ECEN 460, Spring 2026
Power System Operation and Control

Class 2: Power System Structure and History

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Reminders

- Review these topics
  - Complex number math – by hand and calculator
  - Phasors – representing AC voltage and current
  - Impedance – for AC circuit solving
  - Complex power – including power factor, reactive power
  - Three phase – wye/delta, line-to-line/line-to-neutral voltage, per-phase analysis
- Homework #1 and #2 are practice problems on these topics
  - Homework #1 due next Tuesday (Jan 20) and Homework #2 due Tuesday Jan 27
- Take advantage of the textbook, and office hours (me and TAs)
- We’re going to have quizzes most classes to review

Energy and Power

- Energy is *A property of matter that quantifies its ability to perform useful work*.
  - Forms: kinetic, gravitational, heat, light, sound, magnetic, nuclear, chemical, and electric
  - Units for energy: 1 MWh = 1000 kWh
    1 kWh = 3.6 million Joules = 3412.14 Btu
- Power is *Energy on the move from form to form or place to place*.
  - Time derivative of energy as it is transferred
  - Units for power: Watt (Volt-Ampere)
    kW = 1000 W, MW, GW, 1 Hp = 746 Watts

One gallon of gasoline has about 0.125 MBtu (36.5 kWh) of energy stored in chemical form

U.S. annual electric energy consumption is about 3600 billion kWh

> This is about 13,333 kWh per person, which means on average we each use 1.5 kW of power continuously

Installed U.S. generation capacity is about 1000 GW (about 3 kW per person)

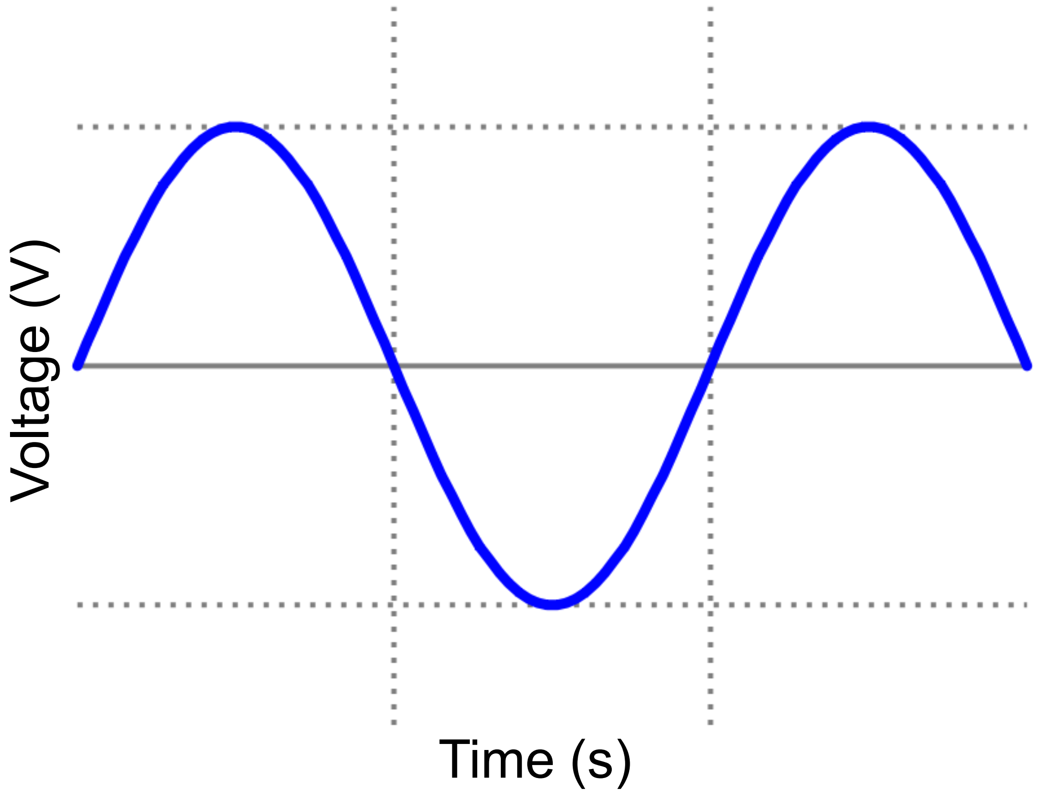
Maximum load of Bryan/College Station is about 500 MW

Electric Power Systems

- Electricity has many advantages for delivering the energy used by humankind
  - Conversion to and from other forms is convenient and efficient (such as motors and generators)
  - Transmission in bulk can be done quickly and efficiently over long distances (power lines)
  - About 40% of U.S. energy consumption is electric
- Power systems range in size
  - Large: four major interconnections in North America
  - Medium: islands, militarily installations, ships
  - Small: airplanes, automobiles, portable battery systems

Alternating Current Power Systems

- Alternating current (ac) systems have sinusoidal voltage and current wave forms, as opposed to direct current (dc)
- Small, battery-based systems such as automobiles are typically dc, and historically some larger systems have used dc
- Ac is nearly exclusively used now for medium and large power system
  - Better performance of motors and generators
  - Allows use of transformers to step-up voltage for efficient long-distance transmission



Choosing the AC Frequency

- Lower frequency systems (10-40 Hz) require larger motors and transformers and can introduce flicker in some lighting technologies.
  - These historically were used some for railroads
- Higher frequency systems (100 Hz – 1 kHz) have higher voltage drops over long distances and can introduce more audible noise
  - 400 Hz is common in airplanes and spaceships, where weight is a primary consideration
- Today, most large power systems use 50 or 60 Hz (60 Hz is used in the USA)

60 Hz

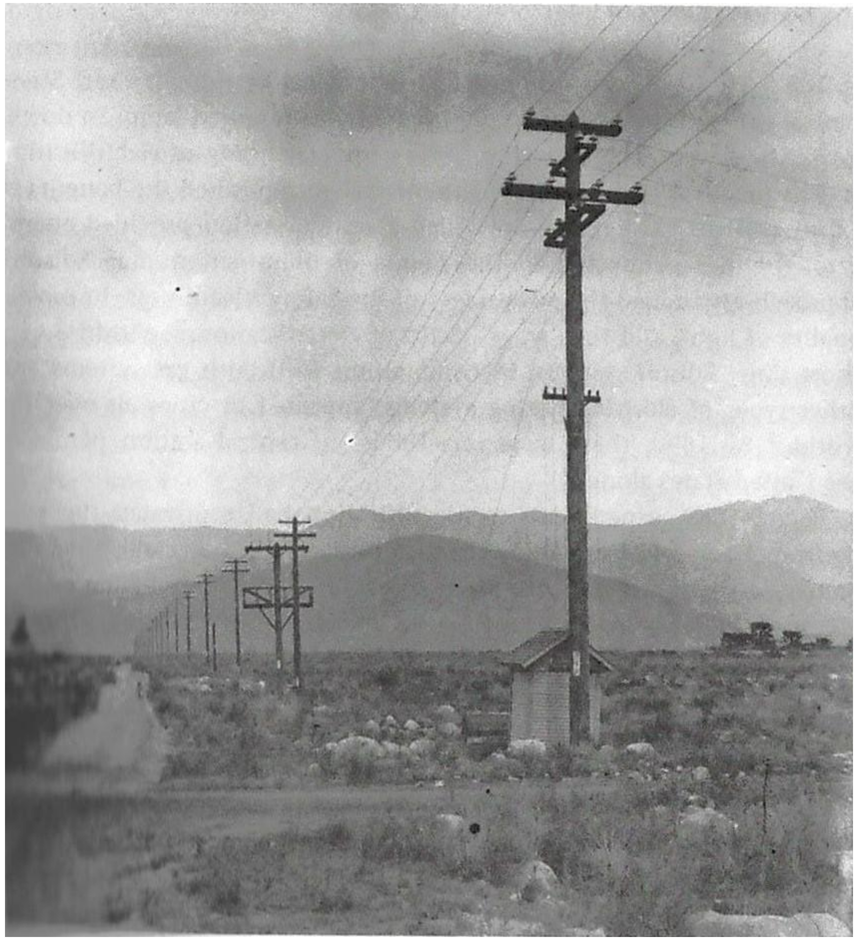
North America, about half of South America, half of Japan, a few other countries

50 Hz

Europe, most of Africa and Asia, part of South America

The Far Past: Origins of the Electric Grid

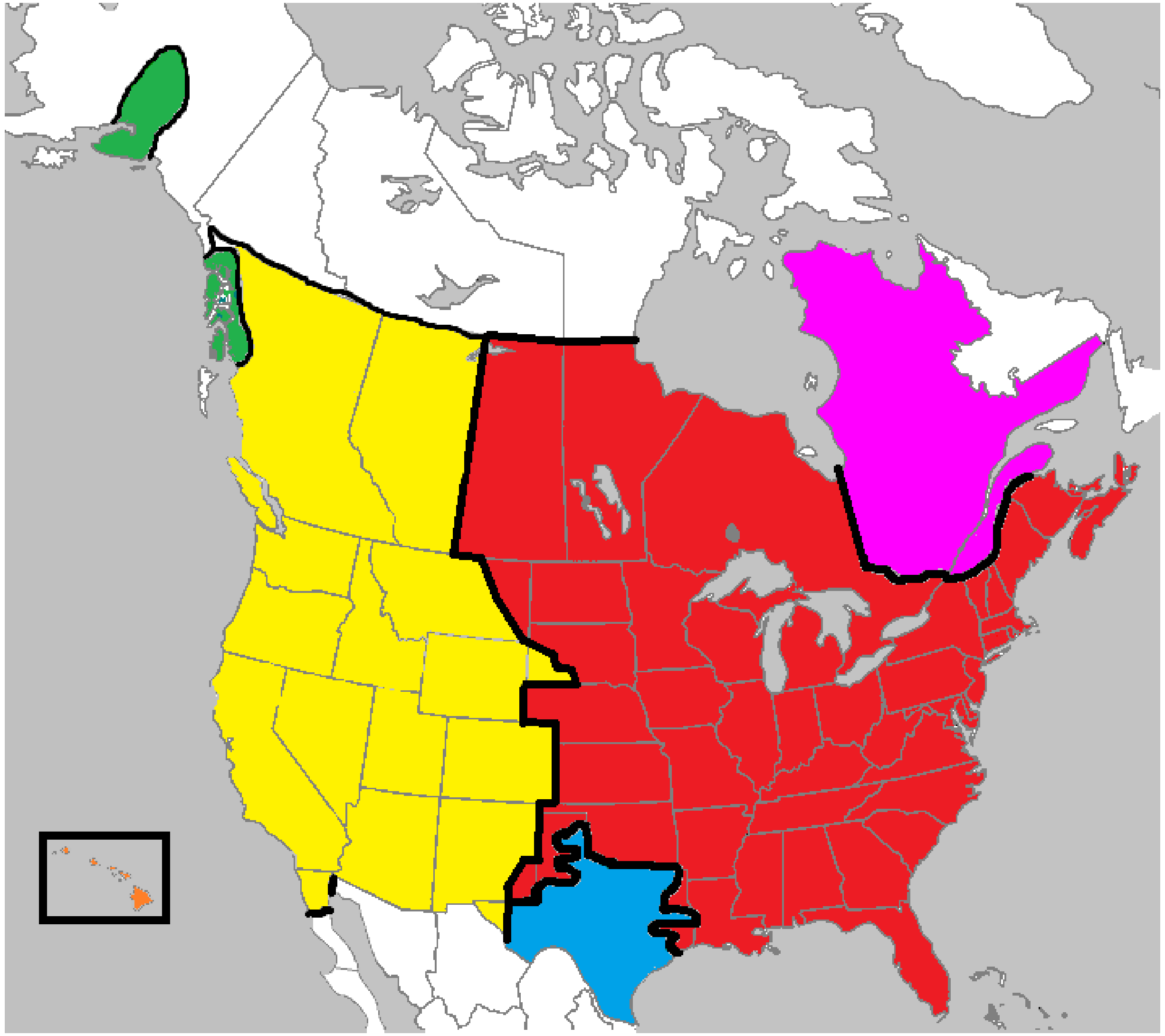
- First practical use of electricity 1860s-70s, mainly telegraph and lighting
- 1880s – Edison dc system in Manhattan, Westinghouse/Tesla ac system, invention of practical motors and transformers
- 1890s-1920s – Local three-phase ac systems (mainly coal and hydro) develop and expand to become large interstate holding companies
- 1930s-40s – Industry standardizes on 60 Hz ac (in the US), load growth with air conditioning, rural electrification and big hydro projects with the New Deal
- 1950s-60s – Interconnection into major grids



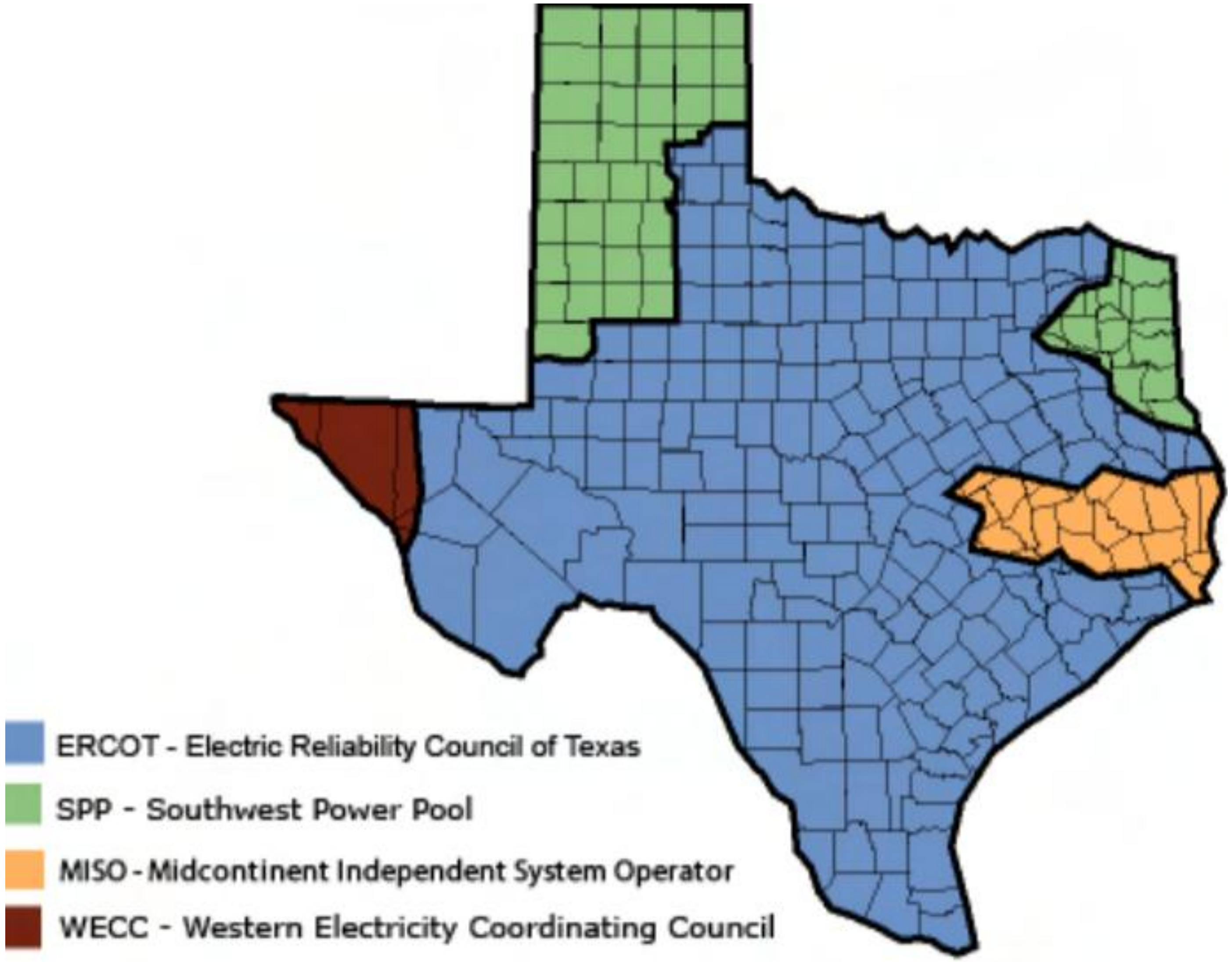
Santa Ana River 33 kV Line, circa 1899. This was the longest power line in the world at the time at 83 miles. (SCE Photograph, from *The Grid* by Julie Cohn)

Major Grids in North America

- Eastern Interconnect (EI)
- Western Interconnect (WECC)
  - EI and WECC were briefly interconnected in the 1970s
- Texas Interconnect (ERCOT)
  - Connected to East and Mexico with small AC-DC-AC interties
- Quebec Interconnect
- Smaller "island" grids in various places like Alaska and Hawaii



The Three US Grids are All in Texas

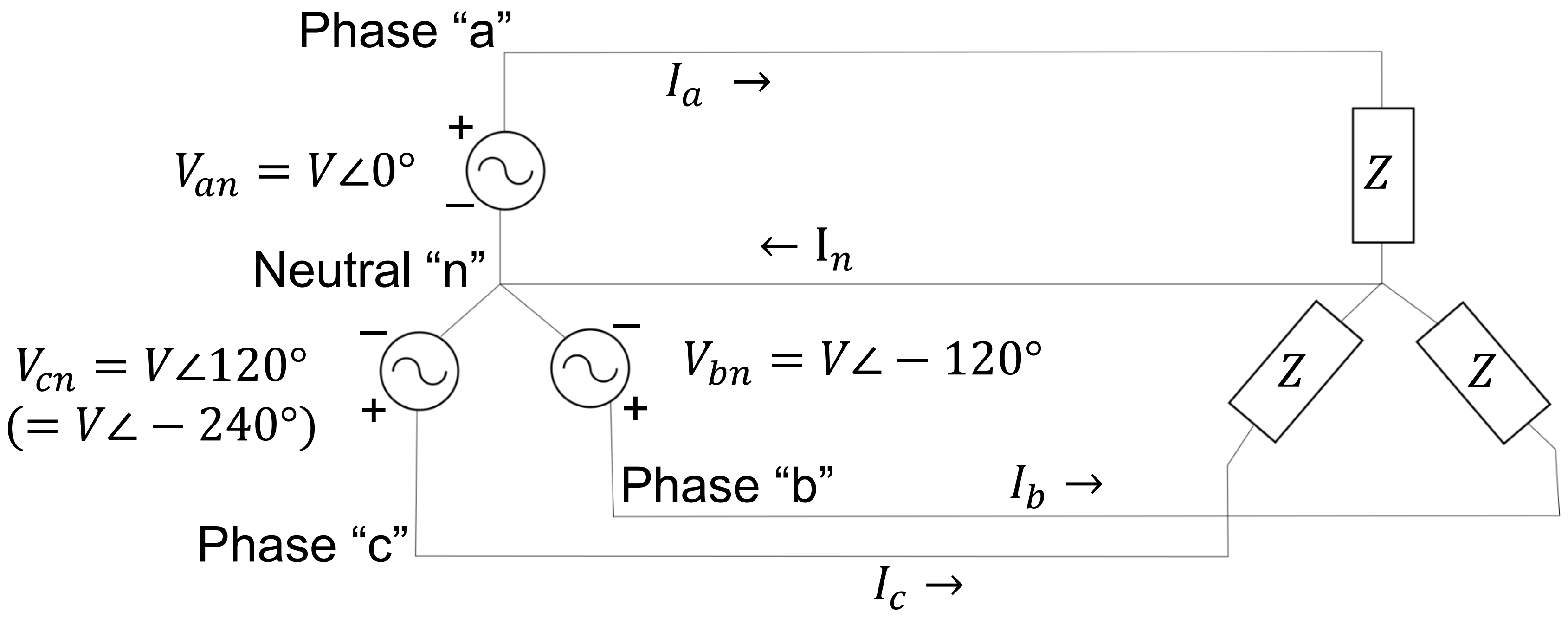


Source: www.puc.texas.gov/industry/maps/maps/ERCOT.pdf

Balanced Three-Phase (ϕ) Systems

- A balanced three-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
- 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

Balanced 3ϕ -- No Neutral Current



$$I_n = I_a + I_b + I_c$$

$$I_n = \frac{V}{Z}(1\angle 0° + 1\angle -120° + 1\angle 120°) = 0$$

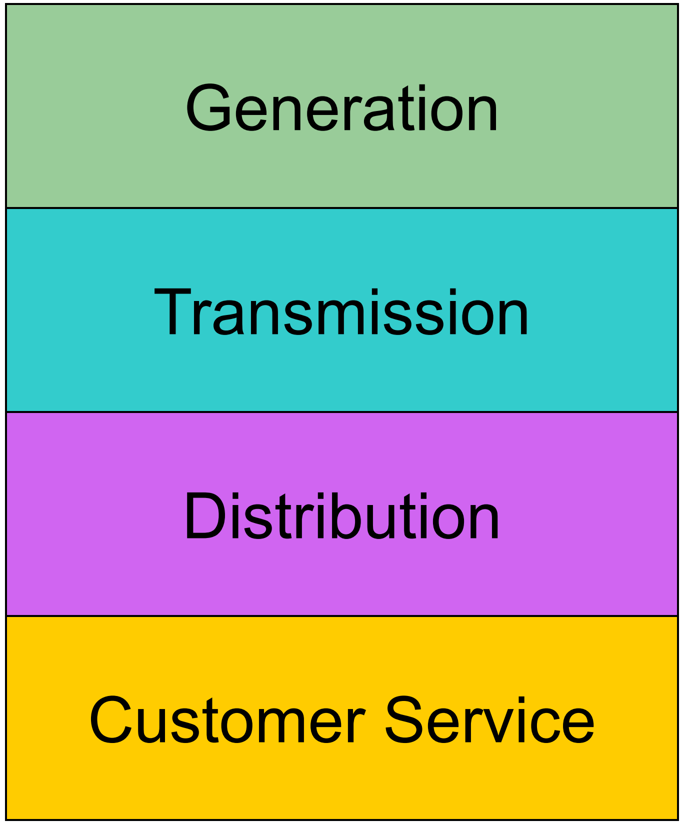
$$S = V_{an}I_{an}^* + V_{bn}I_{bn}^* + V_{cn}I_{cn}^* = 3V_{an}I_{an}^*$$

Advantages of 3ϕ Power

- 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 same power rating
- Three-phase machines start more easily than single-phase machines

Vertical Monopolies

- Within a particular geographic market, the electric utility had an exclusive franchise



In return for this exclusive franchise, the utility had the obligation to serve all existing and future customers at rates determined jointly by utility and regulators

It was a "cost plus" business

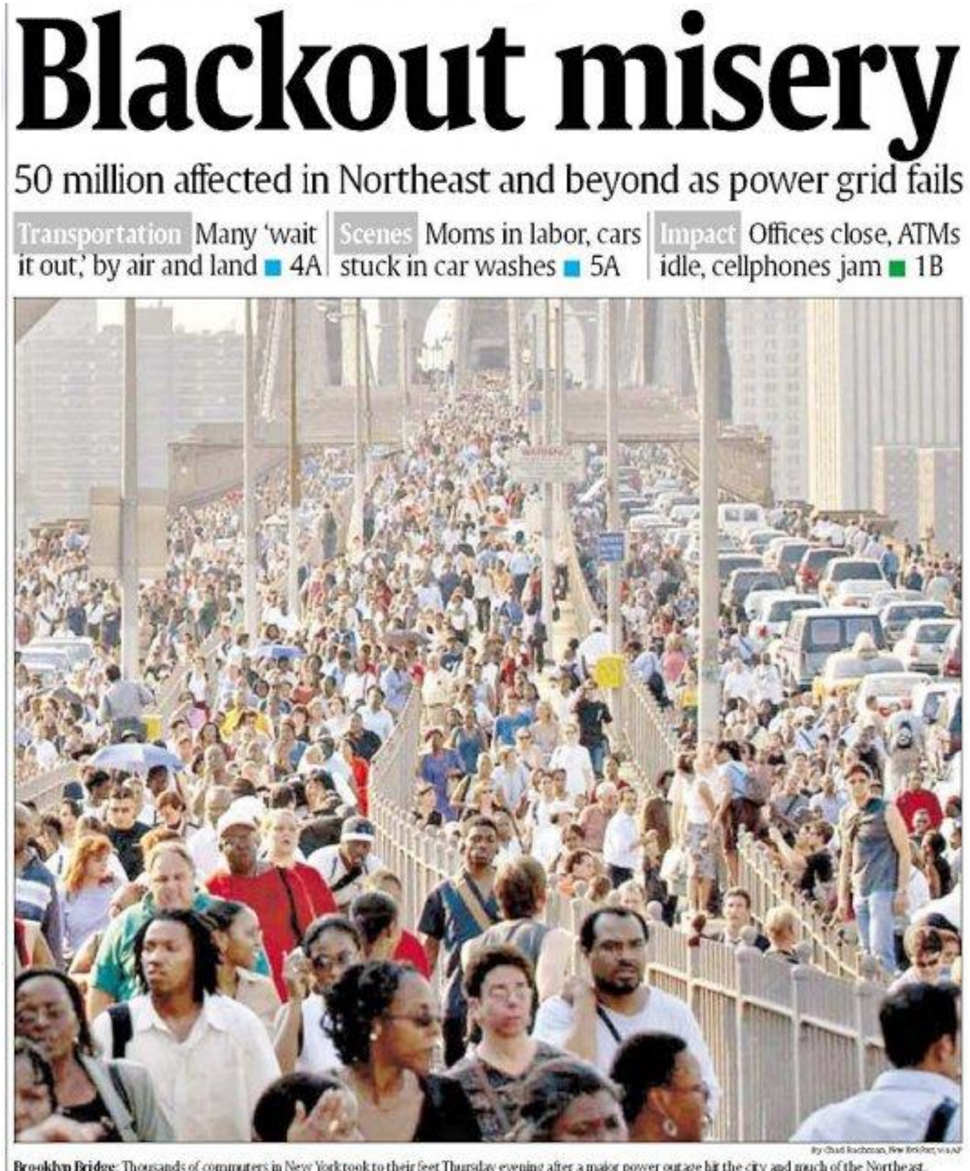
Vertical Monopolies, 2

- Within its service territory each utility was the only game in town
- Neighboring utilities functioned more as colleagues than competitors
- Utilities gradually interconnected their systems so by 1970 transmission lines crisscrossed North America, with voltages up to 765 kV
- Economies of scale keep resulted in decreasing rates, so most every one was happy

The More Recent Past – Restructuring

- 1970’s brought inflation, increased fossil-fuel prices, calls for conservation and growing environmental concerns
- Increasing rates replaced decreasing ones
- As a result, U.S. Congress passed Public Utilities Regulator Policies Act (PURPA) in 1978, which mandated utilities must purchase power from independent generators located in their service territory (modified 2005)
- Major opening of industry to competition occurred as a result of National Energy Policy Act of 1992, mandating that utilities provide “nondiscriminatory” access to the high voltage transmission
- Result over the last few years has been a dramatic restructuring of electric utility industry
- Energy Bill 2005 repealed PUHCA; modified PURPA

August 14th, 2003 Blackout



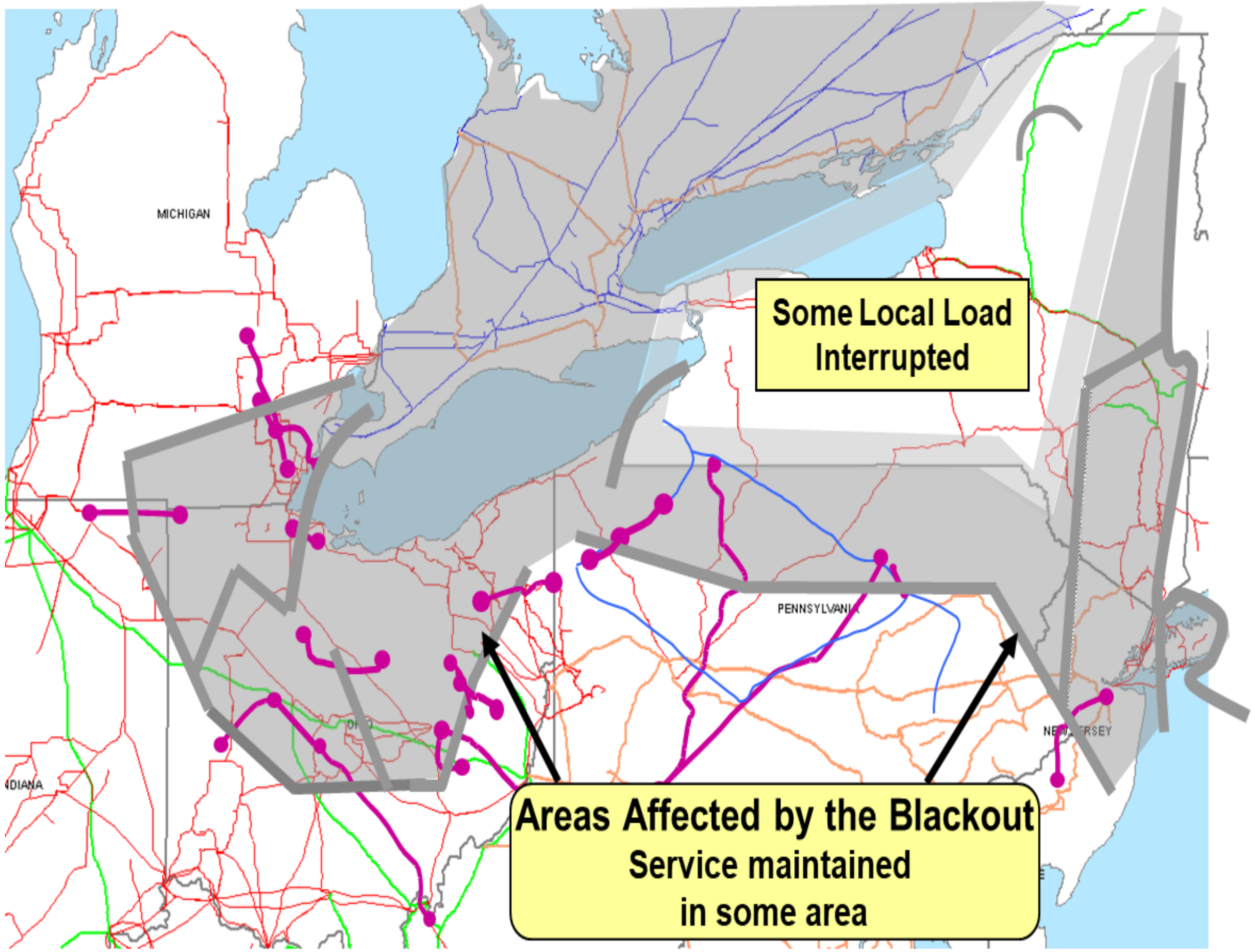
Blackout misery

50 million affected in Northeast and beyond as power grid fails

Transportation Many 'wait it out,' by air and land ■ 4A | **Scenes** Moms in labor, cars stuck in car washes ■ 5A | **Impact** Offices close, ATMs idle, cellphones jam ■ 1B

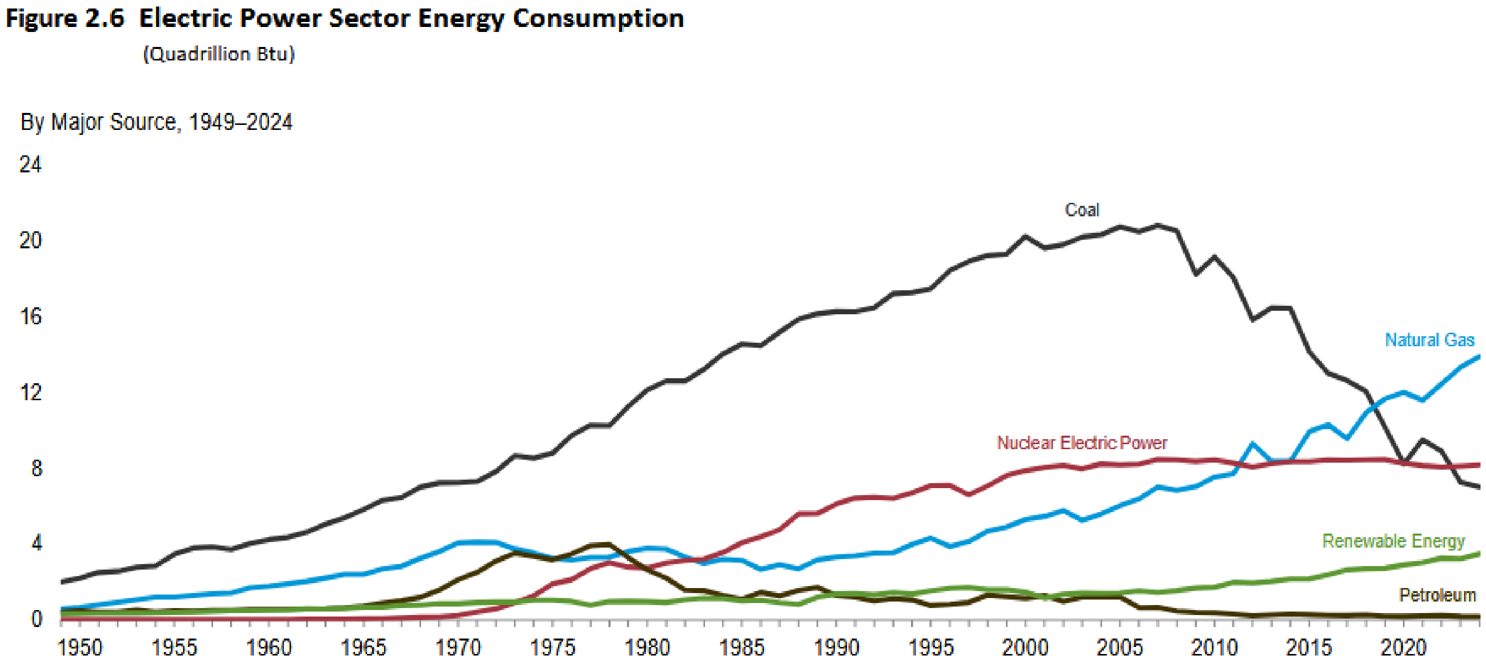
By Chad Rachman, New York Post, via AP

Brooklyn Bridge: Thousands of commuters in New York took to their feet Thursday evening after a major power outage hit the city and much of the Northeast.



Above image from energy.gov, August 14, 2003 Blackout Final Report

The Present: Changing Generation Mix

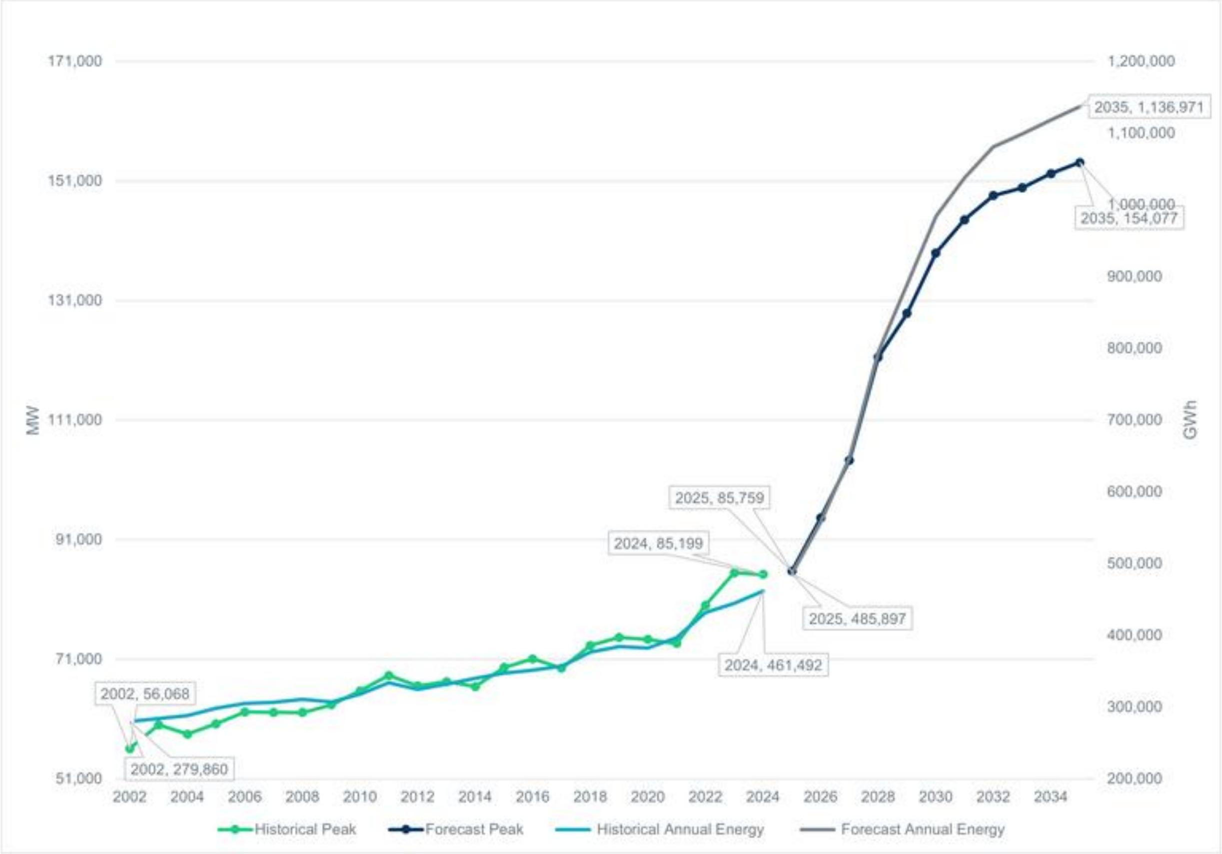


Fuel Source	2024 US Electric Usage	Change from 2023 to 2024	Change from 2014 to 2024
Coal	21.4 %	- 3 %	- 57 %
Natural Gas	42.5 %	+ 4 %	+ 66 %
Petroleum	0.5 %	- 6 %	- 44 %
Nuclear	25.0 %	+ 1 %	- 2 %
Hydro	2.5 %	- 1 %	- 6 %
Solar	2.3 %	+ 33 %	+ 1164 %
Wind	4.7 %	+ 7 %	+ 149 %

Source: US EIA Monthly Energy Review, December 2025

The Present: Changing Generation Mix, 2

- Texas is #1 in wind energy, with over 42,000 MW installed
- Retirements in Texas from 2014-2024 included 7411 MW of coal, 5950 MW of natural gas, and small amounts of others
- Generation listed as "proposed" for 2025-2030 includes 7120 MW natural gas, 5812 MW wind, 43,704 MW solar, plus 32,244 MW batteries



Source: US EIA Monthly Energy Review, EIA annual energy outlook, ERCOT, EIA 860

The Future: New Paradigms for Control

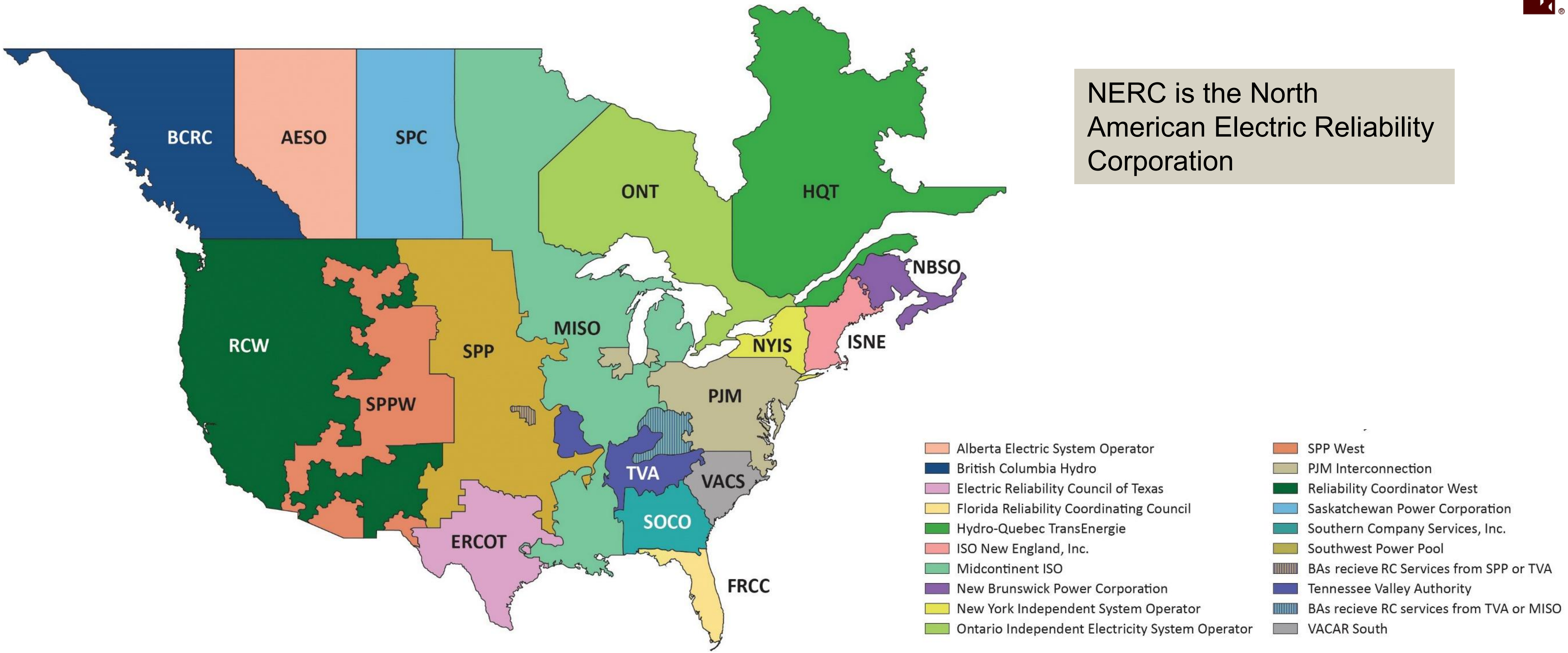
- Inverter-based resources (such as wind and solar) introduce major paradigm shift in power system control
  - Decreasing impact of large synchronous machines with their stabilizing inertia
  - Resources are less dispatchable
- Changes at the “edge” of the grid
  - Data centers for AI (huge load increase)
  - Electric vehicles
  - More controllable or price-sensitive demand resources

What do all of these have in common? Need for high-quality electric grid modeling and simulation to prepare for a resilient and sustainable future.

The Smart Grid

- The term "Smart Grid" dates officially to the 2007 "Energy Independence and Security Act", Title 13 ("Smart Grid")
  - Use of digital information and control techniques
  - Dynamic grid optimization with cyber-security
  - Deployment of distributed resources including
  - Customer participation and smart appliances
  - Integration of storage including PHEVs
  - Development of interoperability standards

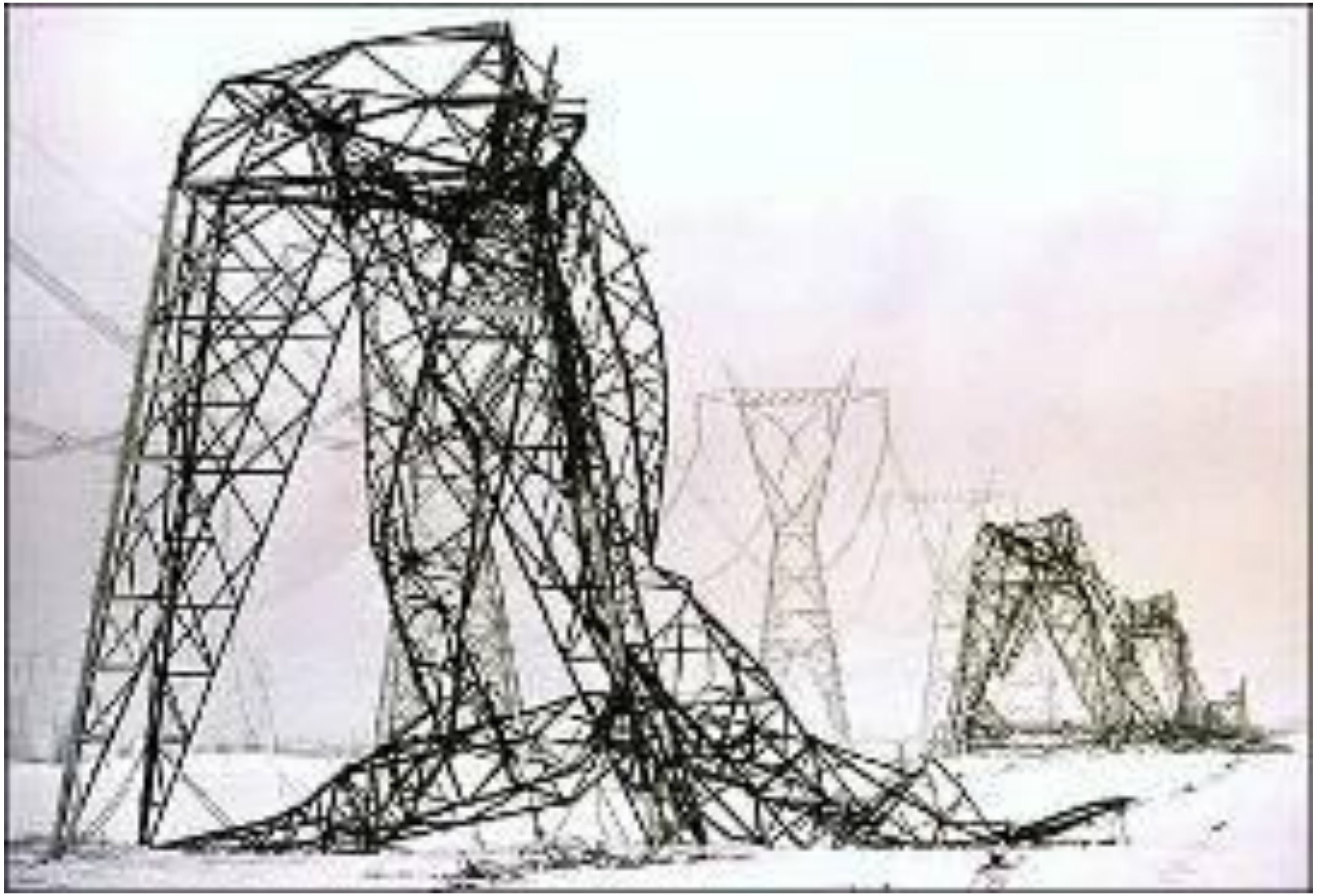
NERC Reliability Coordinators



NERC is the North American Electric Reliability Corporation

https://www.nerc.com/pa/rrm/TLR/Pages/Reliability-Coordinators.aspx

Transmission Lines and the Elements



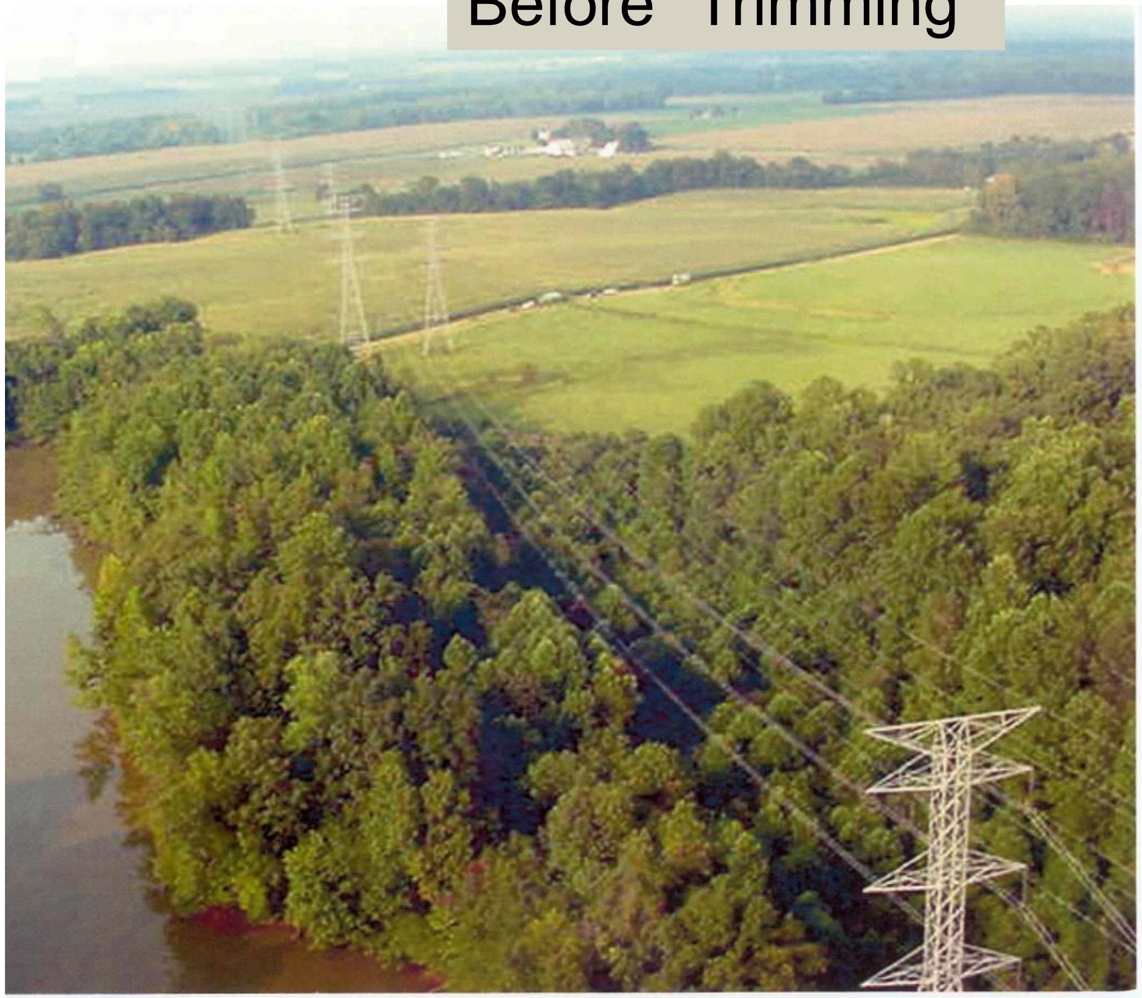
Ike in Beaumont

Quebec Ice Storm

Transmission Lines and Trees

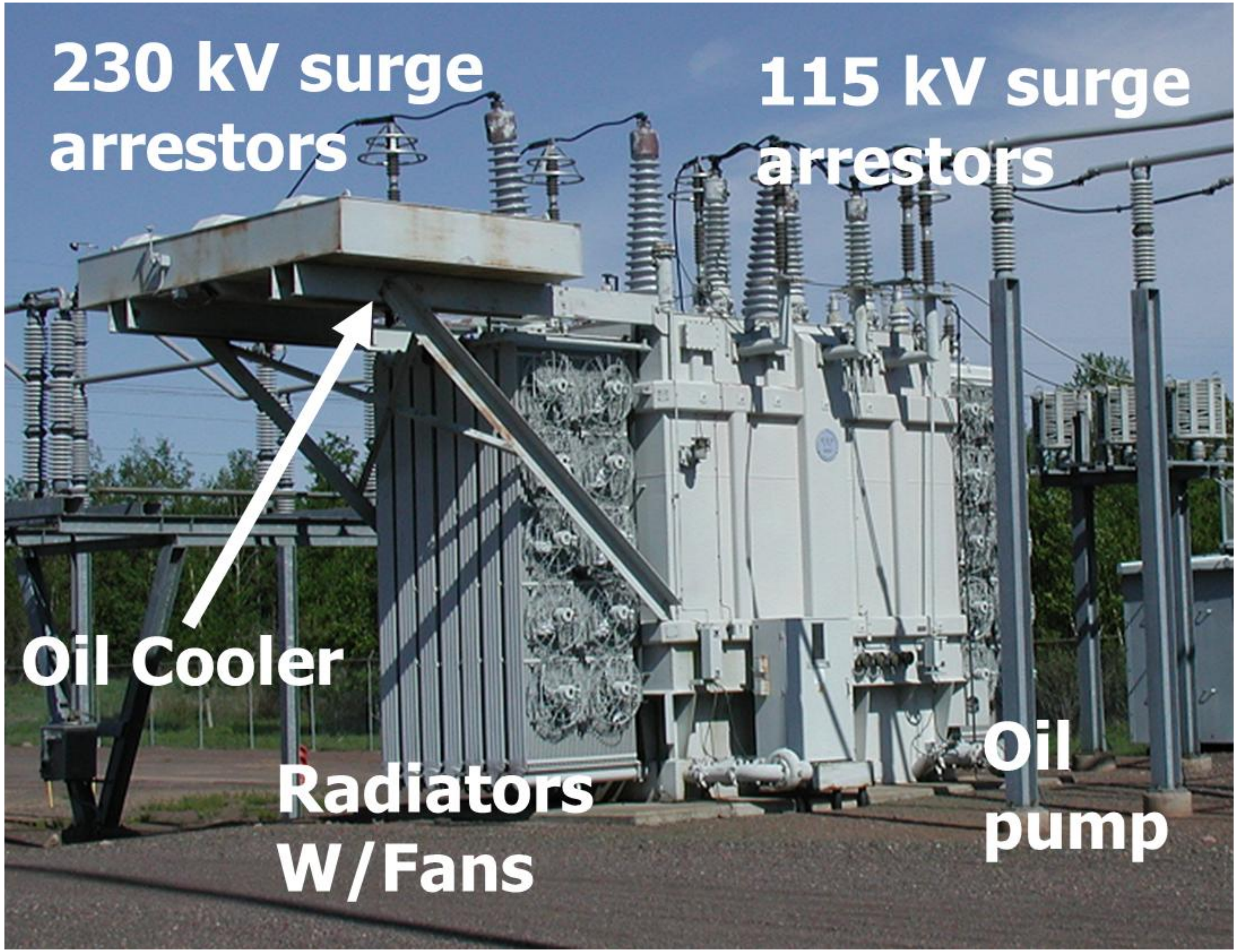
- We like trees, and they grow; but when trees get close to lines bad things can occur.

Before "Trimming"



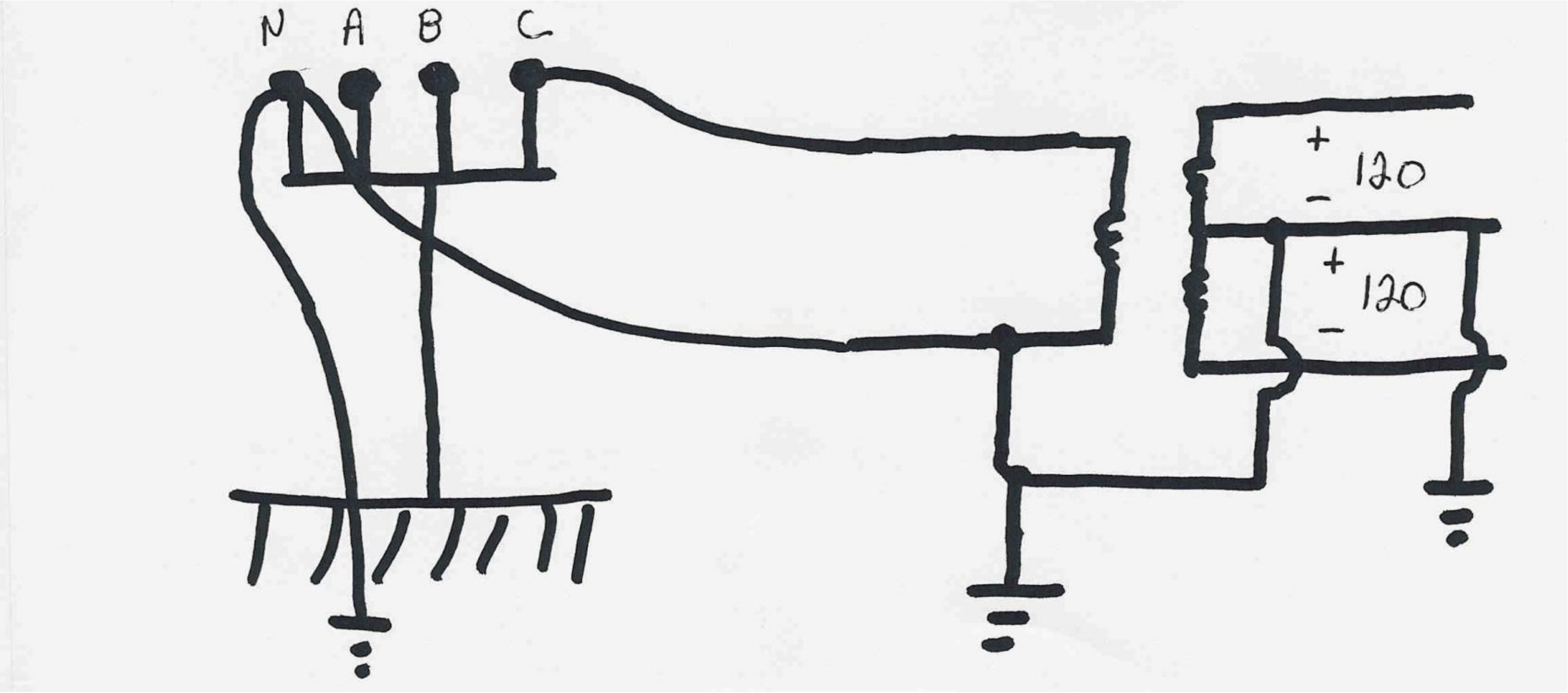
After "Trimming"

230/115 kV Transformer Picture



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

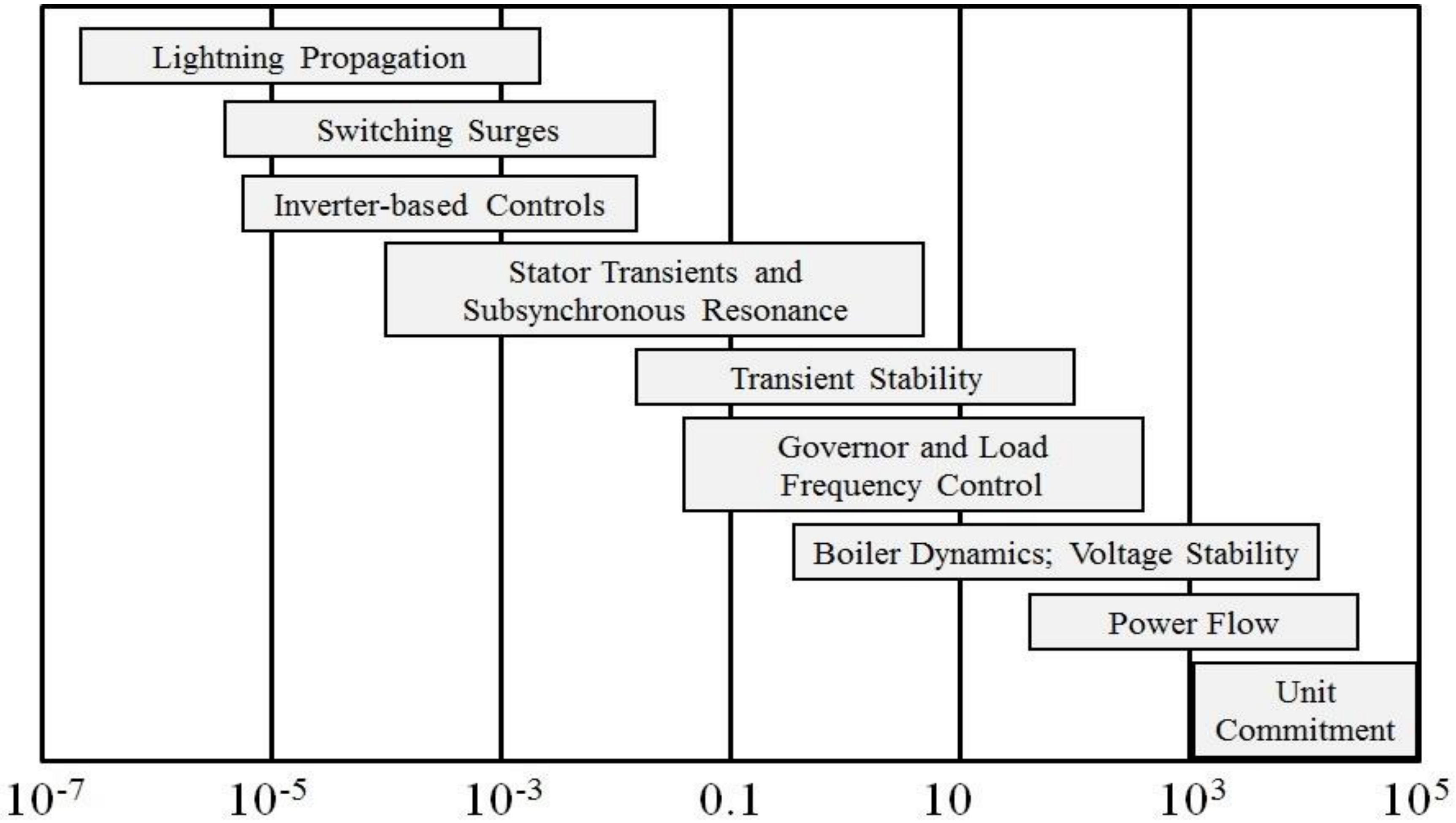
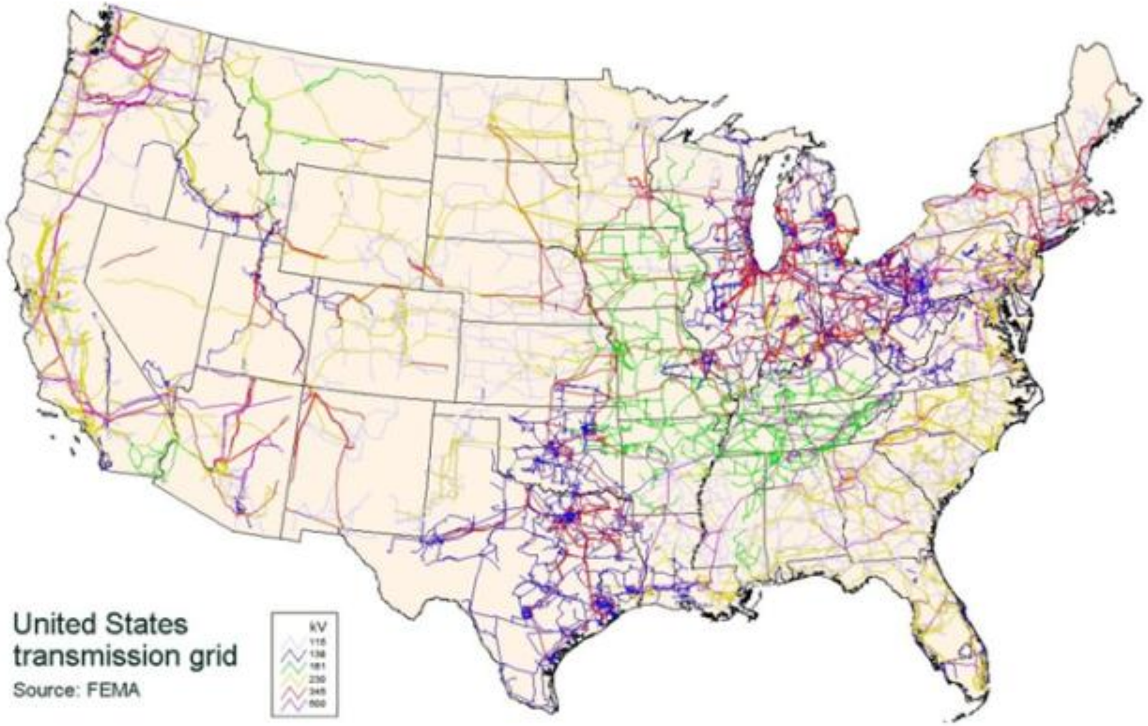


Image source: P.W. Sauer, M.A. Pai, Power System Dynamics and Stability, 1997, Fig 1.2, modified

Important Electric Grid Considerations

- Electricity cannot be economically stored
  - Generation must be continually adjusted to match changes in electric load and losses
- Electric power flows on high voltage transmission lines cannot usually be directly controlled
  - Control is mostly indirect, by changing generation
- Customers have been in control of their load
- Transmission system has finite limits; often operated close to its limit for economic reasons



Power System Components

- Major Components:
  - Generators
    - Power conversion technology, regulation and control
  - Transmission System (69 kV and above)
    - Substations, transmission lines, power transformers, control devices
  - Distribution System (below 69 kV)
    - Distribution feeders, service transformers, metering and control
  - Loads
    - Customer electricity demands, patterns, quality

Voltage Levels Usage Table

- These voltages are measured Line-to-Line (except single phase LV)
- Recall, Line-to-Neutral is less by a factor of $\sqrt{3}$
- Many voltages are in use in U.S. power systems—here are some of the main ones.
- "High Voltage", "Low Voltage" are relative terms, sometimes all can be labeled "High Voltage"
- The labels given are typical

Level	Typical Voltages	Usage
Low Voltage	120 V, 208 V, 240 V, 600 V	Customer-level loads, residential, commercial, smaller industrial
Medium Voltage	4.16 kV, 12.47 kV, 13.8 kV, 20 kV, 22 kV, 34.5 kV	Distribution feeders, generator step-up, larger industrial motors
High Voltage	69 kV, 100 kV, 115 kV, 138 kV, 161 kV, 230 kV	Transmission system network
Extra High Voltage (EHV)	345 kV, 500 kV, 765 kV	Backbone of large transmission systems

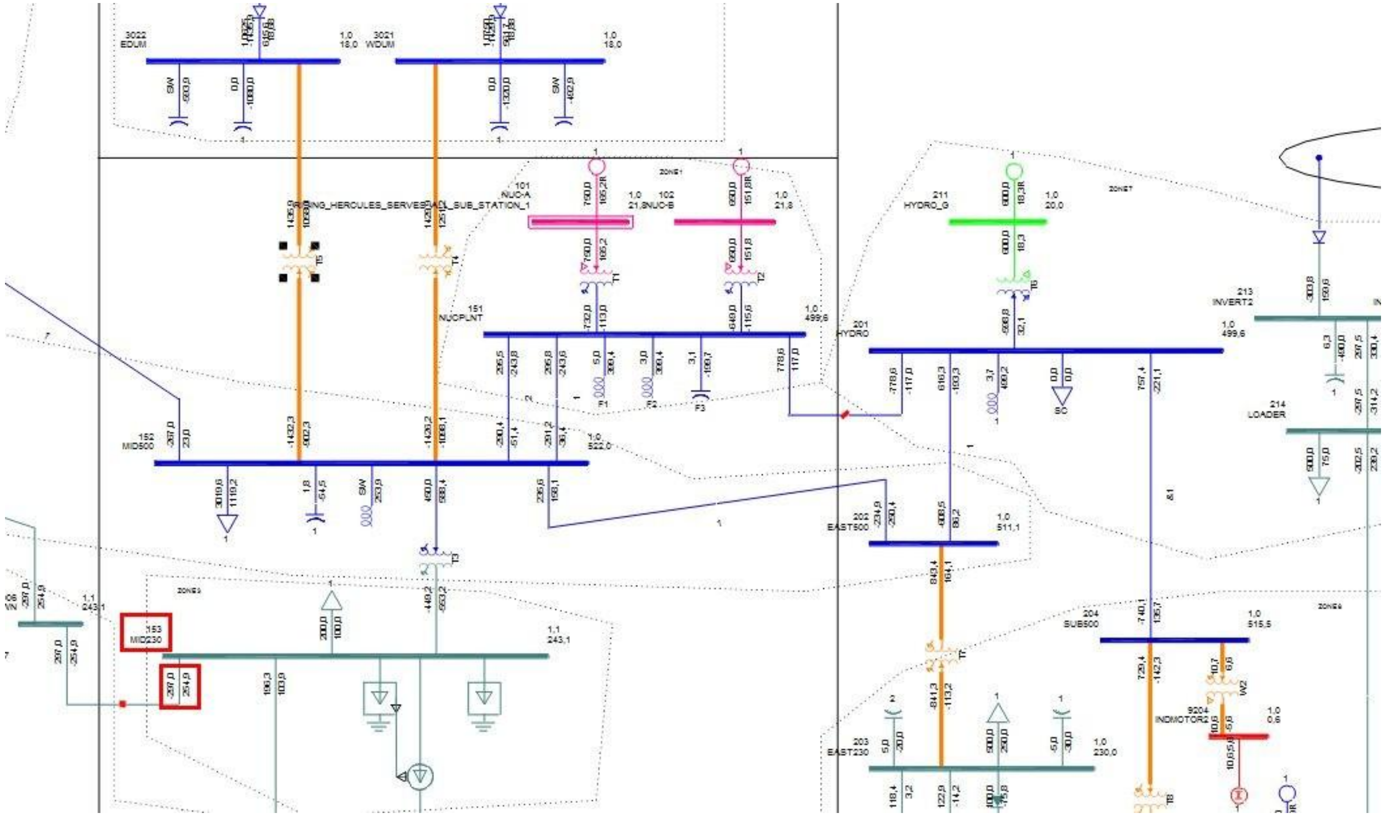
Labs

- The first two labs (and most of the others) will involve power system simulation on PowerWorld Simulator
- This will be in the labs in Zach 326 – not pictured
- TAs will introduce more lab policies on the first week, which is next week

- The main objective of the first two labs is to get familiar with the software and learn some basics about power system operations on smaller and medium-sized grid models

Computer Tools for Power System Analysis

- Positive Sequence Transmission Simulation
  - Siemens PSSE – Common in East
  - GE PSLF – Common in West
  - PowerWorld
  - ETAP
  - Matpower - free, mostly in academia
- Distribution, Unbalanced
  - OpenDSS – free, open source
  - GridLabD
  - CYME
- Electromagnetic Transients
  - EMTP-RV
  - PSCAD
- Custom code – your own or in-house



https://new.siemens.com/global/en/products/energy/energy-automation-and-smart-grid/pss-software/pss-e.html

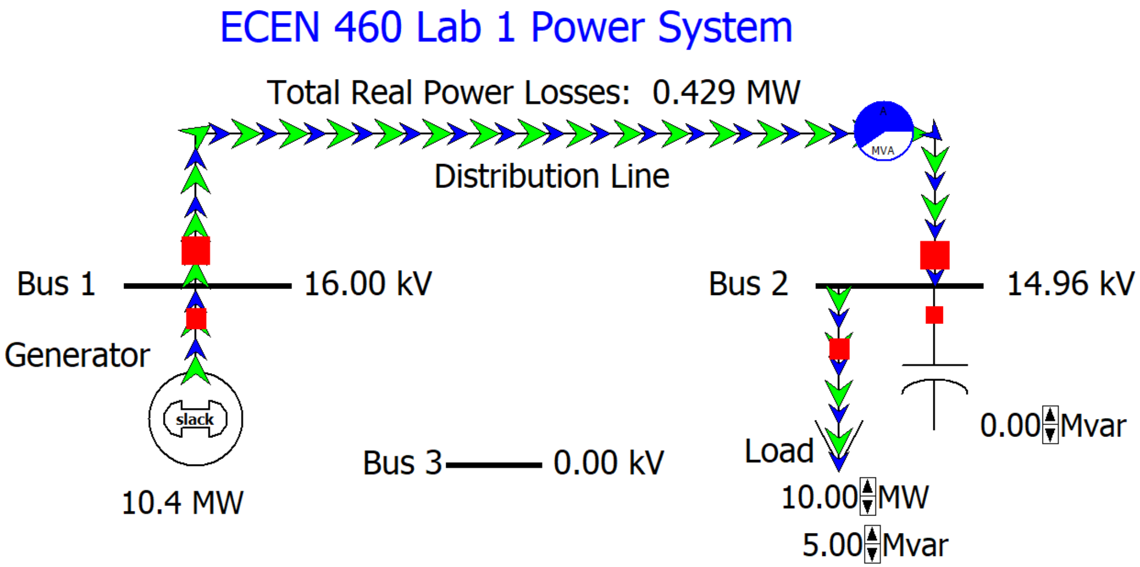
PowerWorld Simulator

- Commercial tool in actual use by utilities and others (1000+ customers in 70 countries)
- Originally developed in 1996 by Prof. Overbye (formerly at University of Illinois, now at Texas A&M)
- Originally designed to be well-suited to teaching students about power systems. Still has that capability while being full-featured for industry use
- Strengths are user-friendliness and advanced data visualization
- There is a free student 42-bus version.
  We will use full (unlimited bus) version for labs in this class.

powerworld.com

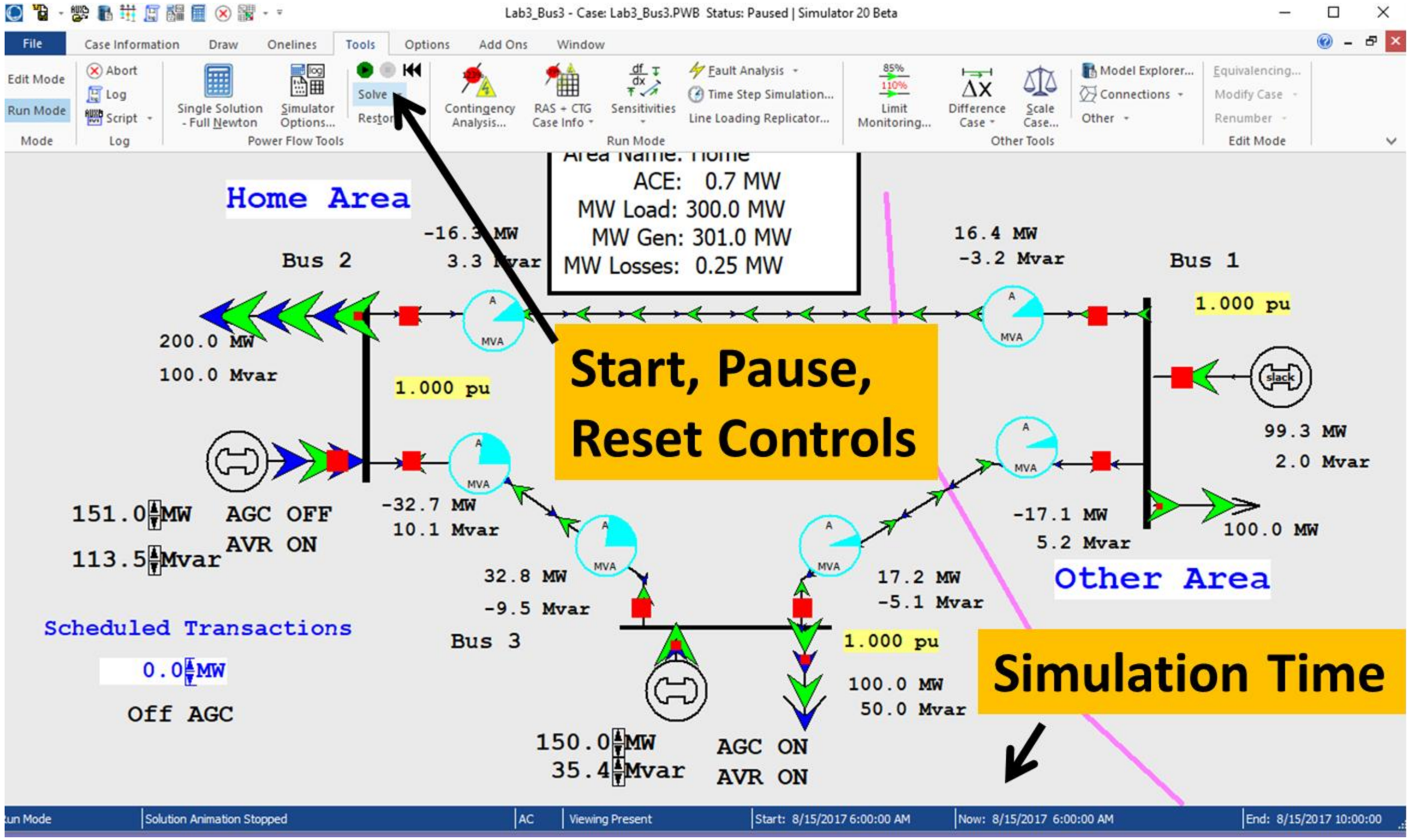
Lab 1 – Part A

- Objectives:
  - Learn the basics of using PowerWorld Simulator to model balanced three-phase systems.
  - Correct the power factor of three-phase load by proper placement of shunt capacitors.
  - Learn the basics of power system operations in the quasi-steady-state (power flow) time frame
- Tasks
  - Explore impact of capacitor on different system metrics: losses, voltage.
  - Add two additional lines to connect bus 3.



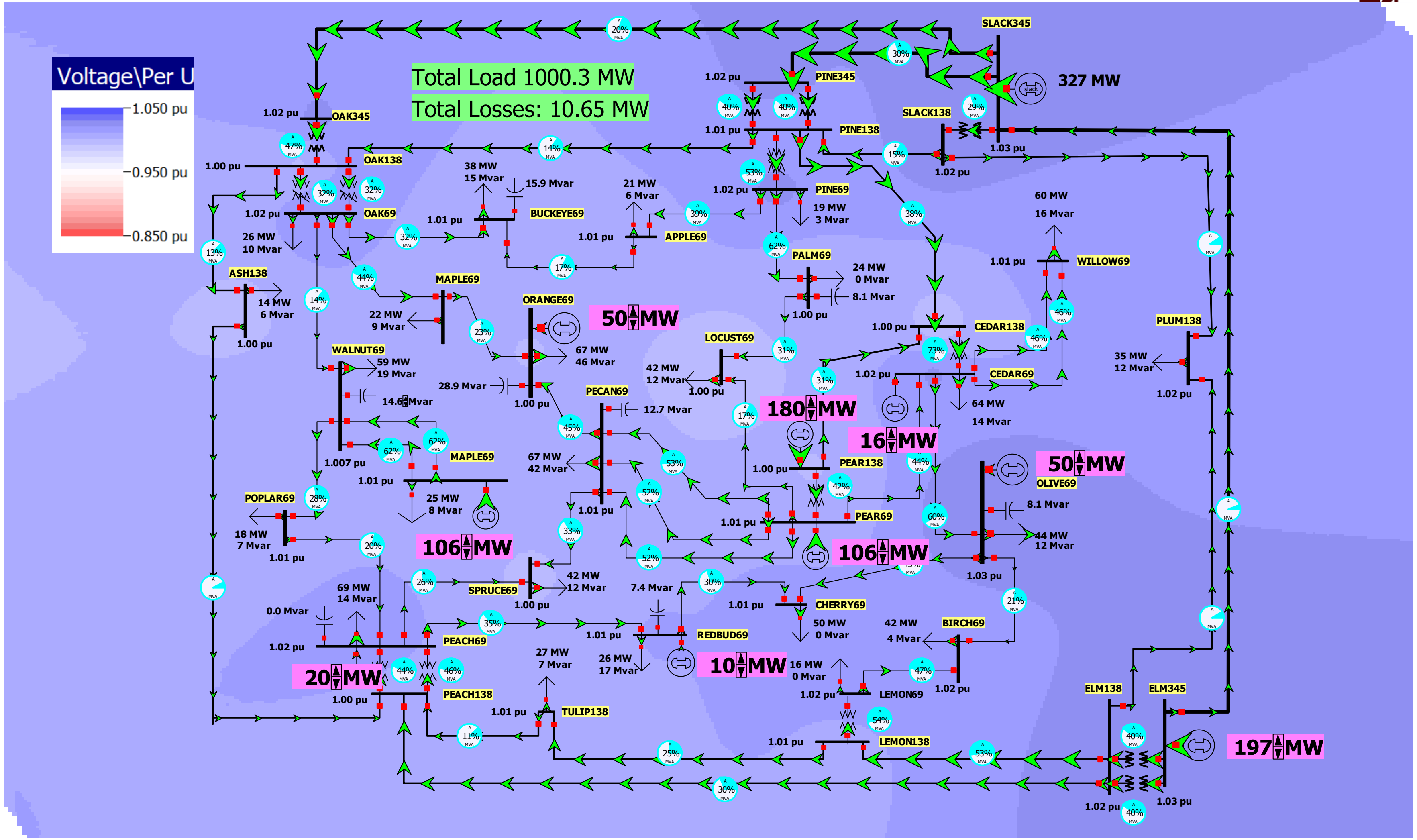
Lab 1 – Part B

- Tasks
  - Run system and observe how load increases and flows and generation respond in a two-area system
- Manually adjust generation during load increase
- Attempt to manage area control error (ACE)
- Observe the operation of automated ACE control by the generators



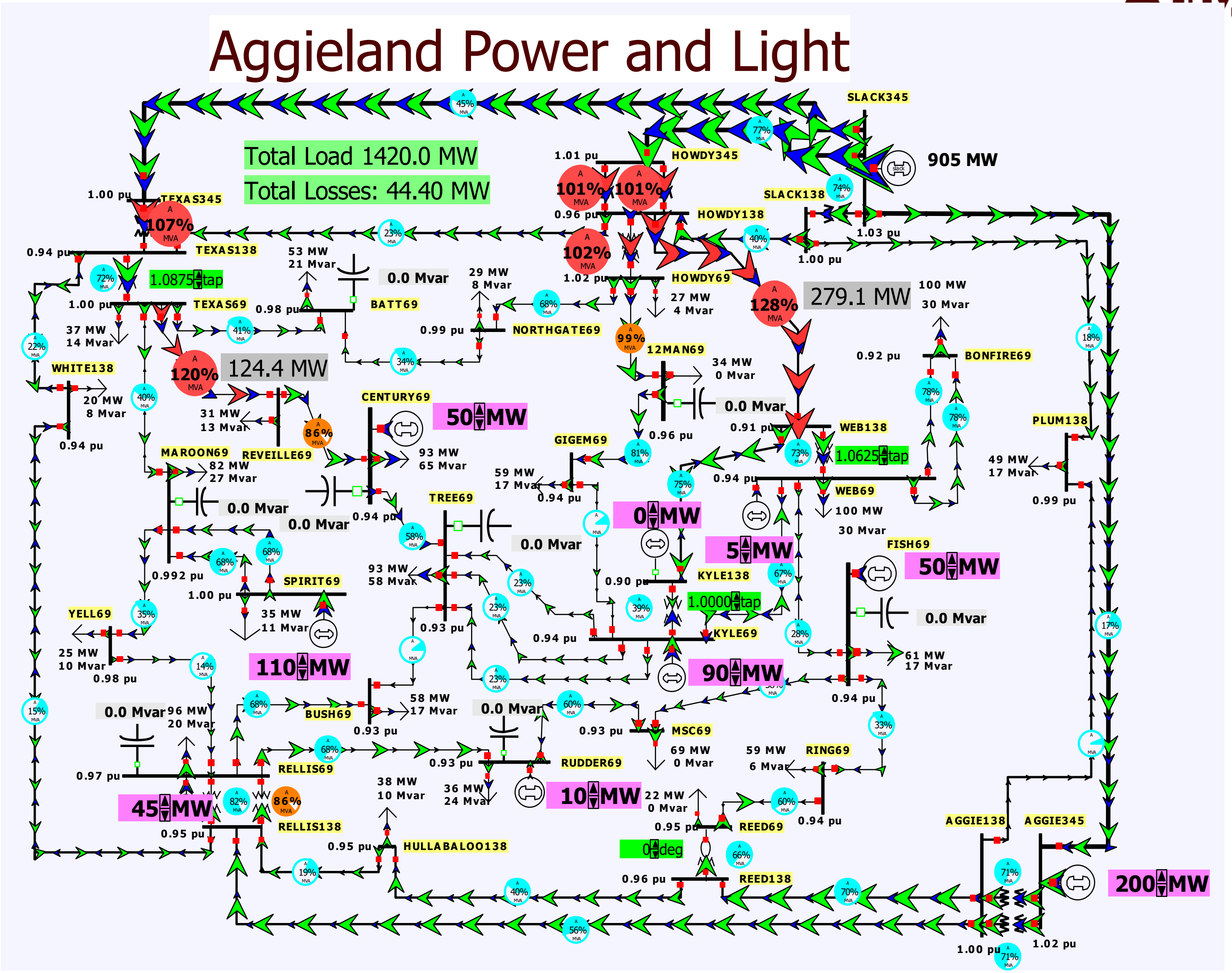
Lab 1 – Last Step

- Extreme loading of 42 bus system



Lab 2 – Aggieland Power and Light

- Fix problems on this grid using various control options
  - Generator setpoints
  - Phase shifting transformer
  - Capacitor bank switching
  - Transformer tap switching
- Use a sensitivity-based approach to estimate impacts of control variables



Synthetic Texas Grid

- This 2000 bus grid will be used a lot in class and lab this semester
- It is similar in some ways to the actual Texas grid: similar generation, load patterns, same geography. However, it is a fictitious (synthetic) transmission network: different voltages, all fictional lines and substations.
- Data on actual Texas grid is too confidential to be used in class
- This grid model was developed by researchers here in the Texas A&M Power and Energy research group and is being used in a lot of research projects.