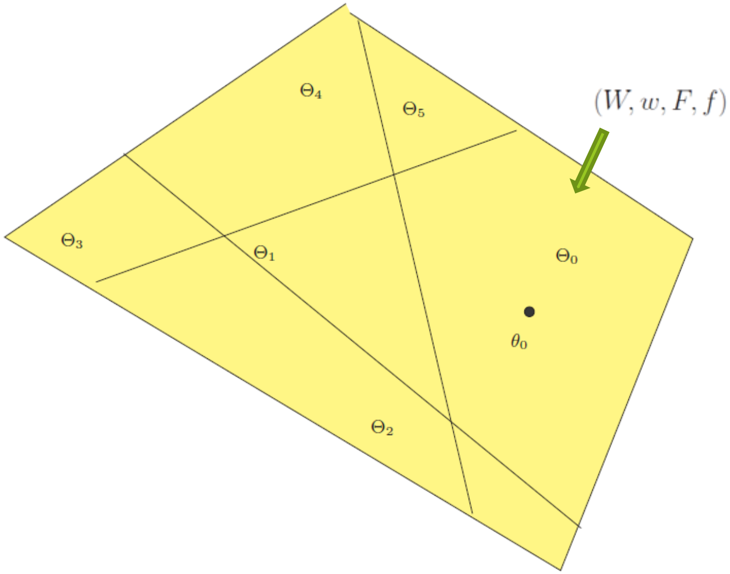


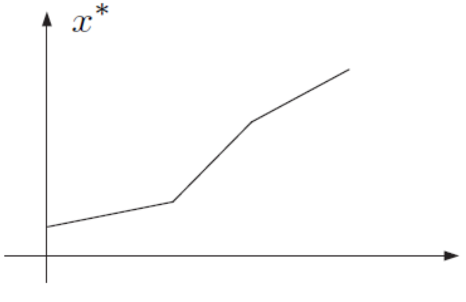
Probabilistic Forecasting of Real-time Operations

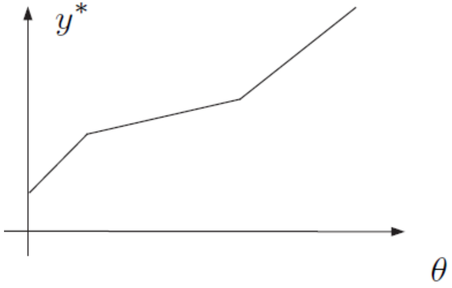
- Summary of major contributions
  - Functionality: a probabilistic simulation and forecasting tool.
  - Scalability: achieving several orders of magnitude reduction in computation costs. (over 0.1% of the computation cost of the state of the art on the 3120 bus 3963 branch Polish network.)
  - Technical innovation:
    - Parametric programming for real-time operations under uncertainty.
    - Online dictionary learning.
- Major publications
  - Weisi Deng, Yuting Ji, and Lang Tong, "Probabilistic forecasting and simulation of electricity markets via online dictionary learning," HICSS'17, January 4-7, 2017. Best paper award.
  - Y. Ji, R. J. Thomas, L. Tong, "Probabilistic forecasting of real-time LMP and network congestion," *IEEE Trans. Power Systems*, vol 32, no. 2, March, 2017

Geometry of Multiparametric LP/QP

$$\begin{array}{ll} \min_x & z(x) \\ \text{subject to} & Ax \le b + E\theta \quad (y) \end{array}$$







Theorem (critial region generation)

Given parameter θ_0 and the solution of a nondegenerate MPLP $x^*(\theta_0)$, the critical region Θ_0 that contains θ_0 is given by the matrix-vector pair (W, w):

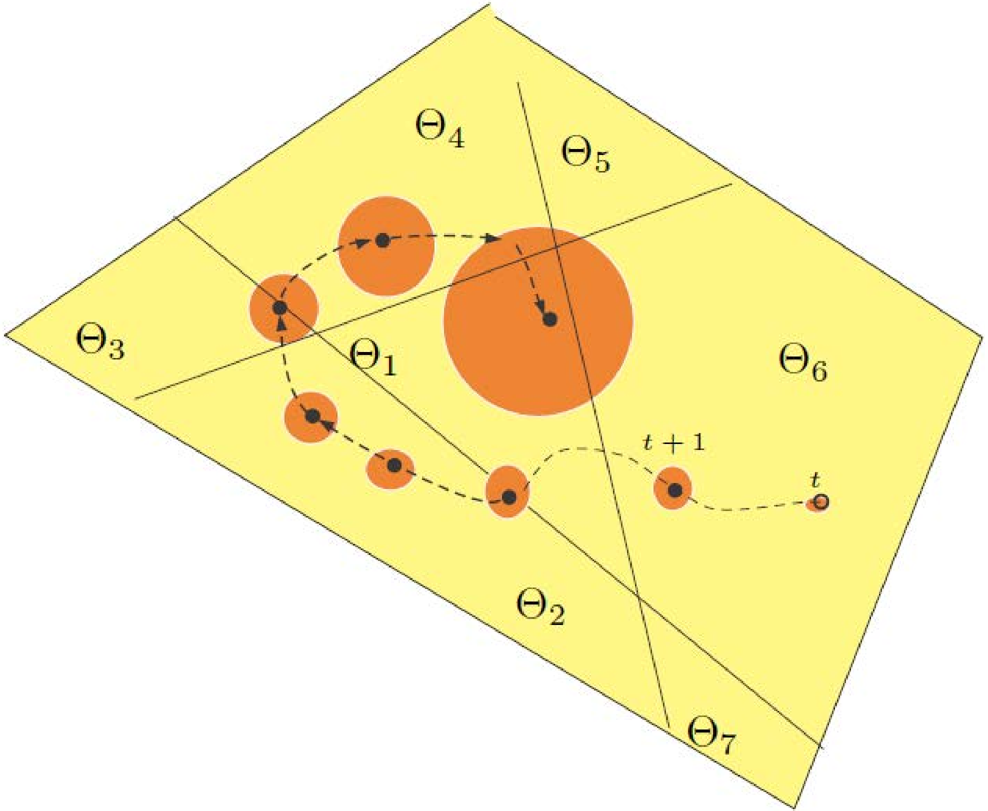
$$\Theta_0 = \left\{\theta \in \Theta \middle| W\theta < w\right\}, \quad W := \bar{A}\tilde{A}^{-1}\tilde{E} - \bar{E}, \; w := \bar{b} - \bar{A}\tilde{A}^{-1}\tilde{b}.$$

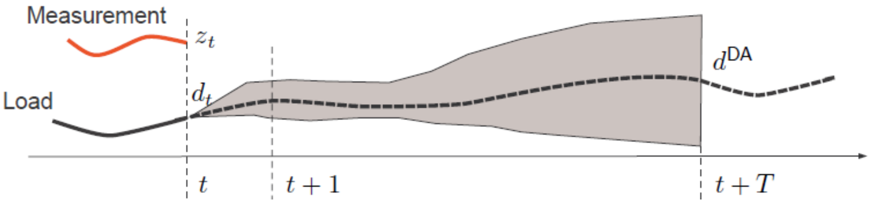
The solution $x^*(\theta)$ for any $\theta \in \Theta_0$ is defined by (F, f)

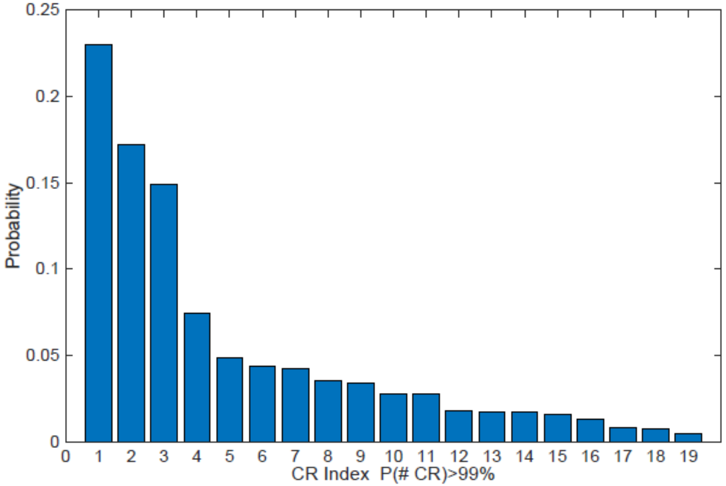
$$x^*(\theta) = F\theta + f, \quad F := \tilde{A}^{-1}\tilde{E}, f := \tilde{A}^{-1}\tilde{b}$$

Here $\tilde{A}, \tilde{E}$ and $\tilde{b}$ are, respectively, the submatrices of corresponding to the active constraints, and $\bar{A}, \bar{E}$ and $\bar{b}$ similarly defined for the inactive constraints.

Weatherman's forecast







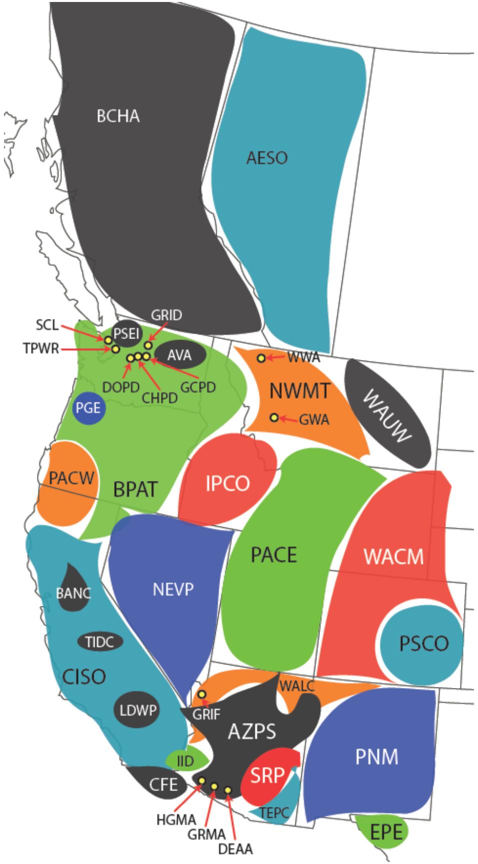
Multi-area Economic Dispatch & Interchange Scheduling

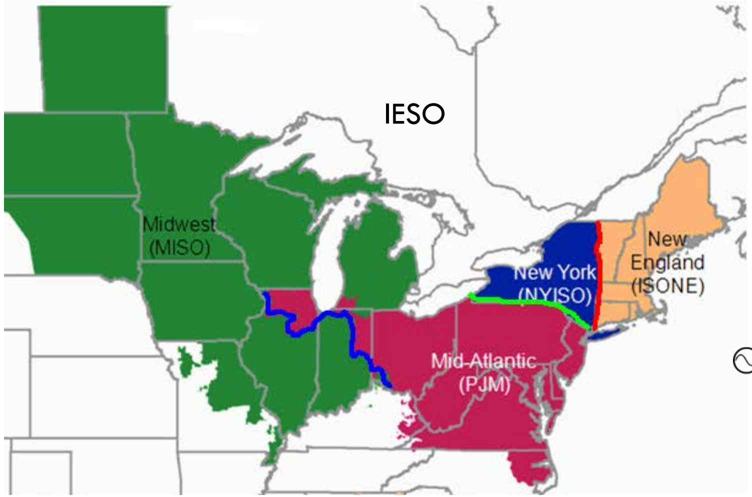
- Summary of major contributions
  - Optimal multi-area interchange scheduling that
    - addresses operation uncertainty in stochastic and robust settings.
    - provides synchronous and asynchronous interchange involving two or more areas.
    - eliminates economic loss from unintended loop flows and guarantees revenue adequacy.

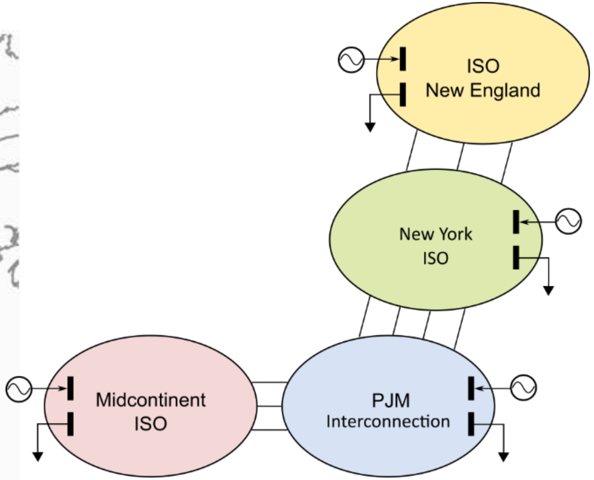
- Selected publications

  - Y. Ji, T. Zheng, and L. Tong, "Stochastic Interchange Scheduling in the Real-Time Electricity Market," *IEEE Trans. Power Systems*, vol 32, no. 3, March 2017
  - Y. Ji and L. Tong, "Multi-proxy interchange scheduling under uncertainty," IEEE Power & Energy Society General Meeting (PESGM), 2016. Best paper nomination.
  - Y. Guo, S. Bose, and L. Tong, "Robust tie-line scheduling in multi-area power systems," submitted to IEEE Transactions on Power Systems, April 2017.

The interchange scheduling (seams) problem



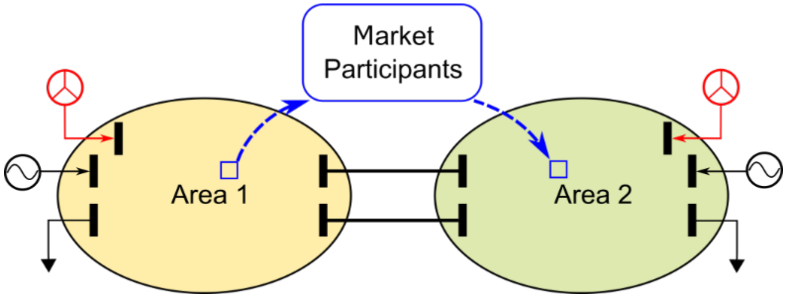




- NE: 402 gen, 260 loads. NY: 582 gen units, 1026 load.
- Tie-line capacity between ISONE and NYISO is 1800MW (12% of ISONE's consumption in 2009).
- In 2009, 1.6 TWh NYISO to ISONE, 1.9 TWh in reverse.

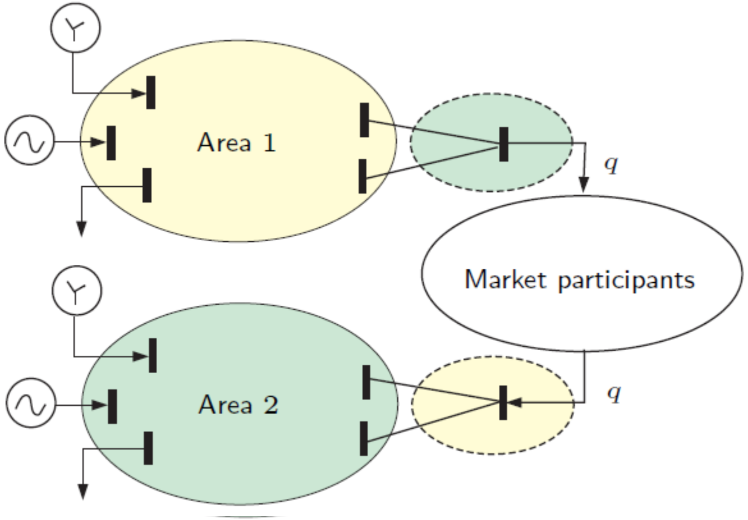
Essential features of interchange scheduling

- ISOs can trade power only through market participants.
  - Market participants submit (virtual) bids to buy and offers to sell electricity at specific "proxy buses."



- A two-stage process
  - ISOs clear bids/offers and set interchange quantity ahead of time.
  - ISOs optimize local dispatch in real time. Trades are settled based on real-time LMP.
- Decentralized scheduling with limited exchange and minimum iterations.
- The state-of-the-art: Coordinated Transaction Scheduling (CTS).
  - Currently being implemented for MISO-PJM, NYISO-ISONE.
  - Estimated cost saving: 9M~26M/year. So far only small portion has been realized
  - Sources of inefficiency: inaccurate forecast, uncertainty, and market illiquidity.

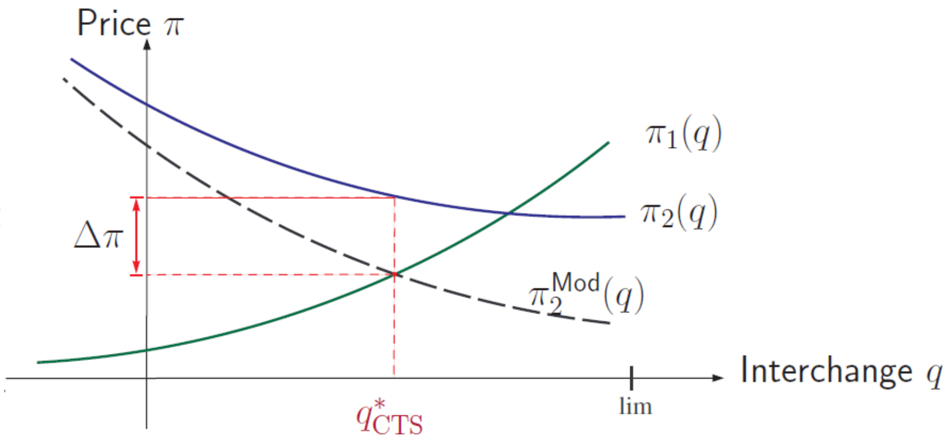
Coordinated Transaction Scheduling



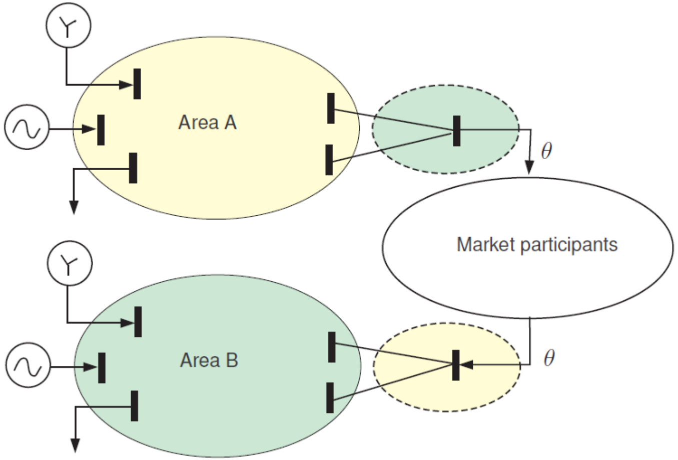
- Each ISO has a simplified model of the neighboring area with a proxy bus
- Market participants submit offers/bids for external transactions at proxy buses

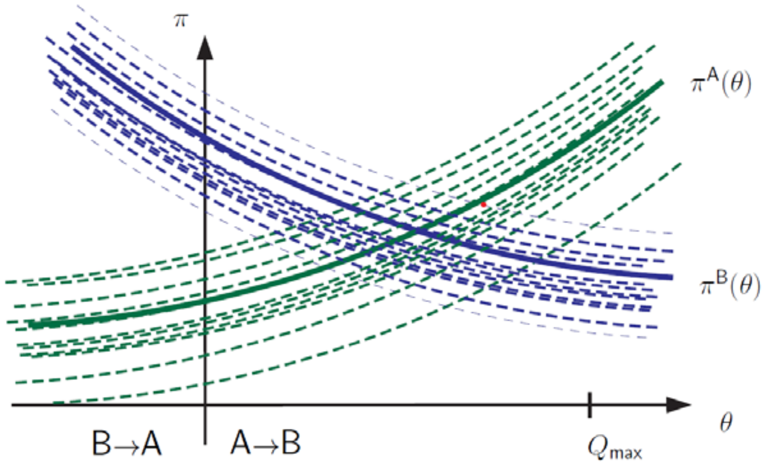
$$\min_{q, g_1, g_2} \quad C_1(g_1) + C_2(g_2) + C_{\text{bid}}(q)$$

subject to
- power balance constraints for Area 1 and 2
- transmission constraints for Area 1 and 2
- generator constraints for Area 1 and 2
- interface capacity constraint



Stochastic Coordinated Transmission Scheduling (SCTS)





$$(P_1)\ \min_{q \le Q} \quad \sum_{i=1}^{2} \mathbb{E}_{d_i}\left[C_i(g_i^*(q, d_i))\right]$$

$$(P_{2i})\ \min_{g_i \in \mathcal{G}_i} \quad C_i(g_i)$$

subject to

$$\mathbf{1}^\mathsf{T}(d_i - g_i) \pm q = 0, \qquad (\lambda_i)$$

$$S_i(d_i - g_i) \pm T_i q \le F_i. \qquad (\mu_i)$$

$$\pi_i(q, d_i) \triangleq \lambda_i(q, d_i) + (T_i)^\mathsf{T} \mu_i(q, d_i)$$

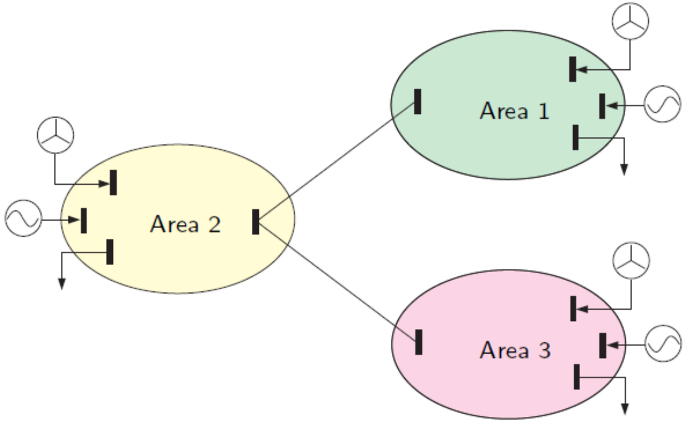
Theorem 1

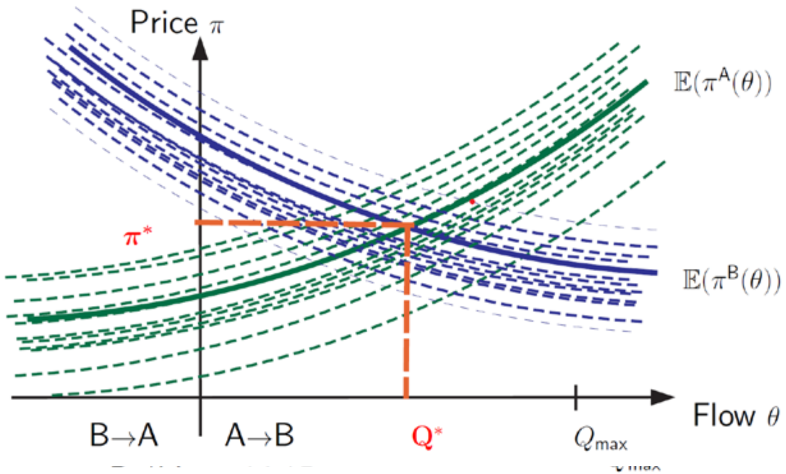
The optimal interchange is given by the solution q^* of

$$\bar{\pi}_1(q) = \bar{\pi}_2(q)$$

if $q^* < Q$ and Q otherwise.

Stochastic Coordinated Transmission Scheduling (SCTS)





$$(P_1)\ \min_{q\le Q}\quad \sum_{i=1}^{2}\mathbb{E}_{d_i}\left[C_i(g_i^*(q,d_i))\right]$$

$$\begin{aligned}(P_{2i})\ \min_{g_i\in\mathcal{G}_i}\quad & C_i(g_i)\\ \text{subject to}\quad & \mathbf{1}^\intercal(d_i-g_i)\pm q=0, && (\lambda_i)\\ & S_i(d_i-g_i)\pm T_i q\le F_i. && (\mu_i)\end{aligned}$$

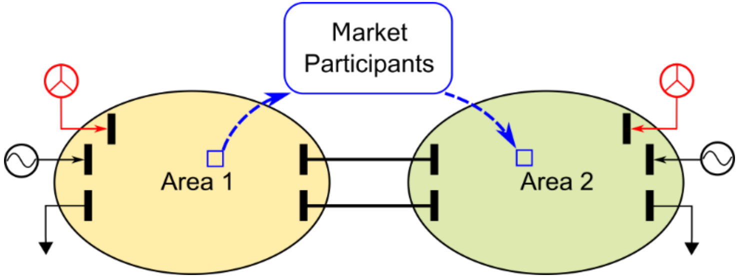
$$\pi_i(q,d_i)\triangleq\lambda_i(q,d_i)+(T_i)^\intercal\mu_i(q,d_i)$$

Theorem 2

Interface-by-Interface Scheduling (IBIS) Algorithm generates a sequence $\{q^{(k)}\}_{k=0}^{\infty}$ that converges to the global optimal solution.

Generalized CTS

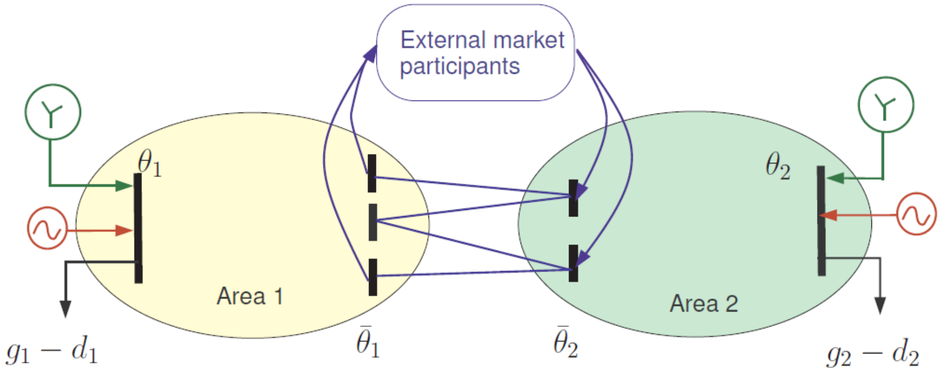
- Key shortcomings of CTS
  - Inaccurate proxy bus approximations.
  - Loop flow causing security violation and loss.
  - Lack of revenue adequacy guarantee.
  - Difficult to deal with multiple interfaces (> 2 areas).



- Features of generalized CTS
  - Preserve the CTS market structure and objective
  - Bids define physical tie-line flows (thus eliminate loop flow).
  - Allow asynchronous/asynchronous scheduling of multiple areas.
  - Guarantees revenue adequacy.

- Y. Guo, Y. Ji, and L. Tong, "Coordinated multi-area economic dispatch with interface bids," submitted to IEEE Transactions on Power Systems, (under second review), May 2017. (Conference version at PESGM 2017)

Key idea 1: Preserving the CTS structure

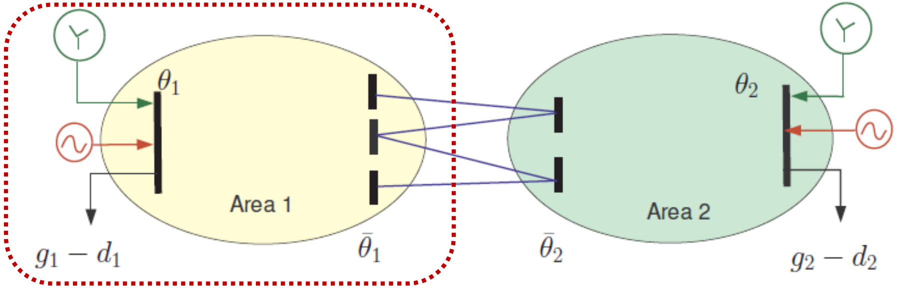


Bid ID	Source	Sink	Quantity
1	B11	B21	[0,50]
2	B12	B22	[0,10]
3	B21	B12	[0,100]
4	B22	B13	[0,60]
:	:	:	:

- Bid-based look-ahead schedule.
  - Allow bids submitted to arbitrary M by N physical buses.
- Bids cleared by minimizing total generation and market costs
- Bids settled by real-time prices (locational).

Key idea 2: bids defined tie-line flows

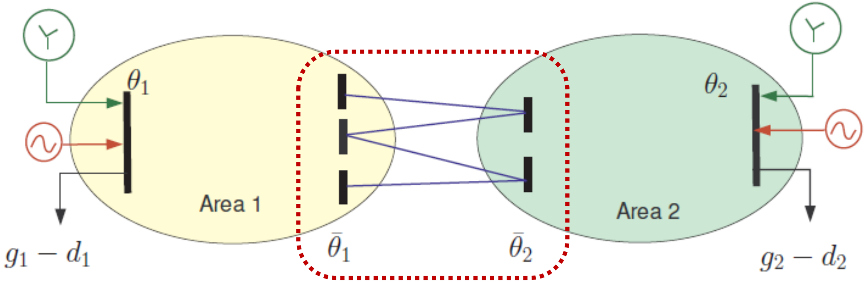
- DC power flow



Power from area 2 — Injection in area 1

$$\begin{bmatrix} Y_{11} & Y_{1\bar{1}} & & \\ Y_{\bar{1}1} & Y_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} & \\ & Y_{\bar{2}\bar{1}} & Y_{\bar{2}\bar{2}} & Y_{\bar{2}2} \\ & & Y_{2\bar{2}} & Y_{22} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \bar{\theta}_1 \\ \bar{\theta}_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} g_1 - d_1 \\ 0 \\ 0 \\ g_2 - d_2 \end{bmatrix}$$

- Tie-line power flow: KCL on the boundary

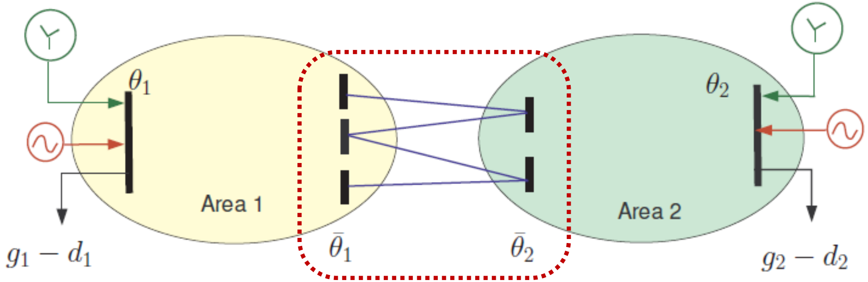


Power from area 2 — Injection at $\bar{\theta}_1$ from area 1

$$\begin{bmatrix} \tilde{Y}_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} \\ Y_{\bar{2}\bar{1}} & \tilde{Y}_{\bar{2}\bar{2}} \end{bmatrix} \begin{bmatrix} \bar{\theta}_1 \\ \bar{\theta}_2 \end{bmatrix} = \begin{bmatrix} -Y_{\bar{1}1} Y_{11}^{-1} (g_1 - d_1) \\ -Y_{\bar{2}2} Y_{22}^{-1} (g_2 - d_2) \end{bmatrix}$$

Key idea 2: Interface bids define tie-line flows

- Tie-line power flows w/o interface bids



Injection at $\bar{\theta}_1$ from area 1

$$\begin{bmatrix} \tilde{Y}_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} \\ Y_{\bar{2}\bar{1}} & \tilde{Y}_{\bar{2}\bar{2}} \end{bmatrix} \begin{bmatrix} \bar{\theta}_1 \\ \bar{\theta}_2 \end{bmatrix} = \begin{bmatrix} -Y_{\bar{1}1}Y_{11}^{-1}(g_1 - d_1) \\ -Y_{\bar{2}2}Y_{22}^{-1}(g_2 - d_2) \end{bmatrix}$$

- Equivalent network with bids

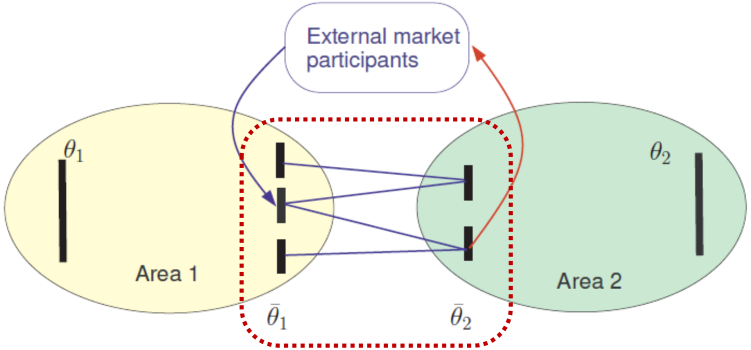
$$\begin{bmatrix} \tilde{Y}_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} \\ Y_{\bar{2}\bar{1}} & \tilde{Y}_{\bar{2}\bar{2}} \end{bmatrix} \begin{bmatrix} \bar{\theta}_1 \\ \bar{\theta}_2 \end{bmatrix} = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} s$$

$$= \left[\begin{array}{c|c|c} \vdots \cdots \vdots & 0 & \vdots \cdots \vdots \\ \vdots \cdots \vdots & 1 & \vdots \cdots \vdots \\ \vdots \cdots \vdots & 0 & \vdots \cdots \vdots \\ \hline \vdots \cdots \vdots & 0 & \vdots \cdots \vdots \\ \vdots \cdots \vdots & -1 & \vdots \cdots \vdots \\ \vdots \cdots \vdots & 0 & \vdots \cdots \vdots \end{array}\right] \begin{bmatrix} \vdots \\ \vdots \\ \vdots \\ s_i \\ \vdots \\ \vdots \\ \vdots \end{bmatrix}$$

Injection @ bus m in Area 1 → (row with 1)

Withdraw @ bus n in Area 2 → (row with −1)

Bid i → s_i



Key idea 3: market clearing & settlement

- Clearing of interface bids

$$\min_{\{g_i, s, \bar{\theta}, \theta_i\}} c(g_i, s) = \sum_{i=1}^{2} c_i(g_i) + \Delta\pi^T s$$

$$\begin{aligned}
\text{subject to } & H_i\theta_i + H_{\bar{i}}\bar{\theta}_i \le f_i,\ i = 1, 2 \\
& \bar{H}_{\bar{1}}\bar{\theta}_1 + \bar{H}_{\bar{2}}\bar{\theta}_2 \le \bar{f} \\
& \check{g}_i \le g_i \le \hat{g}_i,\ i = 1, 2 \\
& 0 \le s \le s_{\max}
\end{aligned}$$

$$\begin{bmatrix} Y_{11} & Y_{1\bar{1}} & & \\ Y_{\bar{1}1} & Y_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} & \\ & Y_{\bar{2}\bar{1}} & Y_{\bar{2}\bar{2}} & Y_{\bar{2}2} \\ & & Y_{2\bar{2}} & Y_{22} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \bar{\theta}_1 \\ \bar{\theta}_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} g_1 - d_1 \\ 0 \\ 0 \\ g_2 - d_2 \end{bmatrix}$$

$$\begin{bmatrix} \tilde{Y}_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} \\ Y_{\bar{2}\bar{1}} & \tilde{Y}_{\bar{2}\bar{2}} \end{bmatrix} \begin{bmatrix} \bar{\theta}_1 \\ \bar{\theta}_2 \end{bmatrix} = \begin{bmatrix} M_1 s \\ M_2 s \end{bmatrix}$$

Tie-line flow constraint

Y. Guo, L. Tong, et. al., "Coordinated multi-area economic dispatch via critical region projection," *IEEE Trans. Power Systems*, vol PP, no. 99, 2017

- Settlement of interface bids

$$\min_{\{g_1, \theta_1, \bar{\theta}\}} c_1^R(g_1),$$

$$\begin{aligned}
\text{subject to } & H_1\theta_1 + H_{\bar{1}}\bar{\theta}_1 \le f_1 && (\eta_1^R) \\
& \check{g}_1 \le g_1 \le \hat{g}_1,\ i = 1, 2 && (\rho_1)
\end{aligned}$$

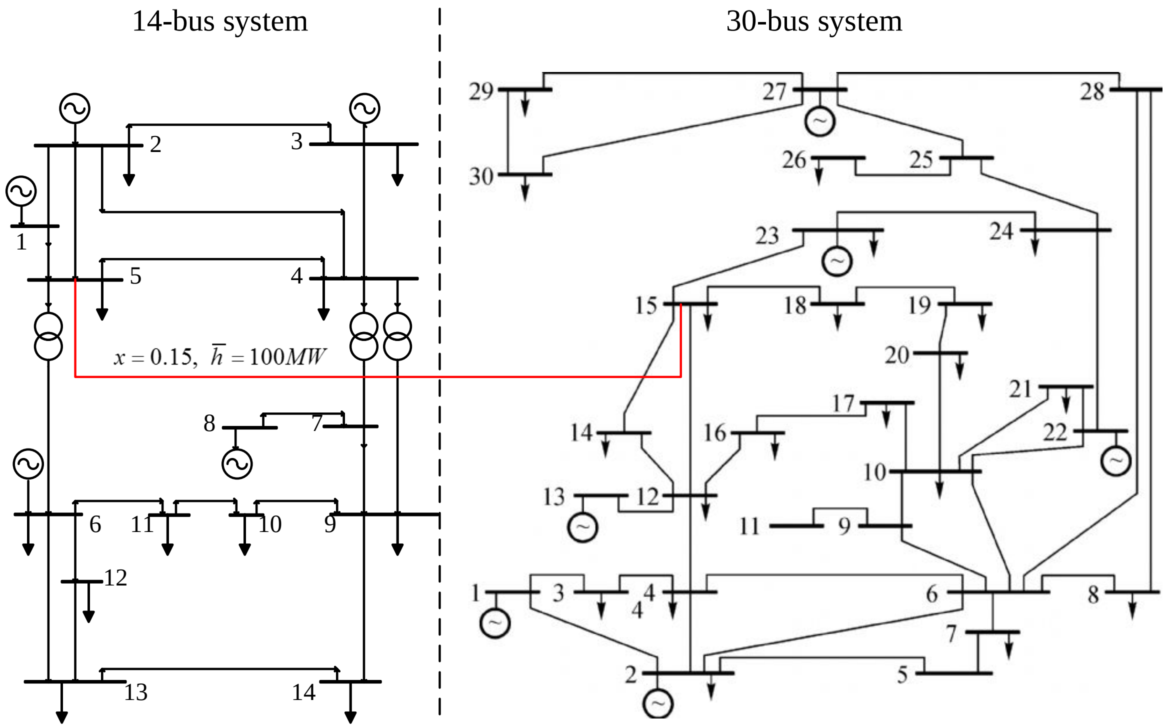
$$\begin{bmatrix} Y_{11} & Y_{1\bar{1}} & \\ Y_{\bar{1}1} & Y_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \bar{\theta}_1 \\ \bar{\theta}_2 \end{bmatrix} = \begin{bmatrix} g_1 - d_1^R \\ 0 \end{bmatrix} \quad \begin{matrix} (\lambda_1^R) \\ (\bar{\lambda}_1^R) \end{matrix}$$

$$\begin{bmatrix} \tilde{Y}_{\bar{1}\bar{1}} & Y_{\bar{1}\bar{2}} \\ Y_{\bar{2}\bar{1}} & \tilde{Y}_{\bar{2}\bar{2}} \end{bmatrix} \begin{bmatrix} \bar{\theta}_1 \\ \bar{\theta}_2 \end{bmatrix} = \begin{bmatrix} M_1 s^* \\ M_2 s^* \end{bmatrix} \quad \begin{matrix} (\mu_1^{R1}) \\ (\mu_2^{R1}) \end{matrix}$$

Tie-line flow constraint

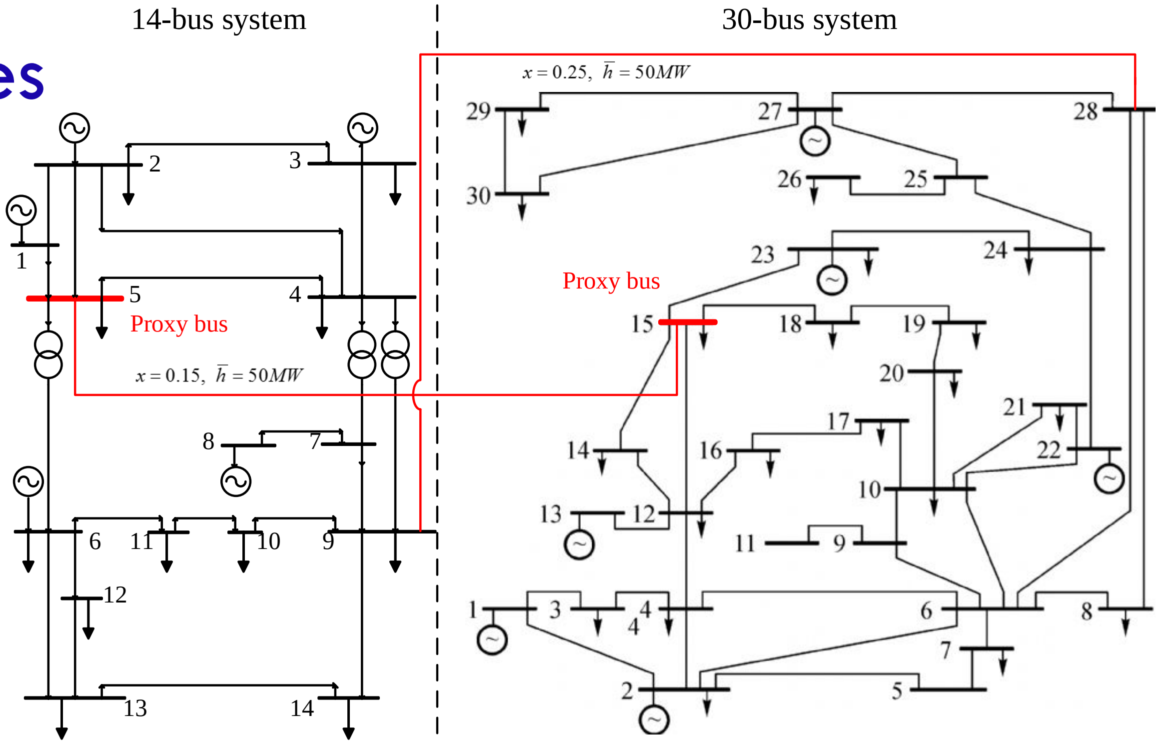
Theorem (revenue adequacy) The net revenue for each area is equal to the congestion rent.

Example 1: single tie line



- JED = CTS = GCTS

Example 2: two tielines



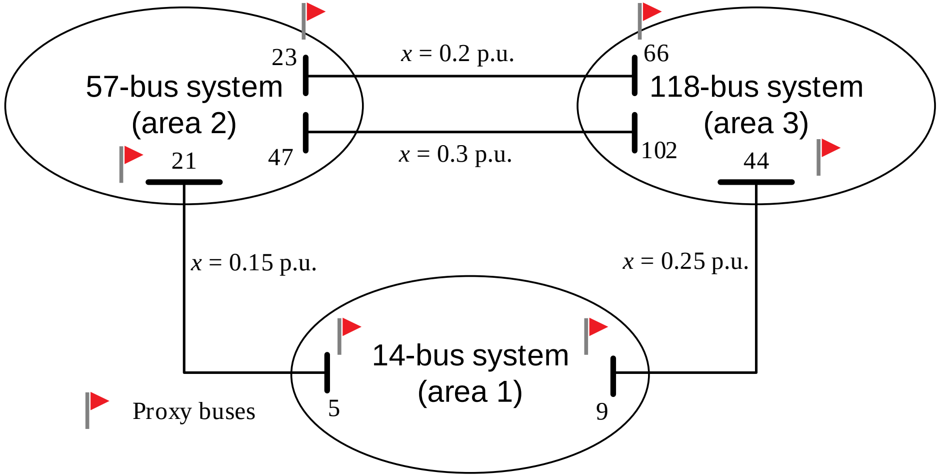
- Default cost coefficients, no internal congestion
- Bids: price 0.1/ max quantity 100MW

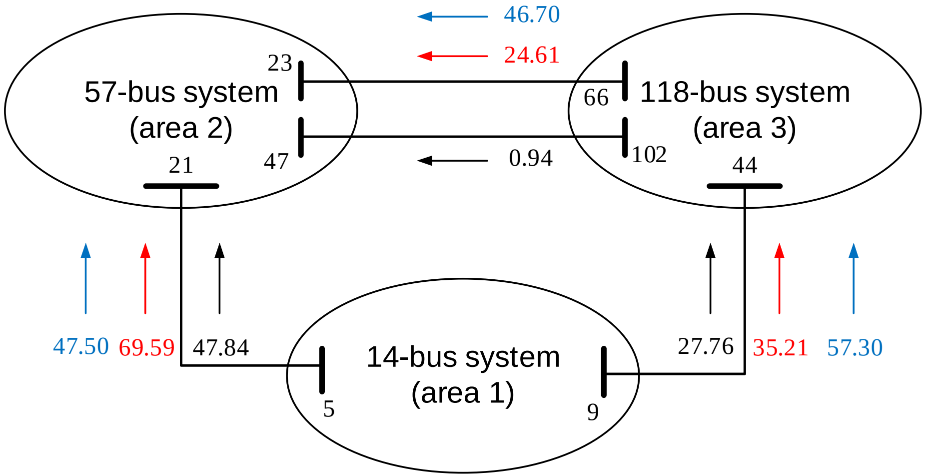
- Loop flow in CTS:
  - Area 1, 16.17MW;
  - Area 2, 15.43MW.

	JED	CTS	G-CTS
Net Inter.	93.4	80.3	93.3
Total cost	3880.6	4115.6	3890.0

Example 3: Three areas

Blue: CTS scheduled
Red: CTS actual
Black: GCTS actual



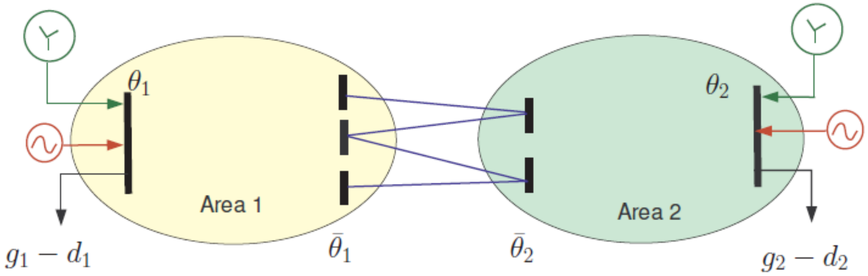


- Bids at proxy buses @ 0.5/MW-h, 100MW.
- Internal flow constraints.
- Pairwise scheduling of CTS

	JED	CTS	GCTS
Total cost	-1.255×10^5	1.262×10^5	1.257×10^5
Gen cost	1.255×10^5	1.261×10^5	1.257×10^5

- CTS has 6 flow constraint violations.
- Loop flow (CTS): 4.58%/29.98%/6.52%

Multi-area interchange via robust optimization



$$\begin{bmatrix} Y_{11} & Y_{1\bar1} & & \\ Y_{\bar11} & Y_{\bar1\bar1} & Y_{\bar1\bar2} & \\ & Y_{\bar2\bar1} & Y_{\bar2\bar2} & Y_{\bar22} \\ & & Y_{2\bar2} & Y_{22} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \bar\theta_1 \\ \bar\theta_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} g_1 - d_1 \\ 0 \\ 0 \\ g_2 - d_2 \end{bmatrix}$$

$$\begin{aligned} \text{minimize} \quad & c_1^\top x_1 + c_2^\top x_2, \\ \text{subject to} \quad & A_1^x x_1 + A_1^\xi \xi_1 + A_1^y y \le b_1, \\ & A_2^x x_2 + A_2^\xi \xi_2 + A_2^y y \le b_2, \\ & y \in \mathcal{Y}. \end{aligned}$$

$$\equiv \underset{y \in \mathcal{Y}}{\text{minimum}} \ \left[J_1^*(y, \xi_1) + J_2^*(y, \xi_2) \right]$$

Robust Problem: $$\underset{y \in \mathcal{Y}}{\text{minimum}} \left[\left(\underset{\xi_1 \in \Xi_1}{\text{maximum}} \ J_1^*(y, \xi_1) \right) + \left(\underset{\xi_2 \in \Xi_2}{\text{maximum}} \ J_2^*(y, \xi_2) \right) \right]$$

- Y. Guo, S. Bose, and L. Tong, "Robust tie-line scheduling in multi-area power systems," submitted to IEEE Transactions on Power Systems, Apr, 2017.

Deliverables and remaining schedule

- Publications
  - IEEE Transactions on Power Systems (TPS): 3 appeared, 3 under review,1 to be submitted by the end of August.
  - 9 conference papers (PESGM, ACC, HICSS). 1 best paper award, 1 best paper nomination.
  - Probabilistic forecasting simulation tools.

- Remaining schedule:
  - Industrial collaborations: PJM (6/29), NYISO (6/23), ISONE (?), PNNL (8/?)
  - Simulation studies on impacts of loop flows
  - Publications: Journal & PESGM submissions

Looking ahead

- Machine learning approach to operation forecasting
  - From market operation to system operation: incorporating probabilistic AC power flow.
  - PROFS: PRobabilistic Online Forecasting and Simulations
- Stochastic and robust multi-area operation
  - Understanding impacts of stochastic loop flow on cost, reliability, and market design
  - Extensions to micro-grid operations

Publications: archival journal

- Y. Ji, R. J. Thomas, L. Tong, "Probabilistic forecasting of real-time LMP and network congestion," *IEEE Trans. Power Systems*, vol 32, no. 2, March, 2017
- Y. Ji, T. Zheng, and L. Tong, "Stochastic Interchange Scheduling in the Real-Time Electricity Market," *IEEE Trans. Power Systems*, vol 32, no. 3, March, 2017
- Y. Guo, L. Tong, et. al., "Coordinated multi-area economic dispatch via critical region projection," *IEEE Trans. Power Systems*, vol PP, no. 99, 2017
- Y. Ji and L. Tong, "Multi-area interchange scheduling under uncertainty," submitted to IEEE Transactions on Power Systems, (under second round review), Mar 2017
- Y. Guo, S. Bose, and L. Tong, "Robust tie-line scheduling in multi-area power systems," submitted to IEEE Transactions on Power Systems, Apr, 2017.
- Y. Guo, Y. Ji, and L. Tong, "Coordinated multi-area economic dispatch with interface bids," submitted to IEEE Transactions on Power Systems, (under second review), June 2017

Publications: conferences

- Y. Guo, Y. Ji, and L. Tong, "Incorporating Interface Bids in the Economic Dispatch for Multi-area Power Systems," IEEE PESGM, July 2017.
- Y. Guo, Y. Ji, and L. Tong, "Robust tie-line scheduling for multi-area power systems with finite-step convergence," IEEE PESGM, July 2017.
- Y. Guo, L. Tong, T. Doan, C. Beck, and S. Bose, "Tie-line scheduling in power networks: an adjustable robust framework," 2017 Information Theory & Applications Workshop, Feb, 2017
- Weisi Deng, Yuting Ji, and Lang Tong, "Probabilistic forecasting and simulation of electricity markets via online dictionary learning," Proc the 50th Hawaii International Conf on System Sciences (HICSS), January 4-7, 2017. Best paper award.
- Y. Ji and L. Tong, "Multi-proxy interchange scheduling under uncertainty," IEEE Power & Energy Society General Meeting (PESGM), 2016. Best paper nomination.
- G. Ye, L. Tong, et. al., "Multi-area economic dispatch via state space decomposition," IEEE American Control Conf. (ACC), 2016
- Y Ji, R.J. Thomas, and L. Tong, "Probabilistic Forecast of Real-Time LMP via Multiparametric Programming," 2015 48th Hawaii International Conference on System Sciences (HICSS), 2015.
- Y. Ji and L. Tong, "Stochastic coordinated transaction scheduling via probabilistic forecasting," IEEE Power & Energy Society General Meeting (PESGM), 2015.
- G. Ye, L. Tong, et. al., "Coordinated multi-area economic dispatch via multi-parametric programming," IEEE Power & Energy Society General Meeting (PESGM), 2015.