Energy Tutorial:
Electric Grid 101

GCEP RESEARCH SYMPOSIUM 2011 | STANFORD, CA

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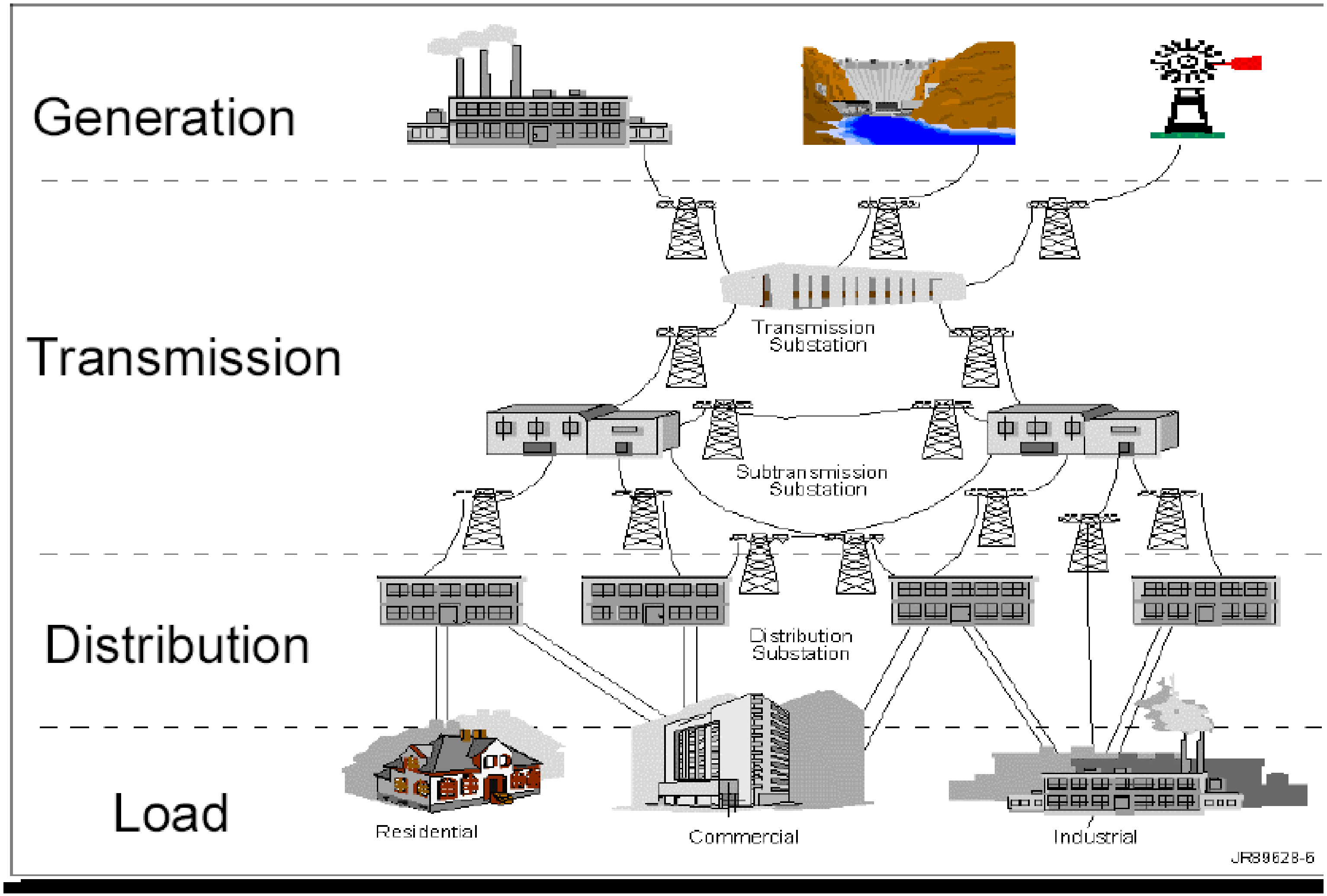
GLOBAL CHALLENGES – GLOBAL SOLUTIONS – GLOBAL OPPORTUNITIES

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

Major Power Grid Components



Power and Energy

- Power is the instantaneous transfer of energy; expressed in watts (W), kW, MW, GW
  - US installed generation capacity is about 1000 GW
- Energy is the integration of power over time; expressed in units of joules (J = 1 W-sec), kWh (3.6×10^6 J), or btu (1055 J; 1 MBtu=0.292 MWh)
- U.S. electric energy consumption is about 3600 billion kWh (about 13,333 kWh per person; 1.5 kW continuous per person on average)

AC System Analysis

- The power grid is an ac system, operating at close to 60 Hz in North America, 50 Hz in many other places
- Constant frequency ac systems are analyzed using phasor analysis, which expresses a time varying value, such as a voltage or current, as a magnitude and phase angle
  - $v(t) = V_{max} \cos(\omega t + \theta_v) \rightarrow V_{rms} \angle \theta_v$
  - Phase angle is always with respect to an arbitrary reference angle

The Advantage of Phasor Analysis

Device	**Time Analysis**	**Phasor**
Resistor	$v(t) = Ri(t)$	$V = RI$
Inductor	$v(t) = L\frac{di(t)}{dt}$	$V = j\omega LI$
Capacitor	$\frac{1}{C}\int_0^t i(t)dt + v(0)$	$V = \frac{1}{j\omega C} I$

$$Z = \text{Impedance} = R + jX = |Z|\angle\phi$$

$$R = \text{Resistance}$$

$$X = \text{Reactance}$$

$$|Z| = \sqrt{R^2 + X^2} \qquad \phi = \arctan\left(\frac{X}{R}\right)$$

Instantaneous Electrical Power

Power

$$p(t) = v(t)\, i(t)$$

$$\mathrm{v(t)} = V_{\max} \cos(\omega t + \theta_V)$$

$$i(\mathrm{t}) = I_{\max} \cos(\omega t + \theta_I)$$

$$\cos\alpha \cos\beta = \frac{1}{2}[\cos(\alpha - \beta) + \cos(\alpha + \beta)]$$

$$p(t) = \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) +$$

$$\cos(2\omega t + \theta_V + \theta_I)]$$

Average Electrical Power

Average Power

$$p(t) = \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)]$$

$$P_{avg} = \frac{1}{T} \int_0^T p(t)\, dt$$

$$= \frac{1}{2} V_{\max} I_{\max} \cos(\theta_V - \theta_I)$$

$$= |V||I| \cos(\theta_V - \theta_I)$$

Power Factor Angle $= \ \phi = \theta_V - \theta_I$

Complex Power

$$S = |V||I| \cos(\theta_V - \theta_I) + j\sin(\theta_V - \theta_I)$$

$$= P + jQ$$

$$= V\,I^*$$

P = Real Power (W, kW, MW)

Q = Reactive Power (var, kvar, Mvar)

S = Complex power (VA, kVA, MVA)

Power Factor (pf) = $\cos\phi$

If current leads voltage then pf is leading

If current lags voltage then pf is lagging

Power Consumption in Devices

Resistors only consume real power

$$P_{Resistor} = \left|I_{Resistor}\right|^2 R$$

Inductors only consume reactive power

$$Q_{Inductor} = \left|I_{Inductor}\right|^2 X_L$$

Capacitors only generate reactive power

$$Q_{Capacitor} = -\left|I_{Capacitor}\right|^2 X_C \qquad X_C = \frac{1}{\omega C}$$

$$Q_{Capacitor} = -\frac{\left|V_{Capacitor}\right|^2}{X_C}$$ (Note-some define X_C negative)

Capacitors for Power Factor Correction

- Many electric loads are reactive, which means they consume reactive power; i.e., a lagging pf
  - Induction motors are a very common example
- Capacitors are commonly used to "correct" the power factor

Balanced 3 Phase (ϕ) Systems

- Bulk power systems are almost exclusively 3ϕ
- Single phase is used primarily only in low voltage, low power settings, such as residential and some commercial
- A balanced 3 phase (ϕ) system has
  - three voltage sources with equal magnitude, but with an angle shift of 120°
  - equal loads on each phase
  - equal impedance on the lines connecting the generators to the loads

Advantages of Three Phase

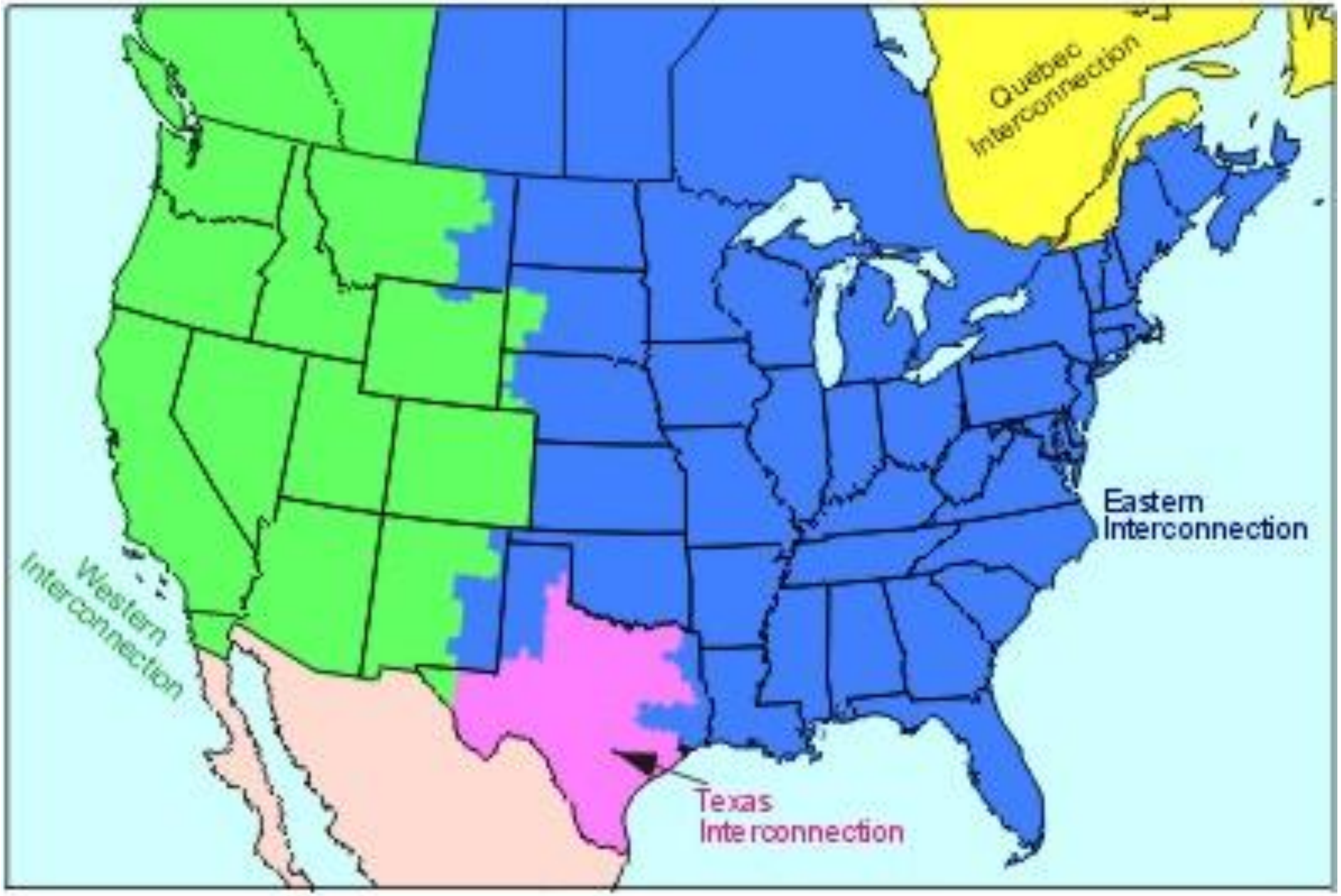
- Can transmit more power for same amount of wire (twice as much as single phase)
- Torque produced by 3ϕ machines is constant
- Three phase machines use less material for the same power rating
- Three phase machines start more easily than single phase machines

Three Phase Transmission Lines

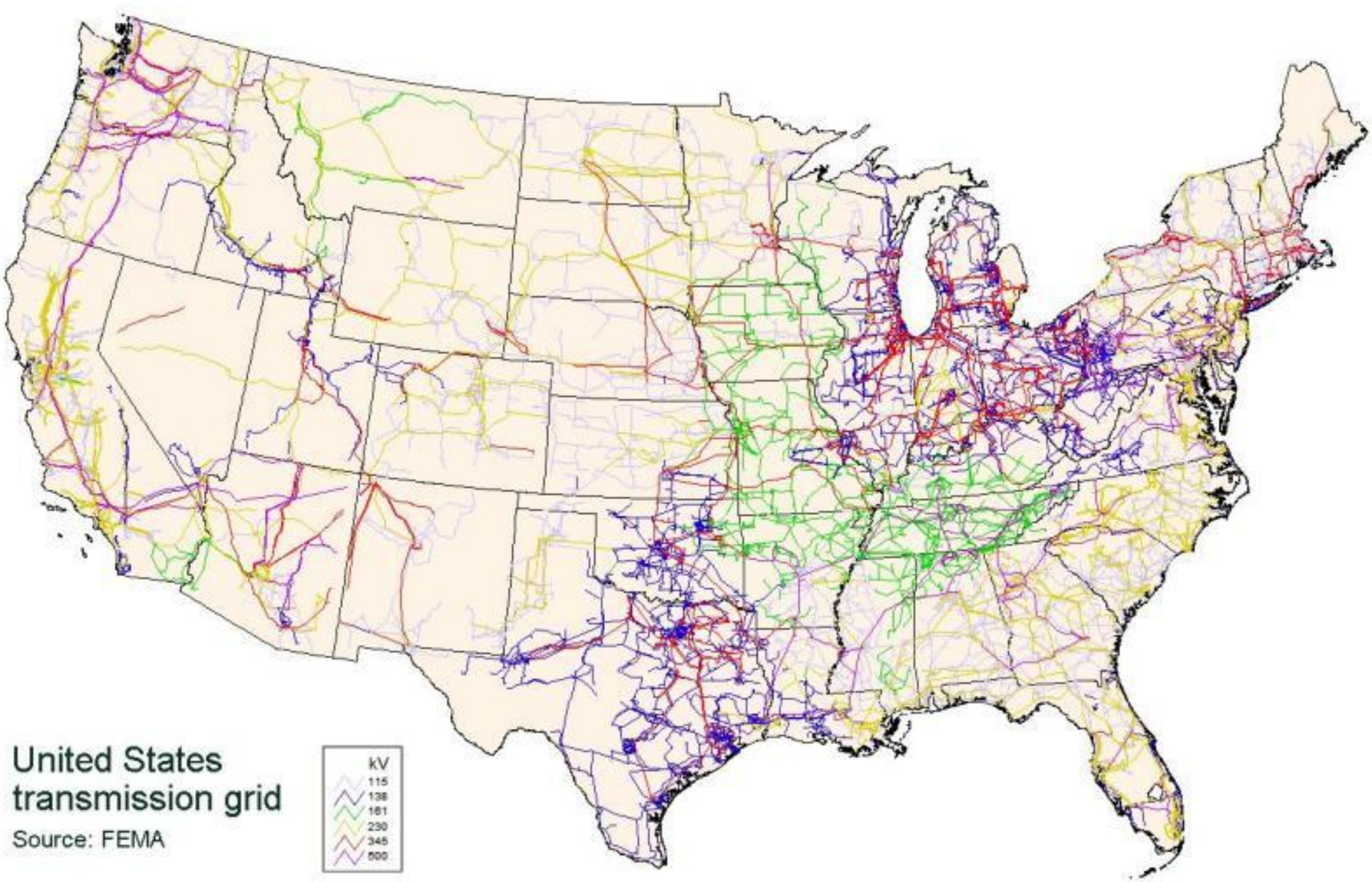
The North American Electric Grid

- One of the largest and most complex 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



North America Transmission Grid



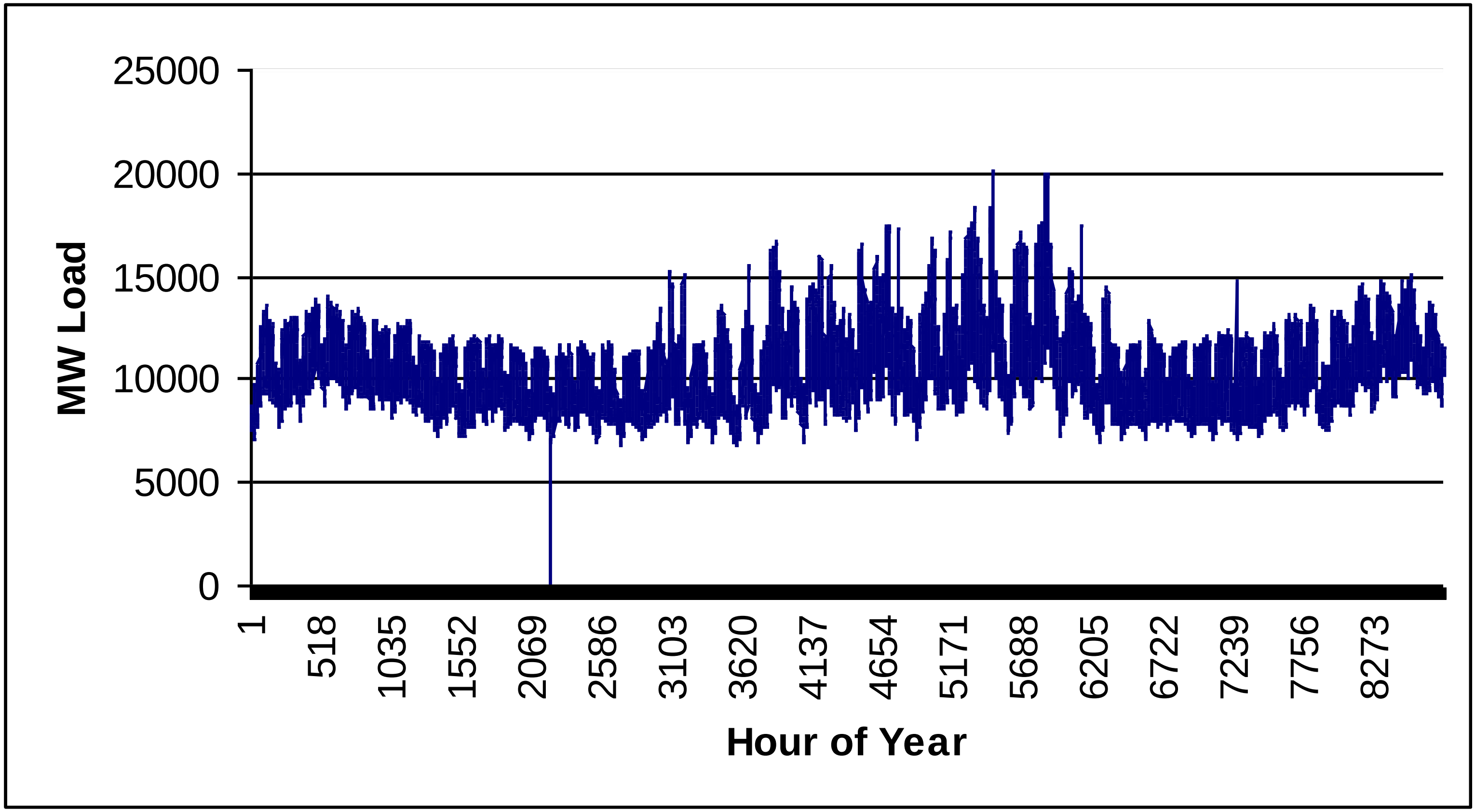
Generation Summary

- Total U.S. Generation consists of more than 10,000 different units with a total capacity of about 800,000 MW
  - largest generation “plant” is Grand Coulee (WA) with 7,000 MW of hydro
  - next largest are Polo Verde (AZ) with 3,700 MW of nuclear, W.A Parish with 3,600 MW of coal (TX), and Scherer with 3,400 MW of coal in (GA).

Electric Load

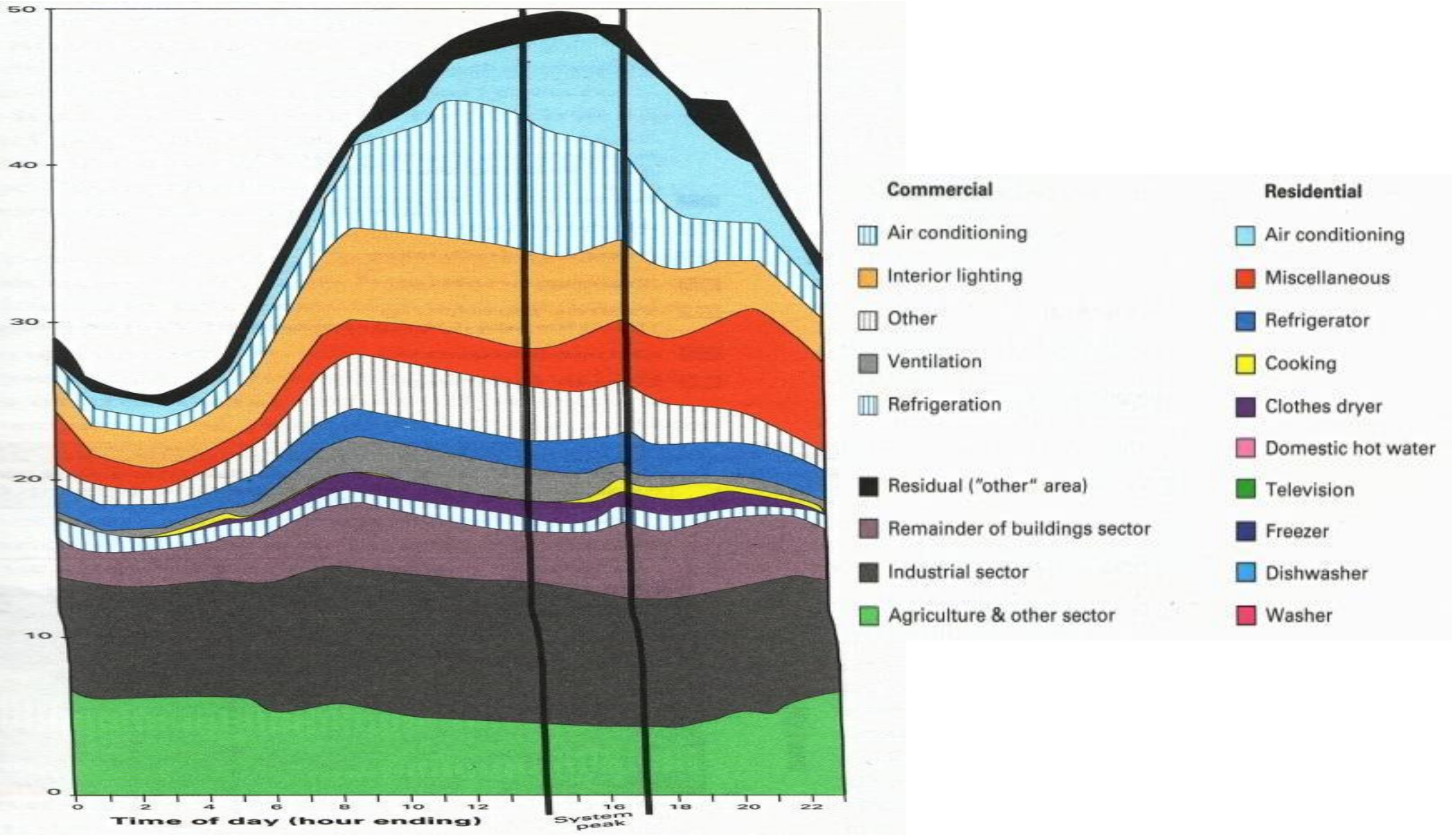
- The aggregate electric load on the power grid varies continuously, with the customer having almost complete control
  – with daily, weekly and seasonal patterns
- Total peak US electric demand is about 710,000 MW, but different areas achieve their peak values at different times

Example Yearly Variation in Load



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

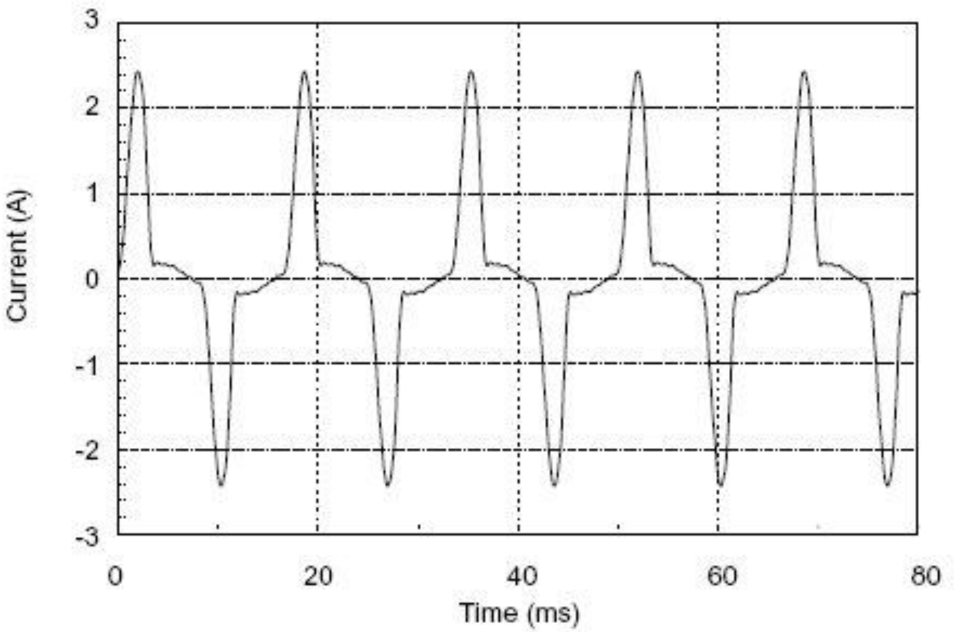
Daily Load Variation: Very Individual



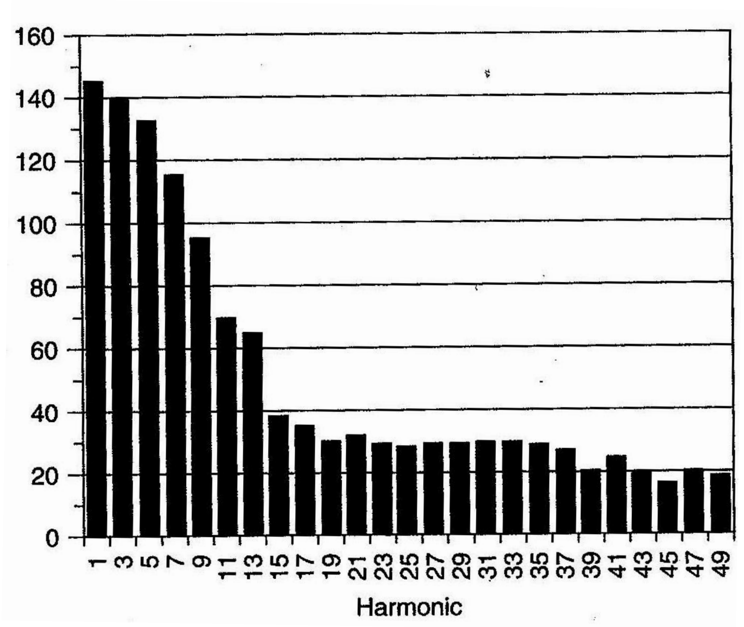
Not All Loads are "Grid Friendly"

- Constant impedance loads are the easiest on the grid; but many loads inject harmonics

Switched-Mode Power Supply Current



Compact fluorescent lamp (CFL)



Source: www.utterpower.com/commercial_grid.htm

Source: Fig 2.34 of "Renewable and Efficient Electric Power Systems" by Masters

Transmission and Distribution

- Goal is to move electric power from generation to load with low losses.
- Less losses at high voltages ($S=VI^*$ and I^2R losses), 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 (12.4 or 13.8 kV).
- Typical losses are about 3 to 5% in transmission and 10 to 15% in the distribution system.

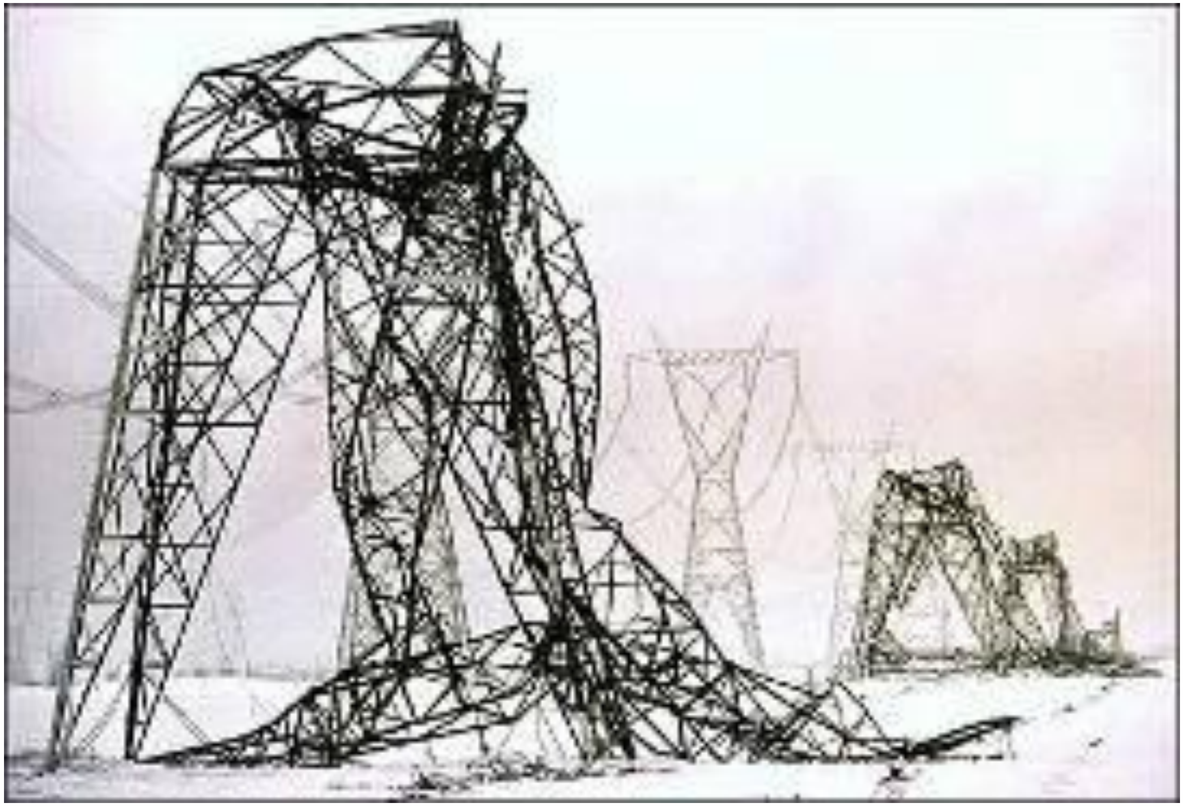
Transmission & Distribution

- Transmission
  - networked connections
  - power can be supplied from multiple sources
  - typically higher voltages, above 100 kV
  - mostly overhead, with some underground in urban areas
  - Often source of large-scale blackouts

- Distribution
  - radial connections
  - power moves in one direction only
  - typically lower voltages, below 100 kV
  - the source of most blackouts, but these are local
  - Most new construction is underground, especially in suburban and urban locations

Transmission Lines and the Elements

Ike in Beaumont, Tx



Quebec Ice Storm

Transmission Lines and Trees

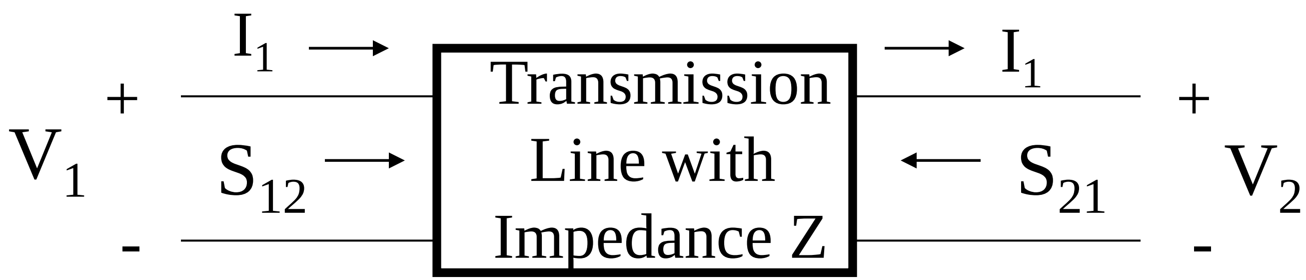
- We like trees, and they grow; but when trees get close to lines bad things can occur.

Before "Trimming"

After "Trimming"

Power Transfer in Transmission Lines

- Below is the full (and more complicated) power flow derivation for a short transmission line



$$S_{12} = V_1 I_1^* = V_1 \left(\frac{V_1 - V_2}{Z} \right)^*$$

$$\text{with } V_1 = |V_1| \angle \theta_1, \quad V_2 = |V_2| \angle \theta_2 \quad Z = |Z| \angle \theta_Z$$

$$S_{12} = \frac{|V_1|^2}{|Z|} \angle \theta_Z - \frac{|V_1||V_2|}{|Z|} \angle \theta_Z + \theta_{12}$$

Approximate Power Transfer

- For high voltage lines, the reactance (X term) dominates so Z has an angle of close to 90°

$$P_{12} + jQ_{12} \quad = \frac{|V_1|^2}{|Z|}\angle 90° - \frac{|V_1||V_2|}{|Z|}\angle 90° + \theta_{12}$$

Since $-\cos(90° + \theta_{12}) = \sin\theta_{12}$, we get

$$P_{12} = \frac{|V_1||V_2|}{X}\sin\theta_{12}$$

Power Transfer is primarily due to a phase angle difference!

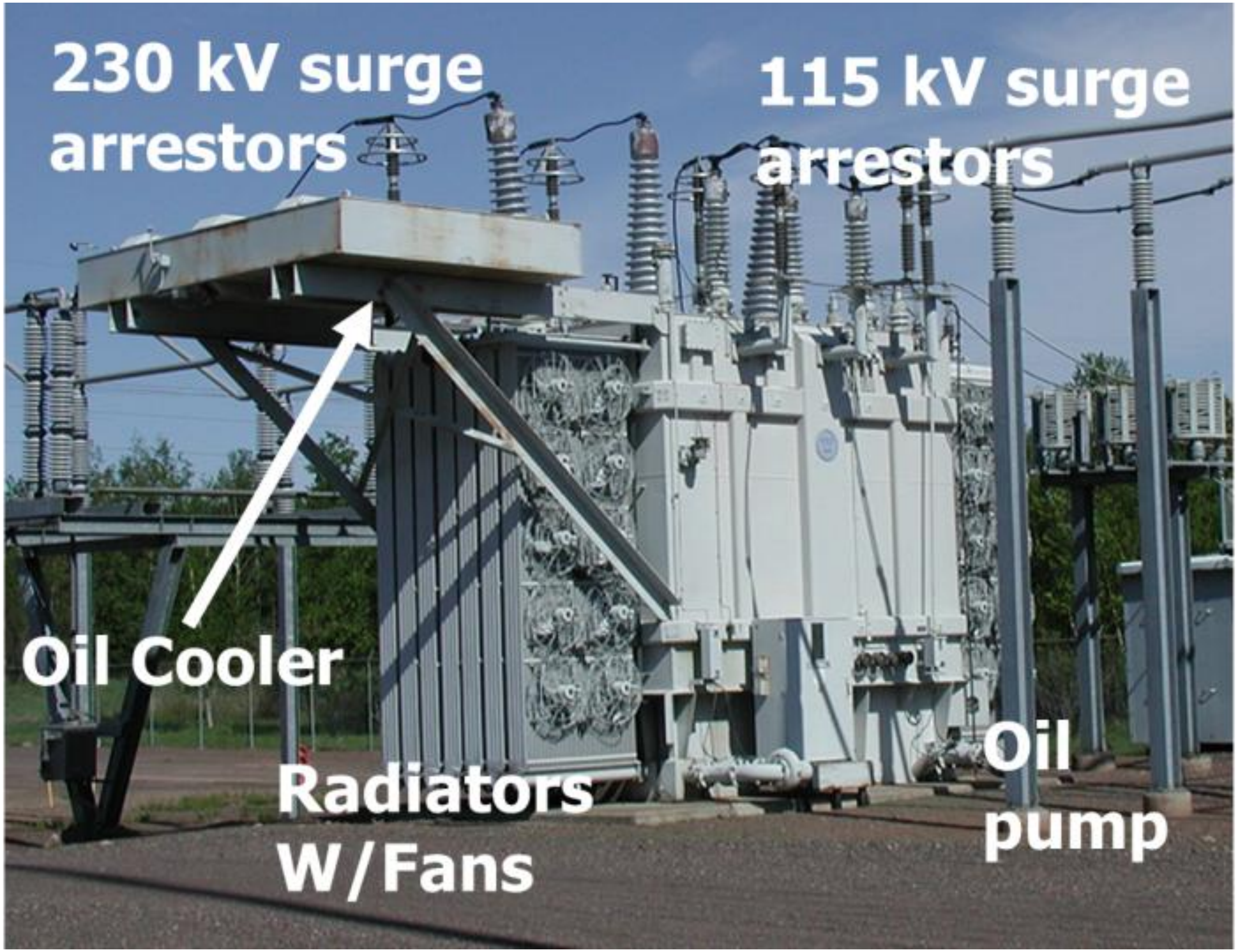
Hence the maximum power transfer is

$$P_{12}^{Max} = \frac{|V_1||V_2|}{X}$$

Transformers

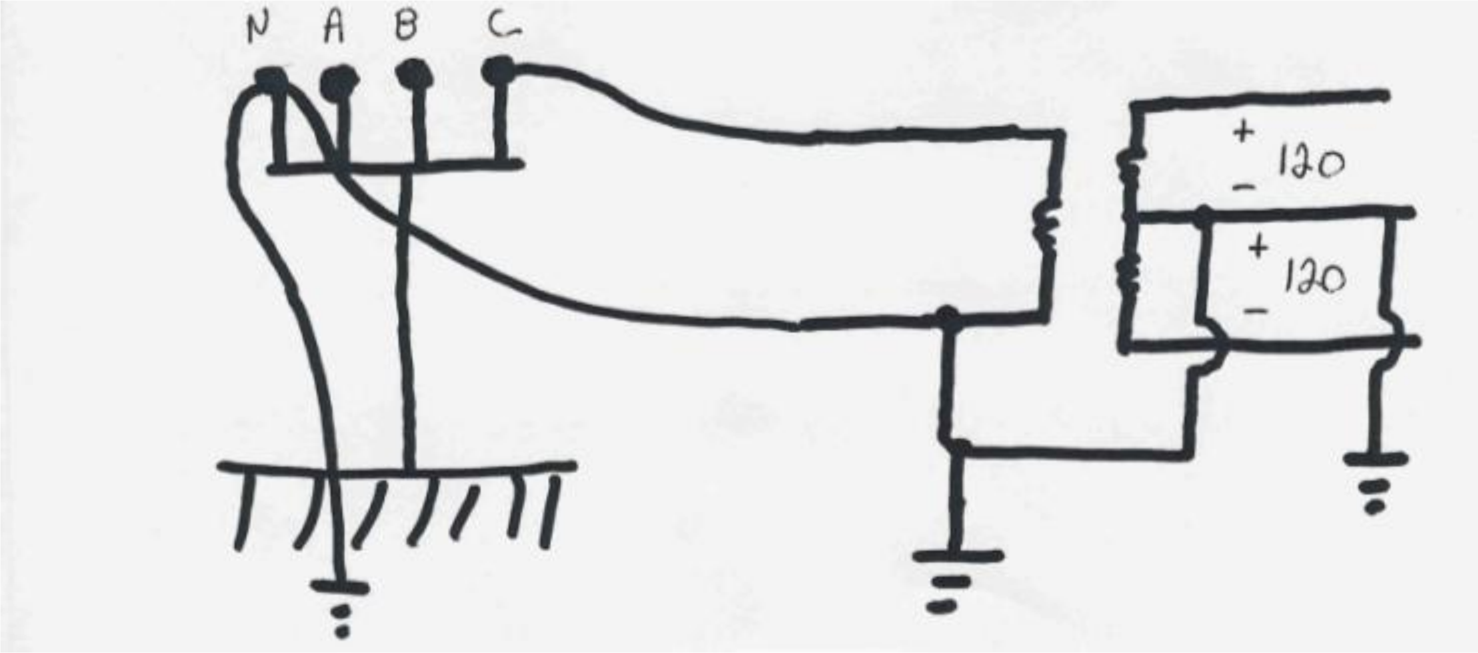
- Transformers provide an easily means for changing ac voltage levels
  - Power flow through transformers is bi-directional
- Heating is a major concern that can quickly lead to loss of transformer life (and occasionally explosions!)
- High voltage transformers (say 230 kV and up) are large, heavy, and difficult to replace

A 230/115 kV Transformer

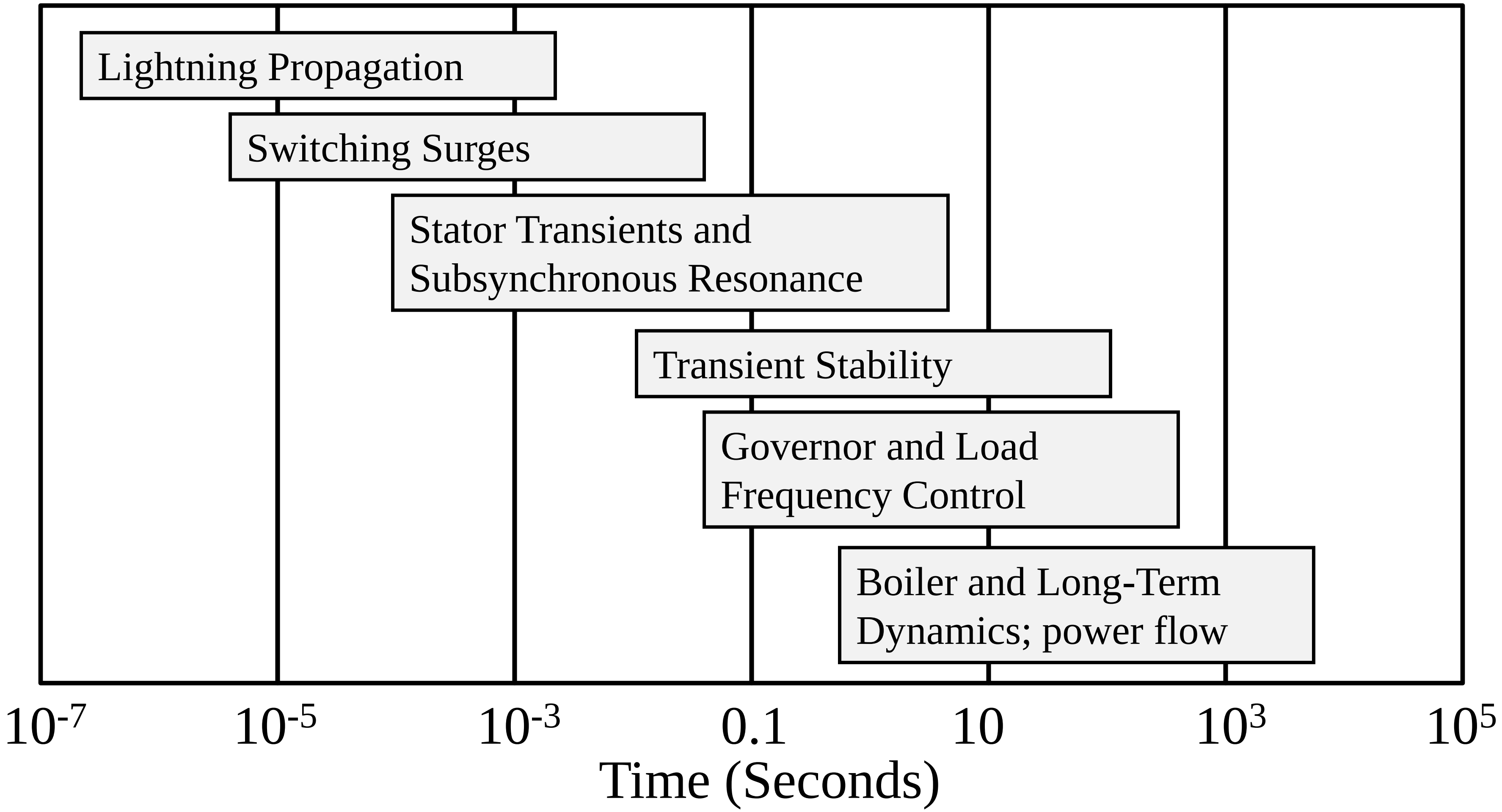


Residential Distribution Transformers

- Residential single phase electric service uses a center tapped transformer to provide 240/120 volt service; a separate ground is used for safety



Power System Time Frames



Power System Operations

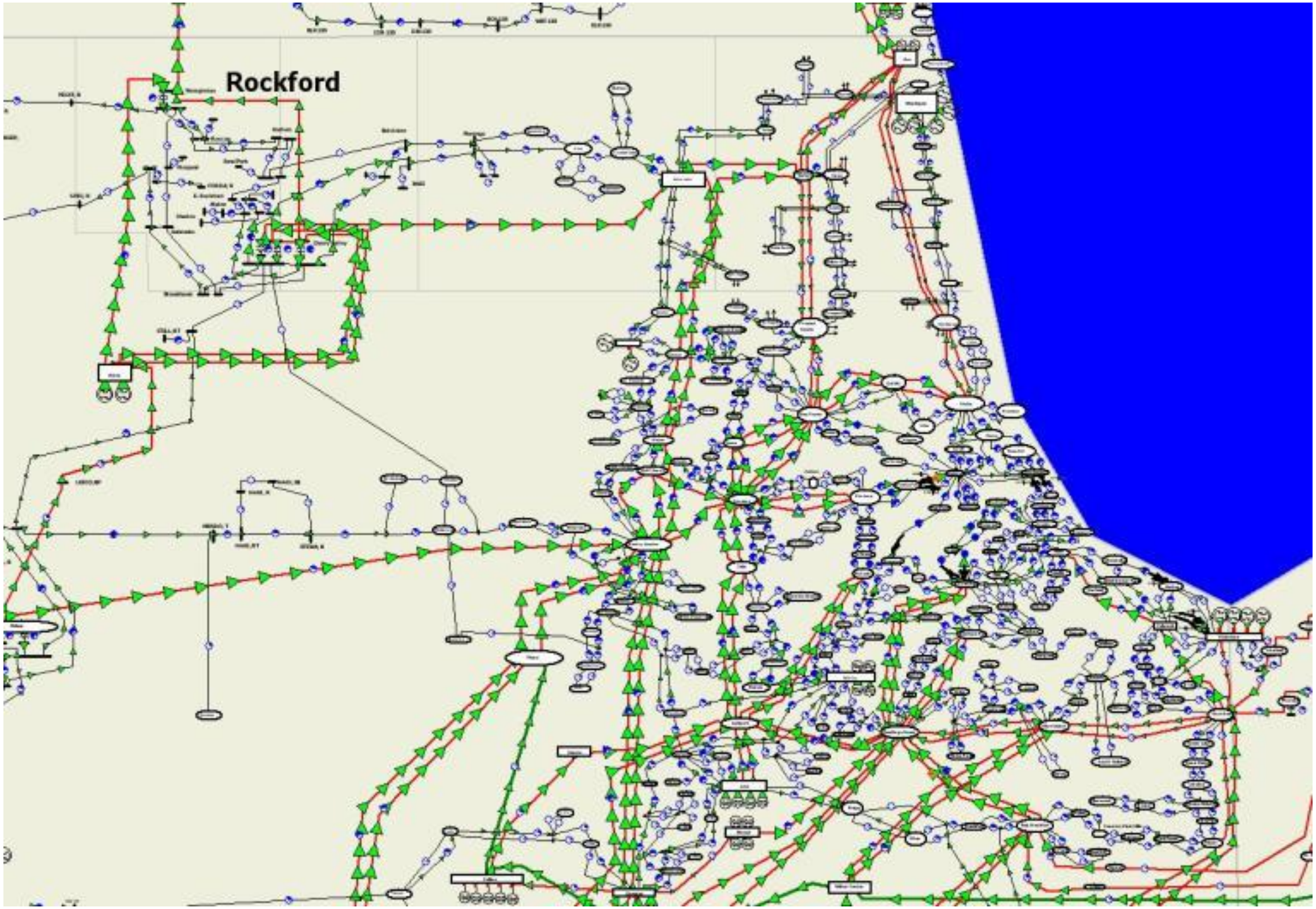
- The next several slides use a power system simulation package, PowerWorld Simulator, to demonstrate the operation of the electric grid over a time period of minutes to hours (quasi-steady state)

One-line Diagram

- 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.

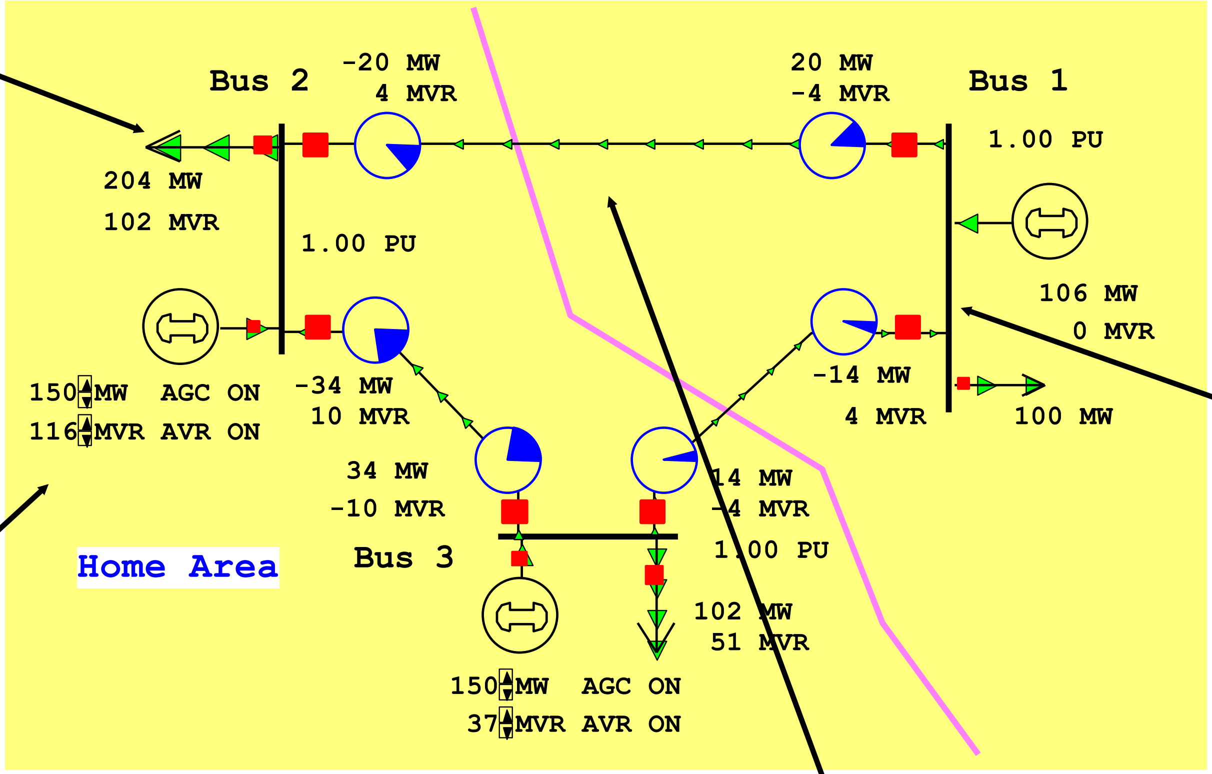
A Substation "Bus"

Metro Chicago Electric Grid



Example Three Bus Power System

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

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.

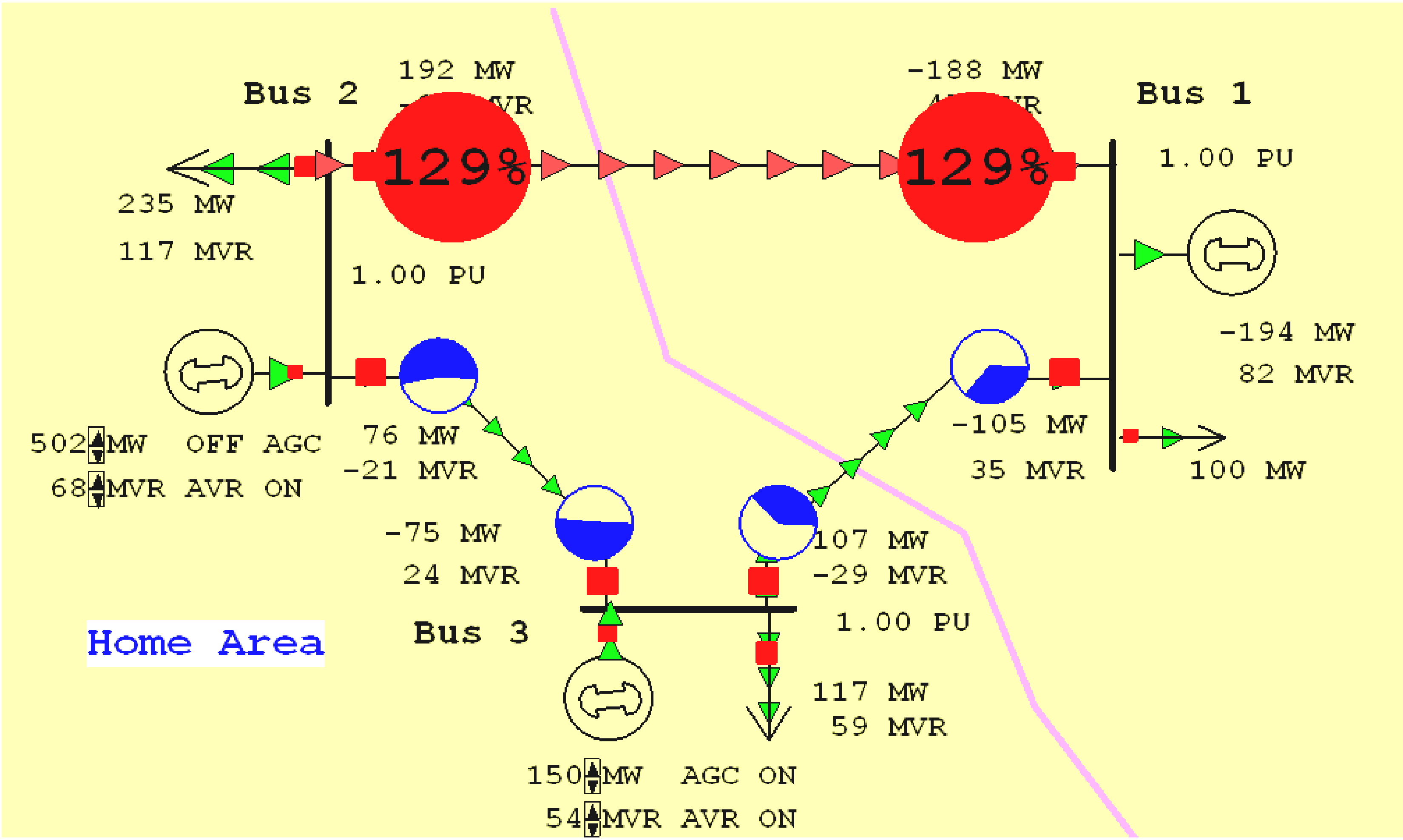
Basic Power Control

- 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 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).

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

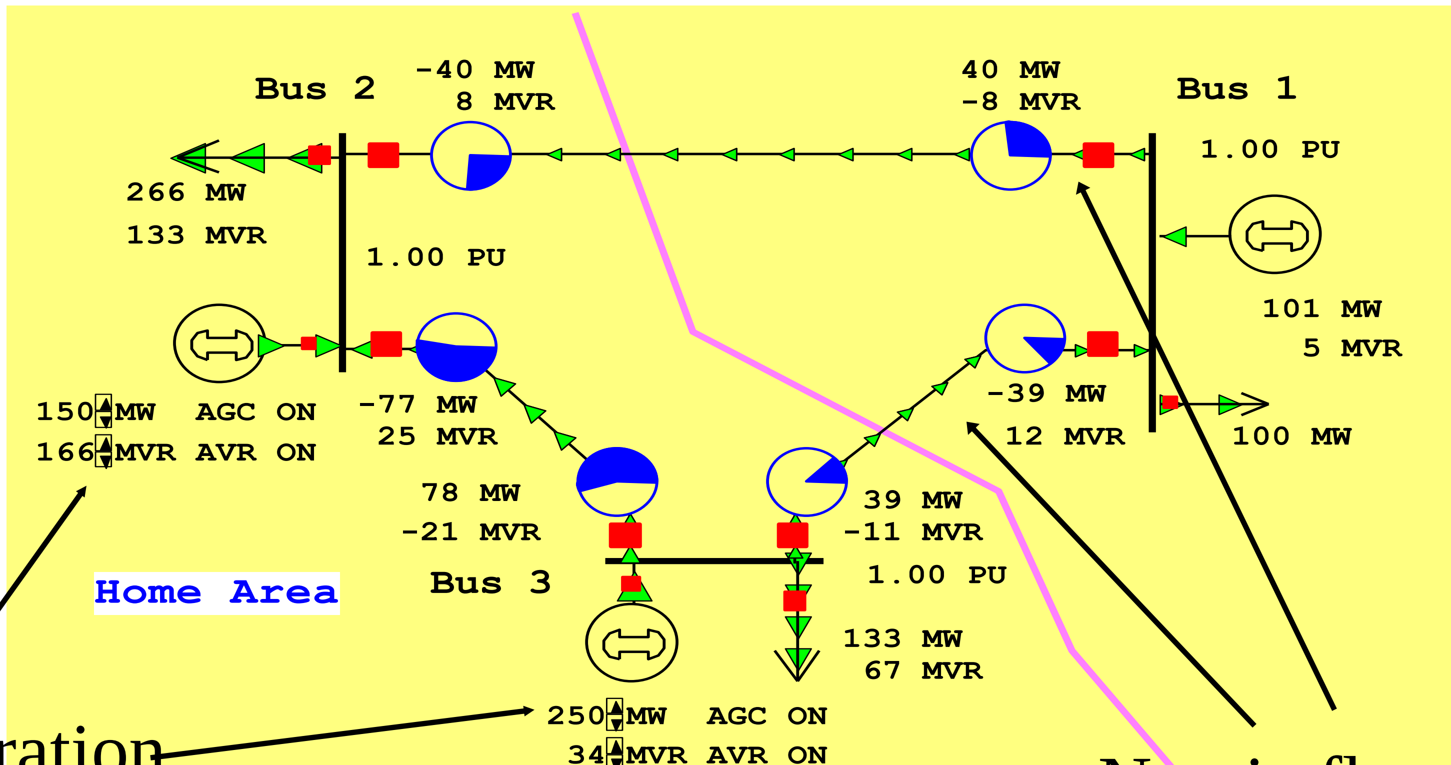
Area Control Error (ACE)

- 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

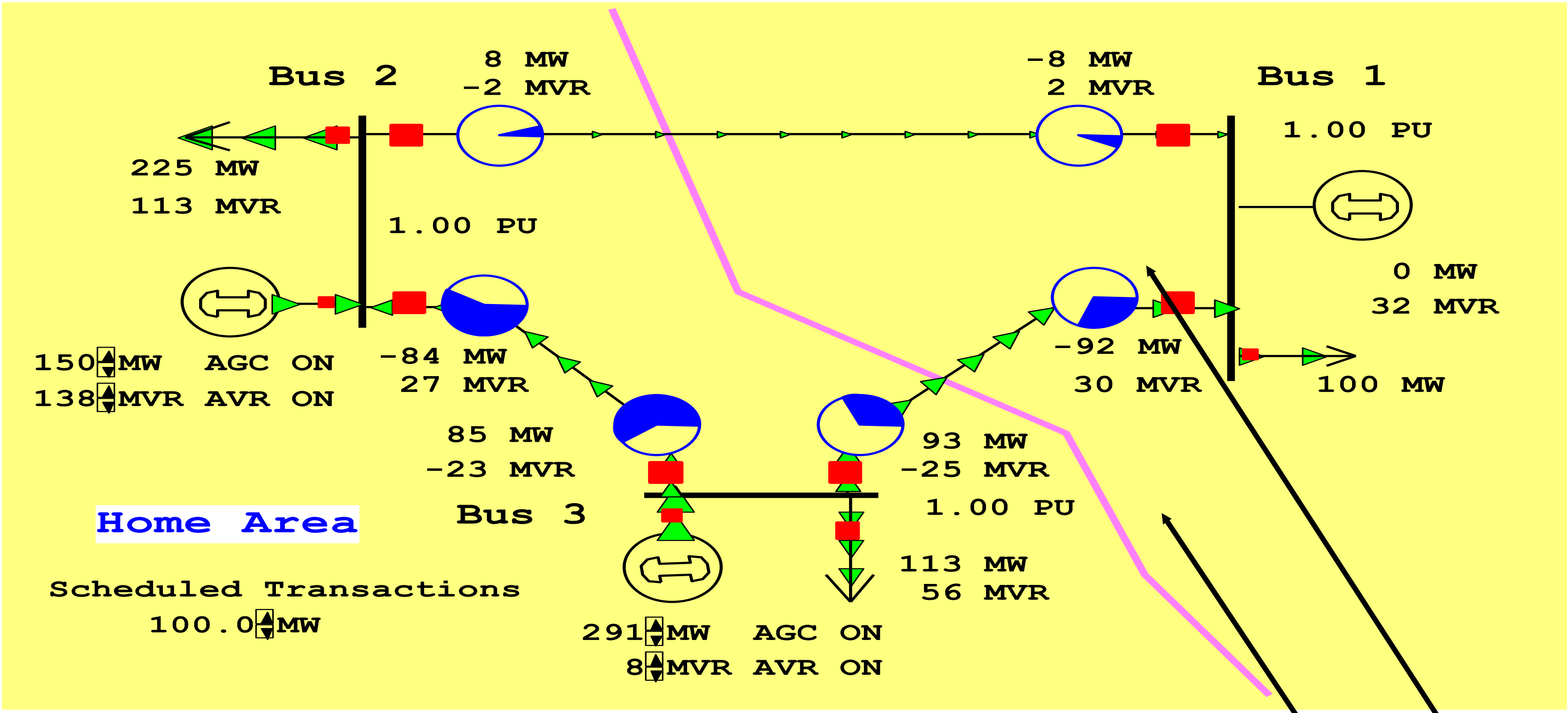
Net tie flow is close to zero

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

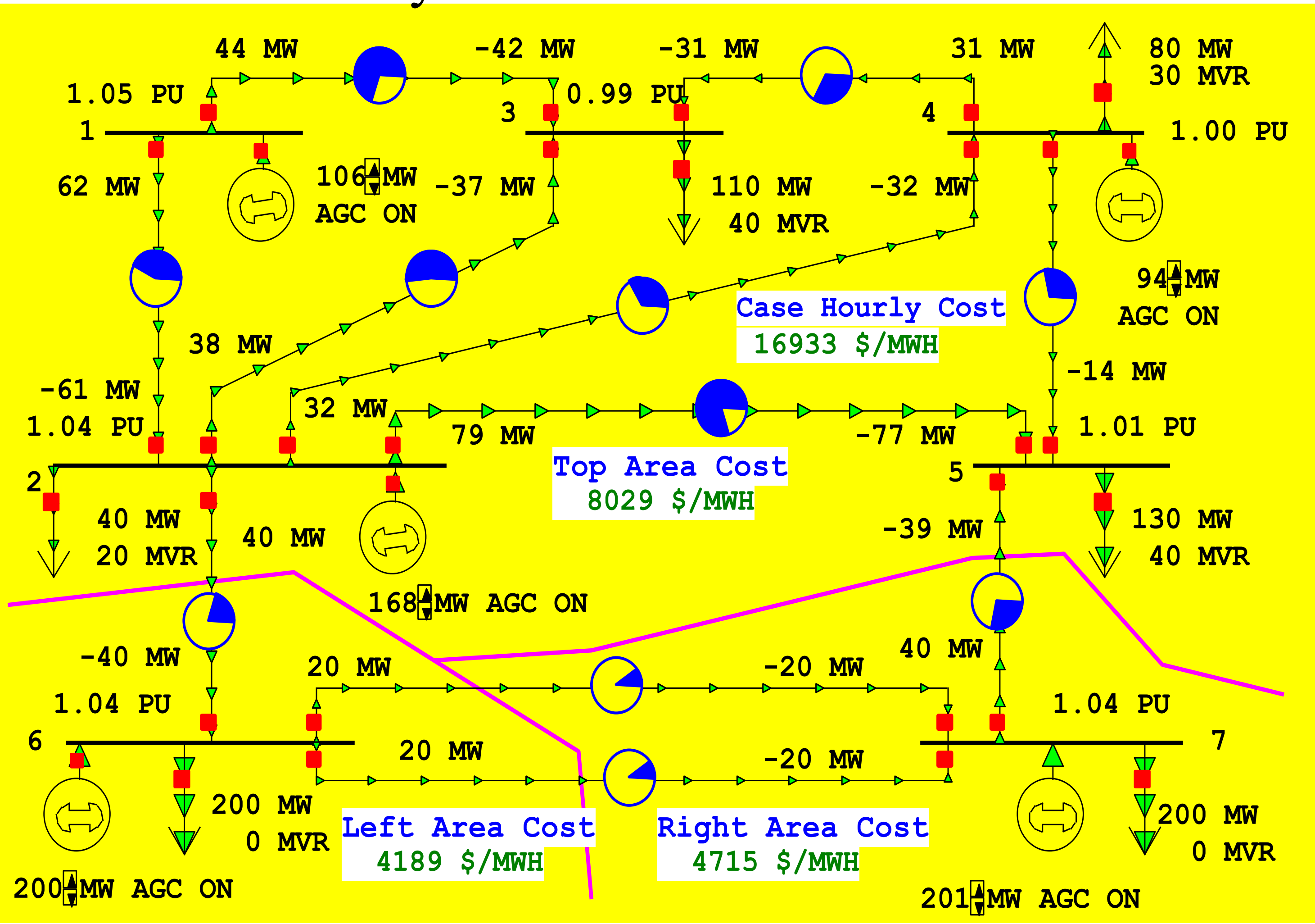
Net tie-line flow is now 100 MW

Multi-Area Operation

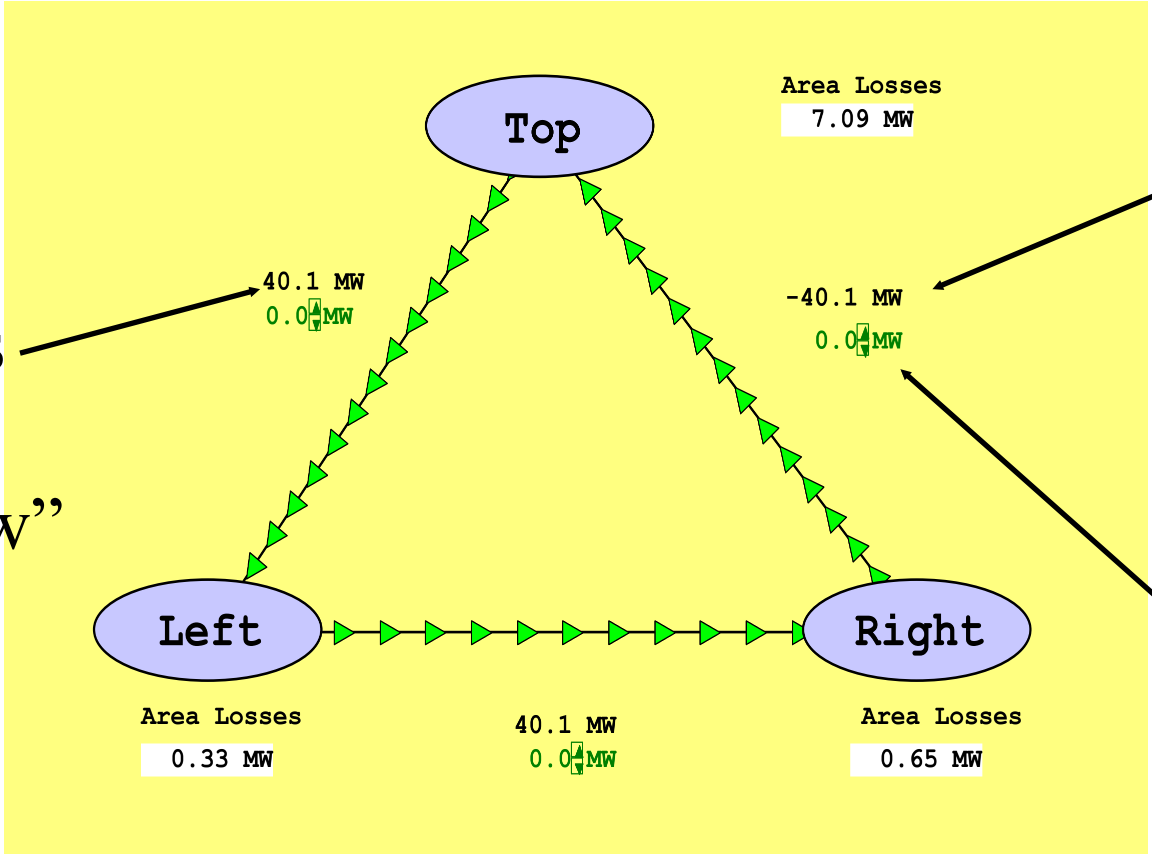
- If Areas have direct interconnections, then they may directly transact up to the capacity of their tie-lines.
- Actual power flows through the entire network according to the impedance of the transmission lines.
- Flow through other areas is known as “parallel path” or “loop flows.”

Seven Bus Case: One-line

System Has Three "Areas"



Seven Bus Case: Area View



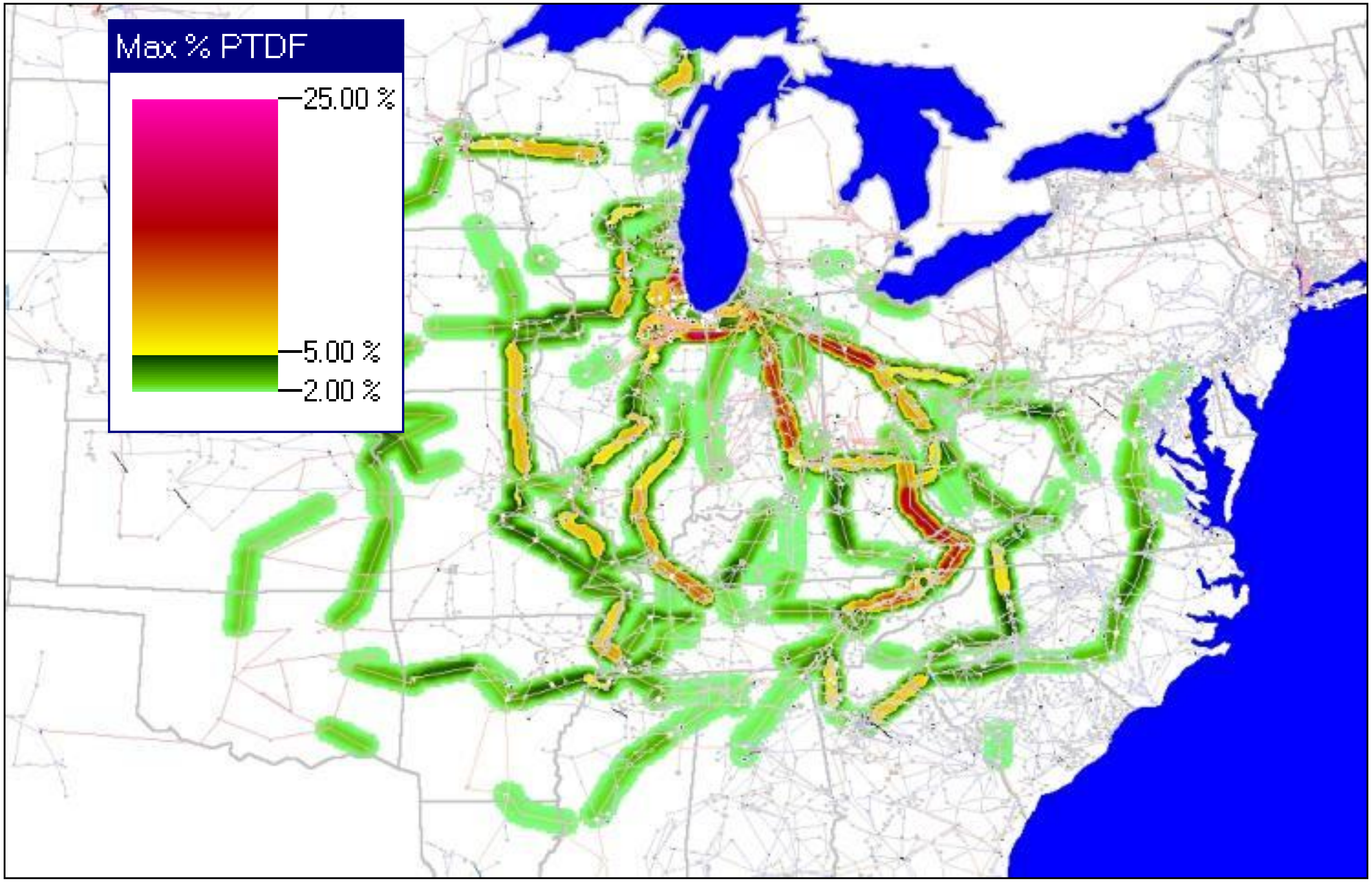
System has 40 MW of "Loop Flow"

Actual flow between areas

Scheduled flow

Loop flow can result in higher losses

Loop Flow in Eastern Interconnect



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

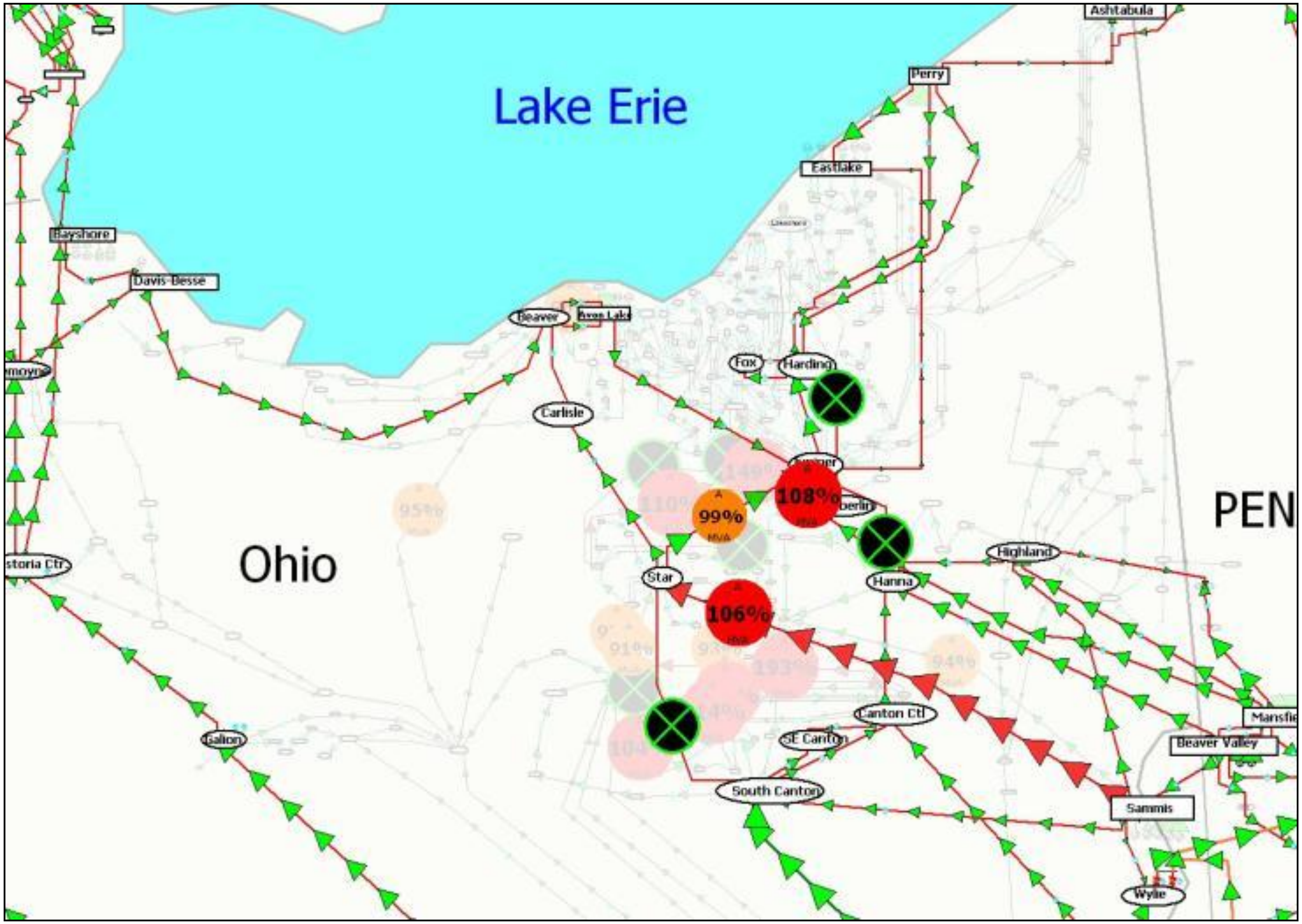
Reactive Power

- Reactive power is supplied by
  - generators, capacitors, transmission lines
- Reactive power is consumed by
  - loads
  - transmission lines/transformers (high losses)
- Reactive power 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.

How the Grid can Fail August 14th, 2003

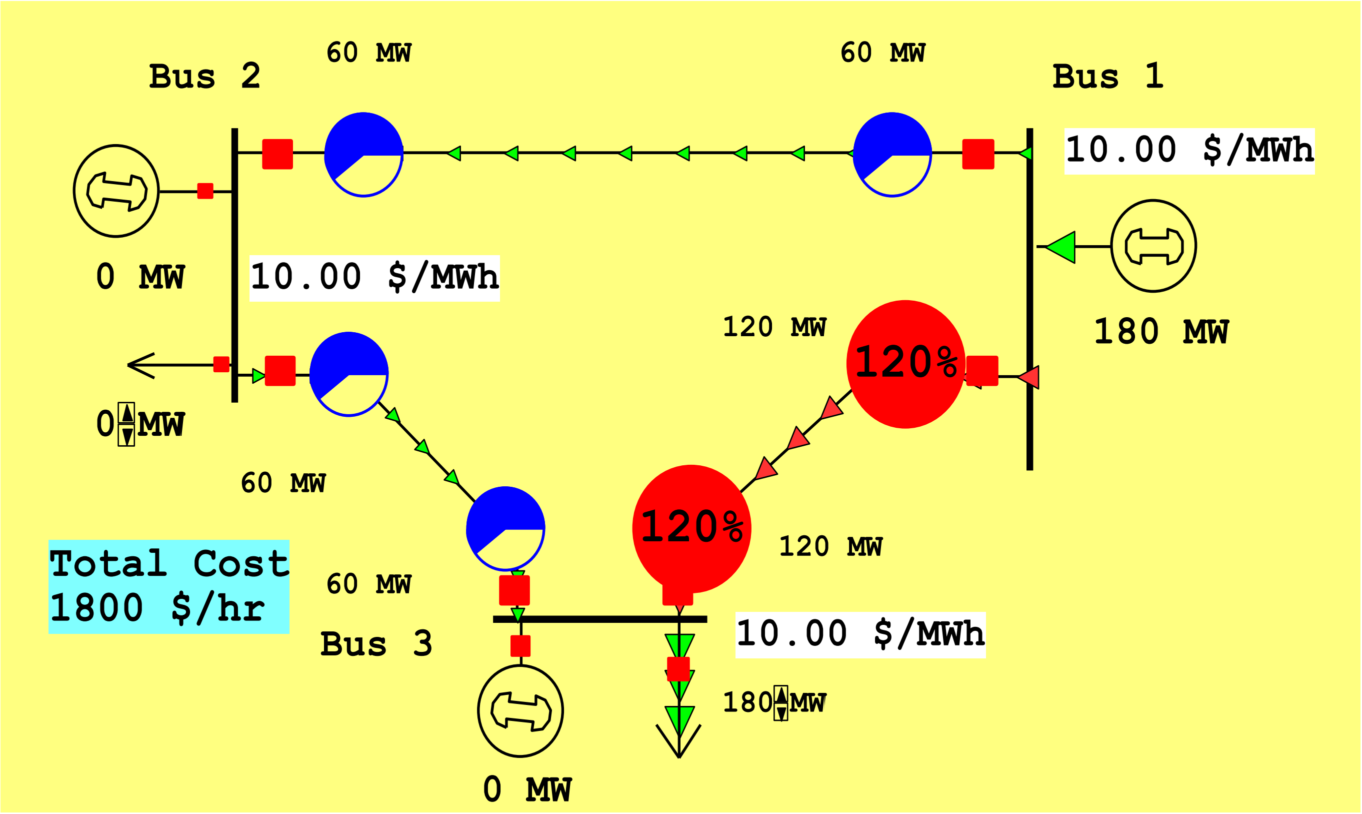


Pricing Electricity and LMPs

- Cost to supply electricity to bus is called the locational marginal price (LMP)
- Presently some electric markets 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 LMP Example: Constraint Ignored

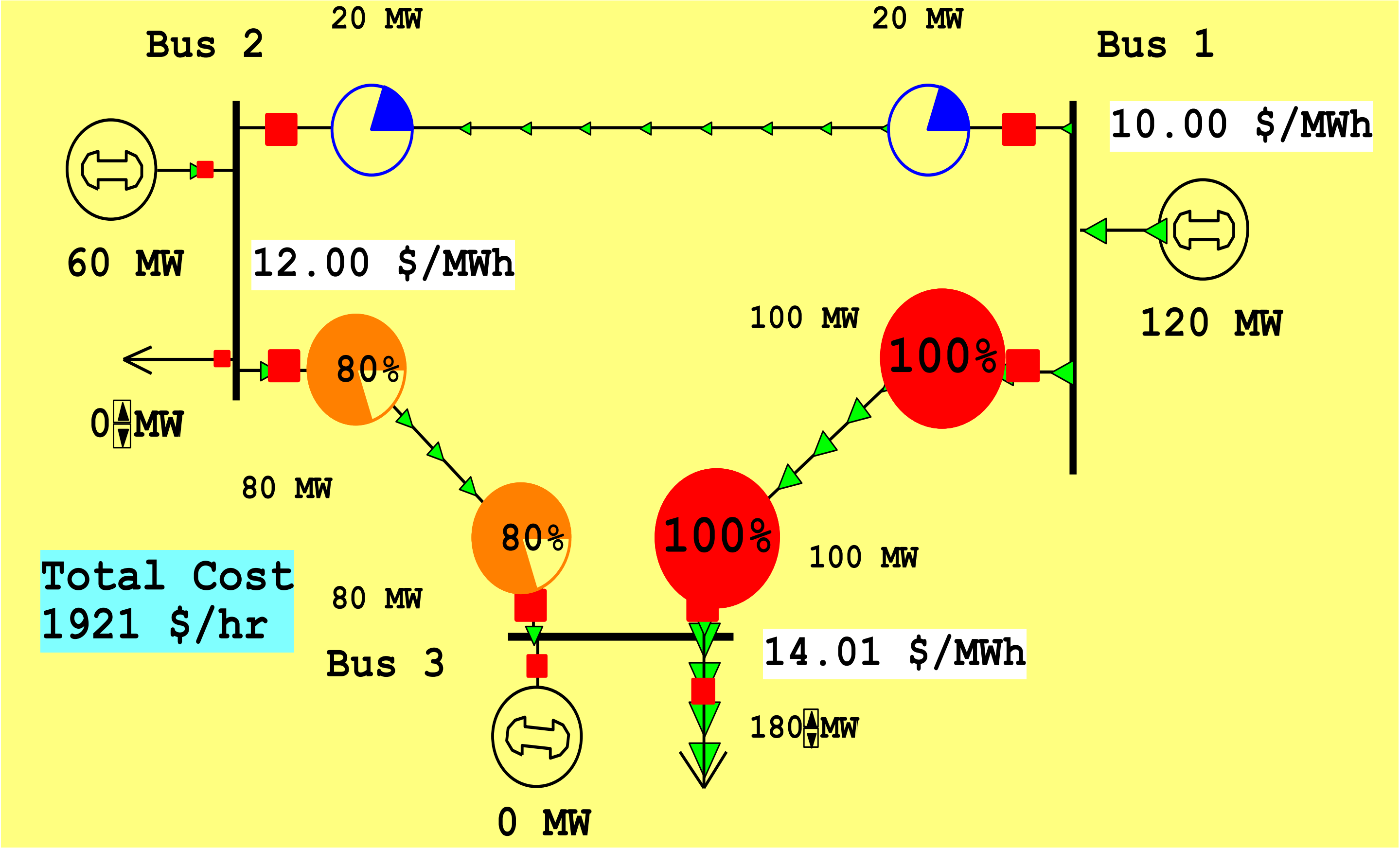
Gen 2's cost is $12 per MWh



Gen 1's cost is $10 per MWh

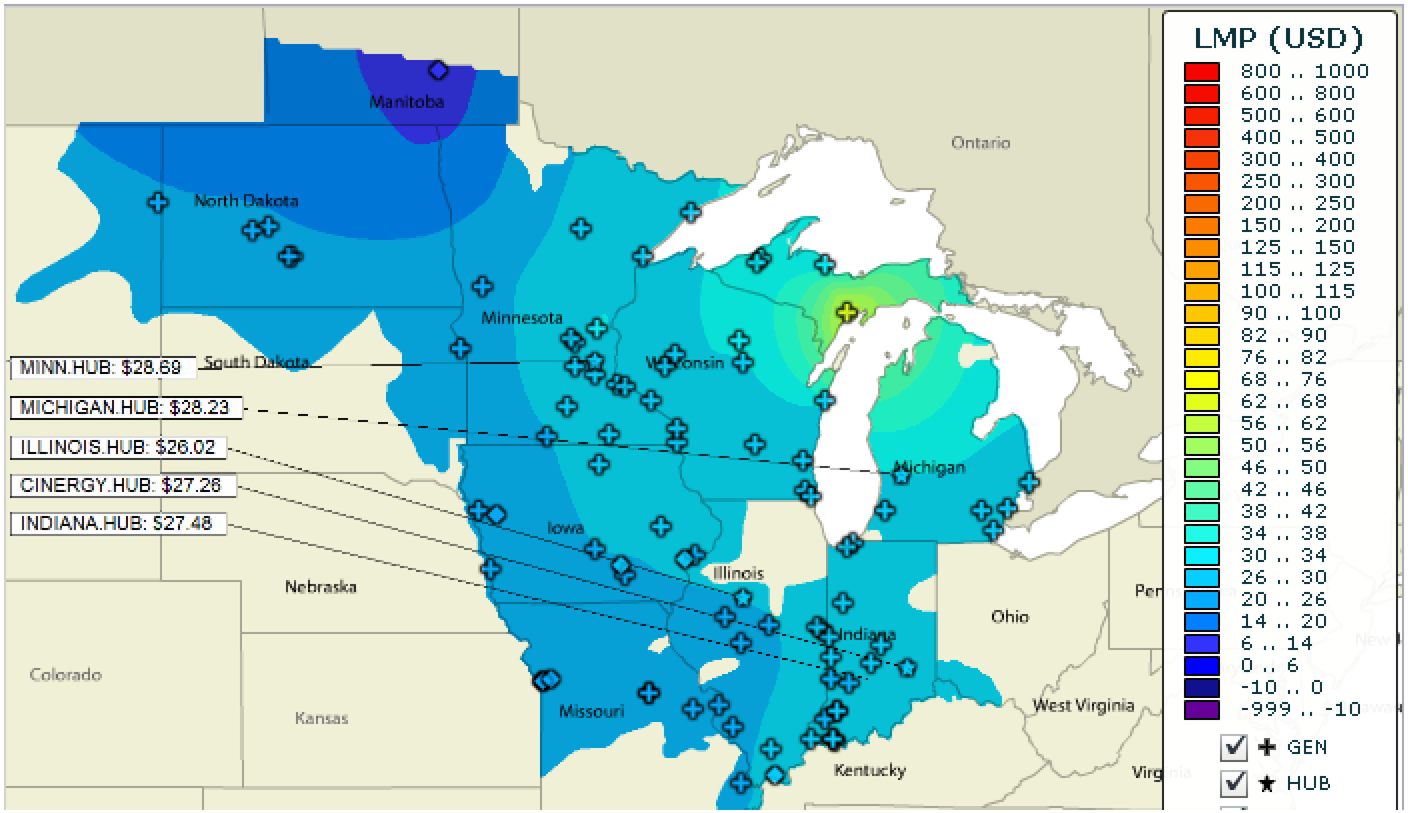
Line from Bus 1 to Bus 3 is over-loaded; all buses have same marginal cost

Three Bus LMP Example: Constraint Considered



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

MISO LMPS from 9/30/11 at 10:55am



Source:https://www.midwestiso.org/MarketsOperations/RealTimeMarketData/Pages/LMPContourMap.aspx

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

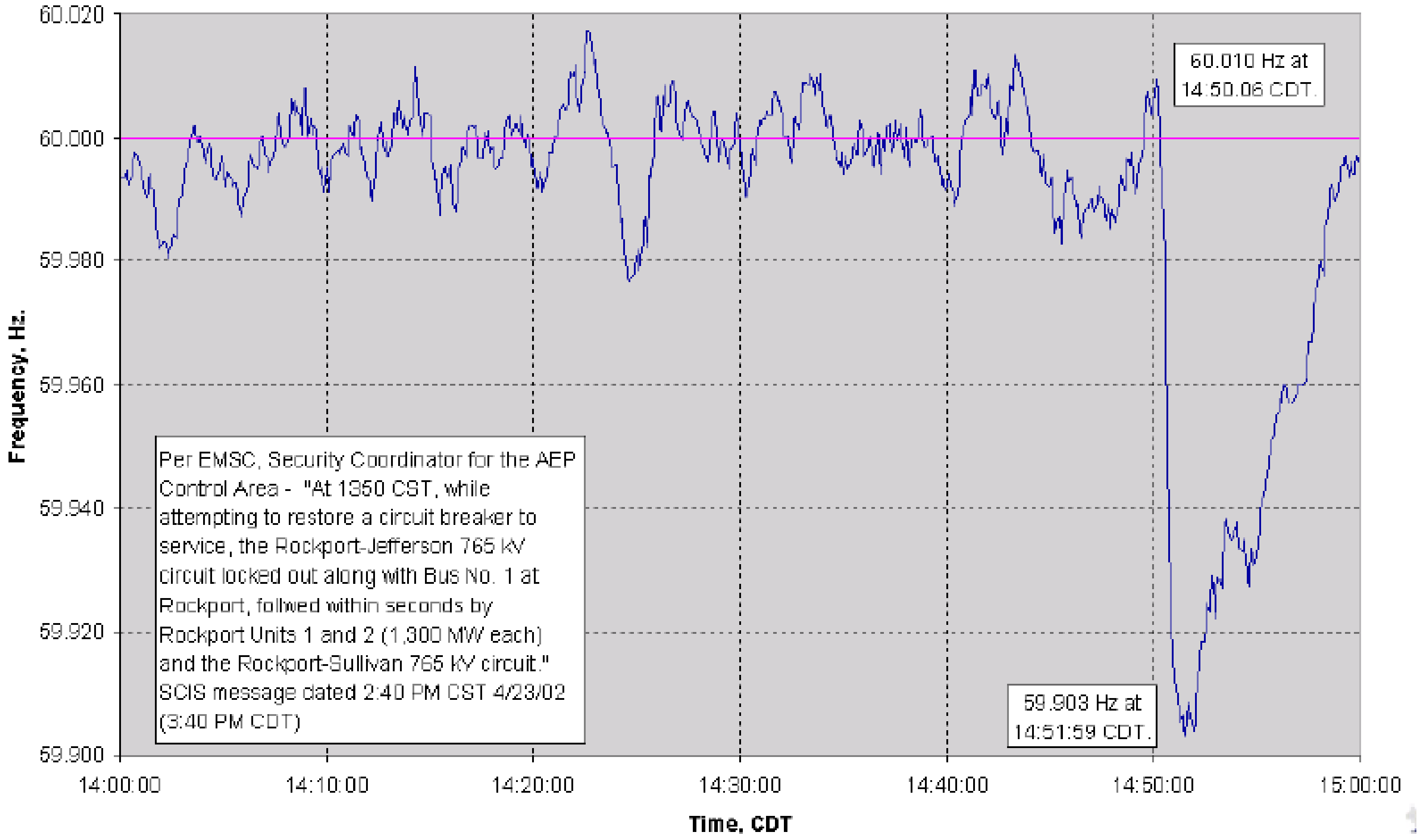
Power Grid Reliability

- Reliable operations requires
  - no transmission lines/transformers are overloaded
  - bus voltages are within limits
  - must be able to withstand loss of any single device
  - must not lose stability during a short-circuit
  - system frequency must be very close to 60 Hz (usually about 0.02 Hz)

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

Freq. Response to 2600 MW Loss



Power System Protection

- A number of different automatic devices are used to protect the power grid
  - several different types of relays sense short-circuits, opening the associated lines or transformers
  - under/over voltage relays protect against voltage problems
  - under/over frequency relays protect against frequency excursions (59.7 Hz or 60.3 Hz)

Power Systems are Adaptable

- The power grid can sustain a loss of several lines/generators without a major system-wide collapse (probably)
  - Northridge 1994 earthquake removed several major lines, splitting the Western Grid in half, and causing under-frequency load-shedding. But the grid remained intact
- Most vulnerable when the loads are highest

Power System Vulnerabilities

- Power system operations have evolved to deal with a number of different problems
  - weather including lightning, wind, tornados, hurricanes and icing
  - earthquakes
  - equipment failures
  - random acts of violence

Utility Control Centers

- The power grid is controlled by local control centers, using a SCADA (supervisory control and data acquisition) system and usually a more advanced EMS (energy management system)
- The grid can operate open-loop, and in an emergency can be manually controlled
- Cyber-security is an important issue as more controls are network accessible

ISO New England Control Center

Questions?