The Electric Power Grid: What Lurks Behind the Outlet and Why it Matters

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The Humble Wall Outlet: Gateway to Our Most Complex Machine

In 2000 the NAE named Electrification (the development of the vast networks of electricity that power the developed world) as the top engineering technology of the 20th century!

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The Power Grid, the Energy Pie and Carbon

- Of the total US energy consumption in 2005 (100 Quad) more than 86% came from fossil fuel sources
- Almost 40% of our energy consumption is related to electricity production, a percentage that has been steadily increasing
- For our non-fossil fuel energy, almost all of it comes in electric form (primarily nuclear and hydro), as does essentially all our coal energy

Source: EIA Annual Energy Outlook 2007

Three Electric System Components

- Generation – source of electric energy
  - coal provides over half of the U.S. electric energy
- Load – consumes electric energy
  - consumers are in complete control of the switch; utilities must supply enough power to meet load
- Transmission and Distribution – the wires that carry the power from generation to load
  - Operating at voltages up to 765 kV (kilovolt), with 500 kV, 345 kV and 230 kV common

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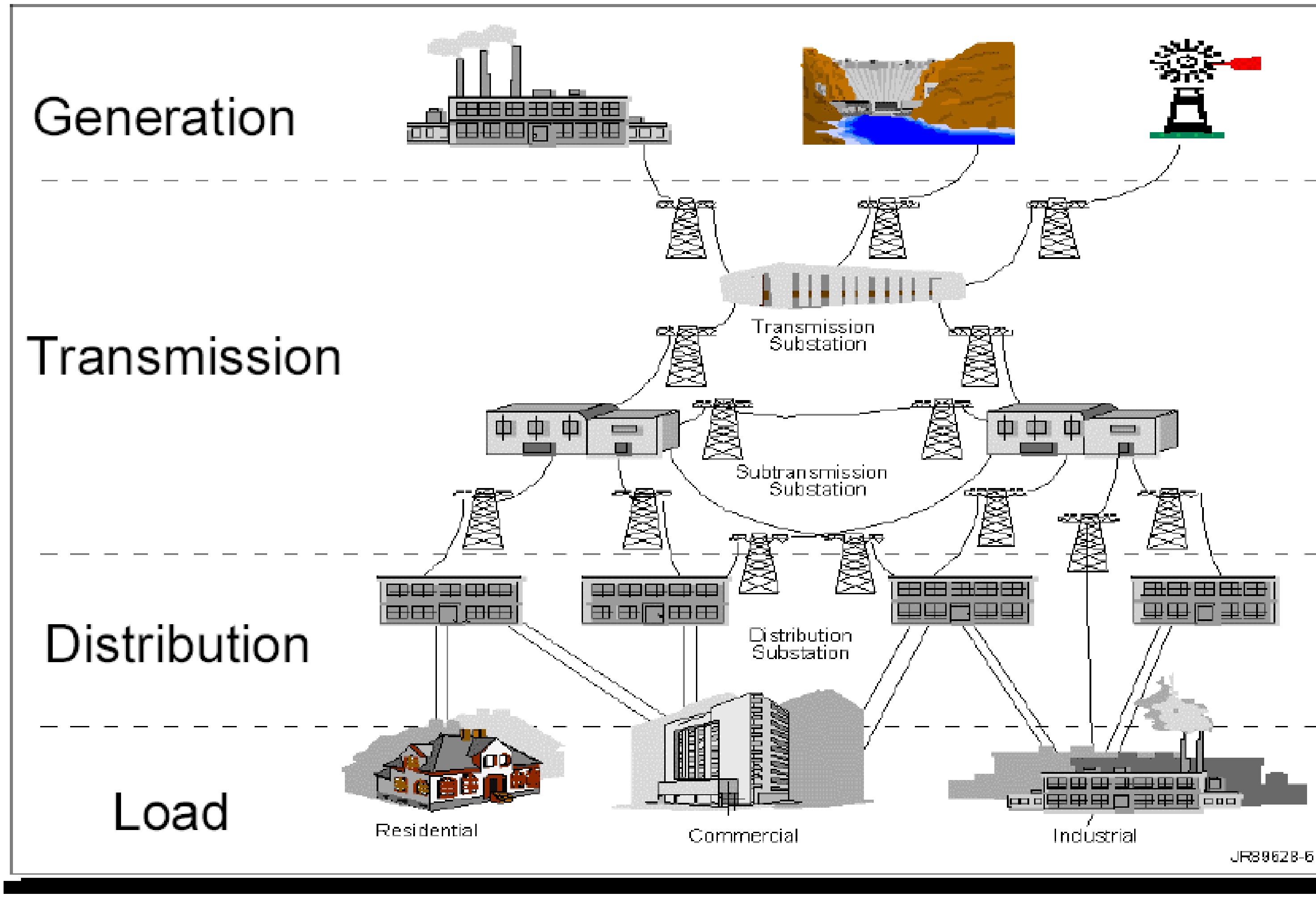
Major Power Grid Components



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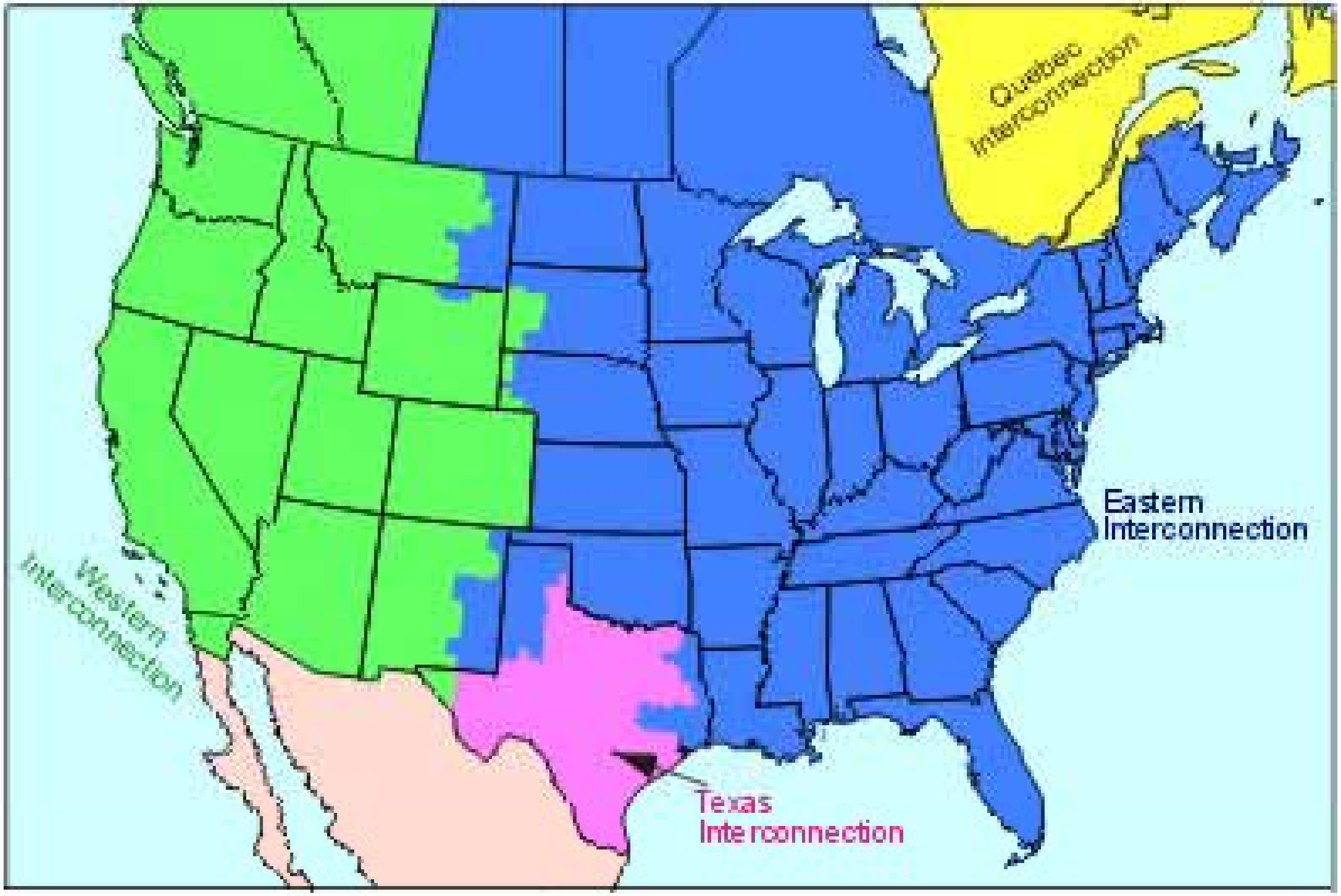
The North American Electric Grid

- One of the largest and most complex man-made objects ever created
- Consists of four large 60 Hz ac synchronous subsystems
  - Eastern Interconnect, Western Interconnect (WSCC), Texas (ERCOT), Quebec
- Small amounts of power can be transferred between subsystems using AC-DC-AC ties

North America Interconnections



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Central U.S. High Voltage Transmission Grid

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on-line version for
data confidentiality

Generation Summary

- Total U.S. Generation consists of more than 10,000 different units with a total capacity of about 986 GW (986,000 MW)
  - largest generation "plant" is Grand Coulee (WA) with 7,000 MW of hydro
  - In 2006 we received 49.0% of our electric energy from coal, 20.0% from natural gas, 19.4% from nuclear, 7.0% from hydro, 1.6% from petroleum, 1.0% from wood, 0.6% from wind, 0.4% waste/biomass, 0.36% geothermal, 0.01% solar

Source: US EIA Electric Power Annual 2006 (October 2007)

Electric Load

- The aggregate electric load on the power grid varies continuously, with the customer having almost complete control
  - with daily, weekly and seasonal patterns
- Total peak US electric demand is about 710,000 MW, but different areas achieve their peak values at different times

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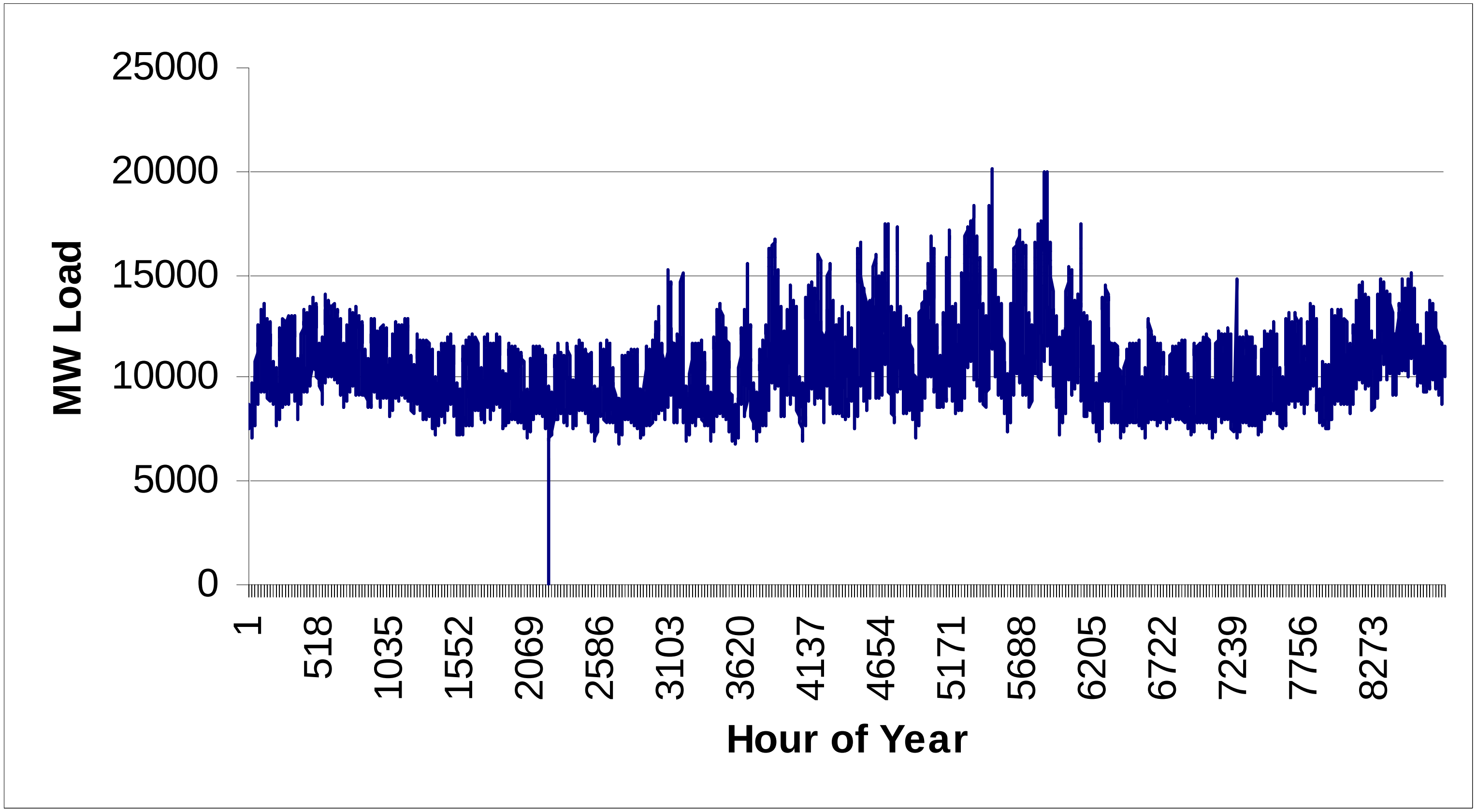
Example Hourly Variation in Electric Load Over a Year



Most of the time the load is significantly below its peak value

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Transmission and Distribution (i.e., the wires)

- 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 765, 500, 345, 230, 161, 138 and 69 kV.
- Lower voltage lines are used for distribution (e.g., 12.4 or 13.8 kV).

Three Phase AC

- Residential electric service is single phase, with a single “hot” wire, a neutral wire, and a separate ground wire (for safety)
- Practically all high power ac systems use a balanced three phase design
  - three “hot” wires are used, with an optional neutral
  - three phase systems can transmit twice as much power as an equivalent single phase system

Three Phase Transmission Line

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Simulation of Power System Operations

- The next several slides use a power system simulation package, PowerWorld Simulator, to demonstrate the operation of the electric grid
- Simulations will start with small system models, and then work up to a simulation of the August 14th 2003 blackout

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Metro Chicago Electric Grid

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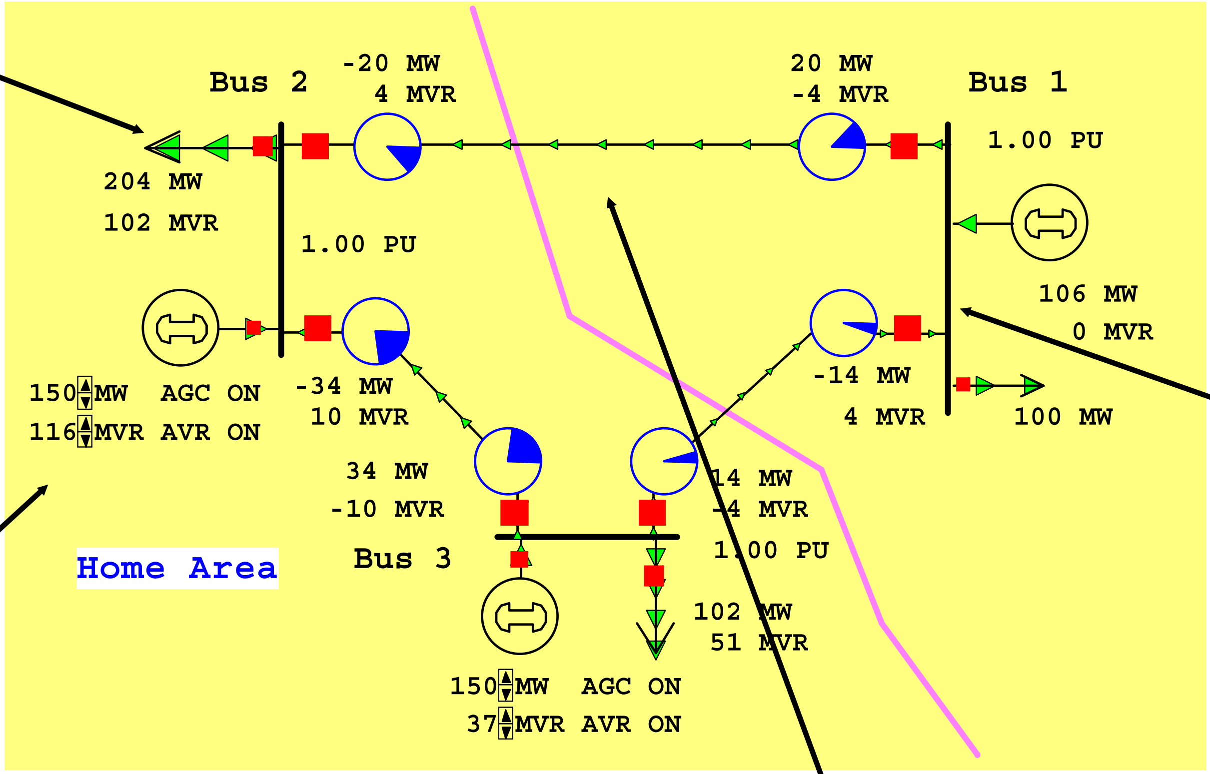
Example Three Bus Power System

Load with green arrows indicating amount of MW flow

Used to control output of generator



Note the power balance at each bus

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

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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.

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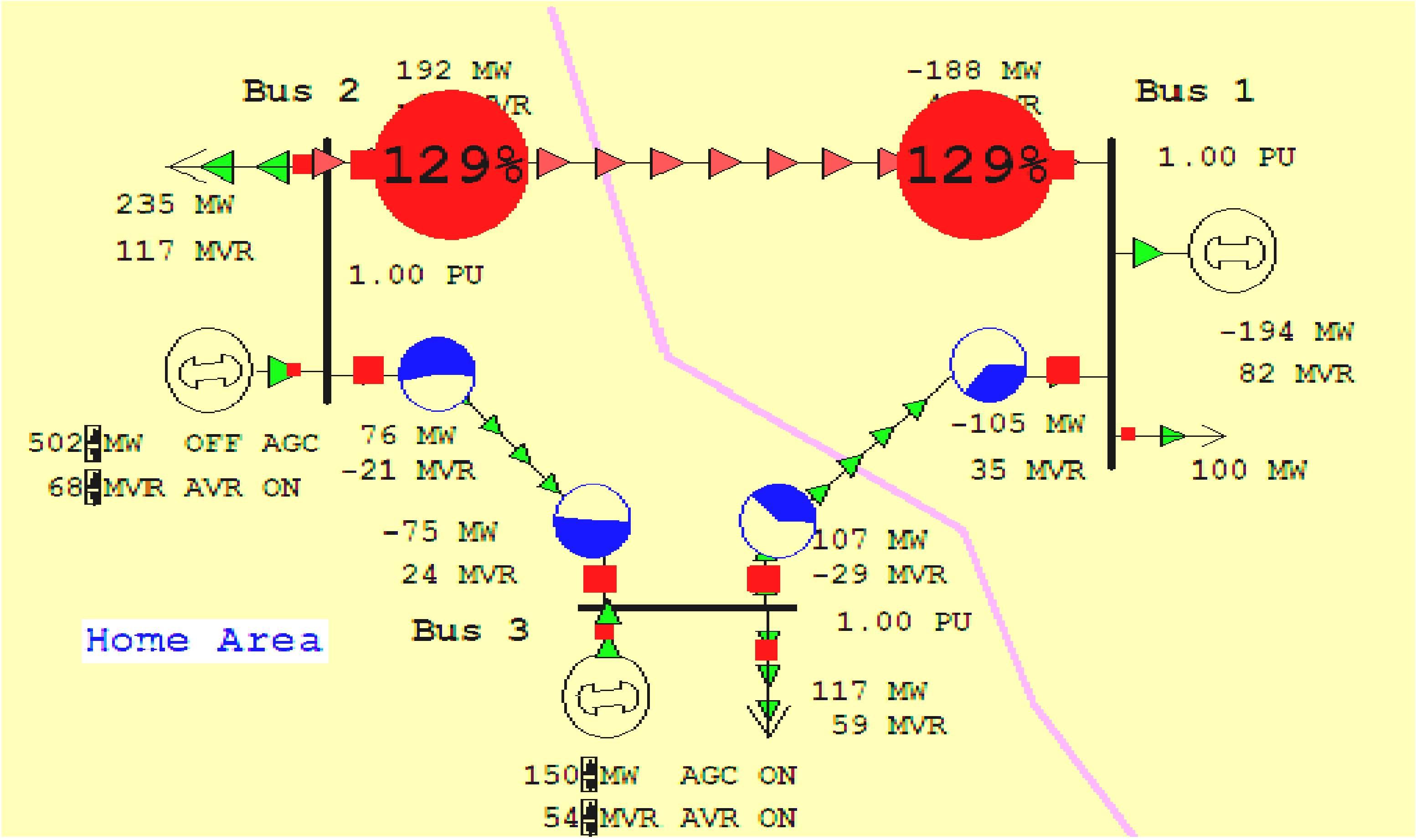
Basic Power Control

- 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



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Interconnected Operation

- Power systems are interconnected across large distances. Most of North America east of the Rockies is one system, with most of Texas and Quebec being major exceptions
- Individual entities (e.g., a utility) only own or operate a small portion of the system, referred to an balancing authority area (previously operating area).

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Balancing Authority 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

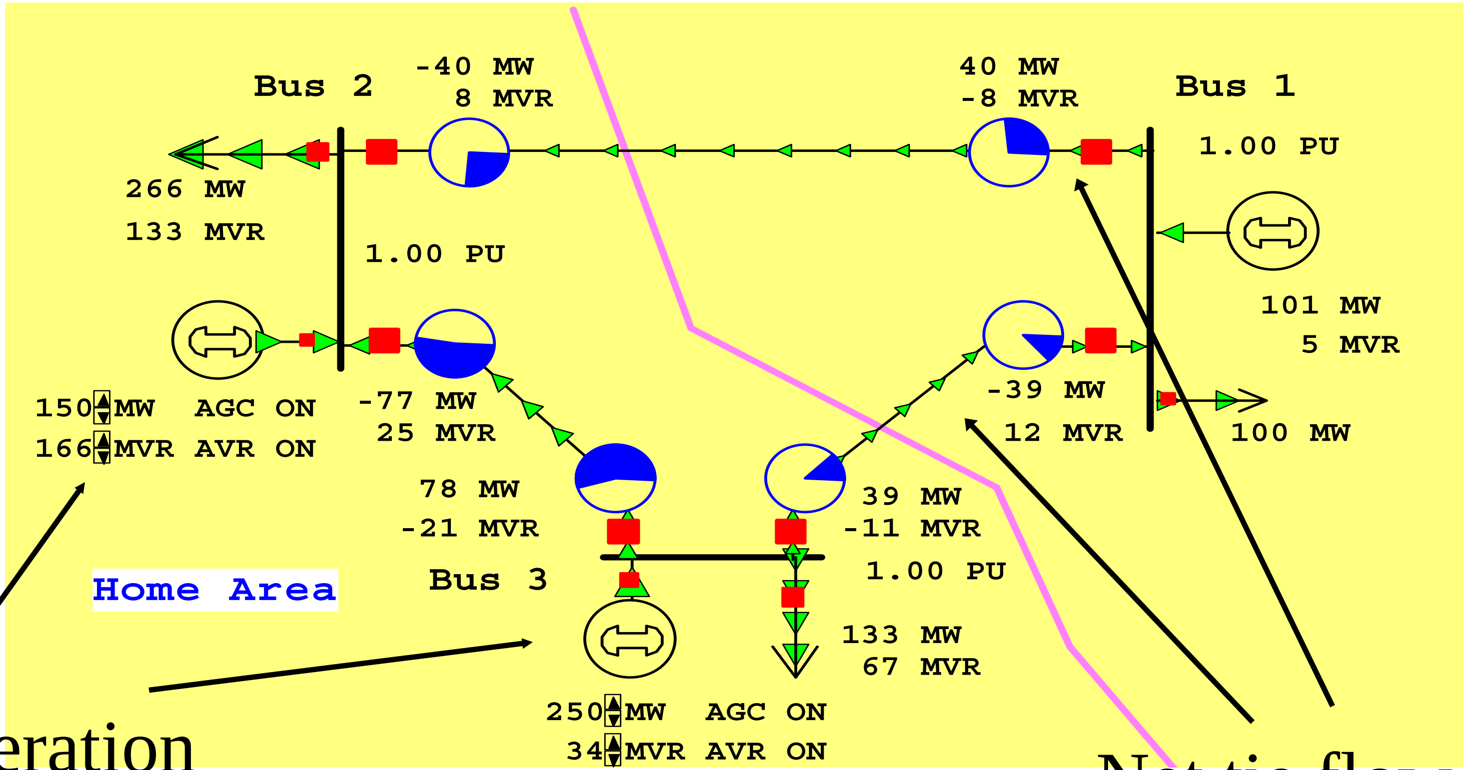
Area Control Error (ACE)

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

Automatic Generation Control

- Most utilities use automatic generation control (AGC) to automatically change their generation to keep their ACE close to zero.
- Usually the utility 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

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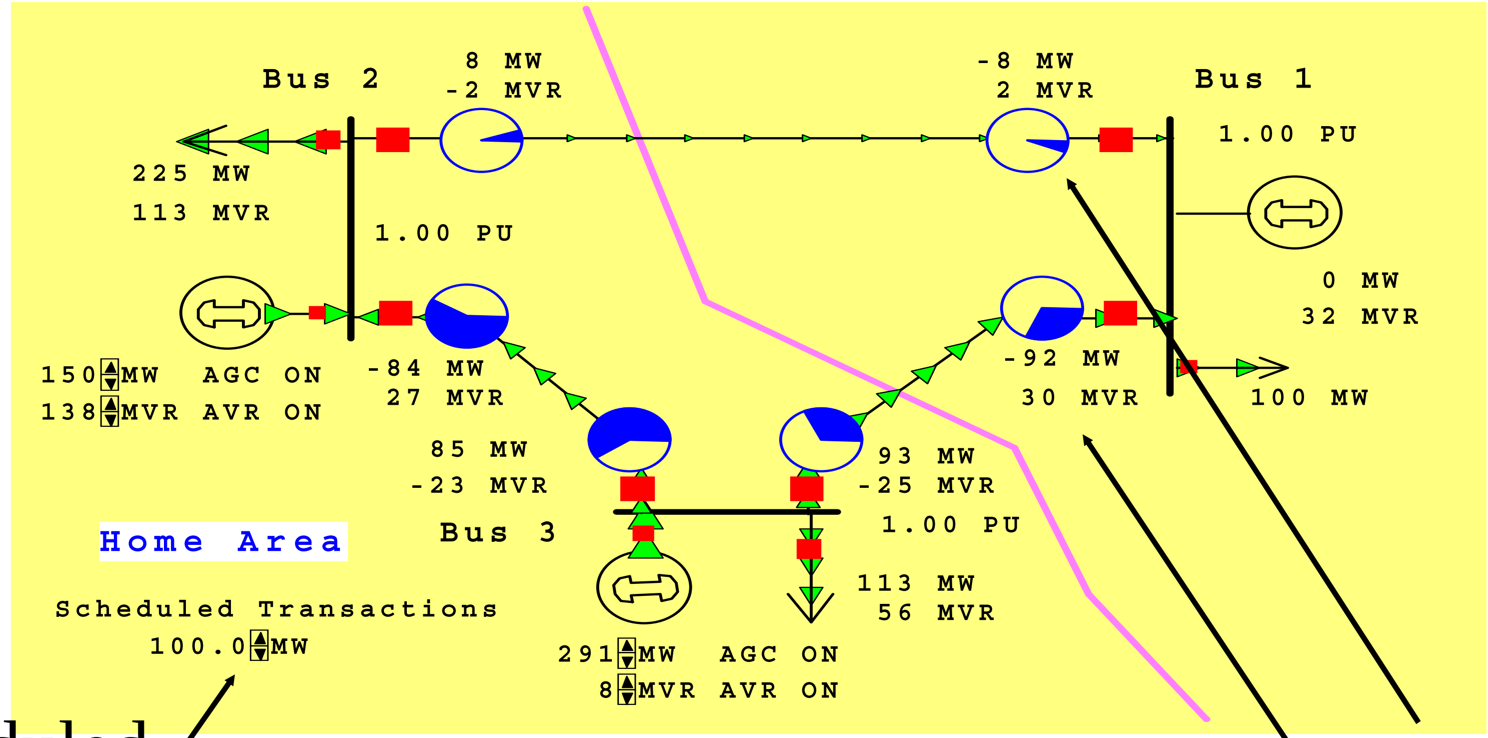
Power Transactions

- 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

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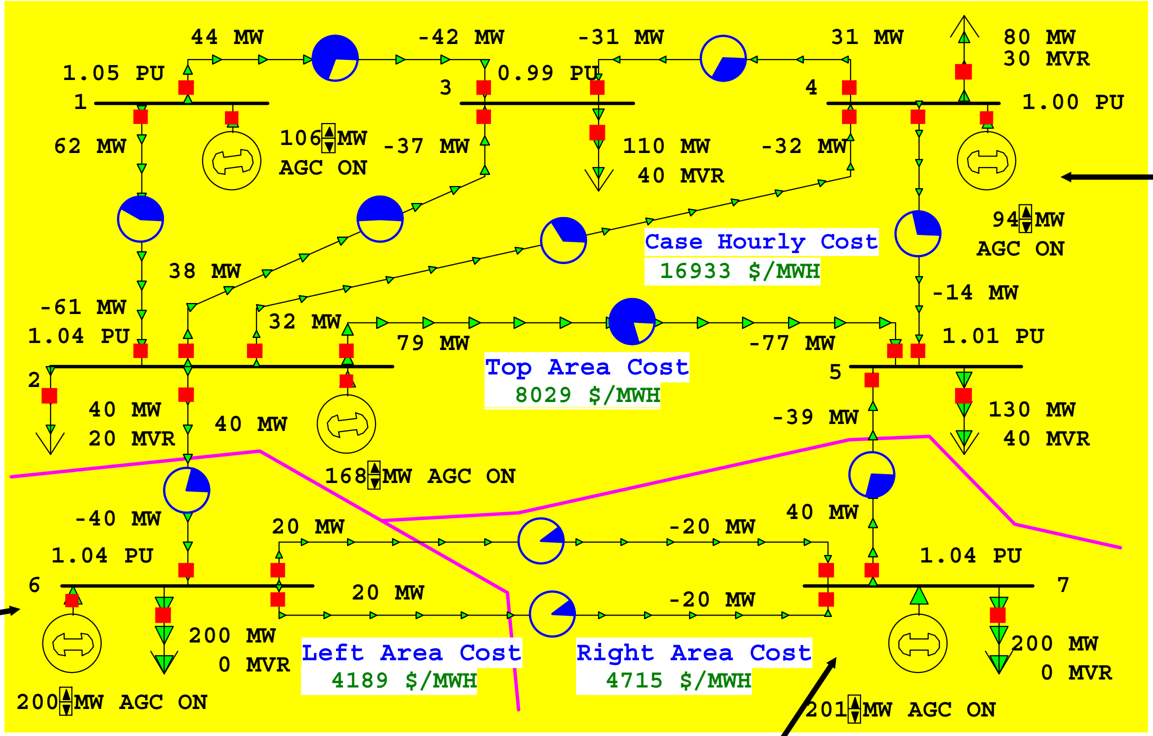
Multi-Area Operation

- 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 Case: One-line

System has three areas



Area top has five buses

Area left has one bus

Area right has one bus

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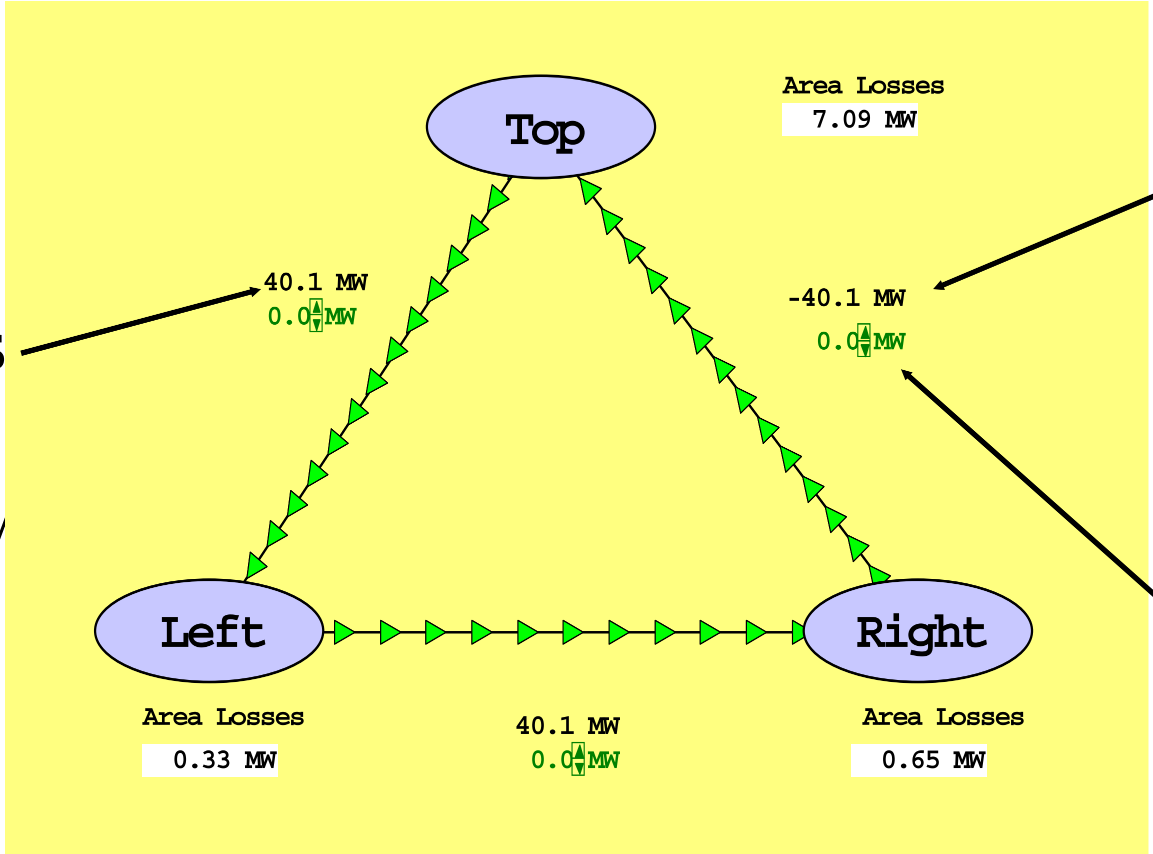
Seven Bus Case: Area View

System has 40 MW of "Loop Flow"



Actual flow between areas

Scheduled flow

Loop flow can result in higher losses

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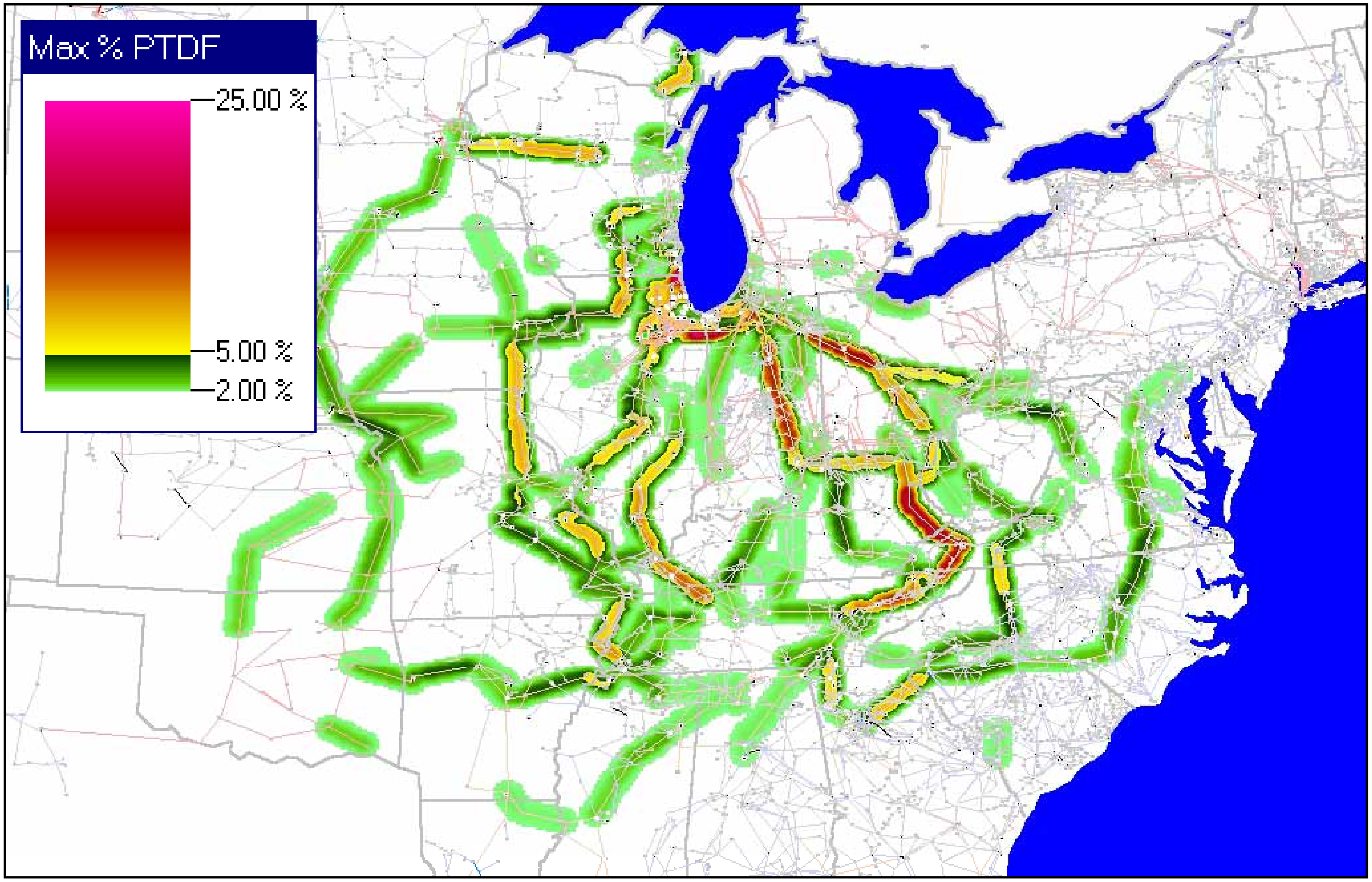
Power Transfer Distribution Factors (PTDFs)

- 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.

PDTFs on for Power Transfer from Wisconsin to TVA



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

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How the Grid can Fail
August 14th, 2003

Demo

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Power Grid Reliability

- Practically all blackouts are due to localized problems in the distribution system
  - distribution system has a radial design, so any break in the circuit will blackout those downstream
  - such blackouts have no impact on the reliability of the interconnected transmission system
- Of course large blackouts, like 8/14/03, can occur

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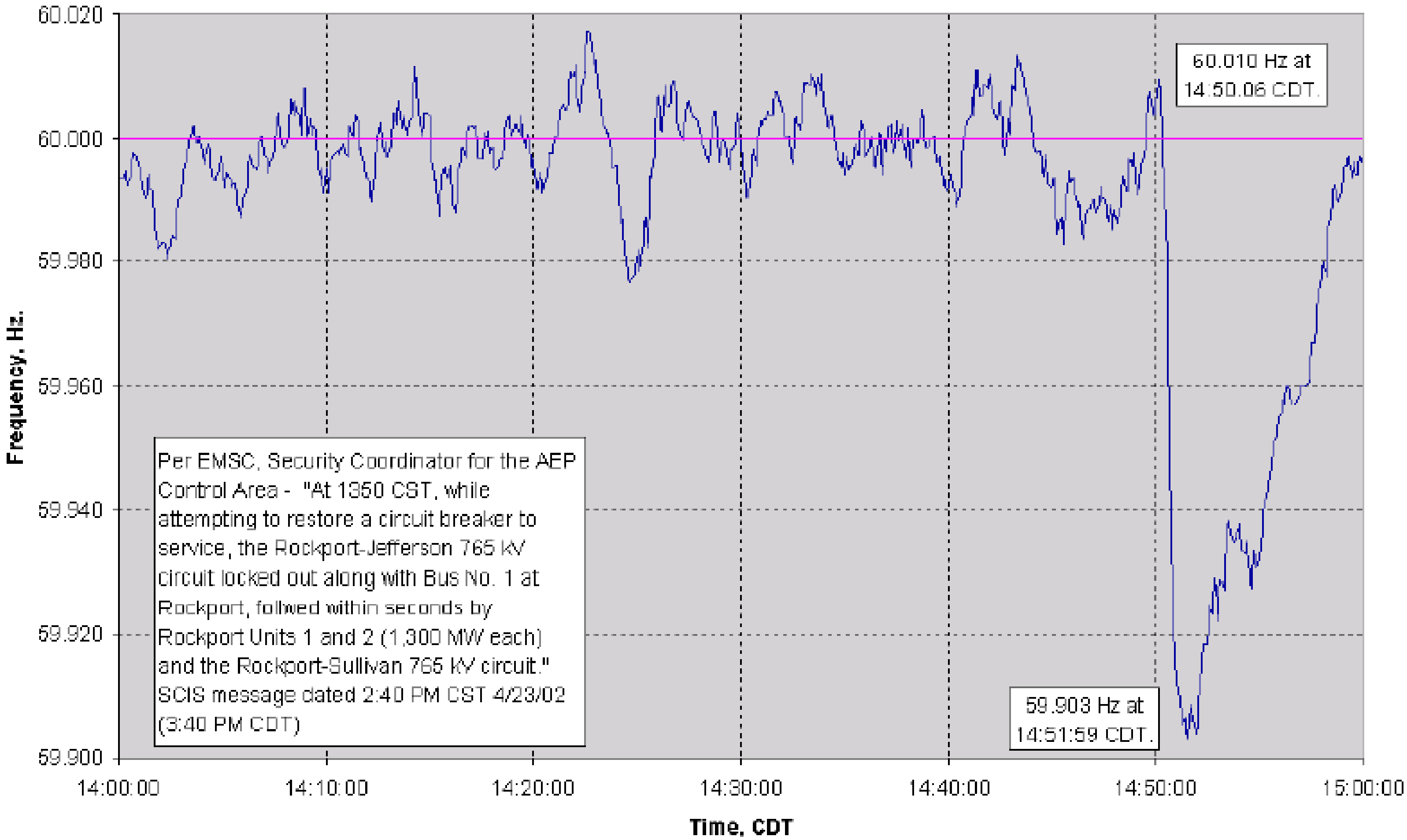
Frequency Control

- Steady-state operation only occurs when the total generation exactly matches the total load plus the total losses
  - too much generation causes the system frequency to increase
  - too little generation causes the system frequency to decrease (e.g., loss of a generator)
- AGC is used to control system frequency

April 23, 2002 Frequency Response Following Loss of 2600 MW



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