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

<table>
<thead>
<tr>
<th>TRM Requirements</th>
<th>LMP at Bus 10 ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% TRM</td>
<td>4.02</td>
</tr>
<tr>
<td>10% TRM</td>
<td>4.67</td>
</tr>
<tr>
<td>20% TRM</td>
<td>5.12</td>
</tr>
</tbody>
</table>

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

Probability distributions of LMPs at bus 10 over the sample year with different TRMs requirements
Power system simulation —
Identification of transmission adequacy and reliability needs

- Sensitivity of reliability index for system transmission reliability margin

![Graph showing the relationship between transmission capacity and reliability index.](image-url)
Power system simulation —
Effectiveness of Transmission Compensation

• A case study: allocation of incremental FTRs

\[
\begin{align*}
\text{Max } & \quad b \delta \\
\text{s.t. } & \quad FP \leq T \\
& \quad F^+ (P + \delta) \leq T^+ \\
\end{align*}
\]

\( b \) : 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, \( P_{20,23} = 529.1, P_{22,21} = 300 \)

\( \delta \) : 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

<table>
<thead>
<tr>
<th>Simulation Results ($/MW)</th>
<th>Zones A-G</th>
<th>Zones A-J</th>
<th>Zones G-J</th>
<th>Zones J-K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sim1 (Hedgers)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual payout</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May-October 2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBMP</td>
<td>60,543.1</td>
<td>97,394.4</td>
<td>36,851.3</td>
<td>67,281.1</td>
</tr>
<tr>
<td>Loss</td>
<td>1,698.1</td>
<td>1,864.1</td>
<td>166.0</td>
<td>140.3</td>
</tr>
<tr>
<td>C.C.</td>
<td>58,845.0</td>
<td>95,530.3</td>
<td>36,685.3</td>
<td>67,140.8</td>
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<tr>
<td>Simulated payouts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBMP</td>
<td>max</td>
<td>72,021.0</td>
<td>108,880.8</td>
<td>50,574.4</td>
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<tr>
<td></td>
<td>mean</td>
<td>52,000.8</td>
<td>89,706.5</td>
<td>37,705.7</td>
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<tr>
<td></td>
<td>median</td>
<td>52,051.0</td>
<td>90,622.3</td>
<td>37,856.7</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>37,079.5</td>
<td>68,974.3</td>
<td>17,080.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Sim2 (Speculators)</strong></th>
<th>A-G</th>
<th>A-J</th>
<th>G-J</th>
<th>J-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual payout</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>LBMP</td>
<td>max</td>
<td>67,501.7</td>
<td>100,596.8</td>
<td>45,393.3</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>48,907.0</td>
<td>82,401.0</td>
<td>33,494.0</td>
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<tr>
<td></td>
<td>median</td>
<td>48,829.6</td>
<td>83,005.9</td>
<td>33,678.5</td>
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<tr>
<td></td>
<td>min</td>
<td>34,767.9</td>
<td>63,205.6</td>
<td>14,342.5</td>
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</tbody>
</table>
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 $x_i, 1 \leq i \leq N$. 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

- 1st dimension coordinates
- 2nd dimension coordinates
- 3rd dimension coordinates
- 4th dimension coordinates
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

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTR</td>
<td>CENTRL to CAPITL</td>
<td>CENTRL to NYC</td>
<td>NORTH to LONGIL</td>
<td>WEST to DUNWOD</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>0.684</td>
<td>0.8166</td>
<td>0.7245</td>
<td>-0.6208</td>
</tr>
</tbody>
</table>
Hub-and-Spoke Representation — Each Coordinate in Low Dimensional Space

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

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTR</td>
<td>WEST to DUNWOD</td>
<td>CENTRL to LONGIL</td>
<td>CENTRL to LONGIL</td>
<td>WEST to DUNWOD</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>0.6316</td>
<td>0.8166</td>
<td>0.7245</td>
<td>-0.6208</td>
</tr>
</tbody>
</table>
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

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

- 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

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

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

- DC power flow
- Transmission network constraints
- Fixed set of active transmission constraints
Forward price risk premium —
Time Sequence of the Decision Problems

**GENs**
Choose \([G^F_1, G^F_2]\)
to maximize expected utility

**LSEs**
Choose \([L^F_1, L^F_2]\)
to maximize expected utility

**ISO**
Balance demand and supply and determine forward prices \([B^F_1, B^F_2, B^F_3]\)

---

**Stage 1**
Day-ahead forward market

---

**Stage 2**
Real-time spot market

---

**GENs**
Given \([G^F_1, G^F_2]\)
choose \([G^S_1, G^S_2]\)
by maxing profit

**LSEs**
Buy \([L^S_2, L^S_3]\)
to serve residual demand

**ISO**
Balance demand and supply and determine spot prices \([P^S_1, P^S_2, P^S_3]\)

---

**GEN1**
\([G^F_1, G^S_1]\)
150 MVA

**GEN2**
\([G^F_2, G^S_2]\)

**GEN3**
\([L^F_2, L^S_3]\)

**LSE3**
\([L^F_2, L^S_2]\)
Forward price risk premium — Quantitative Model of Forward Premiums

\[
(P_F - E[P_S]) \cdot \left( \frac{1}{A_1 \text{Var}(P_{1*}(\omega))} + \frac{1}{A_2 \text{Var}(P_{2*}(\omega))} + \frac{1}{A_3 \text{Var}(P_{3*}(\omega))} \right)
\]

(forward risk premium term)

\[
= (\lambda_F - E[\lambda_S]) \cdot \left( \frac{1/3}{A_1 \text{Var}(P_{1*}(\omega))} + \frac{0}{A_2 \text{Var}(P_{2*}(\omega))} + \frac{0}{A_3 \text{Var}(P_{3*}(\omega))} + \frac{-1/3}{A_2 \text{Var}(P_{3*}(\omega))} \right)
\]

(flowgate shadow price forward premium term)

\[
- \left( \frac{\text{Cov}(\rho_1^G(\omega), P_{1*}(\omega))}{\text{Var}(P_{1*}(\omega))} + \frac{\text{Cov}(\rho_2^G(\omega), P_{2*}(\omega))}{\text{Var}(P_{2*}(\omega))} \right)
\]

(covariance between LSEs' un-hedged profit and the spot market price term)

\[
- \left( \frac{\text{Cov}(\rho_2^L(\omega), P_{2*}(\omega))}{\text{Var}(P_{2*}(\omega))} + \frac{\text{Cov}(\rho_3^L(\omega), P_{3*}(\omega))}{\text{Var}(P_{3*}(\omega))} \right)
\]

(covariance between GPs' un-hedged profit and the spot market price term)
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

Forward premium of shadow price at FG1

Estimates of PTDF coefficients

<table>
<thead>
<tr>
<th>Zone</th>
<th>FG1</th>
<th>FG2</th>
<th>FG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone-CAPITL</td>
<td>-0.1229</td>
<td>-0.1078</td>
<td>0.0045</td>
</tr>
<tr>
<td>Zone-CENTRL</td>
<td>-0.0376</td>
<td>0.02</td>
<td>0.0782</td>
</tr>
<tr>
<td>Zone-DUNWOD</td>
<td>-0.1431</td>
<td>-0.2073</td>
<td>0.0276</td>
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<tr>
<td>Zone-GENESE</td>
<td>-0.0605</td>
<td>0.0615</td>
<td>0.2512</td>
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<td>Zone-HUD VL</td>
<td>-0.1409</td>
<td>0.1722</td>
<td>0.017</td>
</tr>
<tr>
<td>Zone-LONGIL</td>
<td>-0.1493</td>
<td>0.2172</td>
<td>0.0326</td>
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<tr>
<td>Zone-MHK VL</td>
<td>-0.0215</td>
<td>0.0266</td>
<td>0.0331</td>
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<tr>
<td>Zone-MILLWD</td>
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<td>Zone-N.Y.C.</td>
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<td>0.0183</td>
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<tr>
<td>Zone-NORTH</td>
<td>0.0791</td>
<td>0.0652</td>
<td>-0.0341</td>
</tr>
<tr>
<td>Zone-WEST</td>
<td>0.0793</td>
<td>0.1264</td>
<td>0.281</td>
</tr>
</tbody>
</table>

Analytical forward premium formula

\[
(P_{Ref}^F - E[P_{Ref}^S]) = \left( \frac{1}{\sum_{i=1}^G A_i \text{Var}(P_{g_i}(\omega))} + \frac{1}{\sum_{i=1}^L A_i \text{Var}(P_{l_i}(\omega))} \right) \left( \sum_{i=1}^G \frac{f_{g_i,k}}{A_i \text{Var}(P_{g_i}(\omega))} \text{Var}(P_{g_i}(\omega)) + \sum_{i=1}^L \frac{f_{l_i,k}}{A_i \text{Var}(P_{l_i}(\omega))} \text{Var}(P_{l_i}(\omega)) \right) - \left( \sum_{i=1}^G \frac{\text{Cov}(\rho_{g_i}^G(\omega), P_{g_i}(\omega))}{\text{Var}(P_{g_i}(\omega))} + \sum_{i=1}^L \frac{\text{Cov}(\rho_{l_i}^L(\omega), P_{l_i}(\omega))}{\text{Var}(P_{l_i}(\omega))} \right)
\]
Forward price risk premium — Forecasting of Out-of-Sample Spot Market Prices

### Statistics of error terms assuming normality

<table>
<thead>
<tr>
<th>Price ($/MWh)</th>
<th>95% CI of μ</th>
<th>95% CI of σ</th>
</tr>
</thead>
</table>

### Statistics of error terms assuming normality (price spikes excluded)

<table>
<thead>
<tr>
<th>Price ($/MWh)</th>
<th>95% CI of μ</th>
<th>95% CI of σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.07</td>
<td>[5.96, 8.18]</td>
<td>13.52</td>
</tr>
</tbody>
</table>

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.

\[
\begin{align*}
\text{Max} & \quad C^T Q \\
\text{s.t.} & \quad e^T \cdot Q = 0 \\
& \quad G_r \cdot Q \leq L \\
& \quad -G_r \cdot Q \leq L \\
& \quad Q \leq \hat{Q} \\
& \quad Q \geq 0 \\
C &= (c_1, c_2, \ldots, c_n)^T \\
Q &= (q_1, q_2, \ldots, q_n)^T \\
\hat{Q} &= (\hat{q}_1, \hat{q}_2, \ldots, \hat{q}_n)^T = \alpha \cdot \bar{Q} \\
c_i &= \begin{cases} 
E[\text{nodal price}] & \text{for supplier bus} \\
-E[\text{nodal price}] & \text{for demand bus}
\end{cases}
\]

\[
\begin{align*}
\text{Min} & \quad \sum_{r \in R} \left[ (\mu_r^+) \cdot (q_r^+) + (\mu_r^-) \cdot (q_r^-) \right] + \eta^T \hat{Q} \\
\text{s.t.} & \quad \lambda \cdot e^T + \sum_{r \in R} \left[ (\mu_r^+) \cdot q_r^+ - (\mu_r^-) \cdot q_r^- \right] G_r + \eta^T I \geq C^T \\
& \quad \mu_r^+ \geq 0, \forall r \in R \\
& \quad \mu_r^- \geq 0, \forall r \in R \\
& \quad \eta \geq 0 \\
\lambda, \mu^+, \mu^-, \text{ and } \eta \text{ are dual variables associated with 4 categories of constraints in the primal formulation}
\end{align*}
\]
Inherent inefficiency of FTR auctions —
Market Clearing Nodal Prices

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

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

• Proposition
  - If none of the bid quantity constraint is binding $\iff$ FTR auction clearing prices match expected FTR settlements
  - For a generation (load) bus, if the bid quantity constraint is binding $\iff$
    - 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

<table>
<thead>
<tr>
<th>Bus-ID</th>
<th>Supply Bids</th>
<th>Bus-ID</th>
<th>Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus-1</td>
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<td>[37 - 0.05 \cdot q]</td>
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<td>Bus-5</td>
<td>[75 - 0.1 \cdot q]</td>
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<tr>
<td>Bus-4</td>
<td>[42 + 0.025 \cdot q]</td>
<td>Bus-6</td>
<td>[80 - 0.1 \cdot q]</td>
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Inherent inefficiency of FTR auctions —
A 6-Bus System

Computational Results under Transmission Line and Load Contingencies

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<tr>
<td>P ($)</td>
<td>24.3</td>
<td>25.5</td>
<td>28.5</td>
<td>47.1</td>
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<td>50.8</td>
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<tr>
<td>Q (MW) (FTR)</td>
<td>286.4</td>
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<tr>
<td>P ($)</td>
<td>24.3</td>
<td>25.5</td>
<td>28.5</td>
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<td>Q (MW) (α: 1.5)</td>
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</table>

As $\alpha$ 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 $\alpha$ is needed for the FTR market clearing prices converge to the expected ex post FTR prices