Solving the ISO “Seams” Problem for Uniform Boundary LMP’s

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Central Market Designs

- PJM and NYISO are central markets based on Locational Marginal Price
- No identification of individual transactions
- Each generator and each load bids to sell (buy) from a central exchange.
- Central exchange calculates the bus Locational Marginal Prices (LMP’s) which determine payments and transmission charges
Locational Marginal Price (LMP)

- Requires a Security Constrained Optimal Power Flow
- Usually coupled with Unit Commitment (SCUC)
- The only transmission management scheme now in use that uses full AC network model
Optimal Power Flow (linearized)

$$\min \left[ \sum_i C_i(P_{G_i}) - \sum_i W_i(P_{E_i}) \right]$$

$$\begin{bmatrix} \theta_1 \\ \vdots \\ \theta_n \end{bmatrix} - \begin{bmatrix} P_{G_1} - P_{E_1} \\ \vdots \\ P_{G_n} - P_{E_n} \end{bmatrix} = \begin{bmatrix} -P_{D_1} \\ \vdots \\ -P_{D_n} \end{bmatrix}$$

$$\frac{1}{x_{ij}} (\theta_i - \theta_j) + s_{ij} = P_{ij}^{\max}$$

$$\frac{1}{x_{ij}} (\theta_i - \theta_j) + LODF_{ij,mn} \cdot \frac{1}{x_{mn}} (\theta_m - \theta_n) + s_{ij,mn} = 1.1 \cdot P_{ij}^{\max}$$

Gen Bid Cost – Load Bid Cost

Transmission System Power Balance Constraint

Transmission line limits

Transmission contingency constraints
Real World OPF

- 10,000 bus, 15,000 line model
- 20,000 dependent variables
- 300-500 generation bids
- ~ 8000 load bids
- 15,000 line limits
- Very large number of contingency limits
Security Constrained Unit Commitment

- 1/0 problem with generator on/off status added to the Security Constrained OPF
- Solved for 24 hours of the day ahead
Data to drive the OPF

- ~ 20,000 bus measurements
- ~ 30,000 line flow measurements
- ~ 100,000 circuit breaker open/closed status values
- ~ 5000 independent transactions data
- Gather the above data and solve a state estimation every 5 minutes
- Gather generation and load bids for every hour
- Solve OPF for each hour
### CASE 1

<table>
<thead>
<tr>
<th>Generator 1</th>
<th>Generator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asks</strong></td>
<td><strong>Asks</strong></td>
</tr>
<tr>
<td><strong>MW</strong></td>
<td><strong>MW</strong></td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td><strong>Price</strong></td>
</tr>
<tr>
<td>A 400</td>
<td>C 200</td>
</tr>
<tr>
<td>5.00</td>
<td>6.50</td>
</tr>
<tr>
<td>B 400</td>
<td>D 200</td>
</tr>
<tr>
<td>7.50</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Diagram:

```
1 500 MW 400 MW 2
```
CASE 1 (cont)

Schedule of generation:

<table>
<thead>
<tr>
<th>Ask</th>
<th>MW</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>400</td>
<td>5.00</td>
</tr>
<tr>
<td>C</td>
<td>200</td>
<td>6.50</td>
</tr>
<tr>
<td>B</td>
<td>300</td>
<td>7.50 clearing price (same for both buses)</td>
</tr>
</tbody>
</table>

The next MW purchased at either bus will be taken from the B segment of generator 1 for a price of 7.50 $/MWh.
### CASE 2

**Diagram:**
- Nodes 1 and 2 connected by a line marked with "LIMIT 100 MW".
- Arrows indicating power flow: 500 MW from Node 1 to Node 2, 400 MW from Node 2 to Node 1.

<table>
<thead>
<tr>
<th>Generator 1</th>
<th>Generator 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ask</td>
<td>MW</td>
</tr>
<tr>
<td>A</td>
<td>400</td>
</tr>
<tr>
<td>B</td>
<td>200</td>
</tr>
</tbody>
</table>
CASE 2 (cont)

clearing price at bus 1 = 7.50

clearing price at bus 2 = 8.00

<table>
<thead>
<tr>
<th>Ask</th>
<th>MW</th>
<th>Price</th>
<th>Ask</th>
<th>MW</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>400</td>
<td>5.0</td>
<td>C</td>
<td>200</td>
<td>6.50</td>
</tr>
<tr>
<td>B</td>
<td>200</td>
<td>7.50 clearing price</td>
<td>D</td>
<td>100</td>
<td>8.00 clearing</td>
</tr>
</tbody>
</table>

The next MW purchased at bus 1 will come from the B segment of generator 1 for a price of 7.50 $/MWh, but the next MW purchased at bus 2 must come from the D segment of generator 2 at 8.00 $/MWh since the line is at capacity.
## Case 1 Accounting

<table>
<thead>
<tr>
<th>Revenue Collected from Loads</th>
<th>Revenue paid to generators and Transmission Owners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1: 500 x 7.50 = 3750</td>
<td>Gen 1: 700 x 7.50 = 5250</td>
</tr>
<tr>
<td>Load 2: 400 x 7.50 = 3000</td>
<td>Gen 2: 200 x 7.50 = 1500</td>
</tr>
<tr>
<td></td>
<td>Transmission = 0</td>
</tr>
<tr>
<td>Total: 6750</td>
<td>Total: 6750</td>
</tr>
</tbody>
</table>
## Case 2 Accounting

<table>
<thead>
<tr>
<th>Revenue Collected from Loads</th>
<th>Revenue paid to generators and Transmission Owners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1: 500 x 7.50 = 3750</td>
<td>Gen 1: 600 x 7.50 = 4500</td>
</tr>
<tr>
<td>Load 2: 400 x 8.00 = 3200</td>
<td>Gen 2: 300 x 8.00 = 2400</td>
</tr>
<tr>
<td>Total: 6950</td>
<td>Transmission 100(8.00-7.50)= 50</td>
</tr>
<tr>
<td>Total: 6950</td>
<td>Total: 6950</td>
</tr>
</tbody>
</table>
Financial Transmission Right (FTR)

- Transmission charge in an LPM market is:
  - \((LPM_i - LMP_j) \times MW_{flow}\)
- Holder of FTR receives credit of:
  - \((LPM_i - LMP_j) \times MW_{flow}\)
  - Where \(MW_{flow}\) is the “amount” purchased
- Holder can transfer the amount of the FTR from location \(i\) to \(j\) at no charge (credit cancels transmission charge)
FERC Standard Market Design

- FERC’s proposal mirrors the PJM and NY ISO market designs
- Key elements of SMD
  - LMP based congestion management
  - Financial Transmission Rights
  - Financially binding day-ahead energy markets
  - Real time balancing markets
  - Capacity markets (initial reluctance, gradual acceptance)
  - Market power mitigation
The New York – PJM Seam
Seams Problem

Both regions A and B operate by LPM calculations. They will get different costs along the boundary or seam between them.

If both A and B were operated as one market with one LMP calculation – there would be no such difference.
Problems with Seams

- Trading across the seam is difficult due to price differences that are only due to regional OPF solutions
Combined System

100 MW LIMIT

500 MW 400 MW

200 MW 600 MW

SYSTEM NORTH

SYSTEM SOUTH
Pricing Data for Combined System

<table>
<thead>
<tr>
<th>BUS</th>
<th>PRICE ($/MWh)</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.00</td>
<td>400</td>
</tr>
<tr>
<td>1</td>
<td>7.50</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>6.50</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>8.00</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>6.00</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>8.50</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>4.50</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>6.25</td>
<td>200</td>
</tr>
</tbody>
</table>
NORTH System alone

1. 633.3 MW
2. 266.7 MW
3. 500 MW
4. 400 MW
5. 33.3 MW

SYSTEM NORTH

SYSTEM SOUTH
SOUTH System alone

300 MW

25 MW

25 MW

200 MW

75 MW

600 MW

500 MW

PRICE 6.25 EVERYWHERE
Superposition of all flows

SYSTEM NORTH

SYSTEM SOUTH

1

2

3

4

PRICE 7.50

PRICE 8.00

125 MW OVERLOAD

266.7 MW

500 MW

400 MW

8.33 MW

8.33 MW

108.33 MW

500 MW

600 MW

200 MW

300 MW

633.3 MW

PRICES 6.25 AT BOTH SOUTH BUSES

266.7 MW

8.33 MW

500 MW

PRICE 8.00
Optimal Solution for Combined System

SYSTEM NORTH

SYSTEM SOUTH

1

566.7 MW

100 MW AT LIMIT

500 MW

33.3 MW

600 MW

PRICE 7.50

PRICE 8.00

2

233.3 MW

400 MW

66.7 MW

3

500 MW

300 MW

66.7 MW

200 MW

PRICE 7.67

4

600 MW

600 MW

PRICE 7.83

200 MW

PRICE 7.83
Solution to the “Seams” Problem

Regional Market

Bids

Final Schedules

ISO Region I

ISO Region II

Bids

Final Schedules

Regional Market

Data

Public Information Service: Congestion Cost
Schedules
Network Information

ISO Region III

Data
Information Exchanged

- All regions have the same network model covering all regions
- After the solution of each region’s OPF:
  - exchange power injections, LMP’s for each bus
  - exchange binding transmission constraint lambdas
- Each region now recalculates with a penalty term for its effect on other region’s constraints
- Usually converges in three iteration for linear case
Constrained Market Solution

Cadwalader, Harvey, Pope & Hogan
Harvard University 1999
## Iterative Solution to the Constrained Market

<table>
<thead>
<tr>
<th>Region Bus No.</th>
<th>Start Iteration</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Iteration</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; Iteration</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; Iteration</th>
<th>Final Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>82.30</td>
<td>82.95</td>
<td>83.00</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>2000</td>
<td>923</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>2</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>33.62</td>
<td>32.63</td>
<td>32.90</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>-1000</td>
<td>-454</td>
<td>-421</td>
<td>-430</td>
</tr>
<tr>
<td>3</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>42.24</td>
<td>42.75</td>
<td>42.38</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>-1000</td>
<td>-741</td>
<td>-758</td>
<td>-746</td>
</tr>
<tr>
<td>4</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>31.43</td>
<td>31.95</td>
<td>32.00</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>-1000</td>
<td>-381</td>
<td>-398</td>
<td>-400</td>
</tr>
<tr>
<td>5</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>71.32</td>
<td>72.43</td>
<td>72.38</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>2000</td>
<td>1289</td>
<td>1252</td>
<td>1254</td>
</tr>
<tr>
<td>6</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>47.93</td>
<td>46.97</td>
<td>47.00</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>-1000</td>
<td>-931</td>
<td>-899</td>
<td>-900</td>
</tr>
<tr>
<td>7</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>44.03</td>
<td>43.27</td>
<td>43.29</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>-1000</td>
<td>-801</td>
<td>-776</td>
<td>-776</td>
</tr>
<tr>
<td>8</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>36.91</td>
<td>36.64</td>
<td>36.64</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>-1000</td>
<td>-564</td>
<td>-555</td>
<td>-555</td>
</tr>
<tr>
<td>9</td>
<td>Price ($/MW)</td>
<td>50</td>
<td>60.23</td>
<td>60.43</td>
<td>60.40</td>
</tr>
<tr>
<td></td>
<td>Load (MW)</td>
<td>2000</td>
<td>1659</td>
<td>1652</td>
<td>1653</td>
</tr>
</tbody>
</table>
## Congestion Constraints

<table>
<thead>
<tr>
<th>Branch No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Bus</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>To Bus</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Lambda</td>
<td>-69.98</td>
<td>-20.79</td>
<td>0.00</td>
<td>0.00</td>
<td>65.73</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>40.78</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Research Challenge for Seams Problem

- Do all of the OPF matching using an AC network model, an AC OPF and AC security analysis
- This presents a great problem wrt convergence and stability of solutions
- Added complexity: solve the seams problem within a SCUC