Transmission Simulation

Thomas J. Overbye

Texas A&M University
overbye@tamu.edu

© copyright Thomas Overbye, 2022

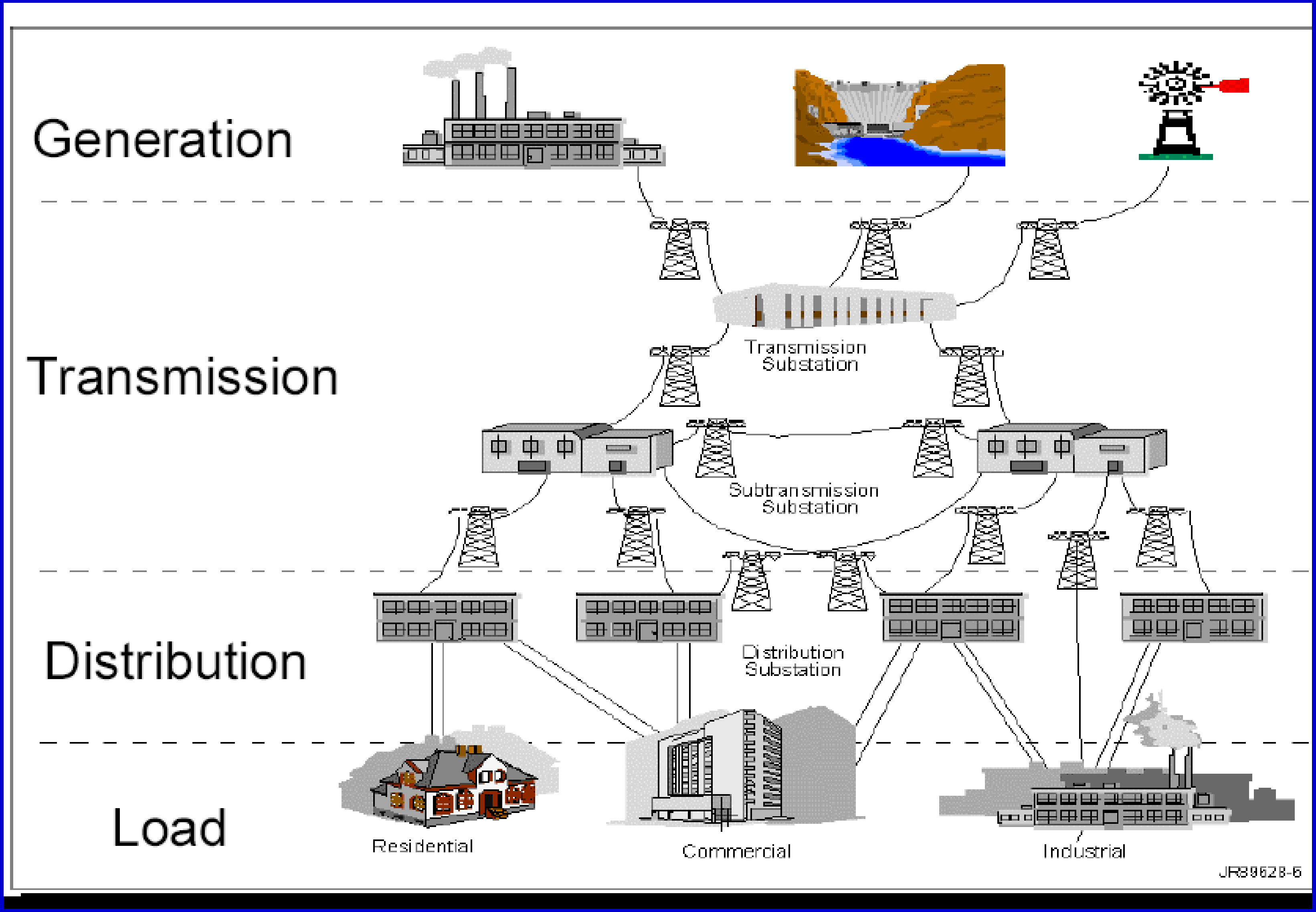
Presentation Overview

- Goal is to demonstrate operation of large scale power market
- Emphasis on the impact of the transmission system
- Introduce basic power flow concepts through small system examples
- Finish with simulation of Eastern U.S. System and the August 14, 2003 Blackout

Power System Basics

- All power systems have three major components: Generation, Load and Transmission.
- Generation: Creates electric power.
- Load: Consumes electric power.
- Transmission: Transmits electric power from generation to load.

Electric Grid Overview



Interconnected Electric Grids

- When operating at the same frequency (either 50 or 60 Hz), electric grids can be connected into interconnects

World Electric Interconnects

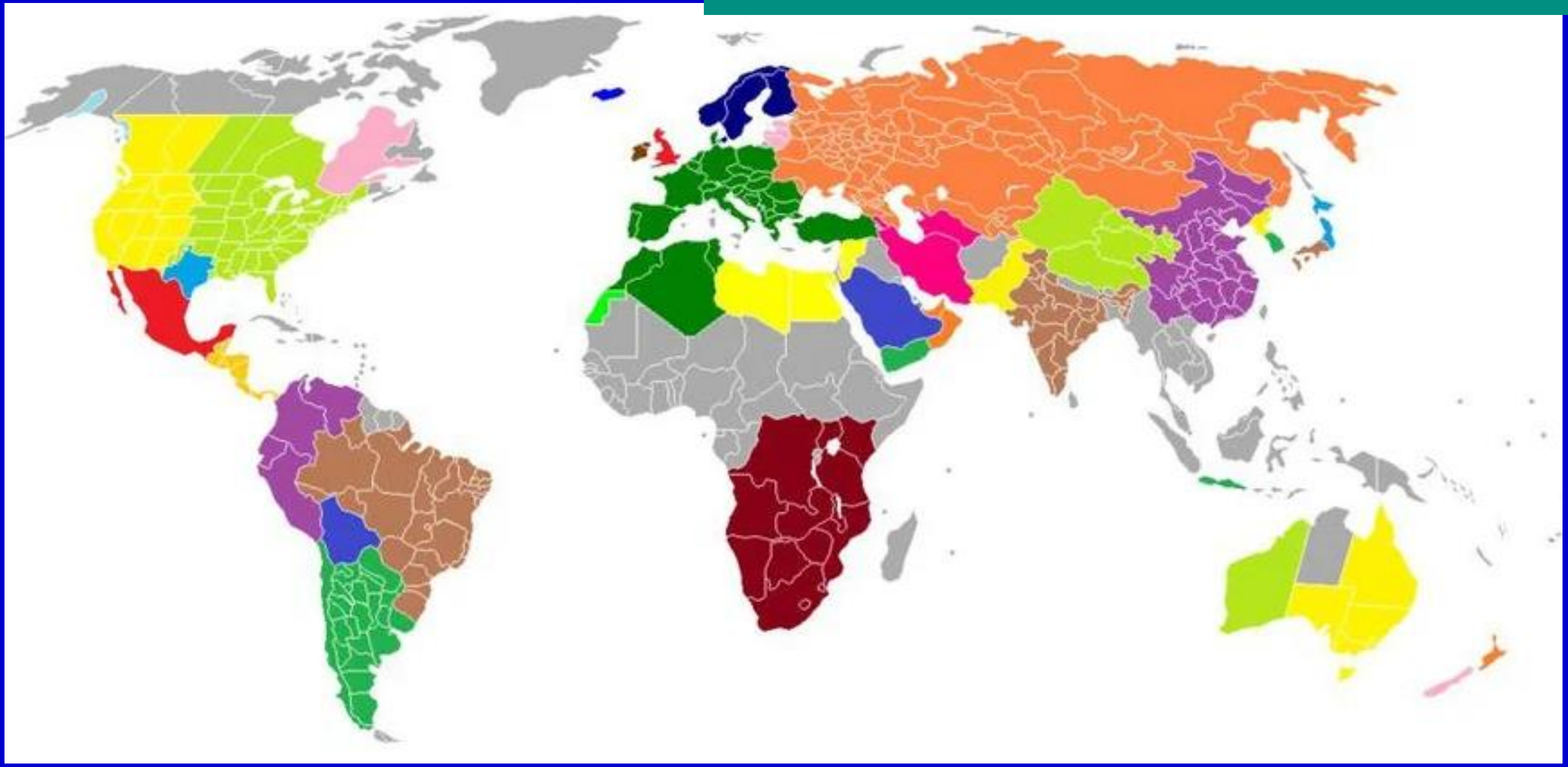
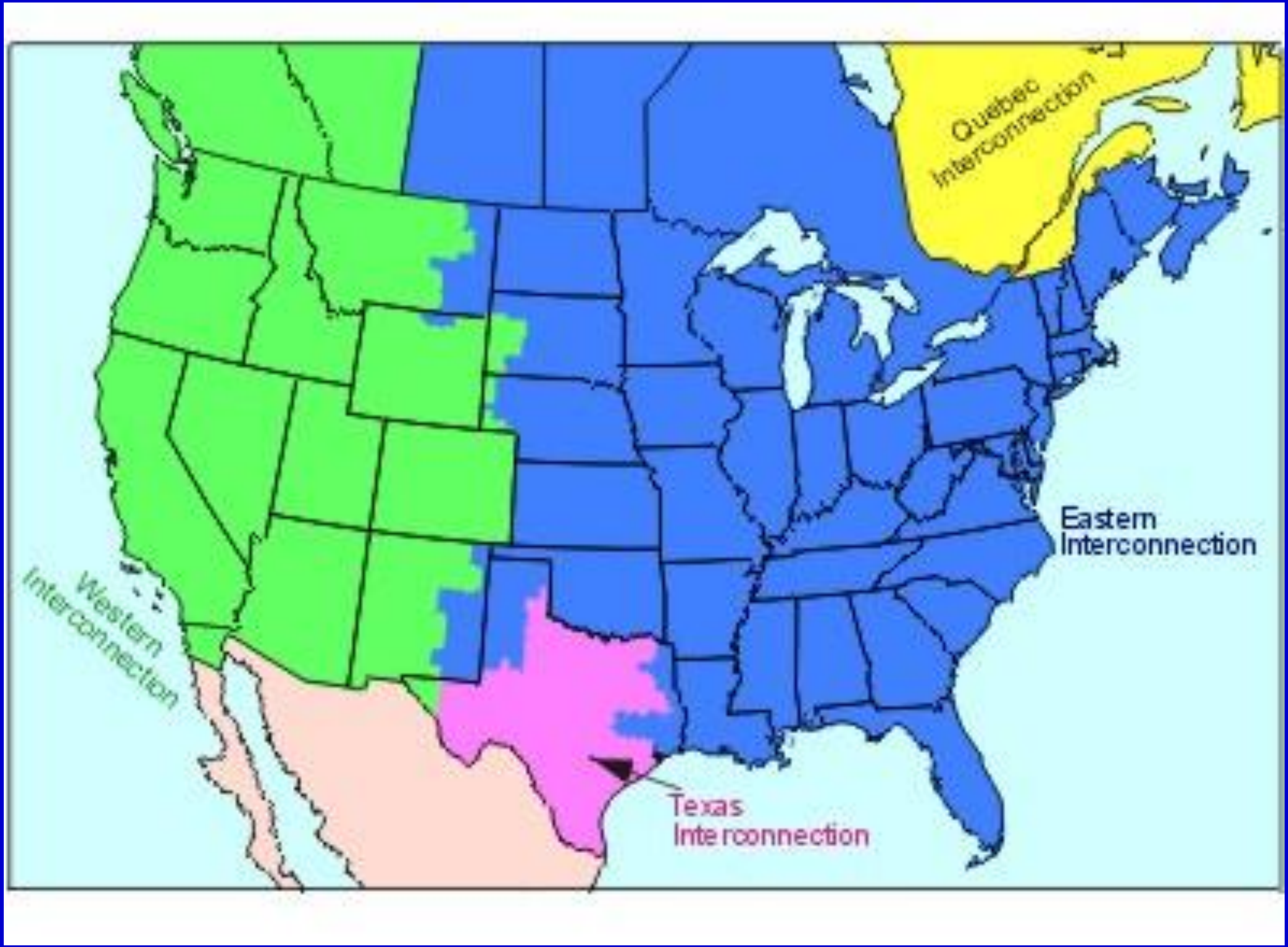


Image Source: i.redd.it/krkhdfslrjh61.jpg

North America Grid Interconnections

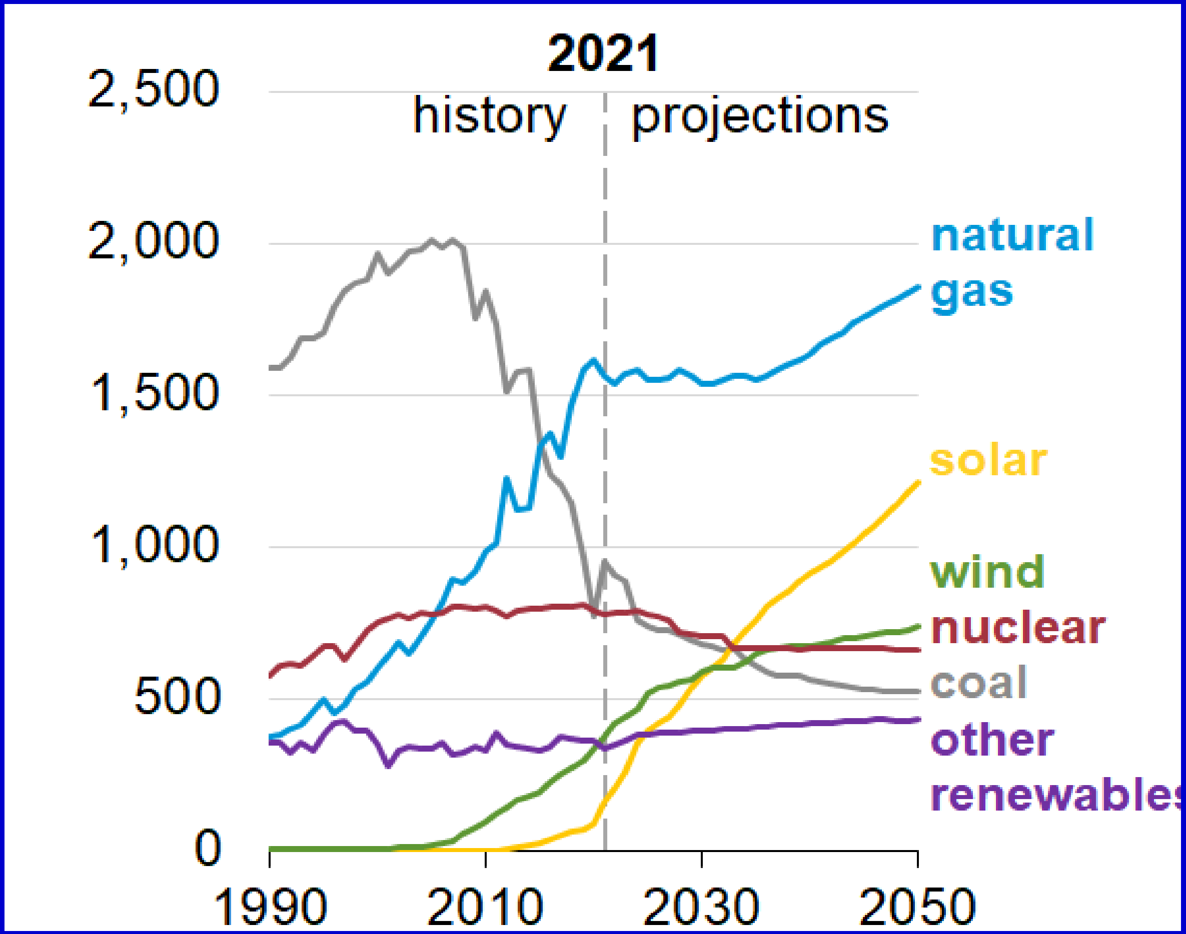


Generation

- Large plants have predominated, up to 1500 MW
- Natural Gas (38.4%) and coal (21.3%) are most common sources, followed by nuclear (18.6%), wind (9.7), hydro (6.4%), solar (4.2%)
  - Wood is 0.9%, geothermal 0.4%
- New construction mostly wind, natural gas and solar

Sources are by energy (not capacity), 4/2021-3/2022; source US EIA

US Generator Capacity Additions



Natural gas and wind generation additions in the last 15 yeats dwarfed all other technologies, but with solar rapidly growing. The gas generation, and previously low natural gas prices were partially responsible for the recent decrease in carbon dioxide emissions

Sources: www.eia.gov/todayinenergy/detail.php?id=25432

US Generation (July 2021)

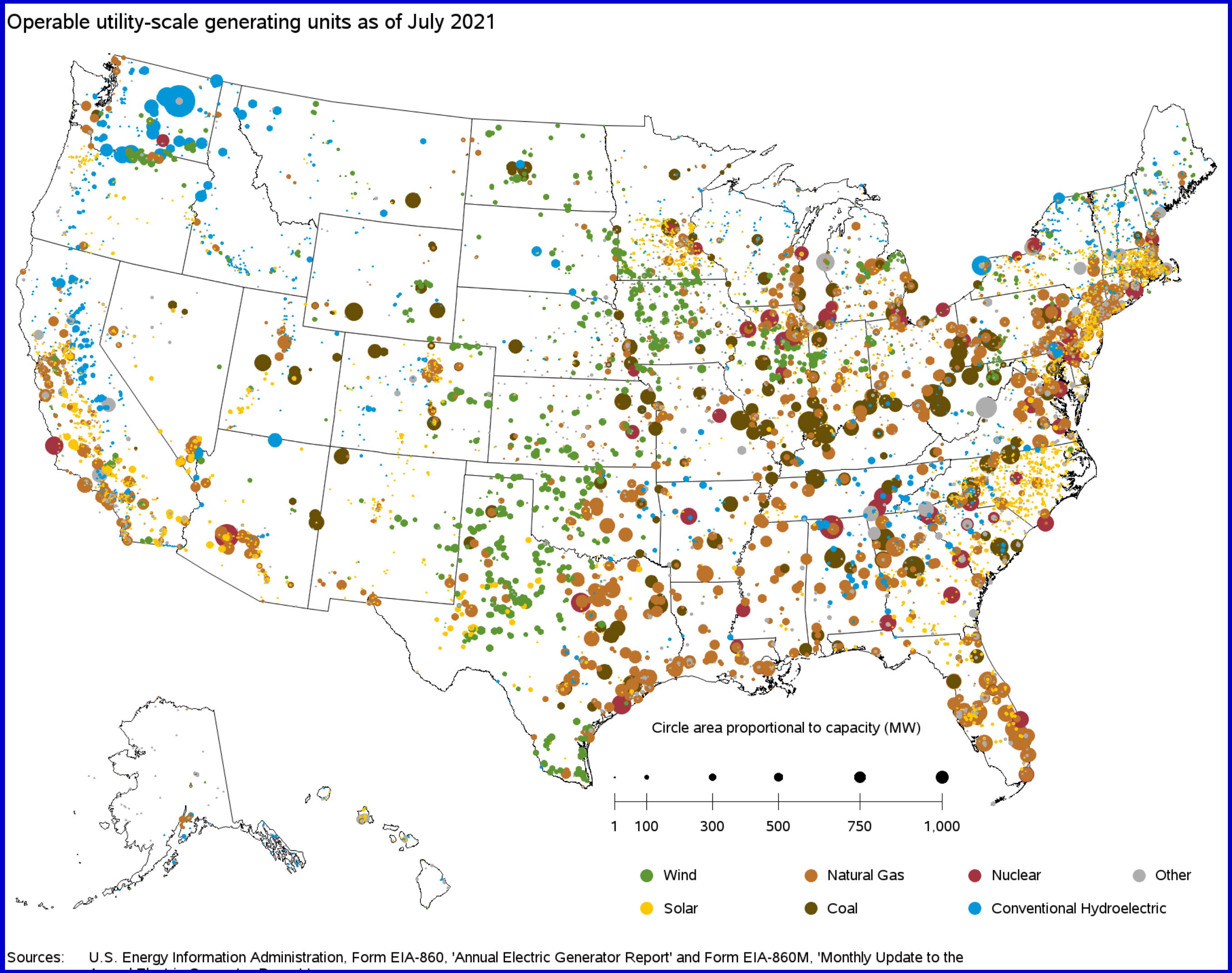
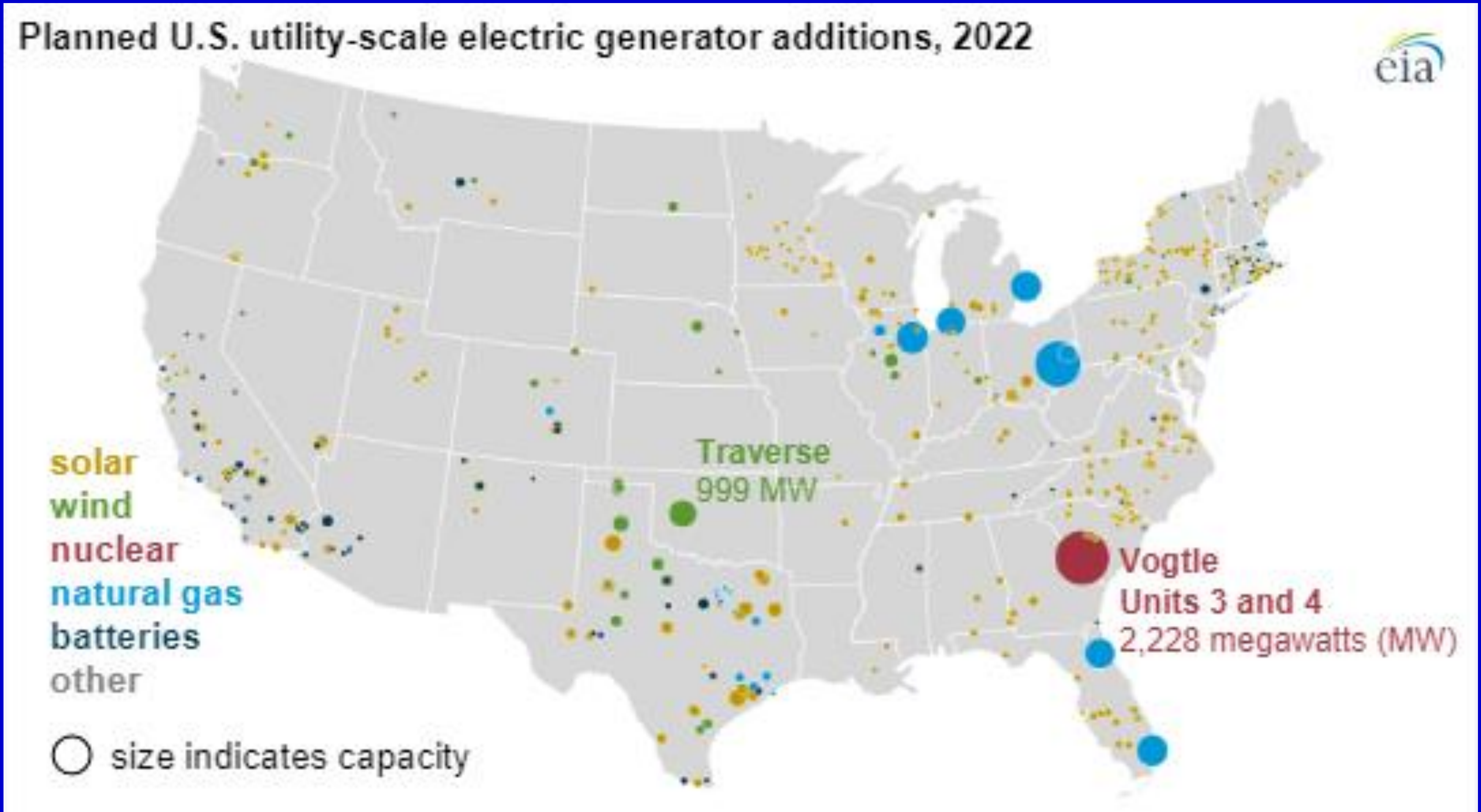


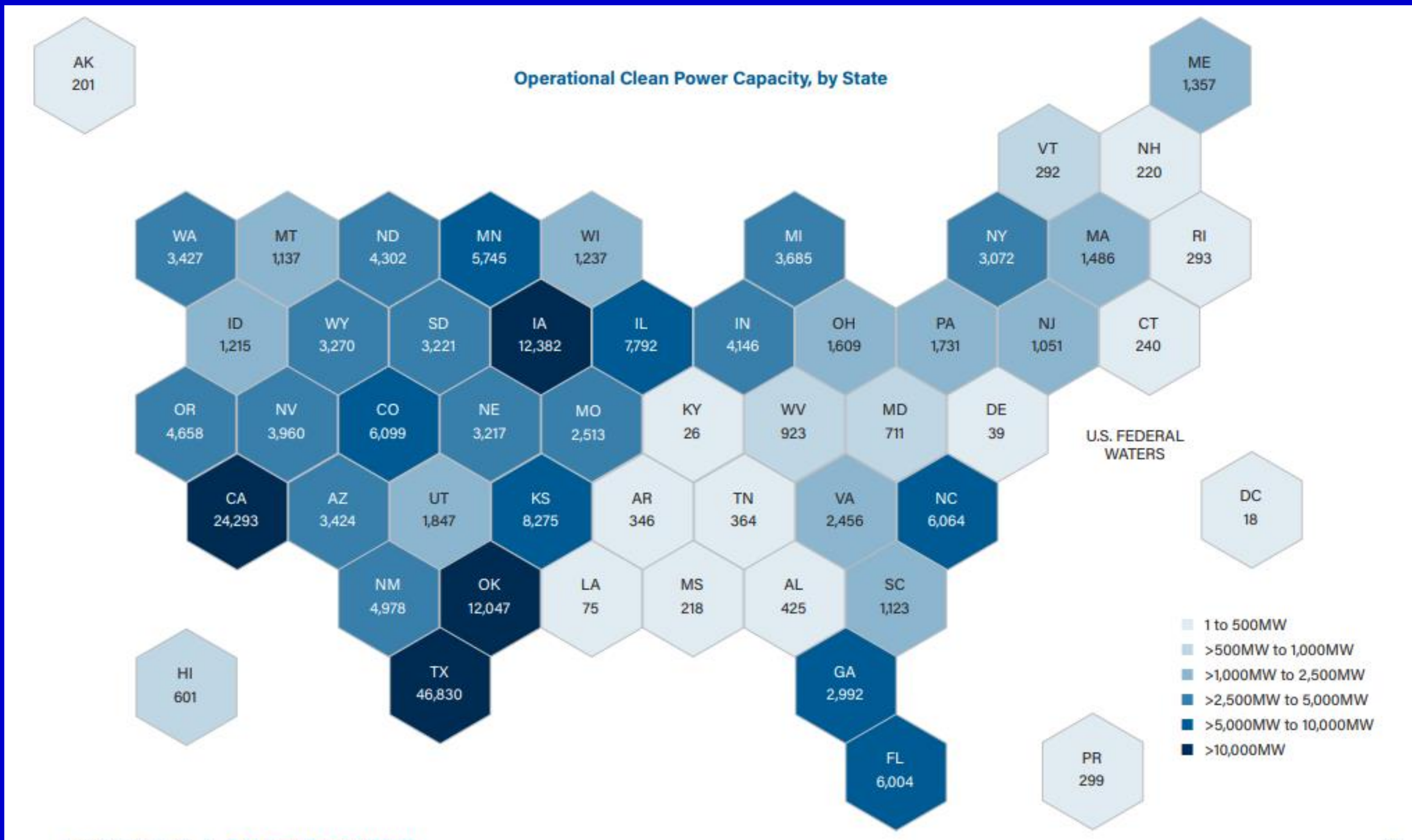
Image Source: www.eia.gov/electricity/data/eia860m/

Planned New Generation 2022



Sources: EIA Electricity Monthly, October 2021

US Wind and Solar Capacity by State



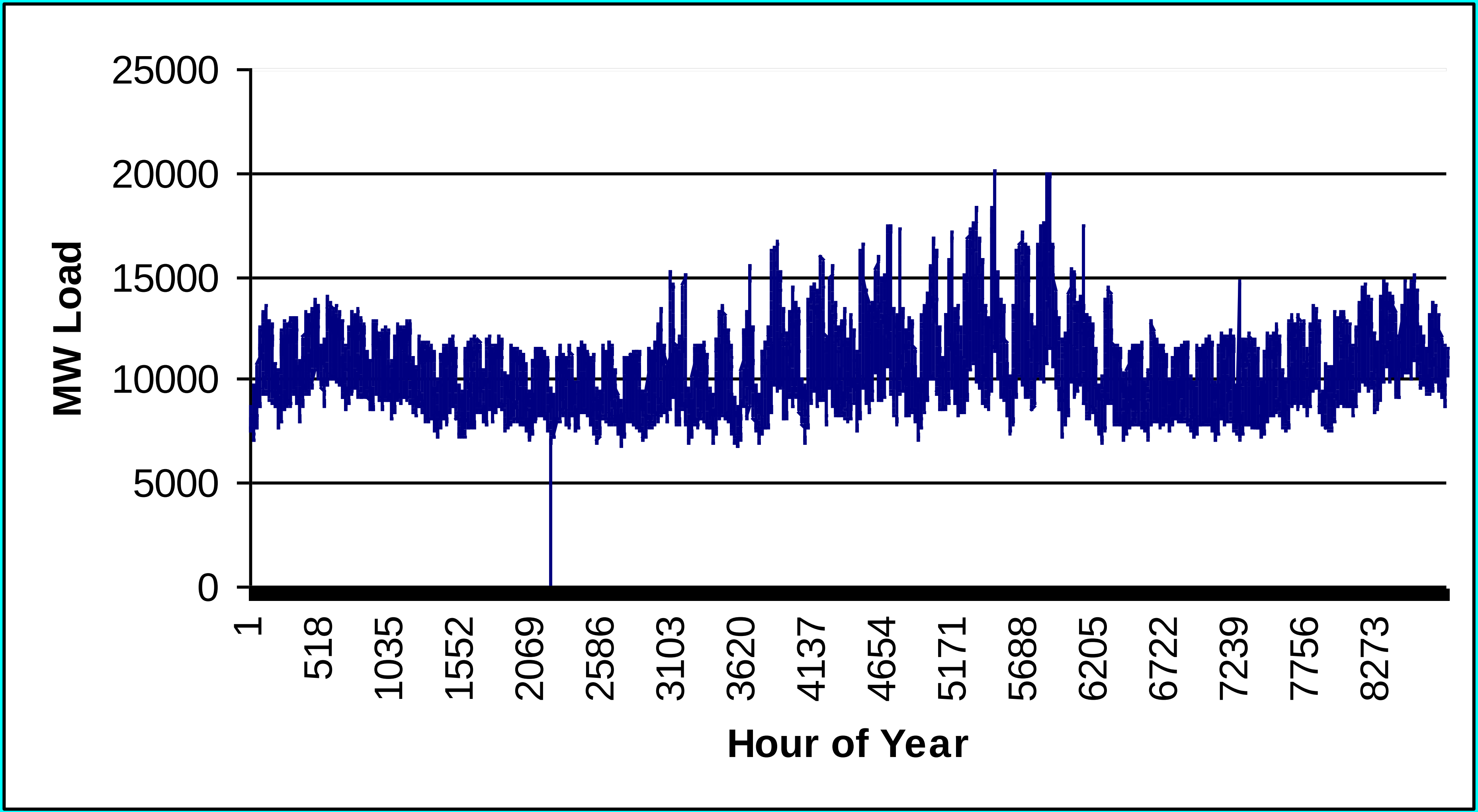
Total capacity at end of 2021 was about 139 GW of wind, and 63 GW of solar

Source: Clean Power Quarterly, 2022 Q1 edition

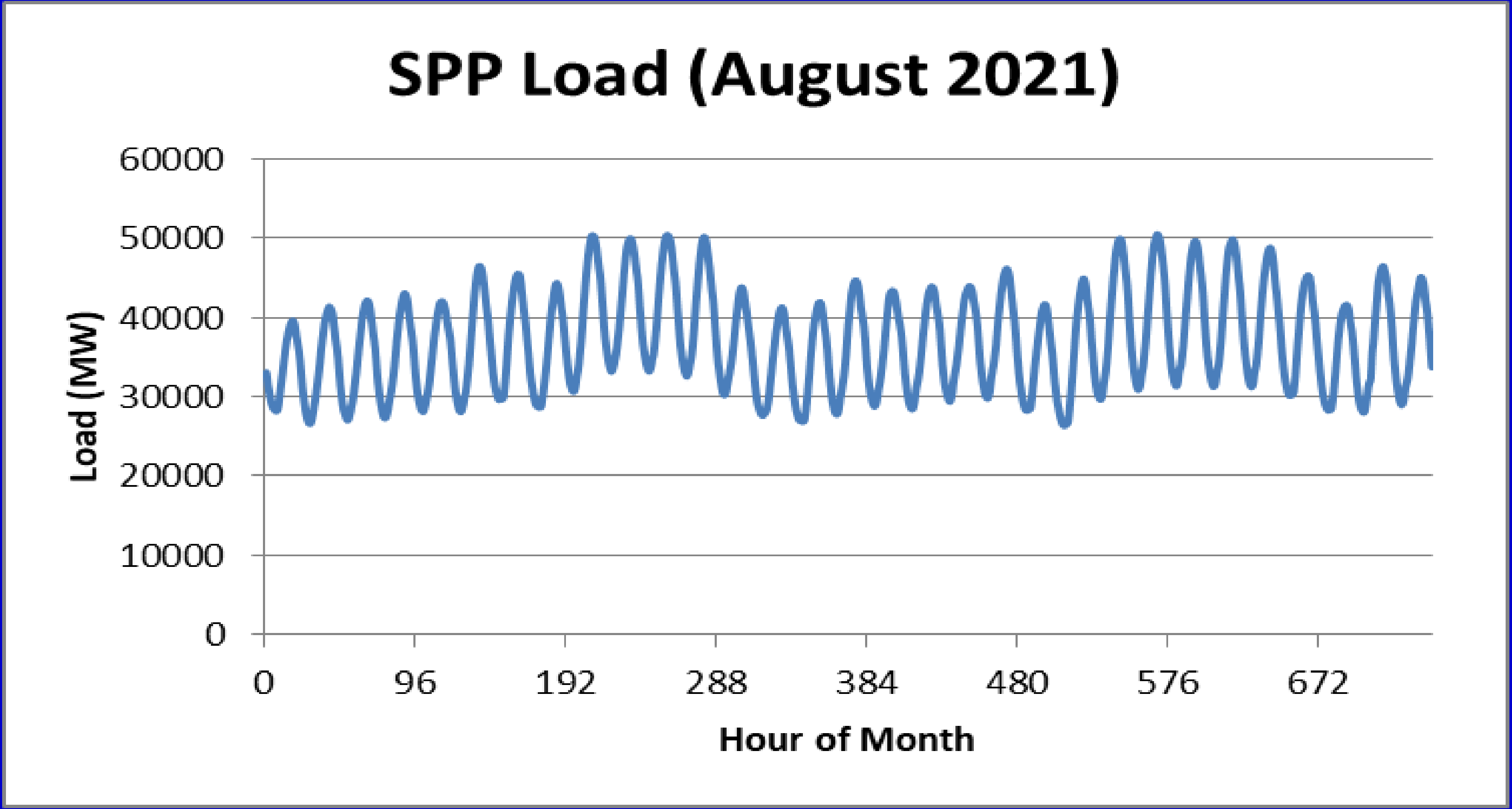
Loads

- Can range in size from less than one watt to 10’s of MW.
- Loads are usually aggregated.
- The aggregate load changes with time, with strong daily, weekly and seasonal cycles.

Example ComEd System Load



Example: SPP Monthly Load



SPP Load Data Source: marketplace.spp.org

Transmission

- Goal is to move electric power from generation to load with low losses.
- Less losses at high voltages, but more difficult to insulate.
- Typical high voltage transmission voltages are 500, 345, 230, 161, 138 and 69 kV.
- Lower voltage lines are used for distribution (12.4 or 13.8 kV).
- Transformers used to change voltages.

Three Phase Transmission Line

Midwest Transmission System

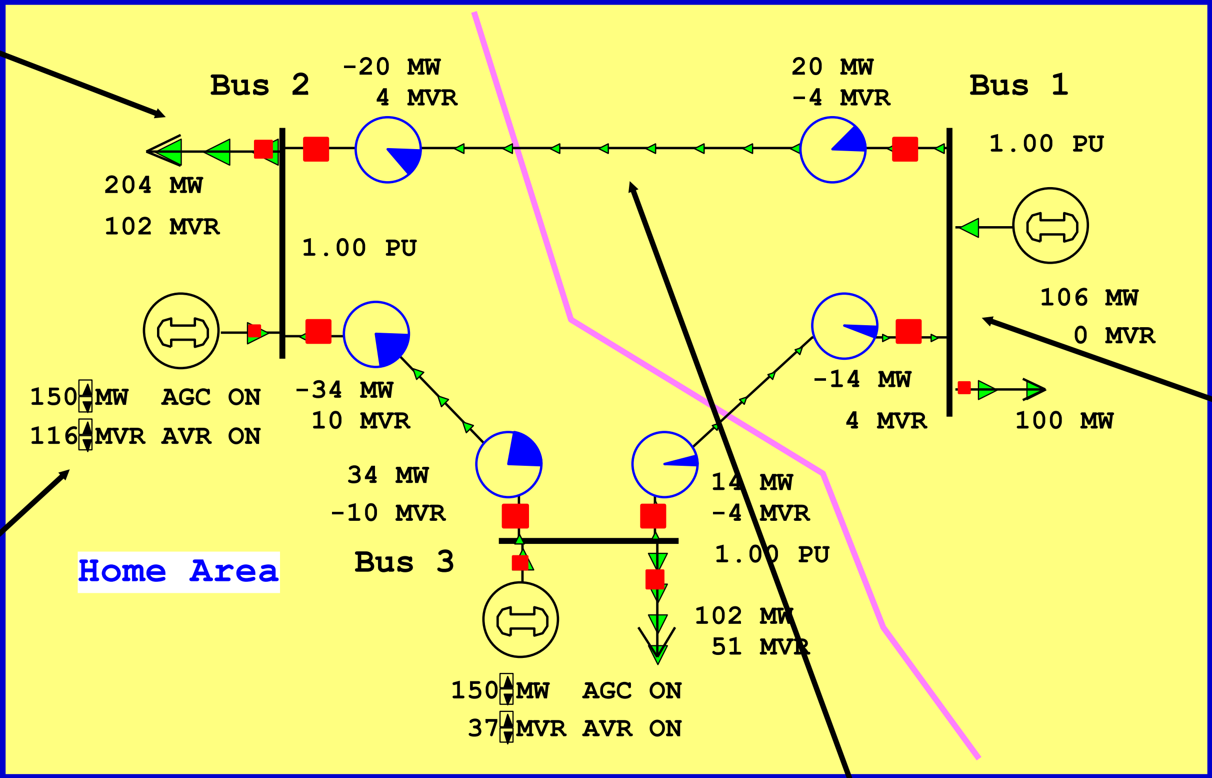
One-line Diagrams

- Most power systems are balanced three phase systems.
- A balanced three phase system can be modeled as a single (or one) line.
- One-lines show the major power system components, such as generators, loads, transmission lines.
- Components join together at a bus.

An Actual Substation Bus

PowerWorld Simulator Three Bus Case

Load with green arrows indicating amount of MW flow



Note the power balance at each bus

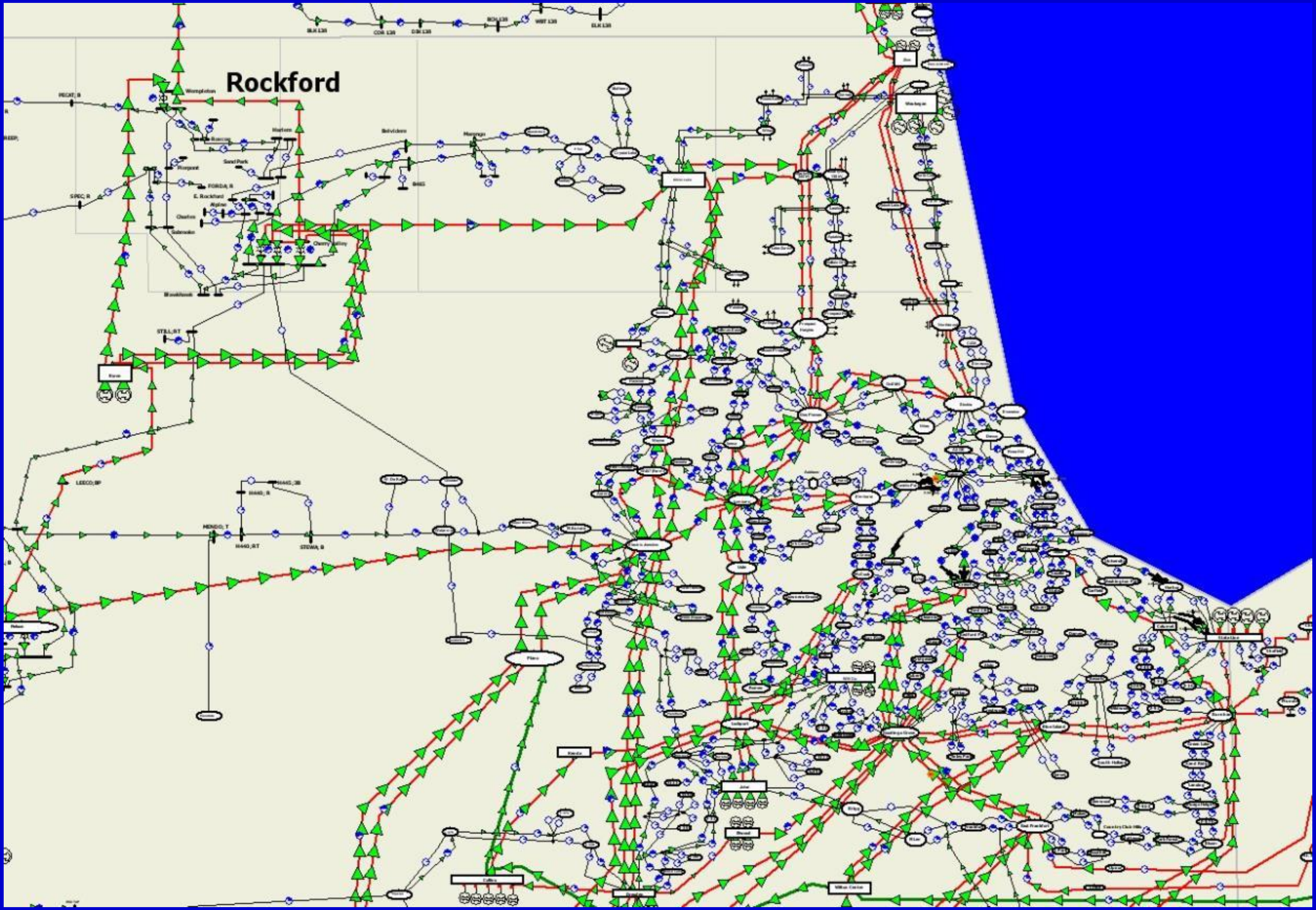
Used to control output of generator

Direction of arrow is used to indicate direction of real power (MW) flow

Free Version of PowerWorld Simulator

- A free, 42 bus version of PowerWorld Simulator can be downloaded at www.powerworld.com/gloveroverbyesarma

Metro Chicago Electric Network



Power Balance Constraints

- Power flow refers to how the power is moving through the system.
- At all times in the simulation the total power flowing into any bus MUST be zero!
- This is know as Kirchhoff's law. And it can not be repealed or modified.
- Power is lost in the transmission system.

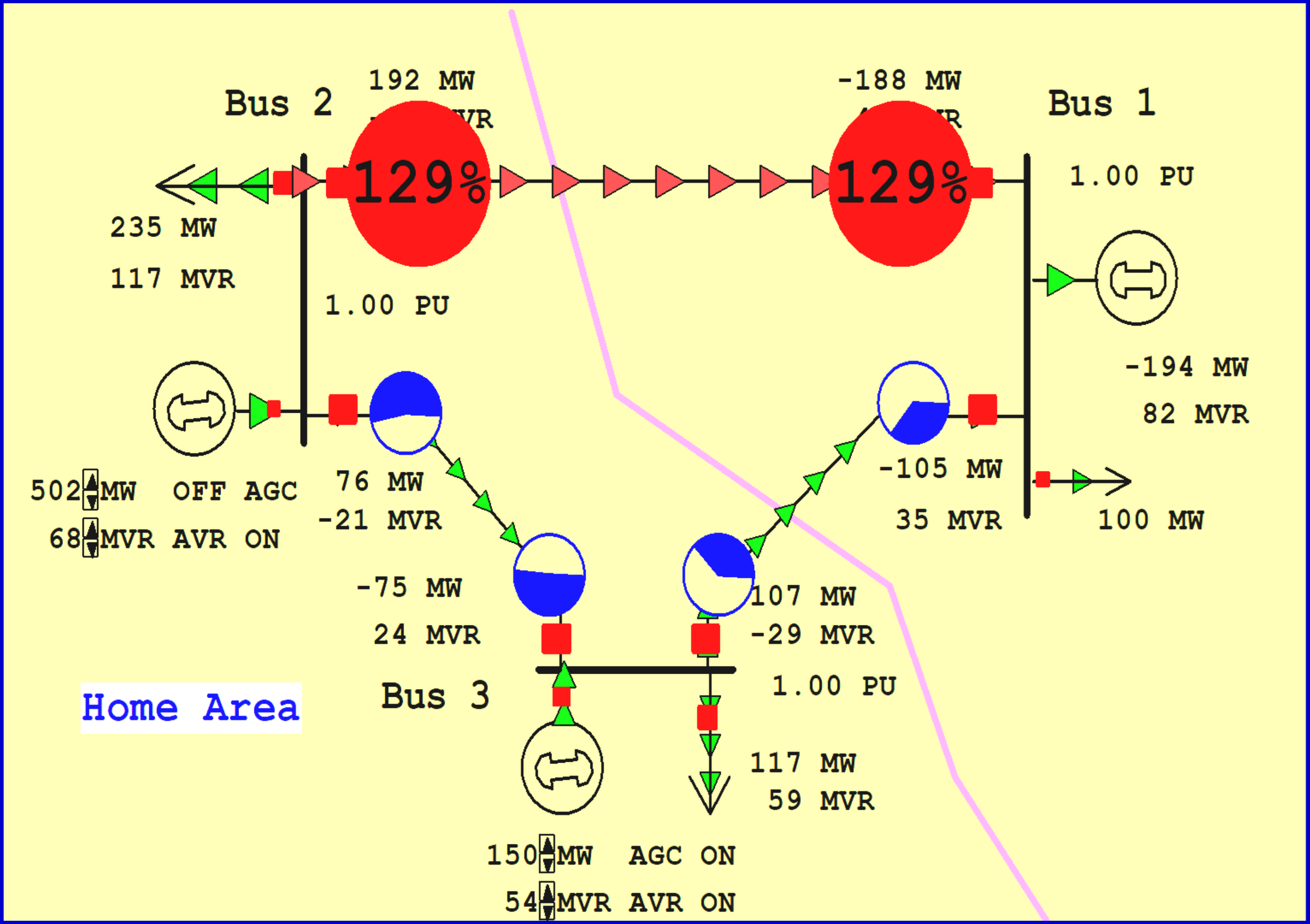
Basic Power Control

- Opening a circuit breaker causes the power flow to instantaneously (nearly) change.
- No other way to directly control power flow in a transmission line.
- By changing generation we can indirectly change this flow.

Transmission Line Limits

- Power flow in transmission line is limited by heating considerations.
- Losses (I^2 R) can heat up the line, causing it to sag.
- Each line has a limit; Simulator does not allow you to continually exceed this limit. Many utilities use winter/summer limits.

Overloaded Transmission Line



Interconnected Operation

- Power systems are interconnected. Most of North America east of the Rockies is one system, with most of Texas and Quebec being exceptions
- Interconnections are divided into smaller portions, called balancing authority areas (previously called control areas)

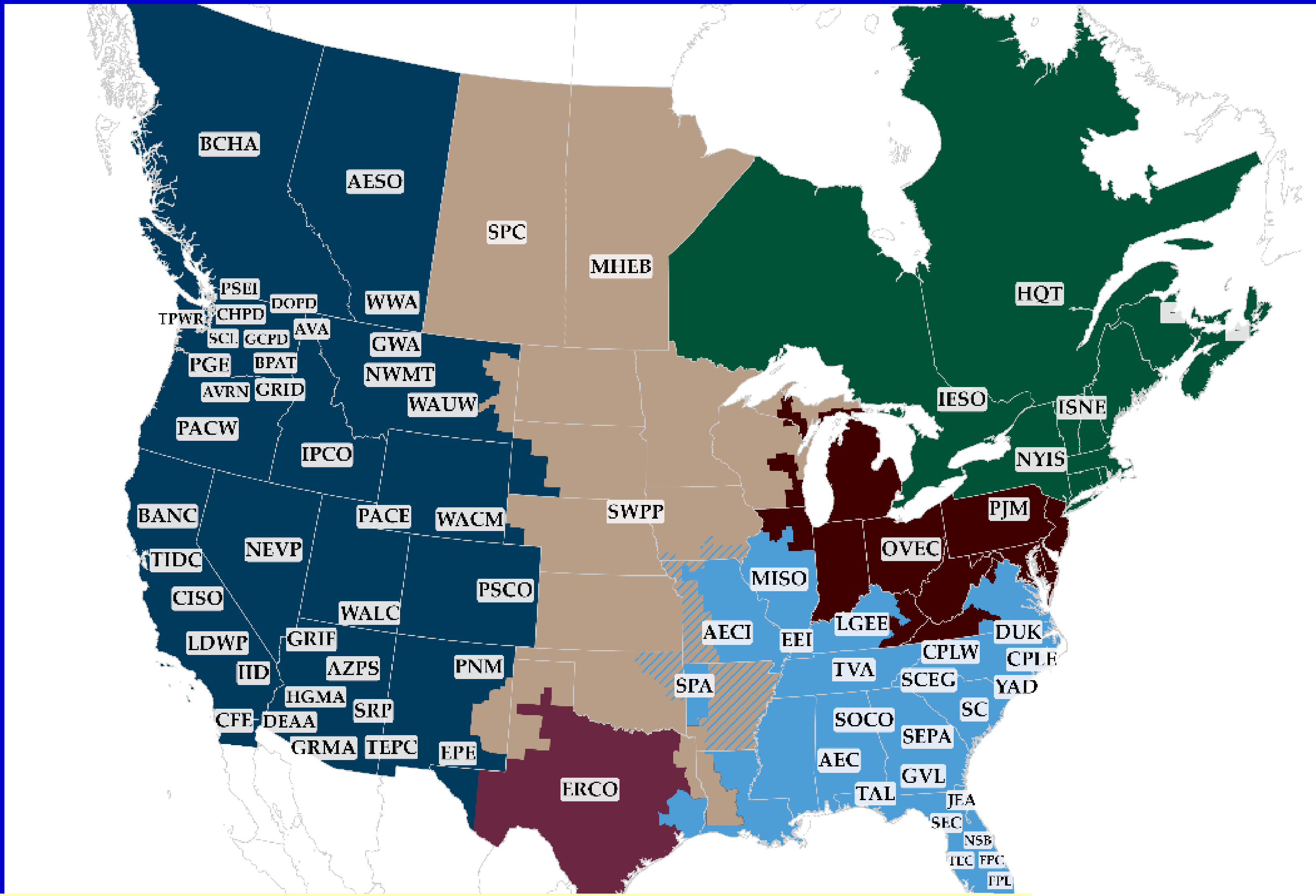
Balancing Authority (BA) Areas

- Transmission lines that join two areas are known as tie-lines.
- The net power out of an area is the sum of the flow on its tie-lines.
- The flow out of an area is equal to

  total gen - total load - total losses

  = tie-flow

Actual Balancing Authorities

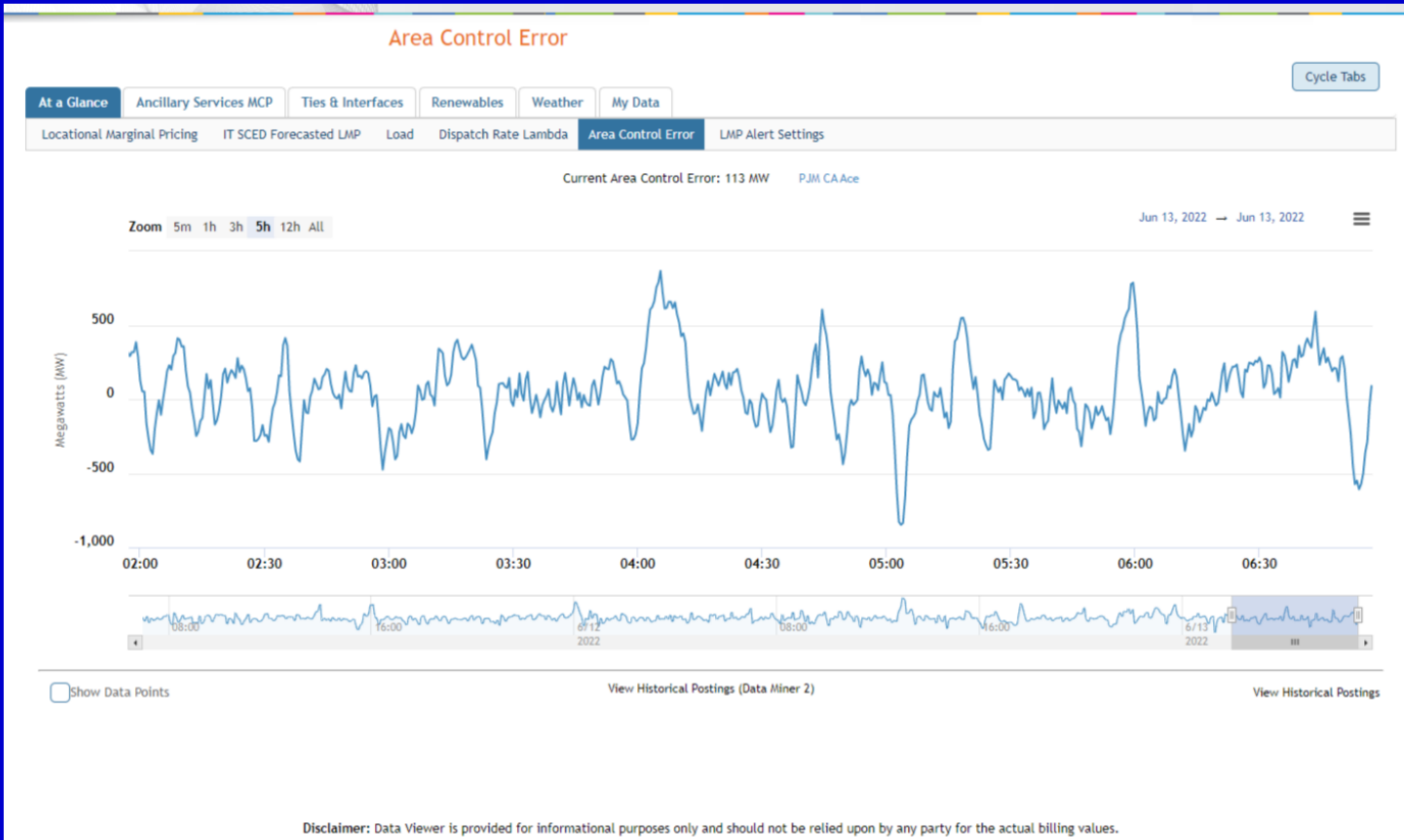


Source: www.wecc.org/epubs/StateOfTheInterconnection/Pages/The-Bulk-Power-System.aspx

Area Control Error (ACE)

- The area control error is the difference between the actual flow out of an area and the scheduled flow (plus a frequency term ignored for now)
- Ideally the ACE should always be zero.
- Because the load is constantly changing, each utility must constantly change its generation to "chase" the ACE.

PJM ACE (June 13, 2022)

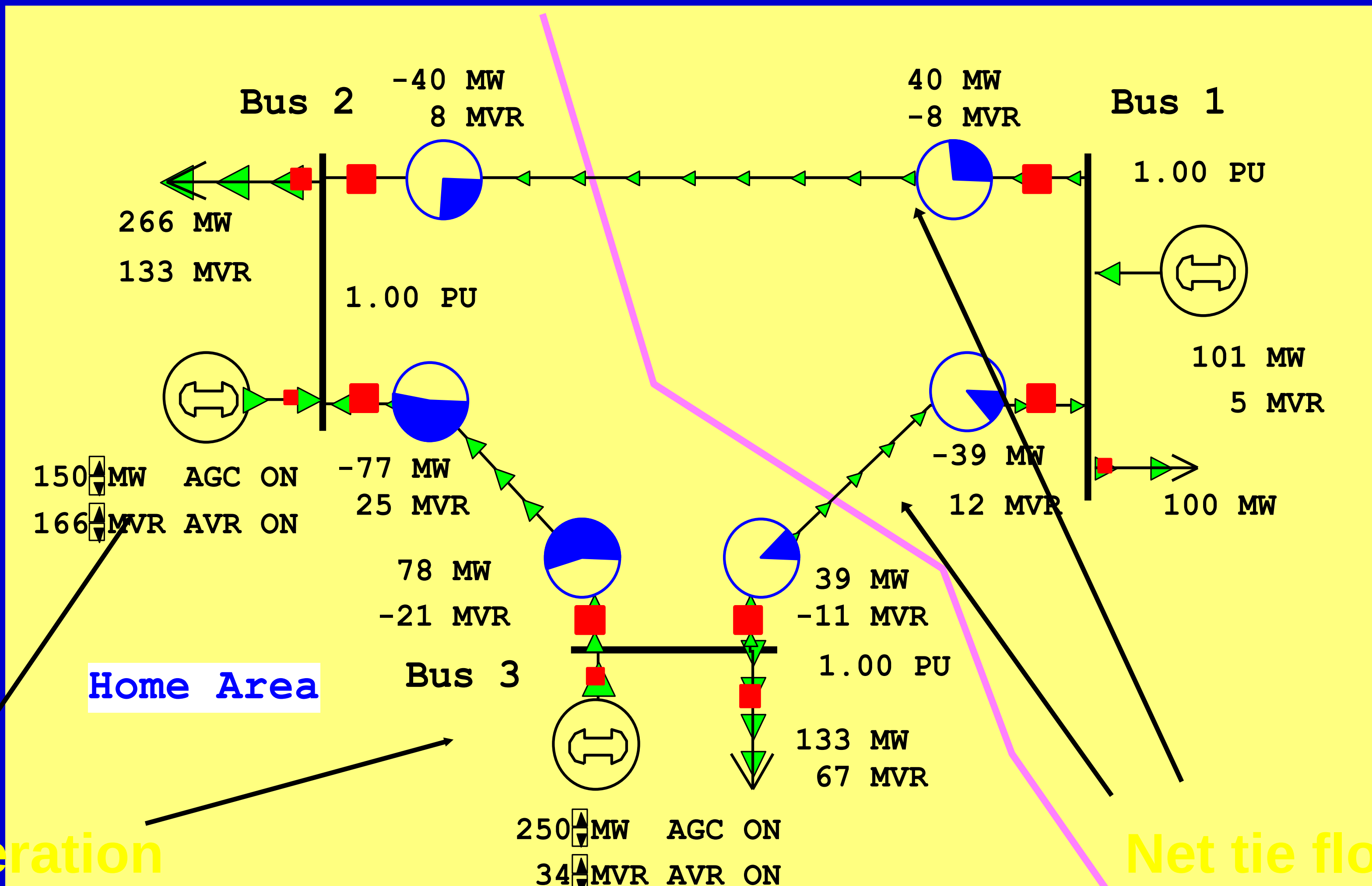


Source: dataviewer.pjm.com/dataviewer/pages/public/ace.jsf

Automatic Generation Control

- BAs use automatic generation control (AGC) to automatically change their generation to keep their ACE close to zero.
- Usually the BA control center calculates ACE based upon tie-line flows; then the AGC module sends control signals out to the generators every couple seconds.

Three Bus Case on AGC



Generation is automatically changed to match change in load

Net tie flow is close to zero

Generator Costs

- There are many fixed and variable costs associated with power system operation.
- The major variable cost is associated with generation.
- Cost to generate a MWh can vary widely.
- For some types of units (such as hydro and nuclear) it is difficult to quantify.
- Many markets have moved from cost-based to price-based generator costs

Economic Dispatch

- Economic dispatch determines the least cost dispatch of generation for an area.
- For a lossless system, the economic dispatch occurs when all the generators have equal marginal costs.

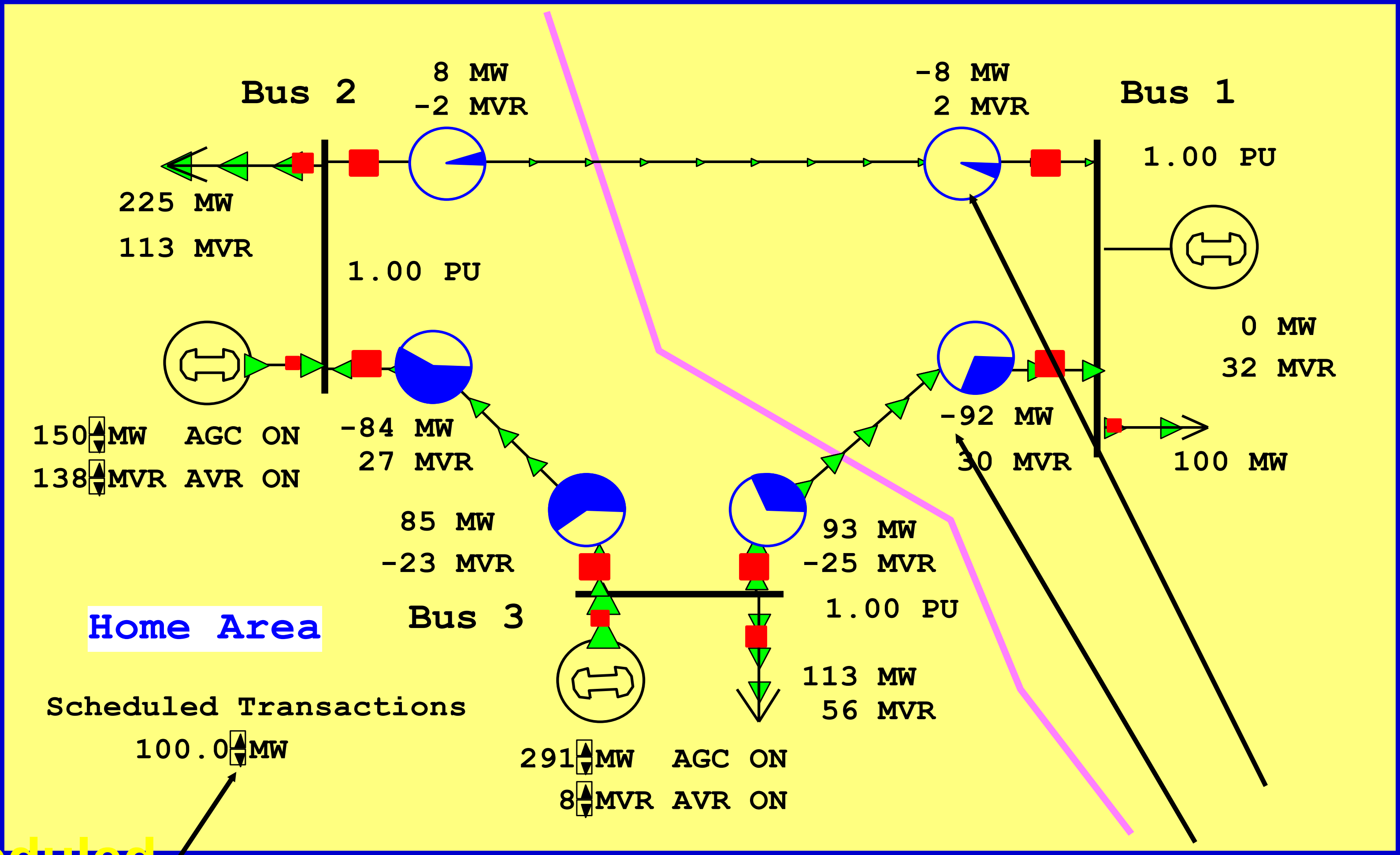
$$IC1(PG,1) = IC2(PG,2) = \ldots = ICm(PG,m)$$

Power Transactions

- Power transactions are contracts between areas to do power transactions.
- Contracts can be for any amount of time at any price for any amount of power.
- Scheduled power transactions are implemented by modifying the area ACE:

$$ACE = P_{actual,tie\text{-}flow} - P_{sched}$$

100 MW Transaction



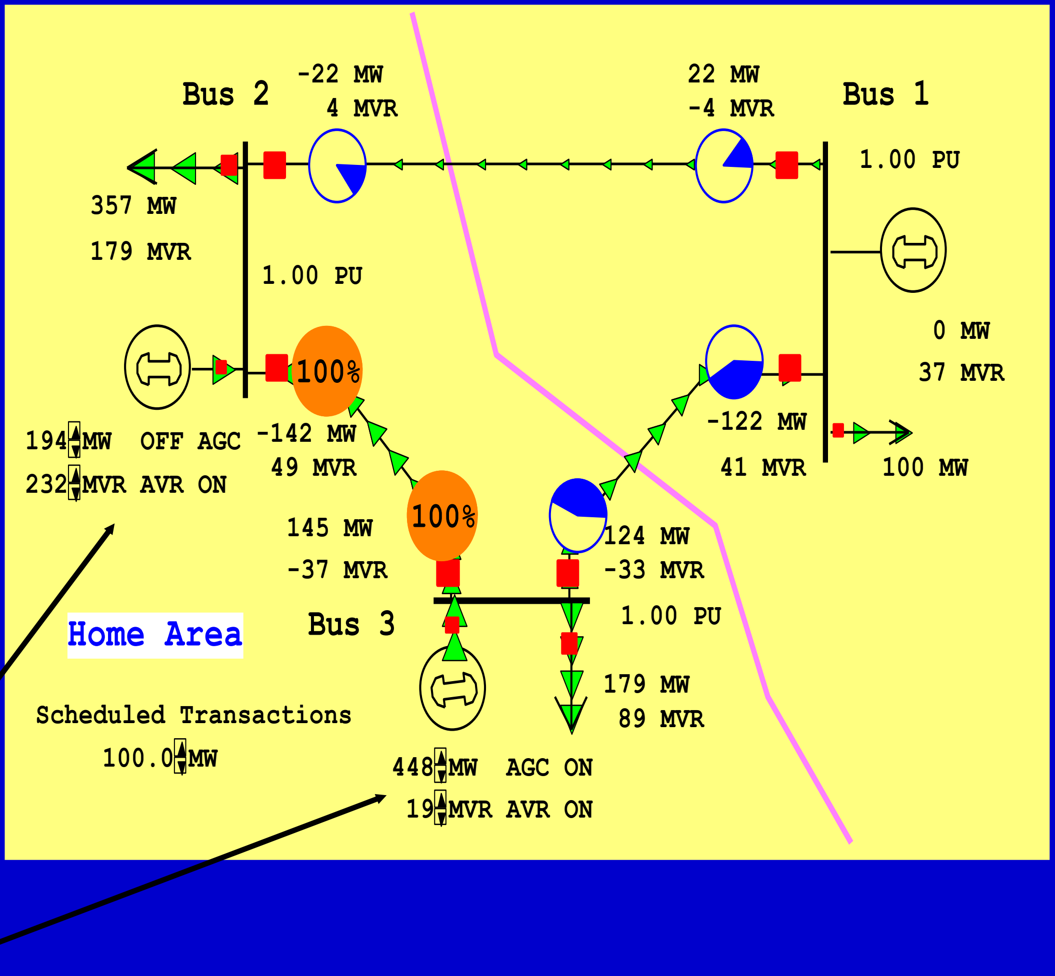
Scheduled 100 MW Transaction from Left to Right

Net tie-line flow is now 100 MW

Security Constrained Economic Dispatch

- Transmission constraints often limit system economics.
- Such limits required a constrained dispatch in order to maintain system security.
- In three bus case the generation at bus 3 must be constrained to avoid overloading the line from bus 2 to bus 3.

Security Constrained Dispatch



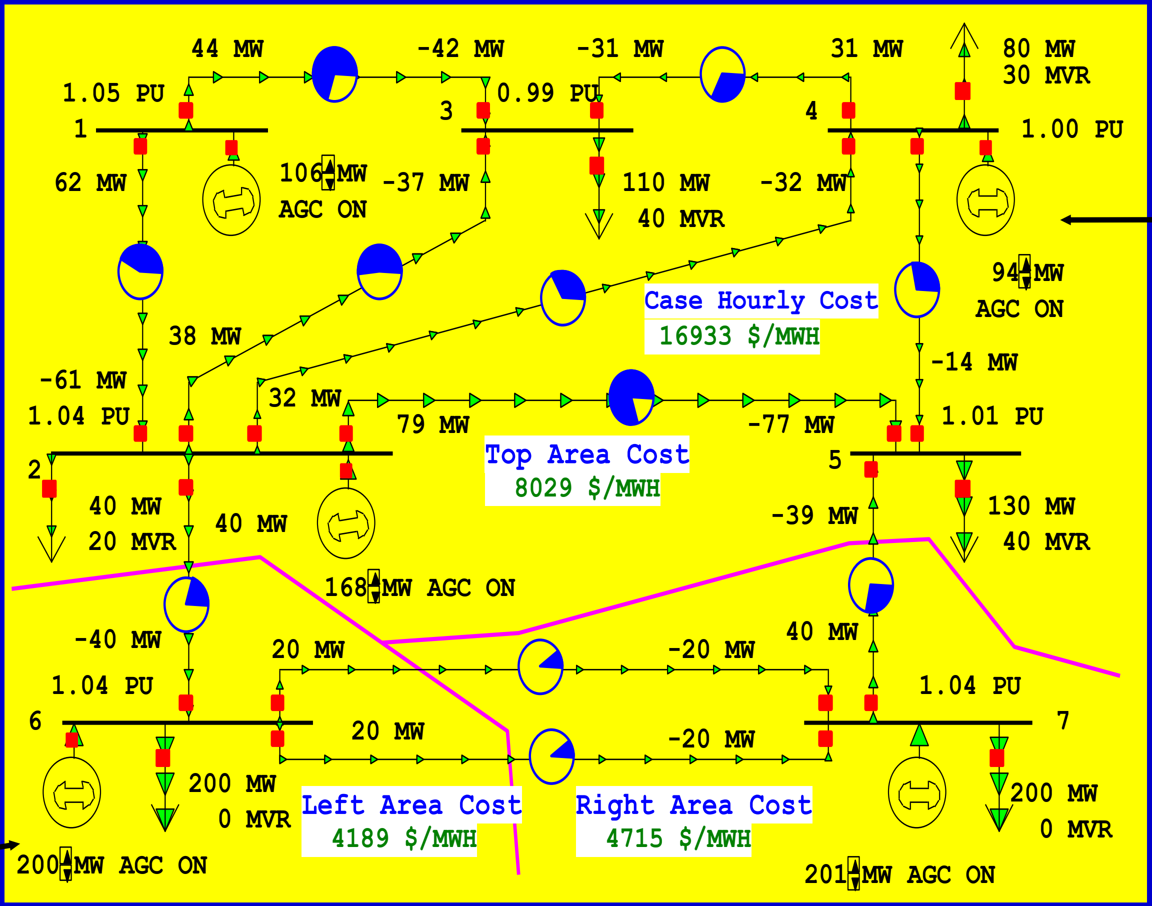
Dispatch is no longer optimal due to need to keep line from bus 2 to bus 3 from overloading

Multi-Area Operation

- If Areas have direct interconnections, then they may directly transact up to the capacity of their tie-lines.
- Actual power flows through the entire network according to the impedance of the transmission lines.
- Flow through other areas is known as "parallel path" or "loop flows."

Seven Bus, Three Area Case

System has three areas

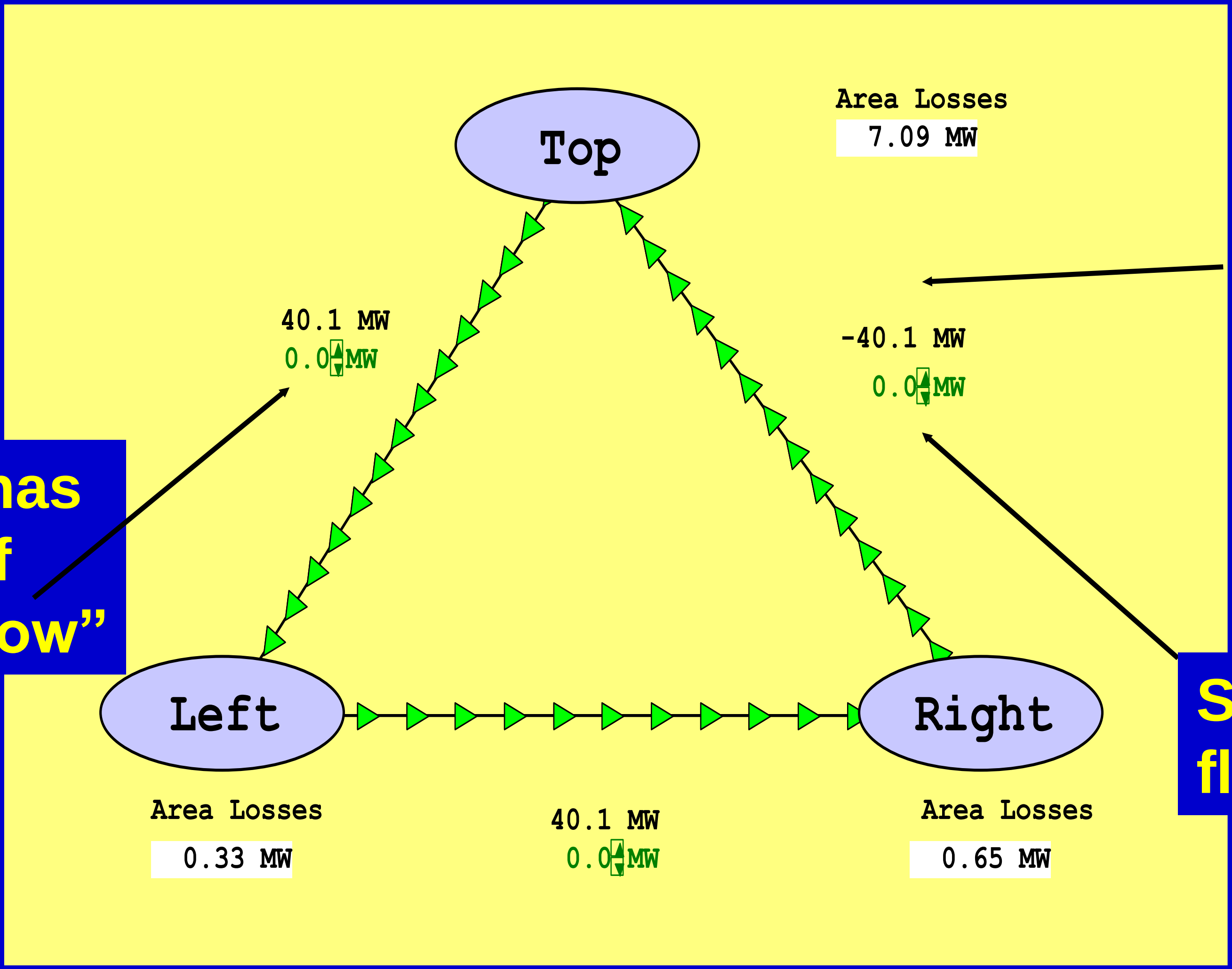


Area top has five buses

Area left has one bus

Area right has one bus

Seven Bus Case: Area View



System has 40 MW of "Loop Flow"

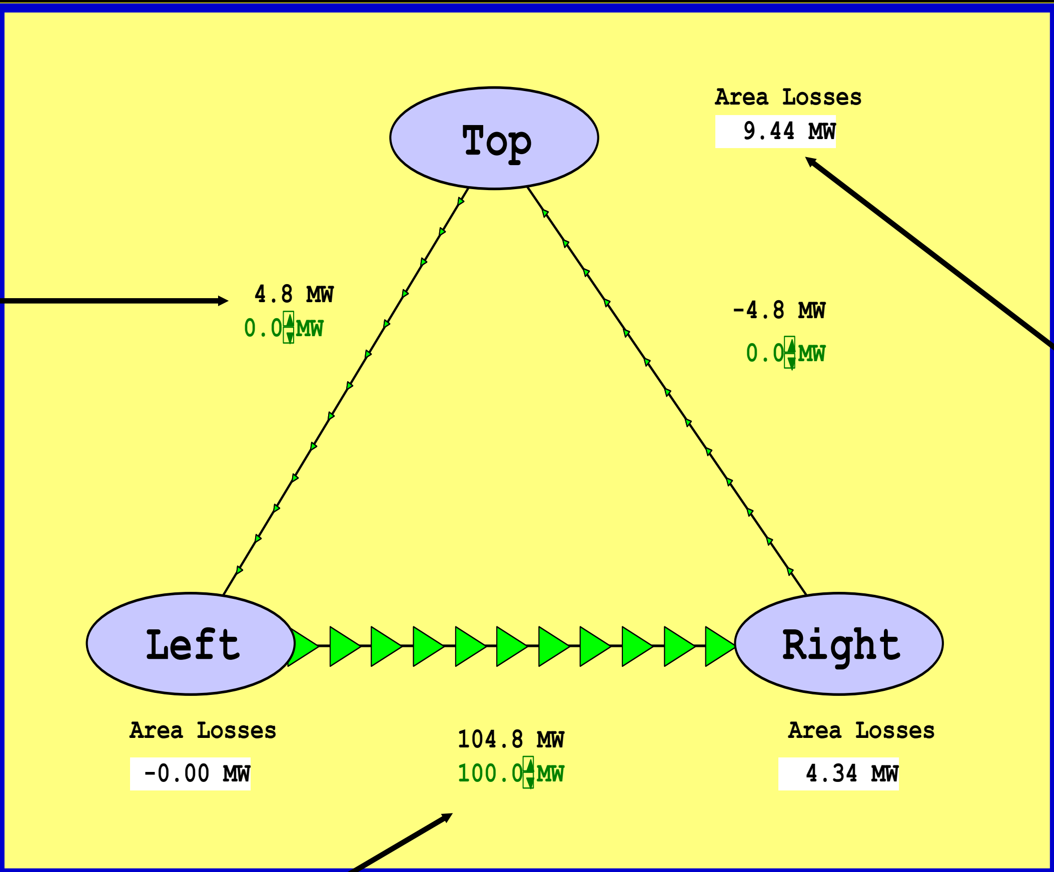
Actual flow between areas

Scheduled flow

Loop flow can result in higher losses

Seven Bus Case Loop Flow

Transaction has actually decreased the loop flow



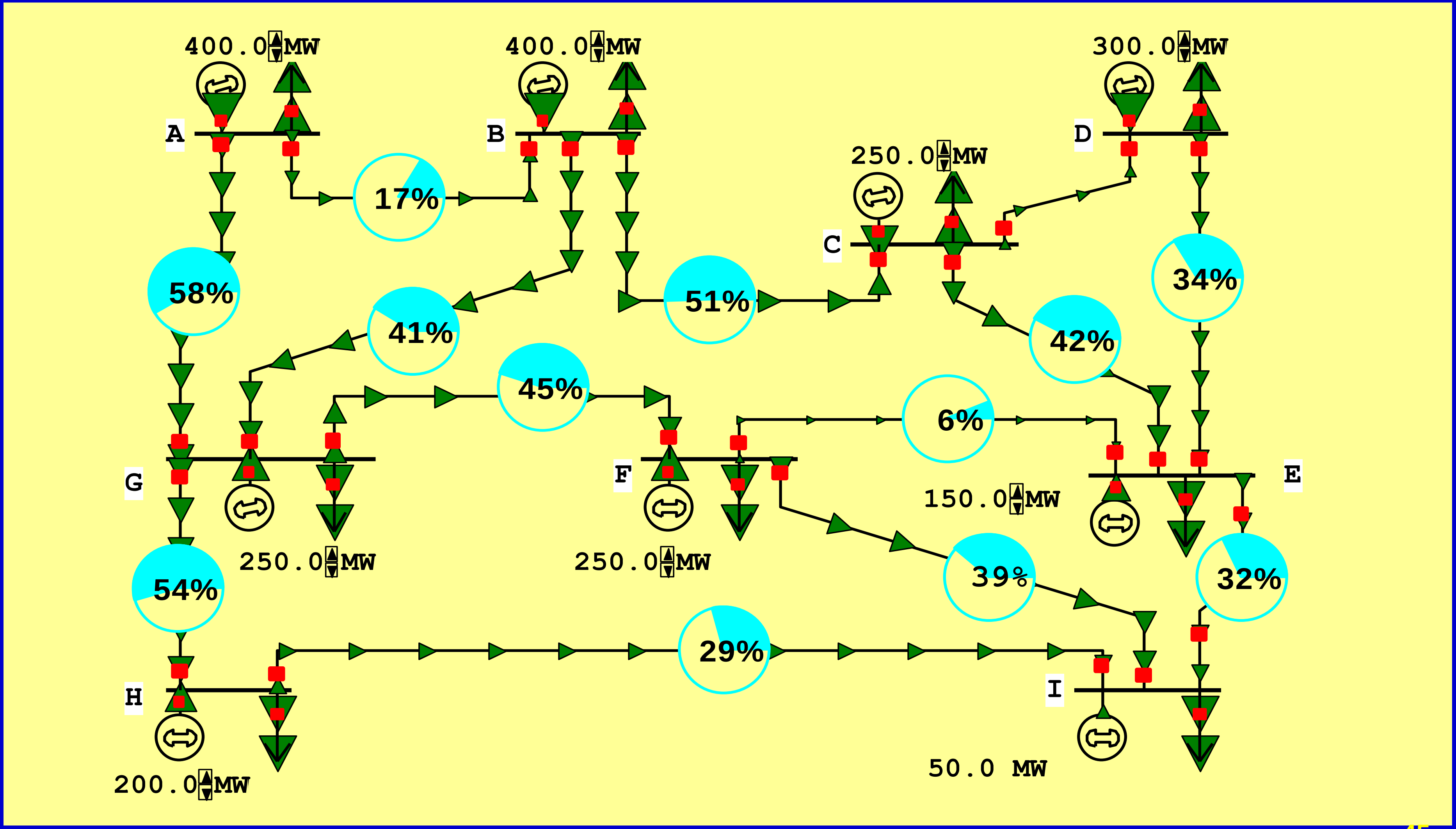
Note that Top’s Losses have increased from 7.09MW to 9.44 MW

100 MW Transaction between Left and Right

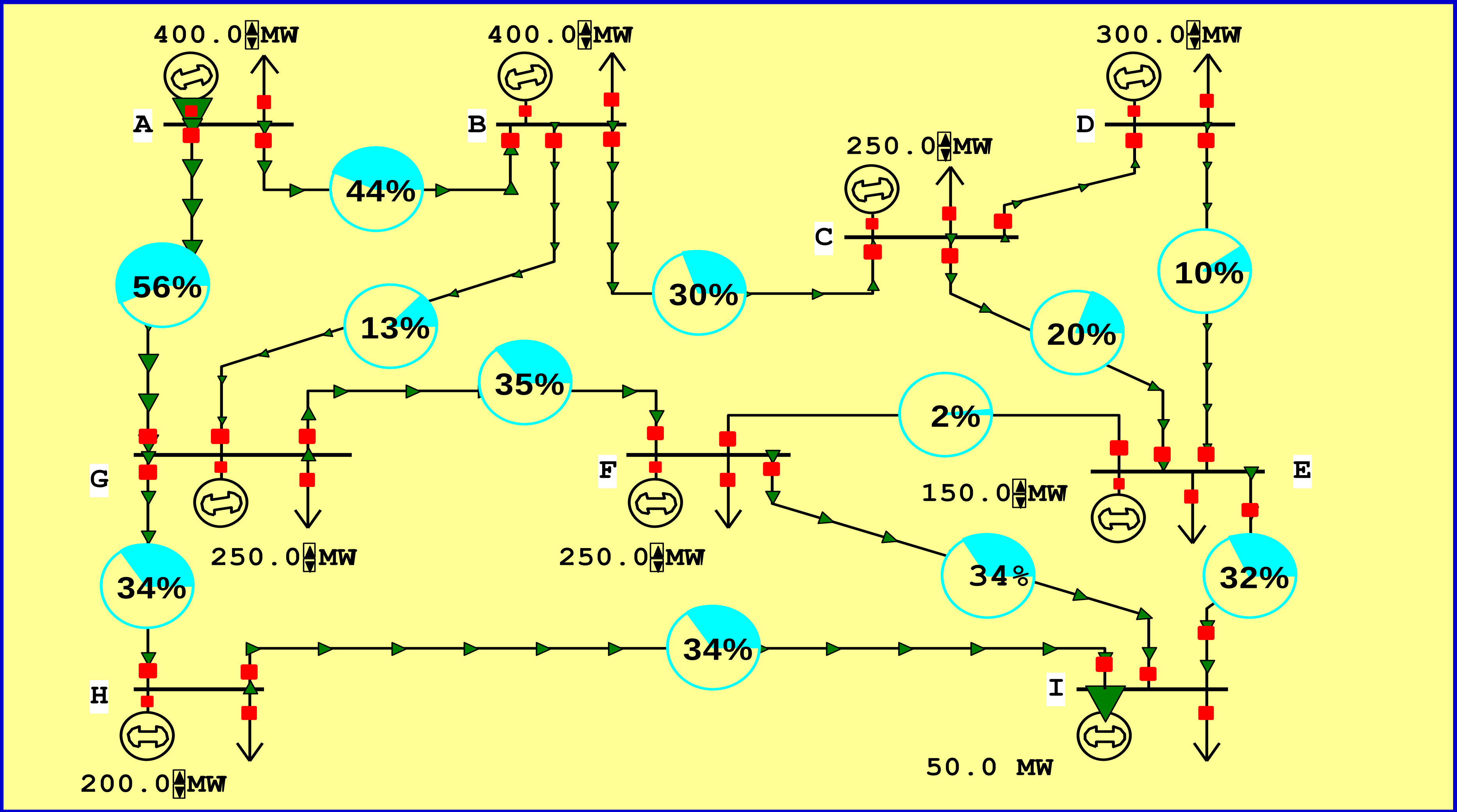
Power Transfer Distribution Factors (PTDFs)

- PTDFs are used to show how a particular transaction will affect the system.
- Power transfers through the system according to the impedances of the lines, without respect to ownership.
- All transmission players in network could be impacted, to a greater or lesser extent.

PTDF Example: Nine Bus Case Actual Flows

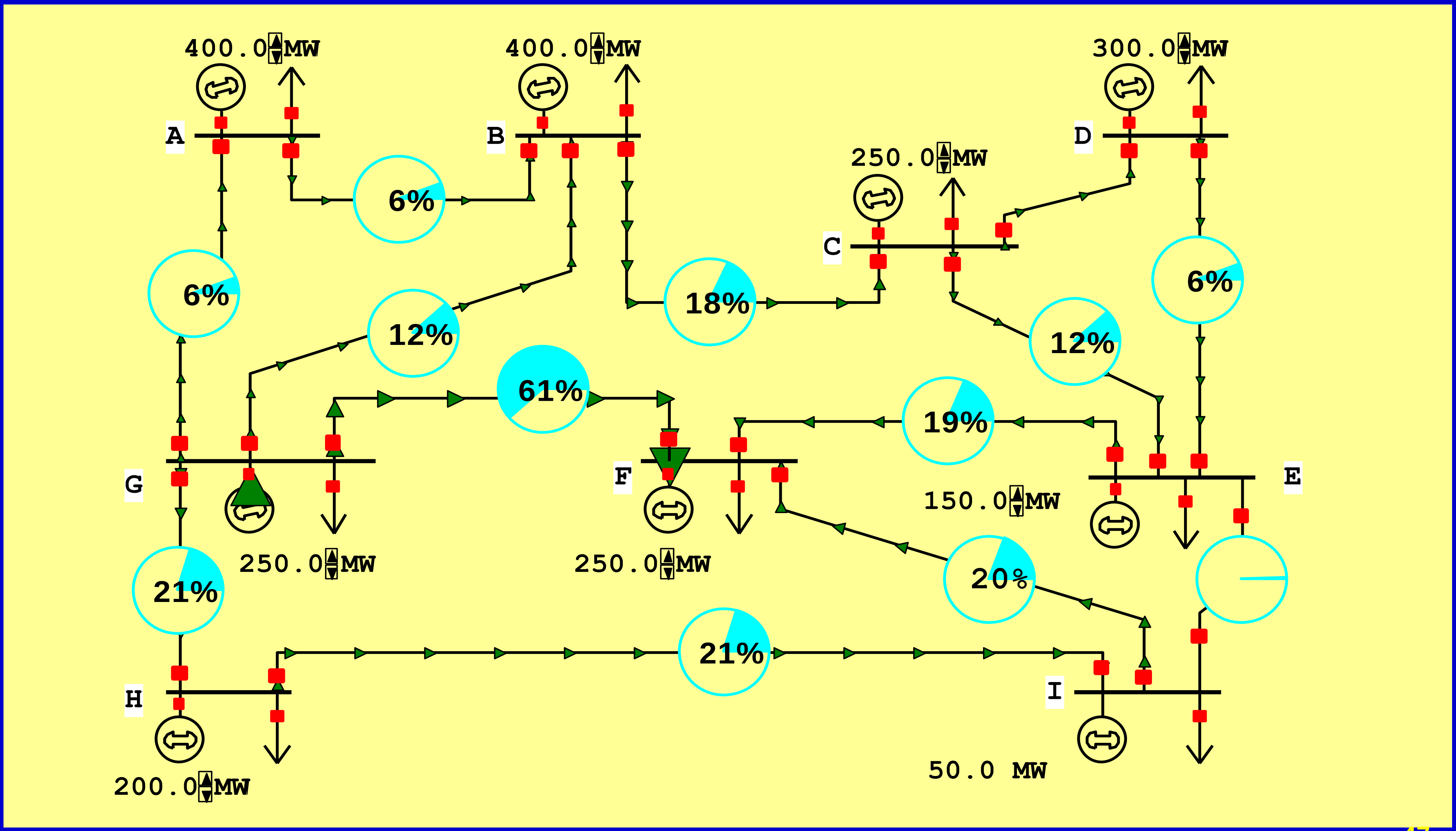


PTDF Example: Nine Bus Case PTDFs for Transfer from A to I

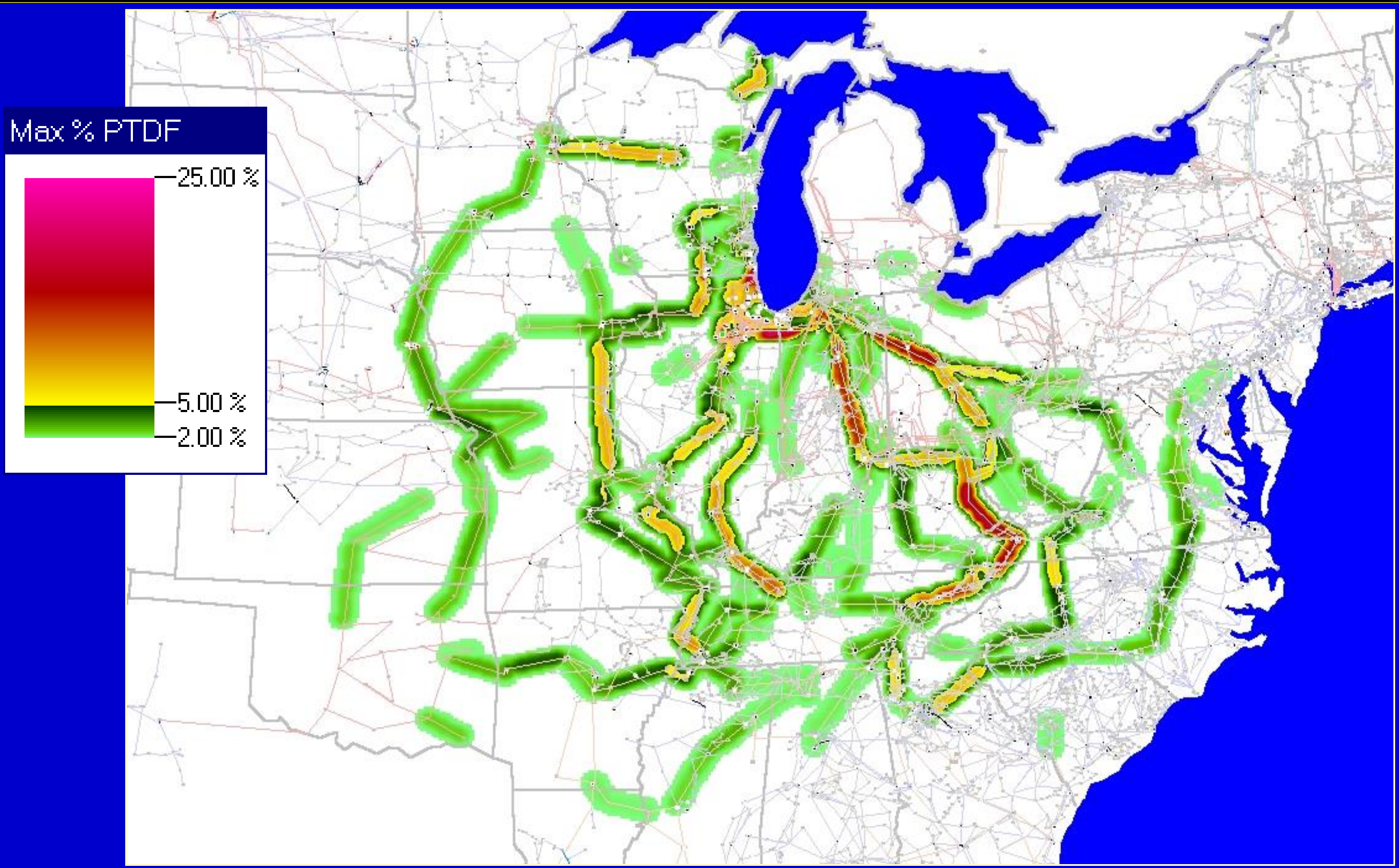


Values now tell percentage of flow that will go on line

PTDF Example: Nine Bus Case
PTDFs for Transfer from G to F



Individual Line PTDFs: Wisconsin to TVA



Contours show lines that would carry at least 2% of a power transfer from Wisconsin to TVA

PTDFs, Flowgates and TLR

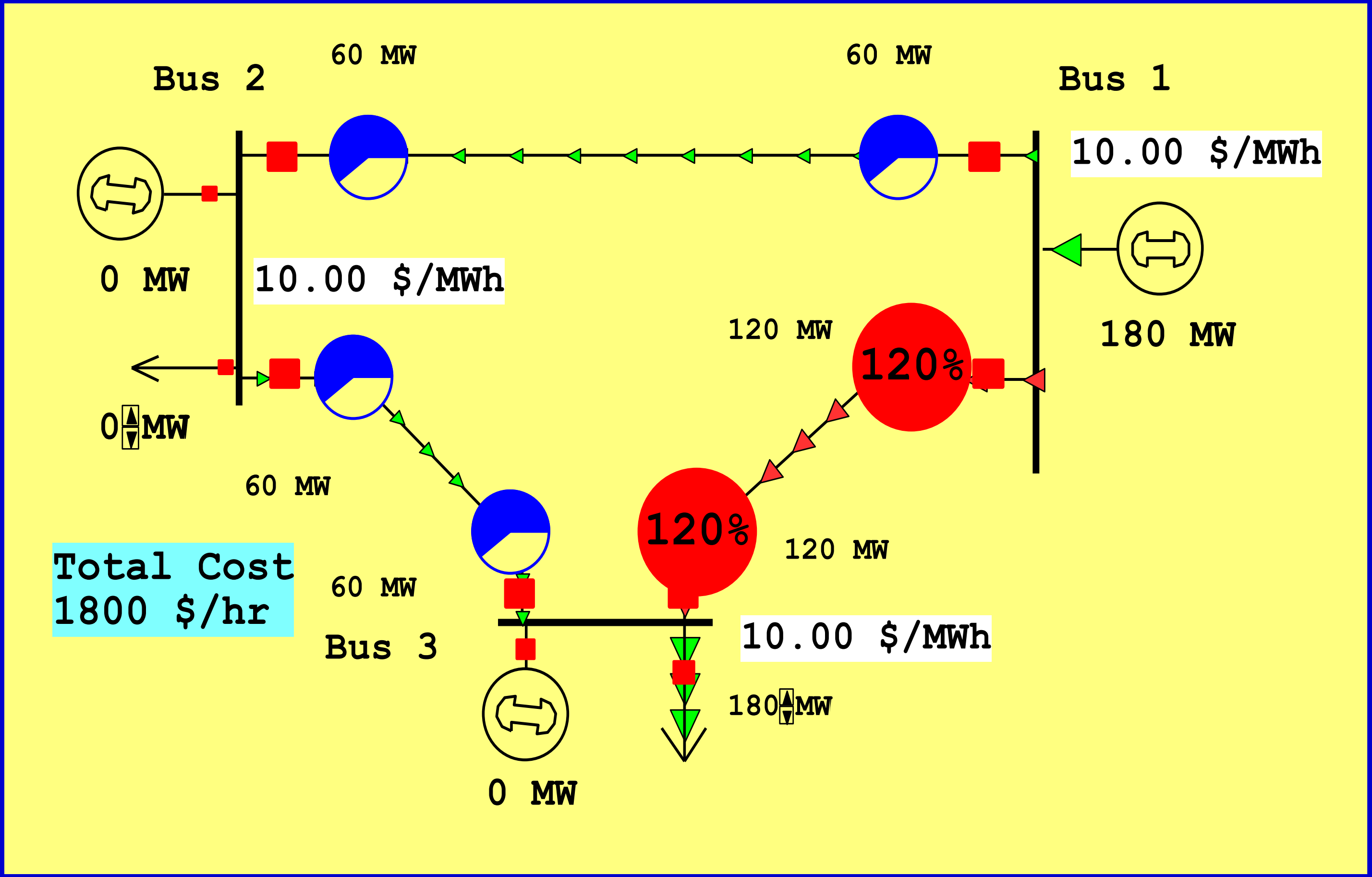
- PTDFs can have a tremendous impact on the ability of buyers and sellers to transact.
- During transmission line loading relief (TLR) all transactions with a PTD above 5% on affected elements are not allowed.
- This can split the market, with resultant high costs for energy.

Pricing Electricity

- Cost to supply electricity to bus is called the locational marginal price (LMP)
- Presently many ISOs post LMPs on the web
- In an ideal electricity market with no transmission limitations the LMPs are equal
- Transmission constraints can segment a market, resulting in differing LMP
- Determination of LMPs requires the solution on an Optimal Power Flow (OPF)

Three Bus LMPs - Line Overload Ignored

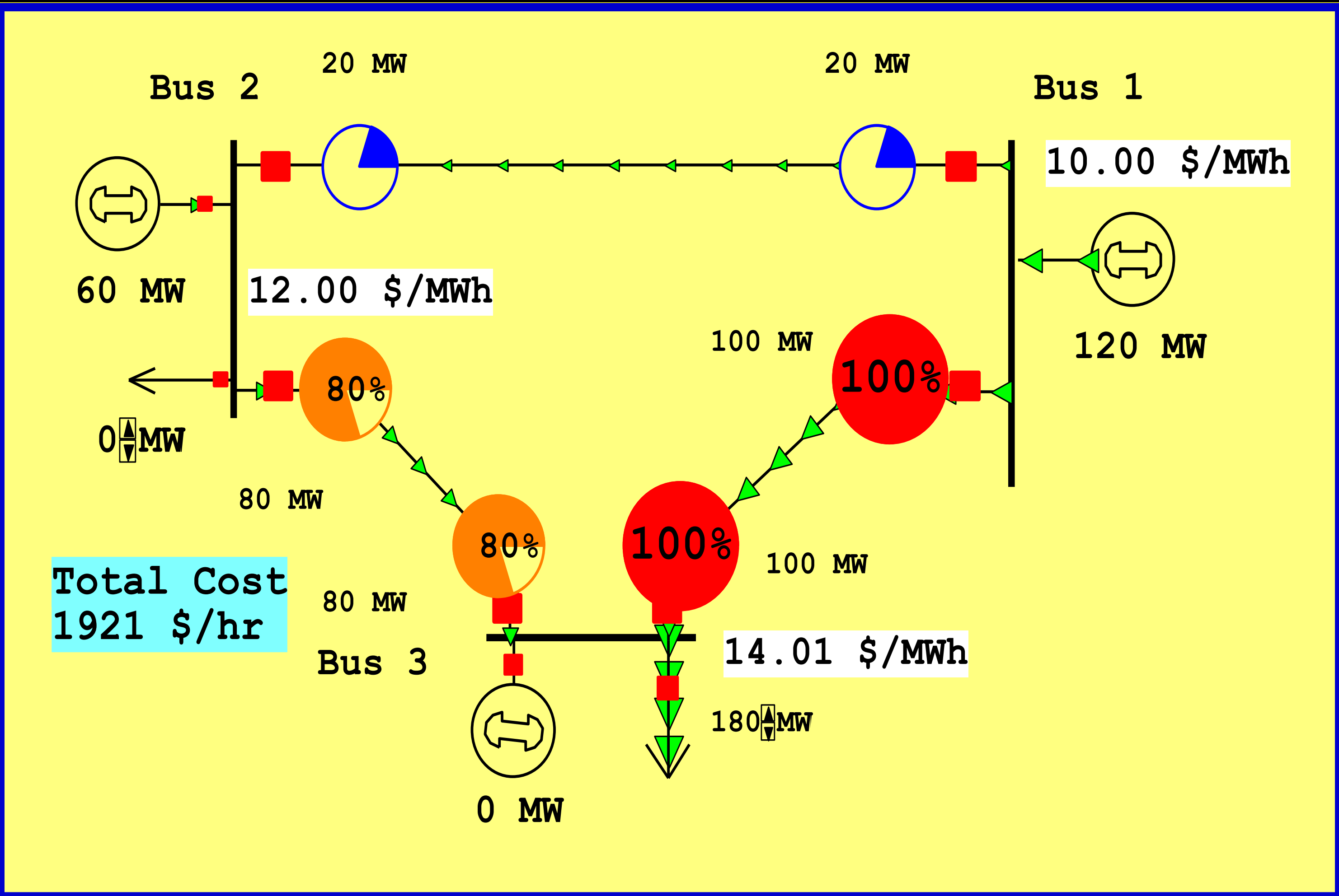
Gen 2's cost is $12 per MWh



Gen 1's cost is $10 per MWh

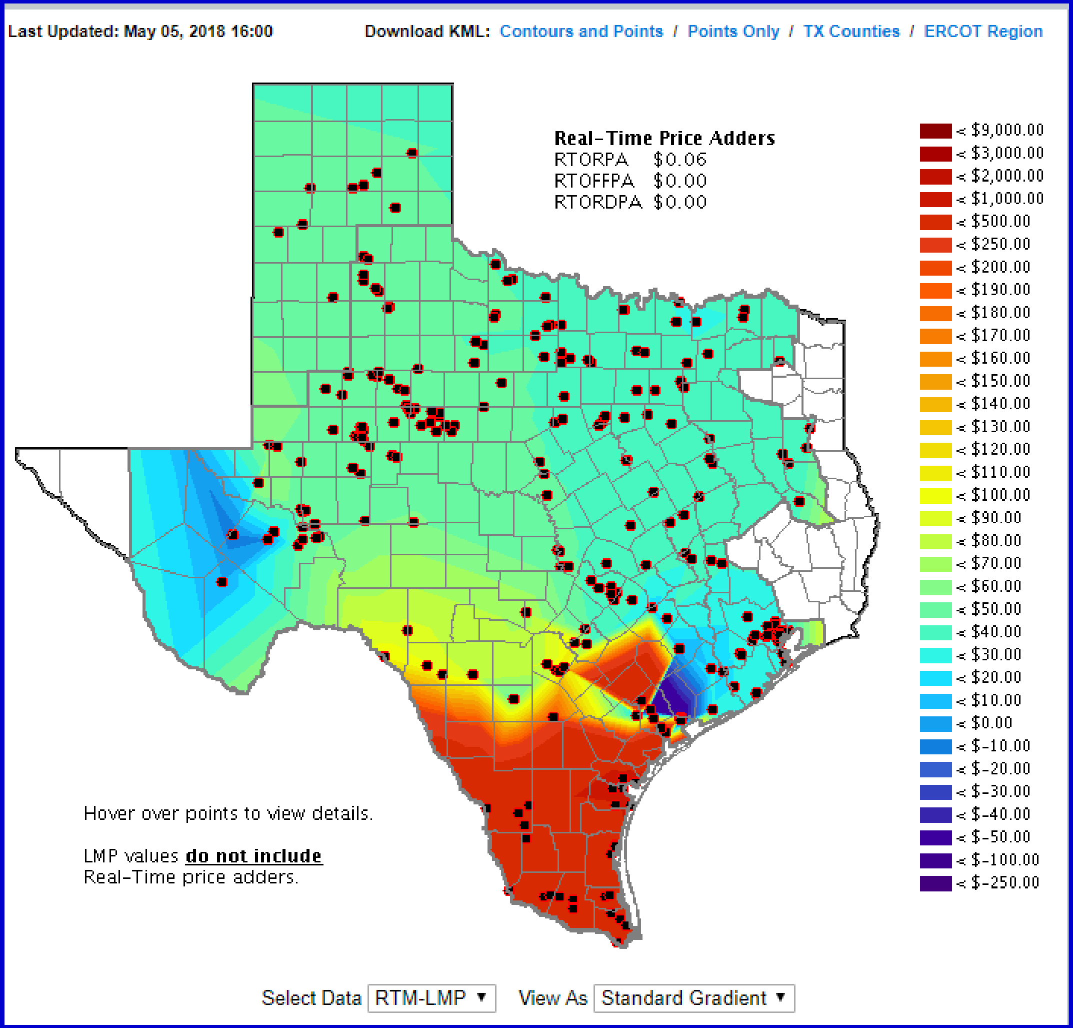
Line from Bus 1 to Bus 3 is over-loaded; all buses have same marginal cost

Three Bus LMPs - Line Overload Enforced



Line from 1 to 3 is no longer overloaded, but now the marginal cost of electricity at 3 is $14 / MWh

ERCOT LMPs: May 5, 2018, 4 PM



MISO's from 6/13/2022

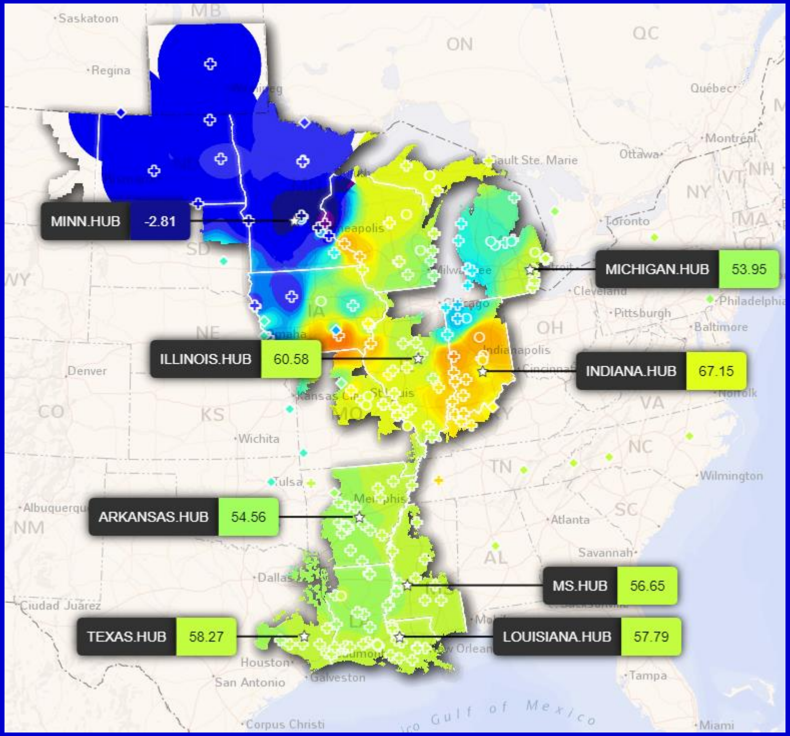


Image Source: http://www.ercot.com/content/cdr/contours/rtmLmp.html

Integration of Renewable Resources

- In many senses the integration of transmission-level renewable resources is similar to that for convention power generation, but a key challenge with most renewable resources is their intermittency (wind is available when the wind blows, solar when the sun is shining

Photo sources: Vestas and NREL

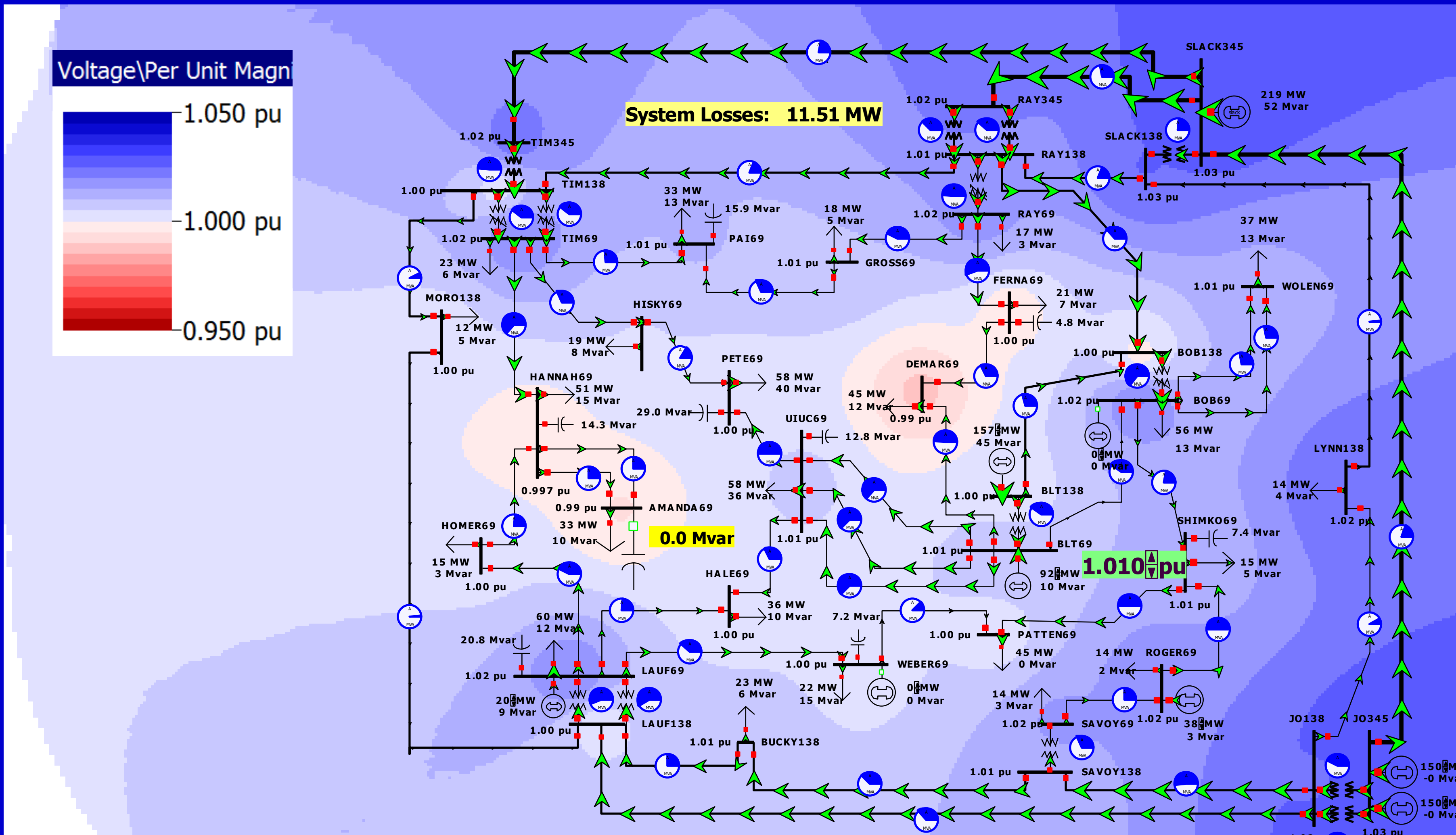
Reactive Power

- Reactive power is supplied by
  - generators, capacitors, transmission lines
- Reactive power is consumed by
  - loads
  - transmission lines/transformers (high losses)
- Reactive power doesn’t travel well - must be supplied locally.
- Reactive must satisfy Kirchhoff’s law - total reactive power into a bus MUST be zero.

Voltage Magnitude

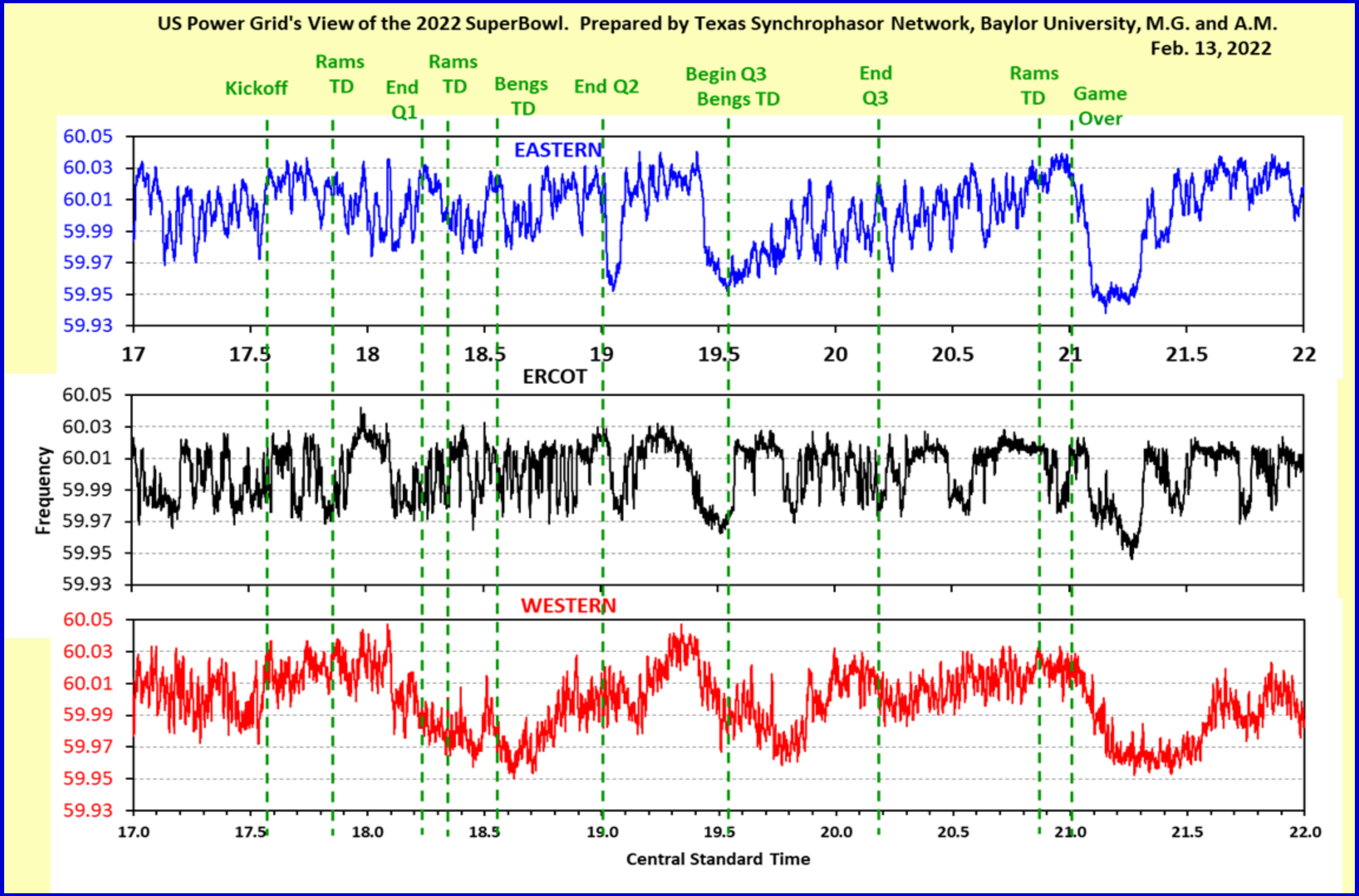
- Power systems must supply electric power within a narrow voltage range, typically with 5% of a nominal value.
- For example, wall outlet should supply 120 volts, with an acceptable range from 114 to 126 volts.
- Voltage regulation performed mostly by generators, LTC transformers and capacitors.

Voltage Magnitude Example



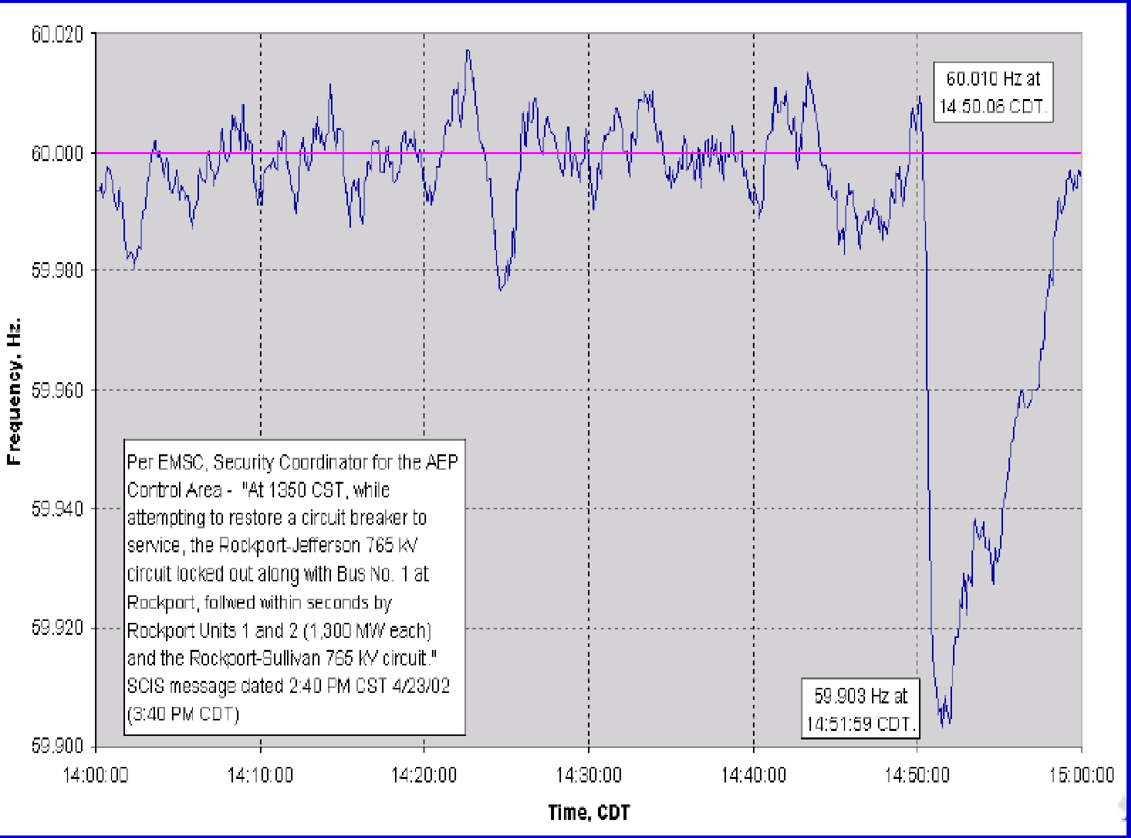
Power System Frequency

Interconnects Always Have Slightly Different Frequencies (During 2022 Super Bowl)

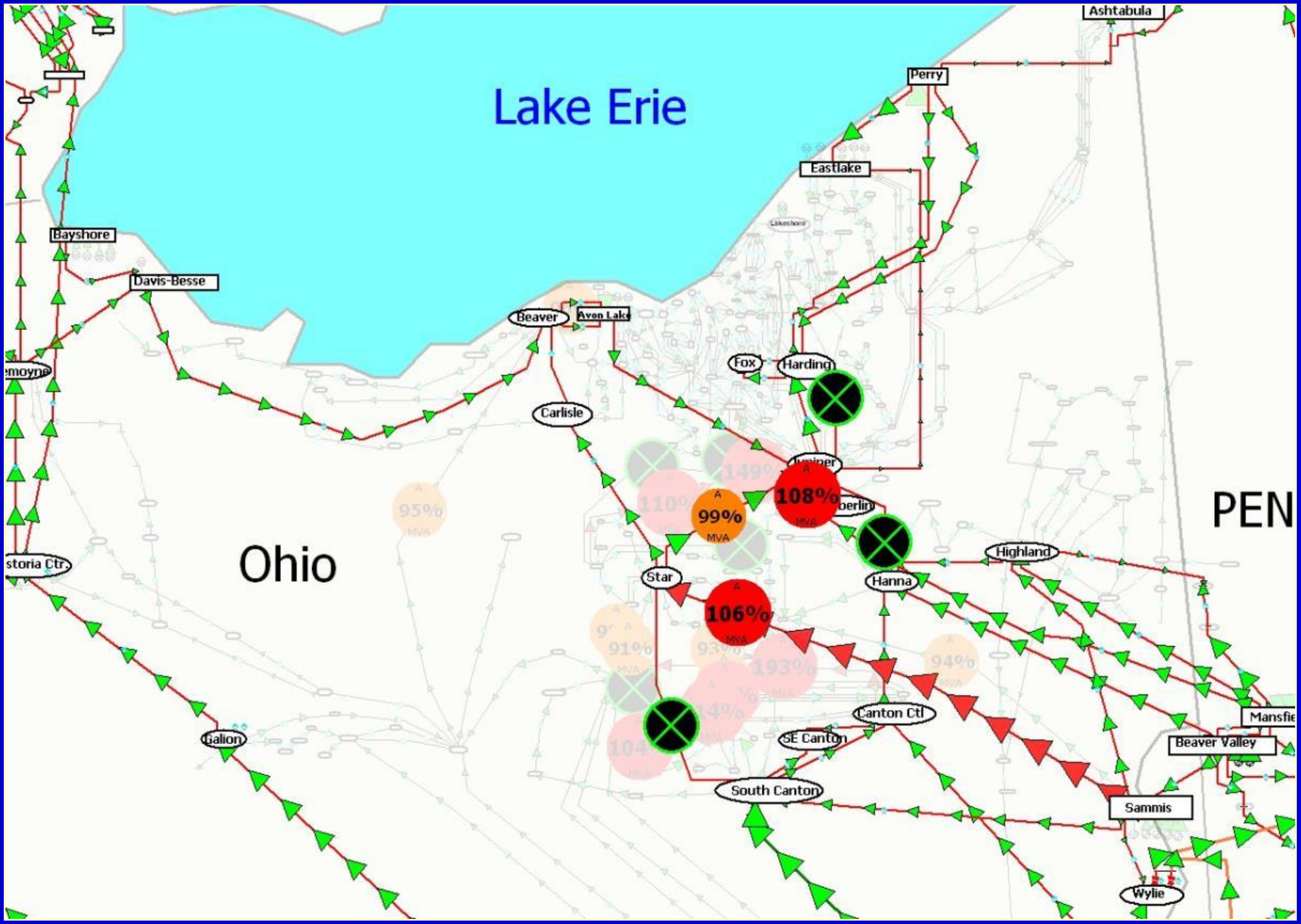


Power System Dynamics

- If power system generation does not exactly match the total load plus losses, the frequency will change
  - Increasing if too much generation
  - Decreasing if too much load



August 14, 2003 Blackout Simulation



Free Version of PowerWorld Simulator

A free, 42 bus version of PowerWorld Simulator can be downloaded at www.powerworld.com/gloveroverbyesarma