ECE 620 Lecture

Nov. 2nd, 2016

Deregulation, Locational Marginal Pricing, and Critical Load Levels with Applications

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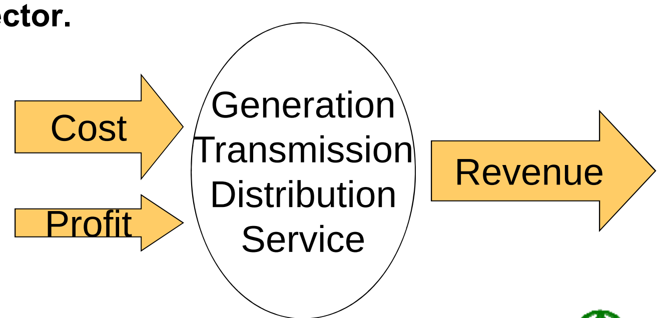
Overview

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

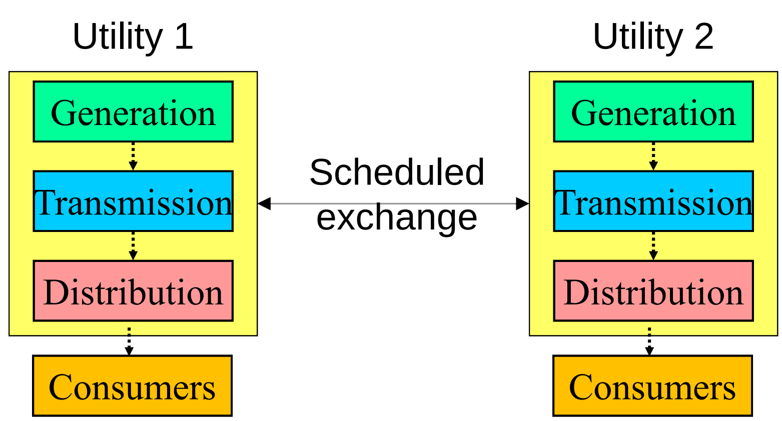
Before De-regulation

- **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.**



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

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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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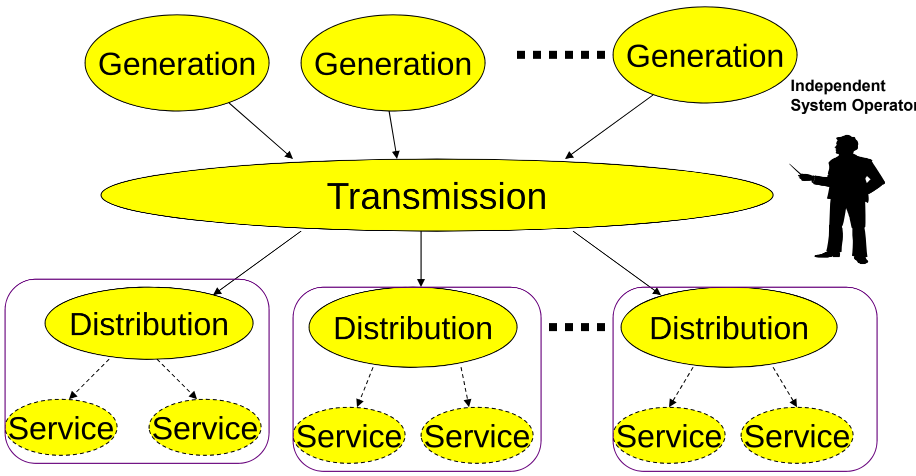
De-regulated power industry: Wholesale energy market



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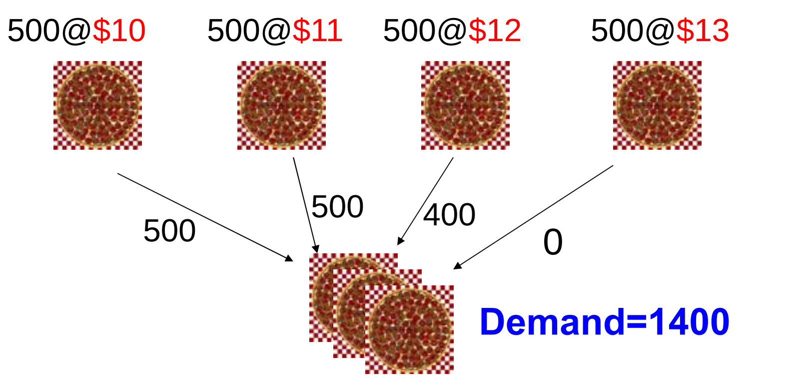
Energy market pricing: LMP

- **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: ∆cost for 1MWh additional load.**
- **Location affects the price.**

Understanding marginal cost

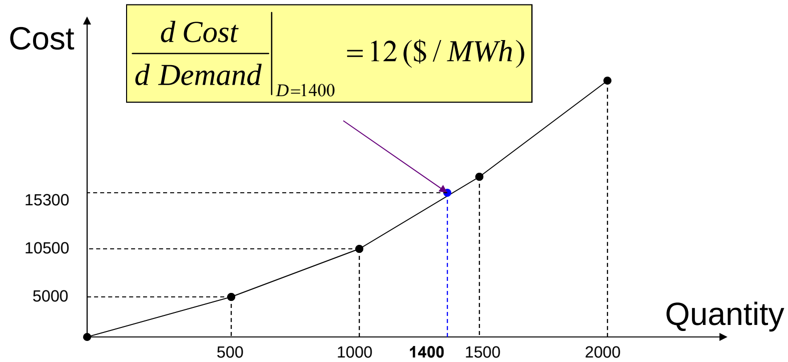


Marginal cost = $12; the cost to serve the next unit of demand.

Understanding marginal cost

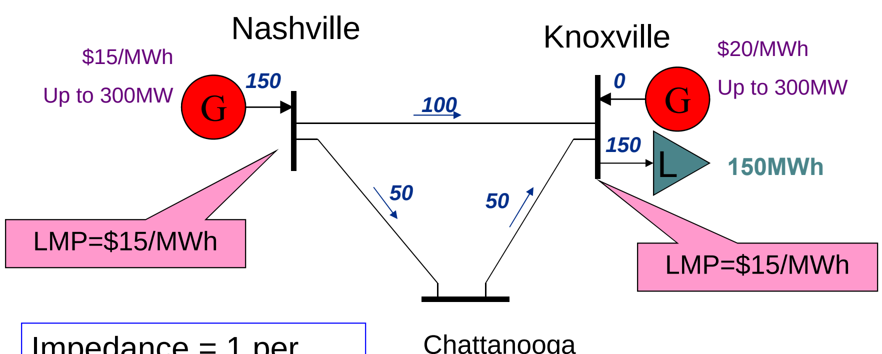
In engineers’ term: MC = *d* Cost / *d* Demand

$$\left.\frac{d\,Cost}{d\,Demand}\right|_{D=1400} = 12\,(\$/MWh)$$



LMP: Uncongested Case

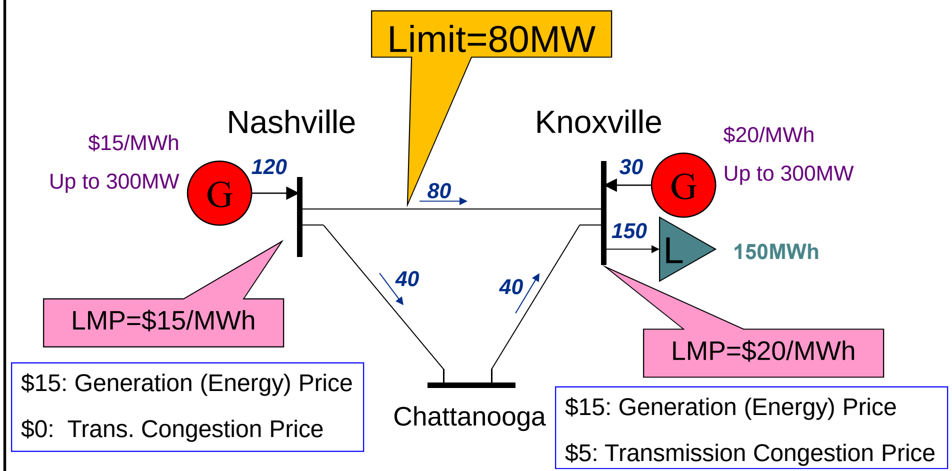
- Marginal price is related to locations: circuit laws.



Impedance = 1 per unit for all three lines;

Line Limit=∞

LMP: Congested Case



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Mathematical LMP Model

- Linearized DCOPF model (losses ignored)

$$\text{Min} \sum_{i=1}^{N} c_i \times G_i \qquad (1)$$

$$\text{s.t.} \quad \sum_{i=1}^{N} G_i = \sum_{i=1}^{N} D_i \qquad (2)$$

$$\sum_{i=1}^{N} GSF_{k-i} \times (G_i - D_i) \leq Limit_k \text{, for } k=1, 2, \ldots, M \qquad (3)$$

GSF_{k-i} = generation shift factor to line k from bus i.

$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{, for } i = 1, 2, \ldots, N \qquad (4)$$

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

λ=Lagrange multiplier of (2)
μ_k=Lagrange multiplier of (3) of the k^{th} transmission constraint

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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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- Concluding Remarks

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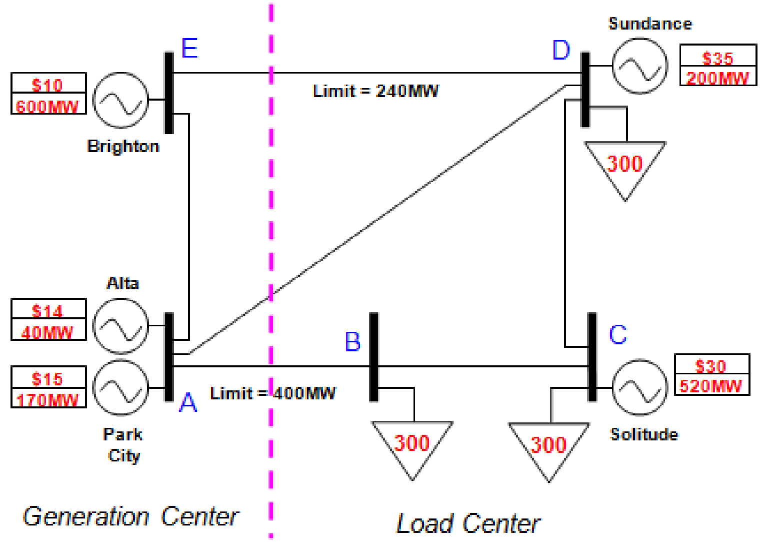
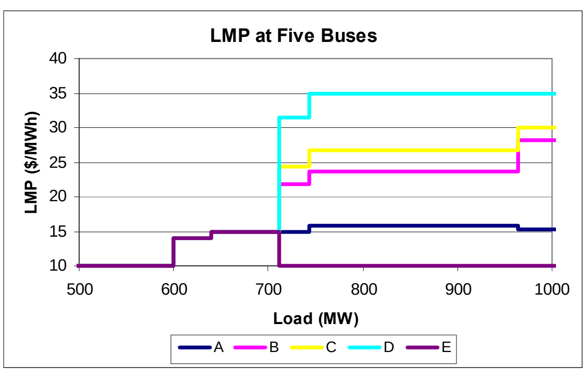
Motivation

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



CLL: Step changes in LMP as load varies



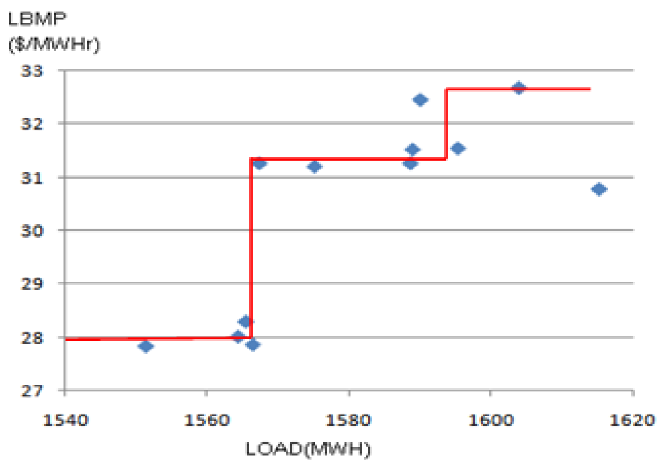
Critical Load Level: where LMP step change occurs as load varies.

- 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.

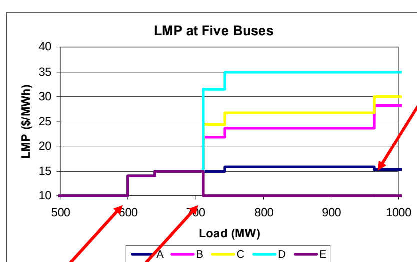
Some observations from actual data

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

12 data points in each hour

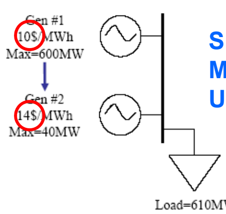


Reasons for step changes

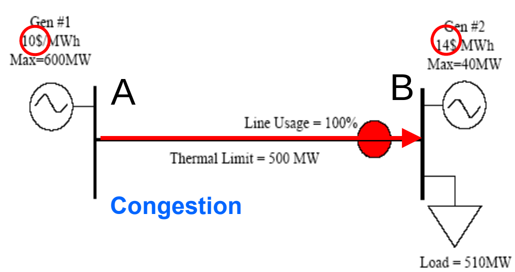


Price may decrease

What happened here (Critical Load Levels)?



Shift of Marginal Unit



Congestion

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.

$$\text{Min} \sum_{i=1}^{N} c_i \times G_i$$

Changing

$$\text{s.t.} \sum_{i=1}^{N} G_i = \sum_{i=1}^{N} D_i$$

$$\sum_{i=1}^{N} GSF_{k-i} \times (G_i - D_i) \leq Limit_k \text{ , for k=1, 2, …, M}$$

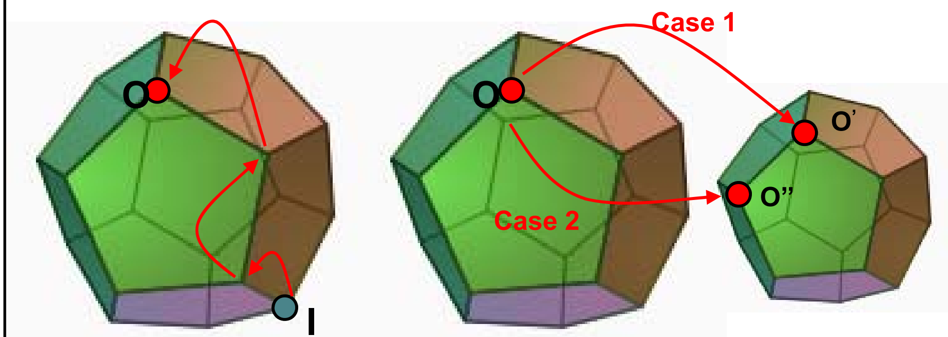
$$G_i^{\min} \leq G_i \leq G_i^{\max} \text{ , for i = 1, 2, …, N}$$

Load Variation Participation Factor:

$$f_i = \frac{\Delta D_i}{\Delta D_\Sigma} \quad \sum_{i \in N} f_i = 1$$

$$\mathbf{\Delta D} = \mathbf{f} \times \Delta D_\Sigma$$

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:
  - Fangxing Li and Rui Bo, "Congestion and Price Prediction under Load Variation," *IEEE Transactions on Power Systems*, vol. 24, no. 2, pp. 911-922, May 2009.

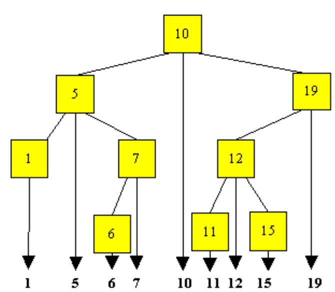
Case Study

- Marginal Units and Congestions versus Load

Load Range(MW)	Marginal Unit(s)	Congested Line
0~600	Brighton	None
600~640	Alta	None
640~ 711.8083	Park City	None
711.8083~ 742.7965	Park City Brighton	ED
742.7965~ 963.9391	Sundance Brighton	ED
963.9391~ 1137.0152	Solitude Sundance Brighton	AB ED

Performance Speedup

Binary Search



Average-case performance:

$O(\log(n))$ DCOPF runs

System	Speedup compared with multiple (~10) DCOPF runs
PJM 5-bus	15.2
IEEE 30-bus	30.0
IEEE 118-bus	51.6

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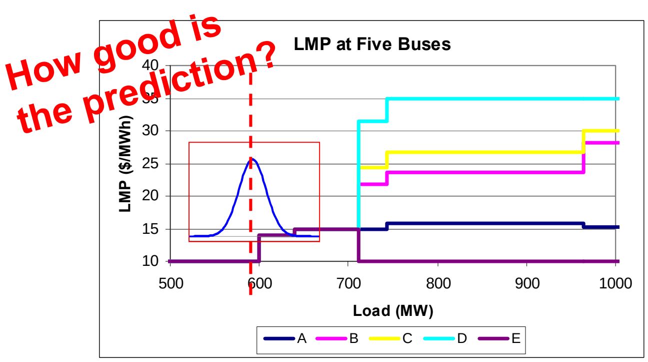
Probabilistic LMP: load uncertainty

- Problem description

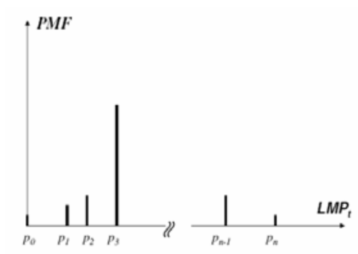


– **How to quantify the risk associated with a forecasted LMP?**

$$\Pr(LMP_t = p_i) = \int_{D_i}^{D_{i+1}} \varphi(u)du = \Phi(D_{i+1}) - \Phi(D_i)$$

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

$$LMP(D_t^F) = p_j, \qquad D_j < D_t^F \le D_{j+1}$$

- Alignment Probability

$$\mathrm{AP} = \Pr\left(LMP_t = LMP(D_t^F)\right) = \Pr\left(LMP_t = p_j\right)$$

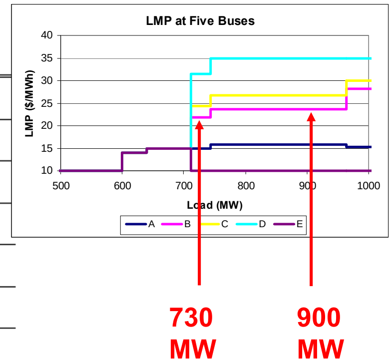
$$= \int_{D_j}^{D_{j+1}} \varphi(u)du = \Phi(D_{j+1}) - \Phi(D_j)$$

$$\mathbf{AP}_\alpha = \mathbf{Pr}\left(p_j \times (1 - \alpha\%) \le LMP_t \le p_j \times (1 + \alpha\%)\right)$$

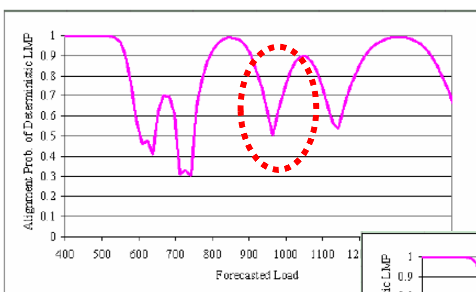
tolerance

Cast Study Results – PJM 5-bus system

LMP($/MWh)	Probability(%) when D^F_t=730MW	Probability(%) when D^F_t =900MW
0	0.00	0.00
10	0.02	0.00
14	0.67	0.00
15	30.23	0.00
21.74	32.80	0.02
23.68	36.29	92.21
28.18	0.00	7.77
26.38	0.00	0.00
2000	0.00	0.00
Total	100	100

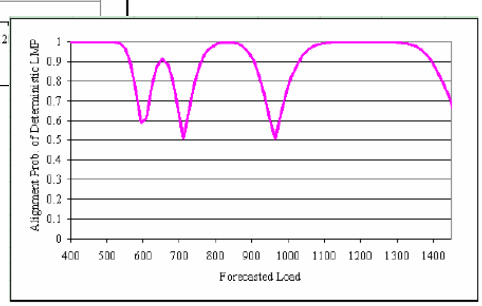


Alignment Probability Curve



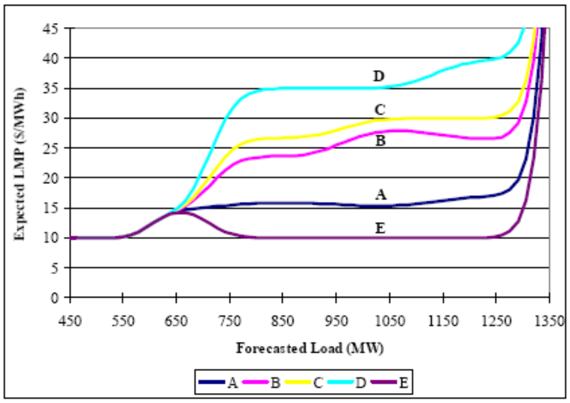
No tolerance

Alignment Probability of LMP at Bus B

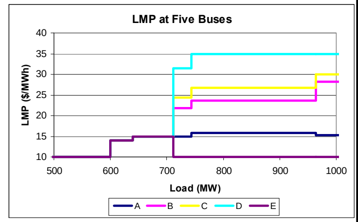


Tolerance = 10%

Expected Value of Probabilistic LMP versus Forecasted Load



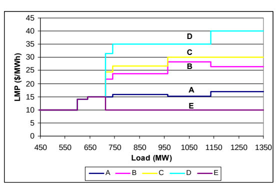
Expected Value of Probabilistic LMP



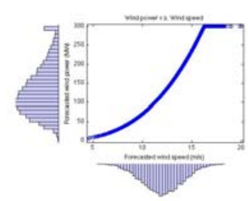
Deterministic LMP Curve

Impact of LMP from wind uncertainty

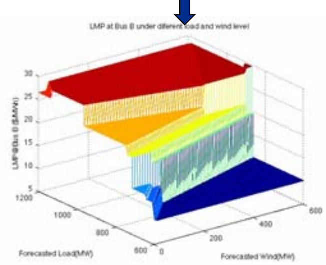
Objective: understand the impact from high-penetration wind power on various aspects in power system operation



The step-change characteristics of LMP versus load



The wind power forecast versus wind speed forecast



Using Correlation Model

$$W_s \sim N(\mu,\sigma)$$

$$\phi(w_{s1},w_{s2}) = \frac{1}{2\pi\sigma_{ws1}\sigma_{ws2}\sqrt{1-\rho_{ws}^2}}\exp[-\frac{z_{ws}}{2(1-\rho_{ws}^2)}]$$

$$z_{ws} = \frac{(Ws_1-\mu_{ws1})^2}{\sigma_{ws1}^2} - \frac{2\rho_{ws}(Ws_1-\mu_{ws1})(Ws_2-\mu_{ws2})}{\sigma_{ws1}\sigma_{ws2}} + \frac{(Ws_2-\mu_{ws2})^2}{\sigma_{ws2}^2}$$

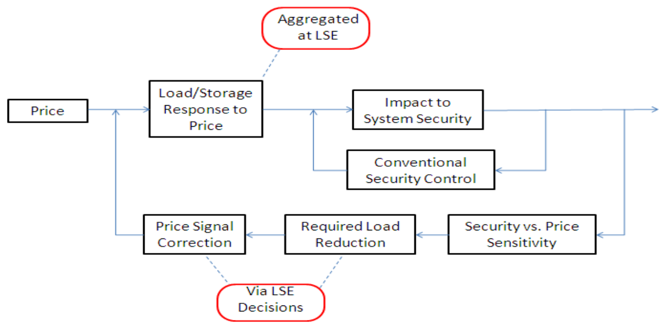
$$\mu = (\mu_{ws1},\mu_{ws2})$$

$$\Sigma = \begin{bmatrix} \sigma_{ws1}^2 & \rho_{ws}\sigma_{ws1}\sigma_{ws2} \\ \rho_{ws}\sigma_{ws1}\sigma_{ws2} & \sigma_{ws2}^2 \end{bmatrix}$$

$$\rho_{ws} = \frac{\mathrm{cov}(W_{s1},W_{s2})}{\sigma_{ws1}\sigma_{ws2}} = \frac{E\left[(W_{s1}-\mu_{ws1})(W_{s2}-\mu_{ws2})\right]}{\sigma_{ws1}\sigma_{ws2}}$$

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

1. F. Li and R. Bo, "DCOPF-Based LMP Simulation: Algorithm, Comparison with ACOPF, and Sensitivity," *IEEE Trans. on Power Systems*, vol. 22, no. 4, pp. 1475-1485, November 2007. (ranked 2nd in the best paper award competition in 2011 by the IEEE System Economics committee)
2. F. Li, "Continuous Locational Marginal Pricing (CLMP)," *IEEE Trans. on Power Systems*, vol. 22, no. 4, pp. 1638-1646, November 2007.
3. R. Bo and F. Li, "Probabilistic LMP Forecasting Considering Load Uncertainty," *IEEE Trans. on Power Systems*, vol. 24, no. 3, pp. 1279-1289, August 2009. (2nd Place Prize at the Student Poster Contest at PSCE 2009).
4. F. Li and R. Bo, "Congestion and Price Prediction under Load Variation," *IEEE Trans. on Power Systems*, vol. 24, no. 2, pp. 911-922, May 2009.
5. F. Li, Y. Wei, and S. Adhikari, "Improving an Unjustified Common Practice in Ex Post LMP Calculation," *IEEE Trans. on Power Systems*, vol. 25, no. 2, pp. 1195-1197, May 2010.
6. F. Li, "Fully Reference-Independent LMP Decomposition Using Reference-Independent Loss Factors," *Electric Power Systems Research*, vol. 81, no. 11, pp. 1995-2004, Nov. 2011.
7. R. Bo and F. Li, "Efficient Estimation of Critical Load Levels Using Variable Substitution Method," *IEEE Trans. on Power Systems*, vol. 26, no. 4, pp. 2472-2482, Nov. 2011.
8. Y. Wei, F. Li, and K. Tomsovic, "Measuring the Volatility of Wholesale Electricity Prices Caused by the Wind Power Uncertainty with a Correlation Model," *IET Renewable Power Generation*, vol. 6, no. 5, pp.315-323, September 2012.
9. X. Fang, Q. Hu, F. Li, et al, "Coupon-Based Demand Response Considering Wind Power Uncertainty: A Strategic Bidding Model for Load Serving Entities," *IEEE Transactions on Power Systems*, vol. 31, no.2, pp. 1025-1037, Mar. 2016.
10. X. Fang, Y. Wei, F. Li, "Evaluation of LMP Intervals Considering Wind Uncertainty," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2495-2496, May 2016.

Thank you!

Questions and Answers?

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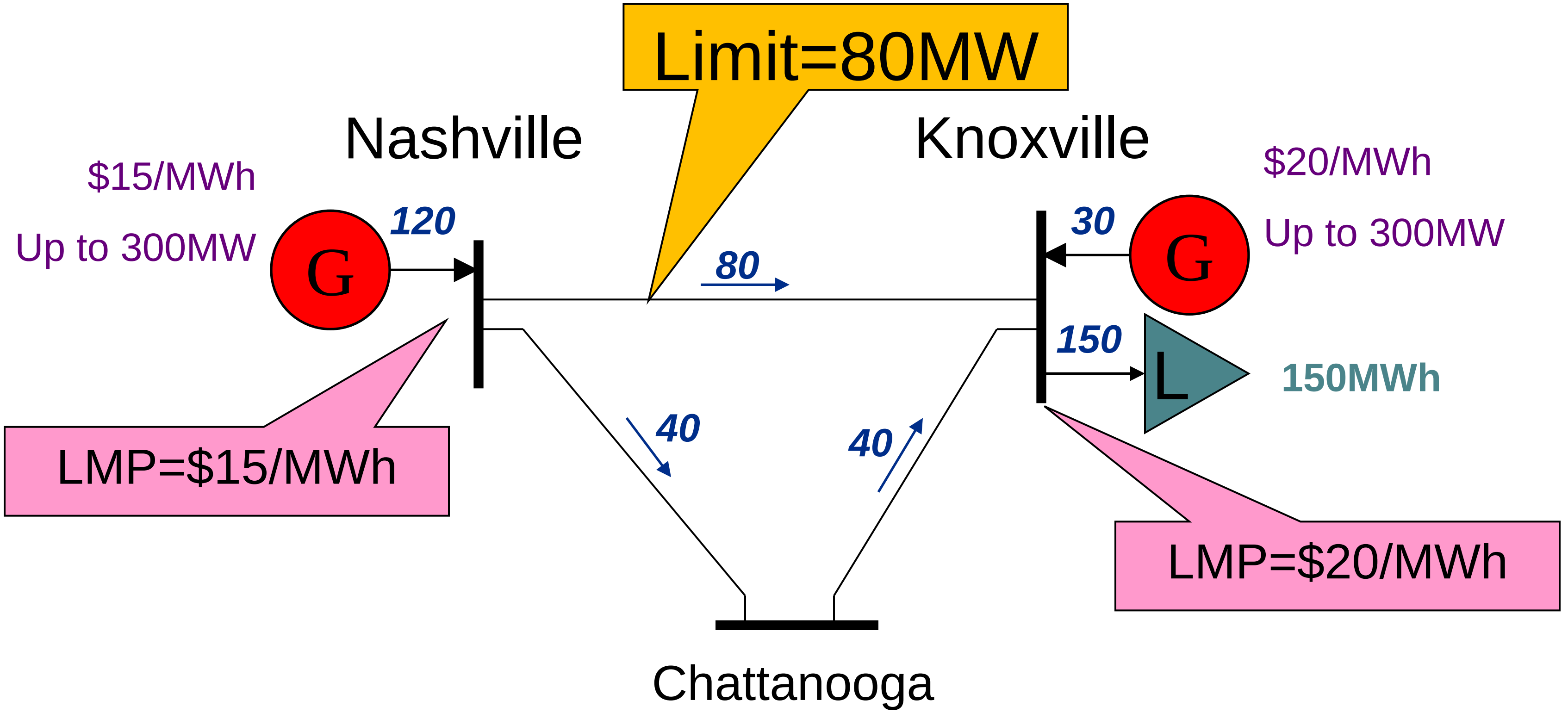
CURENT Course HW Assignment, by Dr. Fran Li, UTK



Question: What's the LMP at the Chattanooga bus?

Hint: Assume 1 MWh load at Chattanooga. How to dispatch additional MWh from the Nashville Generator and the Knoxville Generator to supply this 1MWh load at Chattanooga, without violating the 80MW flow limit?