

Evaluation of Alternative Market Structures and Compensation Schemes for Incenting Transmission Reliability and Adequacy Related Investments

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For PSERC members only**

Project Team



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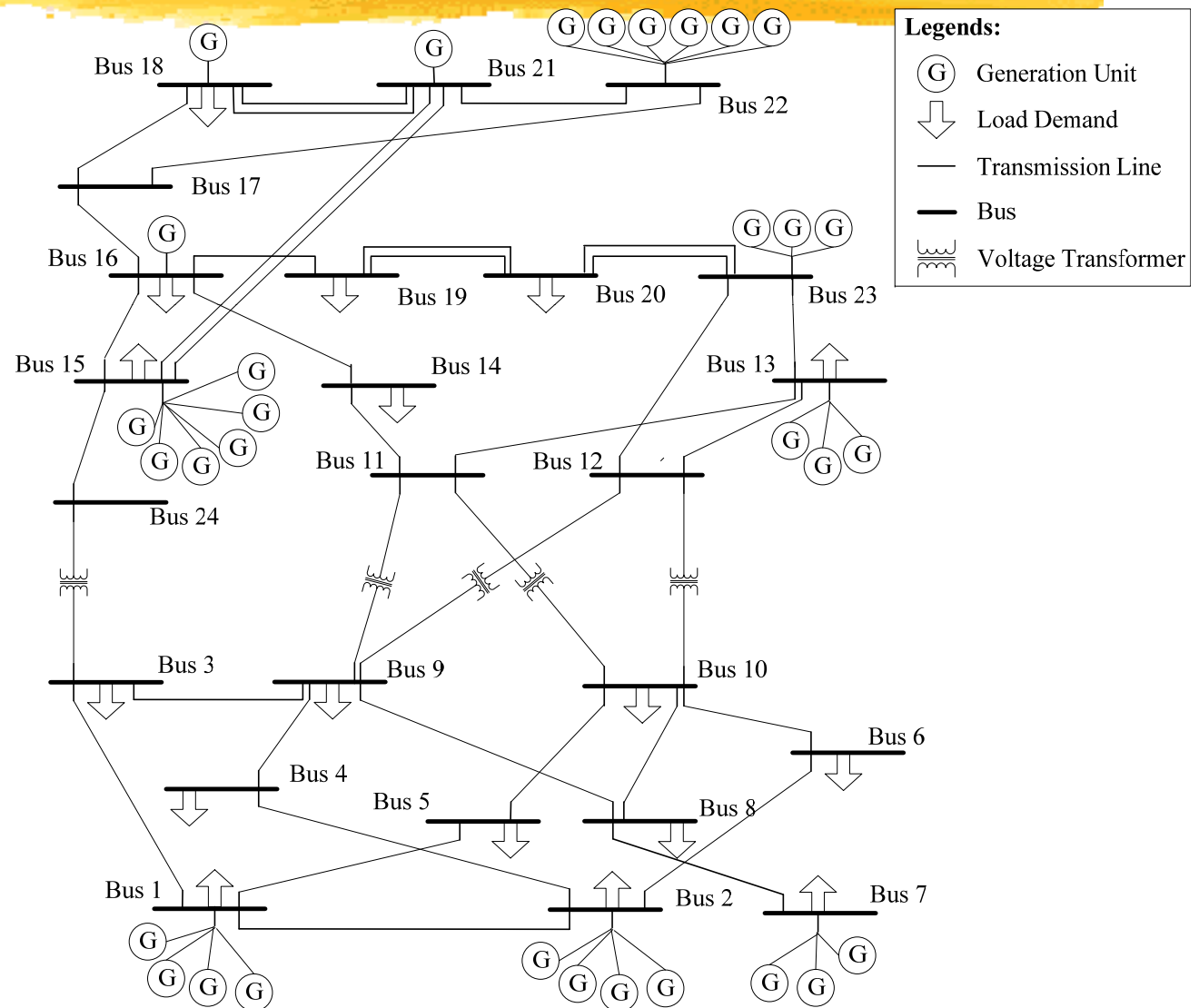
Outline



- Power system simulation modeling
- Econometric modeling of Transmission Congestion Contracts
- Forward price risk premium and implications for transmission investments
- Nonparametric modeling of the Hub-and-Spoke Representation of a Network
- Inherent inefficiency of FTR auctions

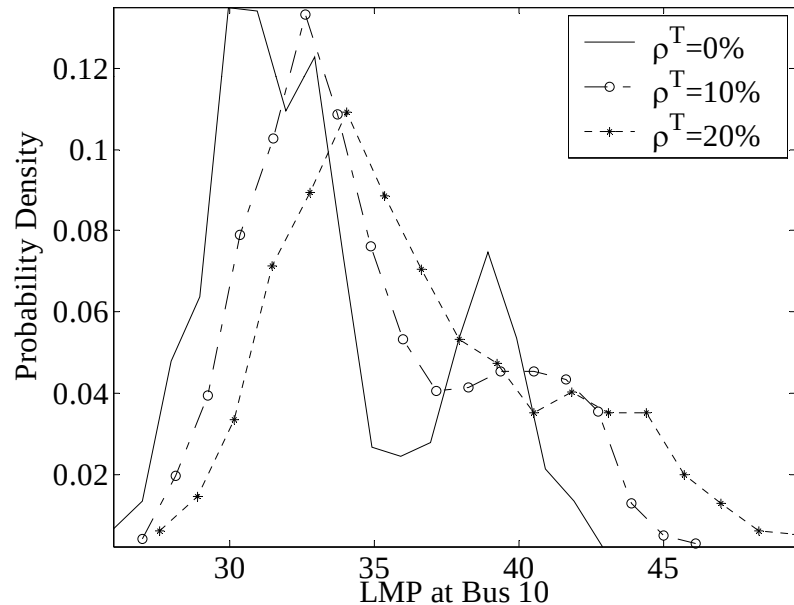
Power system simulation

- Built on PSerc project M-6.
- Market dispatch optimal power flow formulation
- Computations based on IEEE-RTS 24 System



Power system simulation — LMPs and evaluation of reliability constraints

- Incorporating constraints on transmission reliability margin (TRM) and generation reserve margin



Probability distributions of LMPs at bus 10 over the sample year with different TRMs requirements

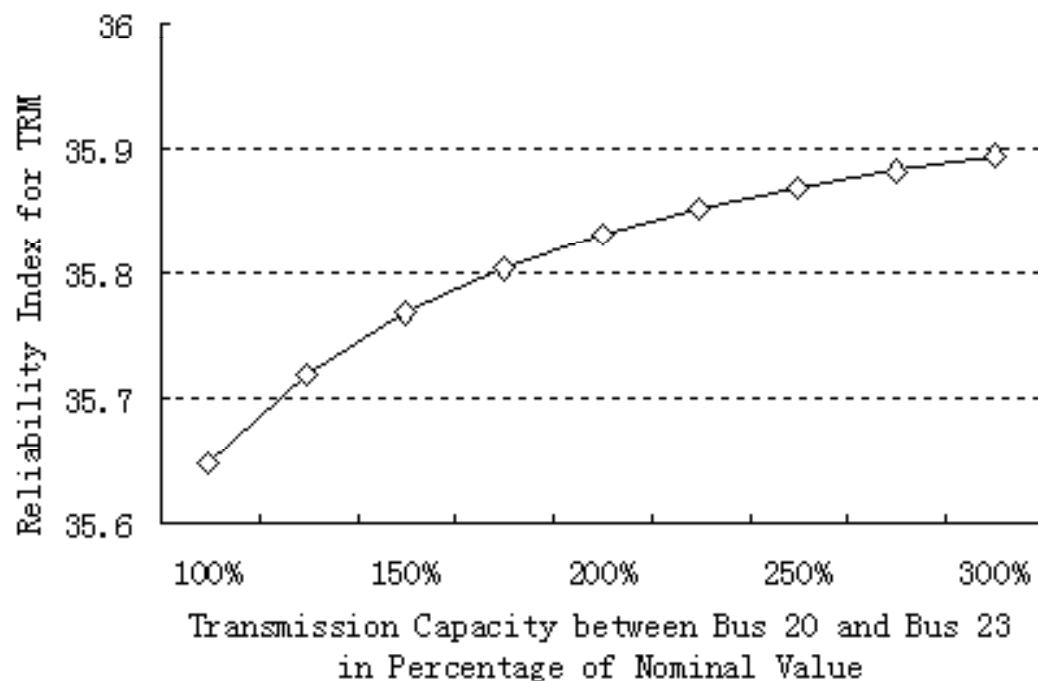
0% TRM	10% TRM	20% TRM
4.02	4.67	5.12

Averaged spatial volatility of LMPs over the sample year when imposing different TRM requirements in the market dispatch (\$/MWh)



Power system simulation — Identification of transmission adequacy and reliability needs

- Sensitivity of reliability index for system transmission reliability margin



Power system simulation — Effectiveness of Transmission Compensation

- A case study: allocation of incremental FTRs

$$\text{Max}_{\delta} b\delta$$

$$\text{s.t. } FP \leq T$$

$$F^+(P + \delta) \leq T^+$$

b : bid preference parameter, $b_{20,23} = 60$, $b_{22,21} = 10$

F and F^+ : system PTDF matrices before and after expansion

T and T^+ : transmission capacity limits

P : existing amounts of FTRs, $P_{20,23} = 529.1$, $P_{22,21} = 300$

δ : amounts of incremental FTRs

Power system simulation — Effectiveness of Transmission Compensation

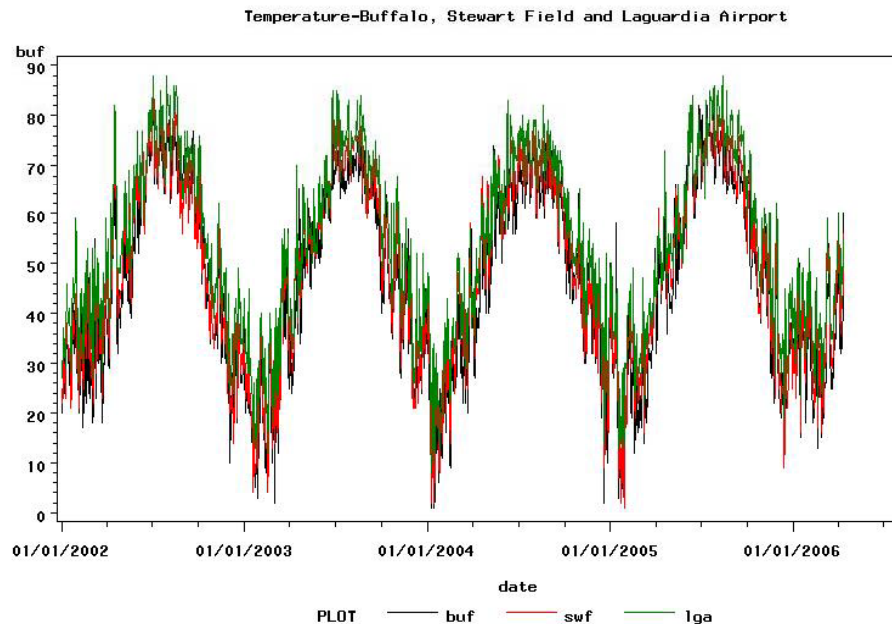
- Increase the capacity between bus 20-bus 23 to 150%, so reliability index is above 35.87
- Optimal incremental FTRs solved:
$$\delta_{20,23} = 264.8, \delta_{22,21} = 57.8$$
- Fully allocate capacities: bus 20-bus 23, bus 22-bus 21
- FTR revenues collected:
bus 20-bus 23 increases 4%, bus 22-bus 21 increases 16%
- The magnitude of incentives depends on
 - Amount of incremental FTRs
 - Bid values
 - Transmission network topology
 - Initial configuration of the allocated FTRs

Econometric modeling of TCCs — Introduction

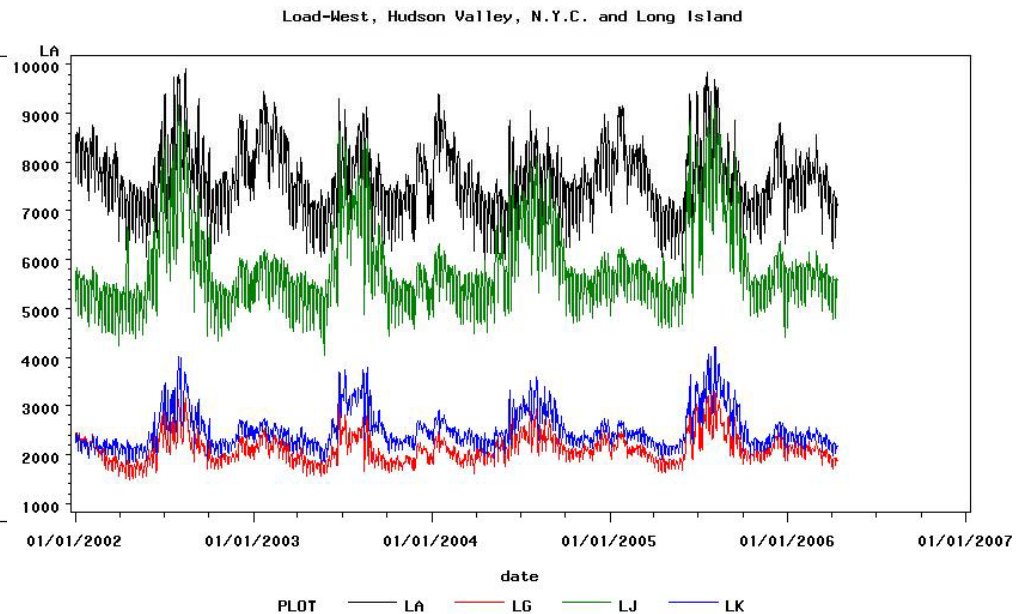
- Price of electricity is a function of
 - The corresponding load
 - Price of natural gas
 - A set of seasonal and daily variables
- Multivariate time-series models were estimated for
 - Daily temperature in different locations
 - Average daily loads in different zones conditional on HDD, CDD, seasonal cycles and dummy variables
 - Prices of electricity in different zones

Econometric modeling of TCCs —

Data used



Daily Temperature Data for Three Locations in New York State



Daily Load Data for Four Locations in New York State

Econometric modeling of TCCs —

The Econometric Results



- Use the estimated models to predict the average daily prices in New York for the summer of 2006

Simulated Payouts from Four Different Six-Month TCCs for the Summer 2006

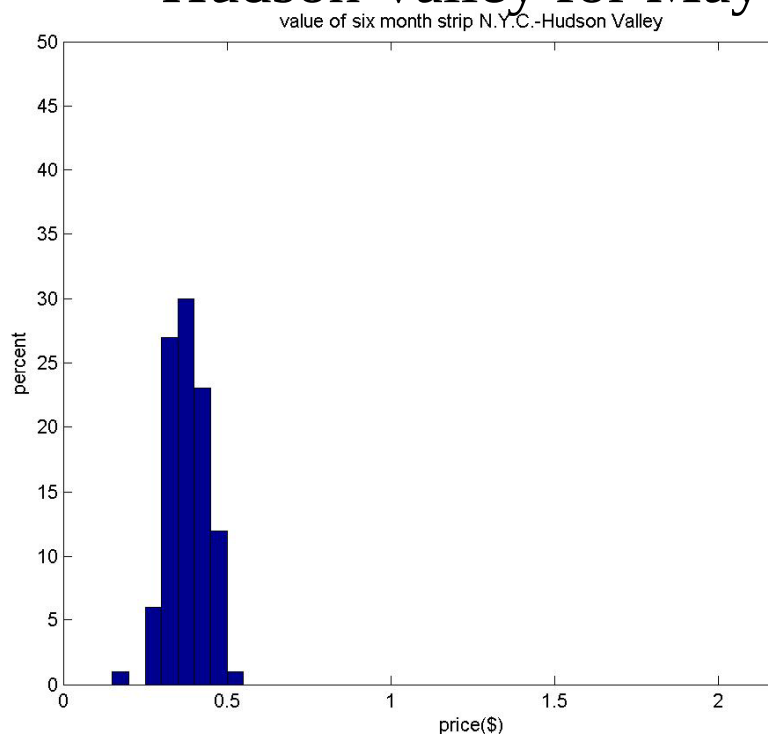
Simulation Results (\$/MW)

Sim1 (Hedgers)		Zones A-G	Zones A-J	Zones G-J	Zones J-K
Actual payout May-October 2006	LBMP	60,543.1	97,394.4	36,851.3	67,281.1
	Loss	1,698.1	1,864.1	166.0	140.3
	C.C.	58,845.0	95,530.3	36,685.3	67,140.8
Simulated payouts LBMP	max	72,021.0	108,880.8	50,574.4	74,419.7
	mean	52,000.8	89,706.5	37,705.7	48,333.1
	median	52,051.0	90,622.3	37,856.7	47,461.4
	min	37,079.5	68,974.3	17,080.3	27,908.9

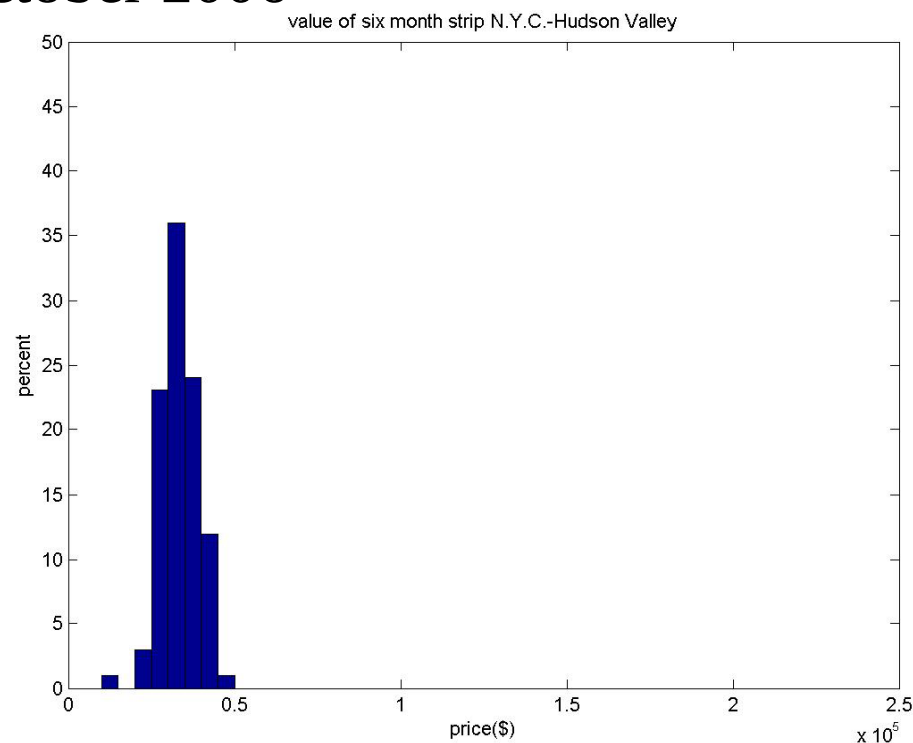
Sim2 (Speculators)		A-G	A-J	G-J	J-K
Actual payout May-October 2006	LBMP	60,543.1	97,394.4	36,851.3	67,281.1
	Loss	1,698.1	1,864.1	166.0	140.3
	C.C.	58,845.0	95,530.3	36,685.3	67,140.8
Simulated payouts LBMP	max	67,501.7	100,596.8	45,393.3	74,000.7
	mean	48,907.0	82,401.0	33,494.0	49,236.2
	median	48,829.6	83,005.9	33,678.5	48,405.5
	min	34,767.9	63,205.6	14,342.5	30,194.3

Econometric modeling of TCCs — The Econometric Results

- Simulated LBMP Payouts for a TCC between NYC and the Hudson Valley for May-October 2006



Hedgers using Actual Forward
Prices for Natural Gas



Speculators using Simulated
Realizations of the Price for
Natural Gas

Hub-and-Spoke Representation — Local Linear Embedding (LLE)

1. Identify the k nearest neighbors based on Euclidean distance for each data point $x_i, 1 < i < N$. Let N_i denote the indices of the k nearest neighbors of the vector x_i .
2. Find the optimal local convex combinations of the k nearest neighbors to represent each original vector. Minimize

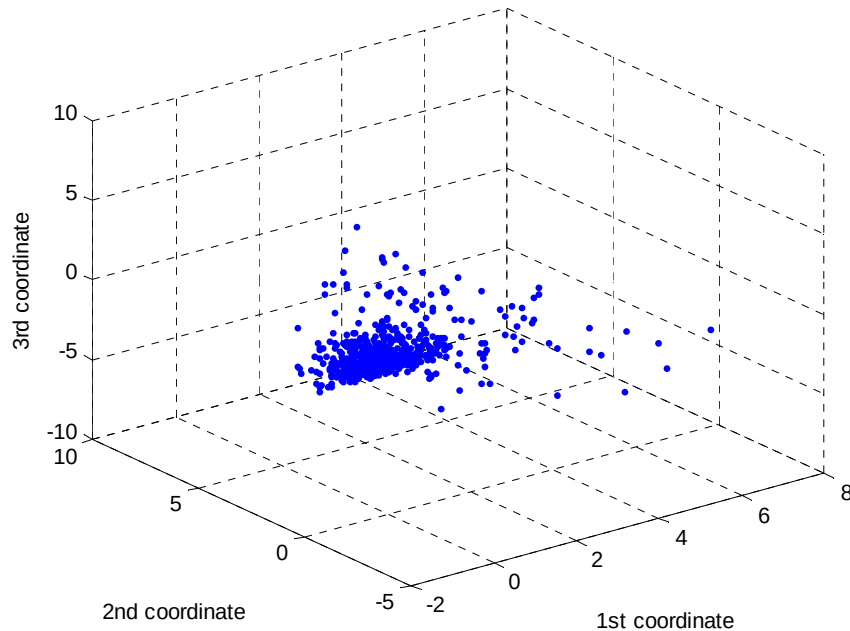
$$E(w) = \sum_i |x_i - \sum_{j \in N_i} w_{ij} x_j|^2. \quad (2)$$

3. Find the representations in the low dimensional space, such that the above local convex representations are best preserved. Minimize

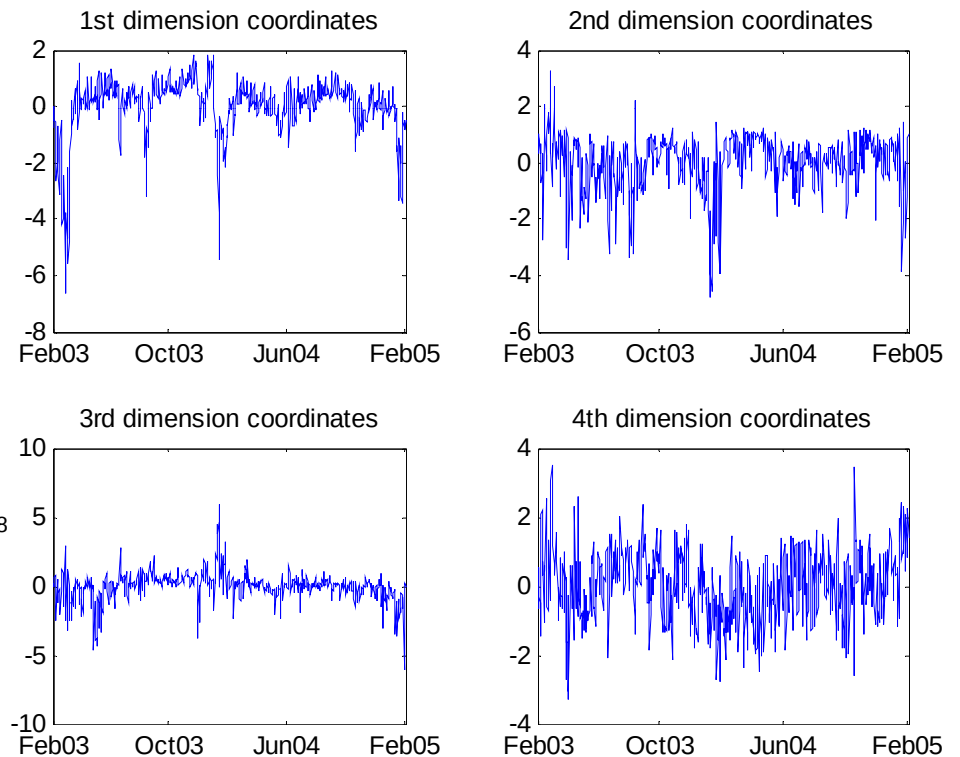
$$\Phi(y) = \sum_i |y_i - \sum_{j \in N_i} w_{ij} y_j|^2. \quad (3)$$

Hub-and-Spoke Representation — Low Dimensional Space

Embedded three-dimensional
manifold after LLP smoothing



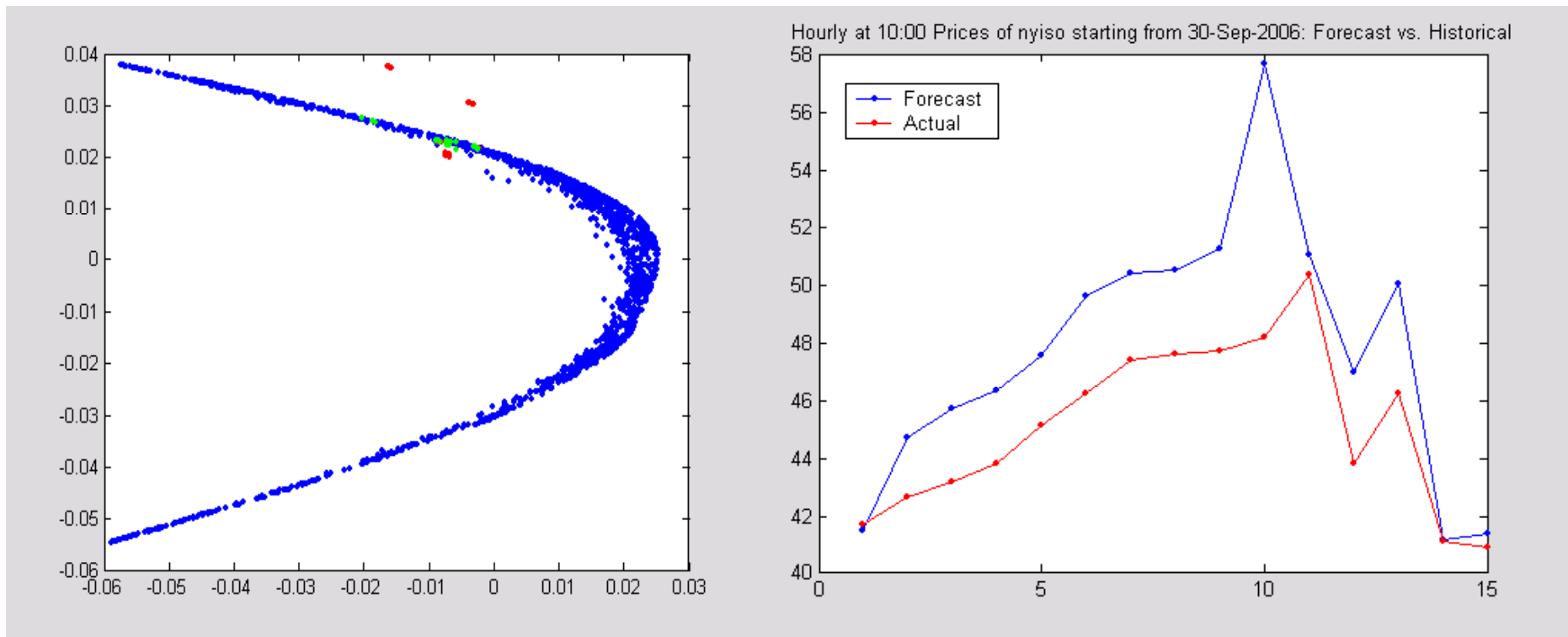
Coordinates of the embedded 4
dimensional manifold



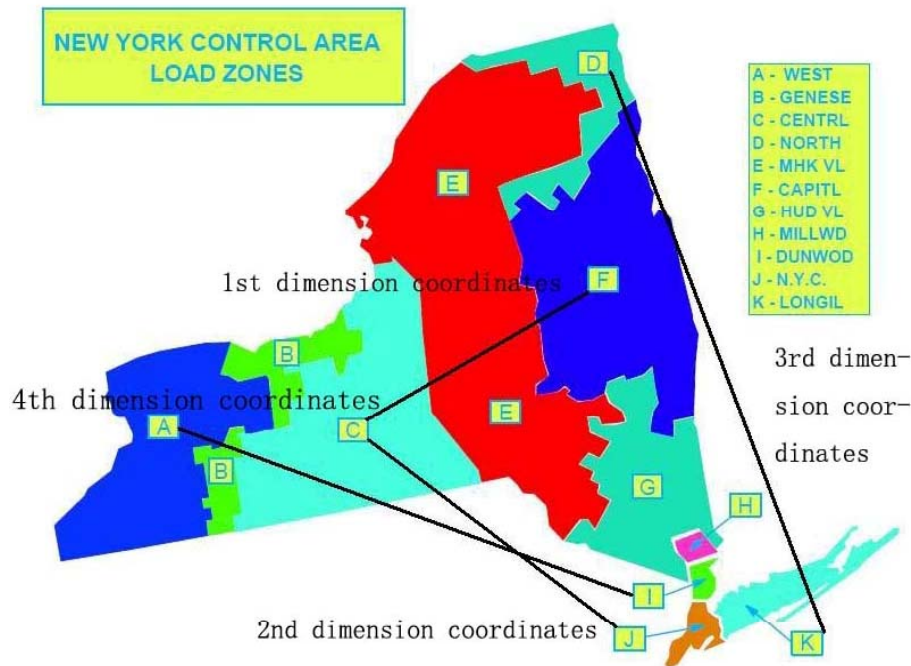
Hub-and-Spoke Representation — Low Dimensional Space

- Embedded 2-dimensional manifold after LLP smoothing

LMP curve of New York ISO: actual vs. forecast



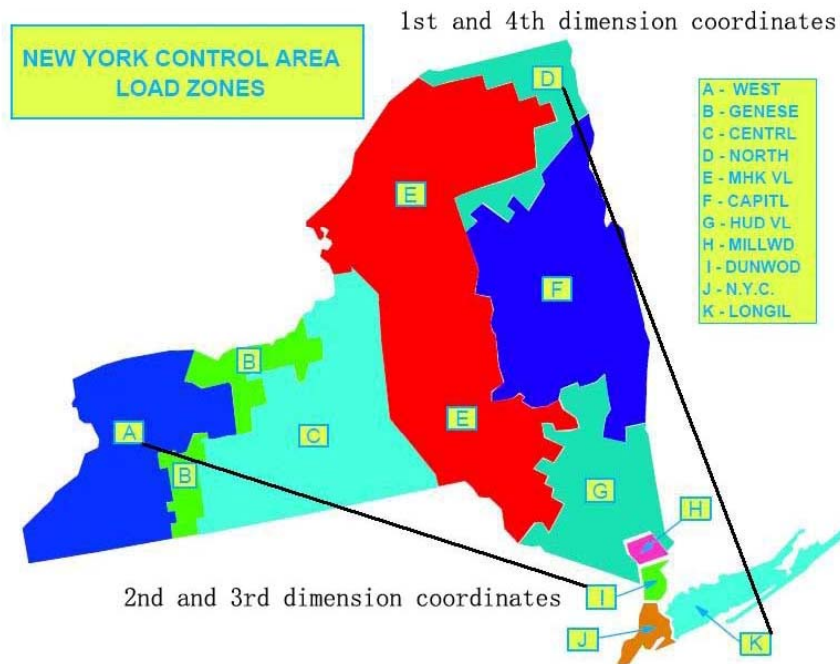
Hub-and-Spoke Representation — Each Coordinate in Low Dimensional Space



Correlation coefficient of the four-dimensional
Coordinates with the four FTRs

Coordinate	1 st	2 nd	3 rd	4 th
FTR	CENTRL to CAPITL	CENTRL to NYC	NORTH to LONGIL	WEST to DUNWOD
Correlation Coefficient	0.684	0.8166	0.7245	-0.6208

Hub-and-Spoke Representation — Each Coordinate in Low Dimensional Space

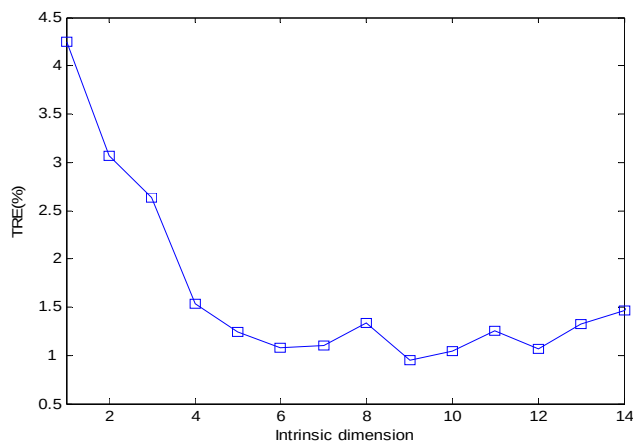


Correlation coefficient of the four-dimensional
Coordinates with the two FTRs

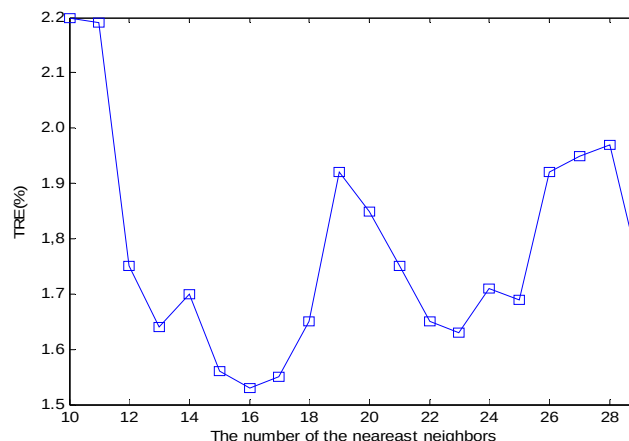
Coordinate	1 st	2 nd	3 rd	4 th
FTR	WEST to DUNWOD	CENTRL to LONGIL	CENTRL to LONGIL	WEST to DUNWOD
Correlation Coefficient	0.6316	0.8166	0.7245	-0.6208

Hub-and-Spoke Representation — Parameter Setting and Sensitivity Analysis

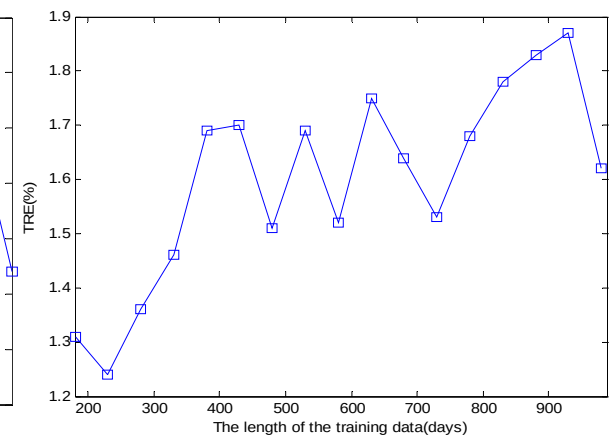
TRE vs. number of
intrinsic dimensions



TRE vs. number of
data in training set

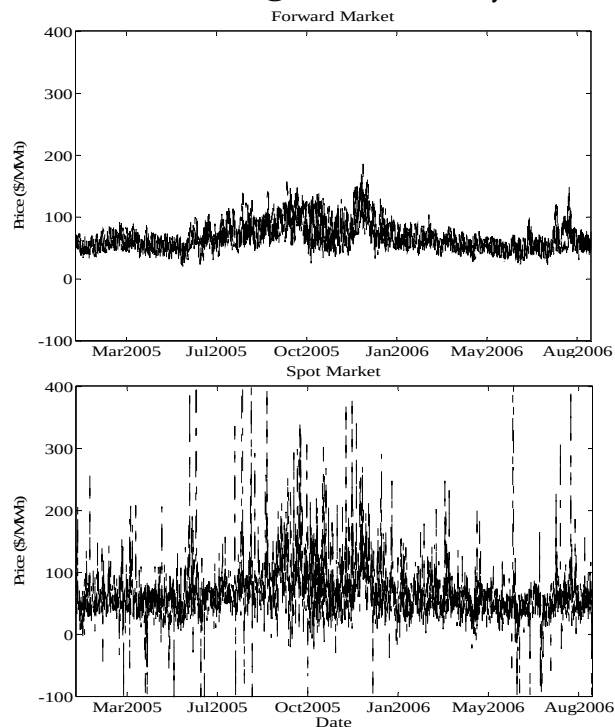


TRE vs. number of
nearest neighbors



Forward price risk premium — Problem Description

Reference bus @ NY electricity market



Statistics of LBMPs in NYISO

Zone	Forward Market		Spot Market		Forward Premium
	Mean	Volatility	Mean	Volatility	
Ref. Bus	66.99	21.95	63.67	40.72	3.32
CAPITL	74.67	25.11	69.82	45.43	4.85
CENTRL	63.72	21.95	61.46	41.29	2.26
DUNWOD	79.78	27.26	73.78	48.06	6.00
GENESE	60.48	21.30	58.89	41.64	1.59
HUD VL	78.38	26.64	73.17	47.87	5.21
LONGIL	82.76	27.88	76.26	48.76	6.50
MHK VL	68.19	22.67	65.79	43.35	2.41
MILLWD	79.79	27.35	73.58	48.03	6.20
N.Y.C.	83.42	29.25	76.24	49.85	7.18
NORTH	63.72	20.64	61.72	39.41	1.99
WEST	54.42	20.38	53.64	38.81	0.78

- High volatility, especially in real-time spot market
- Existence of day-ahead forward risk premiums
- Transmission structure and transmission congestion
- To understand the composition of day-ahead forward risk premiums

Forward price risk premium — Model Assumptions

- Two-stage model
- Forward market: uncertain load and spot price
- Spot market: accurate forecast of load and price in the immediate future
- No speculators
- The wholesale market participants: GENs and LSEs only
- Risk averse GENs and LSEs: mean-variance utility functions

$$U_G(G_i^S, G_i^F) = E[u(\pi(\omega))] = E[\pi(\omega)] - \frac{A_G}{2} \text{Var}(\pi(\omega))$$

$$U_L(L_j^S, L_j^F) = E[u(\pi(\omega))] = E[\pi(\omega)] - \frac{A_L}{2} \text{Var}(\pi(\omega))$$

- DC power flow
- Transmission network constraints
- Fixed set of active transmission constraints

Forward price risk premium — Time Sequence of the Decision Problems

GENs

Choose $[G_1^F, G_2^F]$
to maximize expected utility

LSEs

Choose $[L_2^F, L_3^F]$
to maximize expected utility

ISO

Balance demand and supply
and determine forward prices
 $[P_1^F, P_2^F, P_3^F]$

Stage 1

Day-ahead forward market

GENs

Given $[G_1^{F*}, G_2^{F*}]$
choose $[G_1^S, G_2^S]$
by maxing profit

LSEs

Buy $[L_2^S, L_3^S]$ to
serve residual demand

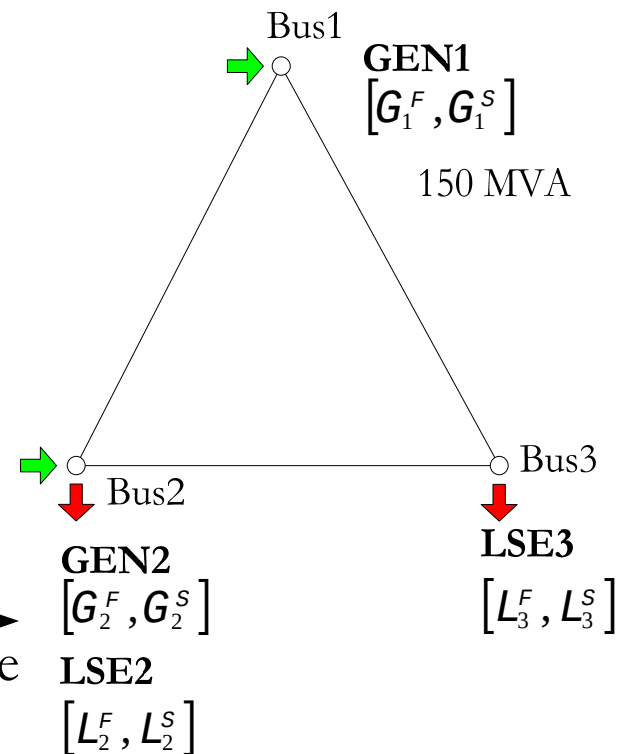
ISO

Balance demand and
supply and determine
spot prices $[P_1^S, P_2^S, P_3^S]$

Stage 2

Real-time spot market

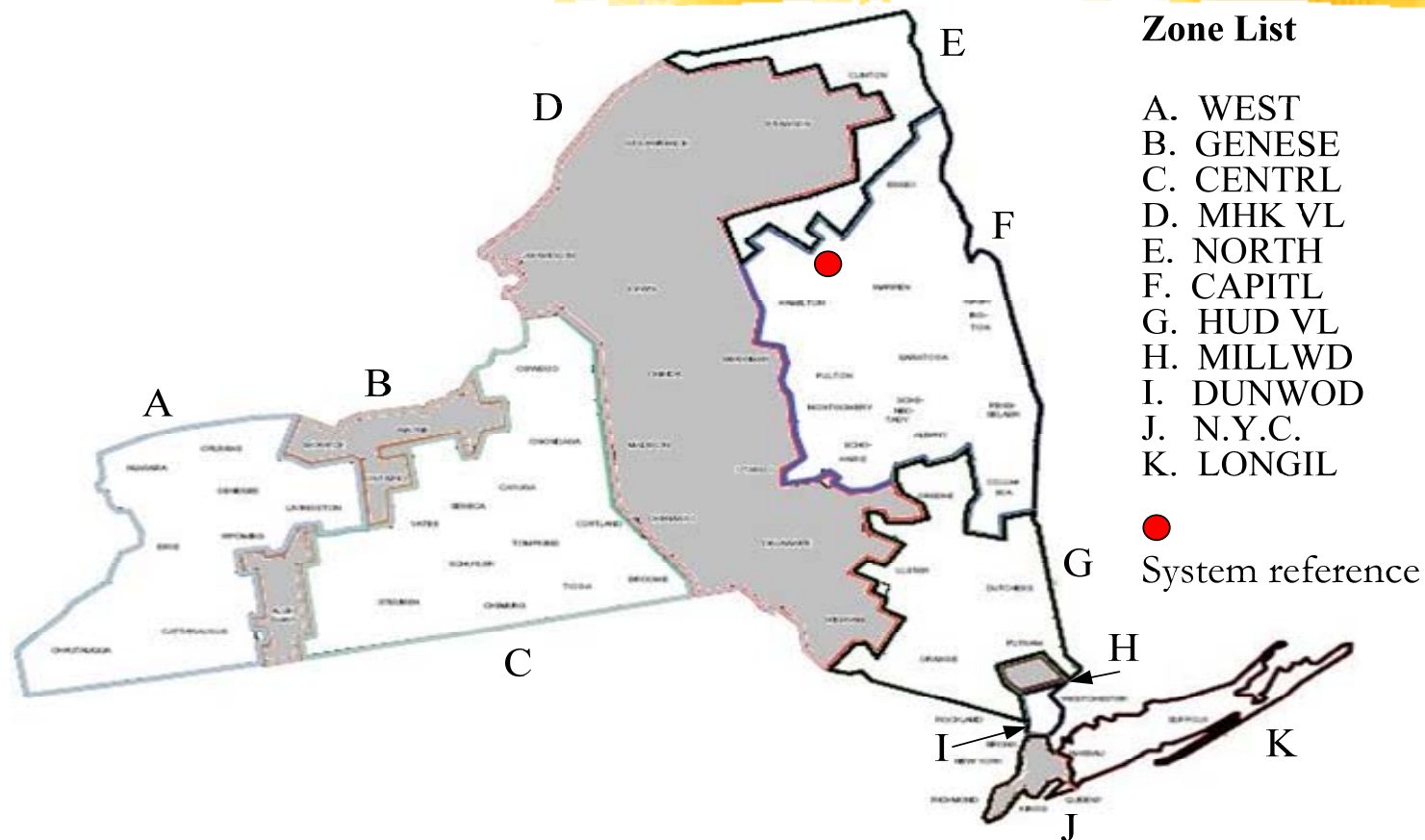
Time Line



Forward price risk premium — Quantitative Model of Forward Premiums

$$\begin{aligned}
 & (P_2^F - E[P_2^S]) \cdot \left(\frac{1}{A_g \text{Var}(P_1^{S*}(\varpi))} + \frac{1}{A_g \text{Var}(P_2^{S*}(\varpi))} + \frac{1}{A_L \text{Var}(P_2^{S*}(\varpi))} + \frac{1}{A_L \text{Var}(P_3^{S*}(\varpi))} \right) \\
 & \text{(forward risk premium term)} \\
 & = (\lambda^F - E[\lambda^S]) \cdot \left(\frac{1/3}{A_g \text{Var}(P_1^{S*}(\varpi))} + \frac{0}{A_g \text{Var}(P_2^{S*}(\varpi))} + \frac{0}{A_L \text{Var}(P_2^{S*}(\varpi))} + \frac{-1/3}{A_L \text{Var}(P_3^{S*}(\varpi))} \right) \\
 & \text{(flowgate shadow price forward premium term)} \\
 & - \left(\frac{\text{Cov}(\rho_1^g(\varpi), P_1^{S*}(\varpi))}{\text{Var}(P_1^{S*}(\varpi))} + \frac{\text{Cov}(\rho_2^g(\varpi), P_2^{S*}(\varpi))}{\text{Var}(P_2^{S*}(\varpi))} \right) \\
 & \text{(covariance between LSEs' un-hedged profit and the spot market price term)} \\
 & - \left(\frac{\text{Cov}(\rho_2^L(\varpi), P_2^{S*}(\varpi))}{\text{Var}(P_2^{S*}(\varpi))} + \frac{\text{Cov}(\rho_3^L(\varpi), P_3^{S*}(\varpi))}{\text{Var}(P_3^{S*}(\varpi))} \right) \\
 & \text{(covariance between GPs' un-hedged profit and the spot market price term)}
 \end{aligned}$$

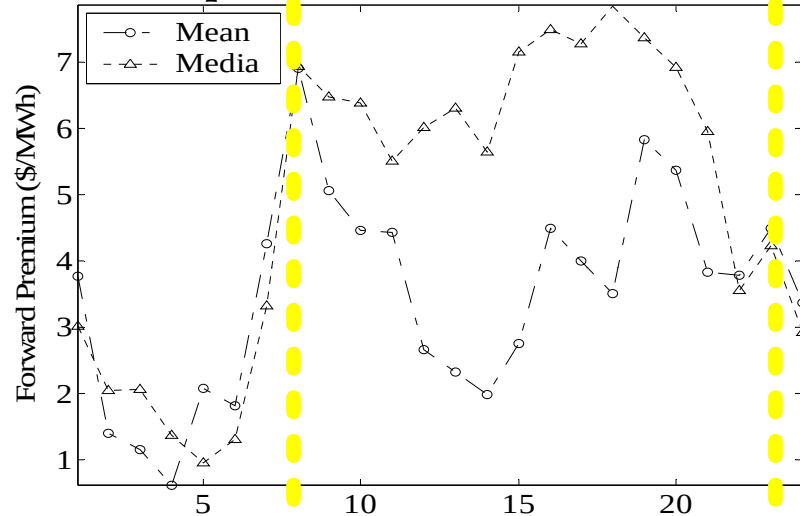
Forward price risk premium — Empirical Study with the New York Market Data



- Estimation of power transfer distribution factors
- Transmission congestion effect on forward premium
- Forecasting of out-of-sample spot market prices

Forward price risk premium — Evidence of Transmission Congestion Effect

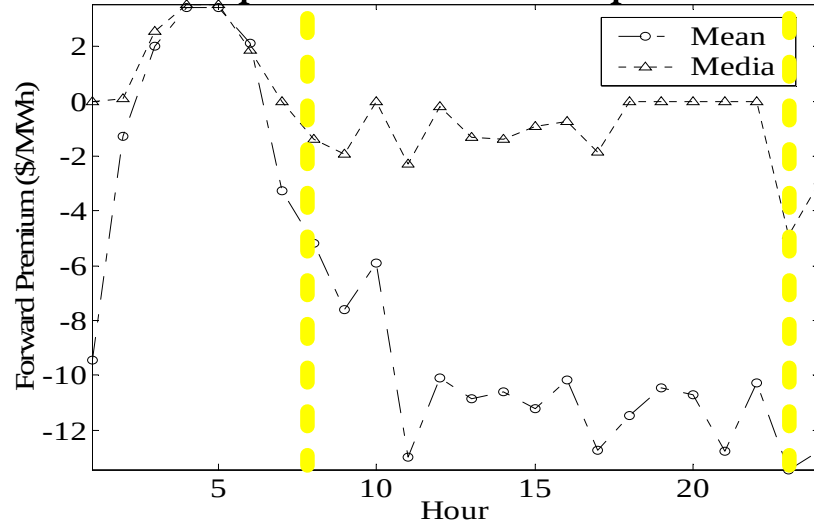
Forward premiums of LMP at reference bus



Estimates of PTDF coefficients

	FG1	FG2	FG3
Zone-CAPITL	-0.1229	-0.1078	0.0045
Zone-CENTRL	-0.0376	0.02	0.0782
Zone-DUNWOD	-0.1431	-0.2073	0.0276
Zone-GENESE	-0.0605	0.0615	0.2512
Zone-HUD VL	-0.1409	-0.1722	0.017
Zone-LONGIL	-0.1493	-0.2172	0.0326
Zone-MHK VL	-0.0215	-0.0266	0.0331
Zone-MILLWD	-0.1513	0.1775	0.0316
Zone-N.Y.C.	-0.18	-0.3314	0.0183
Zone-NORTH	0.0791	0.0652	-0.0341
Zone-WEST	-0.0793	0.1264	0.281

Forward premium of shadow price at FG1



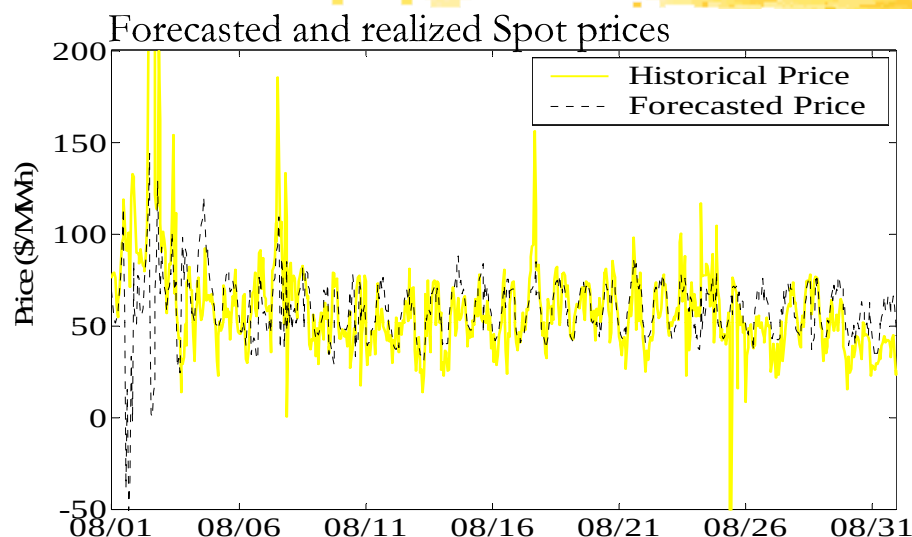
Analytical forward premium formula

$$\begin{aligned}
 & (P_{Ref}^F - E[P_{Ref}^S]) \cdot \left(\sum_{i=1}^I \frac{1}{A_G \text{Var}(P_{g_i}^{S*}(\varpi))} + \sum_{j=1}^J \frac{1}{A_L \text{Var}(P_{l_j}^{S*}(\varpi))} \right) \\
 &= \sum_{k \in \mathcal{K}} (\lambda_k^F - E[\lambda_k^S]) \cdot \left(\sum_{i=1}^I \frac{f_{g_i,k}}{A_G \text{Var}(P_{g_i}^{S*}(\varpi))} + \sum_{j=1}^J \frac{f_{l_j,k}}{A_L \text{Var}(P_{l_j}^{S*}(\varpi))} \right) \\
 &\quad - \left(\sum_{i=1}^I \frac{\text{Cov}(\rho_i^G(\varpi), P_{g_i}^{S*}(\varpi))}{\text{Var}(P_{g_i}^{S*}(\varpi))} + \sum_{j=1}^J \frac{\text{Cov}(\rho_j^L(\varpi), P_{l_j}^{S*}(\varpi))}{\text{Var}(P_{l_j}^{S*}(\varpi))} \right)
 \end{aligned}$$

Forward price risk premium — Forecasting of Out-of-Sample Spot Market Prices



PSERC



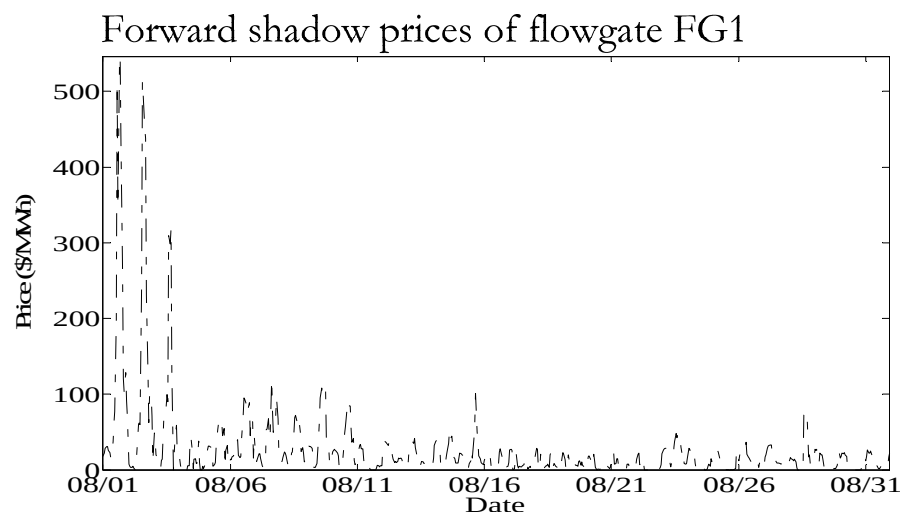
Statistics of error terms assuming normality

μ	95% CI of μ	σ	95% CI of σ
10.22	[8.97, 11.47]	16.67	[15.85, 17.58]

Statistics of error terms assuming normality
(price spikes excluded)

μ	95% CI of μ	σ	95% CI of σ
7.07	[5.96, 8.18]	13.52	[12.81, 14.29]

9.96% relative error



Reasons:

1. Errors introduced in PTDF estimation
2. Incomplete flowgate list
3. Conditional expectation of spot prices and covariances

Inherent inefficiency of FTR auctions — Clearing Mechanism for the FTR Auction

- The FTR auction is equivalent to a virtual energy auction.

$\begin{aligned} & \underset{Q}{\text{Max}} \quad C^T Q \\ & \text{s.t.} \\ & \quad e^T \cdot Q = 0 \\ & \quad G_r \cdot Q \leq L \\ & \quad -G_r \cdot Q \leq L \\ & \quad Q \leq \hat{Q} \\ & \quad Q \geq 0 \\ & \quad C = (c_1, c_2, \dots, c_n)^T \\ & \quad Q = (q_1, q_2, \dots, q_n)^T \\ & \quad \hat{Q} = (\hat{q}_1, \hat{q}_2, \dots, \hat{q}_n)^T = \alpha \cdot \bar{Q} \end{aligned}$	Dual Formulation 	$\begin{aligned} & \underset{\lambda, \mu_r^+, \mu_r^-, \eta}{\text{Min}} \quad \sum_{r \in R} [(\mu_r^+)^T + (\mu_r^-)^T] L + \eta^T \hat{Q} \\ & \text{s.t.} \\ & \quad \lambda \cdot e^T + \sum_{r \in R} [(\mu_r^+)^T - (\mu_r^-)^T] G_r + \eta^T I \geq C^T \\ & \quad \mu_r^+ \geq 0, \forall r \in R \\ & \quad \mu_r^- \geq 0, \forall r \in R \\ & \quad \eta \geq 0 \end{aligned}$ <i>$\lambda, \mu_r^+, \mu_r^-$, and η are dual variables associated with 4 categories of constraints in the primal formulation</i>
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$$c_i = \begin{cases} E[\text{nodal price}] & \text{for supplier bus} \\ -E[\text{nodal price}] & \text{for demand bus} \end{cases}$$

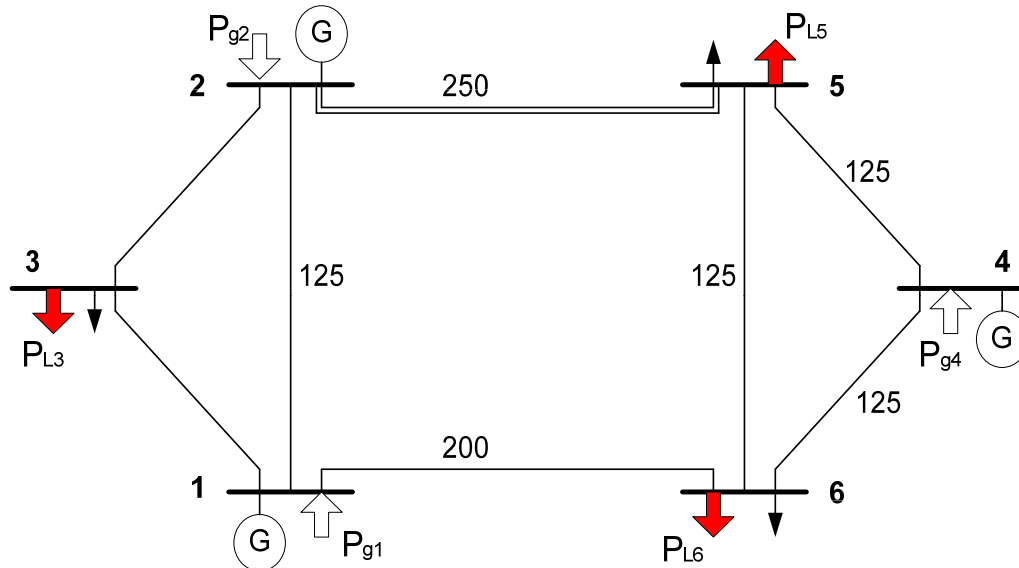
Inherent inefficiency of FTR auctions — Market Clearing Nodal Prices

- The market clearing nodal price vector P of an FTR auction is given by

$$P \equiv \lambda \cdot e^T + \sum_{r \in R} \left[(\mu_r^+)^T - (\mu_r^-)^T \right] \cdot G_r$$

- Proposition
 - If none of the bid quantity constraint is binding $\Rightarrow$
FTR auction clearing prices match expected FTR settlements
 - For a generation (load) bus, if the bid quantity constraint is binding $\Rightarrow$
market clearing nodal price is greater (less) than expected ex post nodal price

Inherent inefficiency of FTR auctions — A 6-Bus System



- DC power flow
 - Supply buses 1,2,4
 - Demand Buses 3,5,6
- 8 transmission lines
- Admittance

$$B_{12} = B_{13} = B_{25} = B_{45} = -j10.0$$

$$B_{16} = B_{46} = -j5.0$$

The supply and demand functions at the 6 buses

Bus-ID	Supply Bids	Bus-ID	Loads
Bus-1	$10 + 0.05 \cdot q$	Bus-3	$37 - 0.05 \cdot q$
Bus-2	$15 + 0.05 \cdot q$	Bus-5	$75 - 0.1 \cdot q$
Bus-4	$42 + 0.025 \cdot q$	Bus-6	$80 - 0.1 \cdot q$

Inherent inefficiency of FTR auctions —

A 6-Bus System

Computational Results under Transmission Line and Load Contingencies

	bus-1	bus-2	bus-3	bus-4	bus-5	bus-6
P (\$)	24.3	25.5	28.5	47.1	53.9	50.8
Q (MW) (FTR)	286.4	210.6	180.0	185.4	210.8	291.6
P (\$)	24.3	25.5	28.5	47.1	53.9	50.8
Q (MW) ($\alpha : 1.5$)	250.0	75.0	125.0	241.7	133.3	308.3
P (\$)	24.3	25.5	28.5	47.8	53.9	50.8
Q (MW) ($\alpha : 1.0$)	250.0	75.0	125.0	185.4	189.6	195.8
P (\$)	25.5	25.5	28.5	50.8	50.8	50.8
Q (MW) ($\alpha : 0.7$)	200.5	124.5	125.0	129.8	147.5	182.3
P (\$)	28.5	28.5	28.5	47.1	47.1	47.1
Q (MW) ($\alpha : 0.5$)	143.2	105.3	48.5	51.2	105.4	145.8

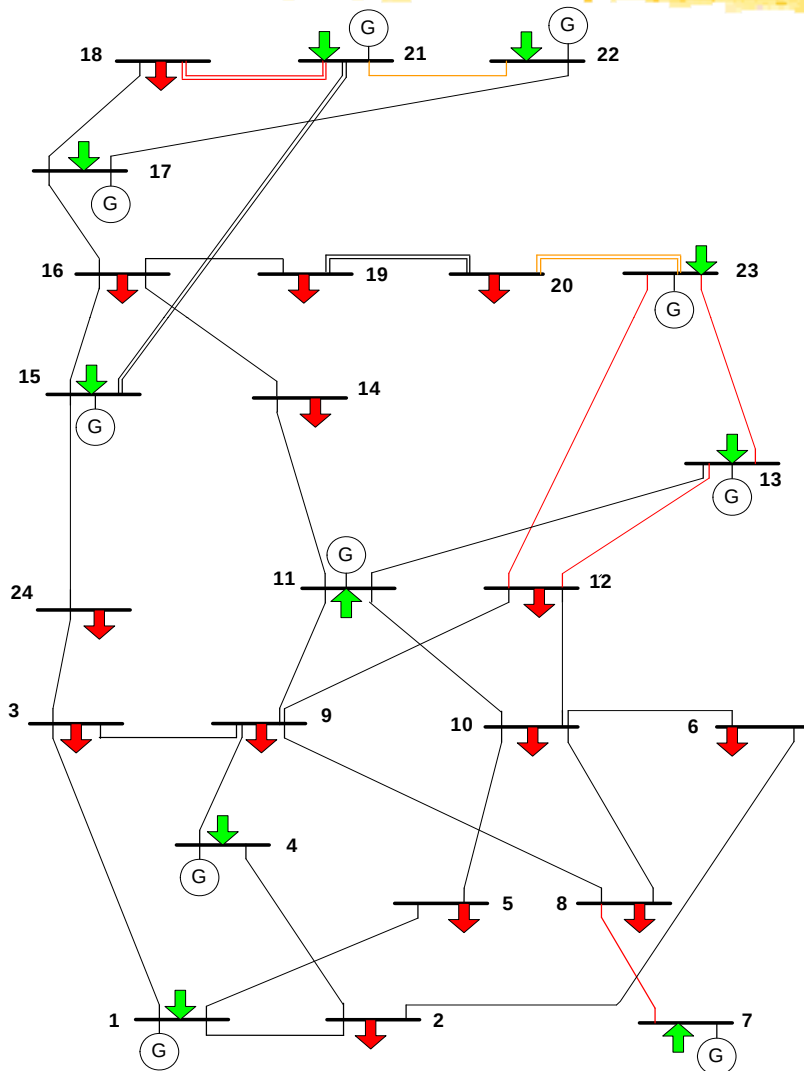
Market Clearing Prices and Quantities

α	1.5	1	0.7	0.5	FTR Bids (<i>ex ante</i>)
FTR-12	1.21	1.21	0	0	1.21
FTR-13	4.18	4.18	2.97	0	4.18
FTR-14	22.82	23.43	25.31	18.64	22.82
FTR-15	29.60	29.60	25.31	18.64	29.60
FTR-16	26.52	26.52	25.31	18.64	26.52
FTR-23	2.97	2.97	2.97	0	2.97
FTR-24	21.60	22.22	25.31	18.64	21.60
FTR-25	28.39	28.39	25.31	18.64	28.39
FTR-26	25.30	25.30	25.31	18.64	25.30
FTR-34	18.64	19.25	22.34	18.64	18.64
FTR-35	25.42	25.42	22.34	18.64	25.42
FTR-36	22.34	22.34	22.34	18.64	22.34
FTR-45	6.79	6.17	0	0	6.79
FTR-46	3.70	3.09	0	0	3.70
FTR-56	-3.09	-3.09	0	0	-3.09

FTR Price Comparison

As α increases, the bid quantity constraints do not bind. The FTR market clearing prices converge to the expected ex post FTR prices

Inherent inefficiency of FTR auctions — IEEE 24-Bus RTS



- DC power flow
 - 14 supply buses
 - 10 demand buses
- Postulated contingency sets
 - Load fluctuation
 - Transmission line outage

Conclusion:

- A much larger α is needed for the FTR market clearing prices converge to the expected *ex post* FTR prices