# Market Power Evaluation in Power Systems with Congestion

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# Introduction

- Power industry is rapidly restructuring
- Key goal of restructuring is to reap benefits of competitive marketplaces
- Significant concerns benefits could be lost through development of horizontal market power

# Horizontal Market Power

- Market power is antithesis of competition
  - ability of a particular group of sellers to maintain prices above competitive levels
- An extreme case is a single supplier of a product, i.e. a monopoly.
- In the short run, Price monopolistic producer can charge depends upon price elasticity of the demand.

# Horizontal Market Power

- Market power can sometimes lead to decreased prices in the long run
  - Accompanying higher prices can result in a quickening of the entry of new players and technological innovation
- Some market power abuses are actually self-inflicted by consumers by their reluctance to respond to favorable prices offered by new vendors in deregulated markets

# Symptoms of Market Power

- Economic theory tells us that in a market with perfect competition, prices should be equal to the marginal cost to supply the product
- Therefore prices above marginal cost can indicate market power

# Market Power Analysis

- Market power analysis requires 3 steps
  - identify relevant product/services
  - identify relevant geographic market
  - evaluate market concentration

# Relevant Product

- FERC defines at least three distinct products
  - non-firm energy
  - short-term capacity (firm energy)
  - long-term capacity
- Emphasis shifting to short-term energy markets
- Presentation considers short-term
- Challenge in electricity markets is demand varies over time

# Relevant Geographic Market

- Most difficult step in electricity market due to impact of transmission system
- Size of market is dependent on
  - competitive prices of generators
  - impacts of charges from transporting energy in transmission network
  - physical/operational characteristics of transmission network

# Herfindahl-Hirshman Index (HHI)

- HHI is a commonly used methodology for evaluating market concentration

$$HHI = \sum_{i=1}^{N} q_i^2$$

- where N is number of participants
- $q_i$ is percentage market share

# HHI Examples

- For monopoly HHI = 10,000
- If N=4, $q_1$=40%, $q_2$=25%, $q_3$=25%, $q_4$=10%, then HHI = 2950
- DOJ/FTC standards, adopted by FERC for merger analysis
  - HHI below 1000 is considered to represent an unconcentrated market
  - anything above 1800 is considered concentrated

# Market Power Without Transmission Considerations

- If transmission system is ignored, market power depends only on concentration of ownership relative to other producers in interconnected system
- Without considering any constraints (using NERC 1997 peak data)
  - Eastern Interconnect HHI = 170
  - ERCOT HHI = 2415

# Market Power with Transmission Charges

- In determining geographic market, FERC requires that suppliers must be able to reach market
  - economically
    - supplier must be able to deliver to customer at cost no greater than 105% of competitive price to customer
    - delivered cost is sum of variable generation cost and transmission/ancillary service charges
  - physically

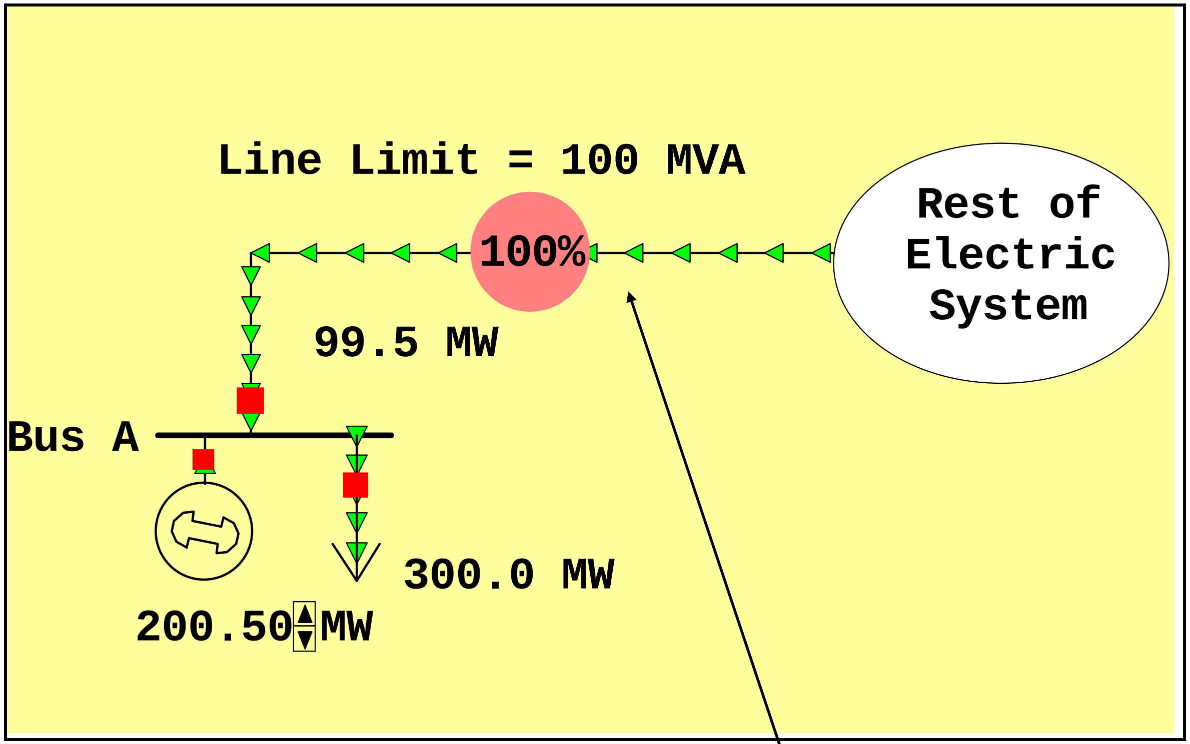
# Pricing Transmission Services

- Goal is to move energy from source to sink
- A number of different mechanisms exist; examples include
  - pancaking of transmission service charges along contract path
  - establishment of Independent System Operator (ISO) with single ISO-wide tariff

# Market Power with Transmission Constraints

- Market size can be limited by physical ability to delivery electricity
- Whenever physical or operational constraints become active, system is said to be in state of congestion
- Congestion arises through number of mechanisms
  - transmission line/transformer thermal limits
  - bus voltage limits
  - voltage, transient or oscillatory stability

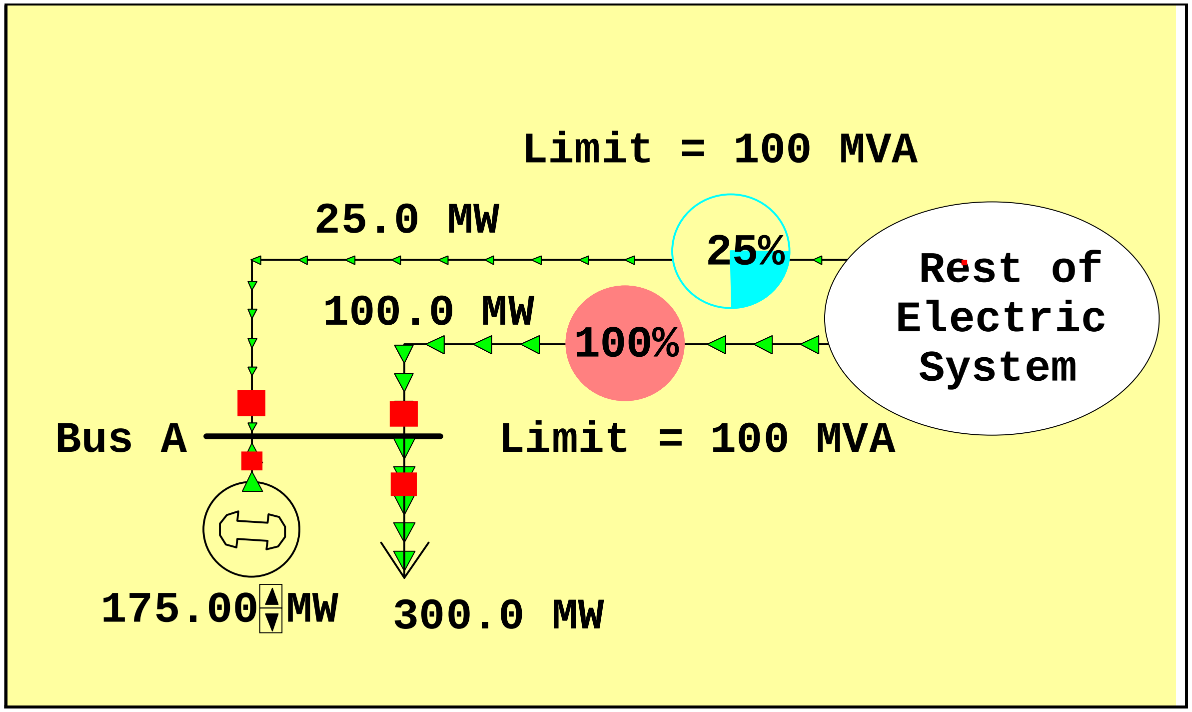
# Radial System with Market Power




Models the remainder of the electrical system

100 MVA limit on line limits bus A imports to 100 MVA

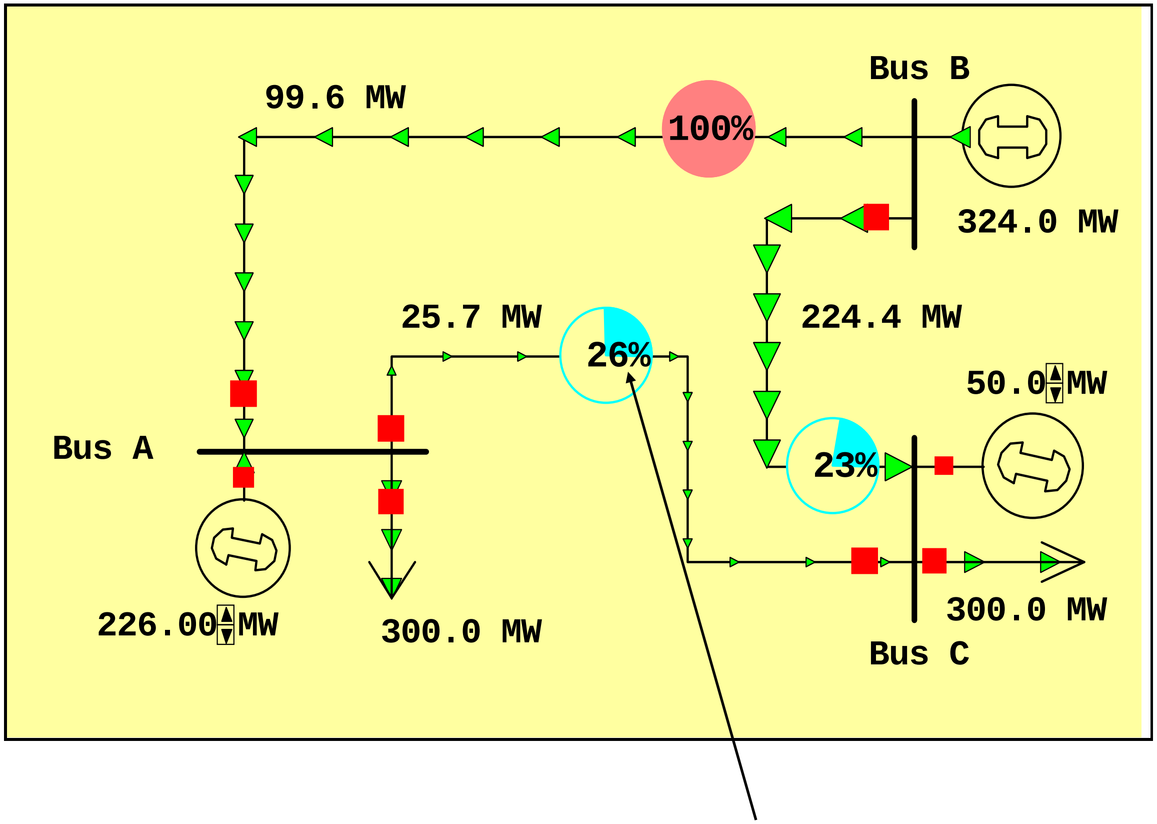
# Networked System




Analysis is substantially more complex.

Transfer capability into bus A is NOT equal to sum of tie-line limits

# Three Bus Networked Example
# Imports = 74 MW




In this example the allowable interchange is less than limit either line

25 MWs of power is wheeling through bus A

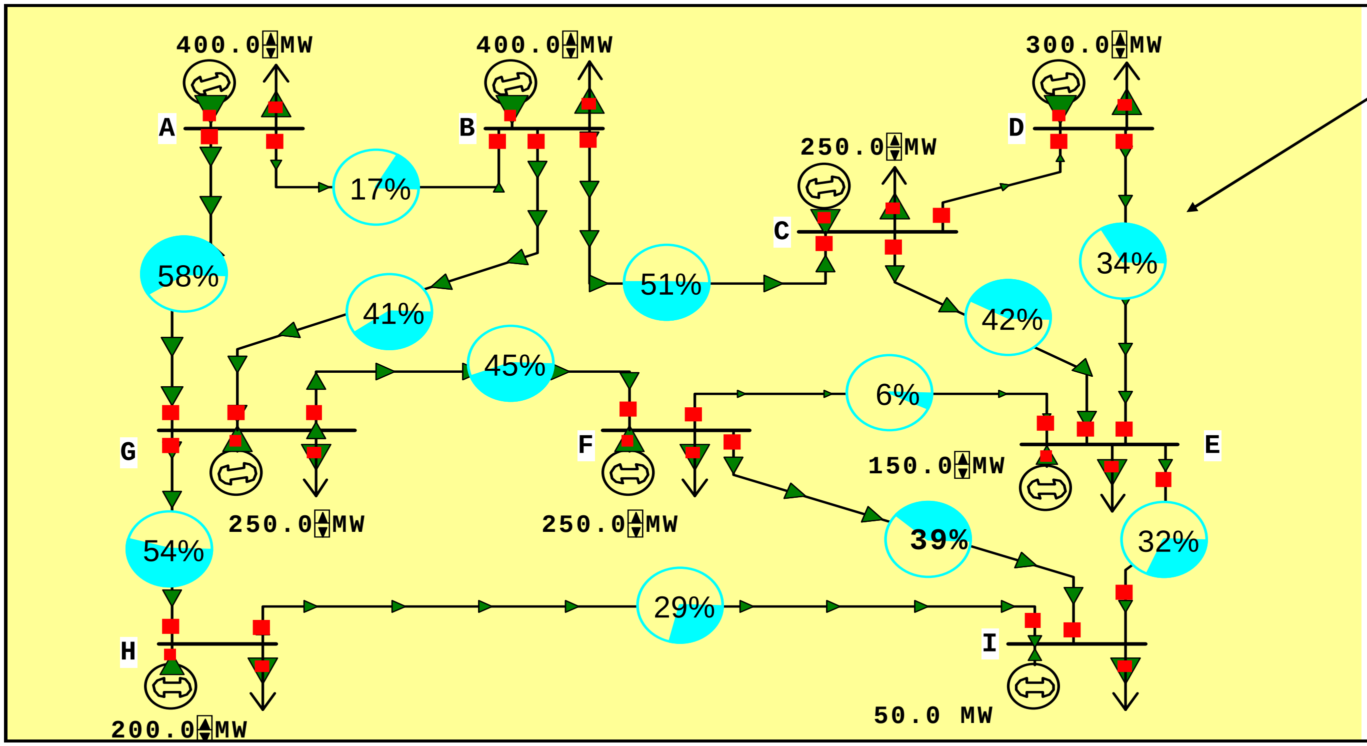
# Congestion in Networks

- Need to introduce several definitions concerning network power transfers
  - source: set of buses increasing their injection of power into network
  - sink: set of buses decreasing their injection of power into network
  - direction: source/sink pair
- Power transfer is then associated with a particular direction

# Congestion in Networks

- To understand impact of congestion in networks, need to consider two interrelated issues
  - power transfer in a particular direction may impact line flows in large portion of system
    - this impact is commonly defined as the power transfer distribution factor (PTDF)
  - once a line is congested, any new power transfers with a PTDF on the congested line above 5% can not take place

# Nine Bus, Nine Area Example

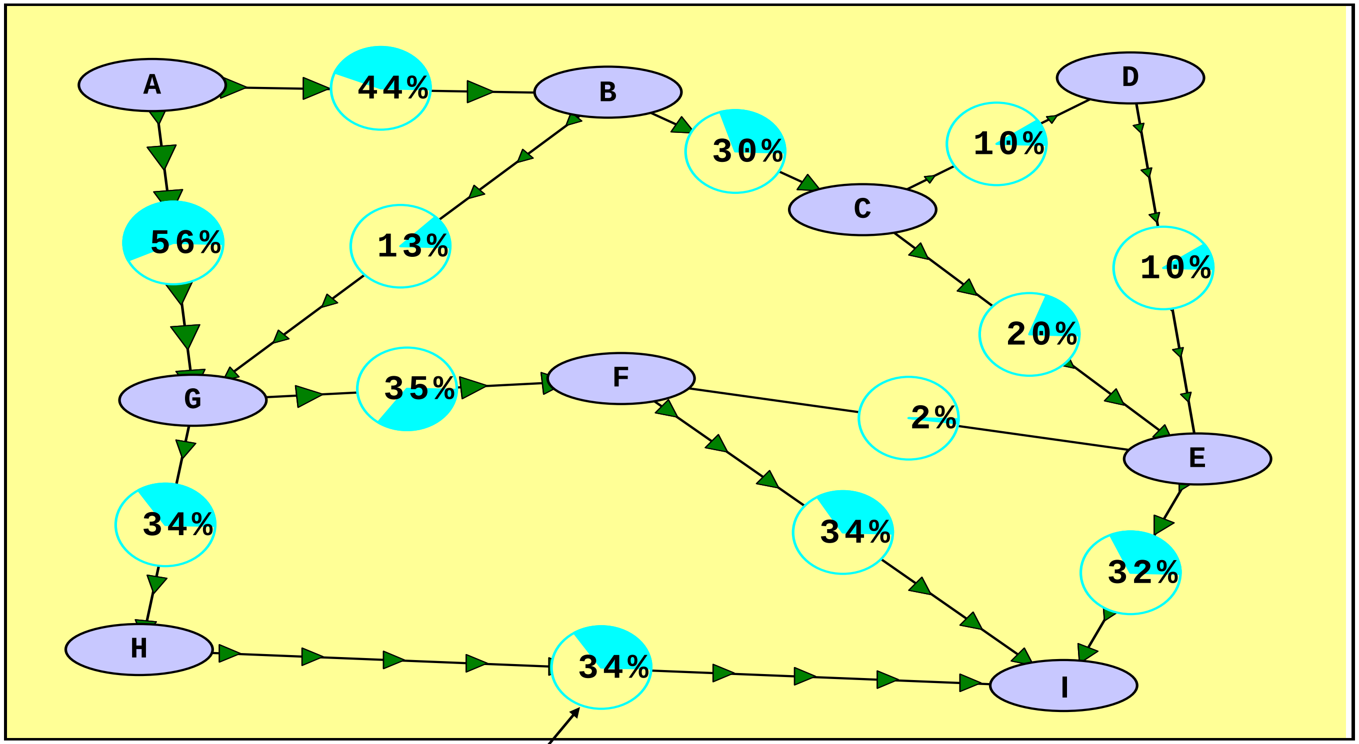



Pie charts show percentage loading on lines

Figure shows base case flows

Each area contains one bus/one 500 MVA generator.
Each line has 200 MVA limits. HHI = 1089

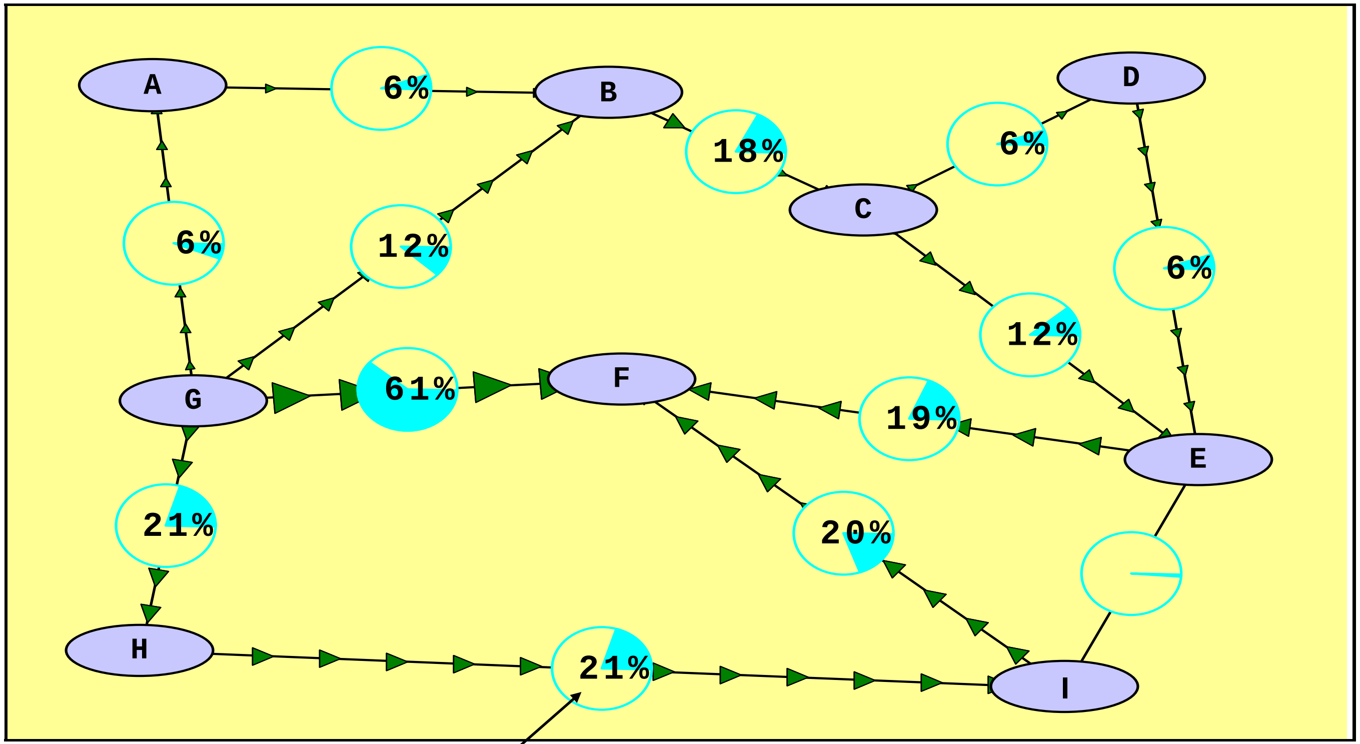
# PTDF Values for A to I Direction




PTDF show the incremental impact on line flows, in this case for a transfer from area A to area I.

Pie charts now show the percentage PTDF value; arrows show the direction.

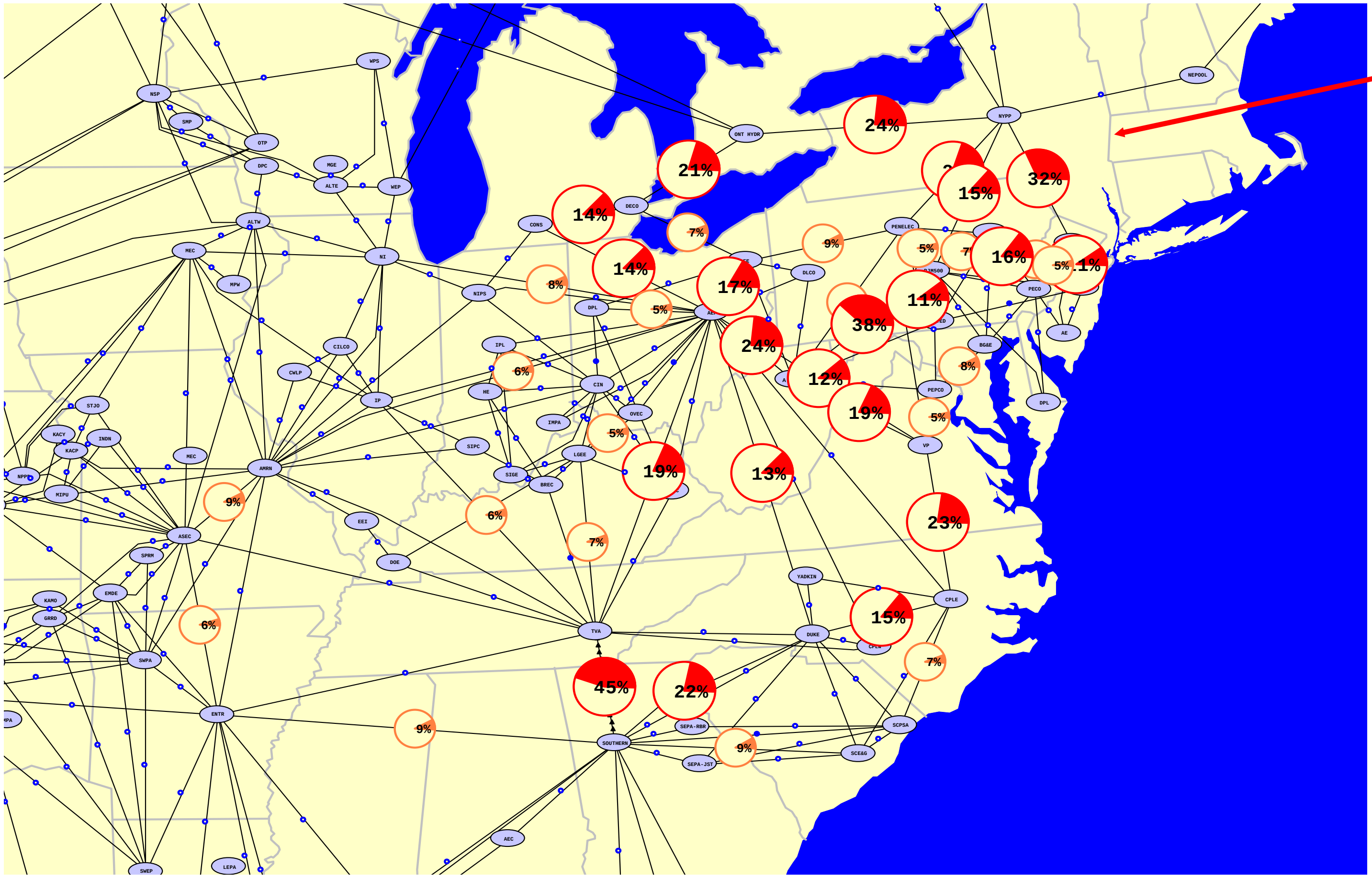
# PTDF Values for G to F Direction




Note that for both the A to I and the G to F directions almost all PTDFs are above 5%

Example: For 200 MW transfer from G to F, line H to I MW flow will increase by 200*21%=42MW

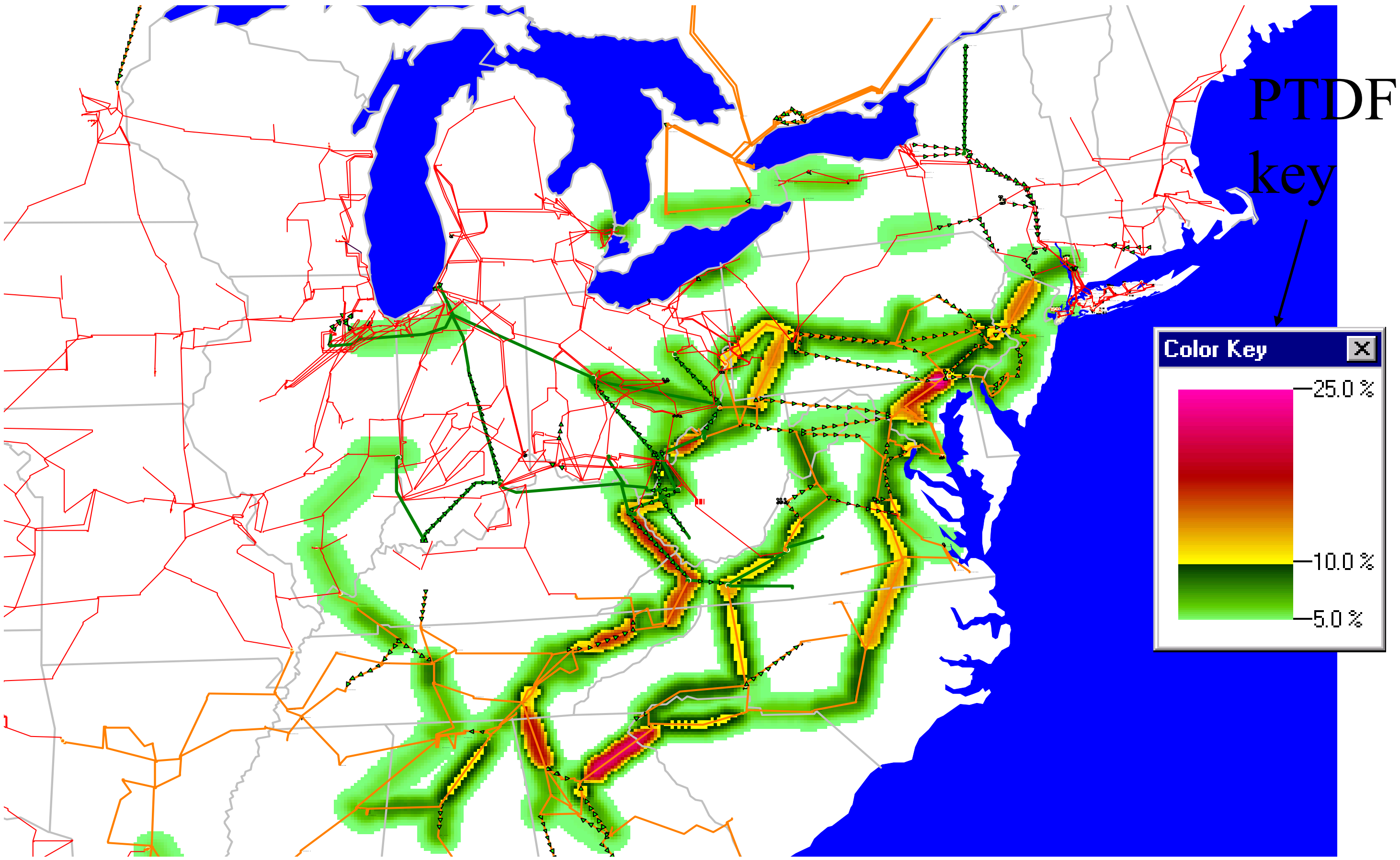
# Large Case PTDF Example: Direction Southern to NYPP



Pie charts show percentage PTDF on interface

Figure shows the area to area interface PTDFs

# Southern to NYPP Line PTDFs




Color contour of PTDFs on 345 kV and up lines

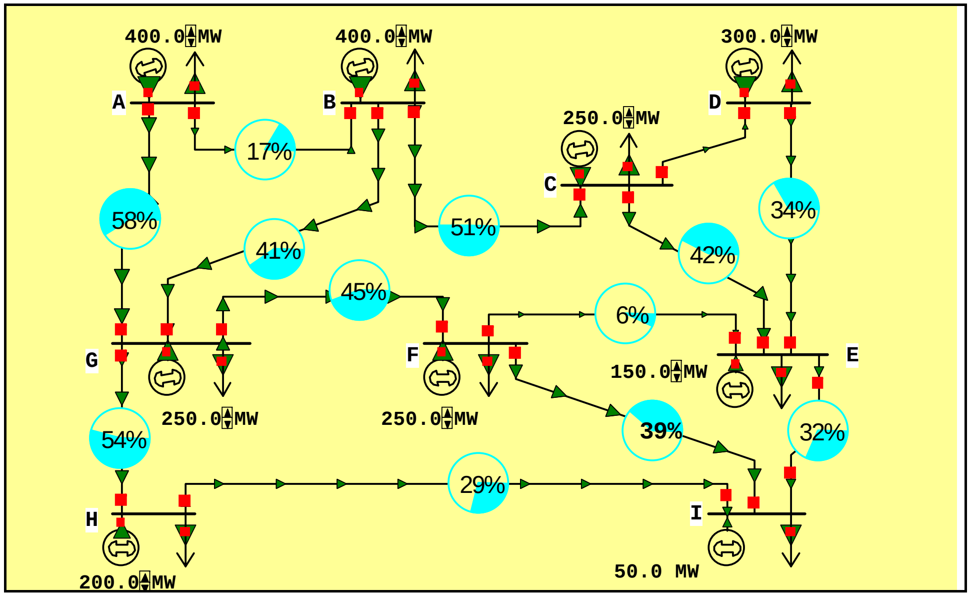
# PTDF Implications on Market Power

- Once congestion is present on line, any power transfer with PTDF above 5% on congested line, in direction such that line loading would be increased, is not allowed
- Congestion on a single line can constrain many different directions

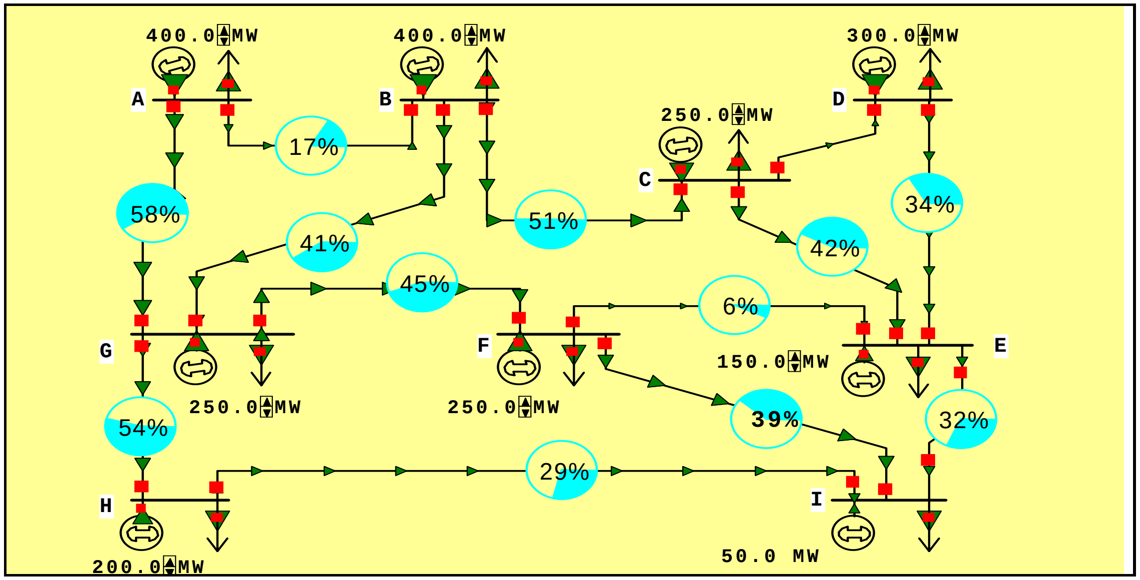
# Nine bus example - Area I buying

- Table : Line G to F PTDF Values

| Seller to Buyer | PTDF for Line G to F |
|---|---|
| A to I | 35% |
| B to I | 29% |
| C to I | 11% |
| D to I | 5% |
| E to I | -1% |
| F to I | -20% |
| G to I | 41% |
| H to I | 21% |



# Nine Bus Example




If the line from G to F were congested, then area I could only buy from areas E, F or I.

When congestion is present, area I load only has possibility of buying from three suppliers. If we assume each supplier has 1/3 of the potential market, resultant HHI is 3333.

# Strategic Market Power

- Characteristic that congestion can limit market size allows possibility that generator portfolio owner may unilaterally dispatch generator to deliberately induce congestion
  - this results in market power
  - allows charging of higher prices
- Ability to induce congestion depends on generator portfolio and transmission system loading

# Portfolio Flow Control

- A portfolio of N generators may be redispatched to unilaterally control the flow on a particular line, i, by an amount

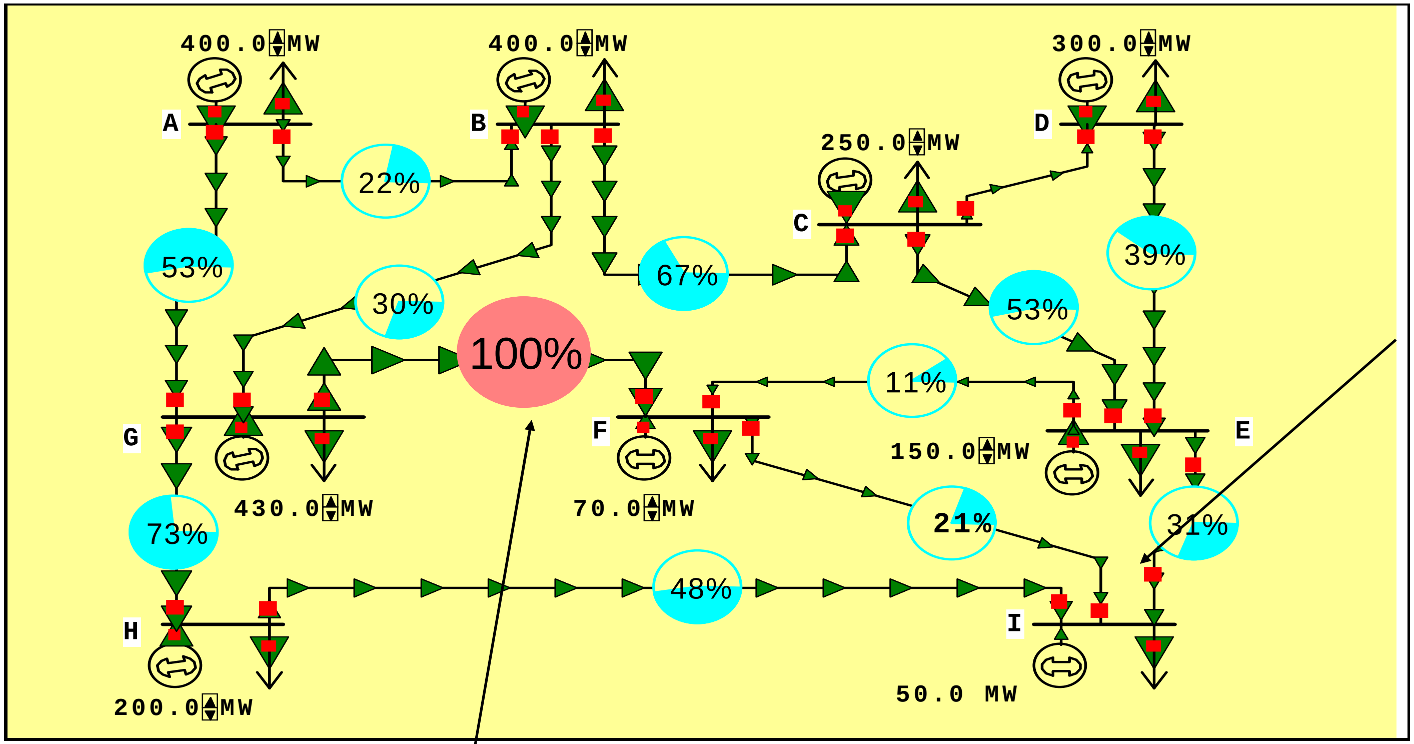
$$\Delta P_i = \max \sum_{k=1}^{N} s_{ik} \Delta P_{gk} \quad \text{such that} \quad \sum_{k=1}^{N} \Delta P_{gk} = 0$$

- where $S_{ik}$ **is sensitivity of line i MW flow to change in generation at bus k**

# Portfolio Flow Control

- Once a line is congested, any generators with a PTDF to a particular load pocket that would increase loading on the congested line are prevented from selling to that market.
- Likewise affected loads are prevented from buying from the “blocked” generators.

# Merged Areas F and G Blocking Line




With G-F congestion area I can only buy from FG, or E

Generators F and G are deliberately dispatched to congest line G to F

# Cost to the Congestors

- Such a strategy of deliberate congestion could certainly involve additional costs to congestors (since they presumably would have to move away from an economic dispatch)
- Congestors need to balance costs versus benefits from higher prices

# Integrating Economics into the Analysis

- The first step to doing this is developing an optimal power flow
- Lagrange multipliers then used as spot-prices

**Benefits** **Costs**

$$\max_{\mathbf{x},\mathbf{s},\mathbf{d}} \quad B(\mathbf{d}) - C(\mathbf{s})$$

**Maximize "Social Welfare"**

$$\text{s.t.} \quad \mathbf{h}(\mathbf{x},\mathbf{s},\mathbf{d}) = \mathbf{0}$$

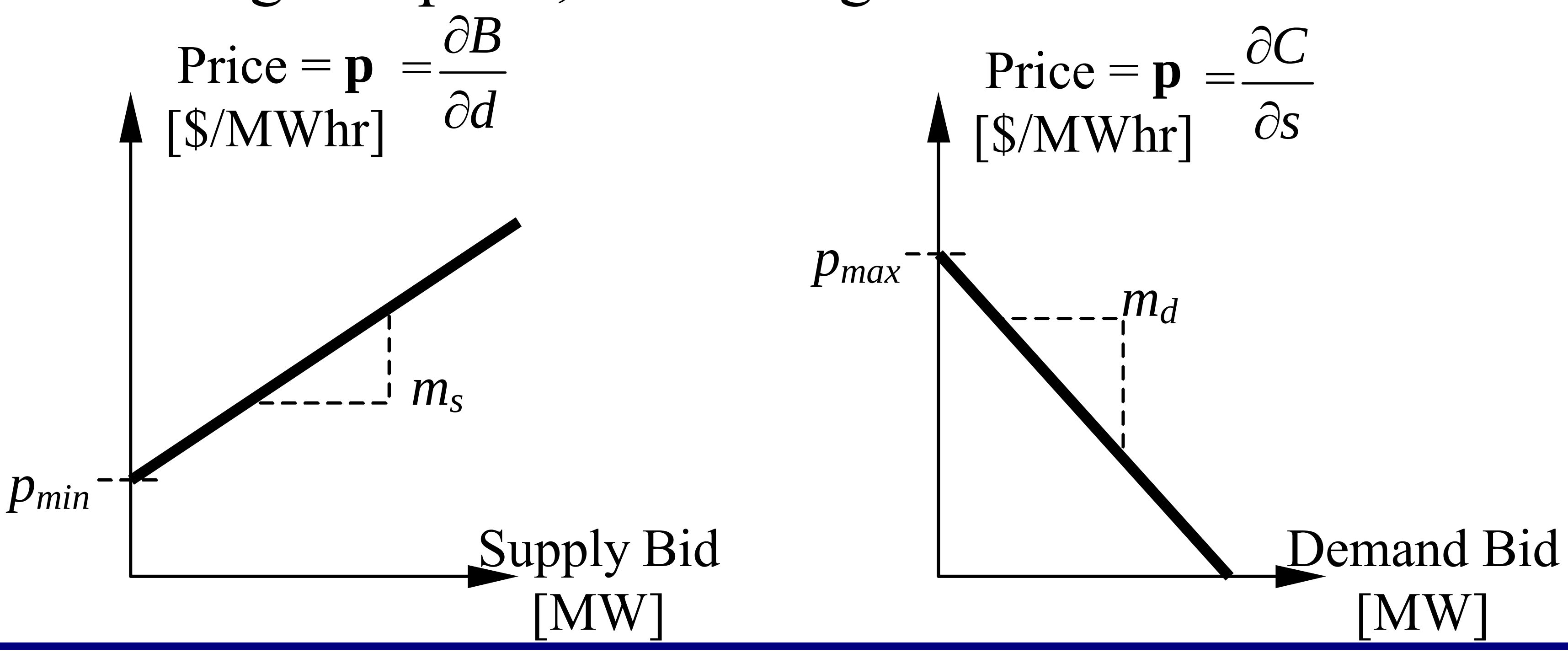
**Include the Power Flow Equations**

$$\mathbf{g}(\mathbf{x},\mathbf{s},\mathbf{d}) \leq \mathbf{0}$$

**Include Limits such as:**
*** transmission line limits**
*** bus voltage limits**

# Market Simulation Setup: Get away from "costs" and "benefits"

- Suppliers and Consumers will submit price-dependent generation and load bids
  - For given price, submit a generation or load level

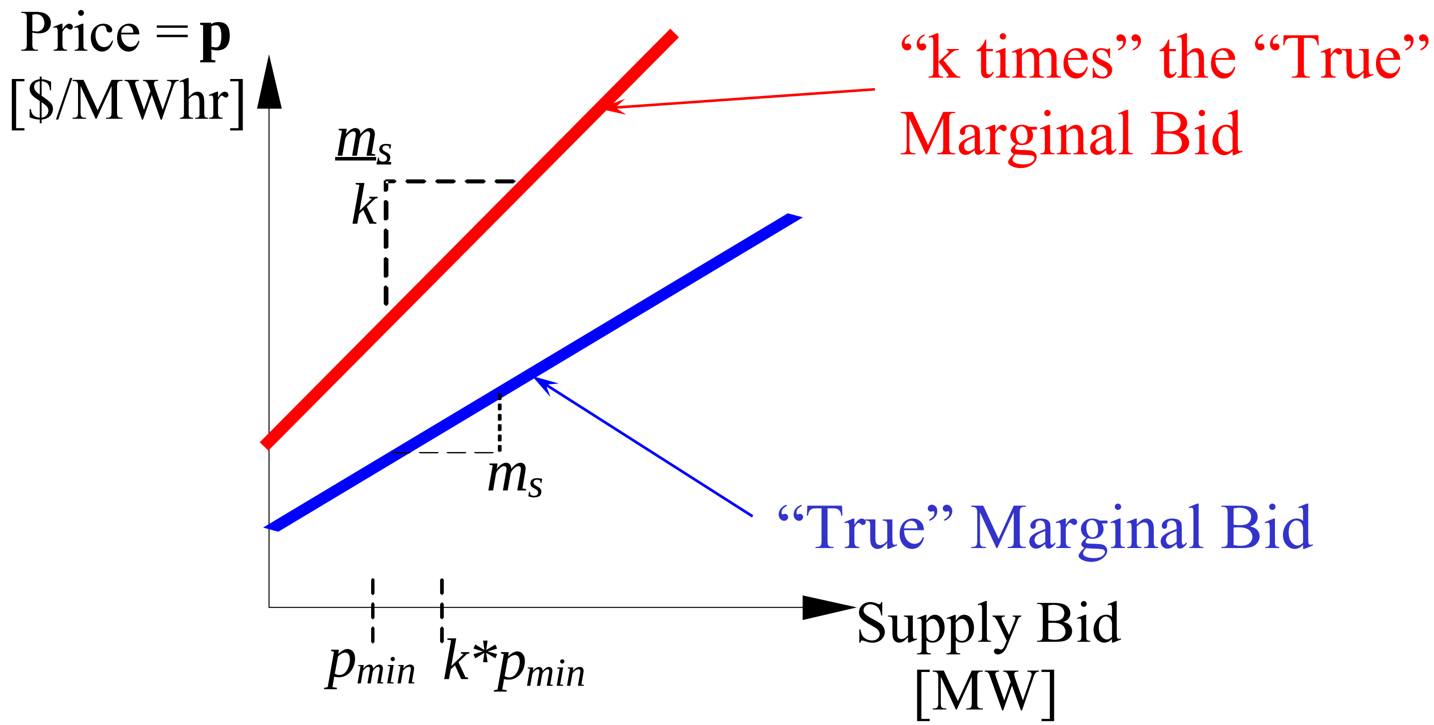


# Market Simulation Setup

- Consumers and suppliers submit bid curves.
- Using the bids, an OPF with the objective of maximization of social welfare is solved
  - This will determine the MW dispatch as well as Lagrange multipliers which will determine the spot price at each bus.
  - The consumers and suppliers are paid a price according to their bid, but their bid will effect the amount at which they are dispatched.

# Limit Possible Bids to Linear Functions

- Each supplier chooses some ratio above or below its true marginal cost function



# What does an Individual Want to do? Maximize its Welfare

- Maximize An Individual's Welfare
  - Individual may control multiple supplies and multiple demands

$$f(\mathbf{s},\mathbf{d},\lambda) = \sum_{i=\text{controlled demands}} [B_i(d_i) - \lambda_i d_i] + \sum_{\text{controlled supplies}} [-C_i(s_i) + \lambda_i s_i]$$

+Benefits

-Expenses

-Costs

+Revenue

  - Note: An individual's welfare is not explicitly a function of its bid (implicitly through **s,d,λ**)

# Determining a Best Response in this Market Structure

- A “Nested Optimization Problem”

Individual’s Welfare

$$\max_{\mathbf{k}} \quad f(\mathbf{s},\mathbf{d},\lambda)$$

s.t. $(\mathbf{s},\mathbf{d},\lambda)$ are determined by

**s,d,λ** are implicit functions of **k**

$$\begin{pmatrix} \max_{\mathbf{x},\mathbf{s},\mathbf{d}} & B(\mathbf{d},\mathbf{k}) - C(\mathbf{s},\mathbf{k}) \\ \text{s.t.} & \mathbf{h}(\mathbf{x},\mathbf{s},\mathbf{d}) = \mathbf{0} \\ & \mathbf{g}(\mathbf{x},\mathbf{s},\mathbf{d}) \leq \mathbf{0} \end{pmatrix}$$

The OPF Problem is a “constraint” now

“OPF Sub-Problem”

# Economic Market Equilibriums: The Nash Equilibrium

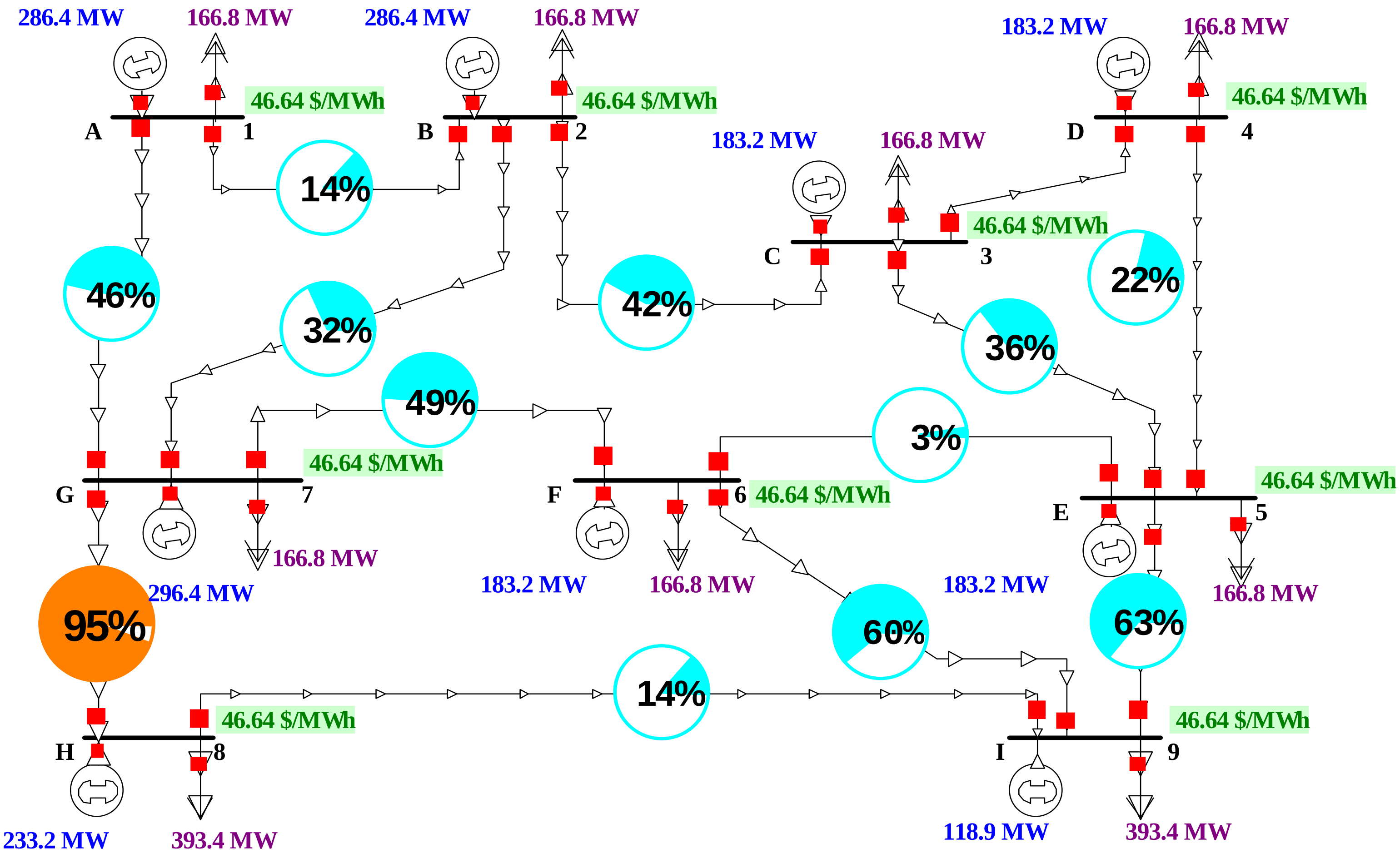
- Definition of a Nash Equilibrium
  - An individual looks at what its opponents are presently doing
  - The individual's best response to opponents behavior is to continue its present behavior
  - This is true for ALL individuals in the market
- This is a Nash Equilibrium
- Nash Equilibrium be found by iteratively solving to individual welfare maximization

# Example: Use 9-bus system and Assign Cost and Benefit Curves

- $C_i(s_i)=b_{si}s_i+c_{si}s_i^2$ = supplier cost
- $B_i(d_i)=b_{di}d_i+c_{di}d_i^2$ = consumer benefit

| Bus | Supplier $b_{si}$ Coefficient | Supplier $c_{si}$ Coefficient | Consumer $b_{di}$ Coefficient | Consumer $c_{di}$ Coefficient |
|---|---|---|---|---|
| 1 (A) | 18 | 0.05 | 80 | -0.10 |
| 2 (B) | 18 | 0.05 | 80 | -0.10 |
| 3 (C) | 21 | 0.07 | 80 | -0.10 |
| 4 (D) | 21 | 0.07 | 80 | -0.10 |
| 5 (E) | 21 | 0.07 | 80 | -0.10 |
| 6 (F) | 21 | 0.07 | 80 | -0.10 |
| 7 (G) | 17 | 0.05 | 80 | -0.10 |
| 8 (H) | 0 | 0.10 | 440 | -0.50 |
| 9 (I) | 30 | 0.07 | 440 | -0.50 |

# Solution for All True Marginal Cost Bids



# Market Behavior

- Assume all consumers always submit bids corresponding to true marginal benefit ($k$=1)
- Assume supplier A-F and I all act alone to maximize their profit
- Assume suppliers G and H collude (or merge) together
  - G and H now make bid decisions together

# What are General Strategies for G and H?

- G and H could act to raise their prices hoping to increase profit
- Also could act to take advantage of the transmission constraint between them
  - G lowers price hoping that overload on the line between G-H will result in increased profit by H
- Nash Equilibria are found for each of these two general strategies by iteratively solving the individual welfare maximum

# Nash Equilibrium Found When Both G and H raise prices

- Combined profit for G and H of **$10,638 $/hr**

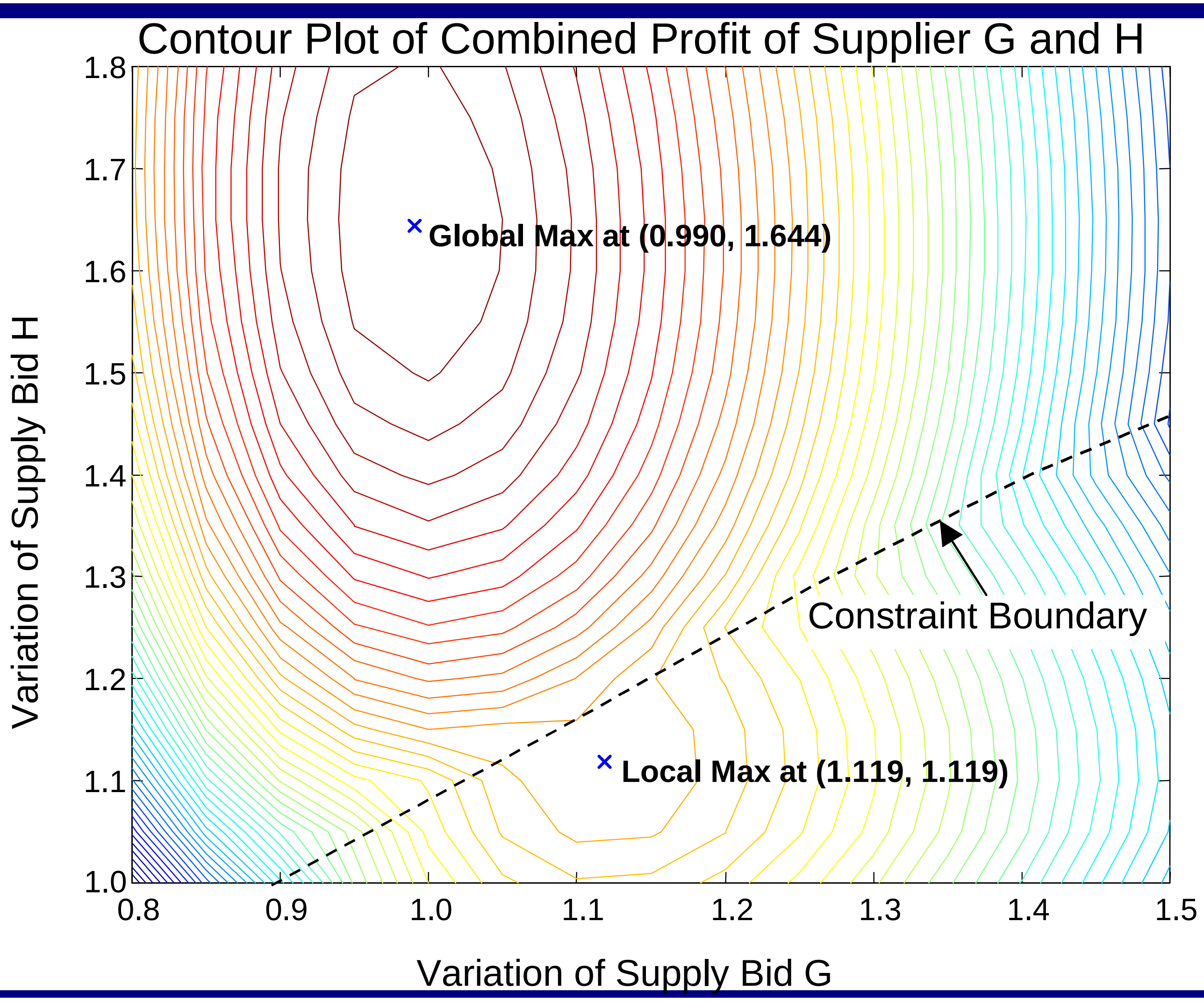
| Bus | Price [$/MWhr] | Supplier Output [MW] | Supplier Profit [$/hr] | Consumer Demand [MW] | Consumer Welfare [$/hr] |
|---|---|---|---|---|---|
| A | 48.51 | 275.8 | 4,612.36 | 157.4 | 2,478.55 |
| B | 48.51 | 275.8 | 4,612.36 | 157.4 | 2,478.55 |
| C | 48.51 | 183.0 | 2,690.69 | 157.4 | 2,478.55 |
| D | 48.51 | 183.0 | 2,690.69 | 157.4 | 2,478.55 |
| E | 48.51 | 183.0 | 2,690.69 | 157.4 | 2,478.55 |
| F | 48.51 | 183.0 | 2,690.69 | 157.4 | 2,478.55 |
| G | 48.51 | 262.1 | **4,824.89** | 157.4 | 2,478.55 |
| H | 48.51 | 216.1 | **5,813.56** | 391.5 | 76,630.97 |
| I | 48.51 | 123.1 | 1,218.26 | 391.5 | 76,630.97 |
| **Totals** | | **1885.0** | **31,844.19** | **1885.0** | **170,611.81** |

# Nash Equilibrium Found G and H try to Game the Constraint

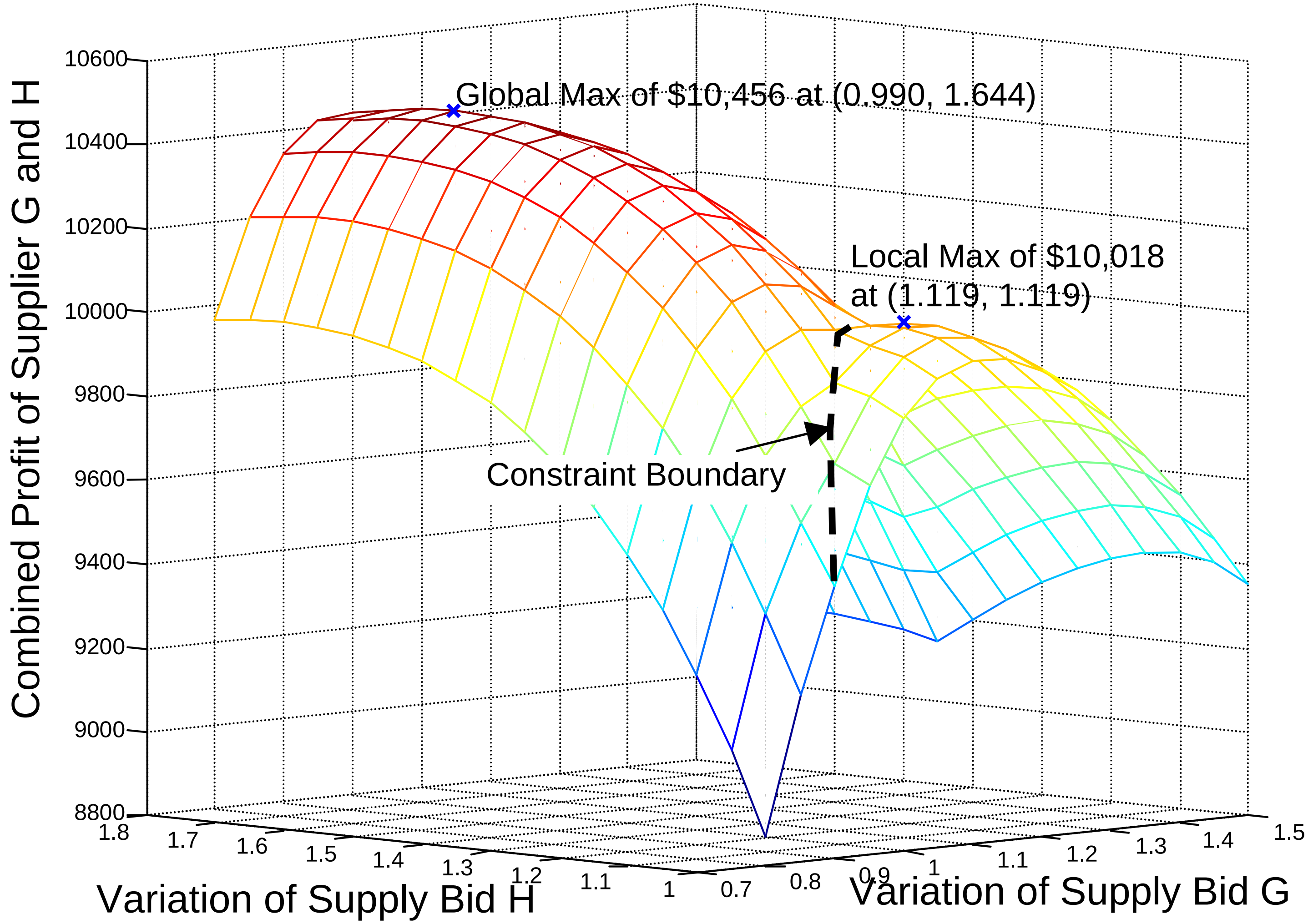
- Combined profit for G and H of **$12,082 $/hr**

| Bus | Price [$/MWhr] | Supplier Output [MW] | Supplier Profit [$/hr] | Consumer Demand [MW] | Consumer Welfare [$/hr] |
|---|---|---|---|---|---|
| A | 47.08 | 241.9 | 4,108.89 | 164.6 | 2,709.01 |
| B | 47.80 | 257.5 | 4,357.63 | 161.0 | 2,592.32 |
| C | 49.95 | 192.4 | 2,978.58 | 150.3 | 2,257.62 |
| D | 50.67 | 196.1 | 3,125.79 | 146.7 | 2,151.16 |
| E | 51.38 | 198.3 | 3,272.70 | 143.1 | 2,047.09 |
| F | 50.67 | 196.1 | 3,126.40 | 146.7 | 2,150.68 |
| G | 46.36 | 295.9 | **4,310.76** | 168.2 | 2,828.57 |
| H | 60.73 | 183.3 | **7,771.83** | 379.3 | 71,921.82 |
| I | 54.29 | 84.0 | 1,546.03 | 385.7 | 74,387.47 |
| **Totals** | | **1845.4** | **34,598.62** | **1845.4** | **163,045.74** |

# Contour Plot of Combined Profit of G and H when A-F,I bid *k* = 1.0



# 3-D Plot of Combined Profit of G and H when A-F,I bid *k* = 1.0



# Results

- G and H acting together can increase their profit by gaming around the transmission constraint
- Transmission Analysis MUST be included in Market Power Analysis
- Engineering Analysis and Economic Analysis can be integrated together

# Conclusions

- Market power abuses in a large power system need to be assessed.
- Regulators need to be cognizant of ability of market participants to act strategically
- Portfolio owners need to be cognizant of their own, and their competitors potential for strategic behavior

# Conclusions

- Rules of the game can make it more difficult to act strategically, but it would be difficult to eliminate possibility completely.
- Load's ability to respond to market power is an important consideration.
- Slides and free 12 bus version of the PowerWorld Simulator software are available at www.powerworld.com