ECEN 667
Power System Stability

Lecture 1: Introduction

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Energy and Power Group (EPG) at Texas A&M

- Texas A&M is a leader in power and energy research!
- 14+ Faculty members in various expertise areas of power systems, power electronics, and electric machines
- Get connected!

Smart Grid Research Facility

EPG Spring 2025 Picnic at Dr. Overbye's house

Texas Power and Energy Conference (**Student Run!!**)

Welcome to ECEN 667!

- Class website: https://birchfield.engr.tamu.edu/667f25/
- Also check out the Canvas page and the syllabus
- Slides and homework will be posted on the website, lecture recordings will be on Canvas
- Office Hours Wednesdays 3-5 pm, Wisenbaker 215-E, or on Zoom (link on Canvas)
- Grading

  10% Class participation – see syllabus

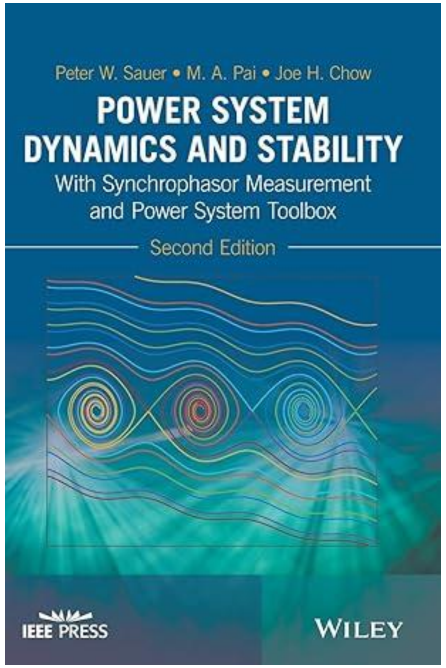
  30% Exam 1 – Tentatively Thursday, Oct. 9th

  30% Exam 2 – Tentatively Thursday, Dec. 4th

  30% Homework Assignments – Assigned in class, 4-7 throughout semester

Before Next Class

- Read Chapter 1 of the book
- Get access to PowerWorld Simulator on your computer and get familiar with the basics
- Review power system fundamentals from this slide deck and attend office hours for any questions



Link to free student 42-bus version
https://www.powerworld.com/gloveroverbyesarma
Link to free training material
https://www.powerworld.com/training/courses
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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)

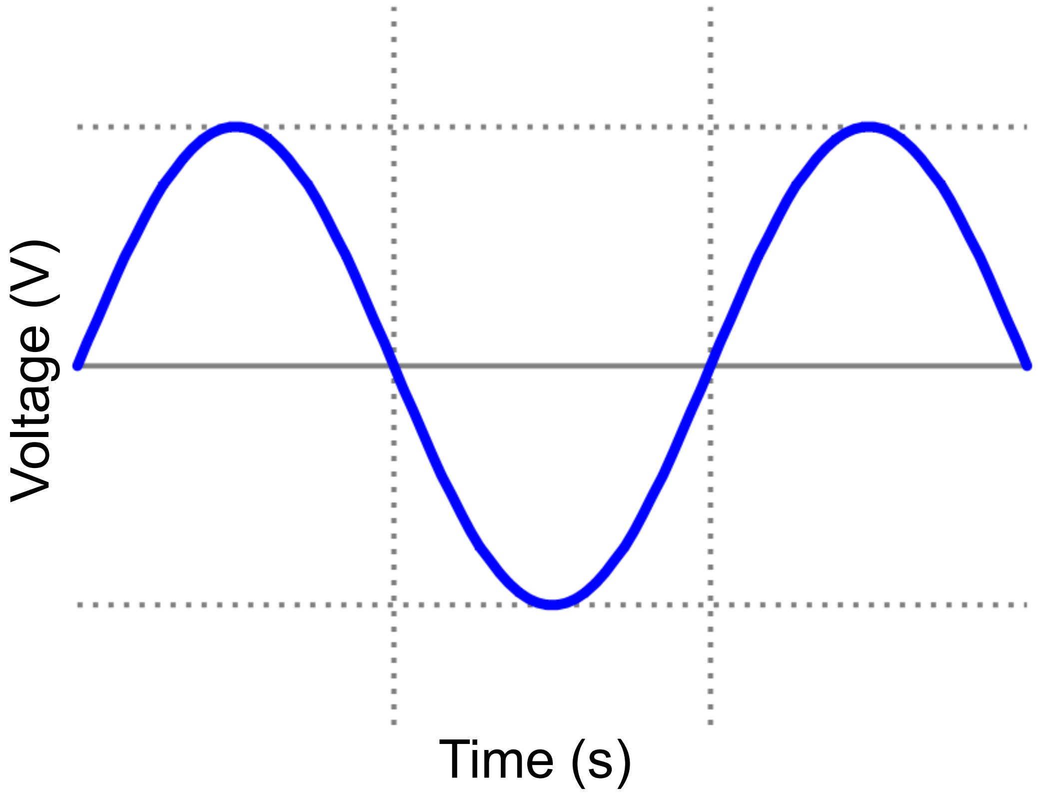
Maximum load of Bryan/College Station is about 500 MW

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

Review of Phasors

We represent ac voltage and current as complex numbers

$$v(t) = V_{\max} \cos(\omega t + \theta_v) \quad \rightarrow \quad \bar{V} = \frac{V_{max}}{\sqrt{2}} \cos\theta_V + j\frac{V_{max}}{\sqrt{2}} \sin\theta_V$$

$$i(t) = I_{\max} \cos(\omega t + \theta_i) \quad \rightarrow \quad \bar{I} = \frac{I_{max}}{\sqrt{2}} \cos\theta_I + j\frac{I_{max}}{\sqrt{2}} \sin\theta_I$$

And impedance is a complex quantity for linear circuit elements

$$\bar{Z} = \text{Impedance} = R + jX = Z\angle\phi \qquad Z = \sqrt{R^2 + X^2} \qquad \phi = \arctan\left(\frac{X}{R}\right)$$

R = Resistance

X = Reactance

Device	**Time Analysis**	**Phasor Analysis**
Resistor	$v(t) = Ri(t)$	$\bar{V} = R\bar{I}$
Inductor	$v(t) = L\frac{di(t)}{dt}$	$\bar{V} = j\omega L\,\bar{I}$
Capacitor	$i(t) = C\frac{dv(t)}{dt}$	$\bar{V} = \frac{1}{j\omega C}\bar{I}$

Complex Power

When using phasors to represent AC voltage and current, we use complex power $\bar{S}$ as follows

$$\bar{S} = VI(\cos(\theta_v - \theta_i) + j\sin(\theta_v - \theta_i)) = P + jQ = S\angle\phi = \bar{V}\bar{I}^*$$

P is real power (W, kW, MW)

Q is reactive power (var, kvar, Mvar)

$\bar{S}$ is complex power (VA, kVA, MVA)

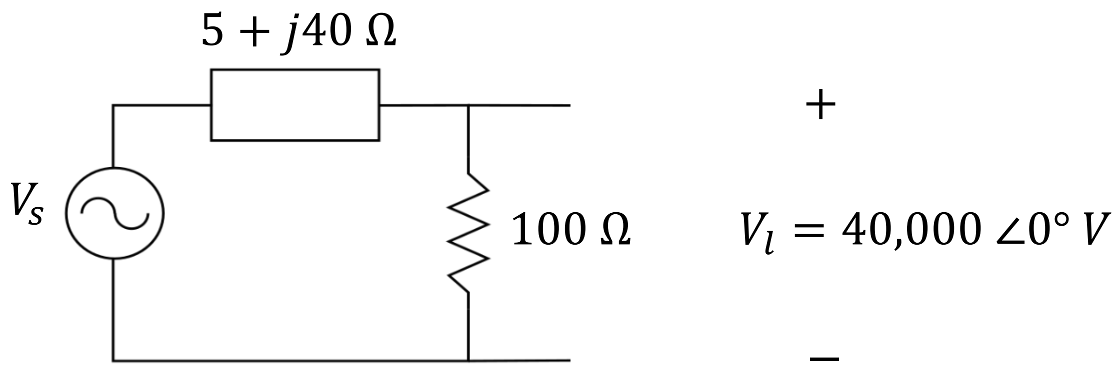
Power Factor (pf) $= \cos\phi$

If current leads voltage then pf is leading

If current lags voltage then pf is lagging

Device	Power Consumption
Resistor	Only consumes real power $\mathrm{P} = I^2 R$
Inductor	Only consumes reactive power $Q = I^2\omega L = I^2 X$
Capacitor	Only produces reactive power $Q = -\frac{I^2}{\omega C} = -I^2 X_c$

Phasors and Complex Power Example



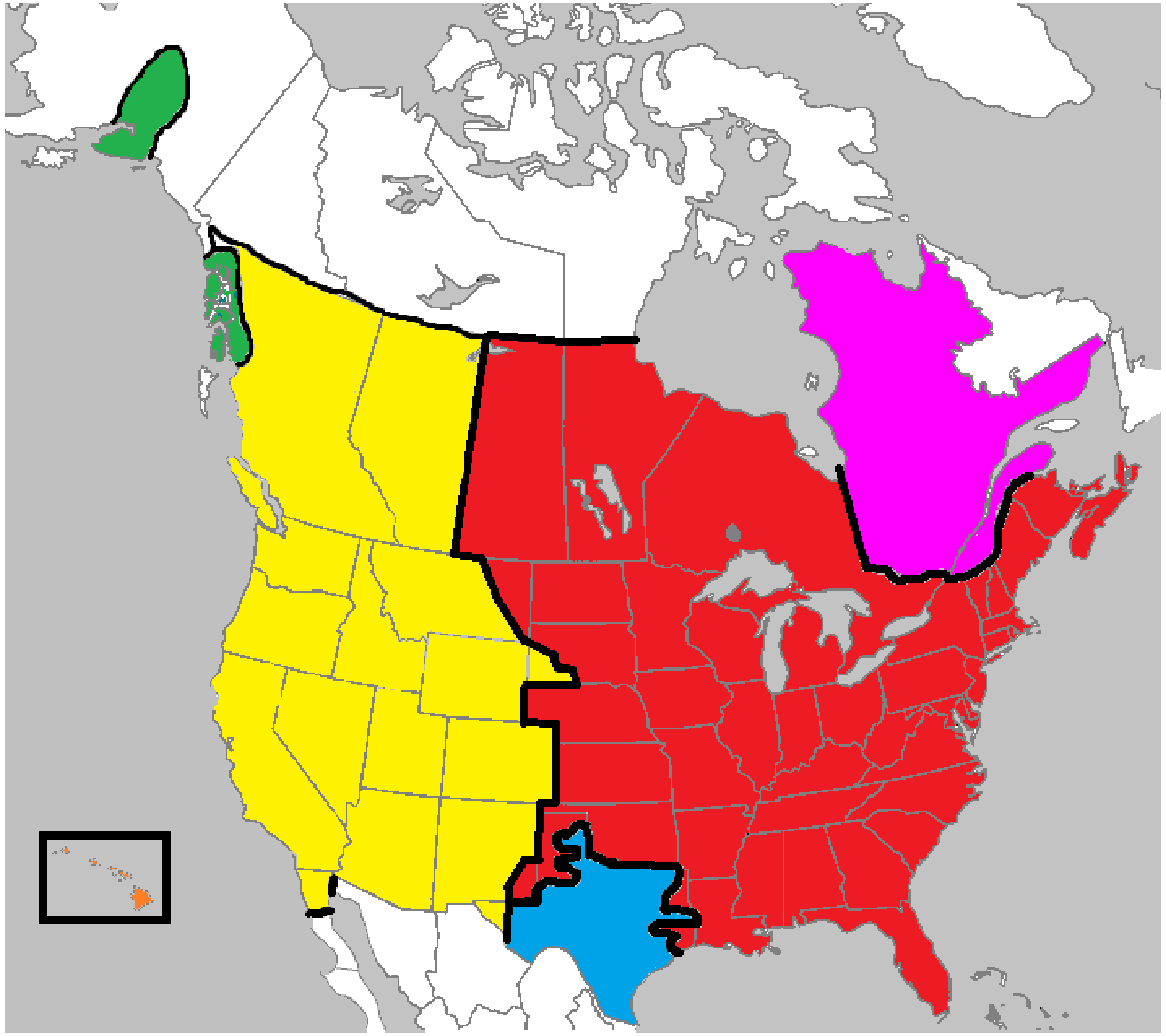
Current in the load: $\bar{I} = \frac{\bar{V}_l}{R} = \frac{40000\angle 0° V}{100\Omega} = 400\angle 0°\ A$

Voltage at source: $\bar{V}_s = \bar{V}_l + \bar{I}\bar{Z}_{line} = 40000 + (5 + j40)\ 400\ = 44.9\ \angle 20.8°\ \text{kV}$

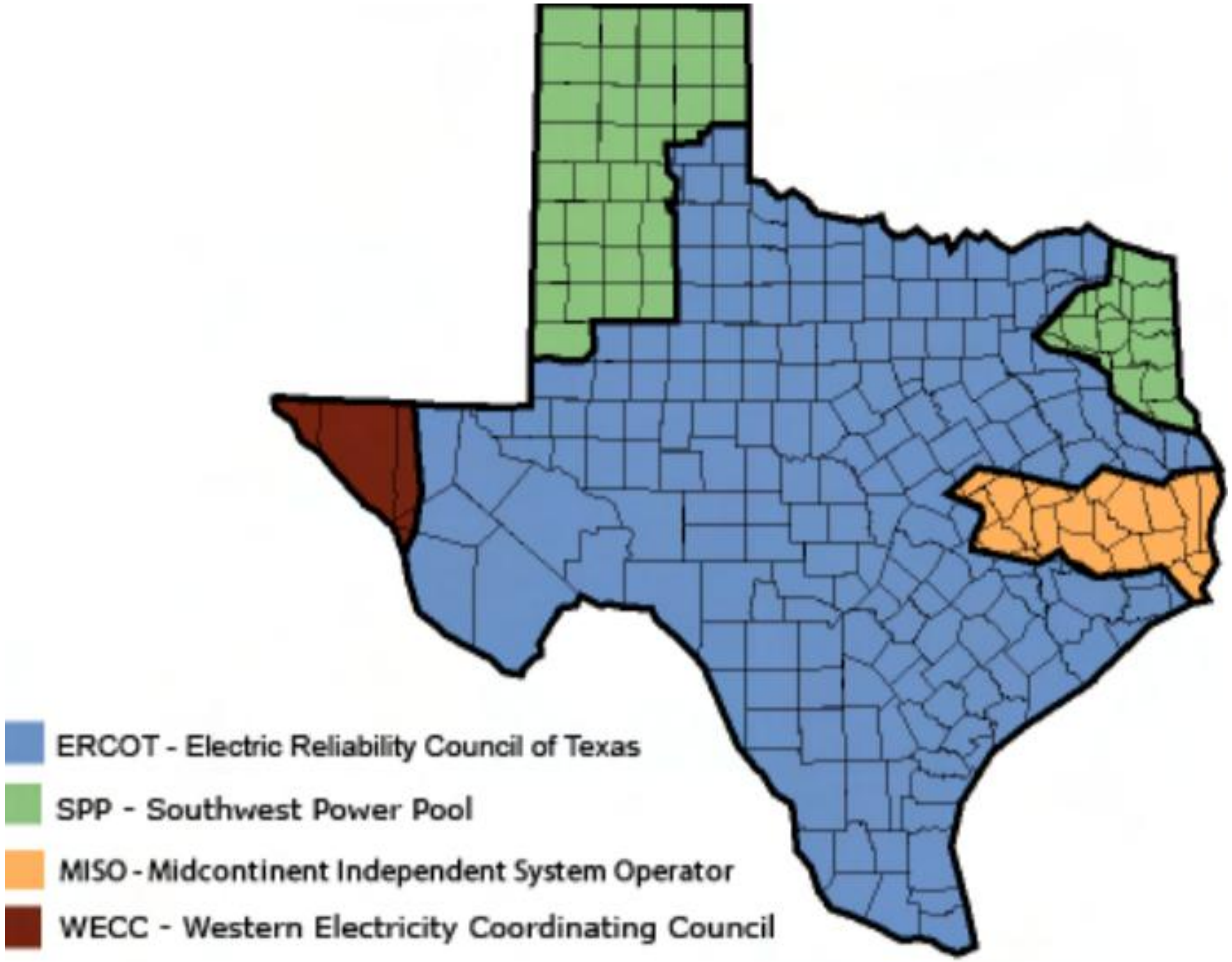
Source power: $\bar{S} = \bar{V}_s\bar{I}^* = (44.9\ \angle 20.8°\ \text{kV})(400\angle 0°\ A)^* = 16.8 + j6.4\ \text{MVA}$

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

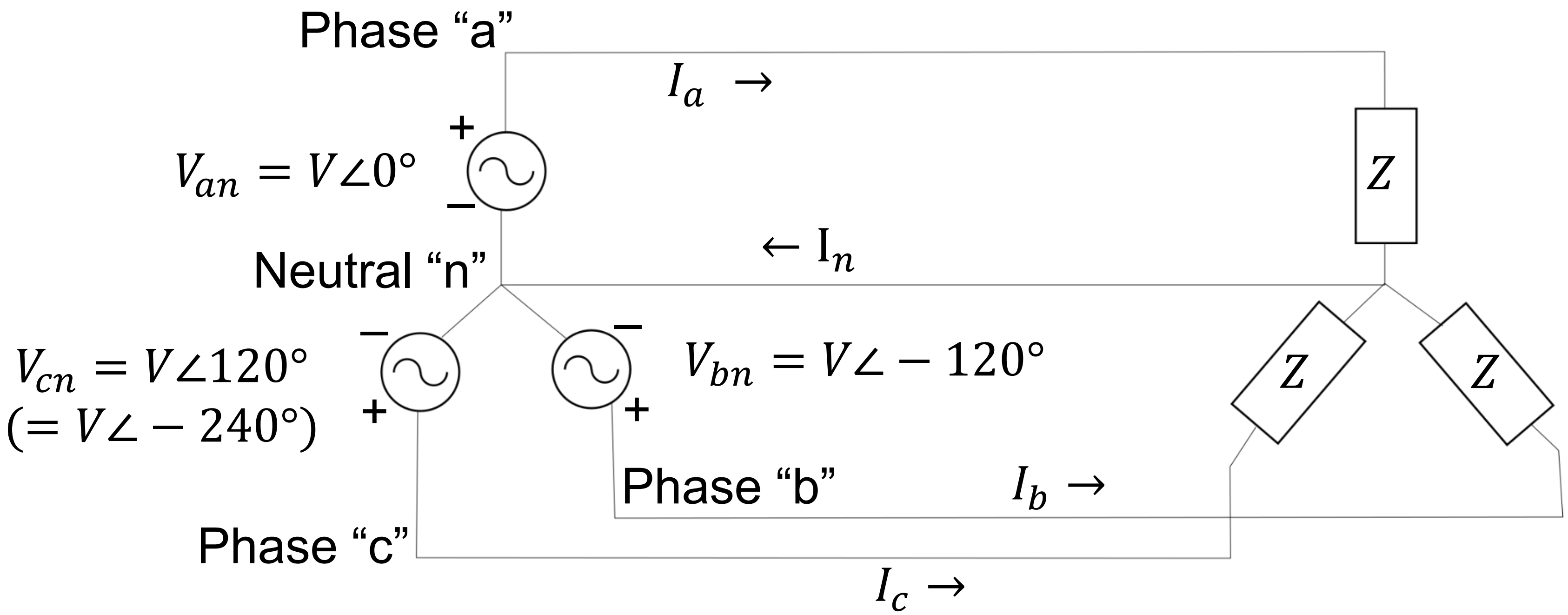


Source: www.puc.texas.gov/industry/maps/maps/ERCOT.pdf

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
- Advantages
  - 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

Balanced 3ϕ Example



$$I_n = I_a + I_b + I_c$$

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

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

Symmetrical Components

- Imbalance is an important part of some power system studies.
- However, there are many studies (including many stability problems) where a completely balanced system is a good assumption.
- If so, we can take advantage of the symmetry by using symmetrical components to transform balanced system into three “sequences”
- Instead of $\bar{V}_a, \bar{V}_b, \bar{V}_c$ and $\bar{I}_a, \bar{I}_b, \bar{I}_c$ we have
  - Positive sequence $\bar{V}_1$ and $\bar{I}_1$
  - Negative sequence $\bar{V}_2$ and $\bar{I}_2$
  - Zero sequence $\bar{V}_0$ and $\bar{V}_2$
- If the system is perfectly balanced, then the three sequences are totally decoupled and the negative and zero sequence values are zero.
- Hence, we focus all our analysis on the positive sequence, which is a single-phase circuit. (Normally $\bar{V}$ and $\bar{I}$ will refer to positive sequence.)

See Fortescue’s paper and standard power system textbooks for more information

Symmetrical Components Example

- Symmetrical components transformation matrix

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}, \text{where } \alpha = 1\angle 120°$$

- So if we have a balanced set of voltages (or, similarly, currents)

$$\begin{bmatrix} \bar{V}_a \\ \bar{V}_b \\ \bar{V}_c \end{bmatrix} = \begin{bmatrix} V\angle\theta_v \\ V\angle(\theta_v - 120°) \\ V\angle(\theta_v + 120°) \end{bmatrix} \rightarrow \begin{bmatrix} \bar{V}_0 \\ \bar{V}_1 \\ \bar{V}_2 \end{bmatrix} = \mathbf{A}^{-1} \begin{bmatrix} \bar{V}_a \\ \bar{V}_b \\ \bar{V}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}^{-1} \begin{bmatrix} V\angle\theta_v \\ V\angle(\theta_v - 120°) \\ V\angle(\theta_v + 120°) \end{bmatrix} = \begin{bmatrix} 0 \\ V\angle\theta_v \\ 0 \end{bmatrix}$$

- Likewise, if we have a balanced impedance system

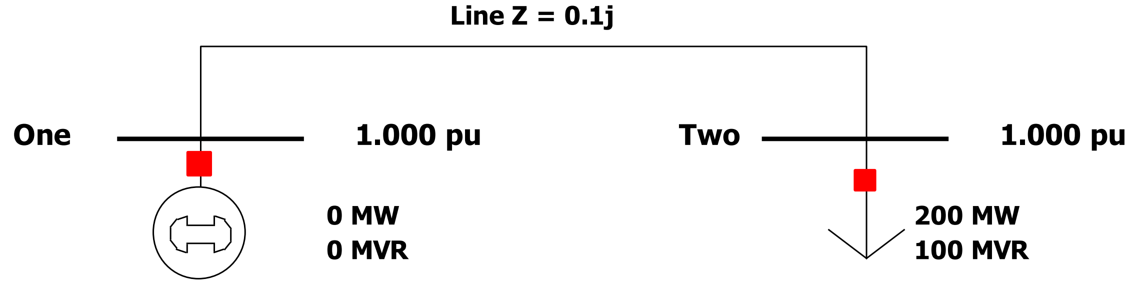
$$\mathbf{Z_{abc}} = \begin{bmatrix} Z_s + Z_m & Z_m & Z_m \\ Z_m & Z_s + Z_m & Z_m \\ Z_m & Z_m & Z_s + Z_m \end{bmatrix} \rightarrow \mathbf{Z_{012}} = \mathbf{A}^{-1}\mathbf{Z_{abc}}\mathbf{A} = \begin{bmatrix} Z_s + 3Z_m & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_s \end{bmatrix}$$

- So we get independent, separate sequence circuits, where only the positive sequence is non-trivial in balanced operation.

Power Flow: Analyzing the Grid in Steady State

- Power flow
  - Standard grid analysis for steady-state conditions (perfect sinusoids)
  - Impedance models for transmission lines and transformers
  - Loads are constant power
  - Generators are constant real power and constant voltage magnitude
  - Need a “slack bus” to be the reference angle and have variable real power
  - Non-linear algebraic problem with P and Q balance equations
  - Solved with Newton-Raphson based iterative method
  - See ECEN 460 and ECEN 615 for more information
- So what happens when something changes? Say open a transmission line?
  - Solve a new power flow and we can find the new steady-state conditions (new voltages, new flows in the other lines)

Power Flow Example



Variables

$$\mathbf{x} = \begin{bmatrix} \theta_2 \\ V_2 \end{bmatrix} \quad \mathbf{Y}_{bus} = \begin{bmatrix} -j10 & j10 \\ j10 & -j10 \end{bmatrix}$$

Power balance equations

$$V_2 V_1 (10 \sin\theta_2) + 2.0 = 0$$
$$V_2 V_1 (-10 \cos\theta_2) + V_2^2 (10) + 1.0 = 0$$

Calculating the power flow Jacobian

$$J(\mathbf{x}) = \begin{bmatrix} \frac{\partial P_2(\mathbf{x})}{\partial \theta_2} & \frac{\partial P_2(\mathbf{x})}{\partial |V|_2} \\ \frac{\partial Q_2(\mathbf{x})}{\partial \theta_2} & \frac{\partial Q_2(\mathbf{x})}{\partial |V|_2} \end{bmatrix}$$
$$= \begin{bmatrix} 10|V_2| \cos\theta_2 & 10 \sin\theta_2 \\ 10|V_2| \sin\theta_2 & -10\cos\theta_2 + 20|V_2| \end{bmatrix}$$

First iteration

Set $v = 0$, guess $\mathbf{x}^{(0)} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

Calculate

$$f(\mathbf{x}^{(0)}) = \begin{bmatrix} |V_2|(10 \sin\theta_2) + 2.0 \\ |V_2|(-10\cos\theta_2) + |V_2|^2(10) + 1.0 \end{bmatrix} = \begin{bmatrix} 2.0 \\ 1.0 \end{bmatrix}$$

$$\mathbf{J}(\mathbf{x}^{(0)}) = \begin{bmatrix} 10|V_2| \cos\theta_2 & 10 \sin\theta_2 \\ 10|V_2| \sin\theta_2 & -10\cos\theta_2 + 20|V_2| \end{bmatrix} = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}$$

Solve $\mathbf{x}^{(1)} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} - \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}^{-1} \begin{bmatrix} 2.0 \\ 1.0 \end{bmatrix} = \begin{bmatrix} -0.2 \\ 0.9 \end{bmatrix}$

Second iteration

$$f(\mathbf{x}^{(1)}) = \begin{bmatrix} 0.9(10\sin(-0.2)) + 2.0 \\ 0.9(-10\cos(-0.2)) + 0.9^2 \times 10 + 1.0 \end{bmatrix} = \begin{bmatrix} 0.212 \\ 0.279 \end{bmatrix}$$

$$\mathbf{J}(\mathbf{x}^{(1)}) = \begin{bmatrix} 8.82 & -1.986 \\ -1.788 & 8.199 \end{bmatrix}$$

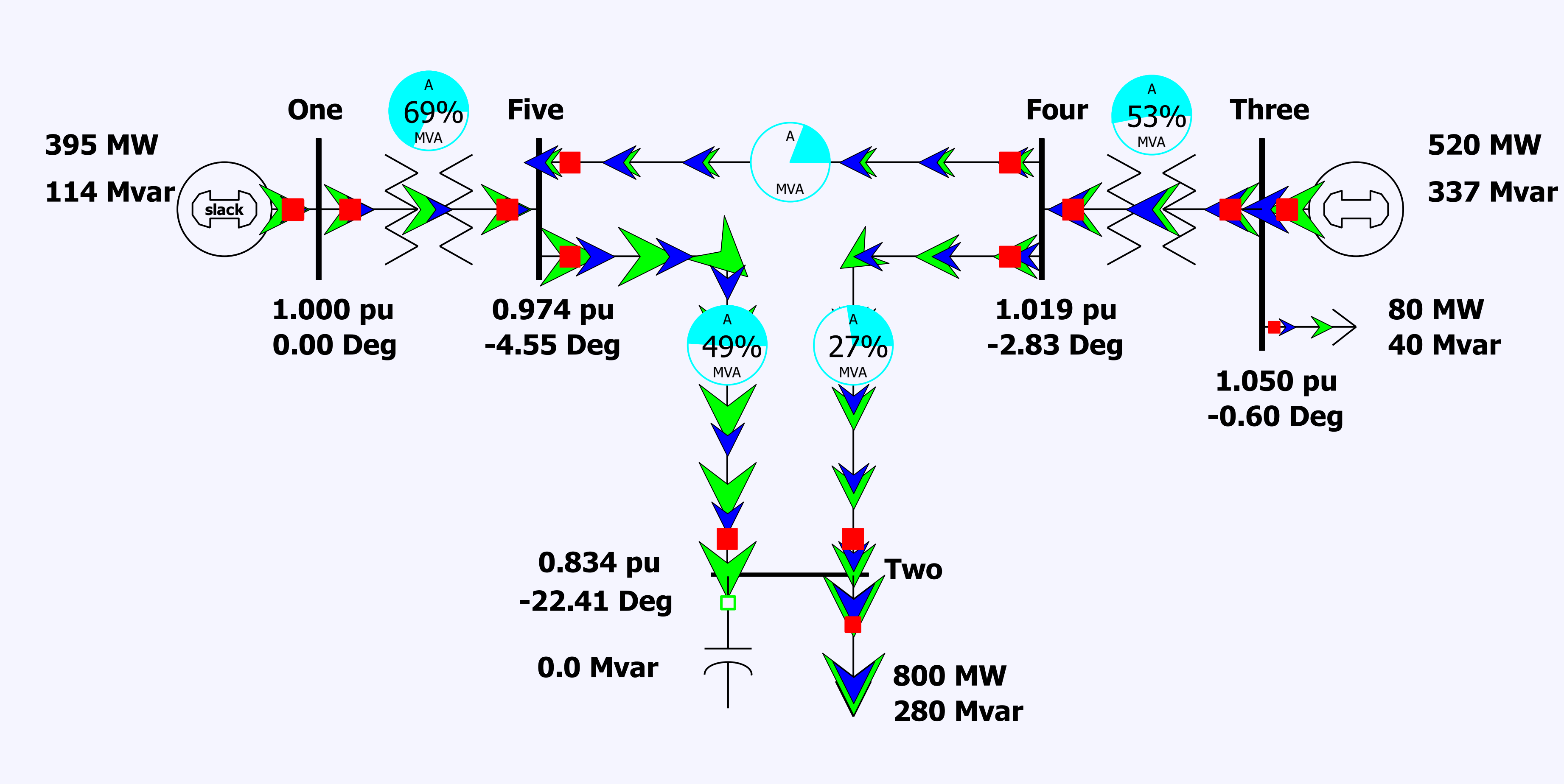
$$\mathbf{x}^{(2)} = \begin{bmatrix} -0.2 \\ 0.9 \end{bmatrix} - \begin{bmatrix} 8.82 & -1.986 \\ -1.788 & 8.199 \end{bmatrix}^{-1} \begin{bmatrix} 0.212 \\ 0.279 \end{bmatrix} = \begin{bmatrix} -0.233 \\ 0.8586 \end{bmatrix}$$

Third iteration

$$f(\mathbf{x}^{(2)}) = \begin{bmatrix} 0.0145 \\ 0.0190 \end{bmatrix} \quad \mathbf{x}^{(3)} = \begin{bmatrix} -0.236 \\ 0.8554 \end{bmatrix}$$

$f(\mathbf{x}^{(3)}) = \begin{bmatrix} 0.0000906 \\ 0.0001175 \end{bmatrix}$ Done! $V_2 = 0.8554\angle -13.52°$

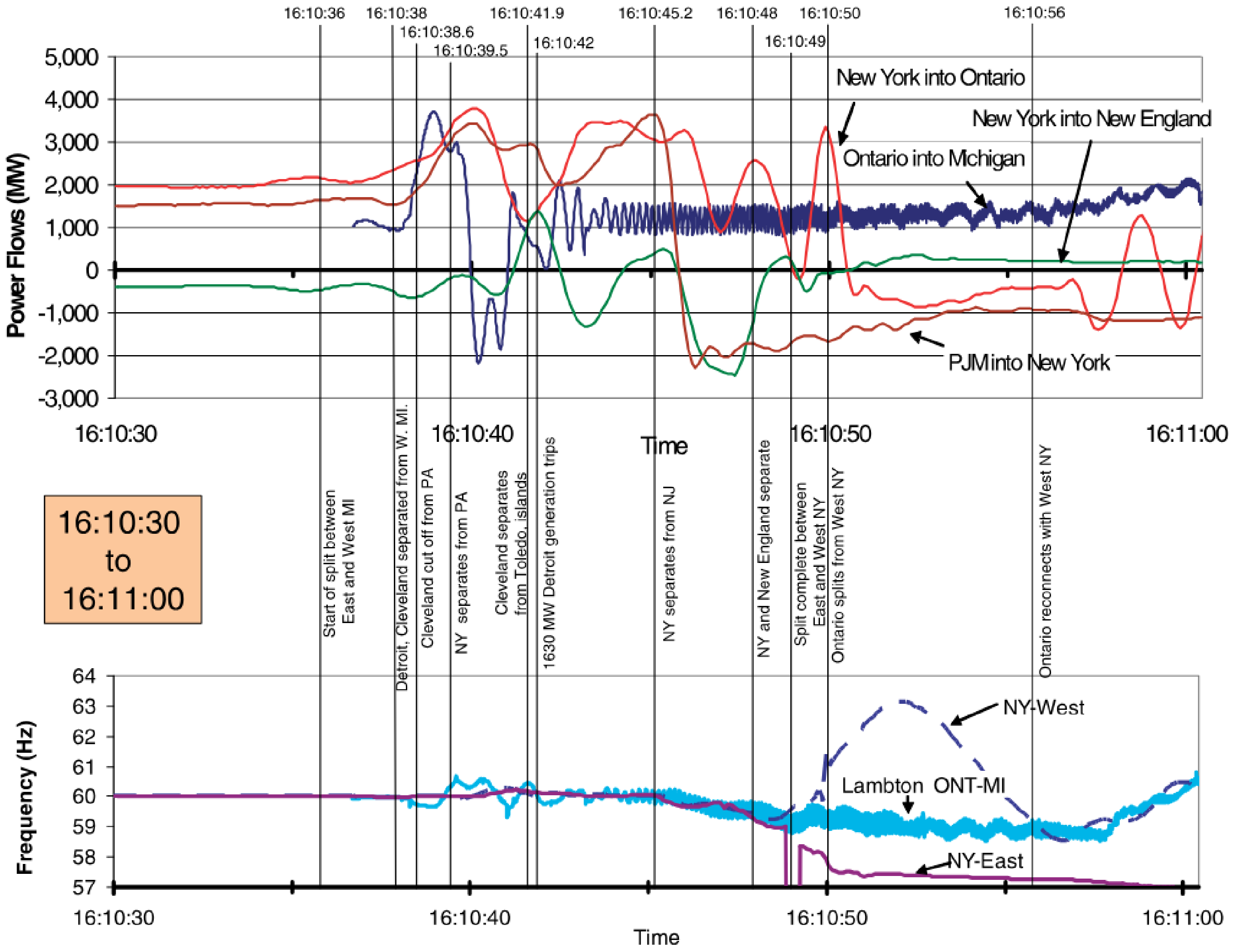
A 5-Bus Power Flow Result in PowerWorld



This gives the steady-state voltage magnitude, voltage angle, real and reactive power, assuming everything is a constant sinusoid

Power Systems Are Dynamic!!

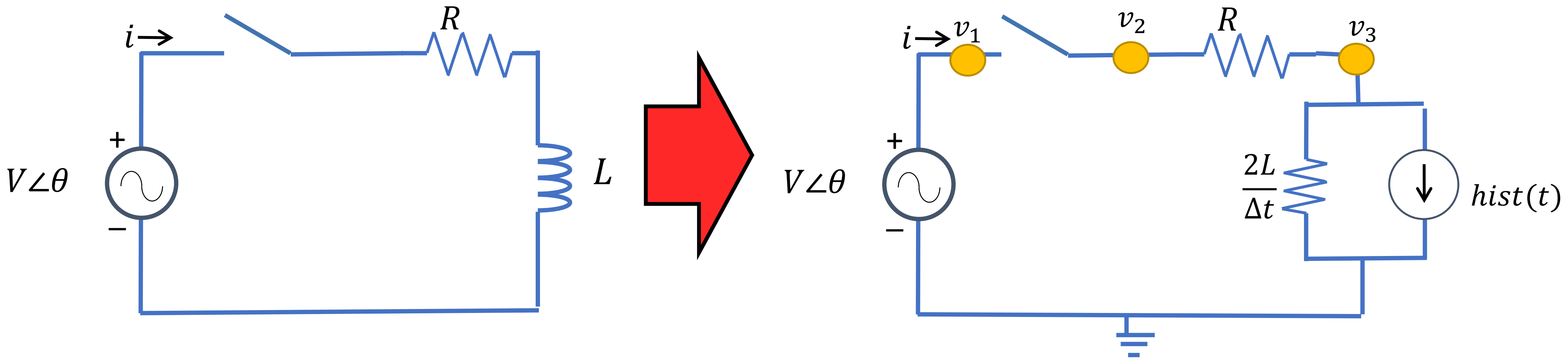
- Power flows and frequencies during the August 14, 2003 blackout event
- In 30 seconds, cascading events caused oscillations, tripping, and separation of the grid
- Image from Blackout Final Report, Fig. 6.17
- Power flow cannot capture these effects!



Electromagnetic Transients

- There are some phenomena on the grid that happen so fast we (generally) aren't concerned with them for system stability analysis
  - Switching surges – line, capacitor, etc.
  - Lightning
  - Transients in transformers, transmission lines, and machine stator windings
  - Fast electronics switching and control loops (although this is somewhat changing)
- Electromagnetic transients is the tool used for this phenomena
  - Historically more localized studies, but increasingly larger systems
  - ECEN 616 covers these in detail
  - These do not use phasor or balanced assumptions
  - Timesteps in the microseconds
  - Generally, they are solved with a trapezoidal integration method based on the work of Hermann Dommel

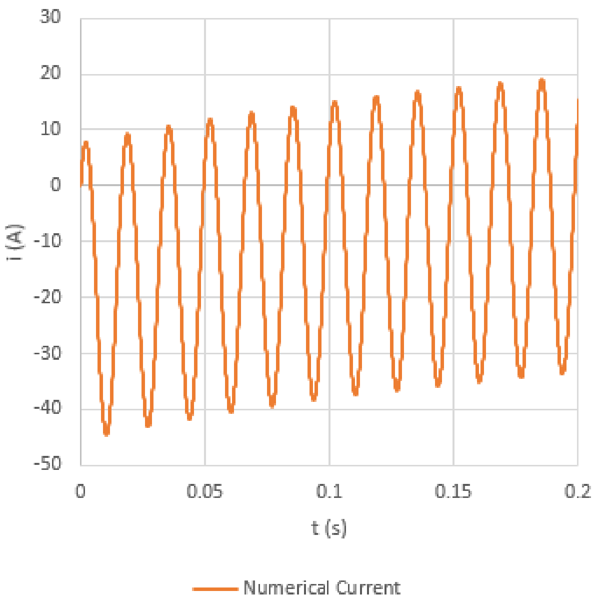
Electromagnetic Transients (EMT) Example



- In matrix form:

$$\begin{bmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & -\frac{1}{4} & \frac{1}{R}+\frac{\Delta t}{2L} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} V\cos(\omega t+\theta) \\ 0 \\ hist(t) \end{bmatrix}$$

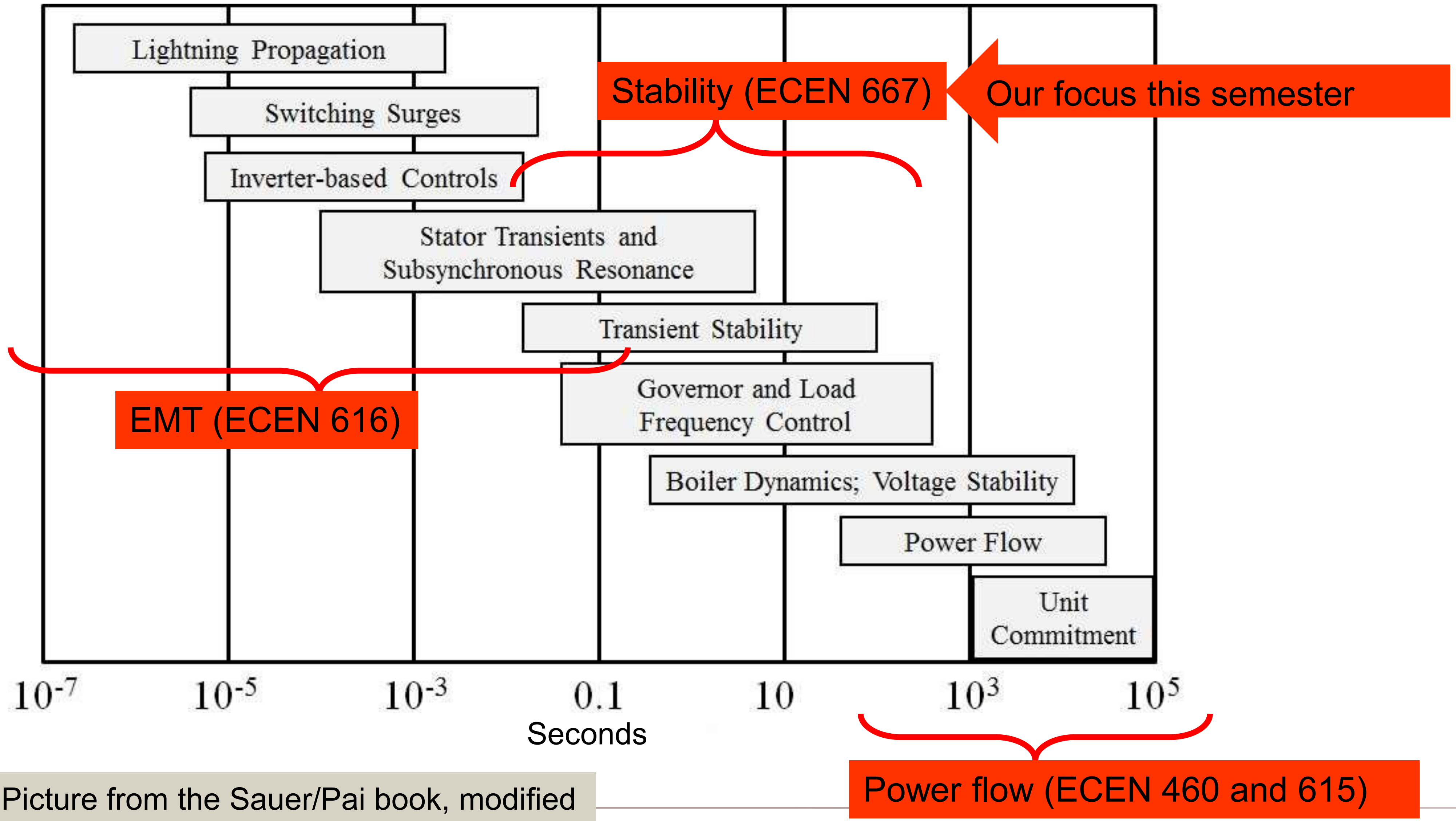
- At each iteration, $hist(t) = i(t) + \frac{\Delta t}{2L} v_3(t)$
- First, solve steady state
- Then, starting with $t = \Delta t$, use the companion circuit on the right to solve



Many models (including the distributed parameter transmission line model) for EMT involve "history terms" which persist from one time step to the next.

See ECEN 616 for more details.

Keeping the Time Scale in Mind



Picture from the Sauer/Pai book, modified

Stability

- Definition:

  Starting with a certain power system operating condition,

  and subjecting the system to some disturbance,

  will the system regain an equilibrium point

  with all important variables within an acceptable range?

- Notice that with this definition, instability can be affected in multiple ways
  - If you subject the system to a sufficiently large disturbance, you will eventually cause an unstable response
  - Alternatively, if you operate the system in sufficiently stressed conditions, even a very small disturbance could cause an unstable response
  - Design of various control systems are crucial to help increase stability
  - The definition of what variables are important and what is an acceptable range also matters

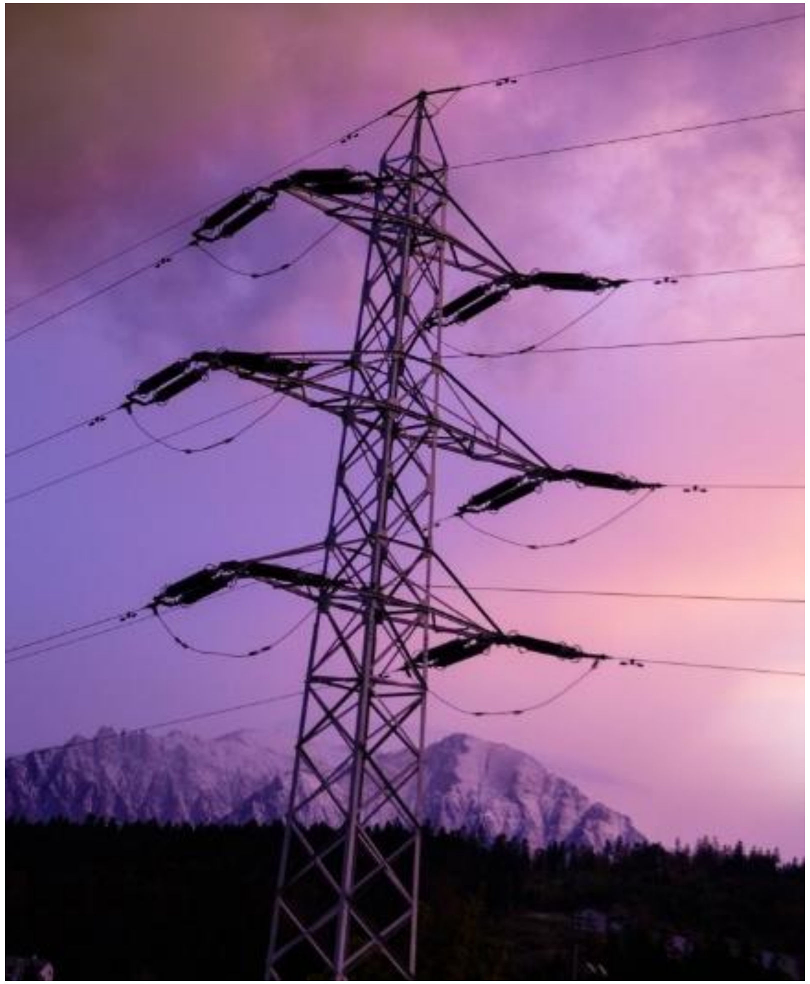
Classification of Stability Problems

Note that everything in a power system is interconnected and these problems are by no means completely independent!! Nevertheless this is a traditional and helpful classification

- **Rotor angle stability** – generators need to stay in synch with each other, hence they need sufficient synchronizing torque and sufficient damping
- **Frequency stability** – load-generation unbalance will cause frequency to deviate from nominal value, destabilizing the grid if not counteracted
- **Voltage stability** – ability of generators to maintain voltage magnitude, highly associated with reactive power supply and load response
- **Resonance stability** – there are natural oscillations that occur at specific frequencies through electrical or torsional interactions
- **Converter-driven stability** – associated with adverse interactions between fast control systems, particularly with multiple nearby inverters

What the Class Will Cover

- Introduction to power system modeling
- Synchronous machine modeling
- Excitation system modeling
- Turbine-governor modeling
- Inverter-based resource modeling
- Power system stabilizer modeling
- Time-scales and reduced order
- Interconnected multi-machine systems
- Transient stability analysis
- Linearized modeling and controls
- Signal analysis and the use of synchrophasor measurements



Stability Research

- There is lots of ongoing research in power system stability! A few examples
  - Modeling research: how to find the right model to use, normally balancing accuracy, data availability, avoiding overfitting, and considering scalability and computational complexity
  - Controller design and analysis: considering practical impact, device physical constraints, interactions in a complex system, and communication delays/interruptions
  - Interaction between stability and protection
  - Computational questions: how can we make stability analysis faster and more efficient, or more detailed while maintaining sufficient computational speed
  - Handling large amounts of simulation and/or real world data: signal analysis and summary techniques, data processing
  - Considering stability in market operations, cyber security, and network expansion planning
  - Potential applications/risks of using AI and large language models
- These are broad topics, with many specific problems in each

Aggie Core Values and Aggie Honor Code

- Aggie Core Values
  - Respect
  - Excellence
  - Leadership
  - Loyalty
  - Integrity
  - Selfless Service
- Aggie Honor Code: An Aggie does not lie, cheat, or steal, or tolerate those who do.

Reveille and I hope you have a great semester!