# Quick Start for Using PowerWorld Simulator for Market Analysis

PowerWorld Corporation

# Overview

- This is a quick tutorial of PowerWorld Simulator's Optimal Power Flow (OPF) tool for analyzing power markets.
- The examples may be performed with the free evaluation software, which may be downloaded at http://www.powerworld.com/downloads/demosoftware.asp.
- The tutorial is intended for those who are familiar with navigating PowerWorld Simulator and have some familiarity with power flow studies.
  - Free online training videos are available at http://www.powerworld.com/services/webtraining.asp to teach program navigation and basic functions in PowerWorld Simulator
  - Live training sessions are also available. Please visit http://www.powerworld.com/calendar.asp

# Objectives

- Provide background on the Optimal Power Flow (OPF) Problem
- Show how the OPF is implemented in PowerWorld Simulator OPF
- Explain how Simulator OPF can be used to solve small and large problems
- Provide hands-on examples
- Provide sample OPF results and visualization on a realistic large power system

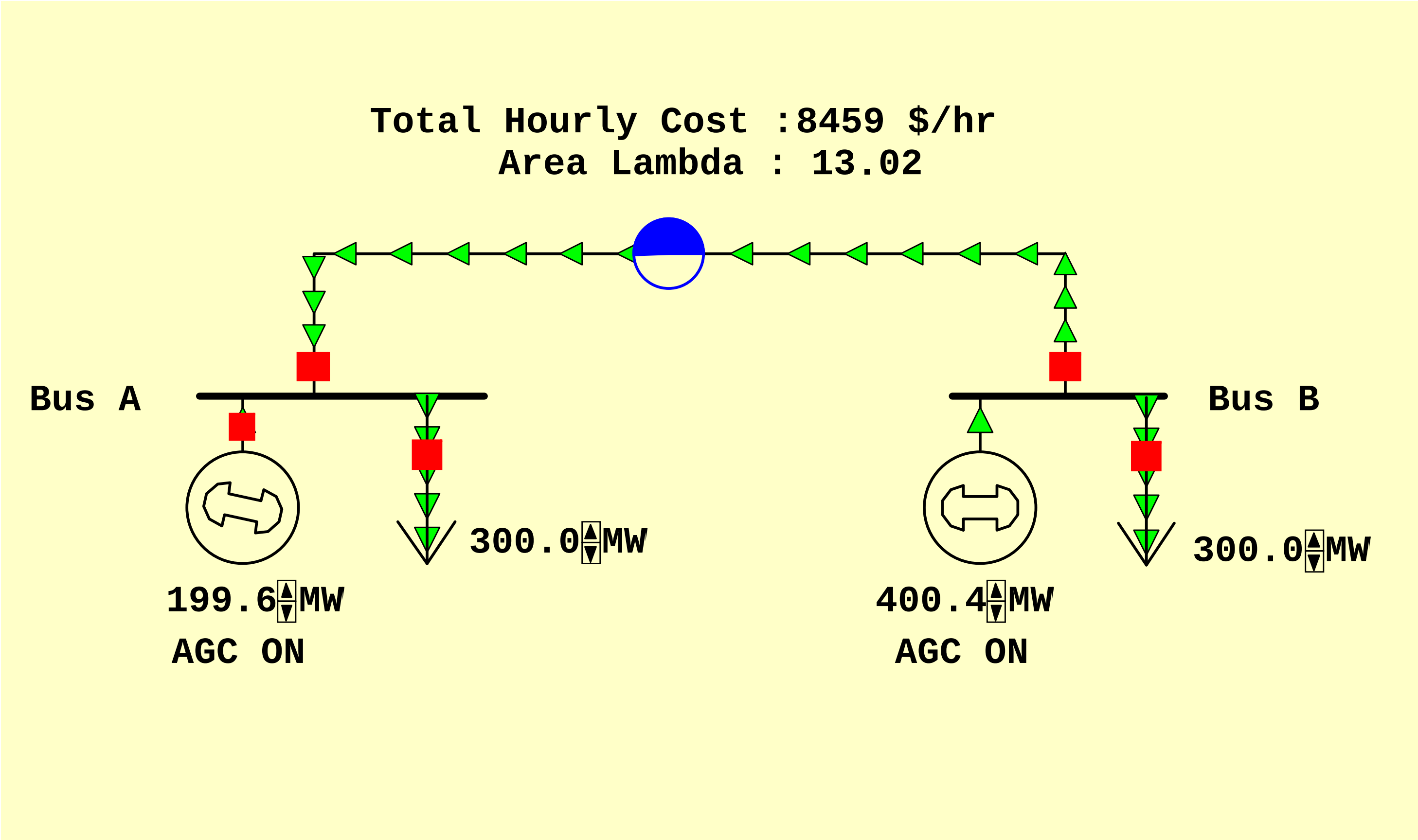
# Optimal Power Flow

- The goal of an optimal power flow (OPF) is to determine the "best" way to instantaneously operate a power system.
- Usually "best" = minimizing operating cost.
- OPF can incorporate and enforce transmission limits, but we'll introduce OPF initially ignoring transmission limits

# "Ideal" Power Market: No Transmission System Constraints

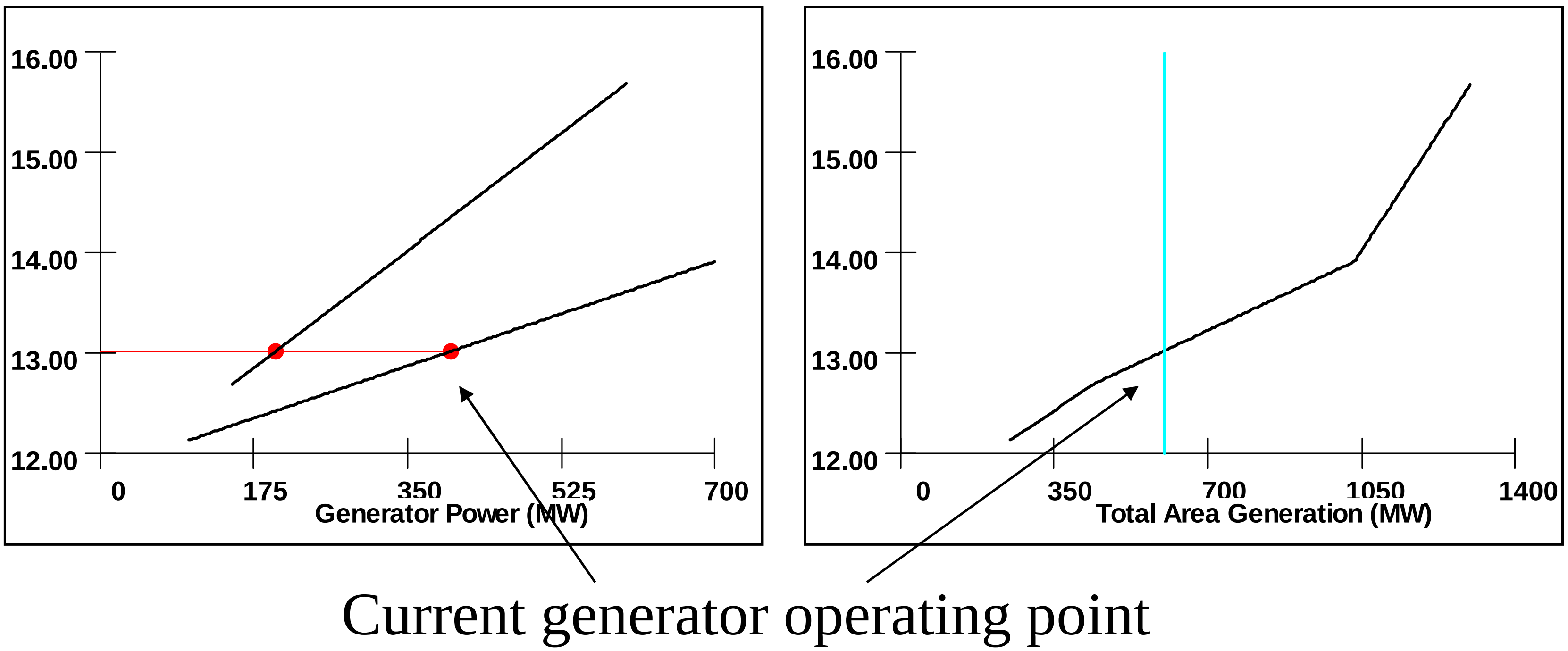
- An ideal power market is analogous to a lake
  - generators supply energy to the lake and loads remove energy
  - no transmission limits and no losses
- There is a single marginal cost associated with enforcing the constraint that supply = demand
  - buy from the least-cost unit that is not at a limit
  - the price of that unit sets the marginal cost

# Two Bus Example

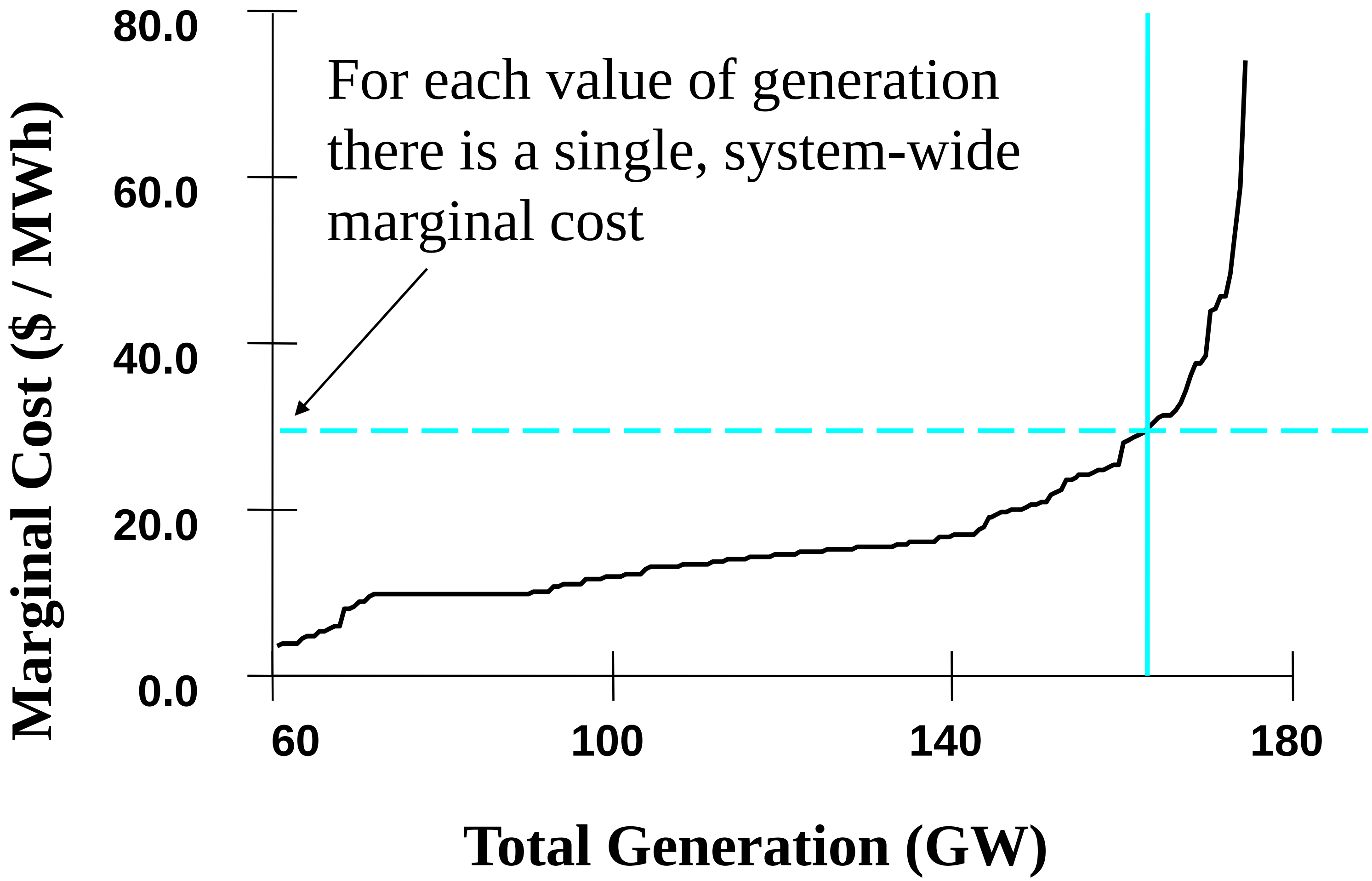


# System Marginal Cost is Determined by Net Generation Cost

Below are graphs associated with this two bus system. The graph on the left shows the marginal cost for each of the generators (which meet the equal lambda criteria). The graph on the right shows the system supply curve, assuming the system is optimally dispatched.



# Typical Supply Curve for Northeast U.S.



# Real Power Market

- Different operating regions impose constraints, e.g. total supply in region must equal total demand plus scheduled exports
- Transmission system imposes constraints (transmission limits)
- Marginal costs become localized

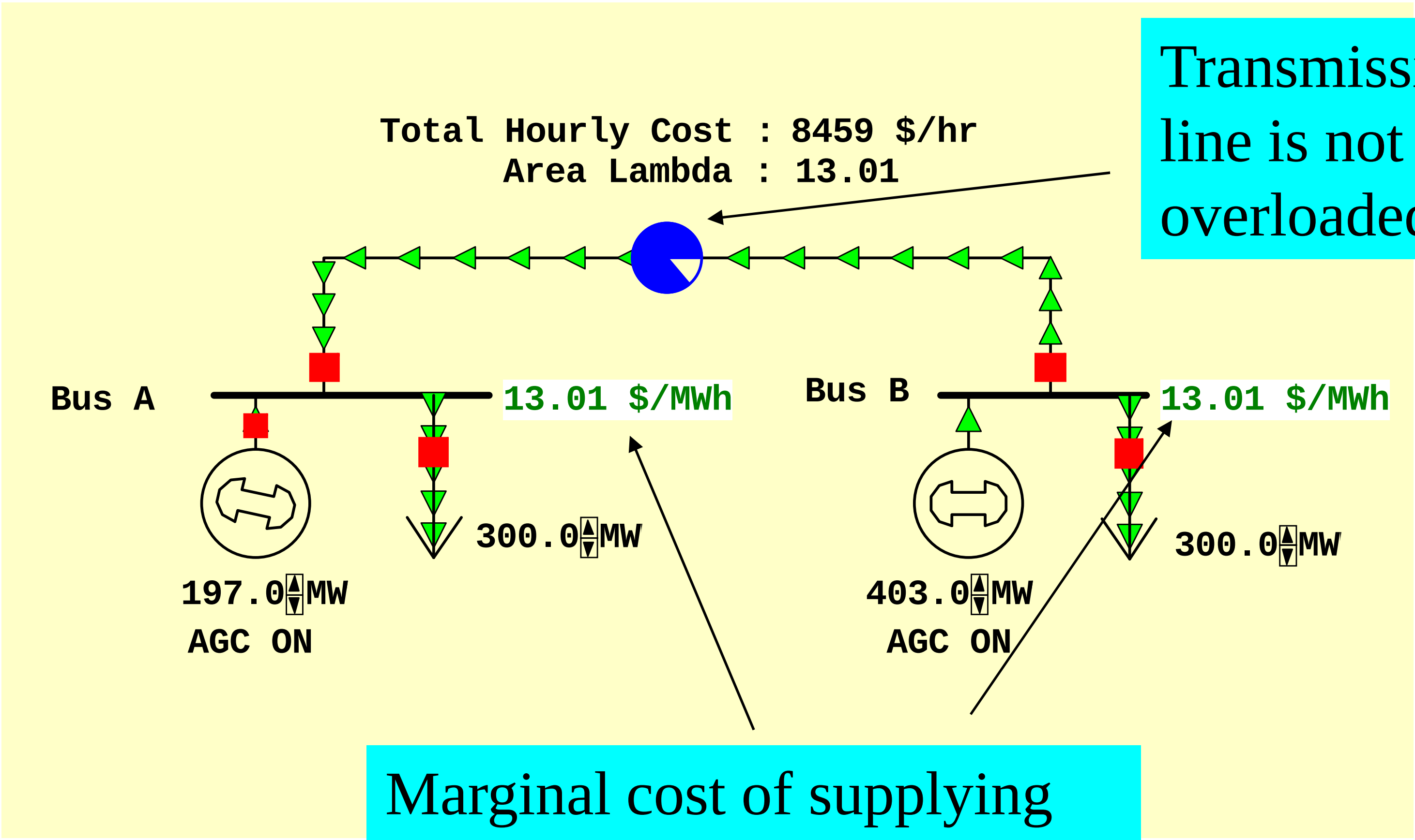
# Optimal Power Flow (OPF)

- Minimize cost function, such as operating cost, taking into account realistic equality and inequality constraints
- Equality constraints
  - Bus real and reactive power balance
  - Generator voltage setpoints
  - Area MW interchange
  - Transmission line/transformer/interface flow limits

# Optimal Power Flow (OPF)

- Inequality constraints
  - Transmission line/transformer/interface flow limits
  - Generator MW limits
  - Generator reactive power capability curves
- Available Controls
  - Generator MW outputs
  - Load MW demands
  - Phase-shifting transformers (or phase angle regulators)
  - Area Transactions
  - DC Transmission Line Setpoints

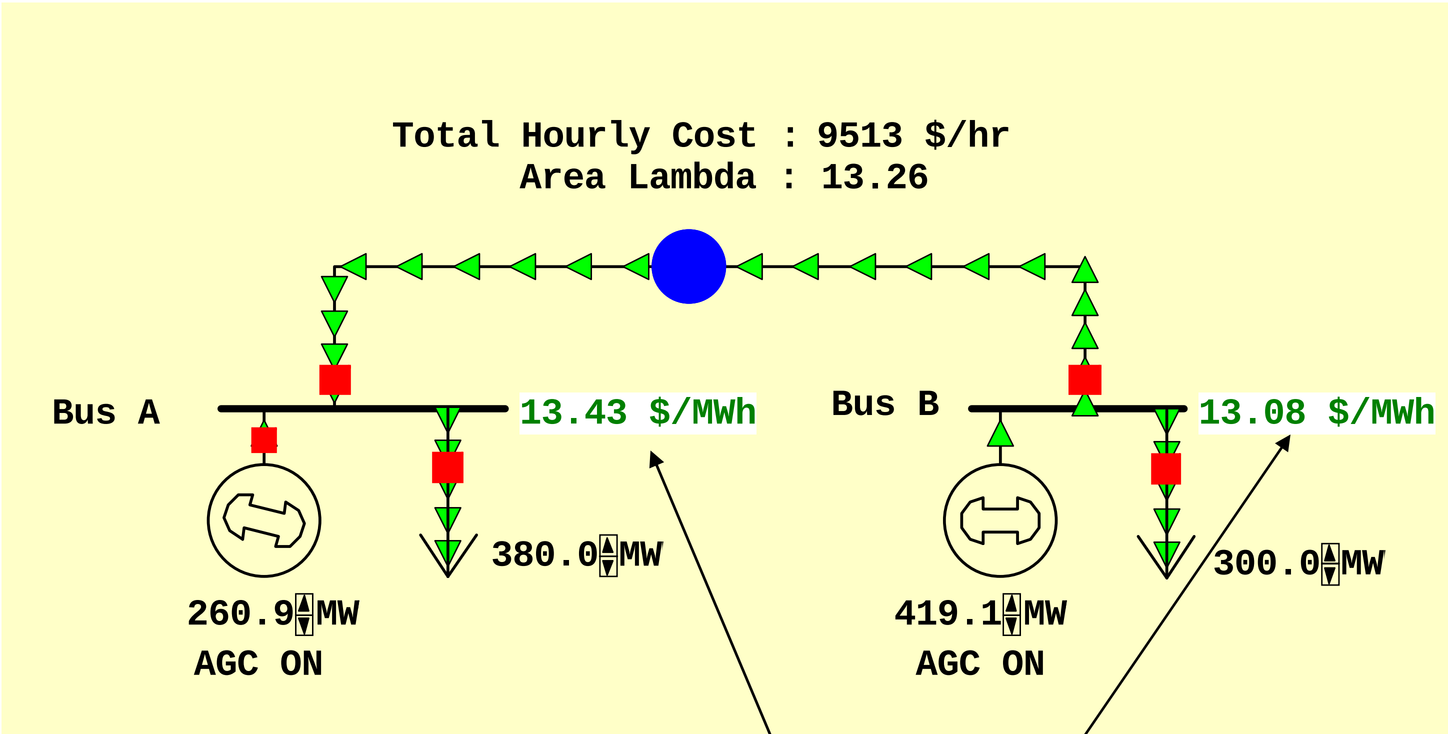
# Two Bus Example:
## No Constraints




Transmission line is not overloaded

Marginal cost of supplying power to each bus (locational marginal price or LMP)

# Two Bus Example:
## Constrained Line



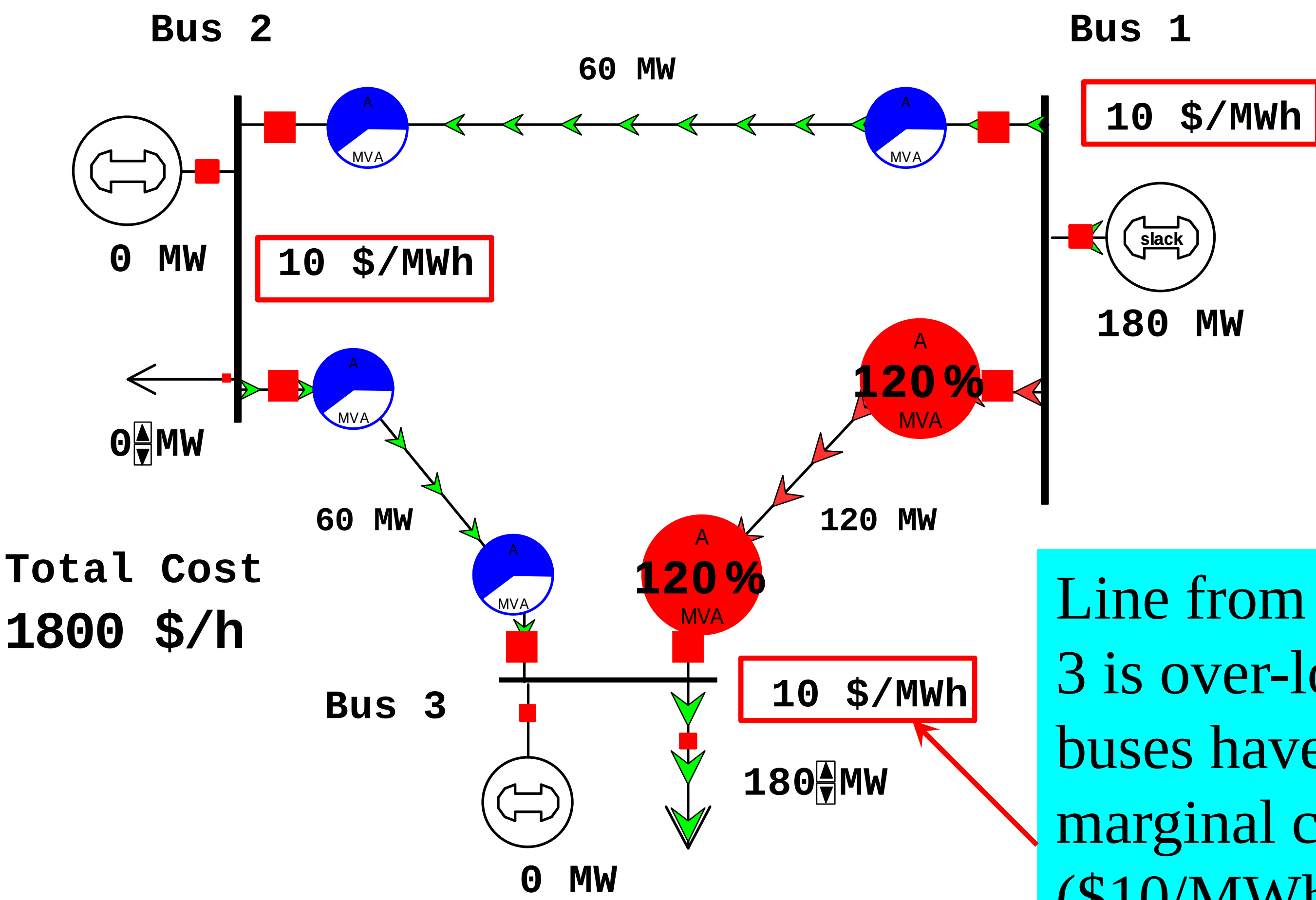

With the line loaded to its limit, additional load at Bus A must be supplied locally, causing the marginal costs to diverge.

# Hands-on: Three Bus Example

- Load the *B3LP.pwb* case.*
- Switch to Run Mode
- Go to the **Add Ons** ribbon tab
- Click **Primal LP** in the **Optimal Power Flow (OPF)** ribbon group to solve the case
- LP = linear program, a technique used to solve the OPF
- Initially the transmission line limits are not enforced

*This case and others referenced herein by file name are included with both the full commercial software and the free evaluation software. They are found in the *Sample Cases* subdirectory where Simulator is installed.

# Three Bus Example



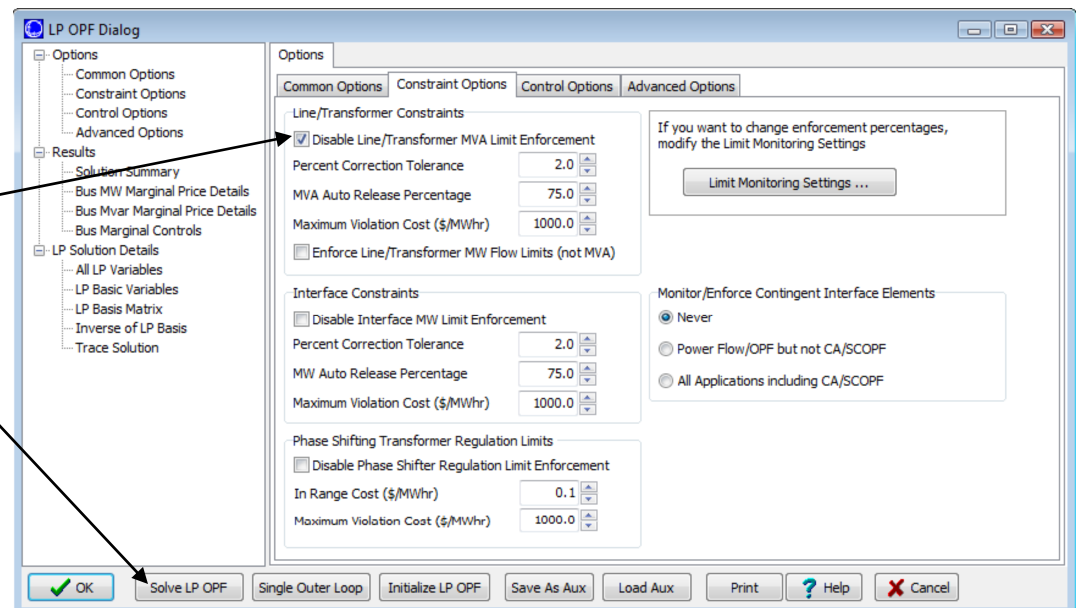

Line from Bus 1 to Bus 3 is over-loaded; all buses have the same marginal cost or LMP ($10/MWh)

# Three Bus Example

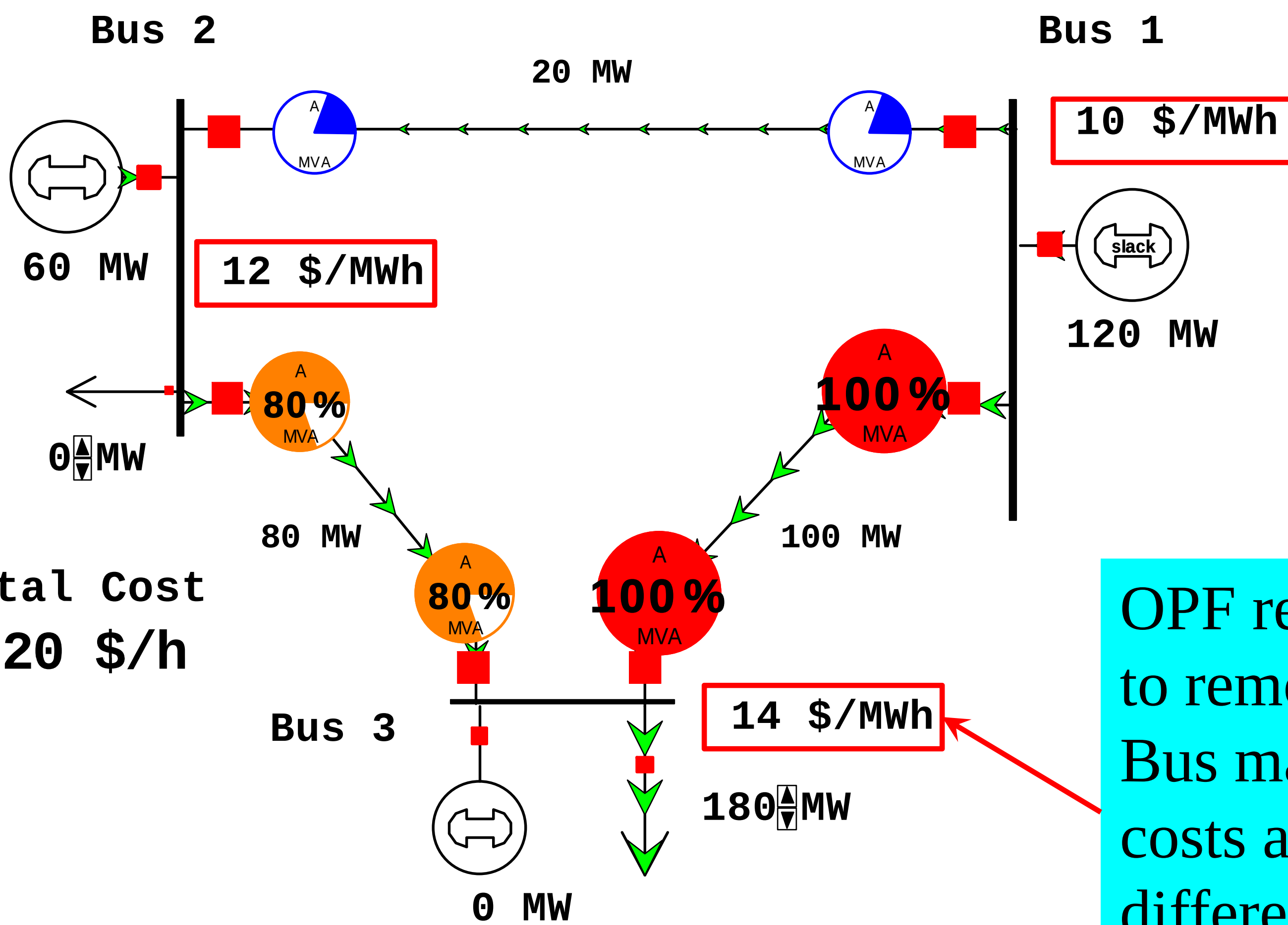
- All buses are connected through 0.1 pu reactance transmission lines (no MW losses), each with a 100 MVA limit
- The generator marginal costs are
  - Bus 1: 10 $ / MWhr; Range = 0 to 400 MW
  - Bus 2: 12 $ / MWhr; Range = 0 to 400 MW
  - Bus 3: 20 $ / MWhr; Range = 0 to 400 MW
- A single 180 MW load is at bus 3
- Ignoring transmission limits, all load is served by the least-cost generator, at bus 1

# Three Bus Example

- To enforce transmission line limits:
  - From the **OPF** ribbon group, Select **OPF Options and Results** to view the main options dialog
  - Select **Constraint Options Tab**
  - Clear the checkbox **Disable Line/Transformer MVA Limit Enforcement**
  - Click **Solve LP OPF**



# Line Limits Enforced




Total Cost
1920 $/h

OPF redispatches to remove violation. Bus marginal costs are now different.

# Why is bus 3 LMP $14 /MWh?

- The least-cost source of marginal power at buses 1 and 2 is the local generator. Each LMP matches the marginal cost of the local generator.
- However, the generator at bus 3 has a marginal cost of $20, and no generator has a marginal cost of $14.
- Power flow in the network distributes inversely to line impedance, and all line impedances are equal.
  - For bus 1 to supply 1 MW to bus 3, 2/3 MW would flow on direct path from 1 to 3, while 1/3 MW would "loop around" from 1 to 2 to 3.
  - Likewise, for bus 2 to supply 1 MW to bus 3, 2/3 MW would go directly from 2 to 3, while 1/3 MW would go from 2 to 1 to 3.

# Why is bus 3 LMP \$14 /MWh?

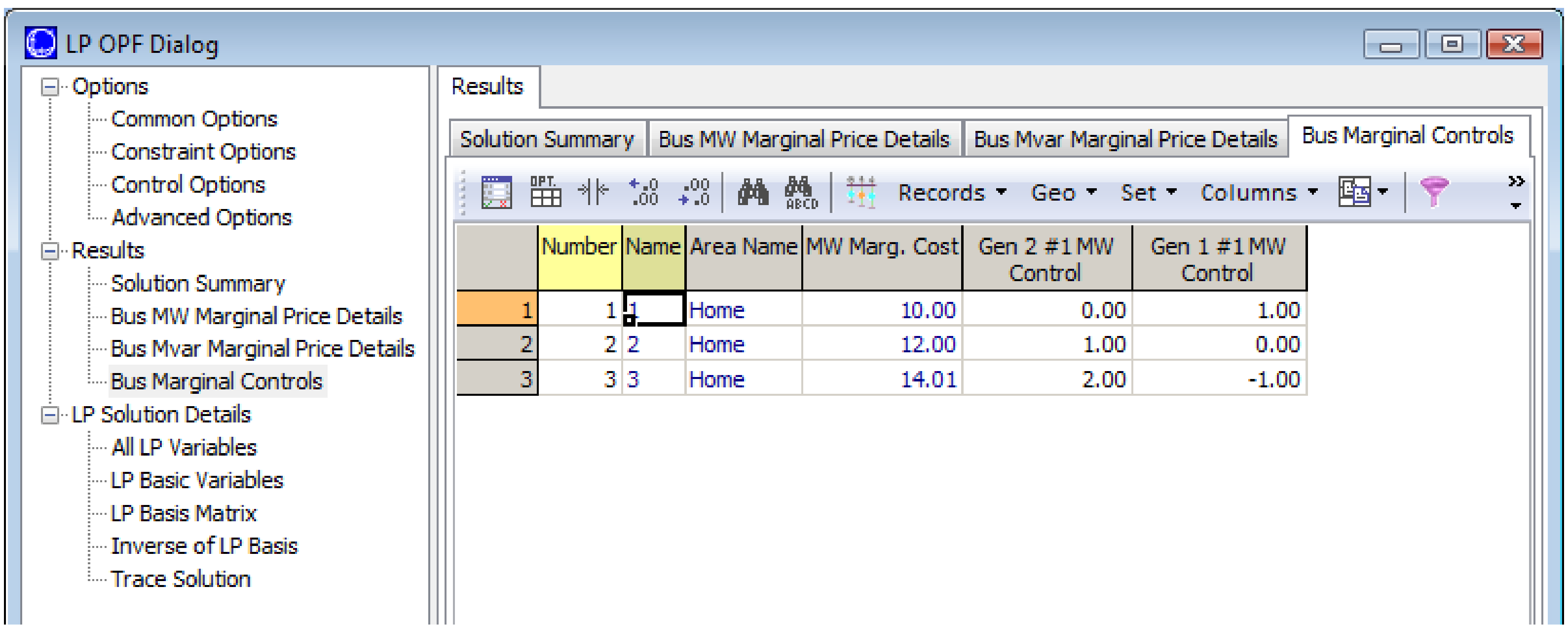
- With the line from 1 to 3 limited, no additional power may flow on it.
- To supply 1 more MW to bus 3 we need

  Pg1 + Pg2 = 1 MW

  2/3 Pg1 + 1/3 Pg2 = 0;  (no more flow on 1-3)
- Solving requires we increase Pg2 by 2 MW and decrease Pg1 by 1 MW: a net cost increase of \$14.

# Bus Marginal Controls

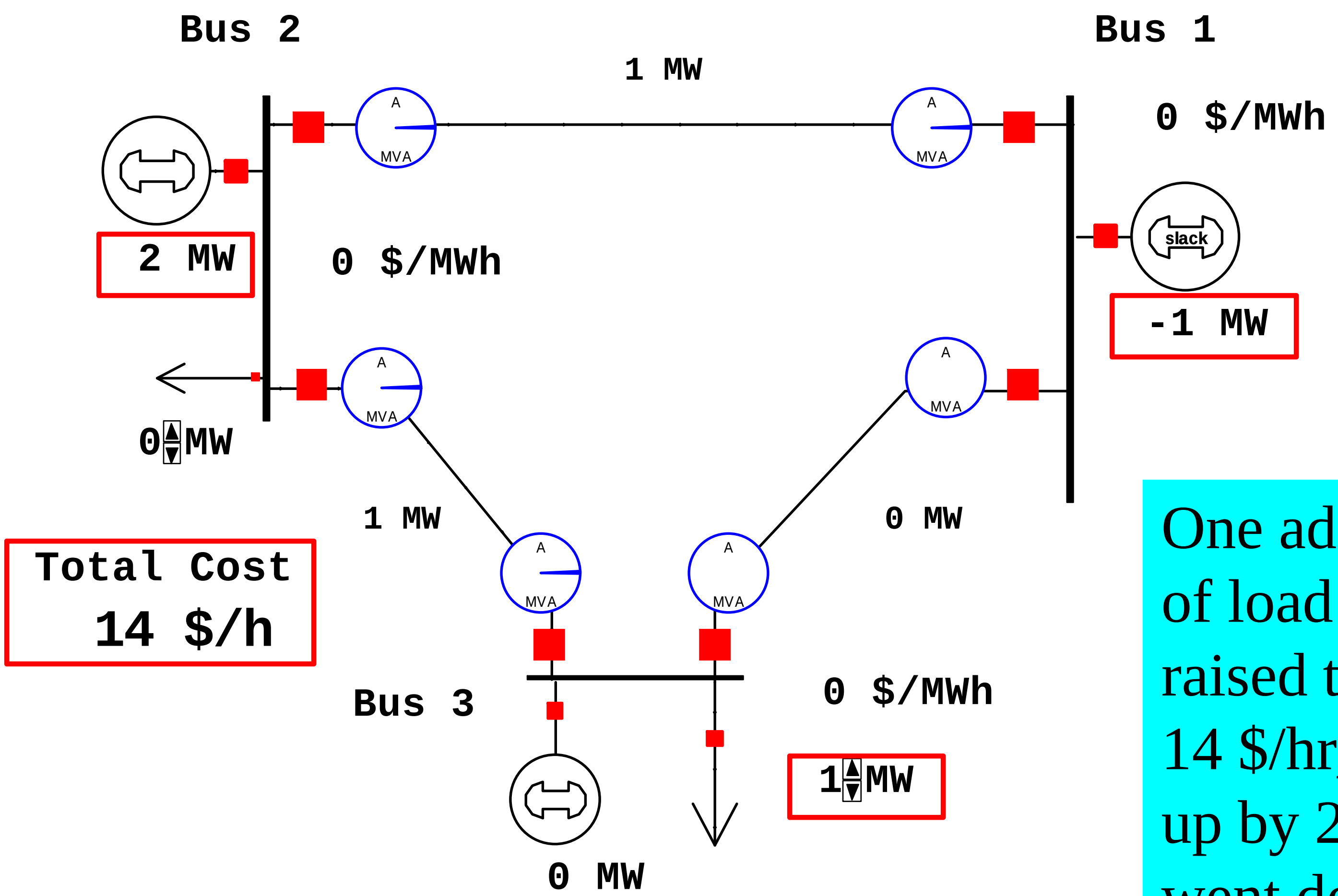
- In the **OPF Options and Results**, go to the **Results → Bus Marginal Controls** tab to identify the marginal units for each bus



# Three Bus Example

- To verify marginal cost, first set the present case as the base case (from **Tools Ribbon**, choose **Difference Flows → Set Present as Base Case**)
- Change bus 3 load to 181 MW
- Solve the OPF
- View the difference case (from **Tools Ribbon**, choose **Difference Flows → Difference Case)**

# Verify Bus 3 Marginal Cost



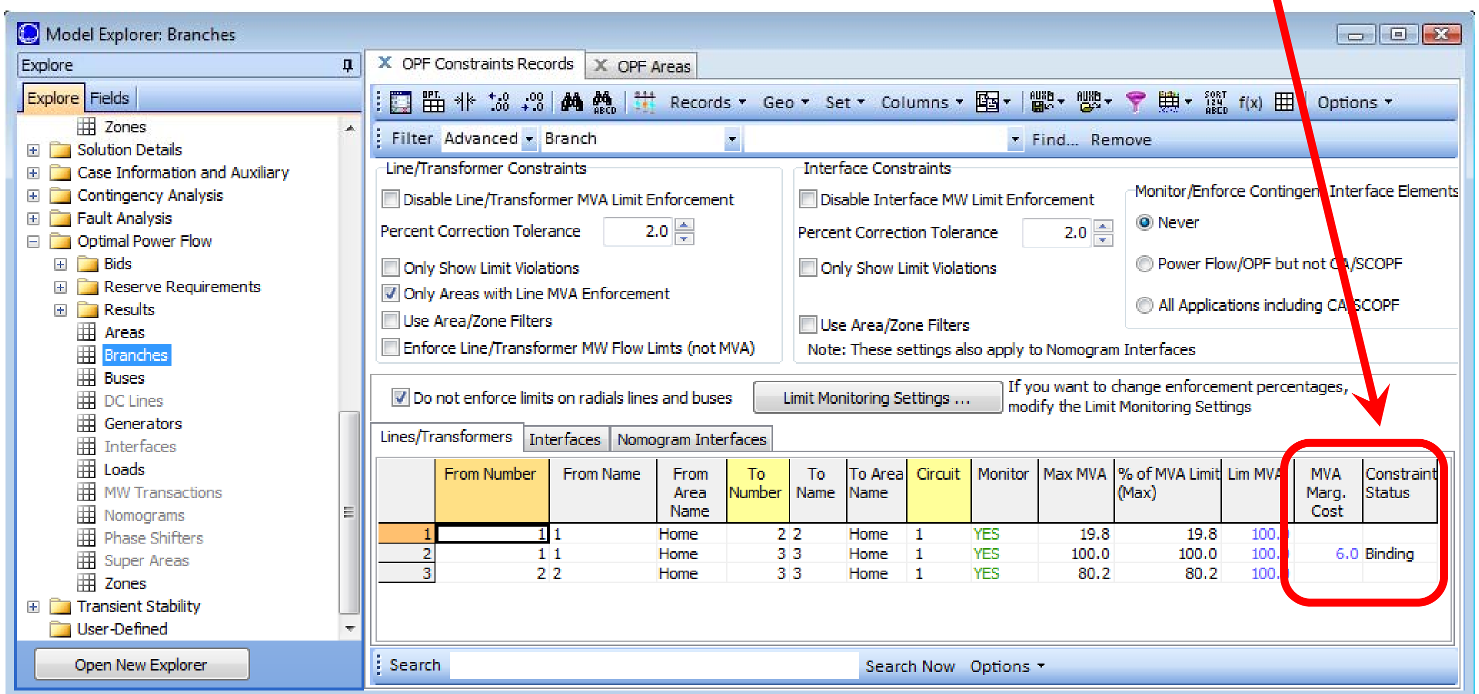

One additional MW of load at bus 3 raised total cost by 14 $/hr, as G2 went up by 2 MW and G1 went down by 1MW

# Marginal Cost of Enforcing Constraints

- Similarly to the bus marginal cost, you can also calculate the marginal cost of enforcing a line constraint
- For a transmission line, this represents the amount of system savings which could be achieved if the MVA rating was increased by 1.0 MVA.

# MVA Marginal Cost

- Switch **Difference Flows** back to **Present Case**
- From the **Add Ons** ribbon, Choose **OPF Case Info → OPF Lines and Transformers** to access OPF Constraint Records
- Look at the column **MVA Marg. Cost**



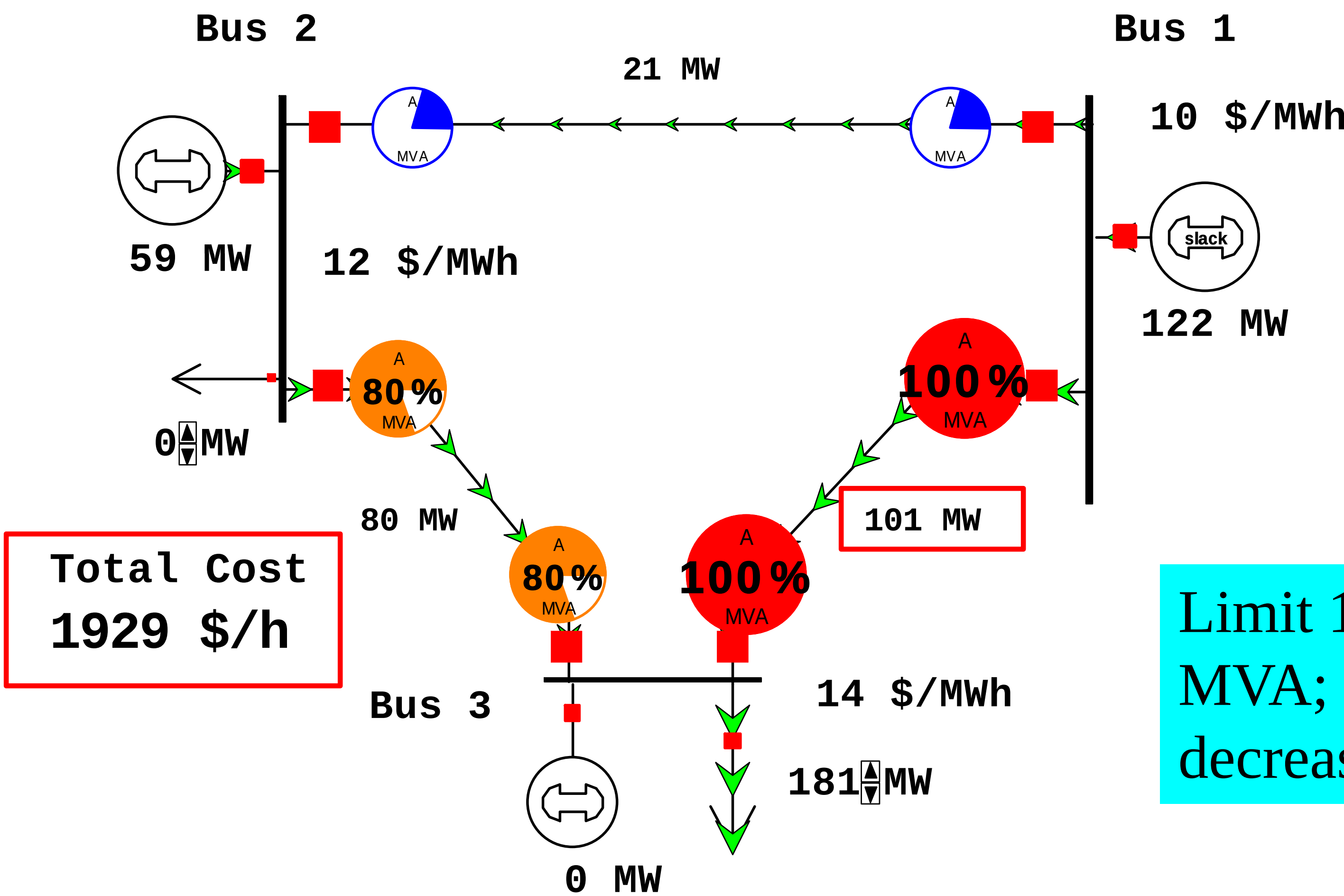
# Why is MVA Marginal Cost $6/MVAhr?

- If we allow 1 more MVA to flow on the line from 1 to 3, then this allows us to redispatch as follows

  Pg1 + Pg2 = 0 MW

  2/3 Pg1 + 1/3 Pg2 = 1; (no more flow on 1-3)
- Solving requires we drop Pg2 by 3 MW and increase Pg1 by 3 MW: a net savings of $6
- Verify by changing the limit on the line to 101 MVA

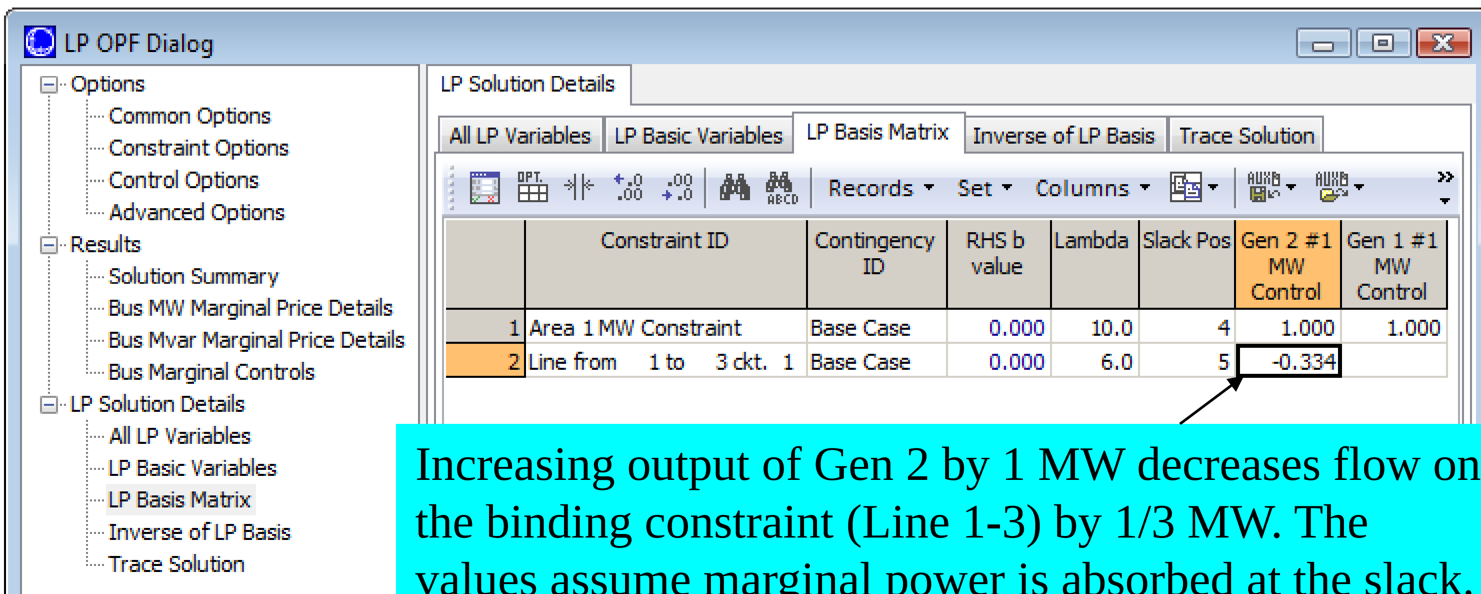
# Increased Line Limit




Limit 1-3=101 MVA; Total Cost decreases $6

# How do Marginal Generators Affect Constraints?

- In the **OPF Options and Results**, go to **LP Solution Details → LP Basis Matrix** tab to identify the sensitivity of each marginal control on each constraint

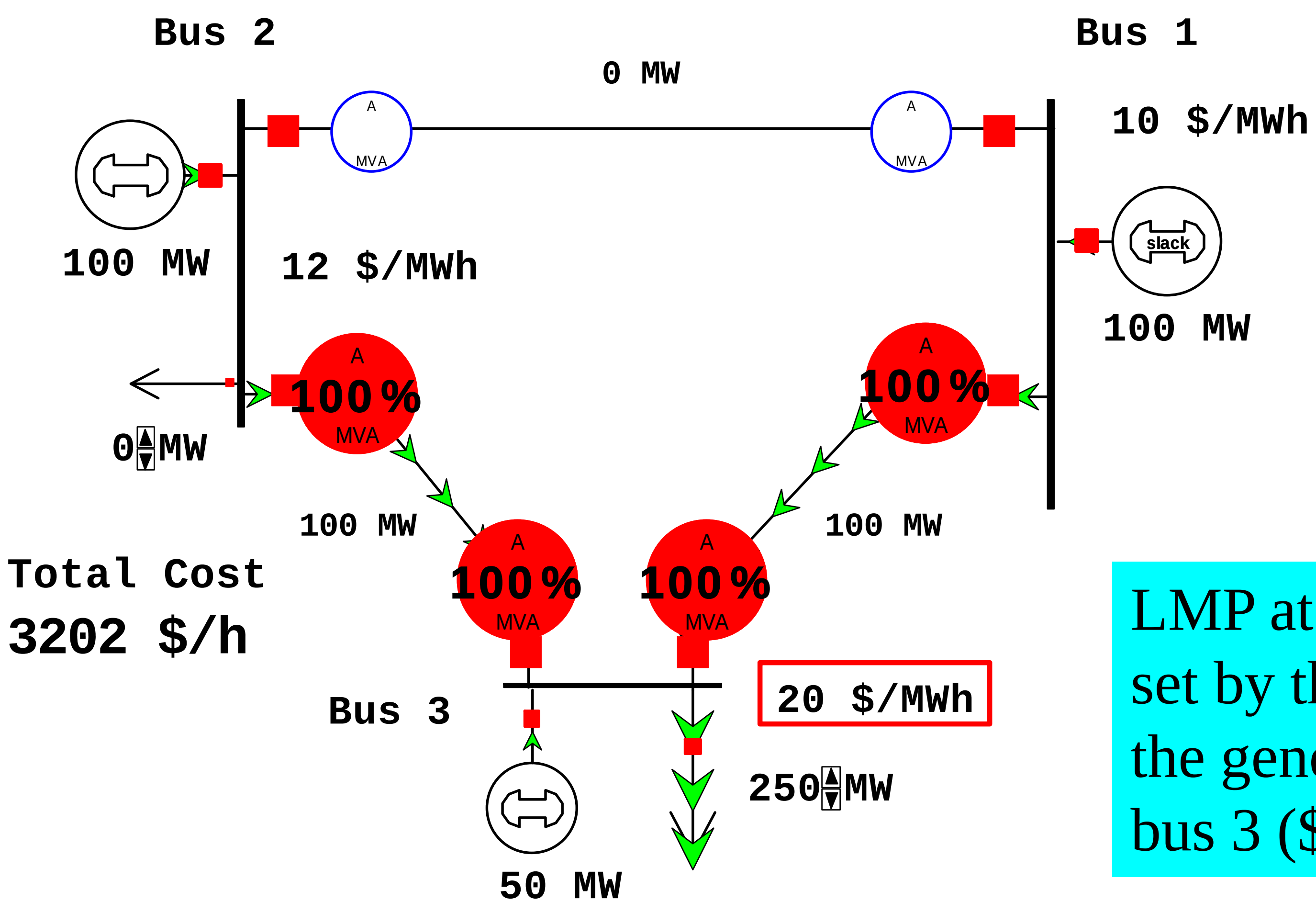



Increasing output of Gen 2 by 1 MW decreases flow on the binding constraint (Line 1-3) by 1/3 MW. The values assume marginal power is absorbed at the slack.

# Both lines into Bus 3 Congested

- For bus 3 load above 200 MW, the marginal load must be supplied locally
- Restore line 1-3 limit to 100 MVA
- Change bus 3 load to 250 MW

# Both lines into Bus 3 Congested

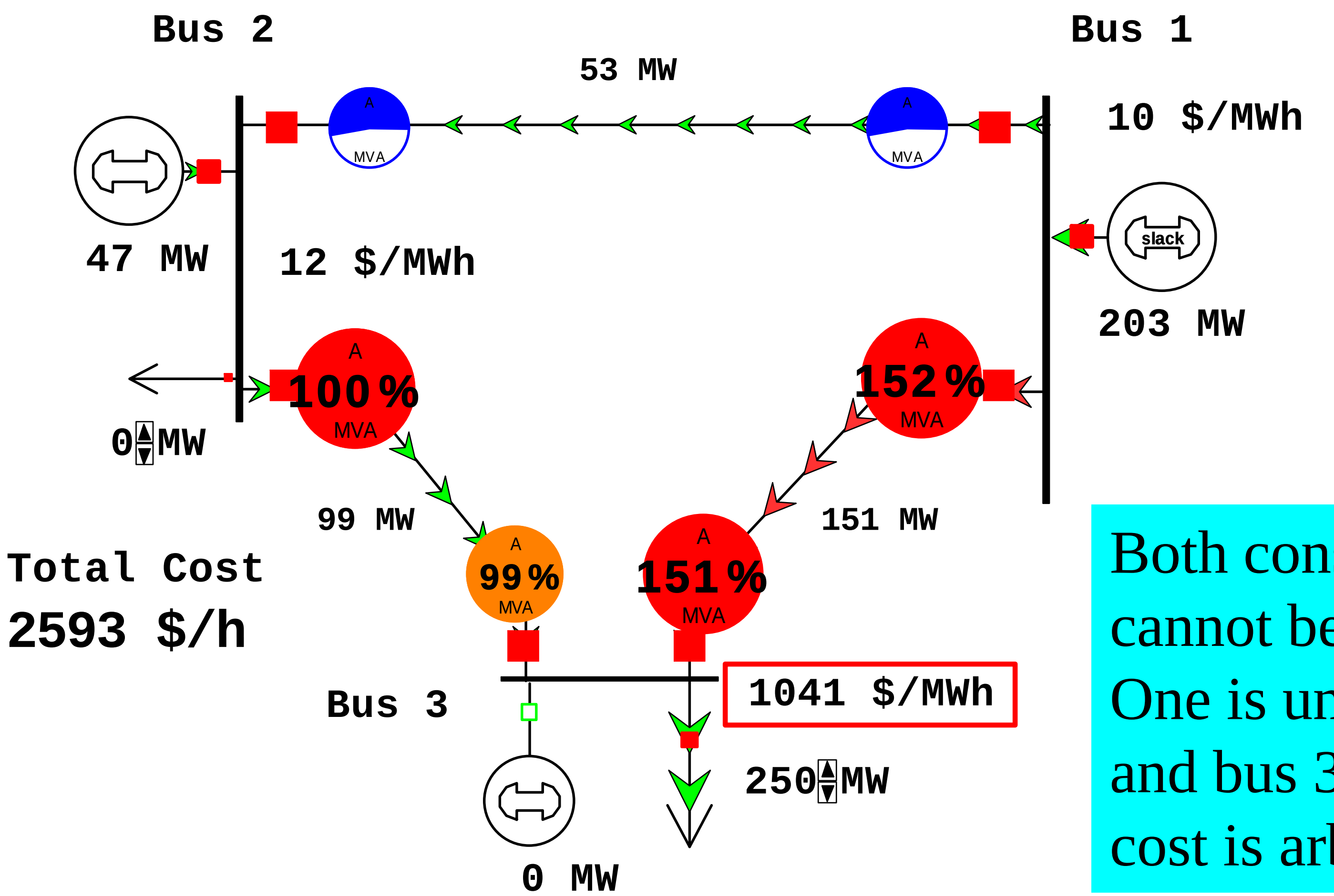



LMP at bus 3 is set by the cost of the generator at bus 3 ($20)

# Loss of Generator at Bus 3

- Now if the generator at Bus 3 is taken out of service, the 250 MW load cannot be served without overloading the lines, which have a total capacity of 200 MW
- Both constraints cannot be enforced
- The marginal cost is now arbitrary, given by a penalty function
- The Maximum Violation Cost is $1000/MWh by default, but may be changed on the **OPF Options and Results** dialog, **Constraint Options** tab

# Unenforceable Constraint

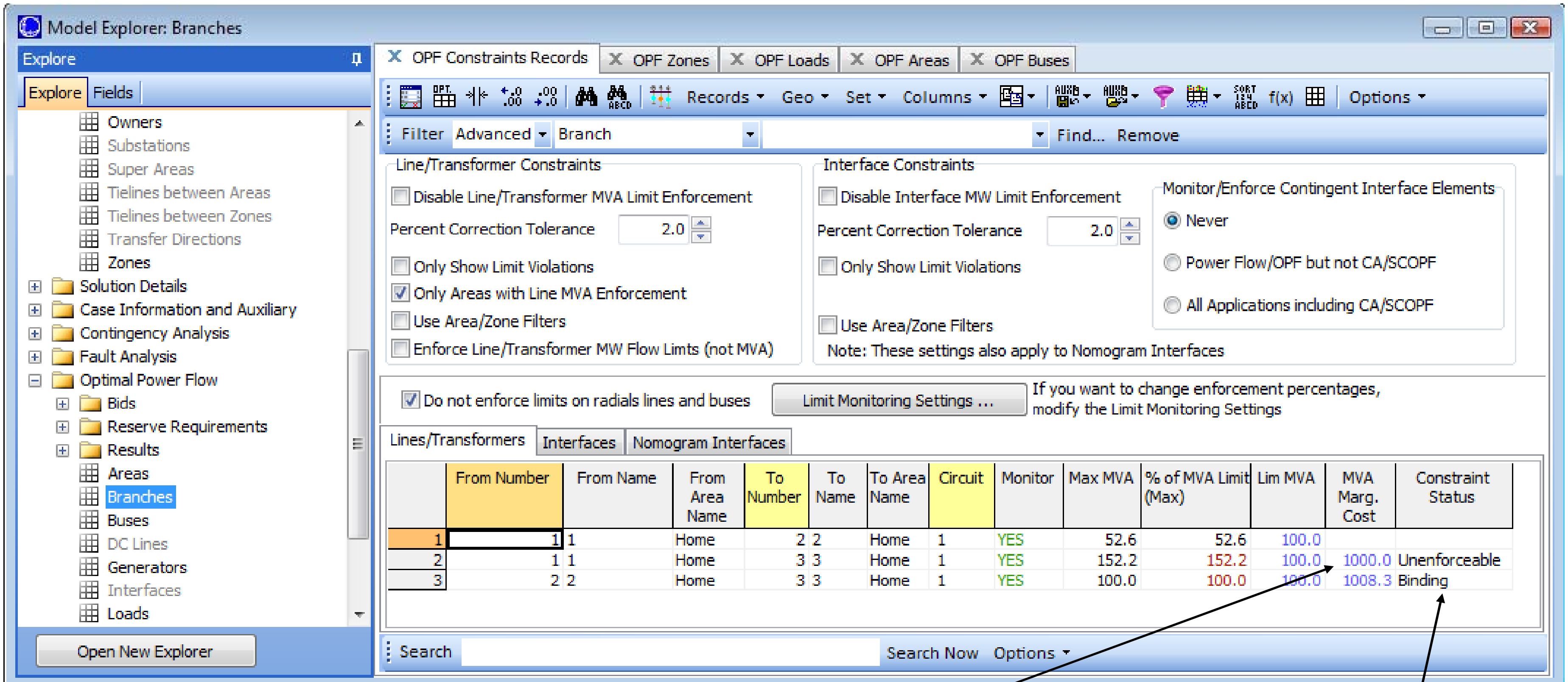



Both constraints cannot be enforced. One is unenforceable and bus 3 marginal cost is arbitrary.

# Unenforceable Limits

- The cost minimization algorithm naturally tries to remove the line violations.
- High marginal prices and the **OPF Constraint Records** will identify binding and unenforceable transmission limits
- Look for generators that are in/out of service near the constraints
- There may be a load pocket without enough transmission: the 3 bus case with generator 3 out of service is an example of a load pocket

# OPF Line/Transformer Constraint Records




Marginal costs are non-zero only for active constraints

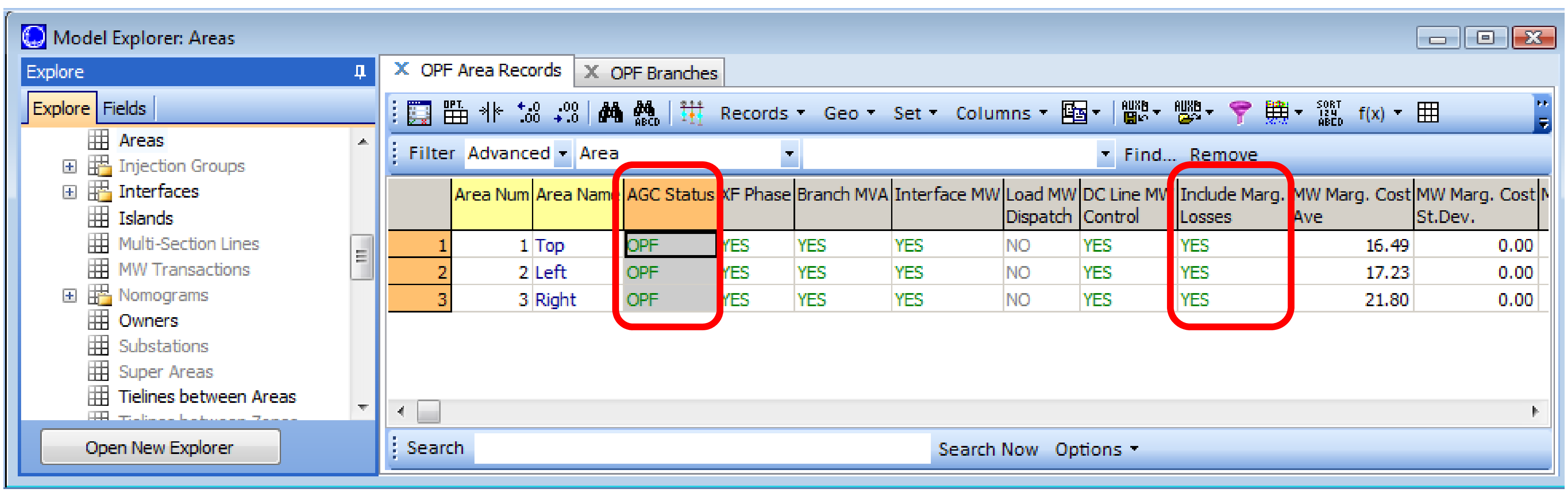
Indicates if constraint is binding or unenforceable

# Cost of Energy, Losses and Congestion

- Some ISO documents refer to cost components of energy, losses, and congestion
- Simulator can resolve the LMP into these components
- Open the *B7OPF.pwb* case for an example, using a slightly more complex system with transmission losses

# Cost of Energy, Losses and Congestion

- From the **Add Ons** ribbon tab, select **OPF Case Info → OPF Areas**.
- For each area:
  – Set **AGC Status** to **OPF**
  – Toggle **Include Marg. Losses** column of each area to *YES*

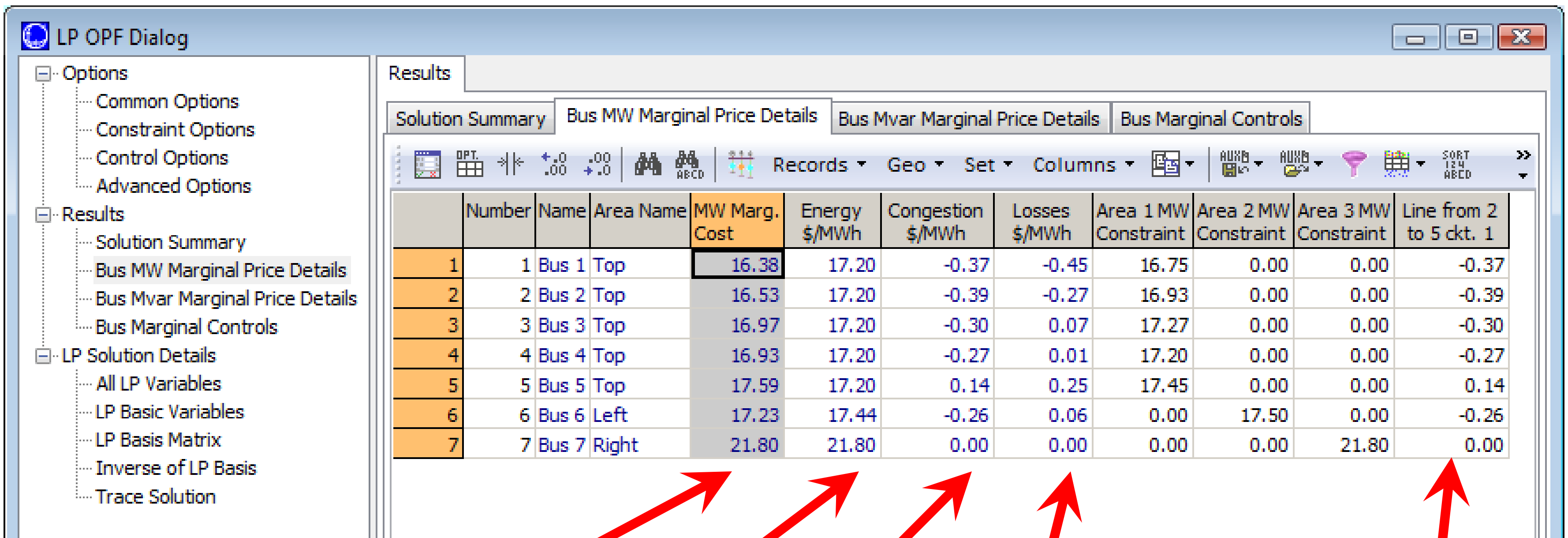


# Cost of Energy, Losses and Congestion

- Change the load at Bus 5 to 170 MW
- From the **Add Ons** ribbon, click **Primal LP** to solve
- The line between buses 2 and 5 is a binding constraint
- Now open **OPF Options and Results**
  - Go to the **Results → Bus MW Marginal Price Details** page
  - Here you will find columns for the MW Marg Cost, Energy, Congestion, and Losses

# Cost of Energy, Losses and Congestion

- Note that the only value that is truly unique for an OPF solution is the total MW Marginal Cost $\lambda_k$




| | Number | Name | Area Name | MW Marg. Cost | Energy $/MWh | Congestion $/MWh | Losses $/MWh | Area 1 MW Constraint | Area 2 MW Constraint | Area 3 MW Constraint | Line from 2 to 5 ckt. 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Bus 1 | Top | 16.38 | 17.20 | -0.37 | -0.45 | 16.75 | 0.00 | 0.00 | -0.37 |
| 2 | 2 | Bus 2 | Top | 16.53 | 17.20 | -0.39 | -0.27 | 16.93 | 0.00 | 0.00 | -0.39 |
| 3 | 3 | Bus 3 | Top | 16.97 | 17.20 | -0.30 | 0.07 | 17.27 | 0.00 | 0.00 | -0.30 |
| 4 | 4 | Bus 4 | Top | 16.93 | 17.20 | -0.27 | 0.01 | 17.20 | 0.00 | 0.00 | -0.27 |
| 5 | 5 | Bus 5 | Top | 17.59 | 17.20 | 0.14 | 0.25 | 17.45 | 0.00 | 0.00 | 0.14 |
| 6 | 6 | Bus 6 | Left | 17.23 | 17.44 | -0.26 | 0.06 | 0.00 | 17.50 | 0.00 | -0.26 |
| 7 | 7 | Bus 7 | Right | 21.80 | 21.80 | 0.00 | 0.00 | 0.00 | 0.00 | 21.80 | 0.00 |

$$\lambda_k = \lambda_{Ek} + \lambda_{Ck} + \lambda_{Lk}$$

"Impact" of constraints on LMP

# Cost of Energy, Loss, and Congestion Reference

- The costs of Energy, Losses, and Congestion are dependent on the *reference* for Energy and Losses, specified for each region on OPF control: either an area or super area
  - Return to **OPF Case Info → OPF Areas**
  - Right-click on Area Top and choose show Dialog
  - The *Cost of Energy, Loss, and Congestion Reference* option group is in the lower left
  - Similar settings may be found on the Super Area dialog

# Super Areas

- Super areas are a record structure used to hold a set of areas
- Super Areas work like ISOs: a number of control areas are dispatched as though they were a single area, without fixed interchanges between the individual areas
- Area records are preserved for calculation of average prices, exports, and other quantities
- For a super area to be used in the OPF, its AGC Status field must be *OPF*

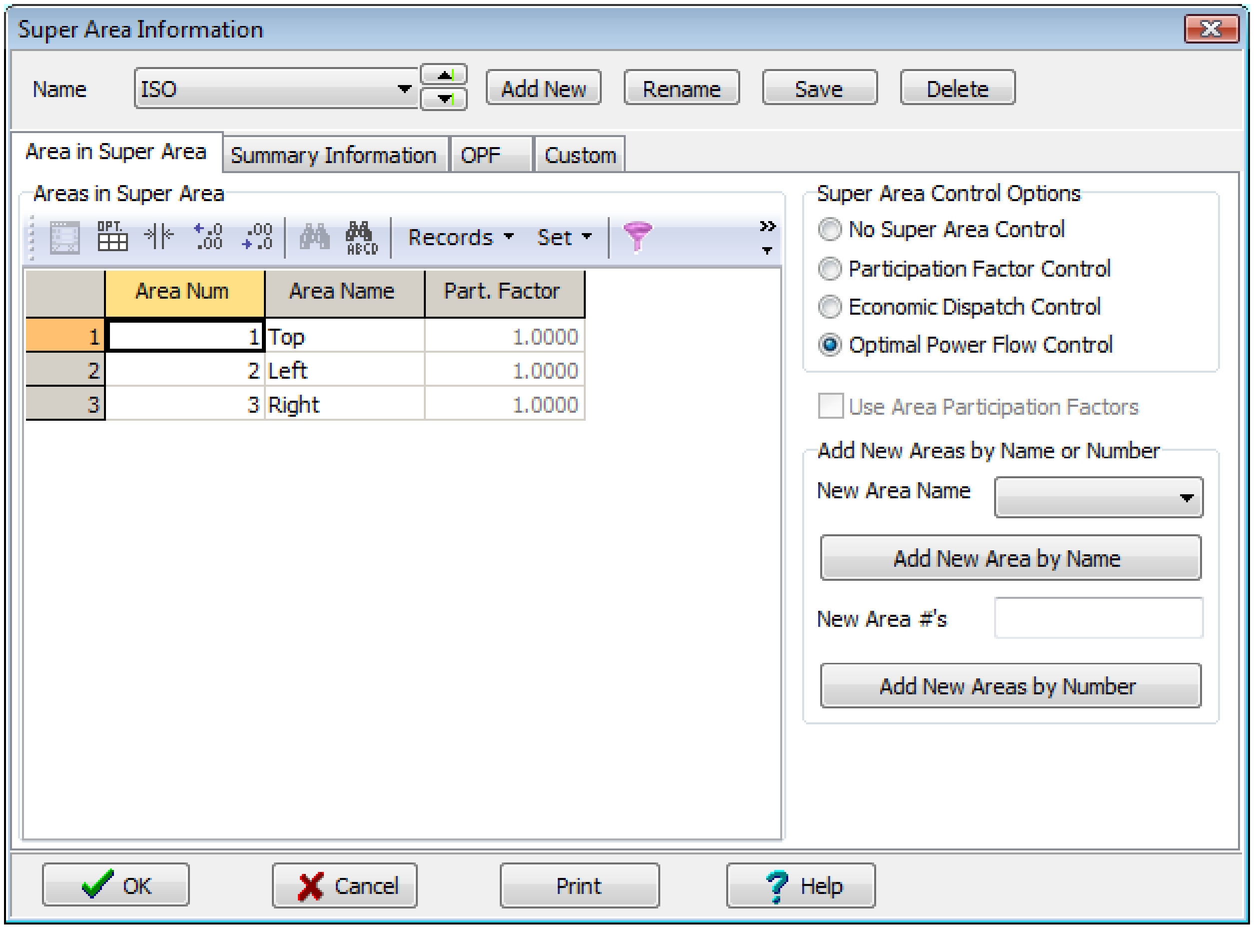
# Super Area Control

- For comparison, set the present case as the base case again (from **Tools Ribbon**, choose **Difference Flows → Set Present as Base Case**)
- From the **Add Ons** ribbon, select **OPF Case Info → OPF Super Areas**
- Right click in the empty grid and select **Insert…**

# Super Area Control

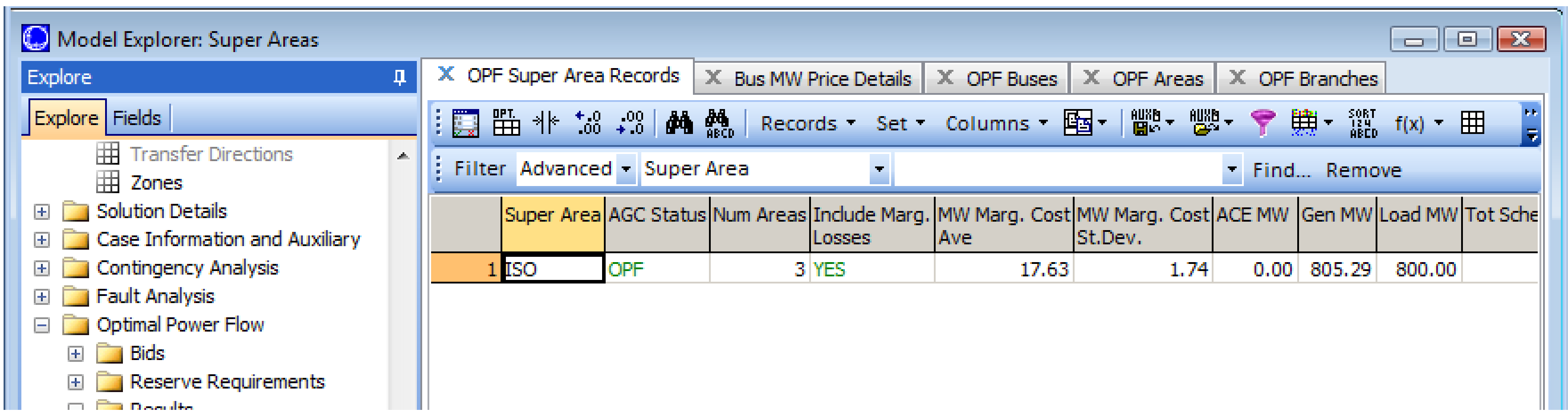
- Right-click in the empty grid and select **Insert…**
- Select all areas and click **OK**
- Choose **Optimal Power Flow Control** from the option group on the right
- Optionally click the **Rename** button and rename the super area "ISO"

# Super Area Control



# Super Area Control

- Click **OK** to close the dialog
- Toggle **Include Marg. Losses** to YES
- Solve the OPF

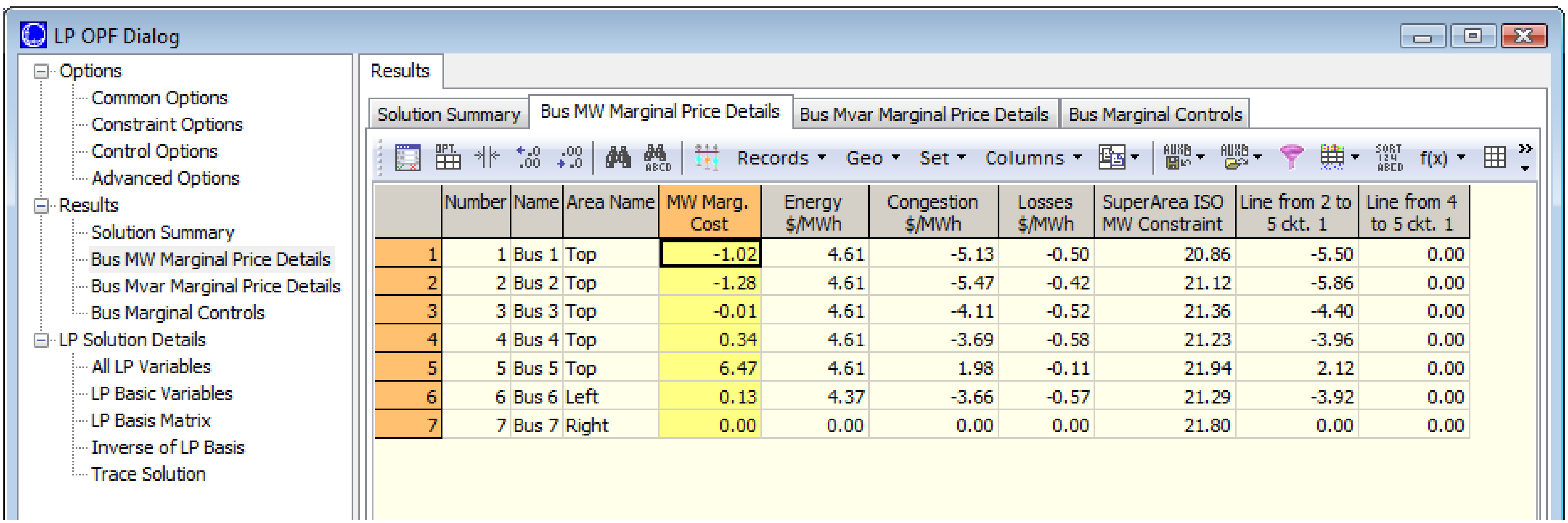


# Super Area Control

- Replacing the 3 area interchange constraints and with a single power balance constraint for the Super Area allowed a redispatch that decrease the total cost by $89/hour
- LMP changes vary by location. LMPs drop at buses 1-3, but increase at buses 4-6
- Generator MW output increased at buses 4 and 6, but decreased at buses 2 and 7
- The line between buses 2 and 5 is still a binding constraint

# Super Area Control

- Change in bus marginal costs with ISO Super Area control vs. individual area control




| | Number | Name | Area Name | MW Marg. Cost | Energy $/MWh | Congestion $/MWh | Losses $/MWh | SuperArea ISO MW Constraint | Line from 2 to 5 ckt. 1 | Line from 4 to 5 ckt. 1 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Bus 1 | Top | -1.02 | 4.61 | -5.13 | -0.50 | 20.86 | -5.50 | 0.00 |
| 2 | 2 | Bus 2 | Top | -1.28 | 4.61 | -5.47 | -0.42 | 21.12 | -5.86 | 0.00 |
| 3 | 3 | Bus 3 | Top | -0.01 | 4.61 | -4.11 | -0.52 | 21.36 | -4.40 | 0.00 |
| 4 | 4 | Bus 4 | Top | 0.34 | 4.61 | -3.69 | -0.58 | 21.23 | -3.96 | 0.00 |
| 5 | 5 | Bus 5 | Top | 6.47 | 4.61 | 1.98 | -0.11 | 21.94 | 2.12 | 0.00 |
| 6 | 6 | Bus 6 | Left | 0.13 | 4.37 | -3.66 | -0.57 | 21.29 | -3.92 | 0.00 |
| 7 | 7 | Bus 7 | Right | 0.00 | 0.00 | 0.00 | 0.00 | 21.80 | 0.00 | 0.00 |

# Options for Further Analysis

- What are the marginal costs of enforcing the line constraints? How do the system costs change if the line constraints are relaxed (i.e., not enforced)? For example, try solving without enforcing line 2 to 5.
- Try these other scenarios
  - Reduce the fuel cost of the generator at bus 1
  - Take the generator at bus 4 out of service
  - Take the line between buses 2 and 5 out of service
  - Increase the load at bus 3 to 200 MW
  - Scale the load by 150%, system-wide
  - Change the minimum MW limit of the generator at bus 2 to 50 MW
  - …and numerous other possibilities

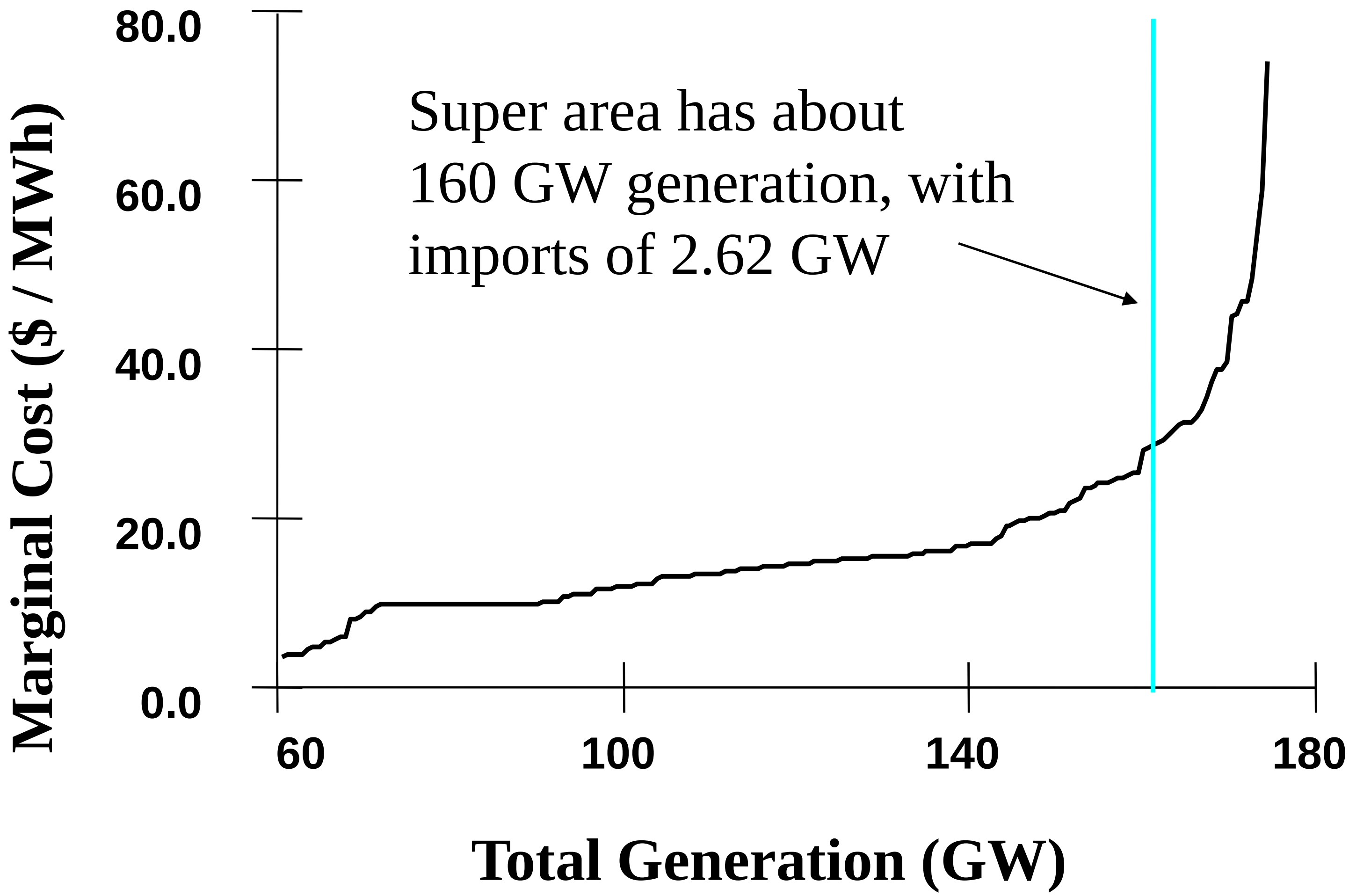
# Summary

- In nodal markets, clearing prices and “winners and losers” may be greatly influenced by inputs and assumptions, including
  - Generator costs or bids
  - Generator availability
  - Network topology (lines in service or out)
  - Transmission limits
  - Load: system-wide and at individual buses
- The concepts analyzed in these simple models apply to real-world power markets as well

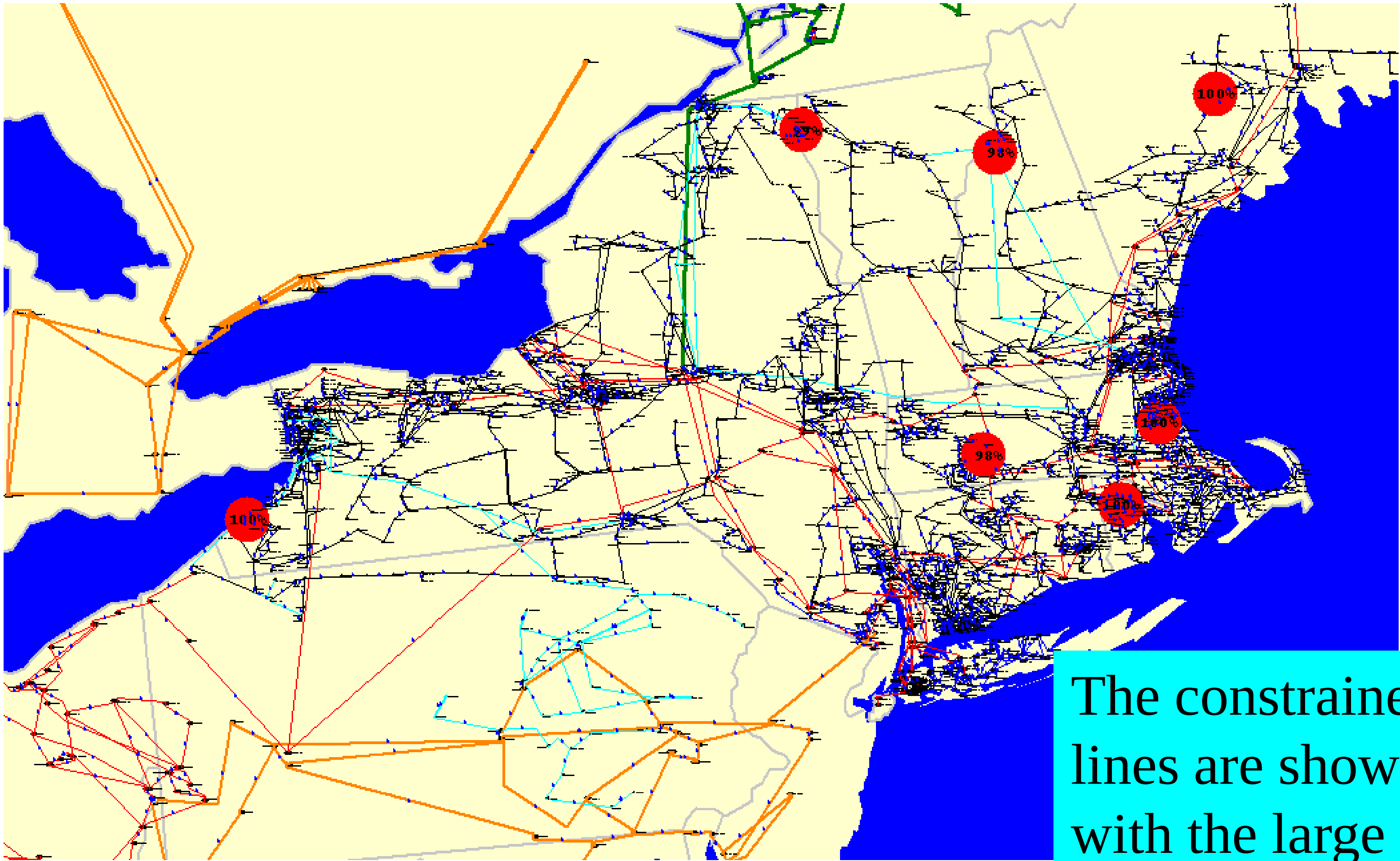
# Application of OPF to a Large System

- Next case is based upon the FERC Form 715 1997 Summer Peak case filed by NEPOOL
  - Case includes NEPOOL, NYPP, PJM, and ECAR, representing a significant portion of the Eastern Interconnect (9270 buses and 2506 generators)
  - The system was modeled both as a single Super Area and as separate power pools with fixed interchanges
  - Most generators have estimated costs (others default to $10/MWh)
  - Market model and results developed in joint project between PowerWorld and U.S. Energy Information Administration
- Such cases are now generally only available in North America from ISOs, Transmission Operators, and NERC entities. They are proprietary and subject to Critical Energy Infrastructure Information (CEII) restrictions on distribution.

# NEPOOL/NYPP/PJM/ECAR Supply Curve

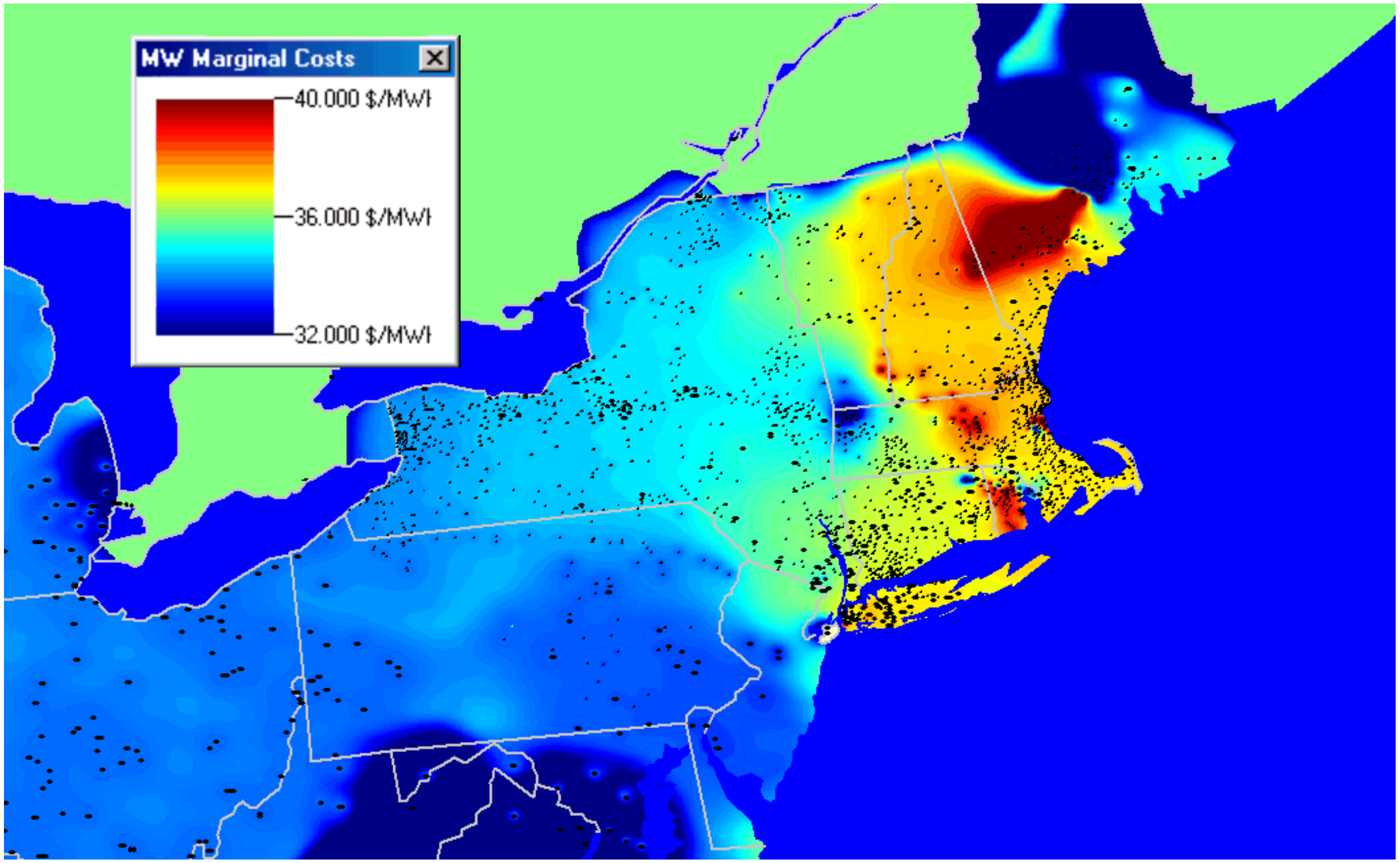


# System-Wide Super Area:
## Transmission Loading at Optimal Solution

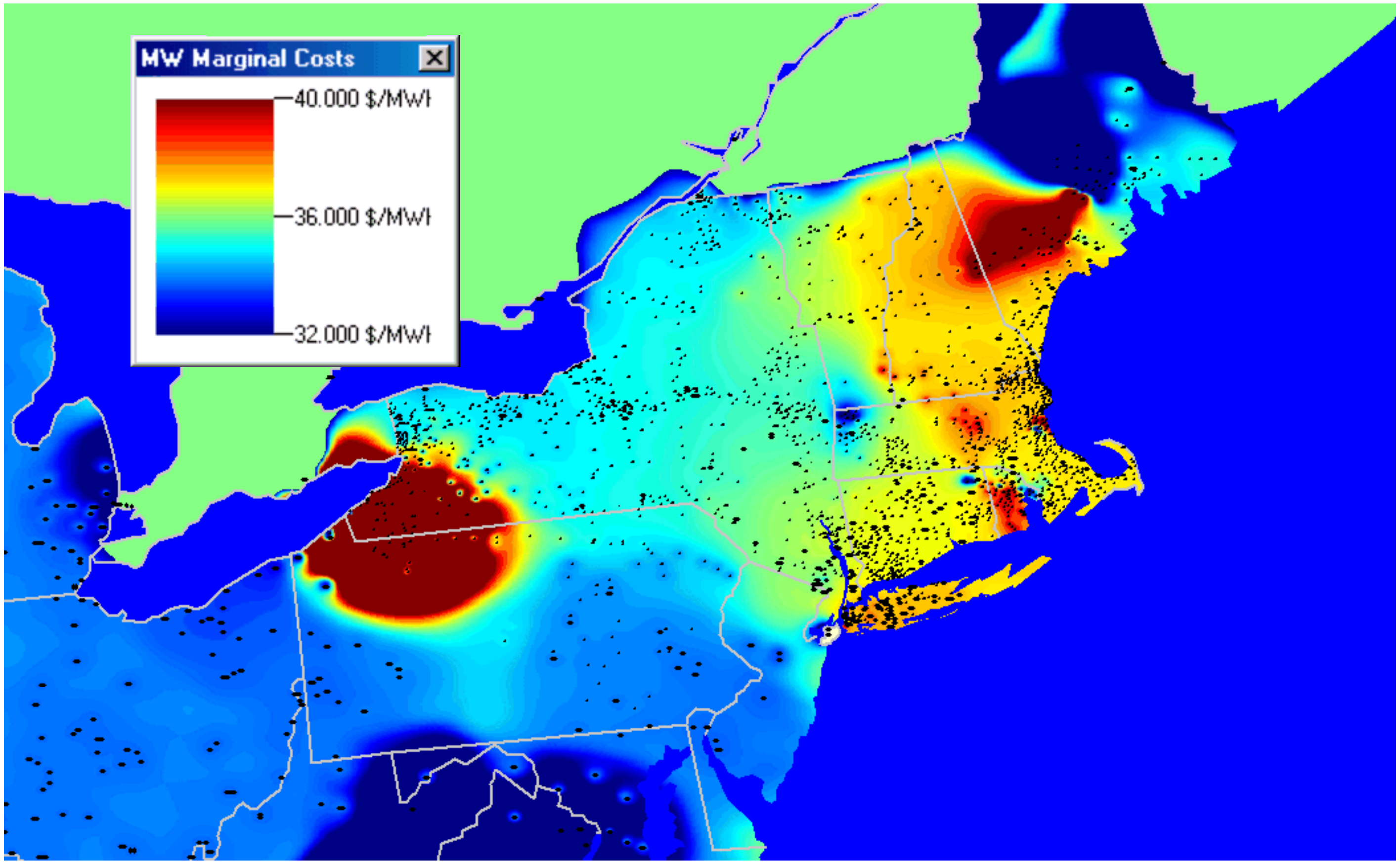



The constrained lines are shown with the large red pie charts

# System-Wide Super Area:
## Bus Marginal Price Contour

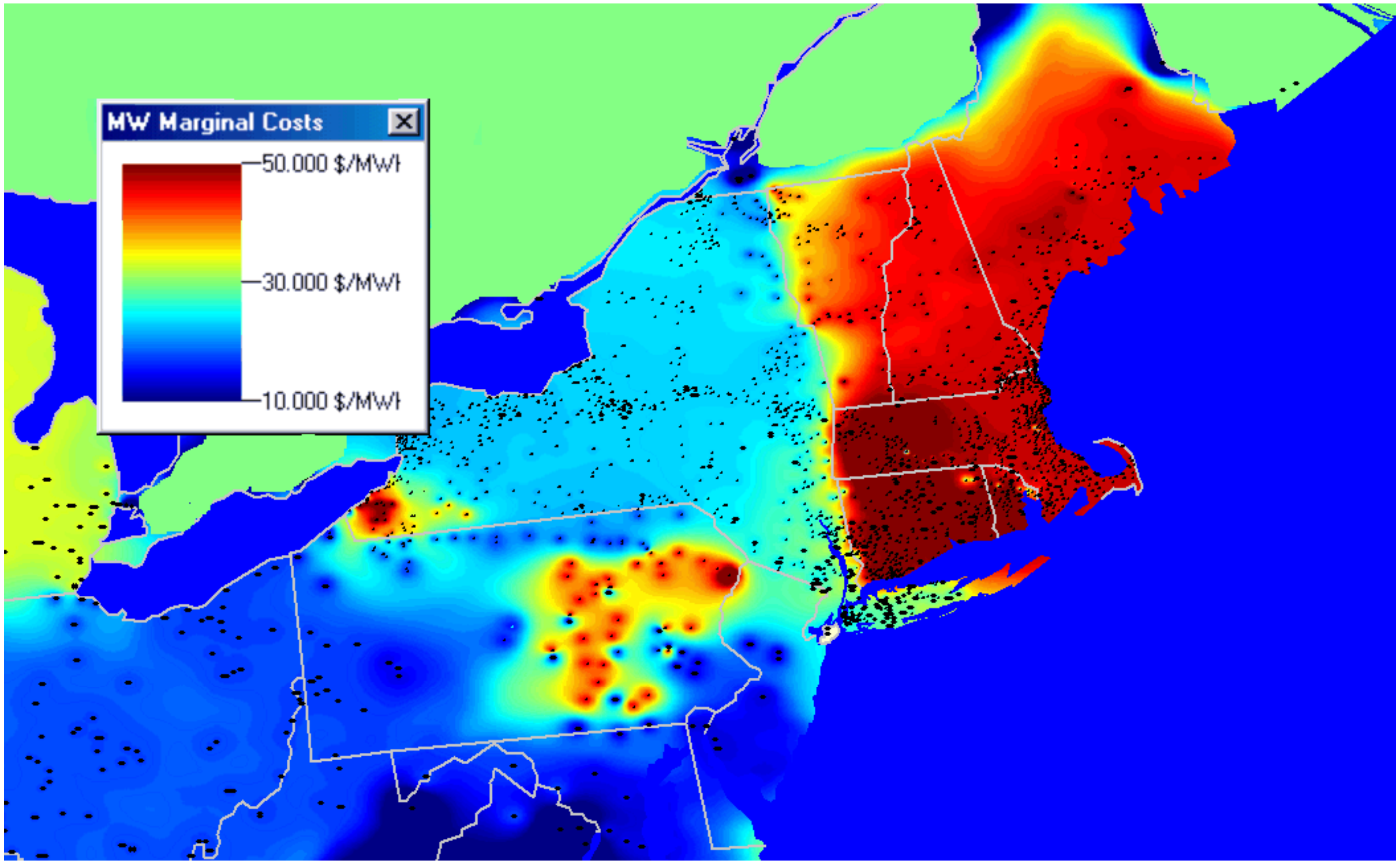


# System-Wide Superarea:
## 85 MW Gen in Western NY is offline




Note the load pocket created and difference in LMPs based on operation of a single 85 MW generator

# Individual Power Pools:
## Bus Marginal Price Contour




Total operating cost = $4,494,170 / hr, an increase of $48,170 / hr
Fixed interchange yields "seams" between power pools