ECEN 667
Power System Stability

Lecture 2: Basic Stability Modeling

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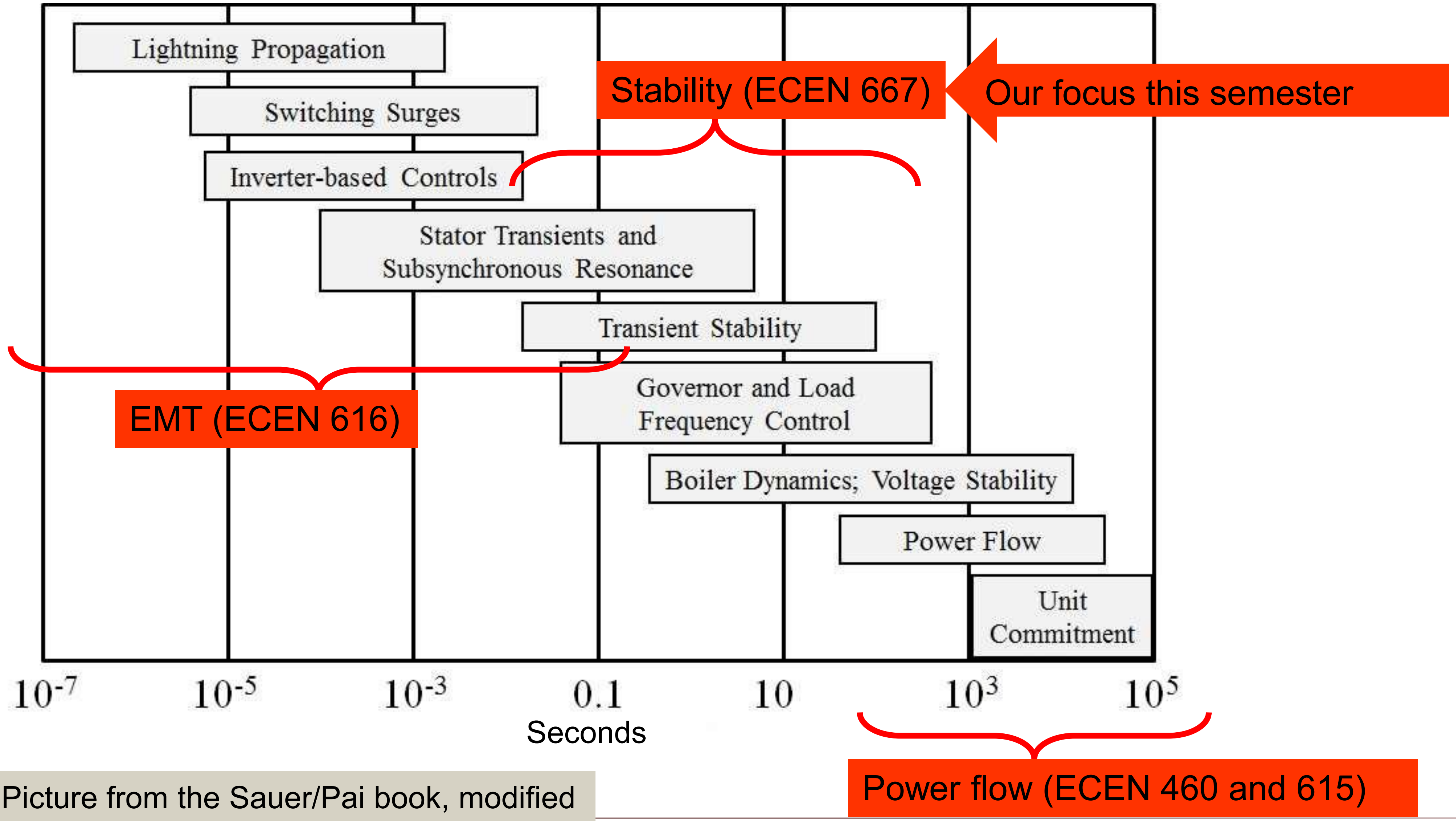
Announcements

- Homework Assignment #1 is on the website
  - It includes some things we won't cover until next week
  - Due Thursday, Sept. 11^{th} at 8 AM. Email me your solution as a single PDF.
- Review the slides and PowerWorld examples

Things to Remember about Modeling

- Take a small, basic 1 Ohm resistor for a breadboard. 10,000 amps should give you 10,000 volts, right? V=IR? Don't try it. The circuit model is wrong.
- Models are always only an approximation of reality, and are dependent upon the assumptions that are made in making that model
- "All models are wrong, but some are useful." – George Box
- The engineer's job in doing analysis is more than just putting numbers into a model and getting results.
  - It is figuring out the appropriate model to use that will be useful (though still ultimately wrong), given the questions you're trying to answer.
  - What range of currents and voltages are we talking about? What time frame? Microseconds? Years? How accurately do we need the answer? The model will change
  - You should always be asking: What assumptions am I making and are they reasonable?
- There are lots of different power system component models, for different purposes, and all of them are ultimately "wrong" i.e., incomplete

Recall – Keeping the Time Scale in Mind



Picture from the Sauer/Pai book, modified

Your Starter Stability Model Library

Starter Model Library

1. Classical synchronous machine
2. PI Branch transmission line
3. Transformer with per-unit scaling
4. Static impedance loads
5. Infinite bus

We will be adding many more models as the semester continues!

Synchronous Machines

- Steam, gas, and hydro turbines use synchronous machines to convert mechanical power to electric
- Hence, they have historically dominated power system dynamics
- The **classical model** is over-simplified and not used by industry very much
- However, it is used in academia often and is a good introduction to understanding the stability dynamics of power systems

Classical Synchronous Machine – Variables

Type	Symbol	Description
Parameter	H	Inertia constant (units are seconds)
Parameter	X_d'	Direct axis transient reactance
Parameter	ω_s	Nominal angular frequency (for example, $2\pi60$ rad/s)
Algebraic Variables	$\bar{V} = V_r + jV_i$	Terminal voltage phasor
Algebraic Variables	$\bar{I} = I_r + jI_i$	Terminal current phasor (oriented leaving the generator)
Input signal	P_m	Mechanical power supplied by prime mover
Input signal	E_p	Excitation voltage (equivalent)
Internal state variable	δ	Relative machine angle
Internal state variable	ω	Relative machine speed (0 is synchronous, -1 is standstill)

Some versions of the classical machine also allow for losses via a resistance and damping.
We will be developing much more complex and detailed models for synchronous machines in future lectures!

Classical Synchronous Machine - Equations

Four equations completely define this model

$$\dot{\delta} = \omega \cdot \omega_s$$

$$\dot{\omega} = \frac{1}{2H}\left(\frac{P_m}{\omega+1} - \frac{E_p}{X_d'}(V_r \sin\delta - V_i \cos\delta)\right)$$

Two differential equations.

The second is known as the "swing equation".

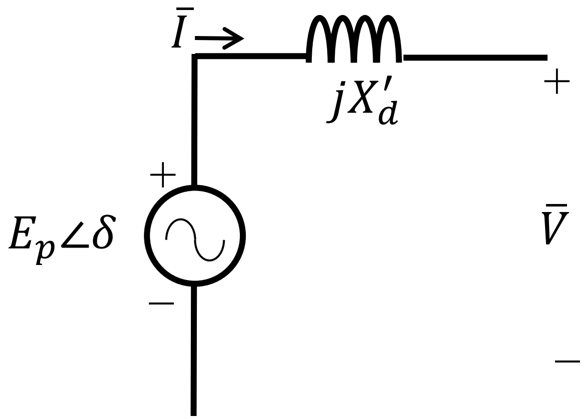
$$I_r = \frac{1}{X_d'}\left(-V_i + E_p \sin\delta\right)$$

$$I_i = \frac{1}{X_d'}\left(V_r - E_p \cos\delta\right)$$

Two algebraic network interface equations.

Check that these are equivalent to the circuit solution below

$$E_p\angle\delta - \bar{V} = jX_d'\bar{I}$$



We use dot notation for time derivatives. I.e.

$$\dot{\delta} = \frac{d\delta}{dt}$$

Transmission Lines

- Conductors are typically multi-stranded and either ACSR (aluminum conductor steel reinforced) or all aluminum
- Lines have resistance, which depends on material, cross-sectional area, and temperature
- Lines have inductance, including mutual inductance, depending on configuration
- Lines have capacitance and mutual capacitance as well

Additional Transmission Line Concepts

- Conductor data is often given in tables
- Ground resistivity and grounding are important in model development
- Lines are often unbalanced in configuration, but transposition is a method to attempt to restore balanced electrical characteristics
- Conductor bundling (using multiple conductors per phase) increases the capacity of very high voltage lines (see next slide)
- Many lines are undergrounded, which generally have lower inductance and higher capacitance
- There are some DC transmission lines in use, but they are cost limited

Formulas for calculating line inductance and capacitance from tower construction are not part of this course but can be found in ECEN 459 and 460.

Bundled Conductor Example

The AEP Wyoming-Jackson Ferry 765 kV line uses 6-bundle conductors. Conductors in a bundle are at the same voltage!

Photo Source: BPA and American Electric Power

The North American Grid of Transmission Lines

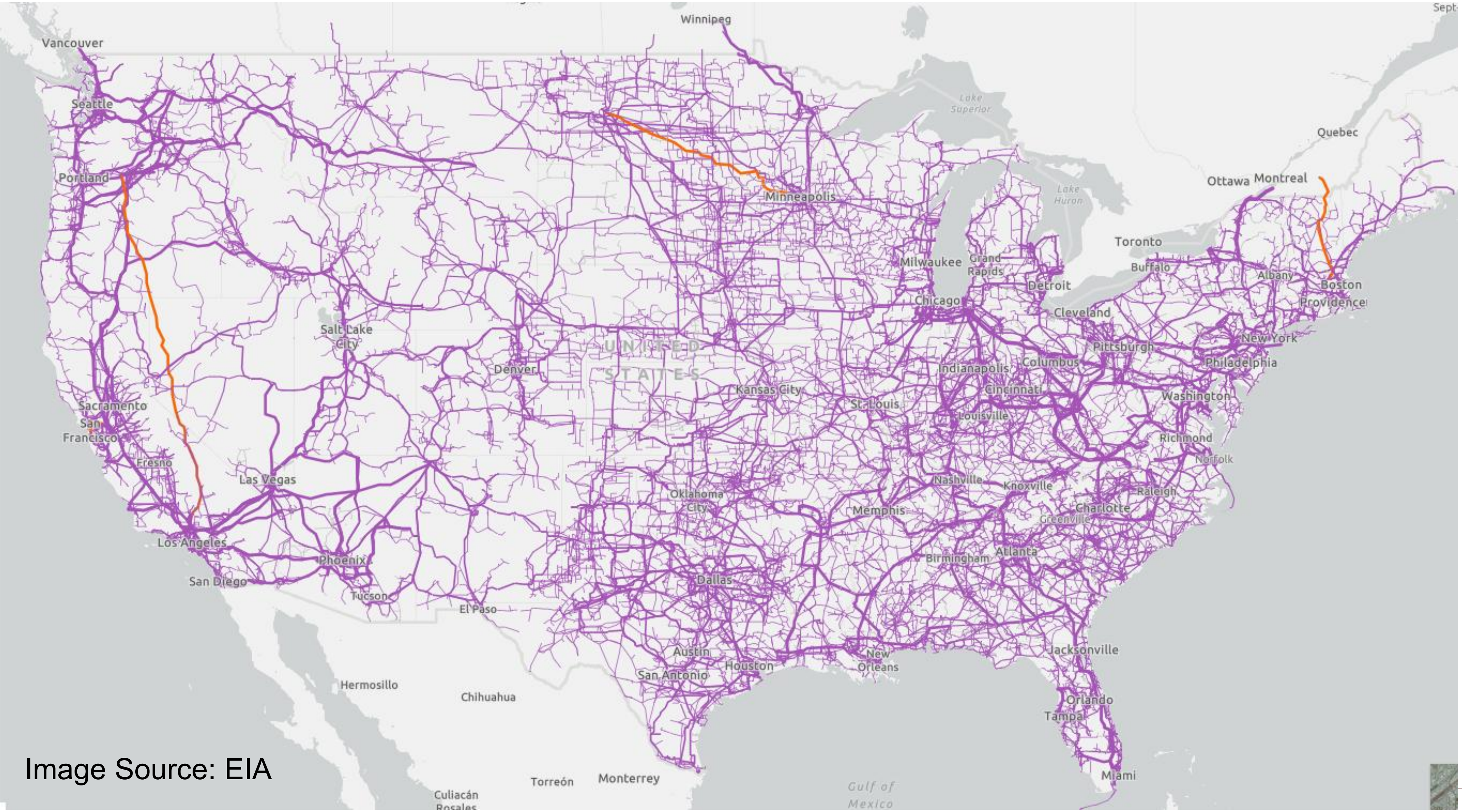
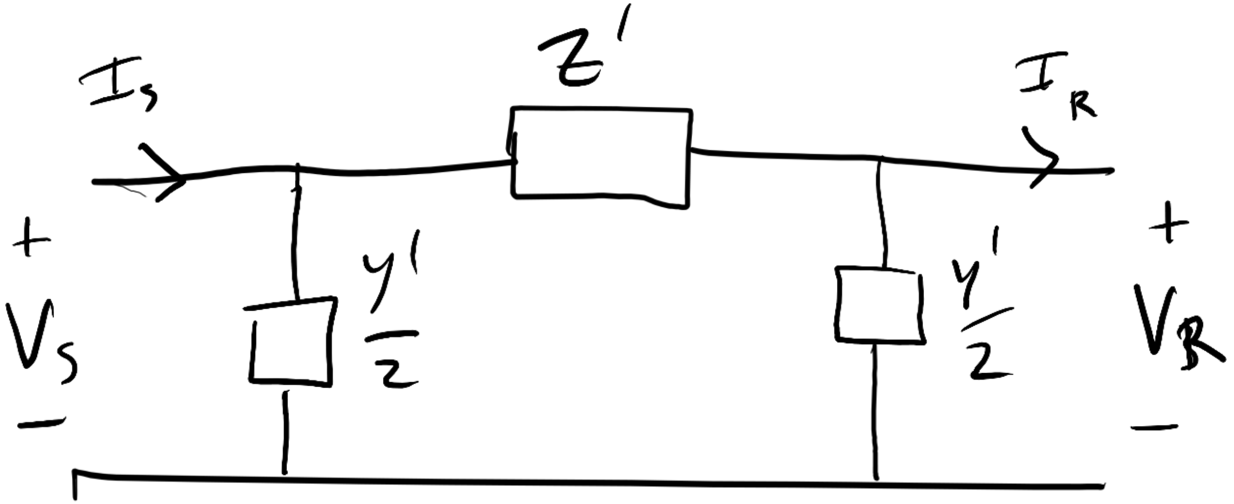


Image Source: EIA

Pi Branch Model for Transmission Lines

- Series impedance $\bar{Z} = R + j\omega L = R + jX$
- Shunt admittance lumped on each end $\bar{Y} = j\omega C = jB$



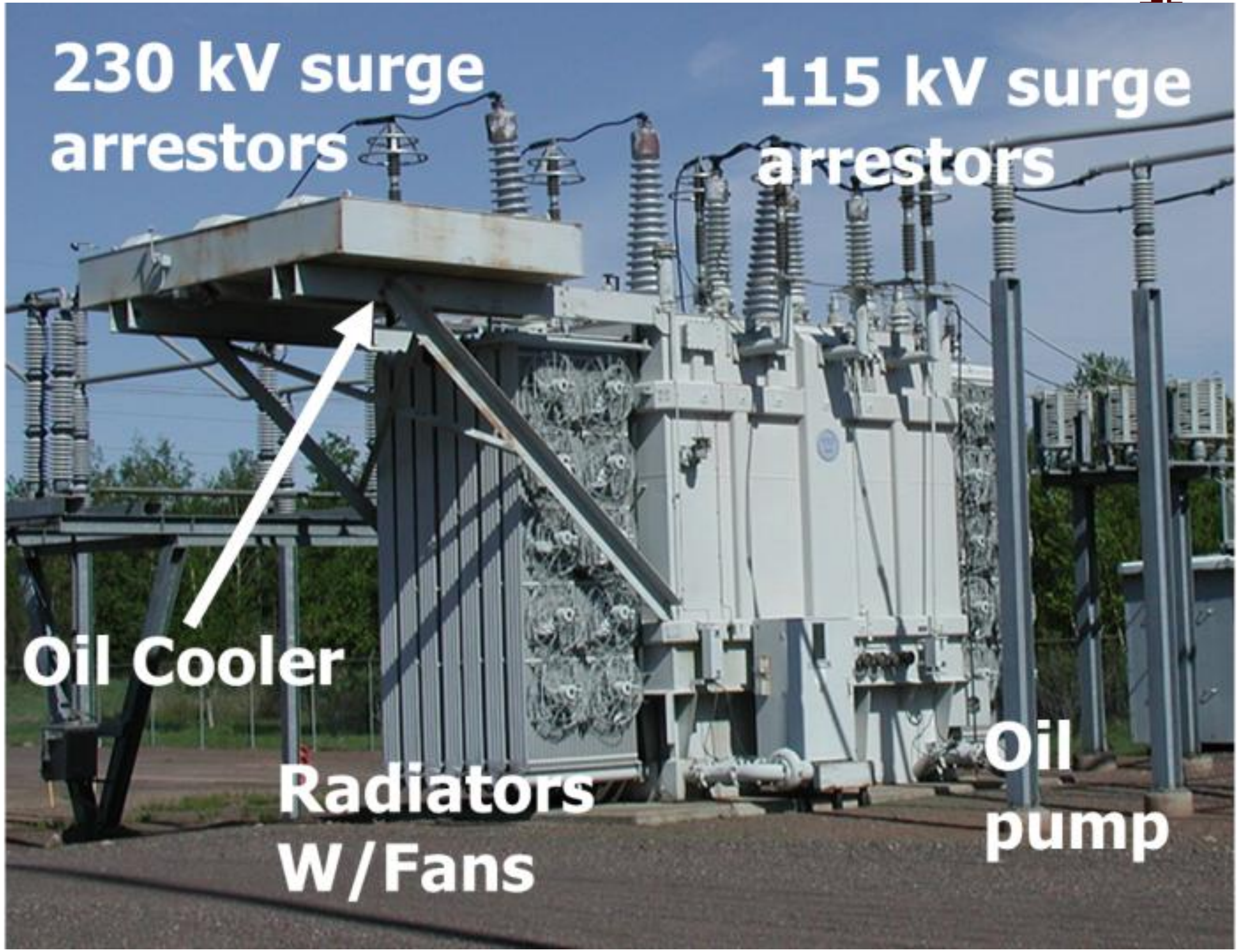
$$\bar{I_S} = \bar{V_S}\left(\frac{\bar{Y'}}{2} + \frac{1}{\bar{Z'}}\right) + \bar{V_R}\left(-\frac{1}{\bar{Z'}}\right)$$

$$\bar{I_R} = \bar{V_S}\left(\frac{1}{\bar{Z'}}\right) + \bar{V_R}\left(-\frac{\bar{Y'}}{2} - \frac{1}{\bar{Z'}}\right)$$

- This is the same model as for power flow! It is normal for stability studies.
- EMT analysis includes more advanced line models, including ones that are valid in high frequency conditions

Transformers

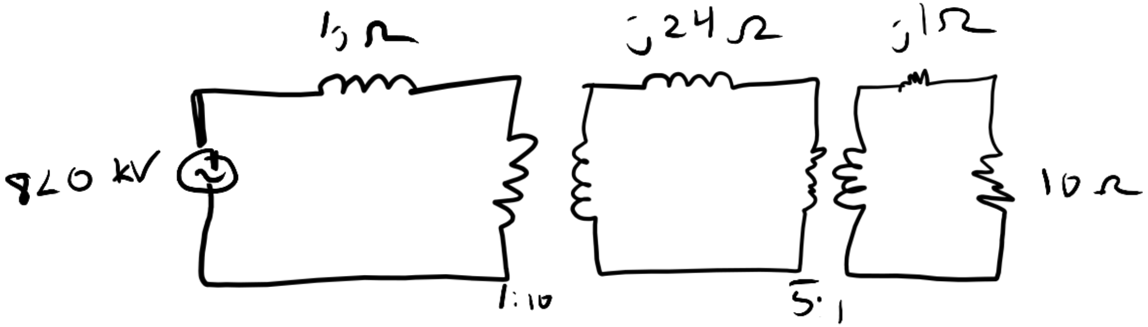
- Ideal transformers provide a turns ratio N to step voltage up or down
  - In power flow and stability, we deal with this by using the per-unit system
- Actual transformers have losses
  - Real losses: copper winding losses, eddy currents, hysteresis
  - Reactive losses: leakage reactance, magnetizing current
- A typical model for transformers in power flow and stability is a series impedance (in per-unit)



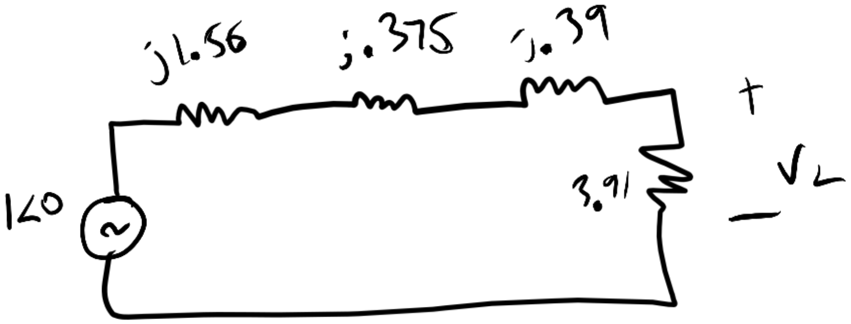
Per-Unit System

- Per-unit is a normalization relative to some base: $x_{pu} = \frac{x_{si}}{x_{base}}$
- Steps
  - Pick a single 3-phase VA base for entire system
  - Pick a L-L voltage base for each voltage level, depending on transformer turns ratios
  - Calculate the impedance base $Z_b = V_b^2/S_b$
  - Calculate the current base $I_b = \frac{S_b}{V_b\sqrt{3}}$
  - Convert actual values to per-unit (magnitudes only angles are not affected)
  - Solve the system in per-unit (power flow or stability)
  - If needed, convert back to actual units at the end

Per-Unit Example



Original Circuit



Same circuit, with values expressed in per unit.

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

$Z_B^{Left} = \frac{8kV^2}{100MVA} = 0.64\Omega \qquad Z_B^{Middle} = \frac{80kV^2}{100MVA} = 64\Omega \qquad Z_B^{Right} = \frac{16kV^2}{100MVA} = 2.56\Omega$

$I = \frac{1.0\angle 0°}{3.91 + j2.327} = 0.22\angle -30.8° \text{ p.u. (not amps)} \qquad \text{V}_\text{L} = 1.0\angle 0° - 0.22\angle -30.8° \times 2.327\angle 90° = 0.859\angle -30.8° \text{ p.u.}$

$S_L = V_L I_L^* = \frac{|V_L|^2}{Z} = 0.189 \text{ p.u.} \qquad S_G = 1.0\angle 0° \times 0.22\angle 30.8° = 0.22\angle 30.8° \text{ p.u.}$

$V_\text{L}^\text{Actual} = 0.859\angle -30.8° \times 16 \text{ kV} = 13.7\angle -30.8° \text{kV} \qquad S_\text{L}^\text{Actual} = 0.189\angle 0° \times 100 \text{ MVA} = 18.9\angle 0° \text{ MVA}$

$\text{I}_\text{B}^\text{Middle} = \frac{100 \text{ MVA}}{80 \text{ kV}} = 1250 \text{ Amps} \qquad \text{I}_\text{Middle}^\text{Actual} = 0.22\angle -30.8° \times 1250 \text{ Amps} = 275\angle -30.8° \text{ A}$

Load Modeling – Static Impedance

- In a transmission system, a "load" is an aggregation of thousands of things using electricity – pumps, compressors, conveyors, lights, computers, heaters, fans, …
- In power flow, a typical model is just a constant P and Q, recognizing that in steady state the power usage is pretty much independent of voltage
- Stability considers a shorter time frame, so a different model is needed
  - **Static models** are algebraic functions of voltage and do not have internal state variables
  - **Dynamic models** have differential equations and include the dynamics of motors, etc.
- The simplest model is constant impedance
  - In the short term, load is more impedance-like than constant-power-like
  - However, this model is not common in industry any more and more complex models are needed, which we will cover later in class

$$\bar{I}_{load} = \frac{\bar{V}}{\bar{Z}_{load}}$$

Infinite Bus

- In some dynamic studies, an "infinite bus" model is used
- This is a bus with such strong dynamic control that the voltage magnitude V_s and angle are assumed to remain constant (usually the angle is 0)
- This could represent a large generator with very high inertia, or an interconnection to another area or larger, stronger part of the grid
- Modeling with an infinite bus tends to give more stable responses
- It is a big assumption and generally industry studies do not include an infinite bus

$$\bar{V} = V_s \angle 0$$

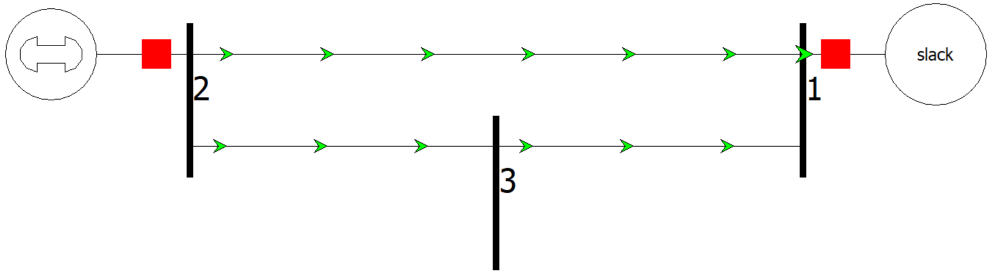
- But we will use it for many of our early examples

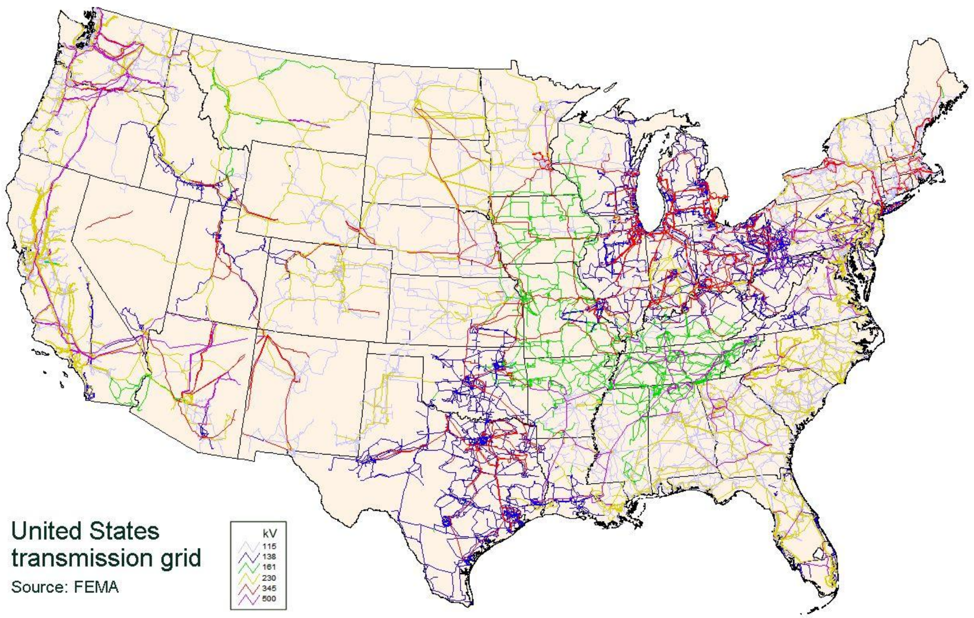
By the Way, What is a Bus?

- Mathematically, it is a circuit node for simulation
- In positive sequence analysis (as in this class) it is one phase representing all 3
- Physically a substation contains large conductors that are buses
- Buses are the main components of oneline diagrams (next slide)

An actual substation bus

Oneline Diagram





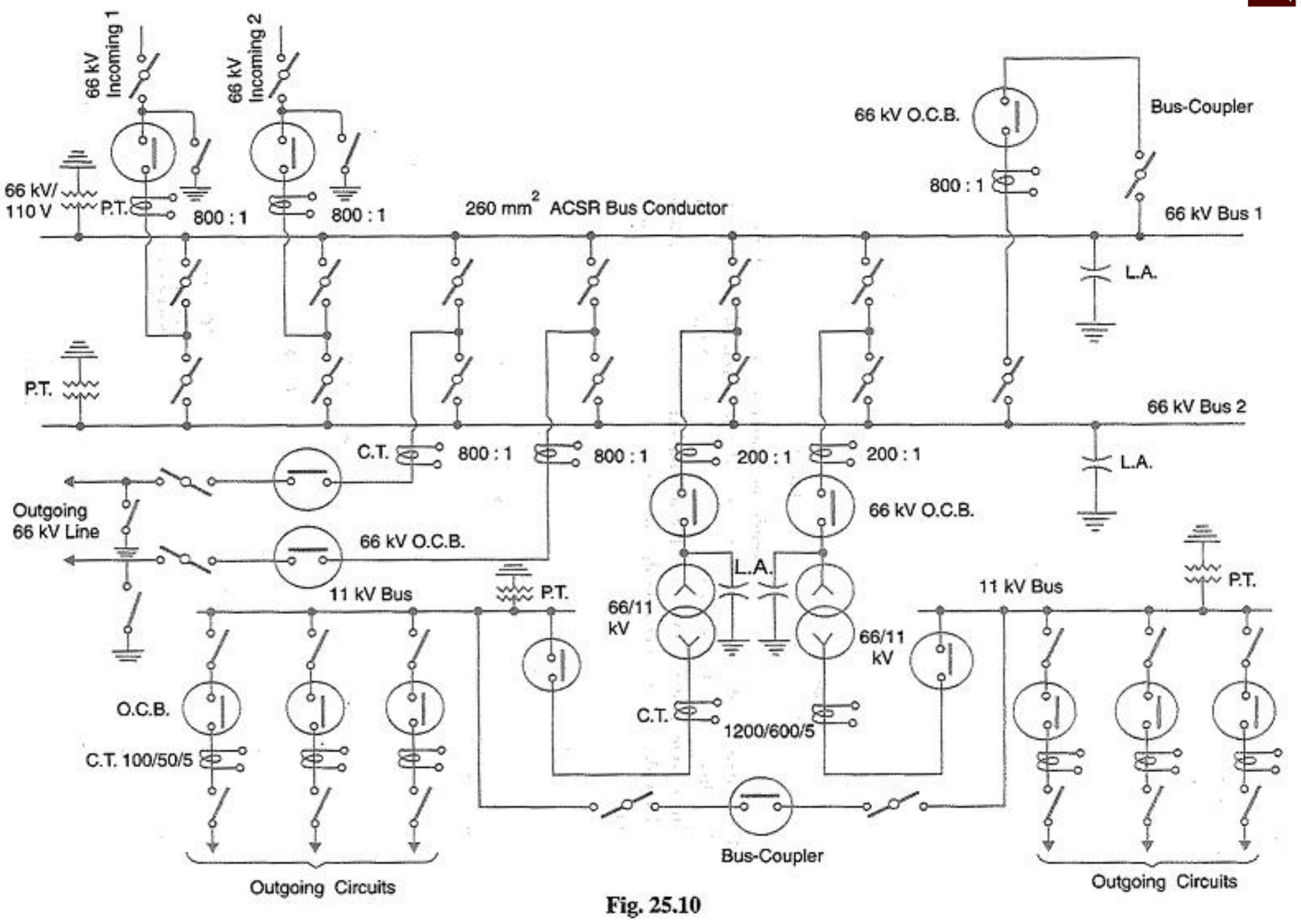


Image Source: www.eeguide.com/key-diagram-of-substation/

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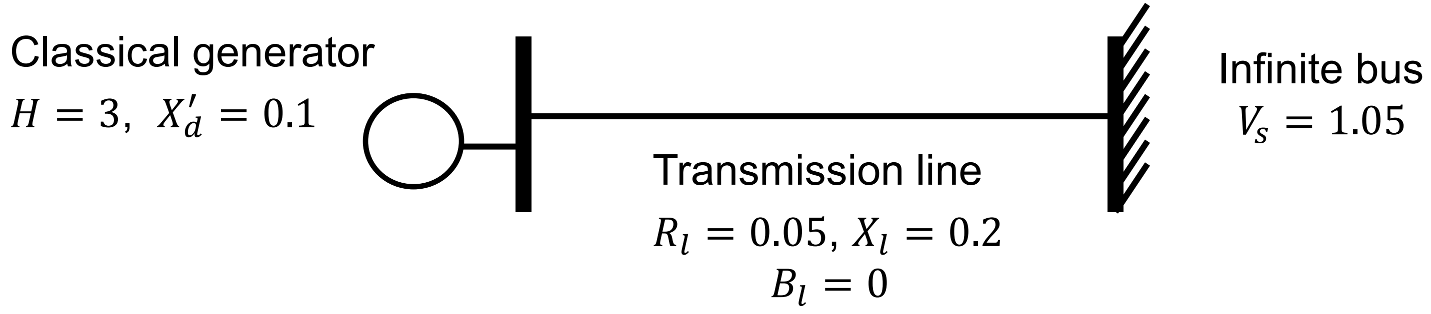
We will be adding many more models as the semester continues!

Example of a Stability Problem (Example 1)

- The diagram on the right shows a single-machine, infinite bus system (SMIB)
  - Write the equations for this dynamical system.
  - Find the equilibrium point(s) for which the generator bus is producing 100 MW and 0 Mvar
  - Assume that you already solved a power flow and got $\bar{V} = 1.07984\angle 10.16°$
  - Later, we will want to add a disturbance and study the dynamic response



Example 1, Equations

- Apply the equations for the classical generator, pi-branch line, and infinite bus

$$\dot{\delta} = \omega \cdot \omega_s$$

$$\dot{\omega} = \frac{1}{2H}\left(\frac{P_m}{\omega+1} - \frac{E_p}{X'_d}(V_r \sin\delta - V_i \cos\delta)\right)$$

$$E_p\angle\delta - \bar{V} = jX'_d\bar{I}$$

$$\bar{V} - V_s\angle 0 = (R_l + jX_l)\bar{I}$$

- Now we can find the equilibrium point where the initial condition is met
- At an equilibrium point, all the derivatives are zero
- So we know $\omega = 0$
- We need to find $\bar{I}, \delta, E_p,$ and P_m at the equilibrium point where $\bar{V} = 1.07984\angle 10.16°$

Example 1, Finding Equilibrium Point

- Using the line equation find $\bar{I}$

$$\bar{V} - V_s\angle 0 = (R_l + jX_l)\bar{I}$$

$$\bar{I} = \frac{\bar{V} - V_s\angle 0}{R_l + jX_l} = \frac{1.07984\angle 10.16° - 1.05}{.05 + j0.2} = 0.9261\angle 10.16°$$

- Now using the machine interface equation find $E_p\angle\delta$

$$E_p\angle\delta = \bar{V} + jX_d'\bar{I} = 1.07984\angle 10.16° + j0.1 \cdot 0.9261\angle 10.16° = 1.0838\angle 15.06°$$

- So we know that $E_p = 1.0838$ and $\delta = 15.06°$
- Now use the swing equation (at equilibrium) to find P_m

$$0 = \frac{1}{2H}\left(\frac{P_m}{\omega + 1} - \frac{E_p}{X_d'}(V_r \sin\delta - V_i \cos\delta)\right)$$

$$P_m = \frac{E_p}{X_d'}(V_r \sin\delta + V_i \cos\delta) = \frac{1.0838}{0.1}(1.0629 \sin 15.06° - 0.19048 \cos 15.06°) = 1.00$$

- Why should we expect $P_m = 1$?

Example 1, Dynamical System

$$\dot{\delta} = \omega \cdot \omega_s$$

$$\dot{\omega} = \frac{1}{6}\left(\frac{1}{\omega+1} - \frac{1.0838}{0.1}(V_r \sin\delta - V_i \cos\delta)\right)$$

$$1.0838\angle\delta - \bar{V} = j0.1\bar{I}$$

$$\bar{V} - 1.05\angle 0 = (0.05 + j0.2)\bar{I}$$

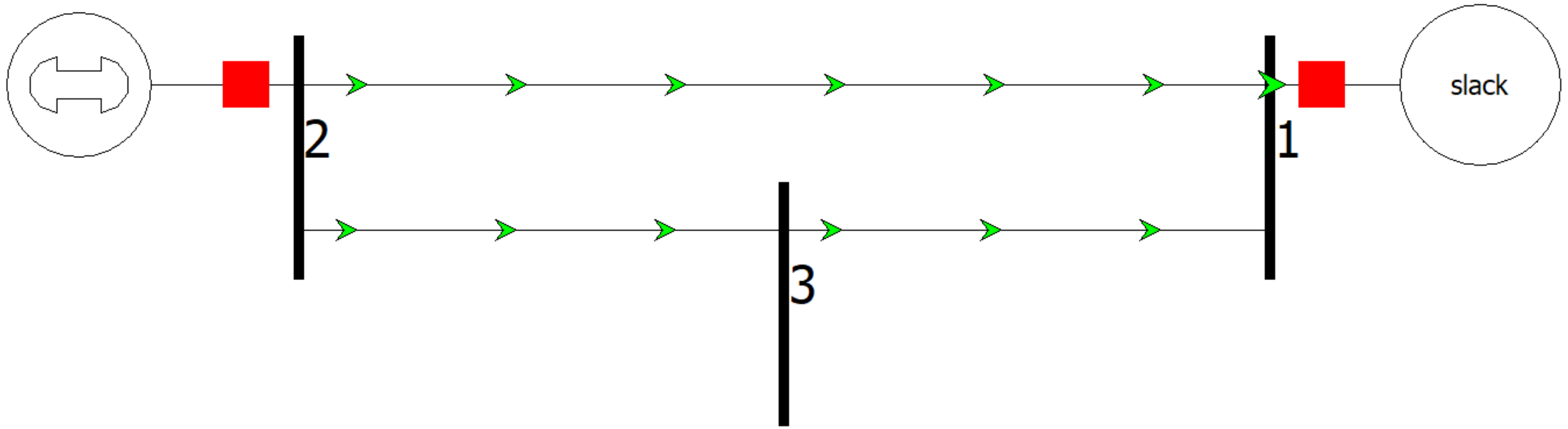
- This system has two real differential variables, two complex algebraic variables, and an equal number of variables and equations
- We found an equilibrium point with $\omega = 0, \delta = 15.06°, \bar{V} = 1.07984\angle 10.16°$
- Analytical solution for the time dynamics would be very difficult, especially as the problems get more complex
- We use numerical methods, which will be introduced next class
- For now, let's look at the results on a commercial tool

PowerWorld Simulator

- We will be using this program extensively in class
  - Link to free student 42-bus version https://www.powerworld.com/gloveroverbyesarma
  - Link to free training material https://www.powerworld.com/training/courses
  - Link to TAMU virtual engineering desktop with full version https://aggievirtualdesktop.tamu.edu/
  - Start getting familiar with the package, particularly the power flow basics
- History
  - Dr. Overbye is the original developer, starting in 1987. Its original goal was to teach power system operations to utility industry non-technical people.
  - Company formed in 1996, and it developed into a fully-featured commercial version
  - State-of-the art visualization and modeling capabilities for both power flow and stability analysis

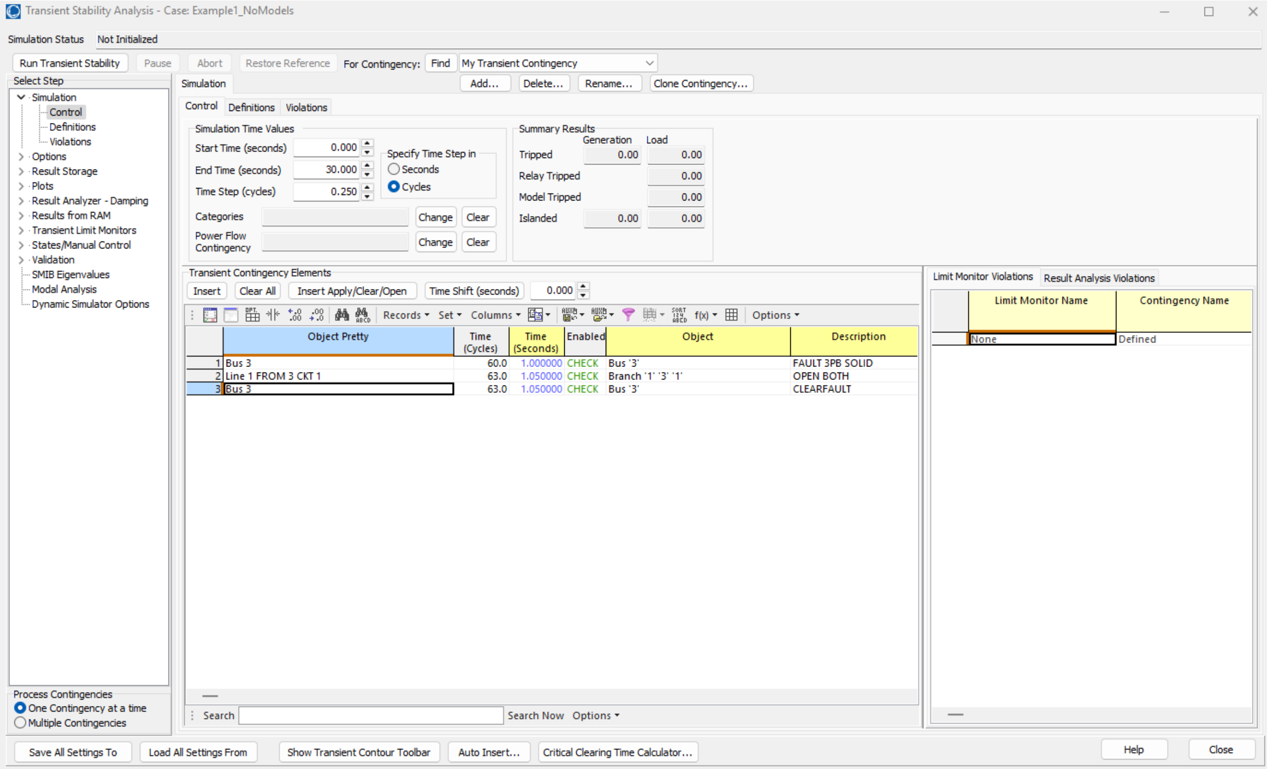
Example 1 in PowerWorld

- Open Case Example_1_NoModels from the class website
- Add a classical generator to the model
  - In run mode, double click on generator on bus 2 to open the generator dialog
  - Select the **Stability** tab and **Machine Models**, then **Insert** and find **GENCLS**
  - Change the X_d' from default of 0.2 our example's value of 0.1
- Note that the 3 lines in the case are equivalent to the 1 line in Example 1



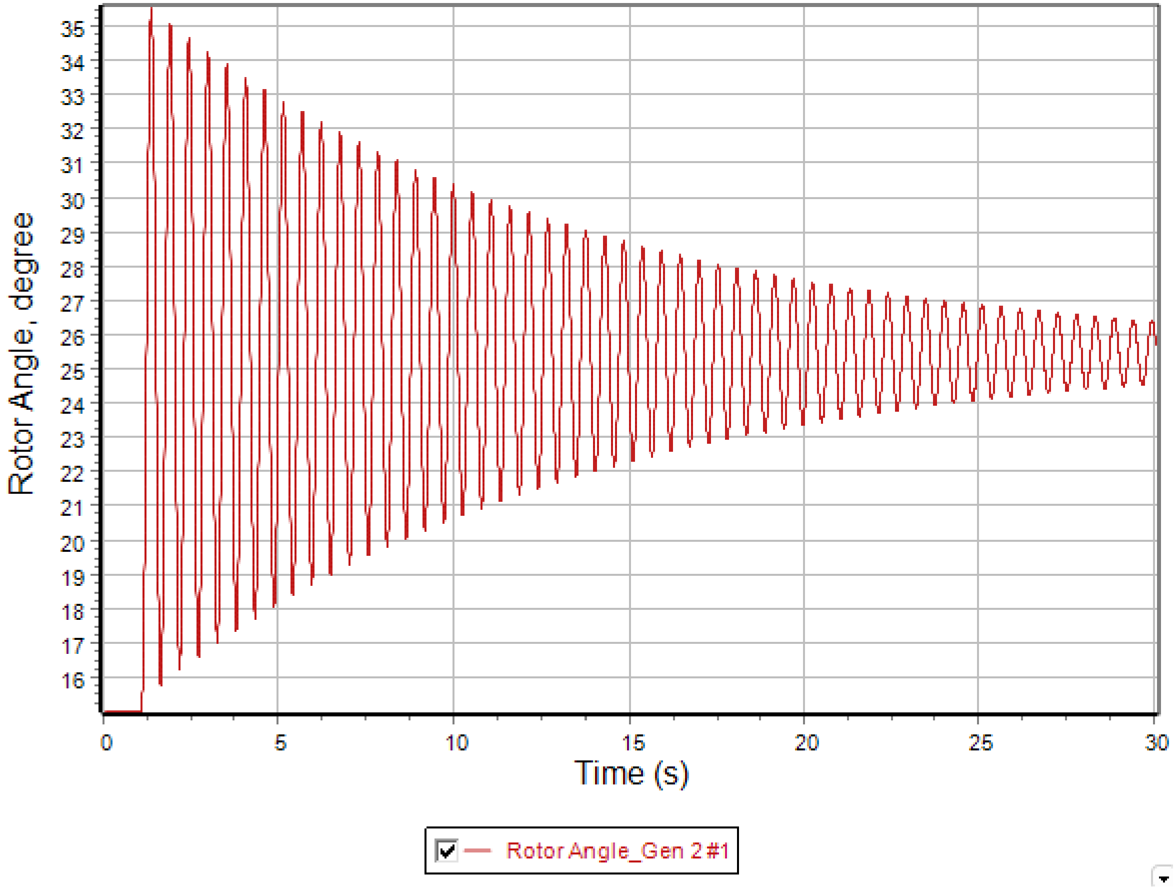
Example 1 in PowerWorld, Transient Simulation

- From the Ribbon, Select **Add Ons**, **Transient Stability**
- This opens up the transient stability dialog
- Note: I already set up this case to use an infinite bus for Bus 1, and to run a contingency that involves a self-cleared fault at Bus 3
- Key pages on this dialog
  - **Simulation**: used for controlling the event and main simulation properties
  - **Options**: various detailed options (including infinite bus setting)
  - **Results Storage**: pick what variables to save in the simulation
  - **Plots**: plot the results
  - **Results**: view the numerical results
- Click **Run Transient Stability**



Results for Example 1 in PowerWorld: Angle

- The angle starts at 15.06° as we calculated
- Oscillations begin, around 2 Hz or so
- Damping is due to the resistance in the line
- Machine speed has similar behavior
- Why does it settle at a different angle?



Results for Example 1: Voltage

- Bus 1 is an infinite bus and voltage doesn't change
- Bus 2 voltage briefly goes very low during the fault itself, then goes back up when the fault clears
- Oscillations appear to be similar to the machine angle oscillations, but opposite in phase