ECEN 615
Methods of Electric Power Systems Analysis

Lecture 2: Power Systems Overview and Modeling

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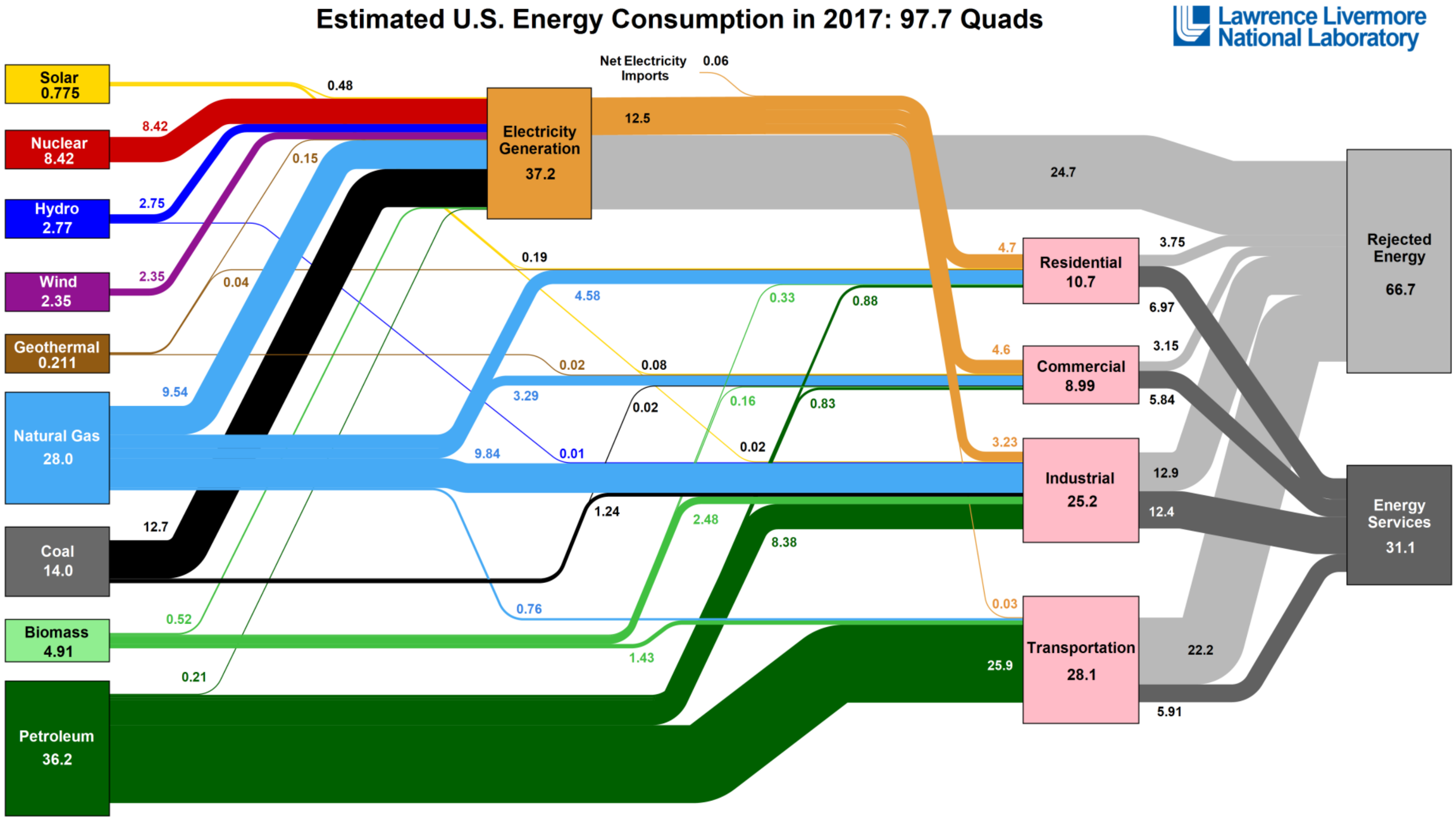
Announcements

- Start reading chapters 1 to 3 from the book (more background material)
- Download the 42 bus educational version of PowerWorld Simulator at

  https://www.powerworld.com/gloveroverbyesarma

US Energy Consumption



Source: LLNL April, 2018. Data is based on DOE/EIA MER (2017). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

https://flowcharts.llnl.gov/content/assets/images/charts/Energy/Energy_2017_United-States.png

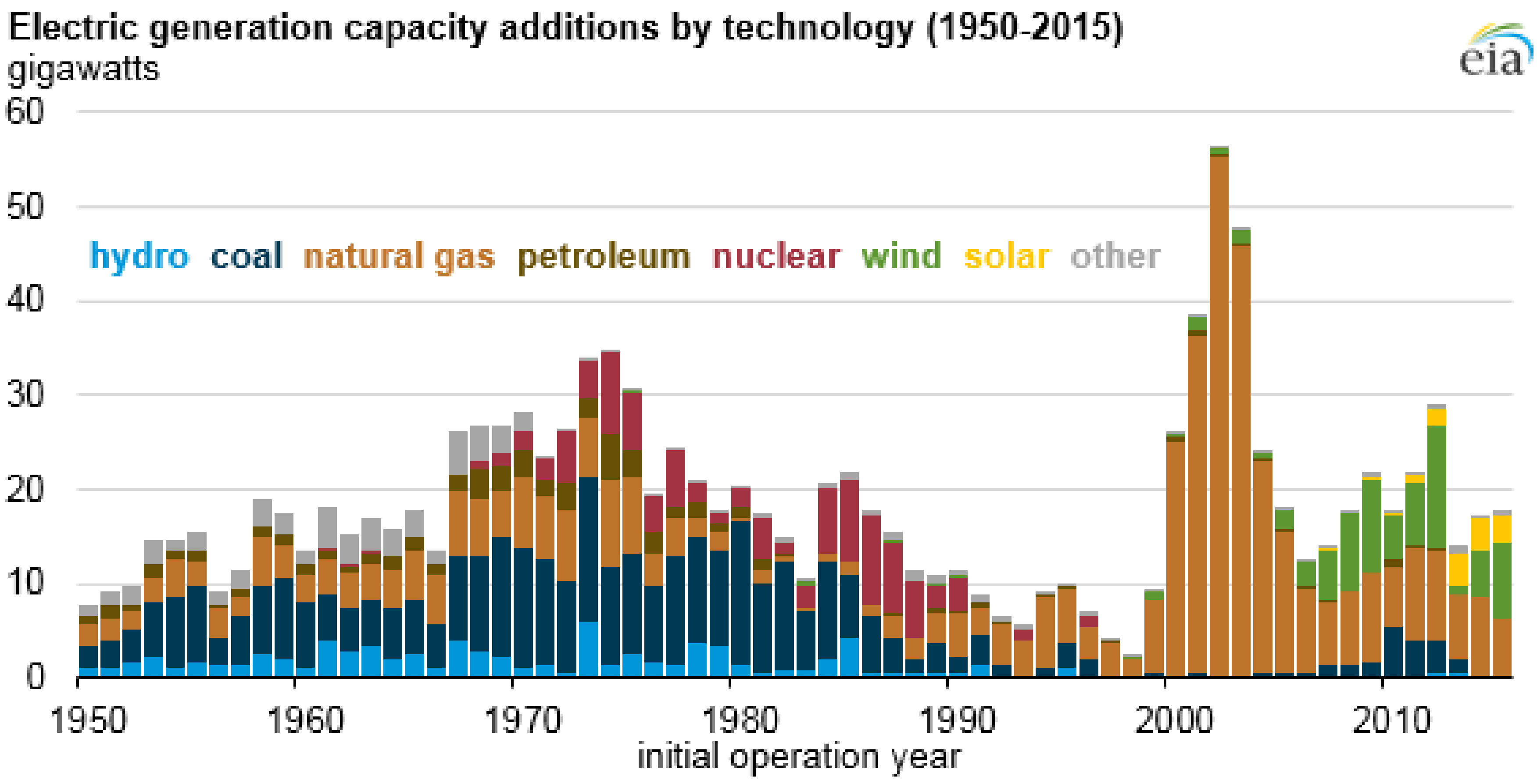
Provided by Brandon Thayer

My Favorite 8/14/2003 Blackout Cartoon!

Suddenly, knowing a lot about the U.S. power grid became sexy at cocktail parties.

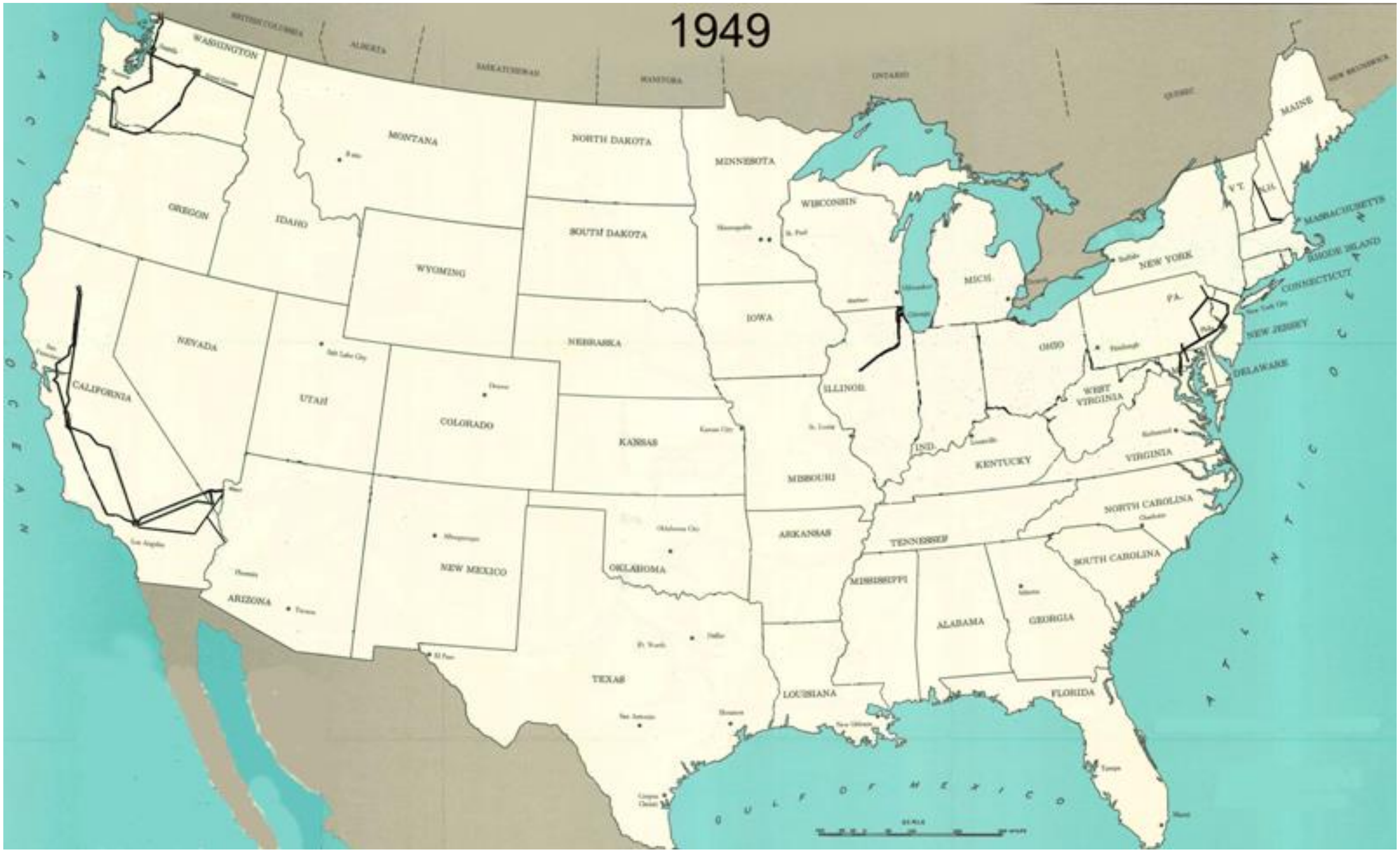
My Favorite Blackout Hoax Photo

Electric Grid History: The Rise of Natural Gas Generation

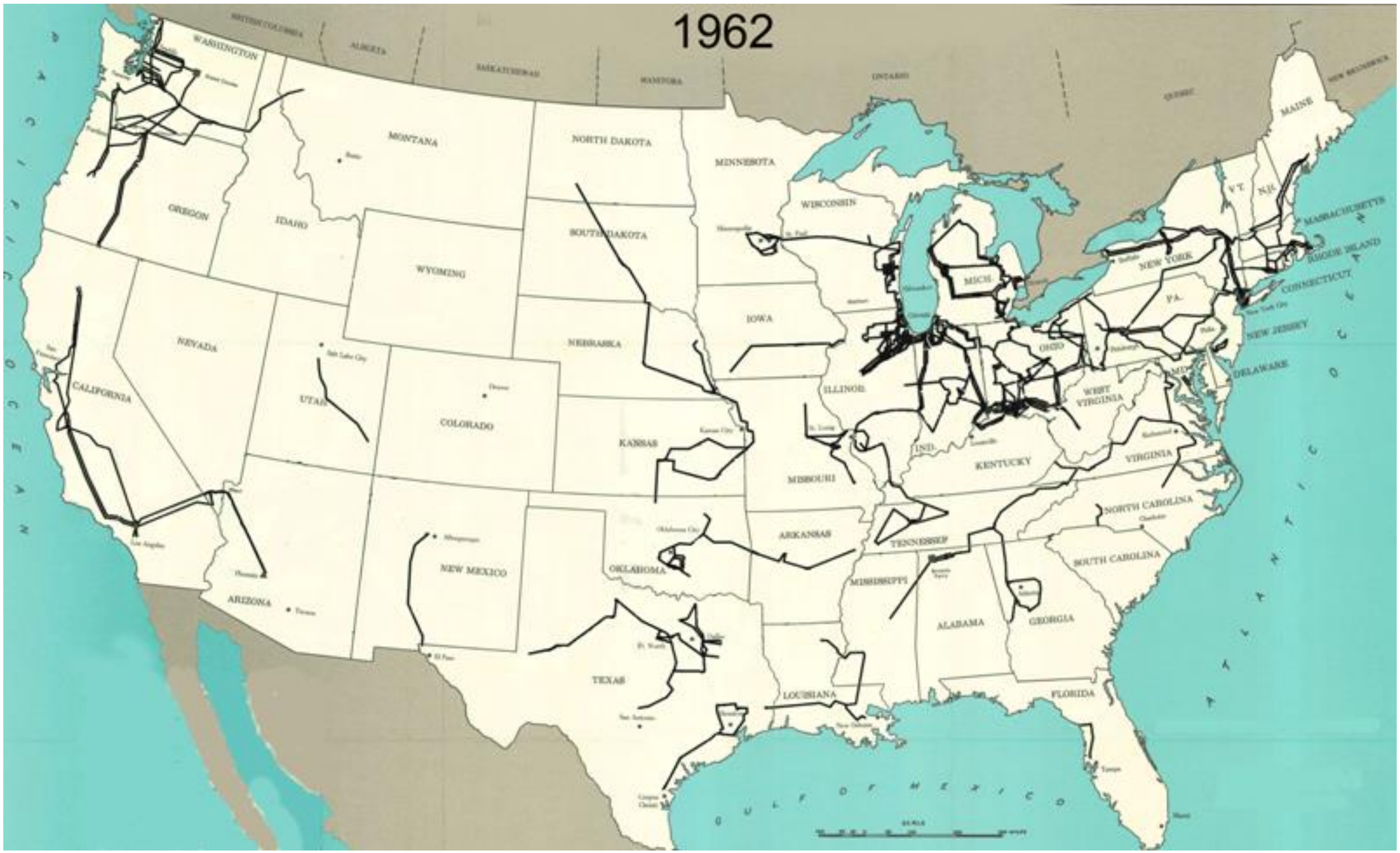


Source: US EIA, 2016

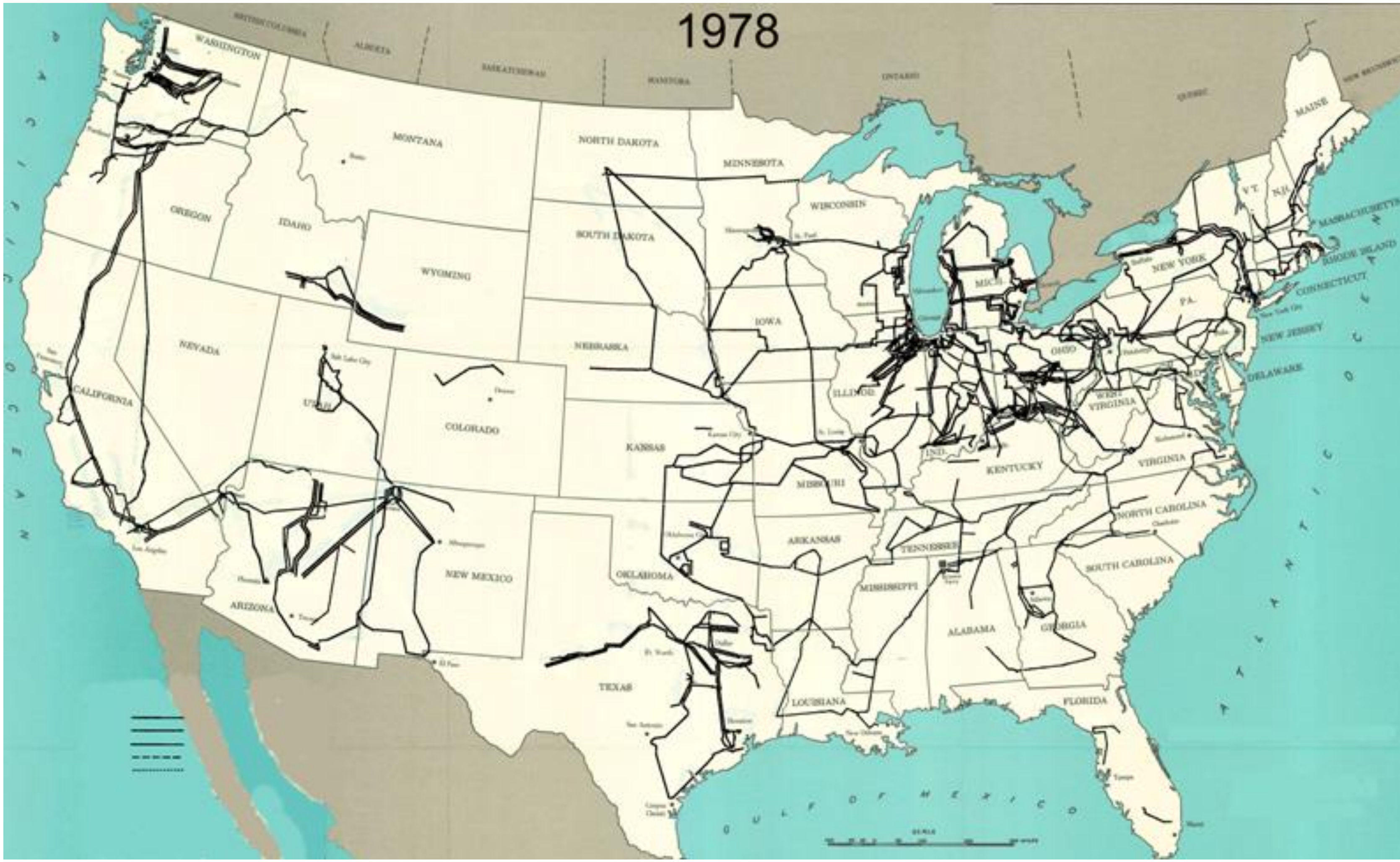
345 kV+ Transmission Growth at a Glance (From Jay Caspary)



345 kV+ Transmission Growth at a Glance (From Jay Caspary)



345 kV+ Transmission Growth at a Glance (From Jay Caspary)



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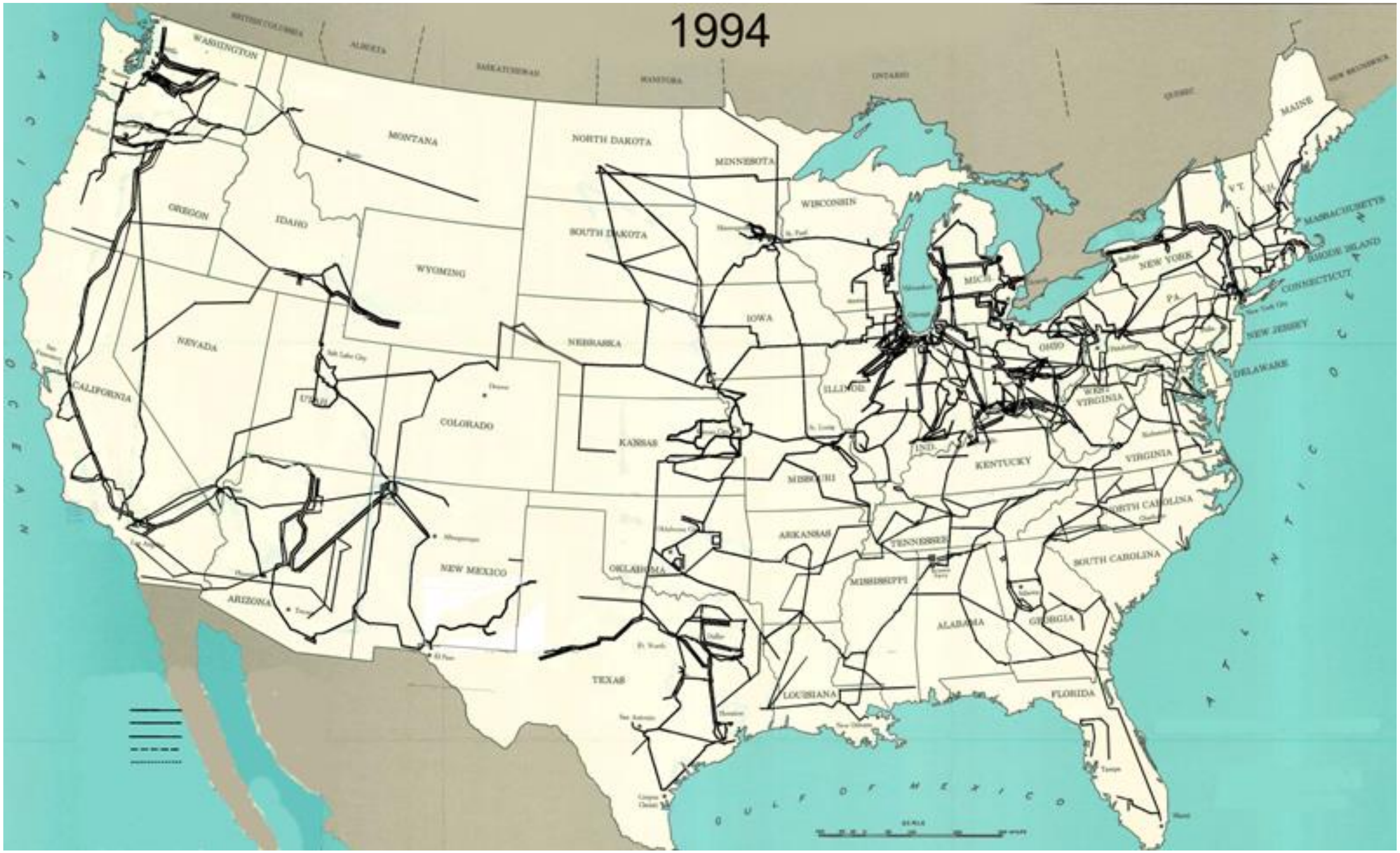
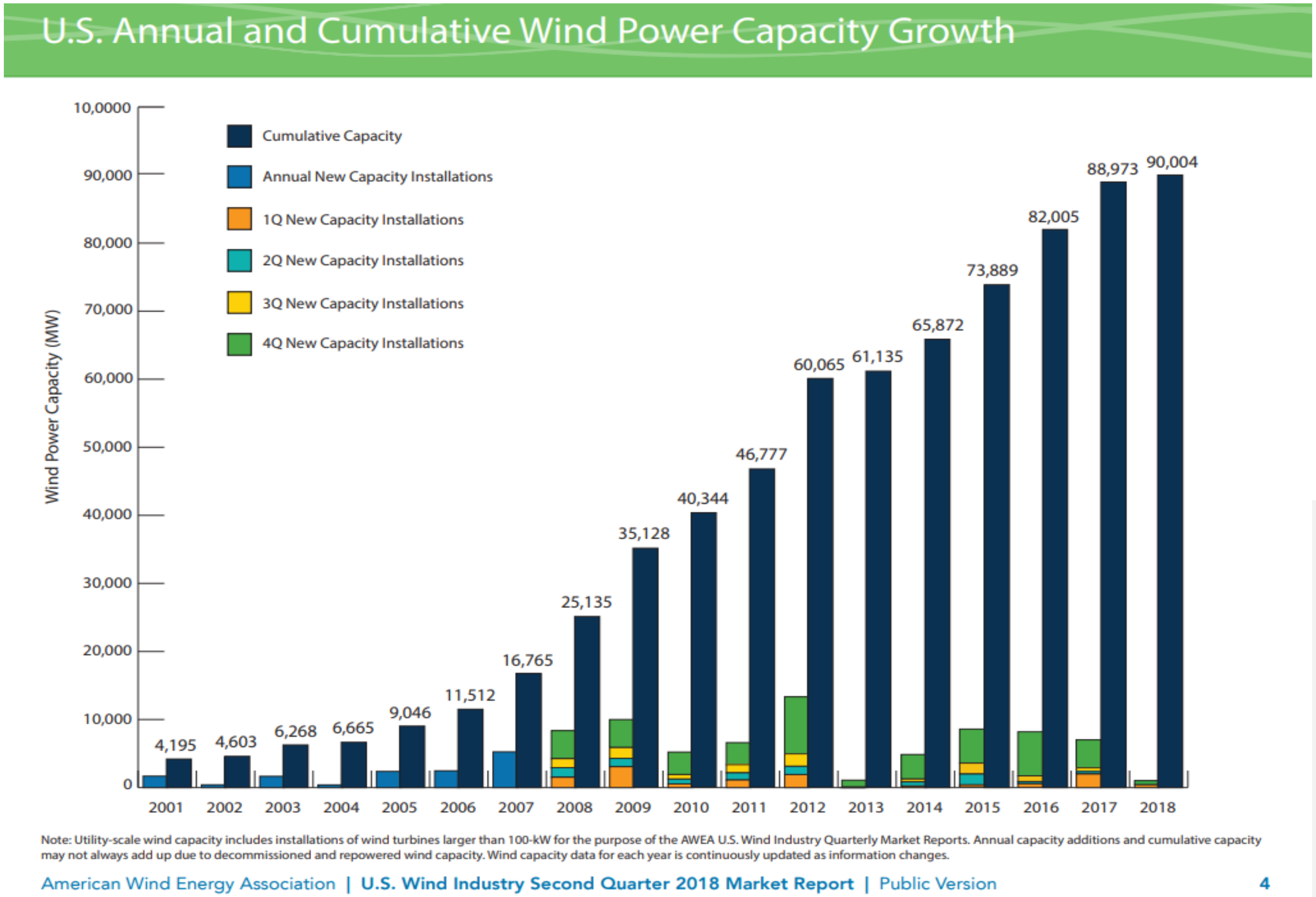


Rise of Renewables: Wind



Currently about 8% of our electric capacity is wind

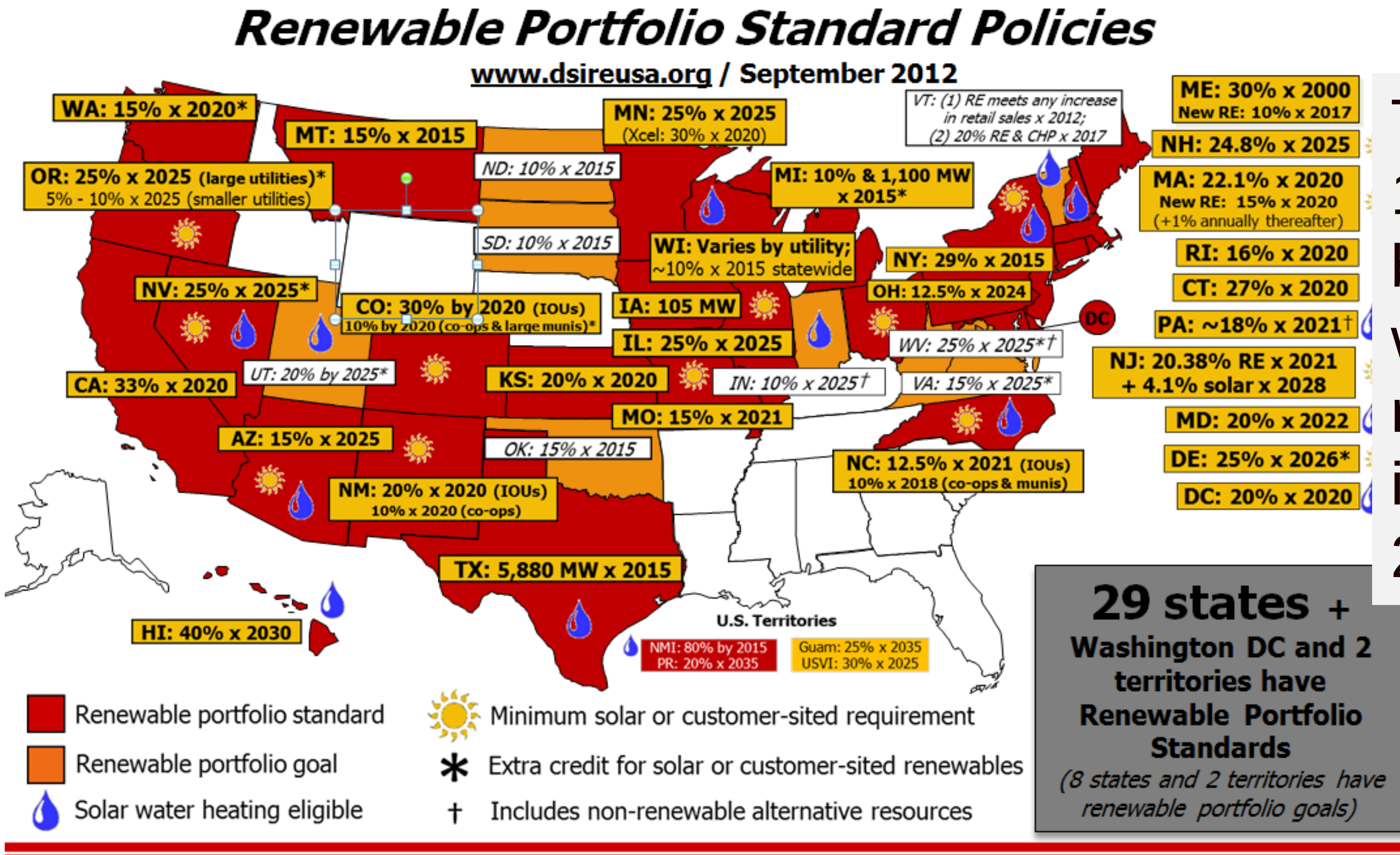
The up/downs in 2001/2 and 2003/4 were caused by expiring tax credits

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

Smart Grid Perceptions (Some of Us Like the Term "Smarter")

Renewable Portfolio Standards (September 2012)

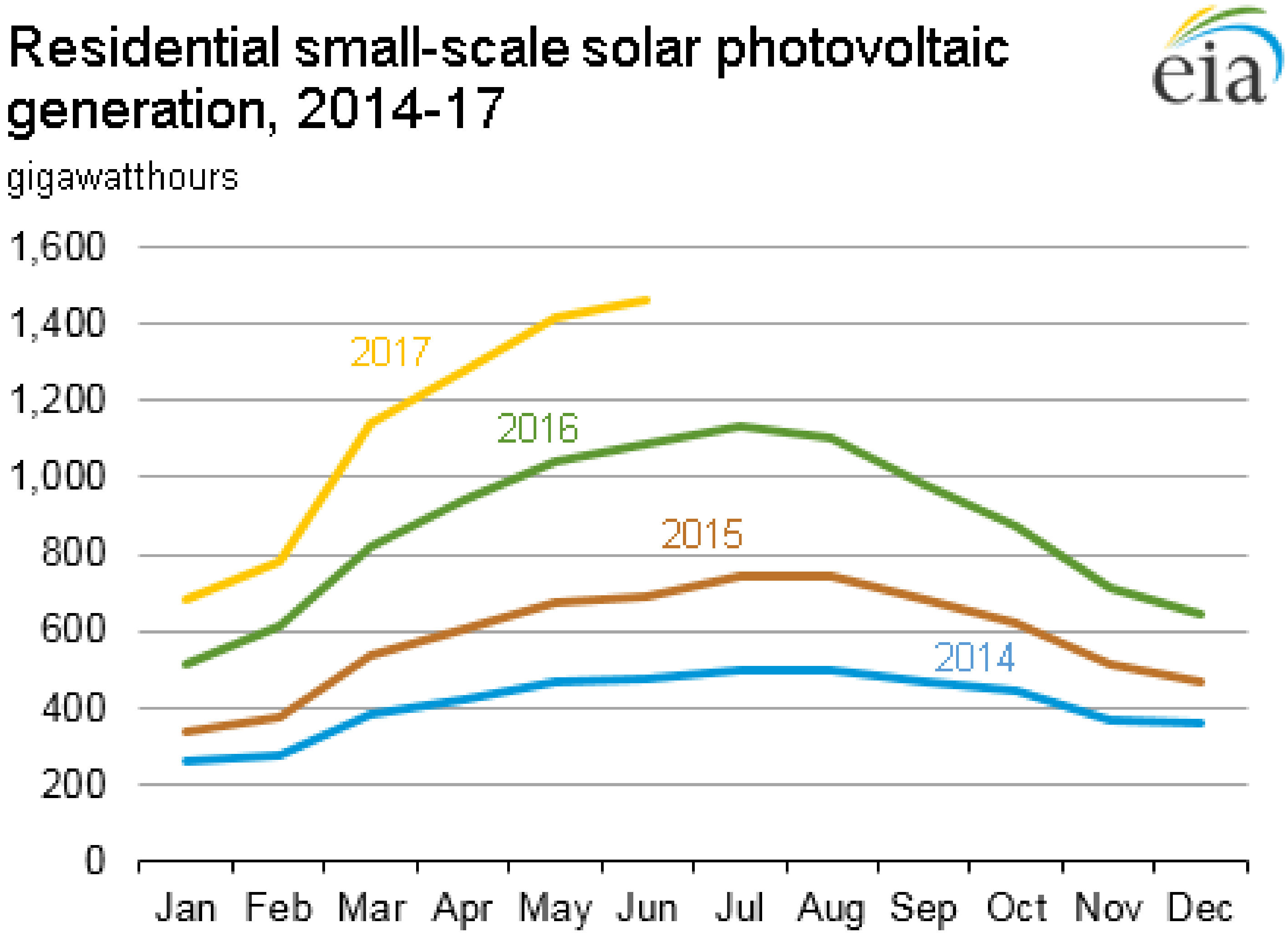


TX is now 10 GW by 2025 which we've met; CA is 50% by 2030

Image source: http://www.dsireusa.org/

See also www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

Growth in Solar PV

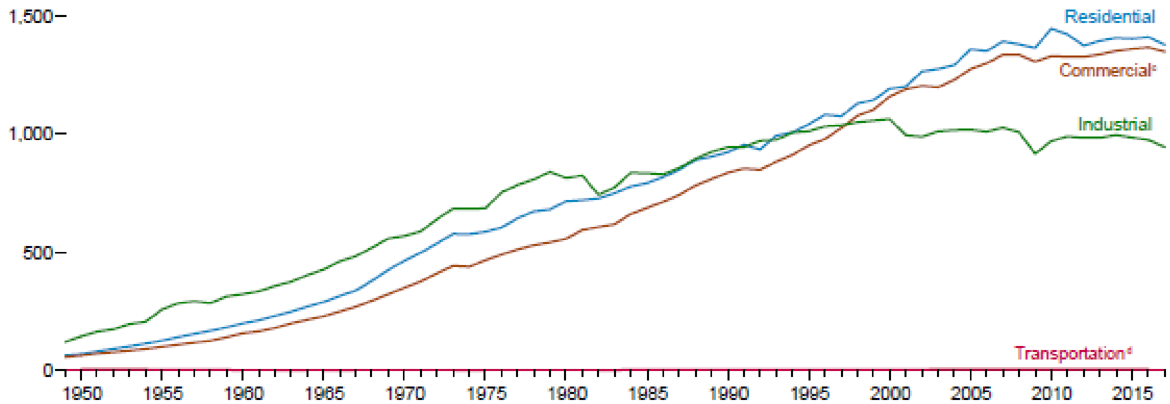


Value in April 2018 was 1596, up 24% from April 2017

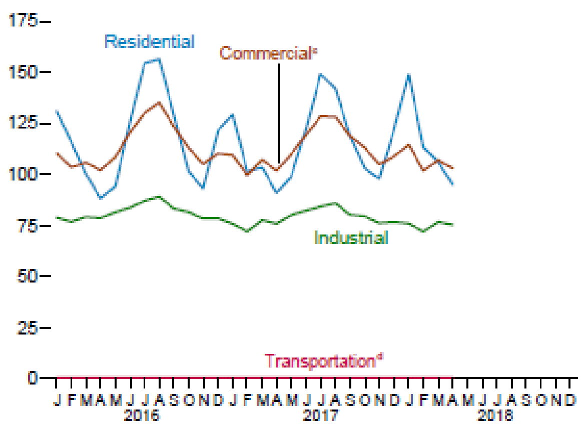
Source: www.eia.gov/electricity/monthly/update/

Slowing Electric Load Growth

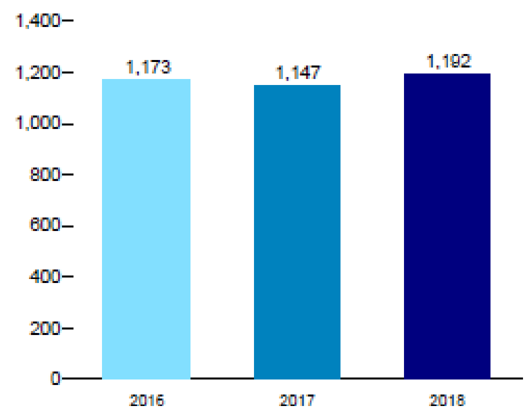
Retail Sales[a] by Sector, 1949–2017



Retail Sales[a] by Sector, Monthly



Retail Sales[a] Total, January–April

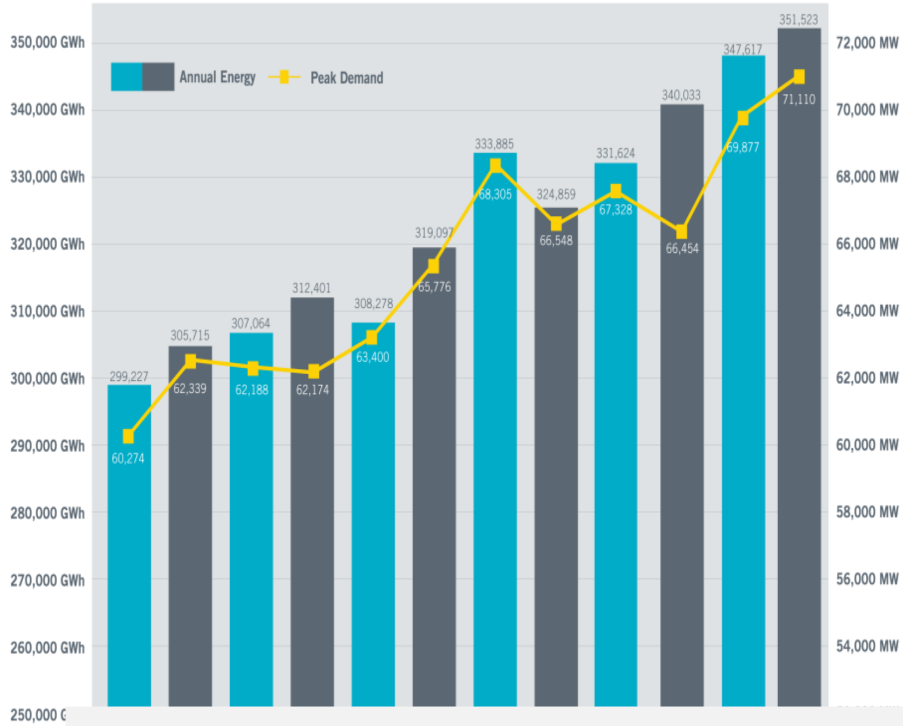


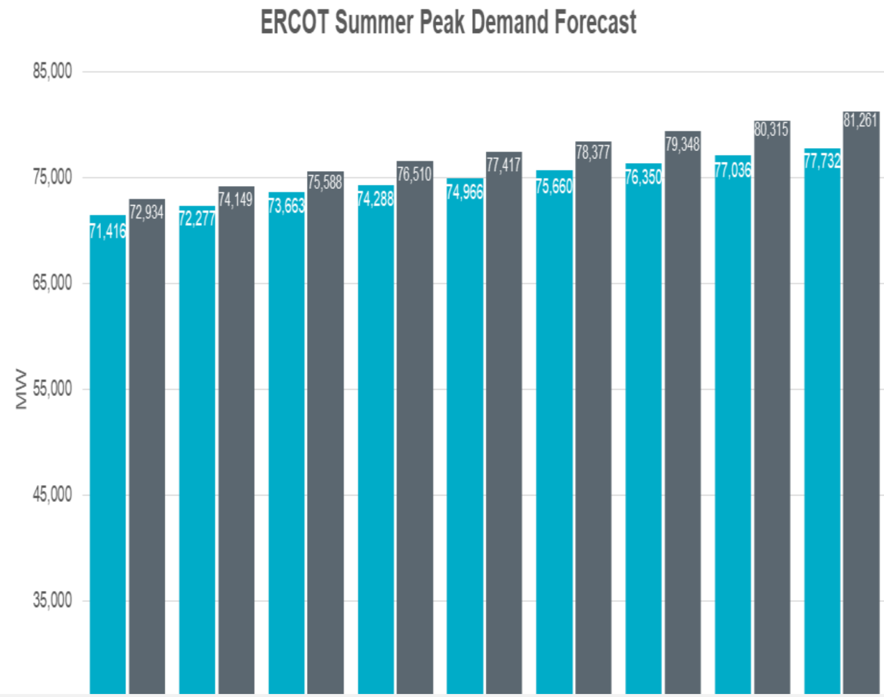
[a] Electricity retail sales to ultimate customers reported by utilities and other energy service providers.
[b] See "Direct Use" in Glossary.
[c] Commercial sector, including public street and highway lighting, interdepartmental sales, and other sales to public authorities.
[d] Transportation sector, including sales to railroads and railways.
Web Page: http://www.eia.gov/totalenergy/data/monthly/#electricity.
Source: Table 7.6.

Much of the slowing load growth is due to distributed generation, such as solar PV, which sits on the customer side of the meter

Source: EIA electric power monthly, August 2017

Except in Texas!





For peak graph, light blue is old forecast, grey is new forecast

ERCOT set a new peak electric load of 73.3 GW on July 19, 2018; total energy in 2017 was 357 billion kWh

Image source: CEO Perspectives, Bill Magness, ERCOT, May 2017

Interconnected Power System Basic Characteristics

- Three – phase AC systems:
  - generation and transmission equipment is usually three phase
  - industrial loads are three phase
  - residential and commercial loads are single phase and distributed equally among the phases; consequently, a balanced three – phase system results
- Synchronous machines generate electricity
  - Exceptions: some wind is induction generators; solar PV
- Interconnection transmits power over a wider region with subsystems operating at different voltage levels

Power Systems: Basic Characteristics

- The transmission network consists of following
  - the high voltage transmission system;
  - frequently, the subtransmission system;
  - sometimes, even the distribution system

- The transmission system forms the backbone of the integrated power system and operates at the highest voltage levels; typically, above 150 kV
- Less losses at high voltages ($S=VI^*$ and I^2R losses), but more difficult to insulate.
- The subtransmission levels are in the 69 to138 kV range

Power Systems: Basic Characteristics

- The generator output voltages are typically in the 11kV to 35 kV range and step up transformers are used to transform the potentials to transmission system voltage levels
  - Wind turbines have voltages in 600V range
- Bulk power system, which includes the transmission system and generators, is networked

Power Systems: Basic Characteristics

- Electrical devices are joined together at buses
- The distribution system is used to supply the electricity to the consumers
  - primary distribution voltages are in the 4 kV to 34.5 kV range at which industrial customers obtain their electricity supply
  - secondary distribution voltage is 120/240 V to the residential/commercial customers
  - distribution system is usually radial, except in some urban areas

A Substation Bus

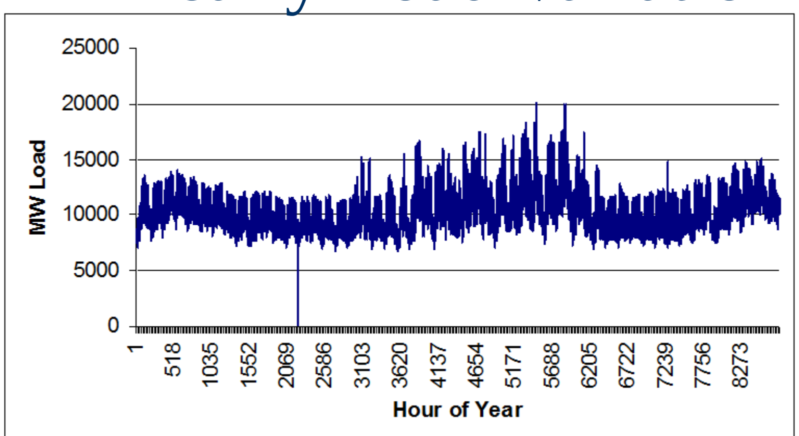
Electricity Supply

- The basic function of a power system is to convert energy from one source to the electrical form; a key characteristic is that energy is not consumed as electricity but converted into heat, light, sound, mechanical energy or information
- The widespread use of electricity is due to its ability to transport and control efficiently and reliably
- Electricity is, by and large, a relatively clean source of energy
  - Most forms of renewable energy are created in the form of electricity; examples include hydro, wind and solar.

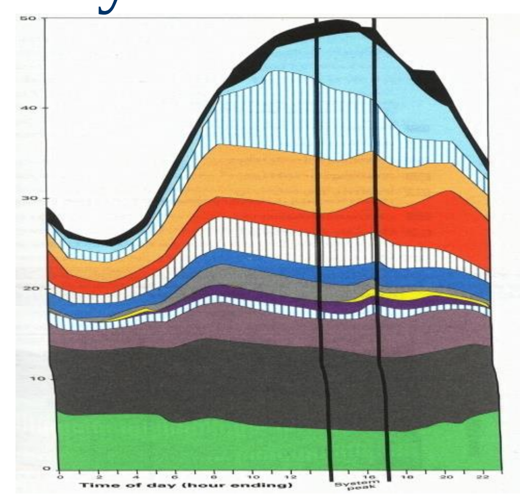
Fundamental Power System Requirements

- System must be able to track load continuously: continuous balance of supply and demand
- System must provide reliable supply of electricity at least cost
- System must have least environmental impacts in providing electricity to meet its customers' demands

Yearly Load Variation



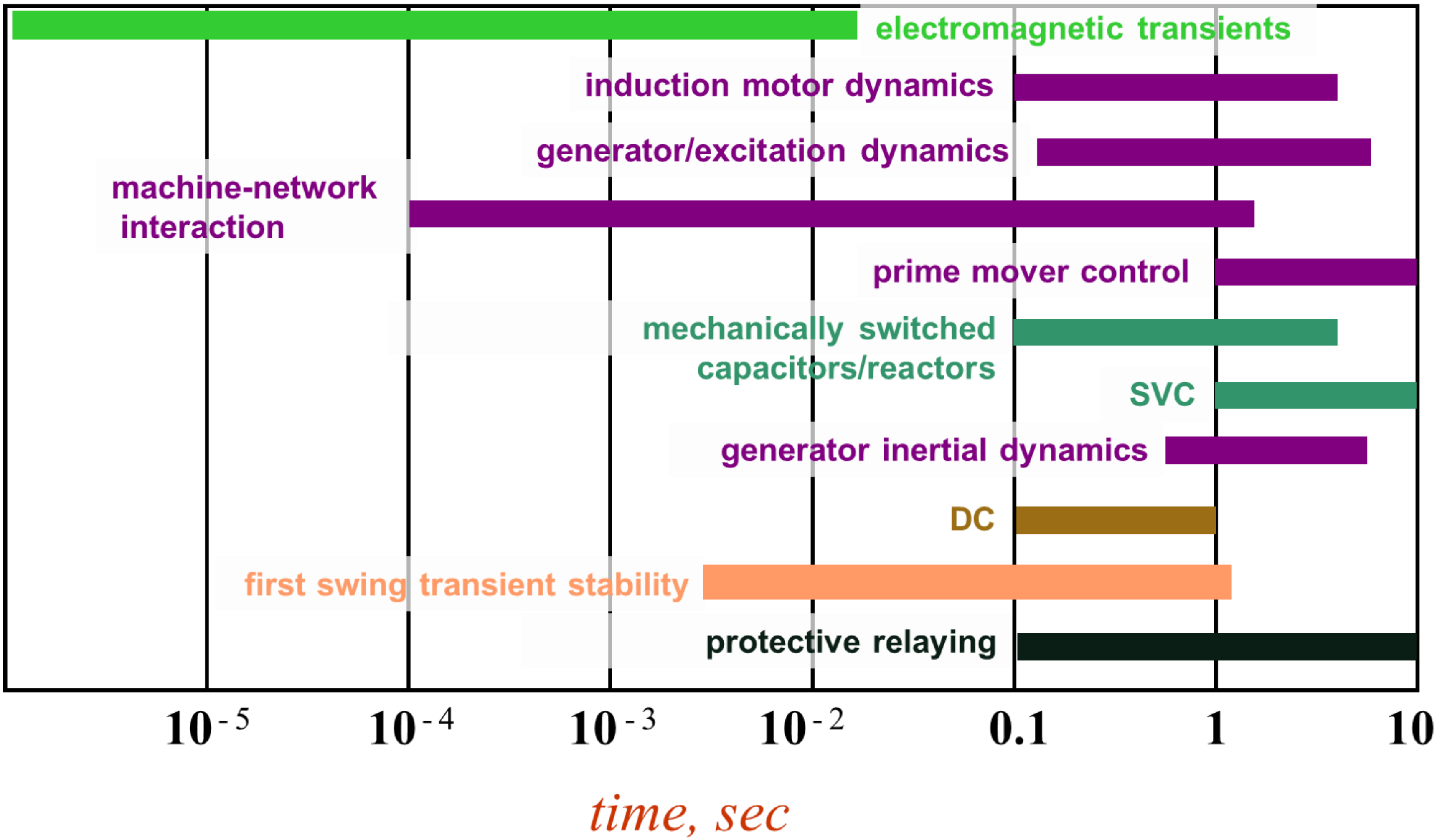
Daily Load Variation



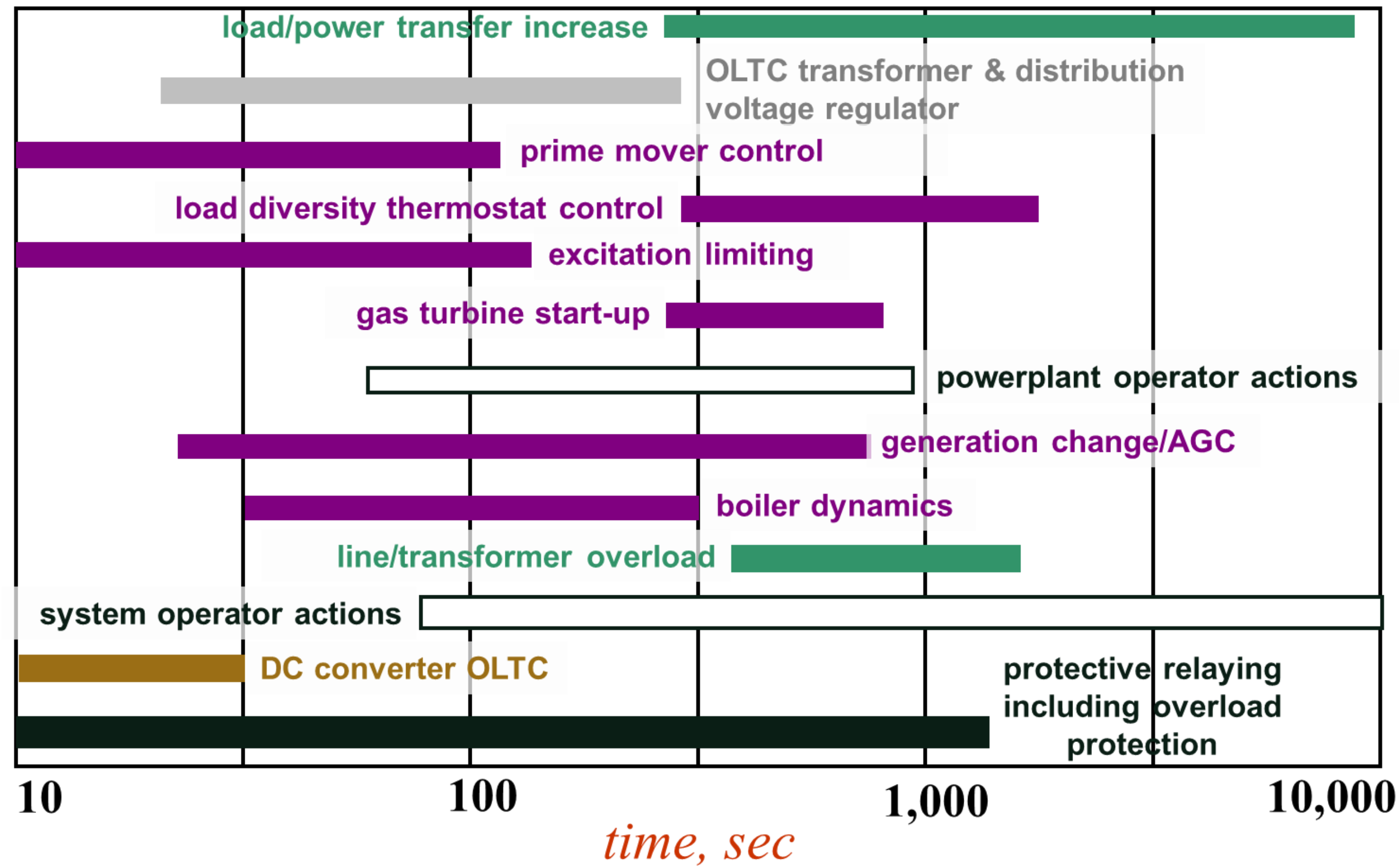
Fundamental Requirements of a Power System

- Electric power delivery by the system must meet minimum standards of power quality
  - constant frequency
  - constant voltage
  - adequate reliability
- System must be able to supply electricity even when subjected to a variety of unexpected contingencies, such as the loss of a transmission line or generator
- A key focus of this course is the control capability to meet these requirements

Power Systems Operate on Many Time Scales

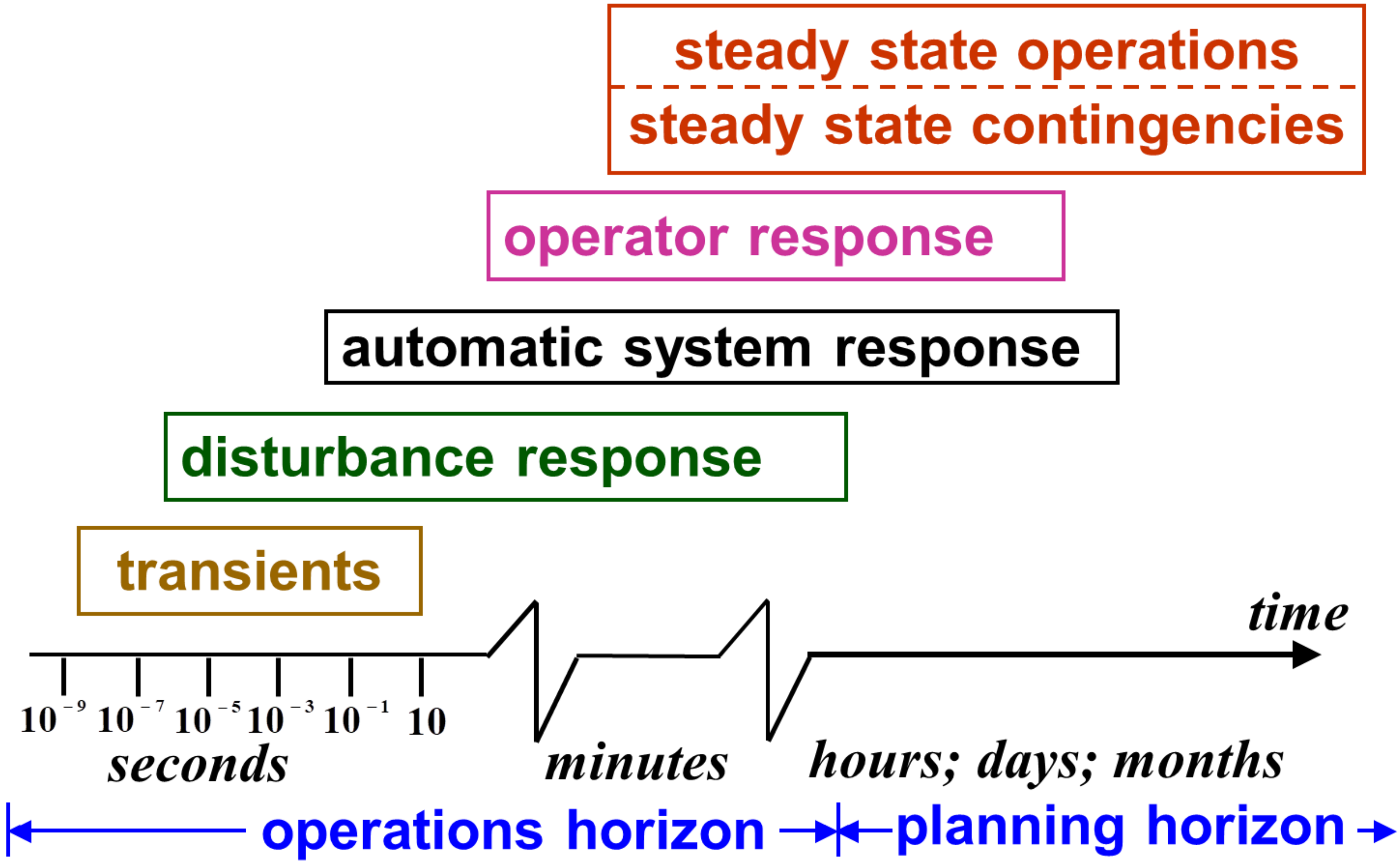


Power Systems Operate on Many Time Scales



Slide source: Prof. George Gross UIUC ECE 530

Power System Operation Regimes



Generation Control and Scheduling Example

time scale	load variations	function	decision
seconds	small & random	automatic generation control	match the on-line generation with the load
minutes	large	economic dispatch	allocate economically the load among the committed generating units
days and hours	wide	hydro scheduling	water releases from reservoirs and hourly hydro generation
		unit commitment	start-up and shutdown of units
		hydrothermal coordination	integrated hydro schedule and unit commitment
		transaction evaluation	interchange of power/energy with neighboring systems
weeks	very wide swings	fuel, hydro and maintenance scheduling	meet load economically with the installed resource mix

Slide source: Prof. George Gross UIUC ECE 530

Modeling Cautions!

- "All models are wrong but some are useful," George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
  - Models are an approximation to reality, not reality, so they always have some degree of approximation
  - Box went on to say that the practical question is how wrong to they have to be to not be useful
- A good part of engineering is deciding what is the appropriate level of modeling, and knowing under what conditions the model will fail
- Always keep in mind what problem you are trying to solve!

Course Objectives

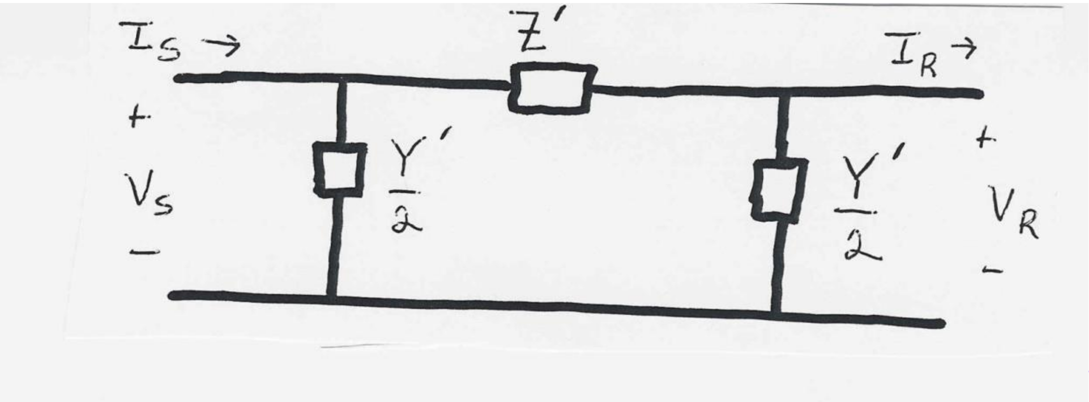
- Acquaint students with some key analytical aspects of large-scale systems
- Stress the importance of problem formulation
- Expose students to some of the major considerations in the design and operation of large-scale systems
- Equip students with skills to read the relevant literature on analytical and computational techniques
- Develop practical skills in solving these types of problems
- Learn how to use example commercial software, especially with application to larger systems

Static Power System Analysis

- One of the most common power system analysis tools is the power flow, which tells how power flows through a power system in the quasi-steady state time frame
  - Load flow is an alternative name for power flow; both terms have been used interchangeably for at least 50 years. I prefer power flow because the power flows, not the load
- The power flow can be used to model the full, three-phase system, but usually (practically always) for transmission system analysis the system is assumed to be balanced. Hence a per phase equivalent model is used.

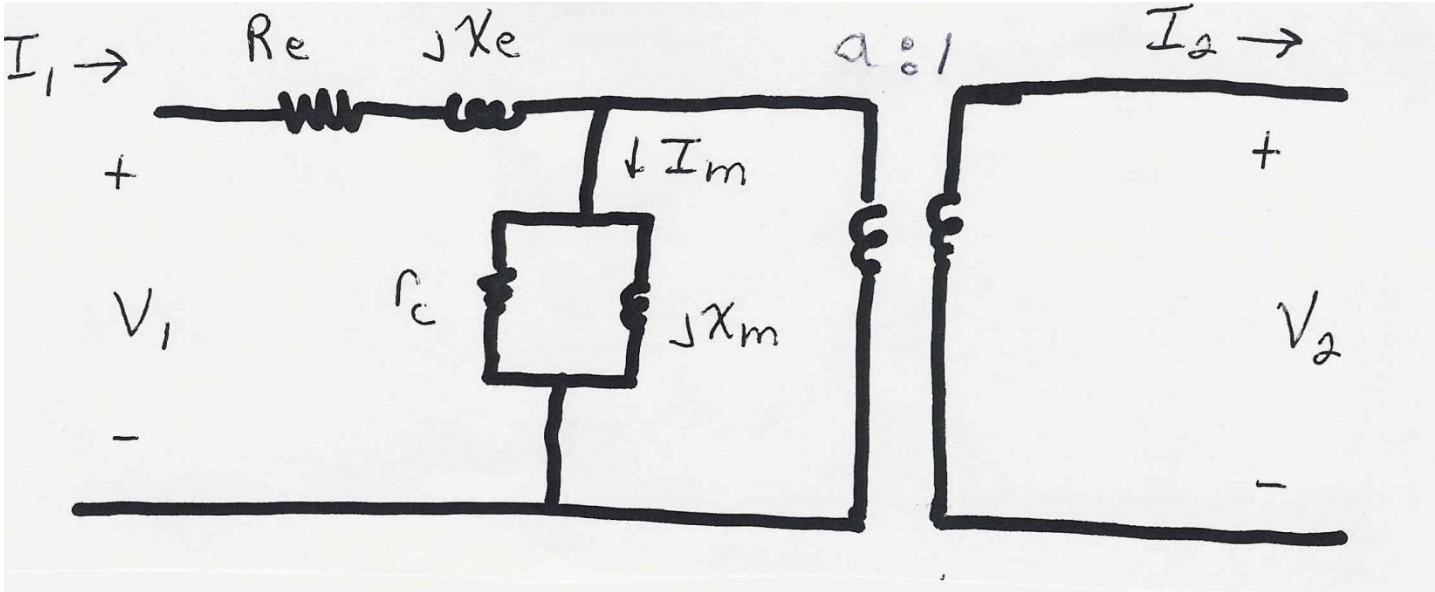
Power System Component Models: Transmission Lines

- Power flow timeframe models for common power system devices, including transmission lines, transformers, generators and loads, are developed in the prerequisite courses ECEN 459 and 460
  - In 615 we will just be using the models, so it isn't strictly required that you know the details on how they were developed; engineers need to know model validity range
- Transmission lines will be modeled using the π circuit



Power System Component Models: Transformers

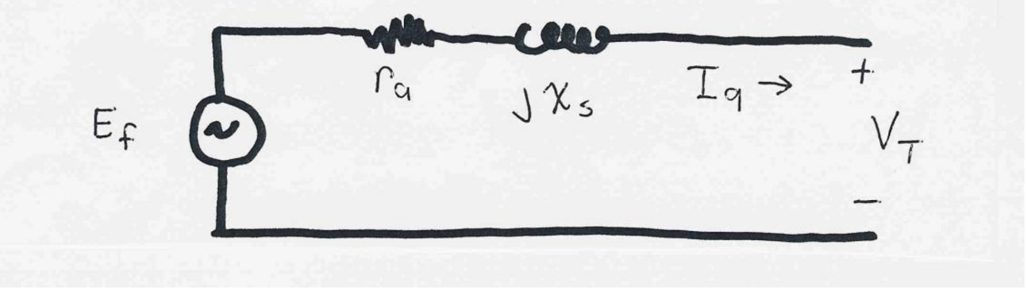
- Transformer equivalent model



In 615 the off-nominal turns ratio, a, will be a key control value. This is potentially a complex number (e.g., with a phase shifting transformer)

Power System Component Models: Generators

- Engineering models depend upon application
- Generators are usually synchronous machines
- For generators we will use two different models:
  - a steady-state model, treating the generator as a constant power source operating at a fixed voltage; this model will be used for power flow and economic analysis
  - a short term model treating the generator as a constant voltage source behind a possibly time-varying reactance (with much more detailed modeled developed in ECEN 667)



Per Phase Calculations

- A key problem in analyzing power systems is the large number of transformers.
  - It would be very difficult to continually have to refer impedances to the different sides of the transformers
- This problem is avoided by a normalization of all variables.
- This normalization is known as per unit analysis

$$\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

Per Unit Conversion Procedure, 1ϕ

1. Pick a 1ϕ VA base for the entire system, S_B
2. Pick a voltage base for each different voltage level, V_B. Voltage bases are related by transformer turns ratios. Voltages are line to neutral.
3. Calculate the impedance base, $Z_B = (V_B)^2/S_B$
4. Calculate the current base, $I_B = V_B/Z_B$
5. Convert actual values to per unit

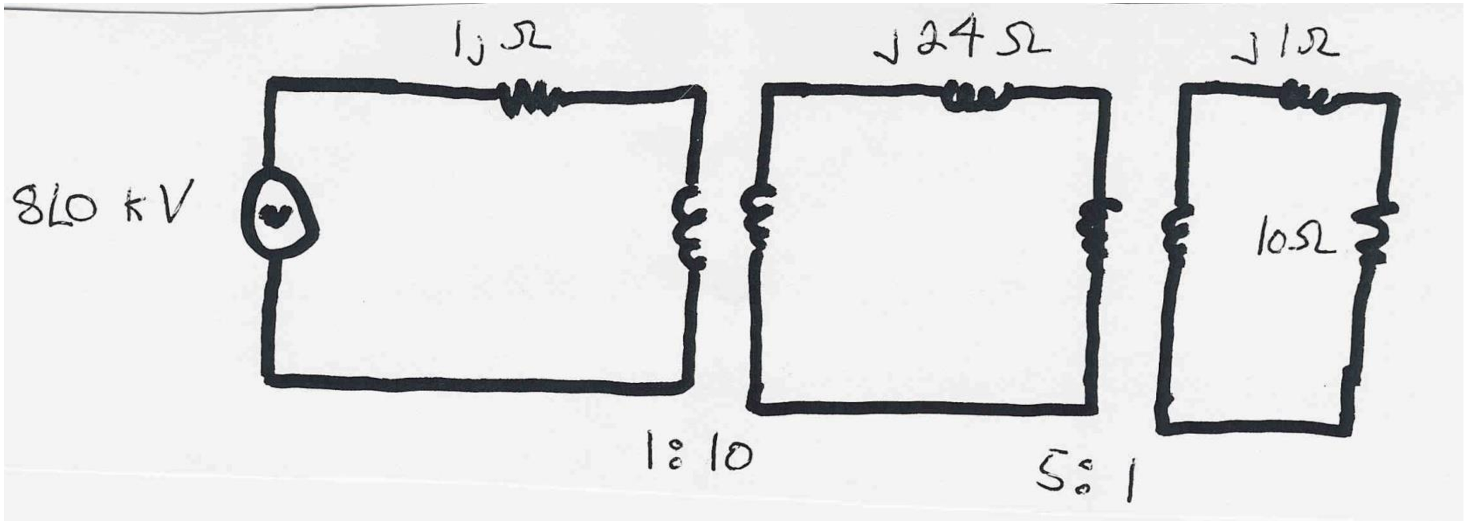
Note, per unit conversion only affects magnitudes, not the angles. Also, per unit quantities no longer have units (i.e., a voltage is 1.0 p.u., not 1 p.u. volts)

Per Unit Solution Procedure

1. Convert to per unit (p.u.) (many problems are already in per unit)
2. Solve
3. Convert back to actual as necessary

Single-Phase Per Unit Example

Solve for the current, load voltage and load power in the circuit shown below using per unit analysis with a single-phase S_B of 100 MVA, and voltage bases of 8 kV, 80 kV and 16 kV



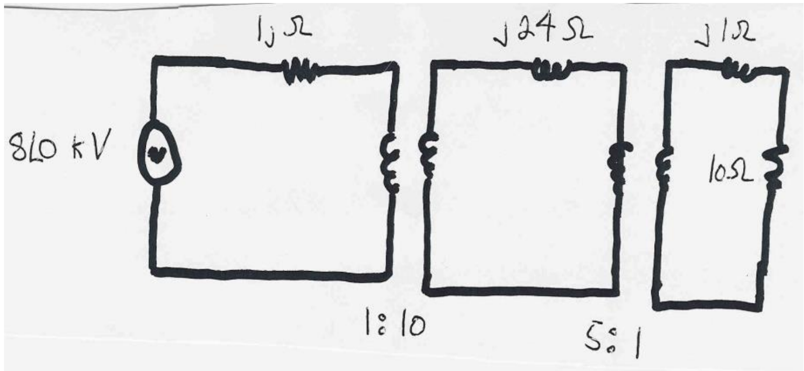
Original Circuit

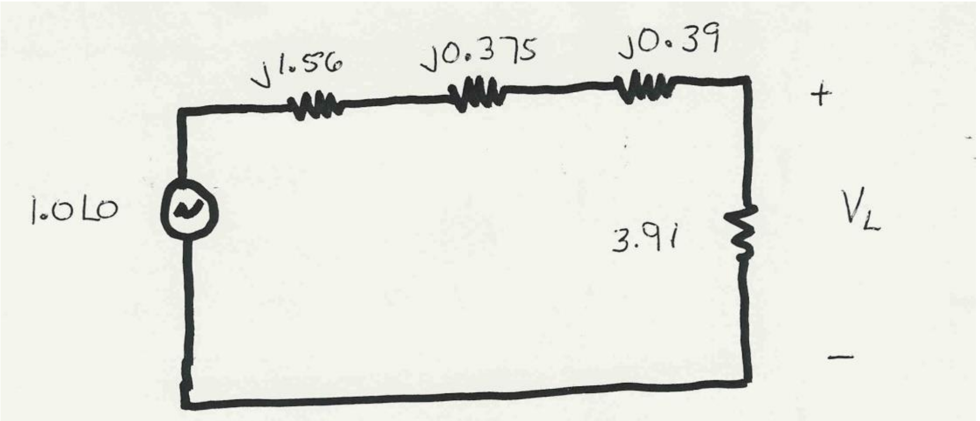
Per Unit Example, cont'd

$$Z_B^{Left} = \frac{8kV^2}{100MVA} = 0.64\Omega$$

$$Z_B^{Middle} = \frac{80kV^2}{100MVA} = 64\Omega$$

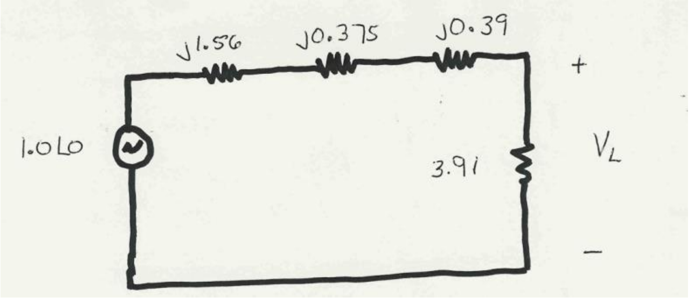
$$Z_B^{Right} = \frac{16kV^2}{100MVA} = 2.56\Omega$$





Same circuit, with values expressed in per unit

Per Unit Example, cont'd



$$I = \frac{1.0\angle 0^\circ}{3.91 + j2.327} = 0.22\angle -30.8^\circ \text{ p.u. (not amps)}$$

$$\begin{aligned} V_L &= 1.0\angle 0^\circ - 0.22\angle -30.8^\circ \times 2.327\angle 90^\circ \\ &= 0.859\angle -30.8^\circ \text{ p.u.} \end{aligned}$$

$$S_L = V_L I_L^* = \frac{|V_L|^2}{Z} = 0.189 \text{ p.u.}$$

$$S_G = 1.0\angle 0^\circ \times 0.22\angle 30.8^\circ = 0.22\angle 30.8^\circ \text{ p.u.}$$

Per Unit Example, cont'd

To convert back to actual values just multiply the per unit values by their per unit base

$$V_L^{\text{Actual}} = 0.859\angle -30.8° \times 16 \text{ kV} = 13.7\angle -30.8° \text{ kV}$$

$$S_L^{\text{Actual}} = 0.189\angle 0° \times 100 \text{ MVA} = 18.9\angle 0° \text{ MVA}$$

$$S_G^{\text{Actual}} = 0.22\angle 30.8° \times 100 \text{ MVA} = 22.0\angle 30.8° \text{ MVA}$$

$$\text{I}_\text{B}^{\text{Middle}} = \frac{100 \text{ MVA}}{80 \text{ kV}} = 1250 \text{ Amps}$$

$$\text{I}_{\text{Middle}}^{\text{Actual}} = 0.22\angle -30.8° \times 1250 \text{ Amps} = 275\angle -30.8° \text{ A}$$

Three Phase Per Unit

Procedure is very similar to 1ϕ except we use a 3ϕ VA base, and use line to line voltage bases

1. Pick a 3ϕ VA base for the entire system,
2. Pick a voltage base for each different voltage level, V_B. Voltages are line to line.
3. Calculate the impedance base

$$Z_B = \frac{V_{B,LL}^2}{S_B^{3\phi}} = \frac{(\sqrt{3}\,V_{B,LN})^2}{3S_B^{1\phi}} = \frac{V_{B,LN}^2}{S_B^{1\phi}}$$

Exactly the same impedance bases as with single phase!

Three Phase Per Unit, cont'd

4. Calculate the current base, I_B

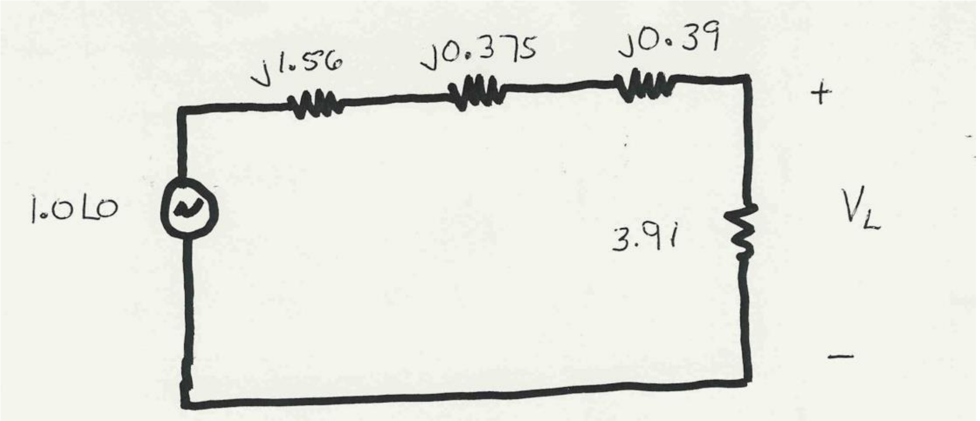
$$I_B^{3\phi} = \frac{S_B^{3\phi}}{\sqrt{3}\,V_{B,LL}} = \frac{3\,S_B^{1\phi}}{\sqrt{3}\,\sqrt{3}\,V_{B,LN}} = \frac{S_B^{1\phi}}{V_{B,LN}} = I_B^{1\phi}$$

Exactly the same current bases as with single-phase!

5. Convert actual values to per unit

Three-Phase Per Unit Example

Solve for the current, load voltage and load power in the previous circuit, assuming a 3ϕ power base of 300 MVA, and line to line voltage bases of 13.8 kV, 138 kV and 27.6 kV (square root of 3 larger than the 1ϕ example voltages). Also assume the generator is Y-connected so its line to line voltage is 13.8 kV.



Convert to per unit as before. Note the system is exactly the same!

Three-Phase Per Unit Example, cont'd

$$I = \frac{1.0\angle 0^\circ}{3.91 + j2.327} = 0.22\angle -30.8^\circ \text{ p.u. (not amps)}$$

$$\mathrm{V_L} = 1.0\angle 0^\circ - 0.22\angle -30.8^\circ \times 2.327\angle 90^\circ$$

$$= 0.859\angle -30.8^\circ \text{ p.u.}$$

$$S_L = V_L I_L^* = \frac{|V_L|^2}{Z} = 0.189 \text{ p.u.}$$

$$S_G = 1.0\angle 0^\circ \times 0.22\angle 30.8^\circ = 0.22\angle 30.8^\circ \text{ p.u.}$$

Again, analysis is exactly the same!

Three-Phase Per Unit Example, cont'd

Differences appear when we convert back to actual values

$$V_L^{\text{Actual}} = 0.859\angle -30.8° \times 27.6 \text{ kV} = 23.8\angle -30.8° \text{ kV}$$

$$S_L^{\text{Actual}} = 0.189\angle 0° \times 300 \text{ MVA} = 56.7\angle 0° \text{ MVA}$$

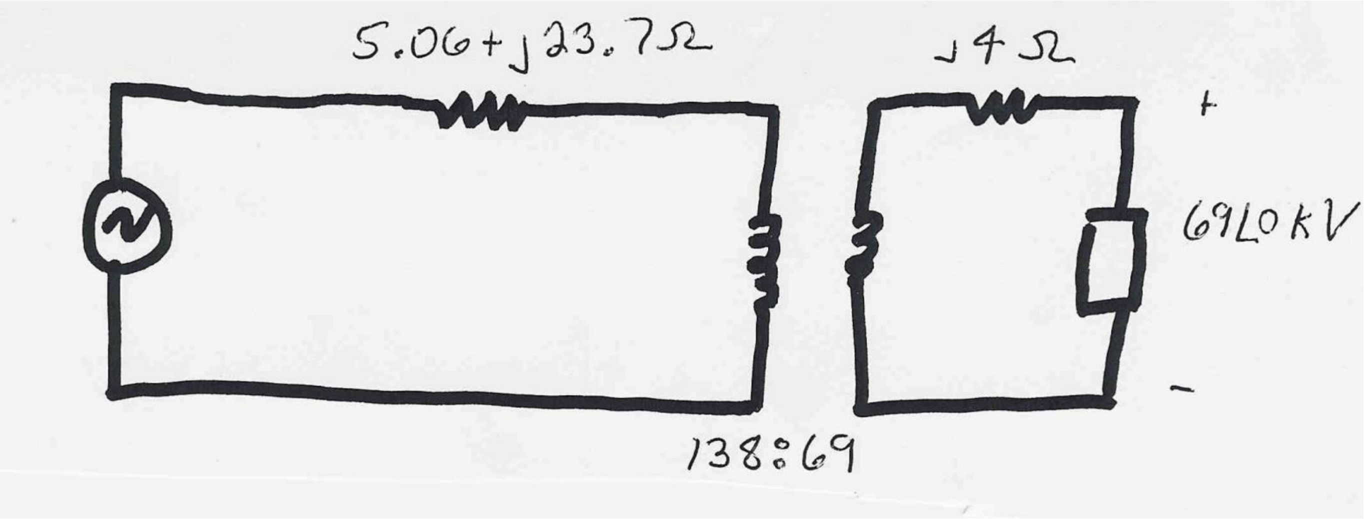
$$S_G^{\text{Actual}} = 0.22\angle 30.8° \times 300 \text{ MVA} = 66.0\angle 30.8° \text{ MVA}$$

$$I_B^{\text{Middle}} = \frac{300 \text{ MVA}}{\sqrt{3}\, 138 \text{ kV}} = 1250 \text{ Amps} \quad \text{(same current!)}$$

$$I_{\text{Middle}}^{\text{Actual}} = 0.22\angle -30.8° \times 1250 \text{ Amps} = 275\angle -30.8° \text{ A}$$

Three-Phase Per Unit Example 2

- Assume a 3ϕ load of 100+j50 MVA with V_{LL} of 69 kV is connected to a source through the below network:



What is the supply current and complex power?

Answer: I=467 amps, S = 103.3 + j76.0 MVA