

Monitoring Electric Power Markets: The role of the electric grid



**A Talk Presented at the
EIA Seminar Series
February 25, 2003**

by

**Robert J. Thomas
Cornell University
Ithaca, NY**



Work in Progress by CERTS/PSerc

Acknowledgements

Sensitivity-based metrics

Bob Thomas, Tim Mount, Ray Zimmerman, Ashkan Kian - Cornell

Bernie Lesieutre - LBNL

Fernando Alvarado - Wisconsin

Implementation

Bob Thomas, Ashkan Kian – Cornell

Jim Dyer – EPG

Bernie Lesieutre - LBNL

References

1. "An Engineering Approach to Monitoring Market Power in Restructured Markets for Electricity," C. Murillo Sanchez, T. D. Mount, R. J. Thomas, R. Zimmerman, presented at the 24th Annual International Association for Energy Economics International Conference, Houston, TX, April 2001
2. "Kirchhoff vs. Competitive Electricity Markets: A Few Examples", C. Murillo-Sanchez, R. Zimmerman, R.J.Thomas, IEEE Power Engineering Society Winter Meeting, 2001. IEEE , Volume: 3 , 2001 Page(s): 1256 -1261 vol.3
3. "A Revenue Sensitivity Approach for the Identification and Quantification of Market Power in Electric Energy Markets," B.C. Lesieutre, R.J. Thomas, and T.D. Mount, submitted to the IEEE Power Engineering Society General Meeting, Toronto, CA, July 2003.
4. "Identification of Load Pockets and Market Power in Electric Power Systems", B. C. Lesieutre , R. J. Thomas, T. D. Mount, submitted to the Elsevier Journal on Decision Support Systems Special Issue on Competitive Electricity Markets, Jan. 2003

Summary of Market Metrics

NEISO



Metric	Category	Usefulness	Frequency	Implementation	Data
Data-Based Measures					
HHI	Ex-Ante; Ex-Post	FERC standard	Variable	Straightforward to calculate	Available
Optimal Hedge Ratio	Ex-Ante	Assess motivation to withhold	Daily	Straightforward to calculate	Forward data must be purchased
Spot/Forward Market Ratio	Near Real Time	Evaluate market performance	Daily	Straightforward to calculate	Available
Spot/Forward Price Ratio	Near Real Time	Evaluate market performance	Daily	Straightforward to calculate	Available
Spark Spread	Near Real Time	Assess motivation to withhold	Variable	Straightforward to calculate	Available
Lerner Index on Price Setters	Near Real Time	Examines ability to set price	Hourly	Straightforward to calculate	MC must be estimated
Relative Market Power (Generator)	Ex-Ante	Evaluate degree of market power	Monthly or Seasonal	Unit Commitment Model; Considerable Effort	Available
Relative Market Power (Aggregate)	Ex-Post	Evaluate market performance	Monthly or Seasonal	Straightforward to calculate	Available
Econometric Studies	Near Real Time	Measure ECP/Capacity relationship	Daily	Model Development; Considerable Effort	Available
Incentives to Withhold	Ex-Ante	Assess whether ECP conditions could motivate withholding	Daily & Spikes	Considerable effort	May be difficult to obtain
Strength of Mean Reversion	Near Real Time	Measures price stability	Monthly & Spikes	Complex	Available for limited time frame
Simulation Analysis	Ex-Ante	Longer run market performance	Periodic studies	Considerable effort	Most collected by system operators
Theory Based Metrics	Development	Assess New Markets/Rule Changes	Periodic studies	Considerable effort	

Market Power: Substitutability



“Market power is the ability to raise prices above the competitive level.” (FERC SMD §393)

**Market power boils down to the issue of
substitutability**

Pairwise substitutability

We know **duopolies** have market power.
That is, two generators in a repeated auction market can and will raise prices with impunity. There is an easy explanation of how they do it. So, the issue of pairs that have market power must be addressed.

Electric markets are:

1. Dynamic in that they are repeated hourly, daily, monthly, etc. so **learning** takes place
2. Enabled by a network that obey laws of **physics**, not economic incentives
3. Necessarily incomplete so that some **monitoring and mitigation** is necessary

On the supply-side

Non-substitutable $\Leftrightarrow$ must-run

e.g.,

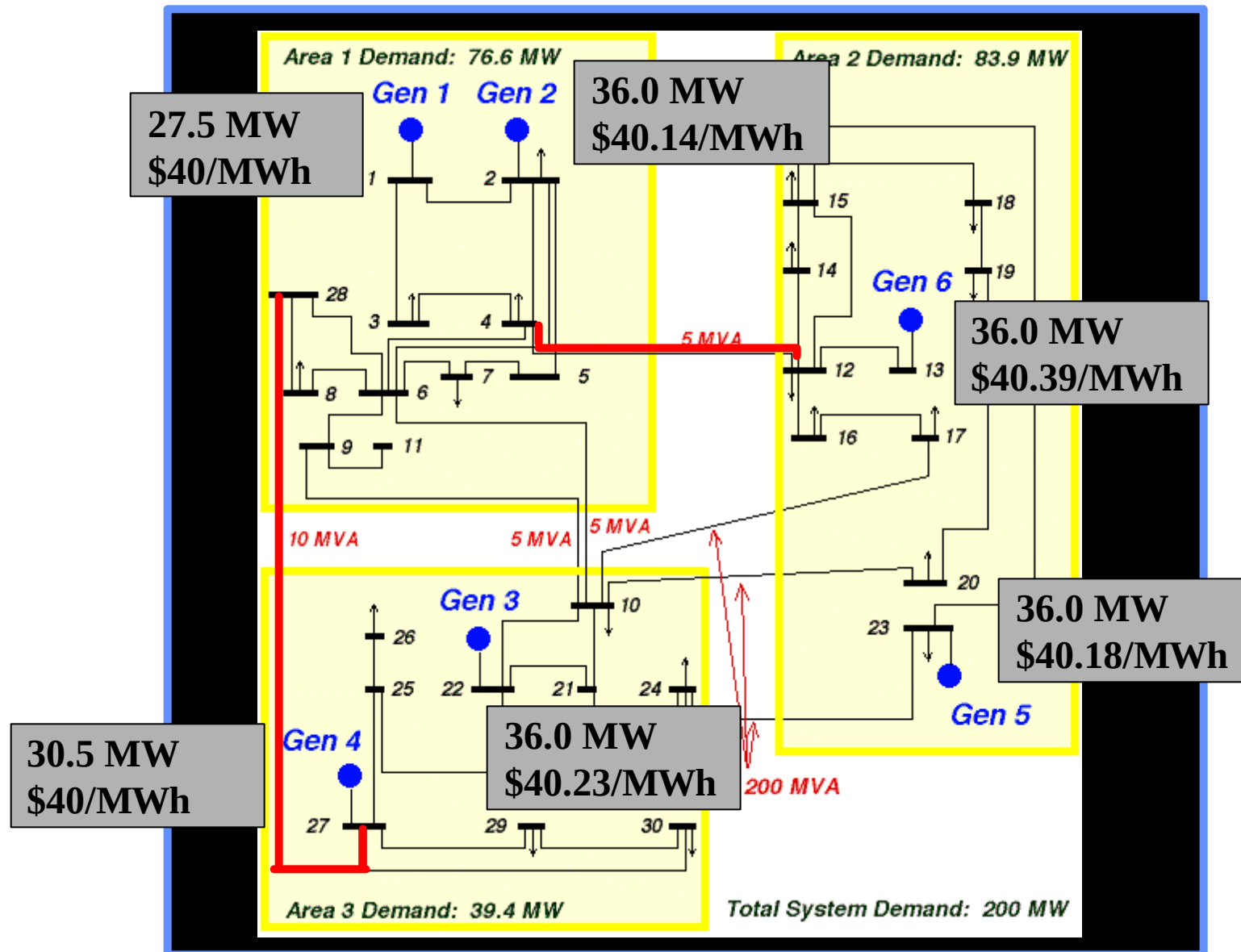
- a. Must-run on load (load pocket, line-flow constraint)**
- b. Must-run on Var's (engineering constraint)**
- c. Must-run on reserves (contingency constraint)**

Show several examples next

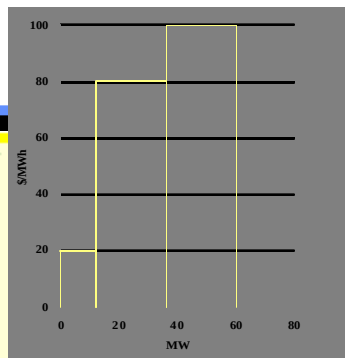
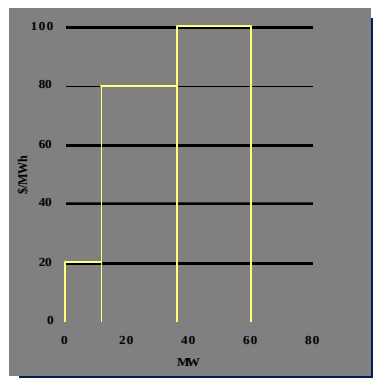
Create/exploit market by

- **Locational advantages**
- **Withholding**
- **Strategic offers**

Example 1 - IEEE 30 bus test system Marginal cost offers

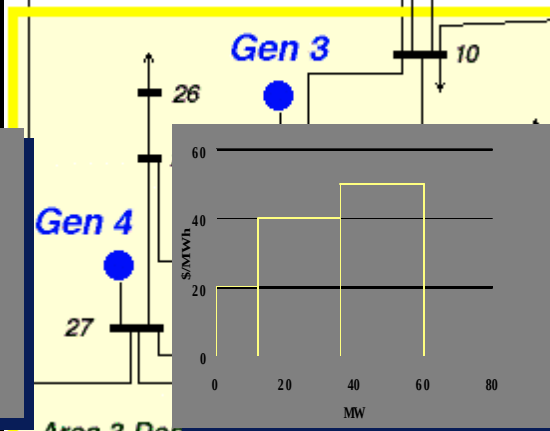
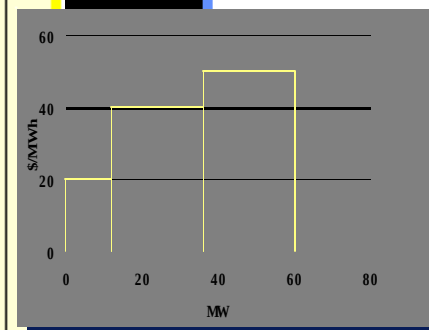
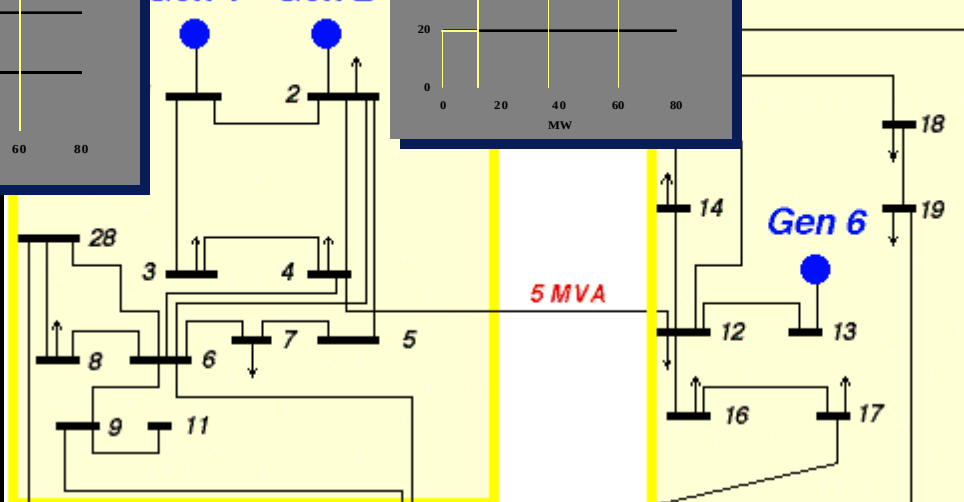


Tacit Collusion



Demand: 76.6 MW
Gen 1 Gen 2

2 Demand: 83.9 MW



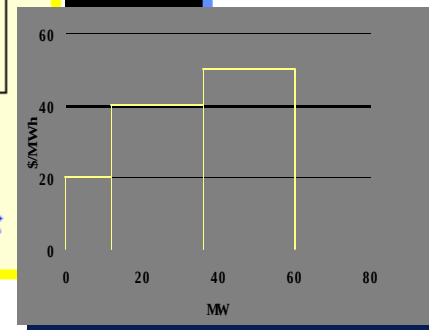
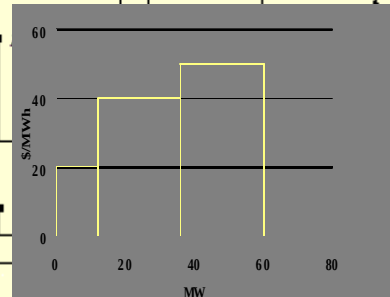
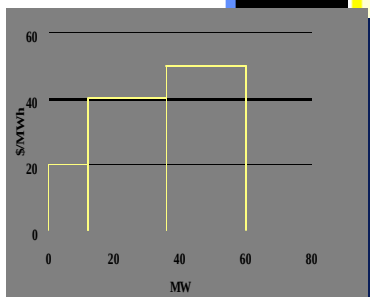
Gen 4

Gen 3

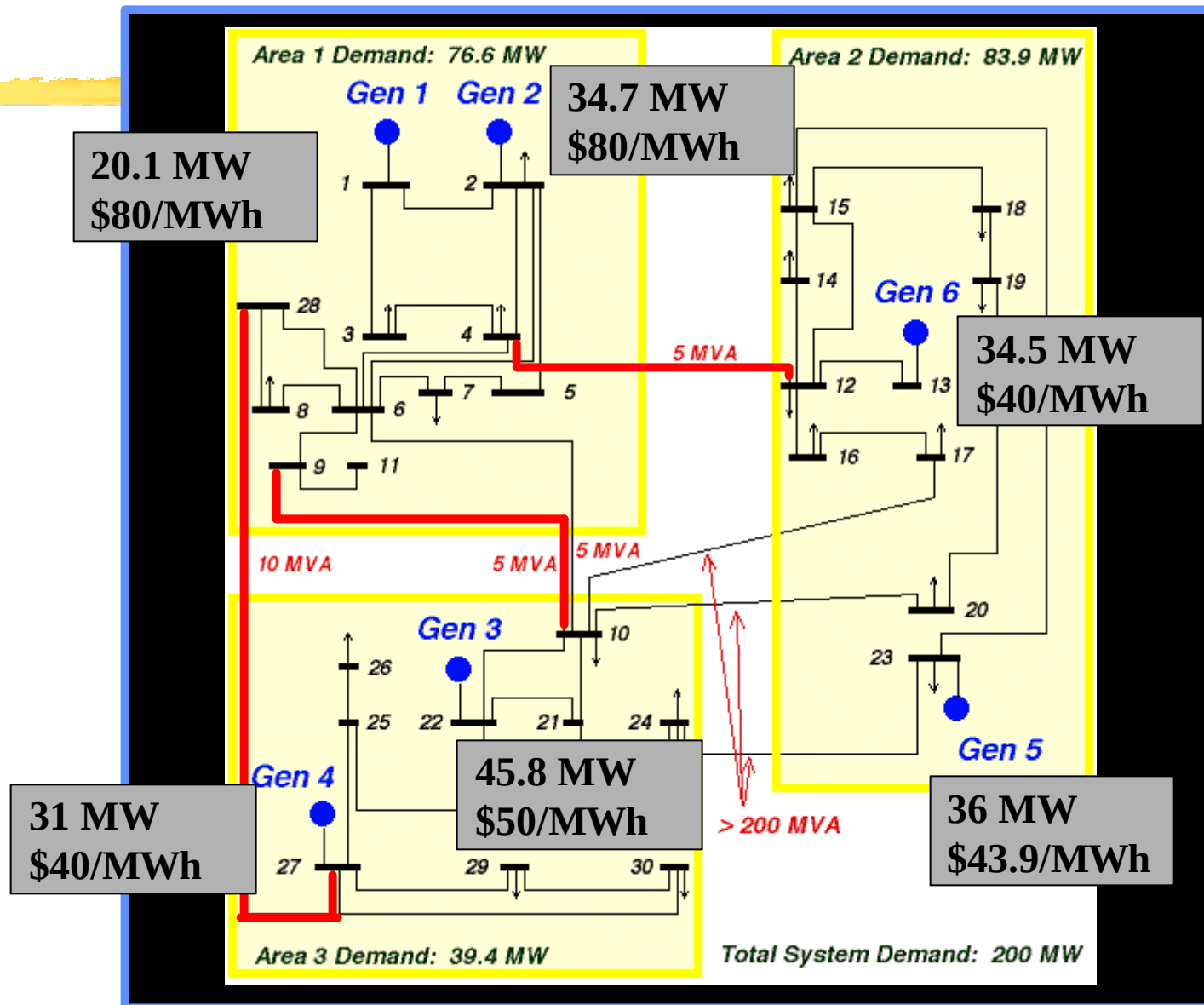
Area 3 Demand: 60 MW

> 200 MVA

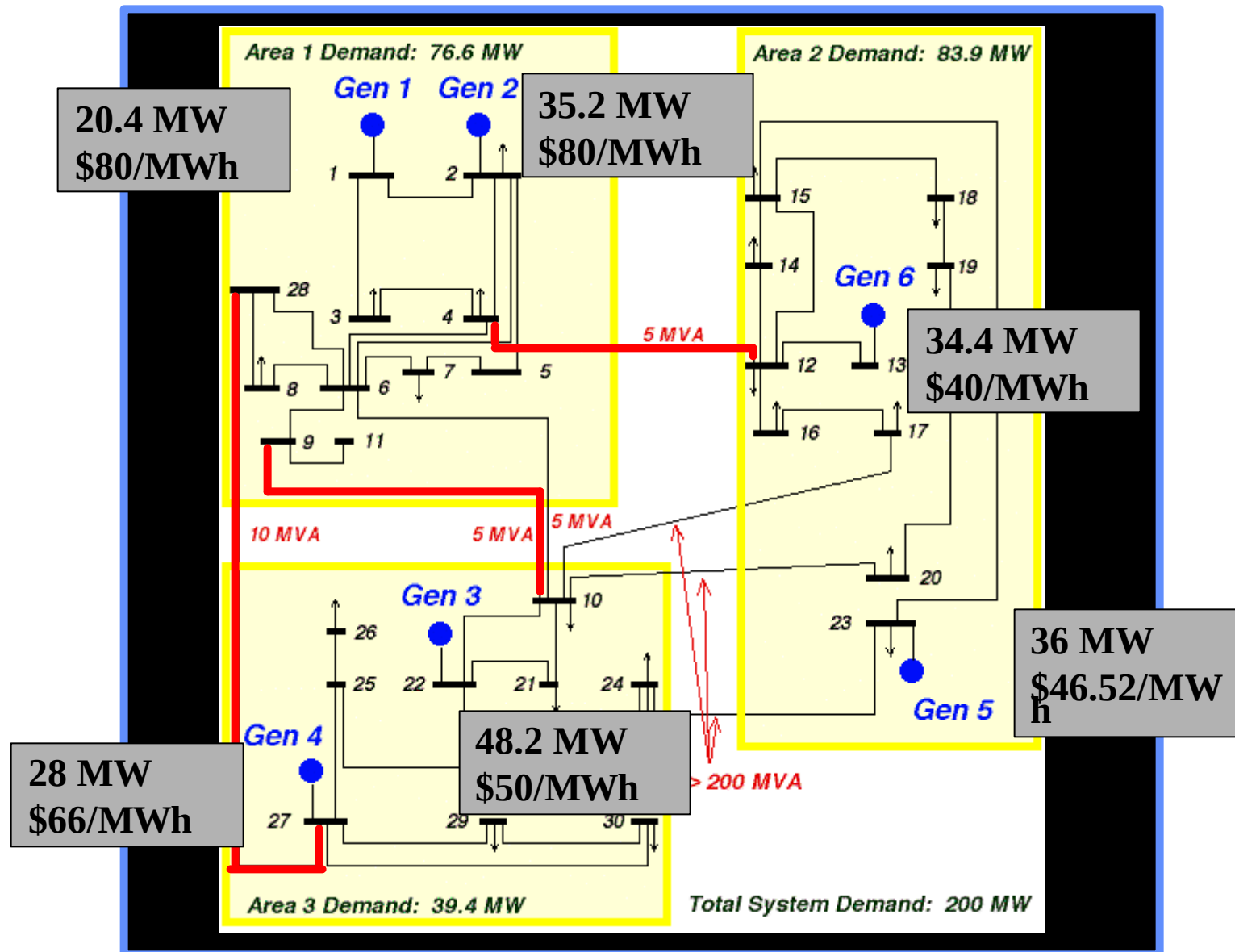
Total System Demand: 200 MW



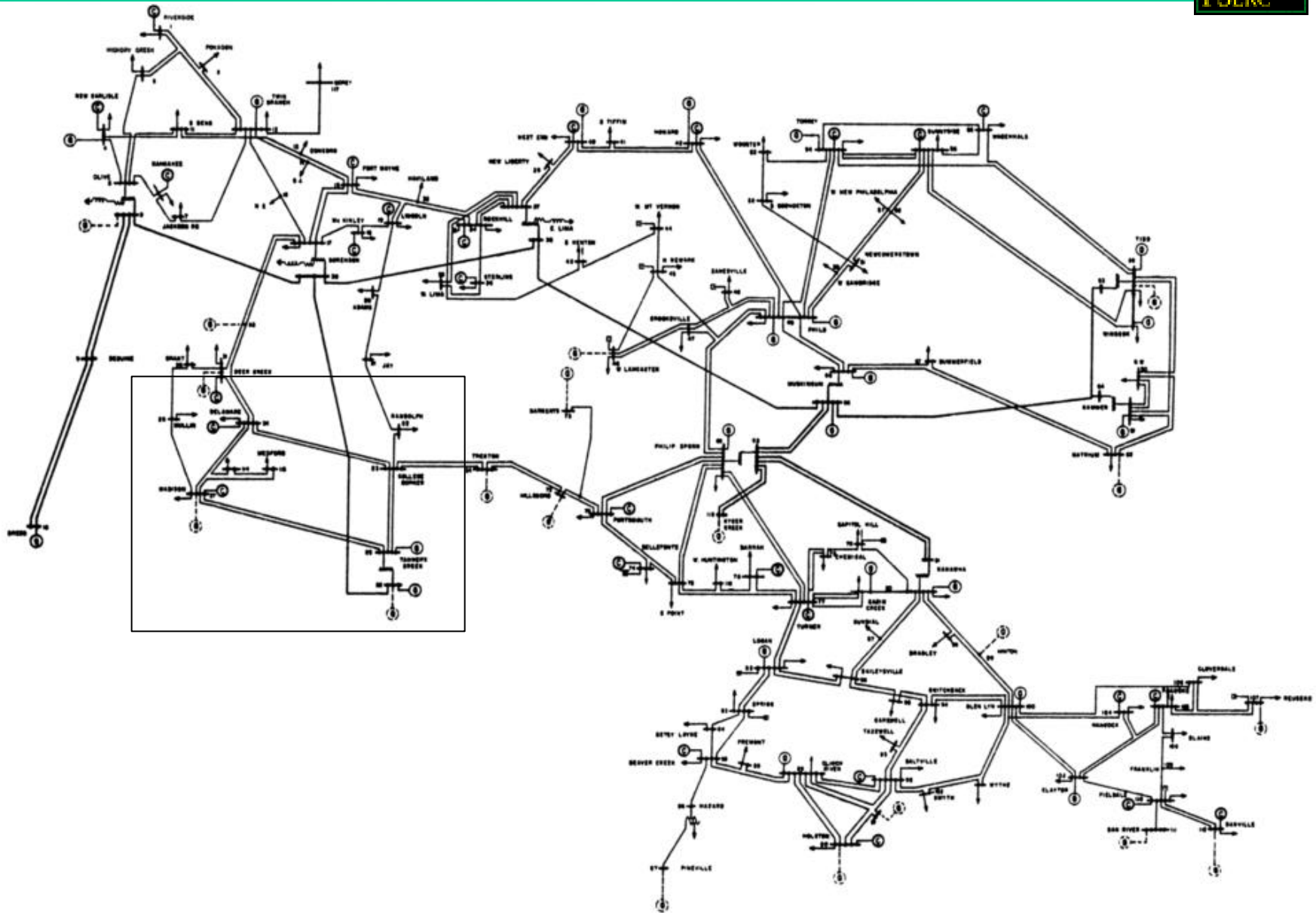
Market Power (duopoly)



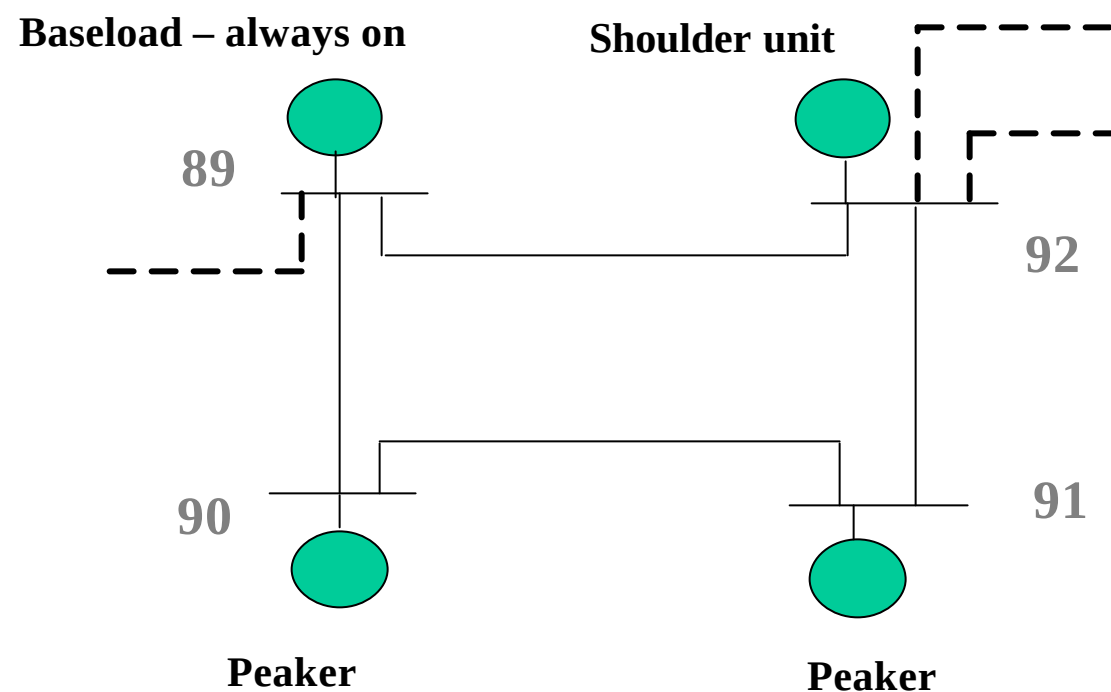
Cascading Market Power



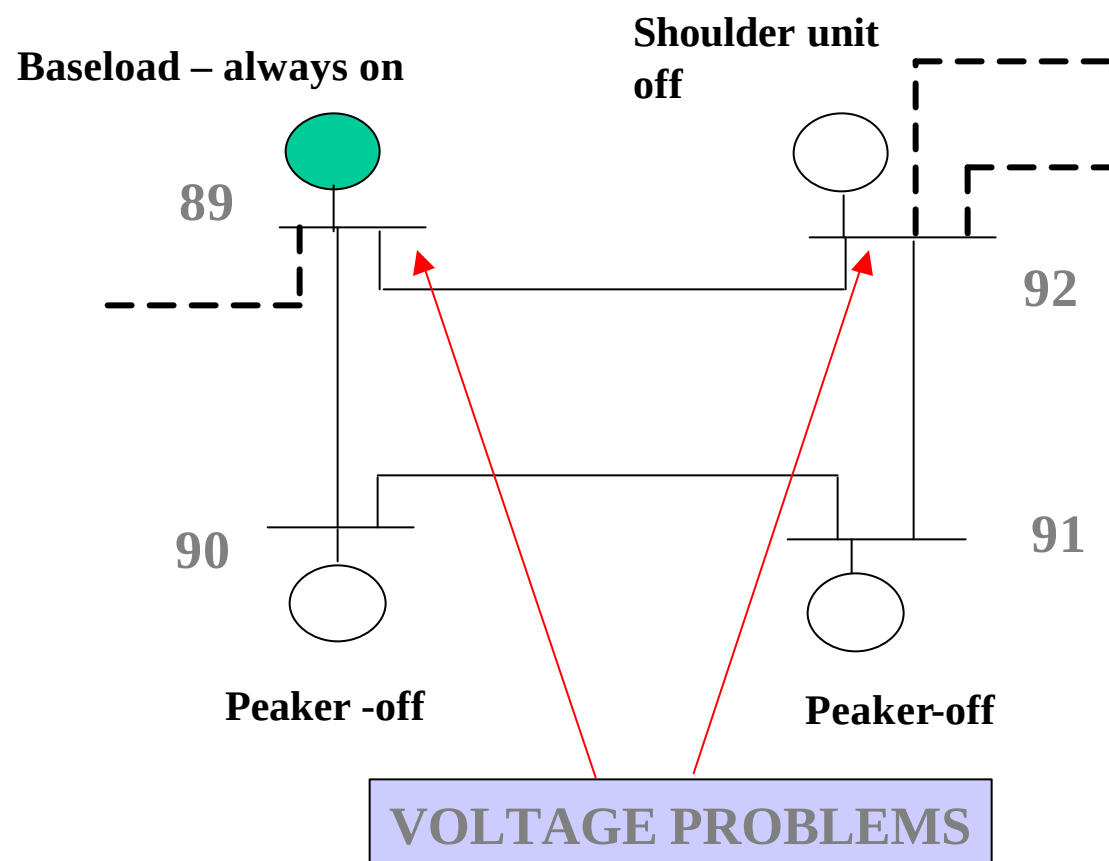
Example 3 - IEEE 118 bus test system



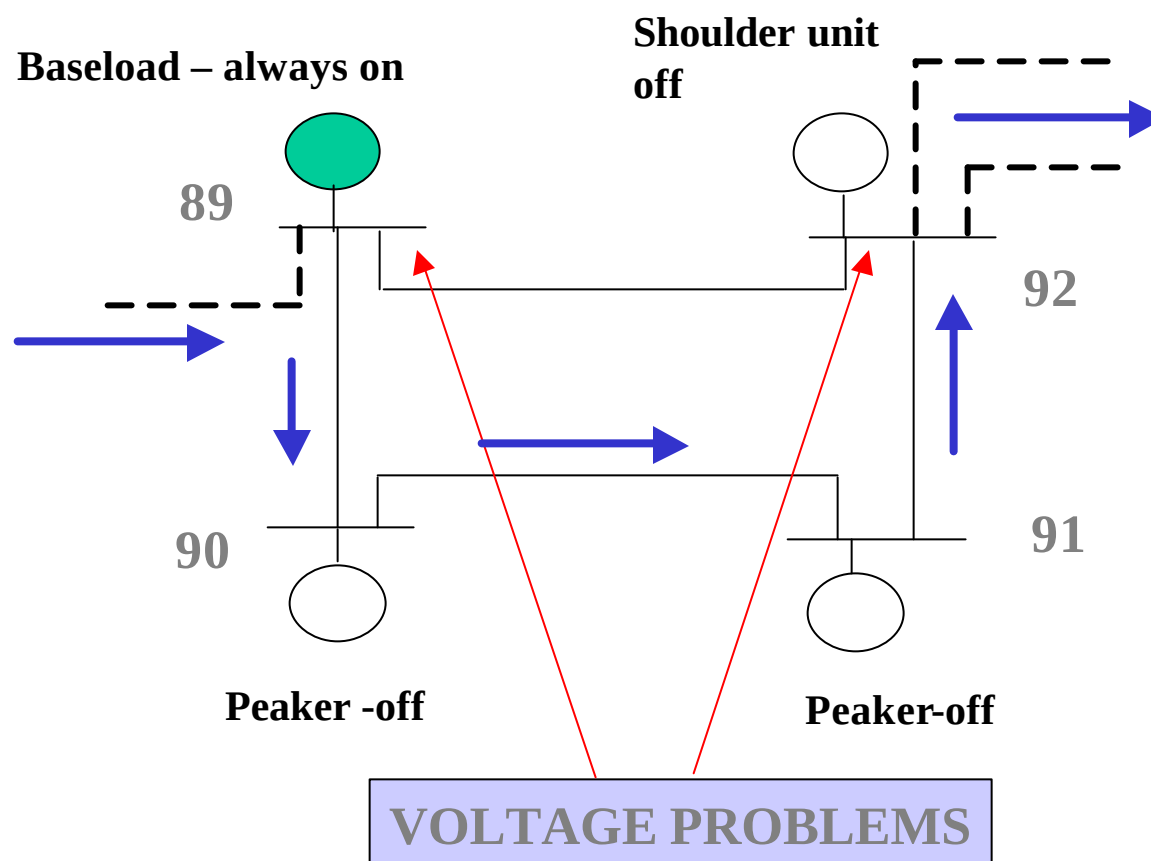
Highlighted area – peak load



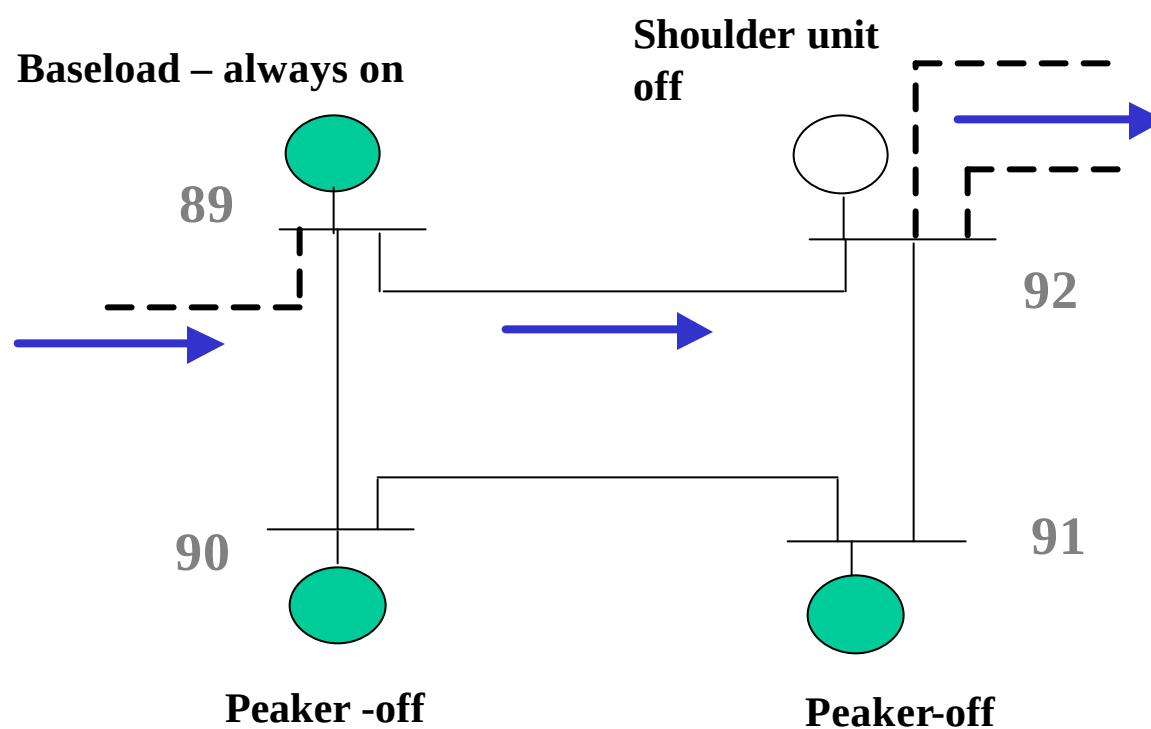
Preferred night solution



Preferred night solution

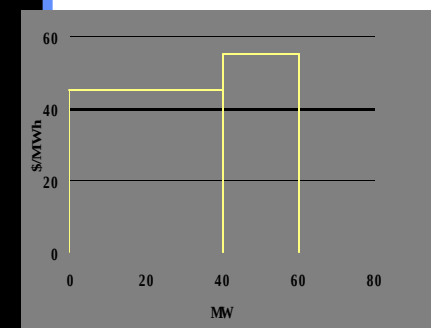
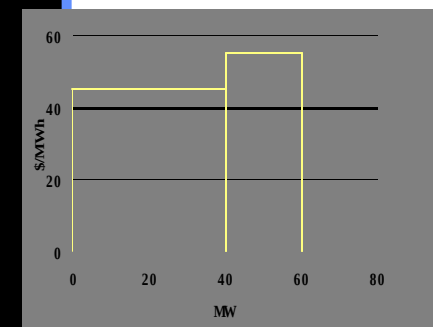
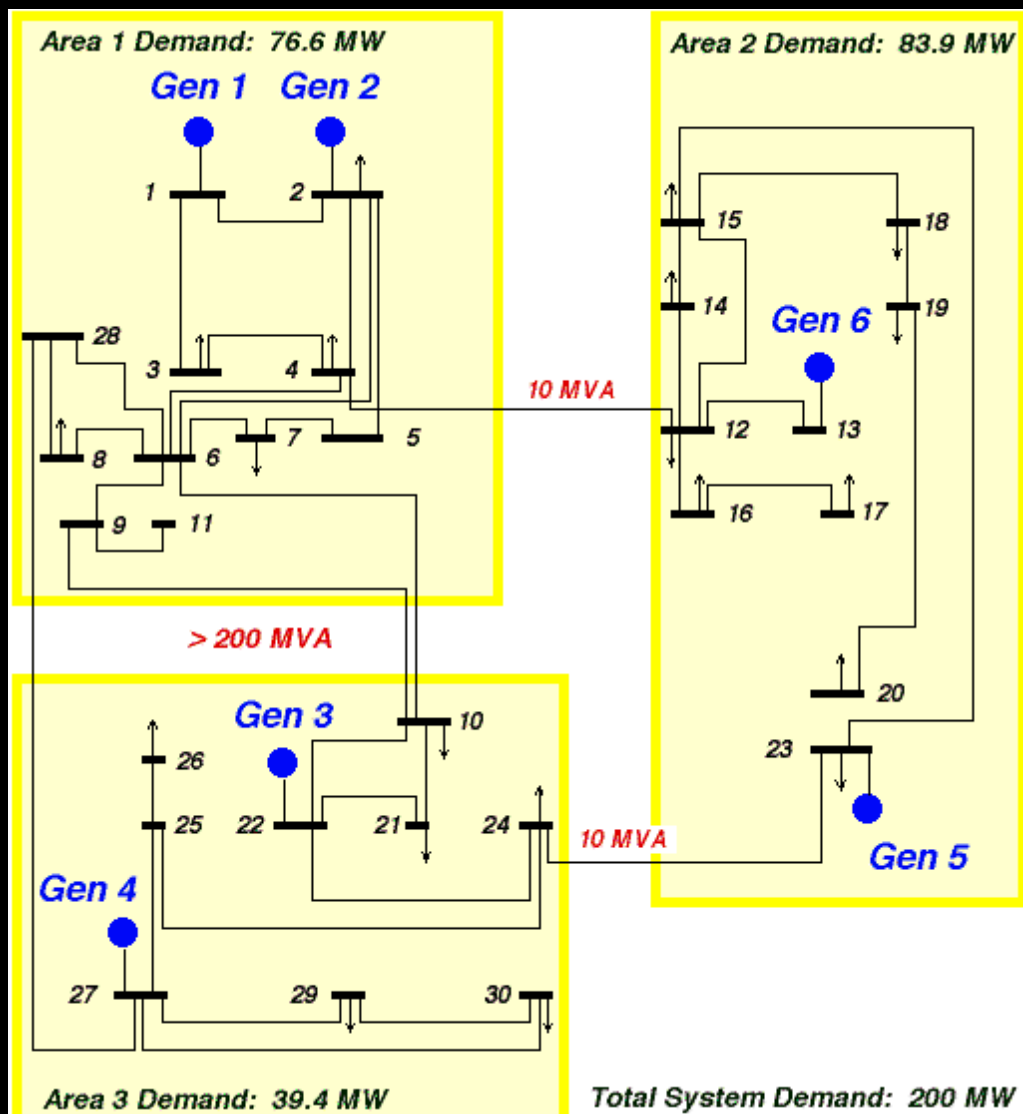


Actual solution

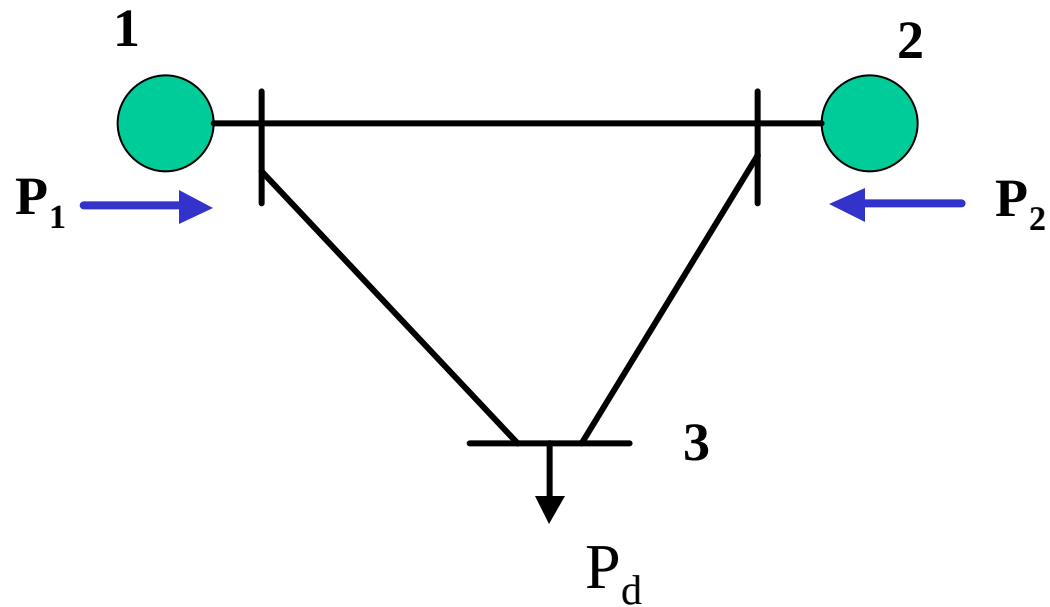


Peakers have market power at night

Example 4 – IEEE 30 bus test system – must run on contingencies



Example 5 – Simple 2 generator system



The problem for generator 1

$$\underset{b_1}{\text{Max}} \, l(b_1) P_1(b_1) = \underset{b_1}{\text{Max}} \, r_1(b_1)$$

subject to

$$l = a_1 * P_1 + b_1$$

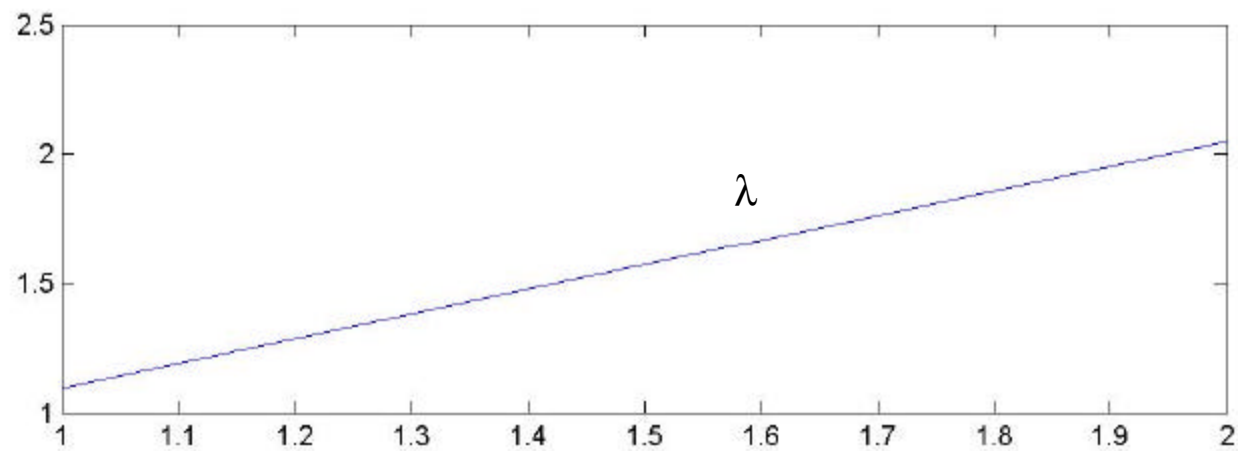
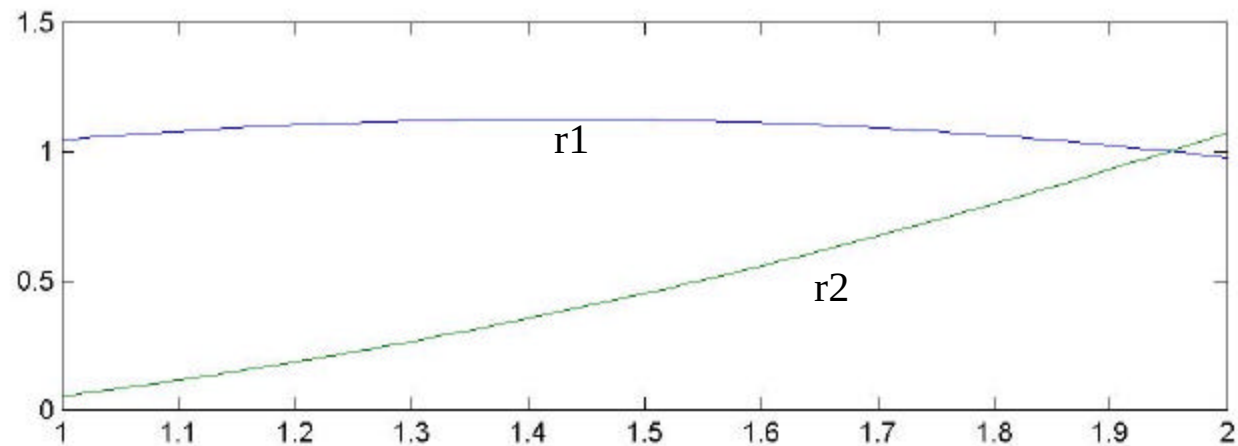
$$l = a_2 * P_2 + b_2$$

$$P_1 + P_2 = P_d$$

i.e., The problem is to find offer b_1 to maximize
Generator 1's revenue

Revenue and Nodal Price vs Generator 1 Offers

Generator 2 offers are at MC

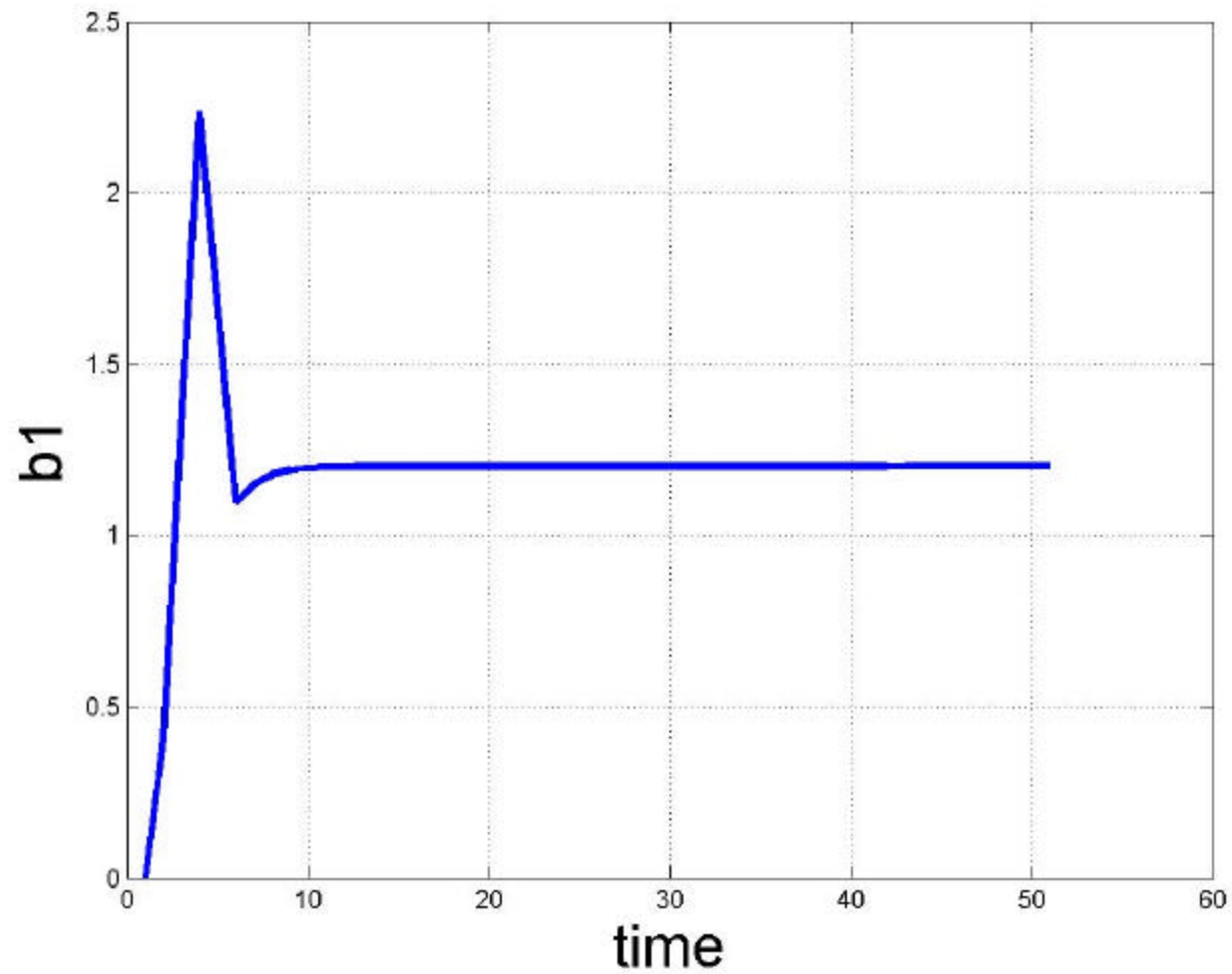


Using a greedy agent to try to achieve the max

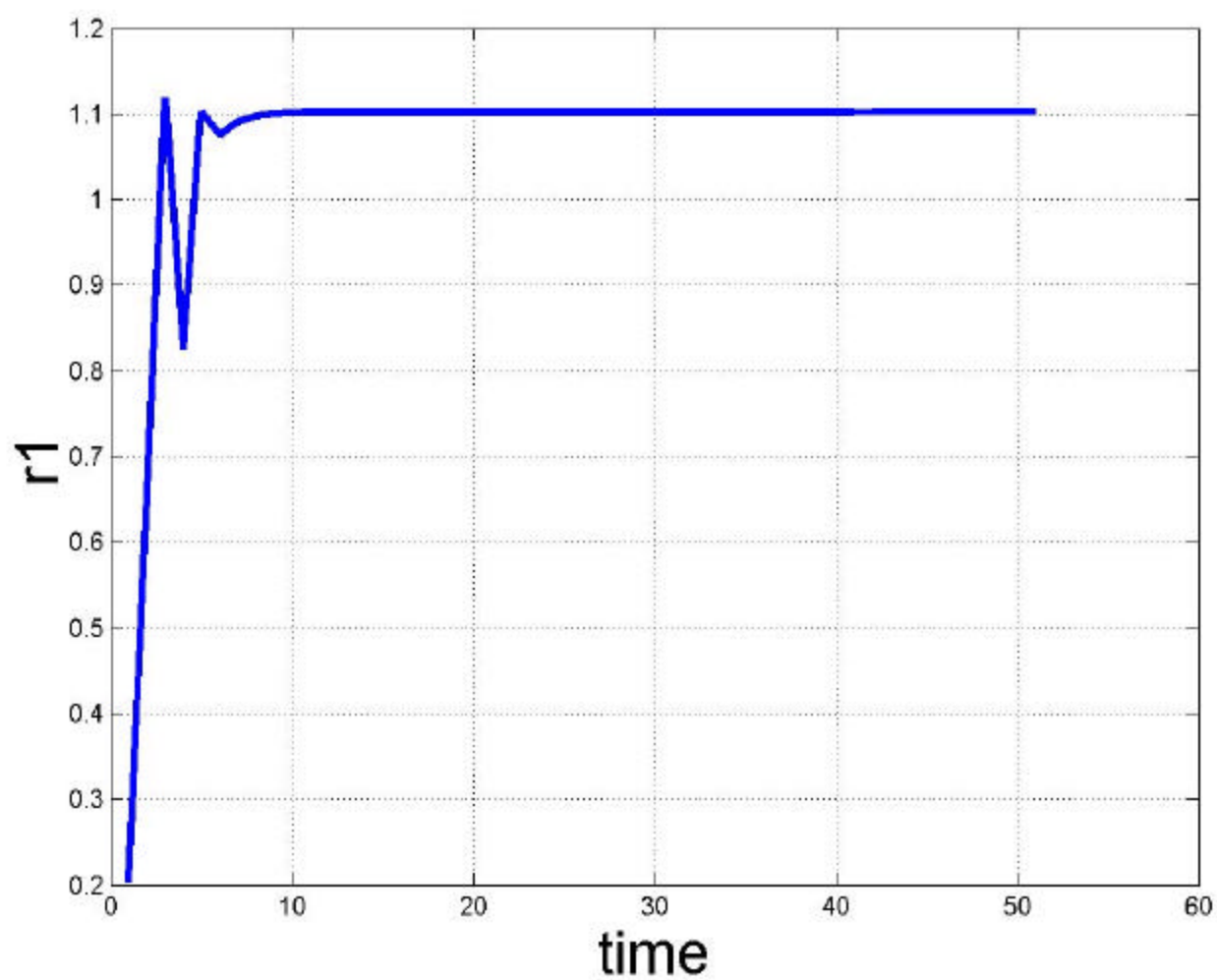


$$b_1(k+1) = b_1(k) + h_1 * \text{sign}(b_1(k) - b_1(k-1)) * (r_1(k) - r_1(k-1))$$

Generator 1 greedy agent offers



Generator 1 Greedy Agent Revenue



Identifying Market Power: A Sensitivity-based Approach



Examine dispatch/offer sensitivities

$$\frac{\Delta G}{\Delta l} = M \quad \text{normalized} \quad \frac{l_i^*}{G_j^*} m_{ij} = e_{ij}$$

**Where G is the dispatch and l is the price
Revenue/offer sensitivities**

$$\frac{\Delta r}{\Delta l} = N$$

Where r = l G is the revenue earned by G

Analytical Framework

- 1) The solution to an OPF corresponds to a minimum cost solution
- 2) Resolving the OPF by replacing the offers with optimal nodal prices gives the same optimal dispatch.
- 3) Minimum Cost = C (nodal prices, loads)

$$\nabla_{\text{price}} C = \text{Optimal Dispatch}$$

$$\nabla_{\text{price}}^2 C = \text{Matrix of Price Effects}$$

**Could calculate the sensitivities from
Hessian/Jacobian calculations (normally
available data for calculations such as
state estimation) if cost curves are
continuous.**

Two-OPF algorithm:

- Obtain the operating point from an OPF using all market and system information.
- Perform a second OPF replacing block offers with the nodal prices from the first OPF.
- Calculate the sensitivity of revenues to offer prices in second OPF (the nodal prices in the first OPF).

Sufficient Conditions for Market Power

(based on the condition $\partial(\text{revenue})/\partial(\text{price}) > 0$)

For a single generator $\partial r_i / \partial l_i > 0$

$$r_i = G_i \times l_i > 0$$

$$\text{For } \Delta r_i = G_i^* \times \Delta l_i + l_i^* \times \Delta G_i$$

$$\text{if } \Delta r_i / \Delta l_i = G_i^* + l_i^* \times (\Delta G_i / \Delta l_i) > 0$$

$$\Rightarrow G_i^* + l_i^* \times m_{ii} > 0$$

$$\text{or } 1 + (l_i^* / G_i^*) m_{ii} > 0$$

that is:

$$\text{Own normalized price sensitivity } = \epsilon_{ii} > -1$$

Sufficient Conditions for Market Power

For a group of generators $Dr_1 + Dr_2 > 0$ for $Dl_1 > 0, Dl_2 > 0$,

Revenue for generator i in the group will increase if :

$$\sum_{j=1}^r e_{ij} > -1$$

and the potential for market power exists for the group if :

$$\sum_{i=1}^r r_i (1 + \sum_{j=1}^r e_{ij}) > 0$$

for, say, a group of two generators out of N

$e_{11} + e_{12} > -1$ (revenue increase for generator 1 for own price increase)

$e_{21} + e_{22} > -1$ (revenue increase for generator 2 for own price increase)

and/or

$r_1 (1 + e_{11} + e_{12}) + r_2 (1 + e_{21} + e_{22}) > 0$ (revenue increase for the pair of generators 1 and 2 if they both increase price)

Withholding

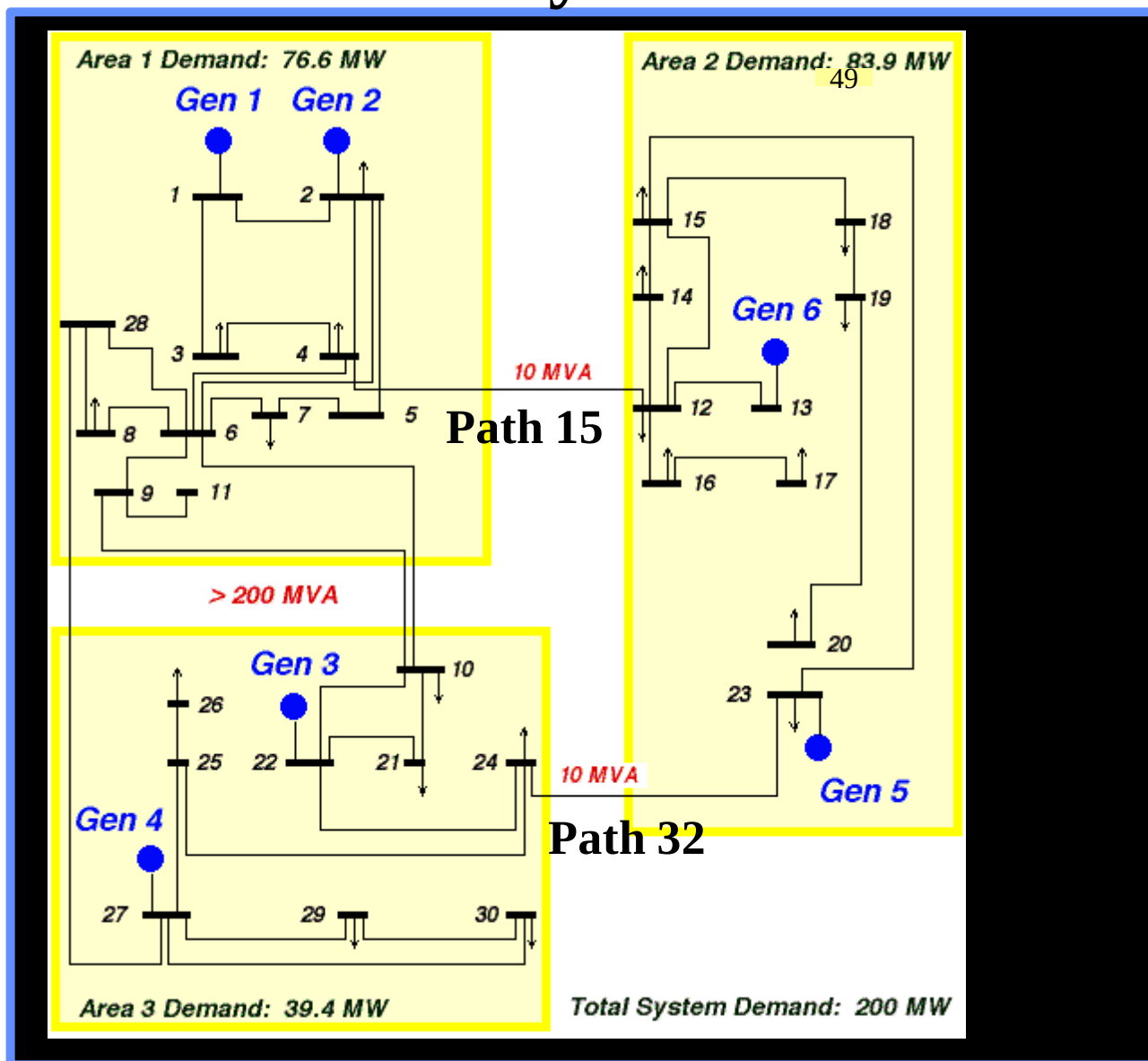
Single generator

$$Dr_i/DG_i < 0$$

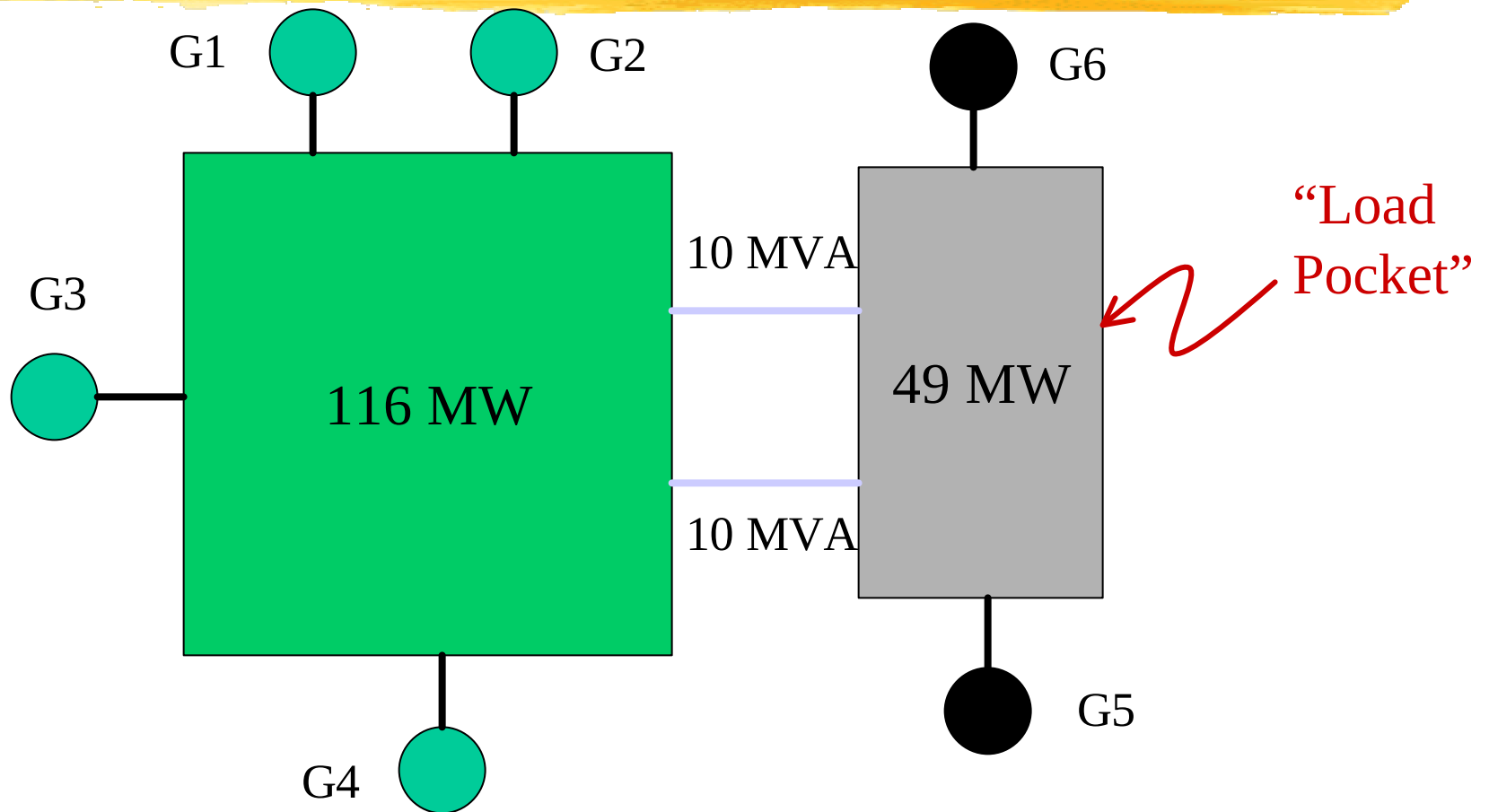
Two generators

$$Dr_1 + Dr_2 > 0 \text{ for } DG_1 \text{ and/or } DG_2 < 0$$

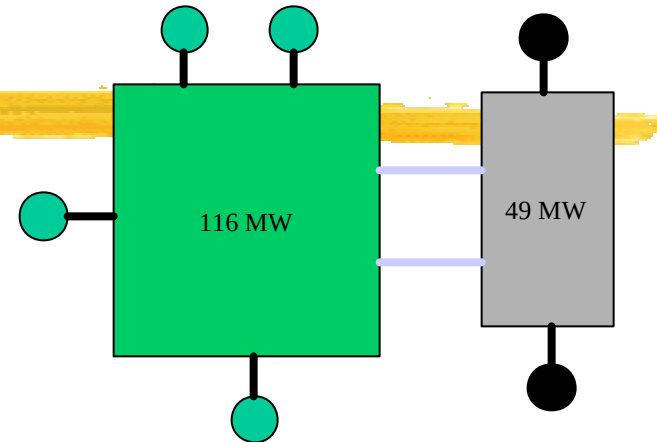
IEEE 30 Bus Test System



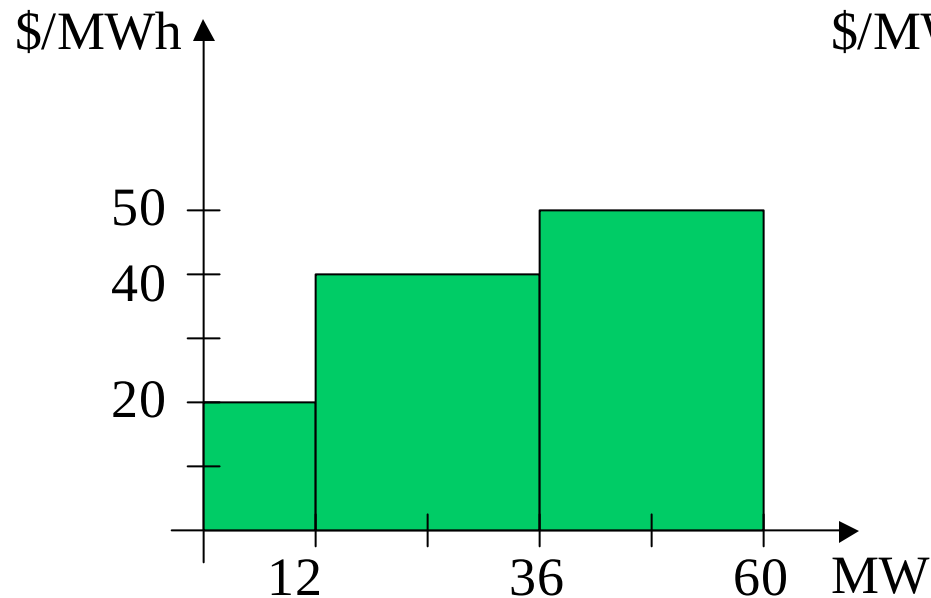
Six Supplier Example (Market Power)



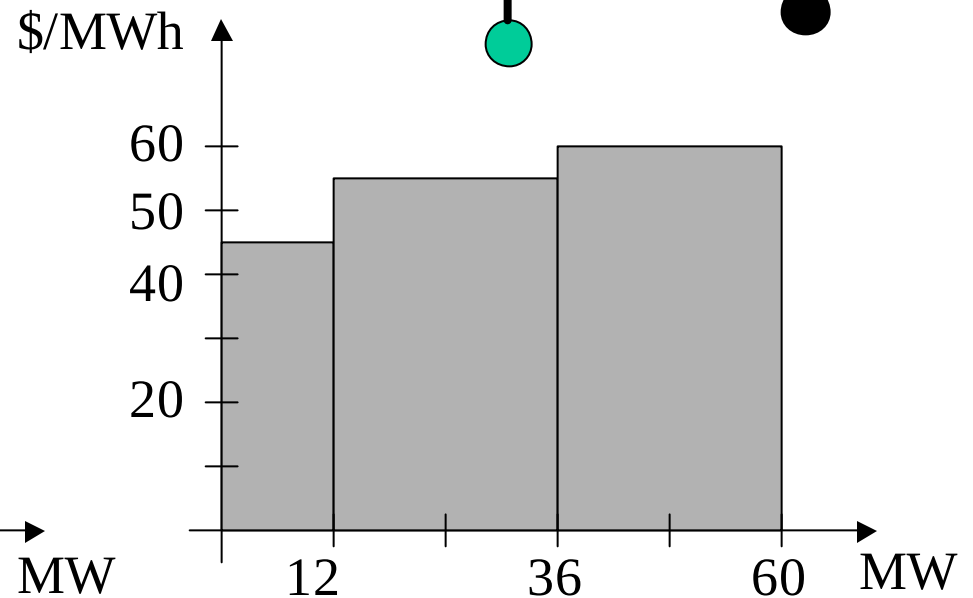
Six Supplier Example (Market Power)



Competitive Offers:



Generators 1-4



Generators 5-6 Higher to create
load pocket



Results (75 round experiment)

Competitive Solution

	G1	G2	G3	G4	G5	G6
Dispatch (MW)	31.7	36.0	34.0	36.0	17.6	12.0
Price (\$/MWh)	40.0	40.1	40.0	40.1	55.0	54.3

Actual Experiment*

* 80 \$/MWh price cap

	G1	G2	G3	G4	G5	G6
Dispatch (MW)	37.9	34.9	30.1	34.9	14.9	14.6
Price (\$/MWh)	48.5	48.7	48.5	48.6	72.0	70.0

Results: Experiment

Generators in the load pocket were able to raise prices well above competitive levels (and would have increased further with a longer experiment).

Matrix of Revenue/Offer Sensitivities



Competitive solution

$$\begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \Delta r_3 \\ \Delta r_4 \\ \Delta r_5 \\ \Delta r_6 \end{bmatrix} = \begin{bmatrix} -3298 & 3231 & 31 & 65 & 52 & -49 \\ 3219 & -3695 & 244 & 263 & 315 & -310 \\ 31 & 244 & -544 & 308 & -234 & -229 \\ 65 & 263 & 307 & -597 & -127 & 125 \\ 38 & 230 & -170 & -93 & -160 & 173 \\ -36 & -229 & 169 & 92 & 175 & -159 \end{bmatrix} \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \\ \Delta l_4 \\ \Delta l_5 \\ \Delta l_6 \end{bmatrix}$$

Observations:

- If any supplier, acting alone, raises its (offer) price, that supplier will lose revenue.
- If all suppliers, acting together, raise (offer) prices, everyone's revenue increases.

Matrix of Revenue/Offer Sensitivities

Competitive solution

$$\begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \Delta r_3 \\ \Delta r_4 \\ \Delta r_5 \\ \Delta r_6 \end{bmatrix} = \begin{bmatrix} -3298 & 3231 & 31 & 65 & 52 & -49 \\ 3219 & -3695 & 244 & 263 & 315 & -310 \\ 31 & 244 & -544 & 308 & -234 & -229 \\ 65 & 263 & 307 & -597 & -127 & 125 \\ 38 & 230 & -170 & -93 & -160 & 173 \\ -36 & -229 & 169 & 92 & 175 & -159 \end{bmatrix} \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \\ \Delta l_4 \\ \Delta l_5 \\ \Delta l_6 \end{bmatrix}$$

Observations:

- If the load pocket generators (5 and 6) raise their (offer) prices together, *their own revenues increase* with almost no effect on the revenue of others.

Competitive Case Price Sensitivities



$$\begin{bmatrix} \Delta g_1 \\ \Delta g_2 \\ \Delta g_3 \\ \Delta g_4 \\ \Delta g_5 \\ \Delta g_6 \end{bmatrix} = \begin{bmatrix} -105 & 101.9 & 1.0 & 2.0 & 1.6 & -1.5 \\ 89.5 & -103.7 & 6.8 & 7.3 & 8.7 & -8.6 \\ 0.9 & 7.2 & -17 & 9.1 & -6.9 & 6.7 \\ 1.8 & 7.3 & 8.5 & -17.6 & -10.1 & 9.8 \\ 2.2 & 13.1 & -9.7 & -5.3 & -10.1 & 9.8 \\ -3.0 & -19.1 & 14.1 & 7.7 & 14.6 & -14.3 \end{bmatrix} \begin{bmatrix} \Delta l_1 \\ \Delta l_2 \\ \Delta l_3 \\ \Delta l_4 \\ \Delta l_5 \\ \Delta l_6 \end{bmatrix}$$

$$\mathbf{G} = \mathbf{M} \mathbf{l}$$

The price sensitivity matrix shows that



if generators 5 and 6 together raise their offer prices by one unit each while all other offers remain constant, generator 5 will experience a decrease in dispatch of only 0.4 units while the dispatch of generator 6 will increase by only 0.3 units.

That is:

For

$$Dl_1 = Dl_2 = Dl_3 = Dl_4 = 0$$

From the matrix of revenue sensitivities

$$Dr_5 = -160 Dl_5 + 173 Dl_6$$

$$Dr_6 = 170 Dl_5 - 159 Dl_6$$

Conclusion - If generators 5 and 6 raise their offers together by \$1/MWh, generator 5 will **increase** its revenue by \$13/hr (while decreasing its dispatch by 0.4 MW) and generator 6 will **increase** its revenue by \$16/hr (while increasing its dispatch by 0.3 MW)

NOTE: INDIVIDUALLY THEY CANNOT RAISE PRICES

Load Pocket Market Power

Generators 5 and 6 have the **potential** to exercise market power when the load is above 165MW

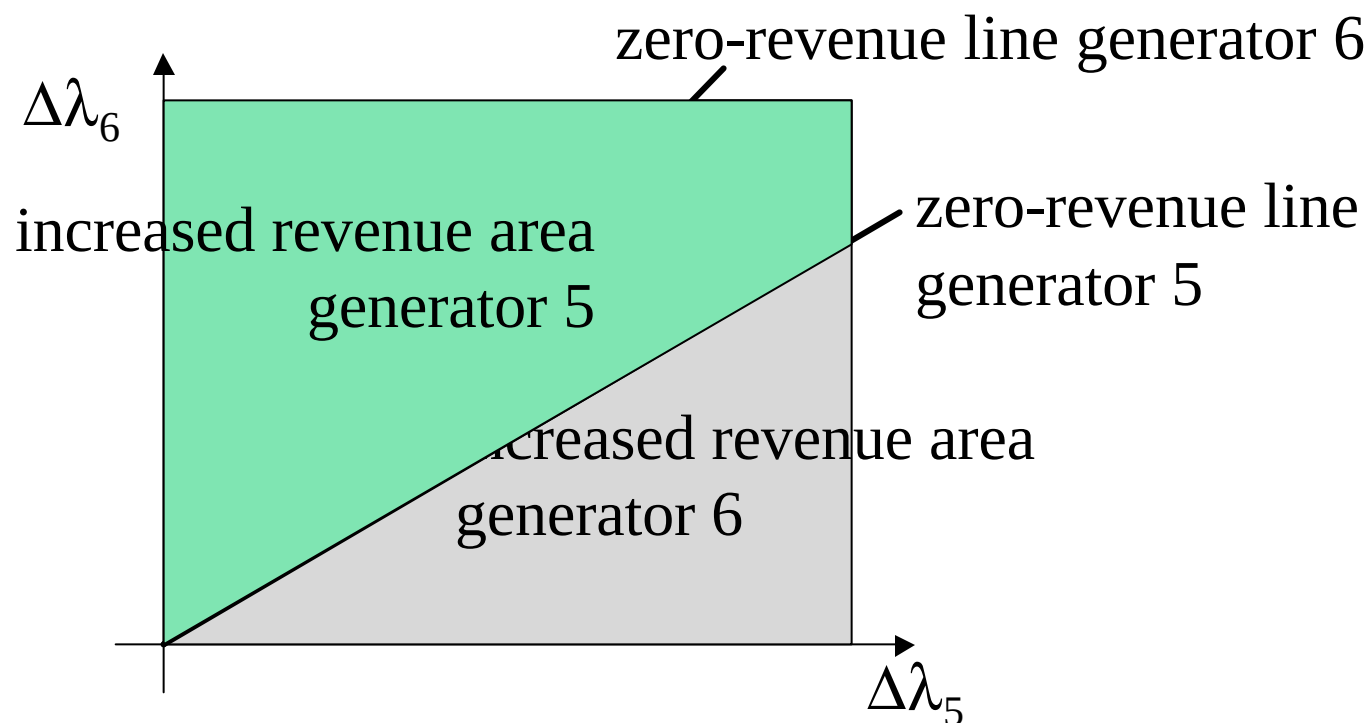
Experiments show that they do exploit this potential.

How do they do it without direct collusion?

Load Pocket Market Power

Closer examination:

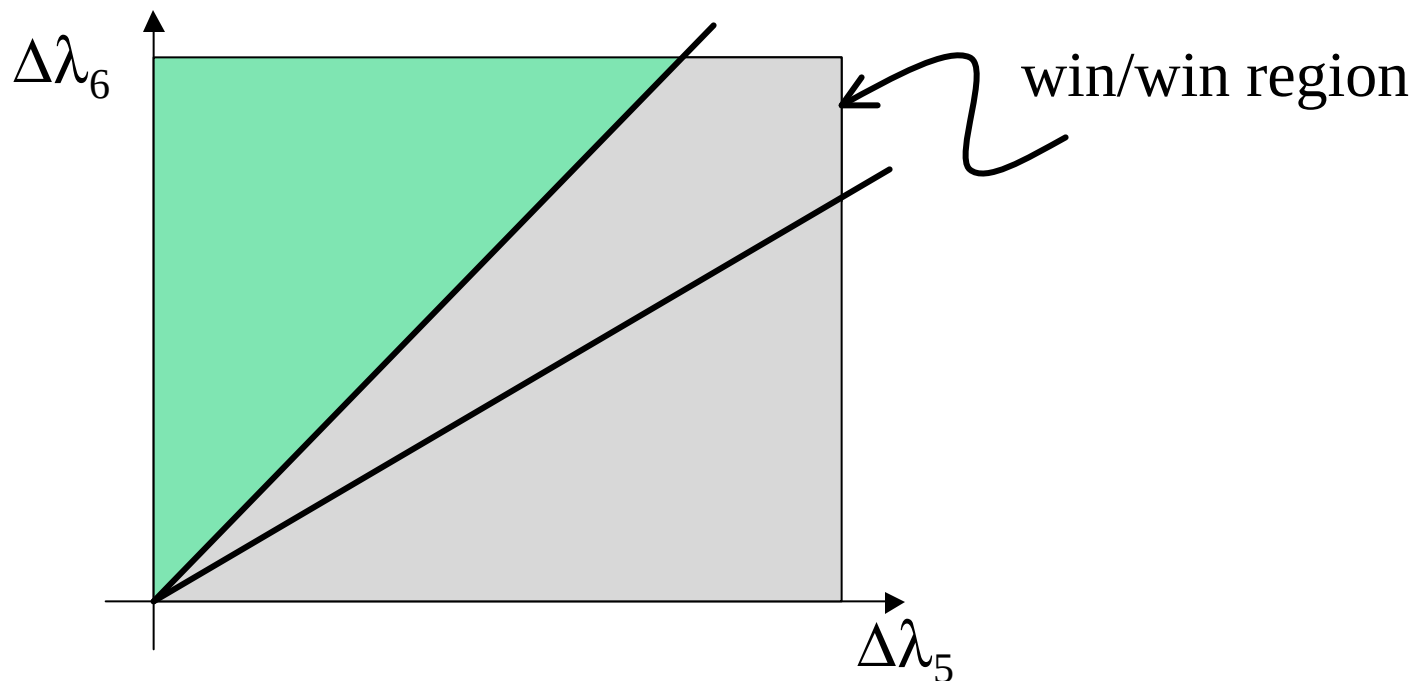
$$\begin{bmatrix} \Delta r_5 \\ \Delta r_6 \end{bmatrix} = \begin{bmatrix} -160 & 173 \\ 175 & -159 \end{bmatrix} \begin{bmatrix} \Delta l_5 \\ \Delta l_6 \end{bmatrix}$$



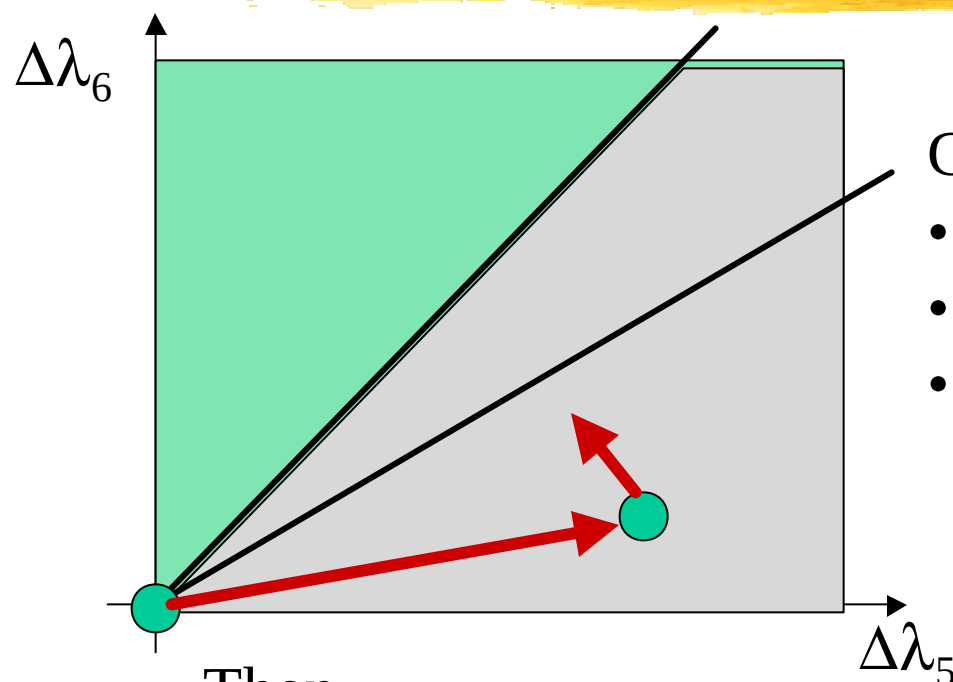
Load Pocket Market Power



Generators 5 and 6 will find their win/win region.



Load Pocket Market Power



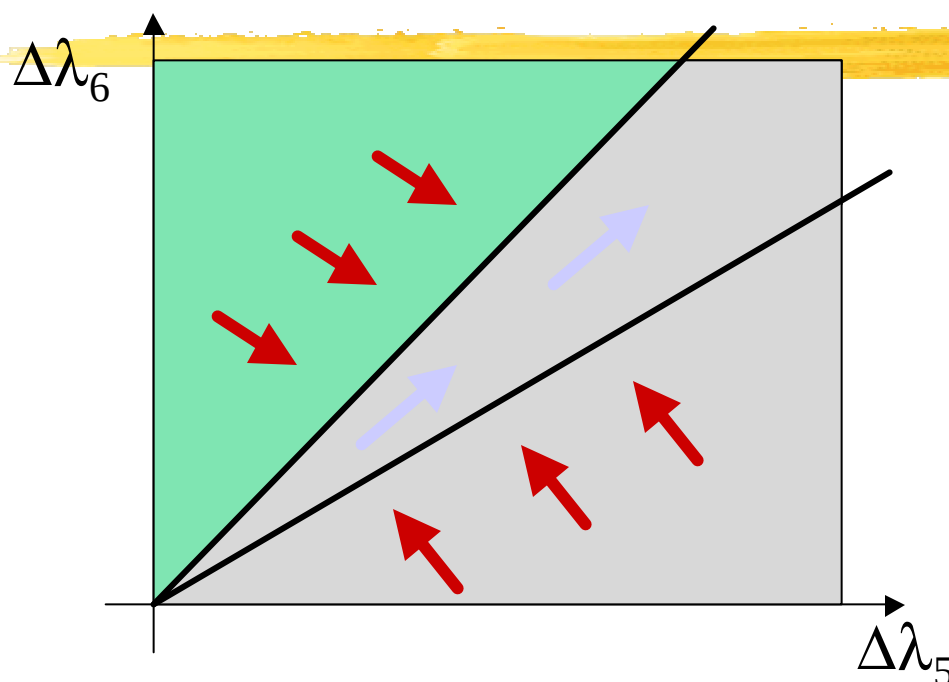
Consider:

- both increase offers and
- generator 5 loses revenue
- generator 6 gains revenue

Then

- generator 5 will decrease its offer and
- generator 6 will increase its offer
- and they will move towards the win/win region

Load Pocket Market Power



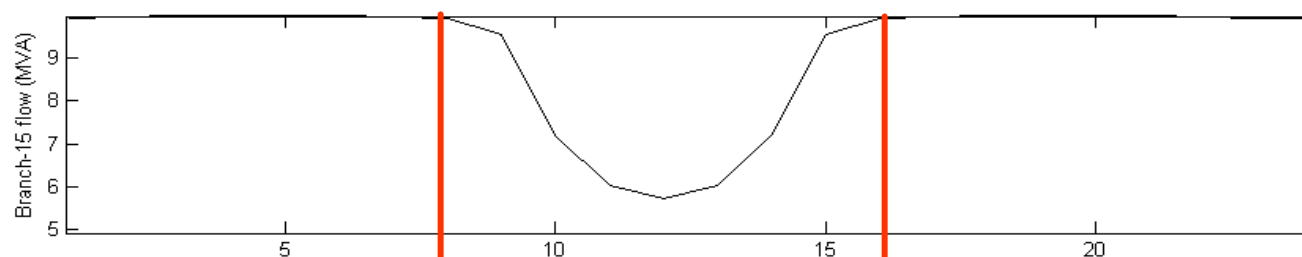
It will take time, but

- prices will increase and
- revenues will increase.

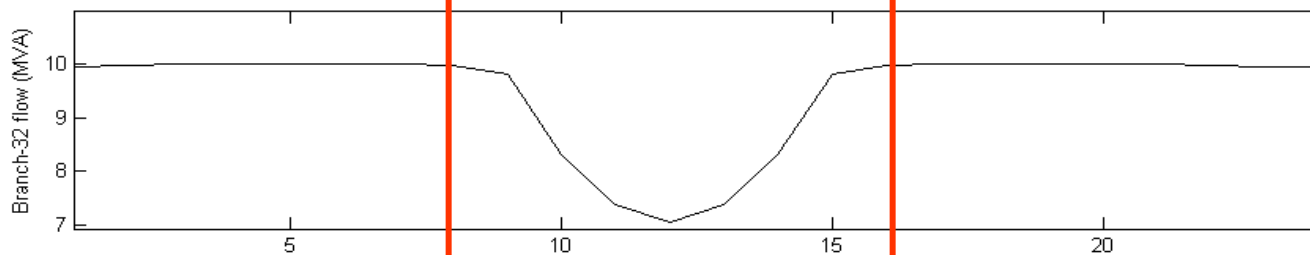
There isn't direct collusion – each generator acts on its own price and revenue signals.

Tie-line flows vs system load

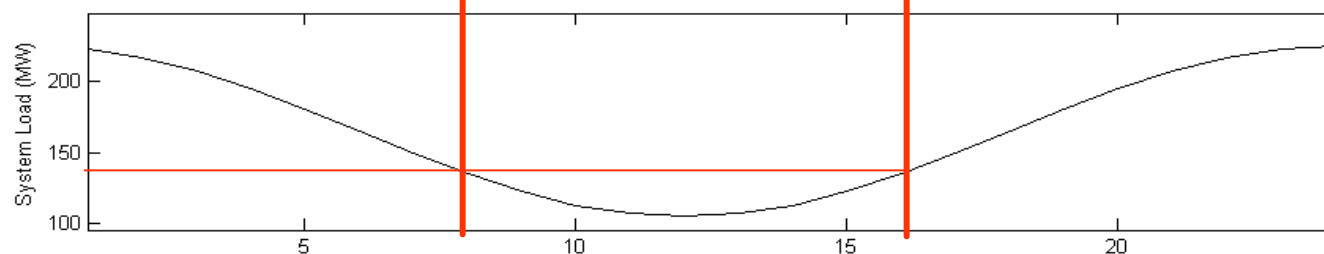
Path 15



Path 32



System Load



Both lines are congested for system load above 135 MW

$$\Delta r1 = a11 * \Delta p1 + a12 * \Delta p2$$

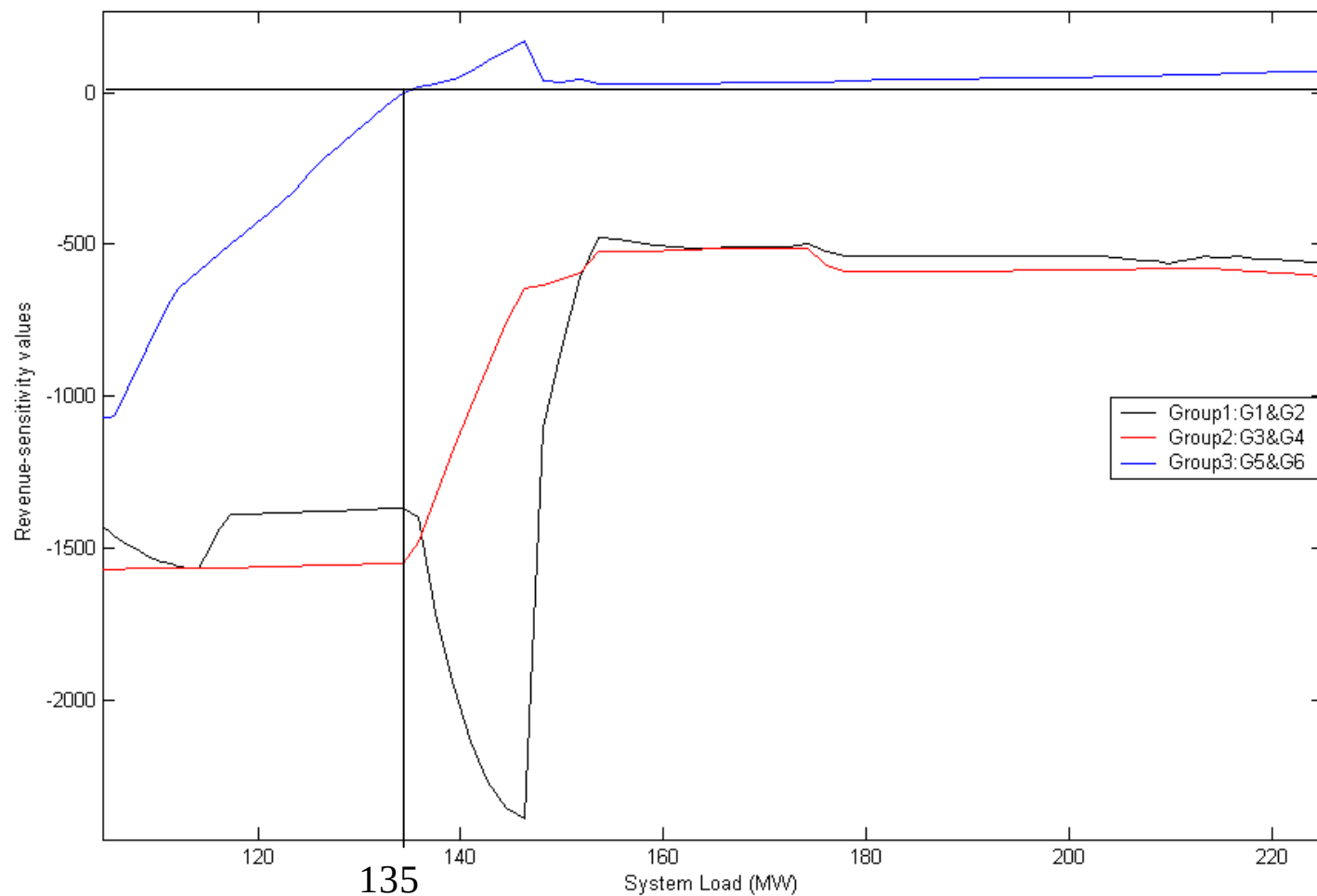
$$\Delta r2 = a21 * \Delta p1 + a22 * \Delta p2$$

therefore:

$$\Delta r1 + \Delta r2 = (a11 + a21) * \Delta p1 + (a12 + a22) * \Delta p2.$$

where: $a_{ij} = \Delta (\text{rev-i}) / \Delta (\text{price-j})$

Group Sensitivities



Relative Market Power (RMP)

A measure of how much market power is being exploited.

$$\text{RMP} = \frac{l_{\text{actual}} - l_{\text{NMP}}}{l_{\text{FMP}} - l_{\text{NMP}}}$$

l_{actual} observed nodal price

l_{NMP} (lower) price at which No Market Power is evident

l_{FMP} (higher) price at which Full Market Power is achieved (at price cap).

Relative Market Power (RMP)

RMP for 6 supplier example

	G5	G6
competitive	0.32	0.32
experiment*	0.70	0.66

* This value would likely increase with a longer experiment.

Conclusions



1. The derived matrix of price sensitivities from an OPF can provide sufficient conditions for identifying the **potential** for market power
2. The data required to make these calculations are available to the ISO.
3. A relative market power index can be calculated.
4. This approach can be extended to include revenue sensitivities to other quantities.

What's next?



- Examine several metrics derived from the price/revenue sensitivities (e.g., eigenvalues, max singular value, RMP, others)
- Apply a visualization of the metrics to PowerWeb and monitor them during experiments
- Integrate into real-time monitoring tools being developed by CERTS