Overview

- Introduction to power industry de-regulation
- Locational marginal pricing (LMP)
- Critical Load Levels: observation and solution algorithm
- Applications of the CLL concept
- Concluding Remarks
Before De-regulation

- Regulated power industry
  - Regulated by government boards
  - A monopoly system and “vertically” integrated
  - Obligation to serve with guaranteed rate of return
  - Historical reason for regulated business model to stimulate the private investment in the power sector.

Regulated power industry

- Vertically integrated monopoly business.

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Utility 1

- Generation
  - Transmission
  - Distribution
  - Consumers

Utility 2

- Generation
  - Transmission
  - Distribution
  - Consumers

Scheduled exchange
Why De-regulation

- To improve efficiency and reduce cost
  - Local load is mainly served by local generation, even if there is cheaper power available somewhere else
- To encourage technology innovation
- No need for regulation
  - The primary goal of regulation has been achieved

What’s new with de-regulation

- Create competition and market mechanism
- Mainly at the wholesale market at the current stage
- Transmission is the platform for sellers (GenCo) and buyers (DisCo) to trade energy
- Generation may be owned by Independent Power Providers (IPPs)
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Energy market pricing: LMP

- Pricing method: Locational Marginal Pricing (LMP).
  - PJM, NYISO, ISO-New England, CAISO, ERCOT, MISO & SPP.

- Marginal cost for pricing
  - The extra/incremental cost to produce an extra unit of output
  - In energy market: $\Delta$cost for 1MWh additional load.

- Location affects the price.

Understanding marginal cost

Demand=1400

Marginal cost = $12; the cost to serve the next unit of demand.
Understanding marginal cost

In engineers’ term: \( MC = \frac{d \text{Cost}}{d \text{Demand}} \)

\[
\begin{align*}
\frac{d \text{Cost}}{d \text{Demand}} & = 12 (\text{$/MWh}) \\
D & = 1400
\end{align*}
\]

LMP: Uncongested Case

- Marginal price is related to locations: circuit laws.

Impedance = 1 per unit for all three lines;
Line Limit = \( \infty \)
Mathematical LMP Model

- Linearized DCOPF model (losses ignored)

\[
\begin{align*}
\text{Min} & \quad \sum_{i=1}^{M} C_i \times G_i \\
\text{s.t.} & \quad \sum_{i=1}^{N} G_i = \sum_{i=1}^{N} D_i \\
& \quad \sum_{k=1}^{N} GSF_{k-i} \times (G_i - D_i) \leq \text{Limit}_k, \text{ for } k = 1, 2, \ldots, M \\
& \quad G_{i_{\text{min}}} \leq G_i \leq G_{i_{\text{max}}}, \text{ for } i = 1, 2, \ldots, N \\
\end{align*}
\]

\[
LMP_B = \lambda + \left( \sum_{k=1}^{M} \mu_k \times GSF_{k-B} \right)
\]

\(\lambda\) = Lagrange multiplier of (2)

\(\mu_k\) = Lagrange multiplier of (3) of the \(k^{th}\) transmission constraint
More about LMP model

- LMP calculation based on linearized DCOPF model
  - Production (generation) cost minimization model for economic dispatch
  - Linear Model: piece-wise linear generation cost, transmission constraints modeled with linearized DC power flow model, approximated loss model, etc
  - Can be robustly and efficiently solved
  - Employed by ISOs (with variations to include non-linear losses) and by market simulators from ABB, GE, etc.

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Motivation

Let’s start with the PJM 5-bus system sample.

CLL: Step changes in LMP as load varies

Critical Load Level: where LMP step change occurs as load varies.

- The system load variation is based on a linear pattern.
- This is aligned with other studies such as voltage stability study using Continuation Power Flow.
Some observations from actual data

- 5-minutes real-time prices within a hour (10-11am) for on 07/24/2009 at the CAPITAL zone in NYISO.

![Graph showing real-time prices](image)

12 data points in each hour

Reasons for step changes

- **Congestion**
  - Price may decrease
  - What happened here (Critical Load Levels)?

- **Shift of Marginal Unit**
  - Load = 510 MW

- **A**
  - Load = 810 MW
  - Max = 600 MW
  - List Usage = 100%

- **B**
  - Load = 510 MW
  - Max = 410 MW
Predict CLL as load varies

- Now the questions is: how to find CLLs?
  - A brute-force approach by running repeated DCOPF at every load levels is too time consuming.
  - This can be solved systematically.

\[
\begin{align*}
\text{Min } & \sum_{i=1}^{N} c_i \times G_i \\
\text{s.t. } & \sum_{i=1}^{N} G_i = \sum_{i=1}^{N} D_i, \\
& \sum_{i=1}^{N} GSF_{k-i} \times (G_i - D_i) \leq \text{Limit}_k, \text{ for } k=1, 2, \ldots, M \\
\end{align*}
\]

Load Variation Participation Factor:

\[
f_i = \frac{\Delta D_i}{\Delta D} \sum_{k=1}^{M} f_i = 1
\]

\[
\Delta D = f \times \Delta D \sum_{k=1}^{M}
\]

\[
G_r^{\text{min}} \leq G_r \leq G_r^{\text{max}}, \text{ for } i = 1, 2, \ldots, N
\]

Mathematical Interpretation

Simplex Method

Proposed Simplex-like Method

- Detailed algorithm description is too mathematical to be included in this short presentation, but can be found in:
Case Study

Marginal Units and Congestions versus Load

<table>
<thead>
<tr>
<th>Load Range (MW)</th>
<th>Marginal Unit(s)</th>
<th>Congested Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–600</td>
<td>Brighton</td>
<td>None</td>
</tr>
<tr>
<td>600–640</td>
<td>Alta</td>
<td>None</td>
</tr>
<tr>
<td>640–711.8083</td>
<td>Park City</td>
<td>None</td>
</tr>
<tr>
<td>711.8083–742.7965</td>
<td>Park City</td>
<td>ED</td>
</tr>
<tr>
<td>742.7965–963.9391</td>
<td>Sundance</td>
<td>ED</td>
</tr>
<tr>
<td>963.9391–1137.0152</td>
<td>Solitude</td>
<td>AB</td>
</tr>
<tr>
<td></td>
<td>Brighton</td>
<td>ED</td>
</tr>
</tbody>
</table>

Performance Speedup

Average-case performance: \( O(\log(n)) \) DCOPF runs

<table>
<thead>
<tr>
<th>System</th>
<th>Speedup compared with multiple (-10) DCOPF runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PJM 5-bus</td>
<td>15.2</td>
</tr>
<tr>
<td>IEEE 30-bus</td>
<td>30.0</td>
</tr>
<tr>
<td>IEEE 118-bus</td>
<td>51.6</td>
</tr>
</tbody>
</table>
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Probabilistic LMP: load uncertainty

- Problem description

How good is the prediction?

- How to quantify the risk associated with a forecasted LMP?

\[ \Pr(LMP = p_i) = \int_{D_i} \phi(u)du = \Phi(D_{\omega_2}) - \Phi(D_\omega) \]
Probability Mass Function of Probabilistic LMP

- LMP_t is a discrete random variable
- Named “Probabilistic LMP”

Probabilistic LMP at a specific (mean) load level is not a single deterministic value. Instead, it represents a set of discrete values at a number of load intervals. Each value has an associated probability.

Alignment Probability (AP)

- Probability that the deterministically calculated LMP (based on the deterministic, forecasted load) and the actual LMP are the same.
- Deterministically forecasted LMP
  \[ LMP(D^f_t) = p_j, \quad D_j < D^f_t \leq D_{j+1} \]
- Alignment Probability
  \[
  AP = \Pr(LMP_t = LMP(D^f_t)) = \Pr(LMP_t = p_j)
  \]
  \[
  = \int_{D_j}^{D_{j+1}} \varphi(u) du = \Phi(D_{j+1}) - \Phi(D_j)
  \]
  \[
  AP_{\alpha} = \Pr\left( p_j \times (1 - \alpha \%) \leq LMP_t \leq p_j \times (1 + \alpha \%) \right)
  \]
  tolerance
### Cast Study Results – PJM 5-bus system

<table>
<thead>
<tr>
<th>LMP($/MWh)</th>
<th>Probability(%) when $D^P = 730$ MW</th>
<th>Probability(%) when $D^P = 900$ MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
<td>0.67</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>30.23</td>
<td>0.00</td>
</tr>
<tr>
<td>21.74</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>23.68</td>
<td>36.29</td>
<td>92.25</td>
</tr>
<tr>
<td>28.18</td>
<td>0.00</td>
<td>7.77</td>
</tr>
<tr>
<td>28.38</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2000</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

### Alignment Probability Curve

- **Alignment Probability of LMP at Bus B**
  - No tolerance
  - Tolerance = 10%
Impact of LMP from wind uncertainty

**Objective**: understand the impact from high-penetration wind power on various aspects in power system operation

Using Correlation Model

\[
W_i \sim N(\mu_i, \sigma)
\]

\[
\begin{align*}
\phi(W_i, W_j) &= \frac{1}{2\sqrt{\sigma_i \sigma_j}} \exp \left( - \frac{\sigma_i^2 - 2\rho \sigma_i \sigma_j + \sigma_j^2}{2(1-\rho)^2} \right) \\
\mu = (\mu_i, \mu_j) \\
\Sigma &= \begin{bmatrix}
\sigma_i^2 & \rho \sigma_i \sigma_j \\
\rho \sigma_i \sigma_j & \sigma_j^2
\end{bmatrix}
\]

Expected Value of Probabilistic LMP versus Forecasted Load

Expected Value of Probabilistic LMP

Deterministic LMP Curve

The step-change characteristics of LMP versus load

The wind power forecast versus wind speed forecast

Using Correlation Model

\[
\begin{align*}
W_i \sim N(\mu_i, \sigma) \\
\phi(W_i, W_j) &= \frac{1}{2\sqrt{\sigma_i \sigma_j}} \exp \left( - \frac{\sigma_i^2 - 2\rho \sigma_i \sigma_j + \sigma_j^2}{2(1-\rho)^2} \right) \\
\mu = (\mu_i, \mu_j) \\
\Sigma &= \begin{bmatrix}
\sigma_i^2 & \rho \sigma_i \sigma_j \\
\rho \sigma_i \sigma_j & \sigma_j^2
\end{bmatrix}
\]

Controllable Loads

- With the expected large-scale deployment of smart meters, it is interesting to model *residential load response* and its impact to the price volatility and system security.
- We may want to increase/decrease the load “just right” (i.e., right before/after a transmission congestion occurs.)
- Feedback control framework is proposed.

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Conclusions

➢ In this seminar, the power industry deregulation and market operation is briefly introduced.
➢ Locational marginal pricing, the key to market operation, is introduced.
➢ Critical load level (CLL): where the step changes in LMP versus load occur.
➢ CLL can be used for various applications in market-based studies: probabilistic LMP concept, renewable energy impact, controllable loads, etc.

Related Publications

Thank you!

Questions and Answers?