

ECEN 667

Power System Stability

Lecture 5: Stability Overview with PowerWorld Simulator

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Announcements

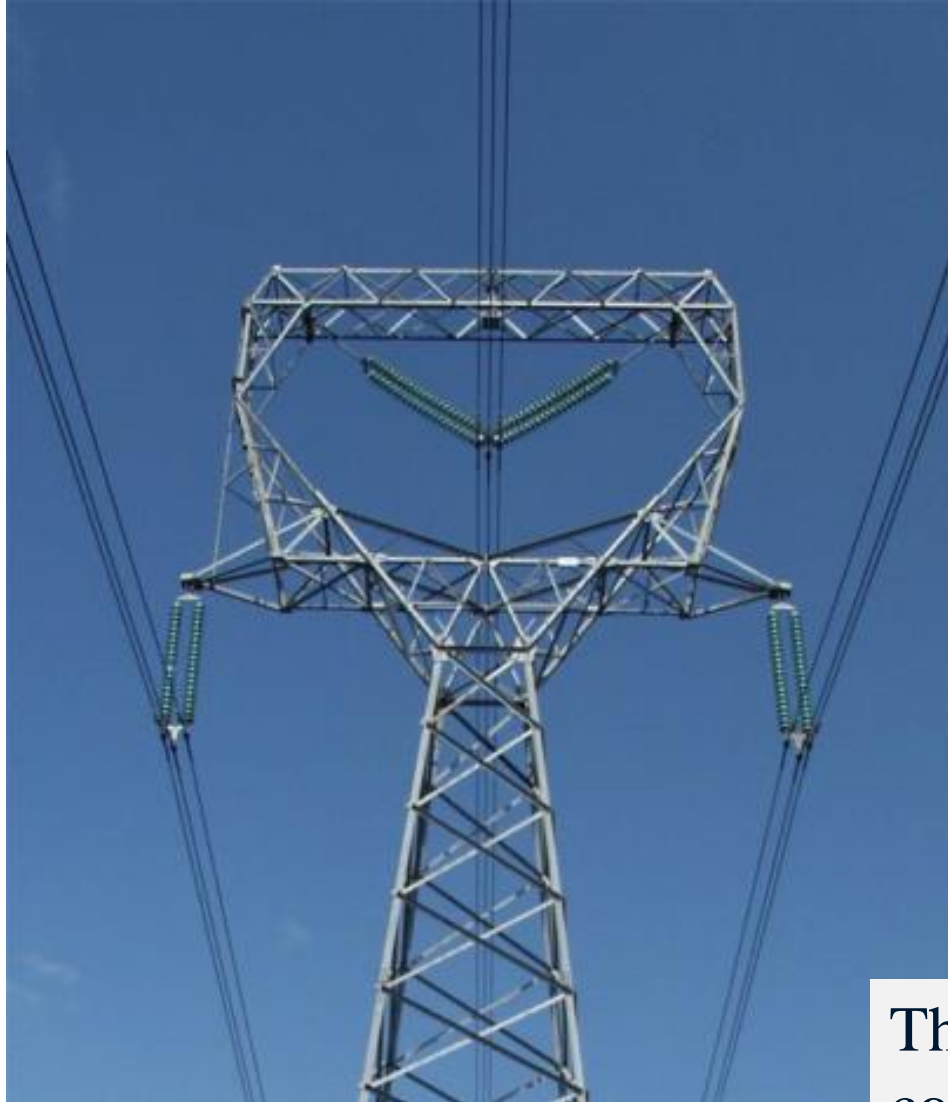


- Start reading Chapters 3
- Homework 1 is due on Thursday September 7

Three-Phase Transmission Lines

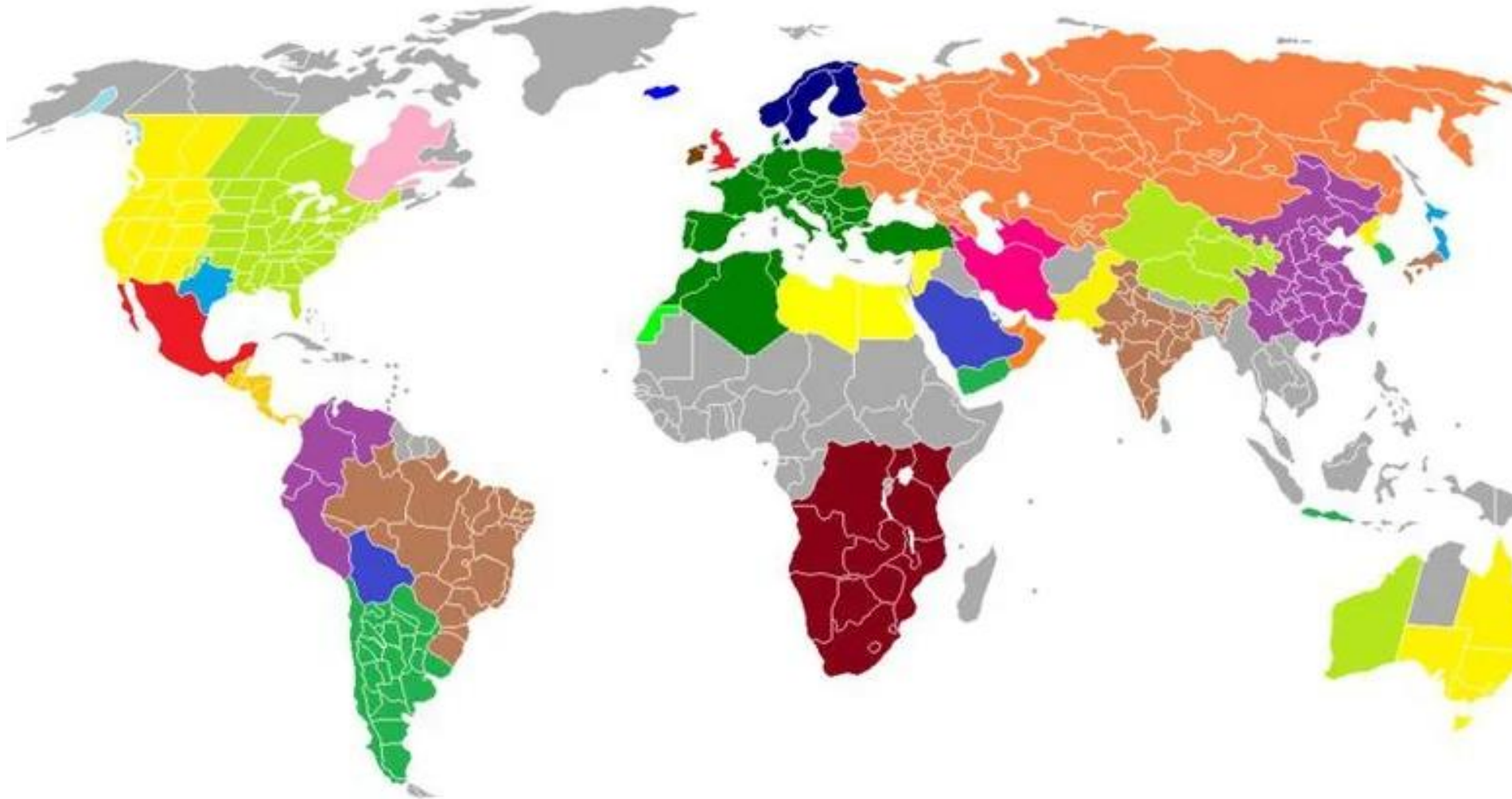


Bundled Conductor Pictures



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

Large-Scale Electric Grid Interconnects (50 or 60 Hz)



The map is a little out-of-date (e.g., with Ukraine).

The largest grids by GW: 1) State Grid of China (1700) 2) Continental Europe (860), 3) Eastern NA (610), 4) India (400), 5) former Soviet Union (350 GW), 6) China Southern Grid (320), 7) WECC (265)

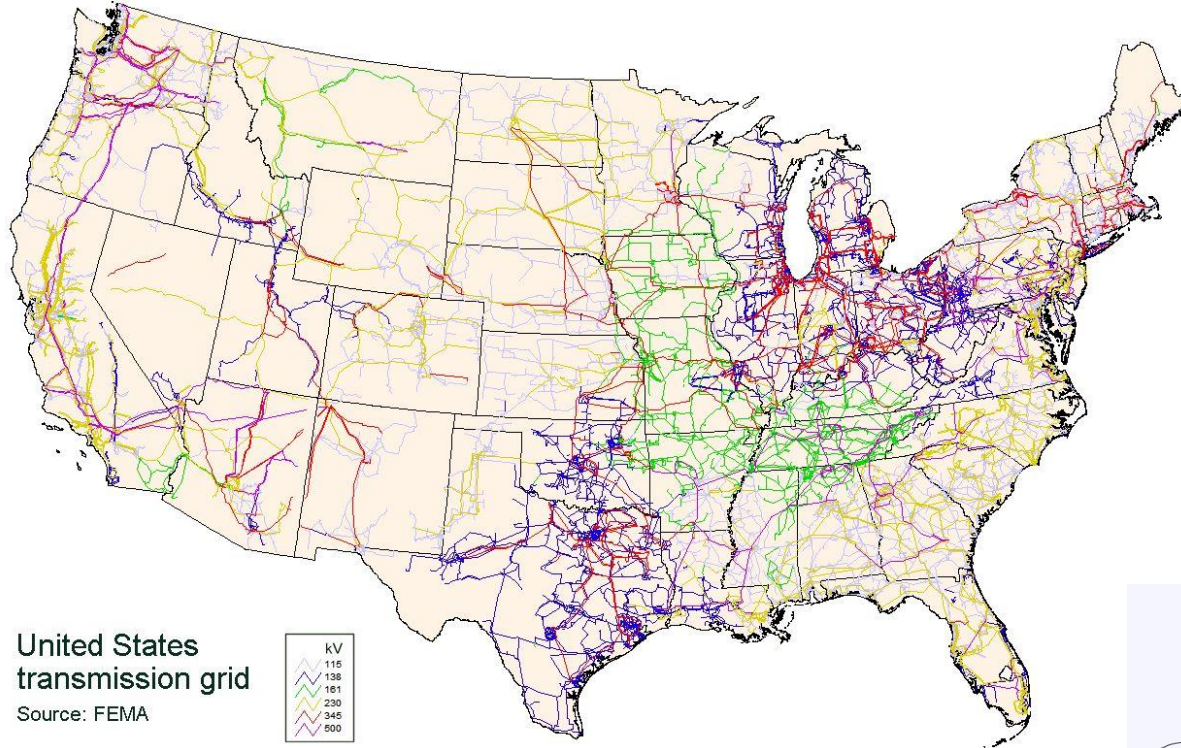
Key Power System Terms: Bus and One-Line



- Most power systems are (mostly) 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

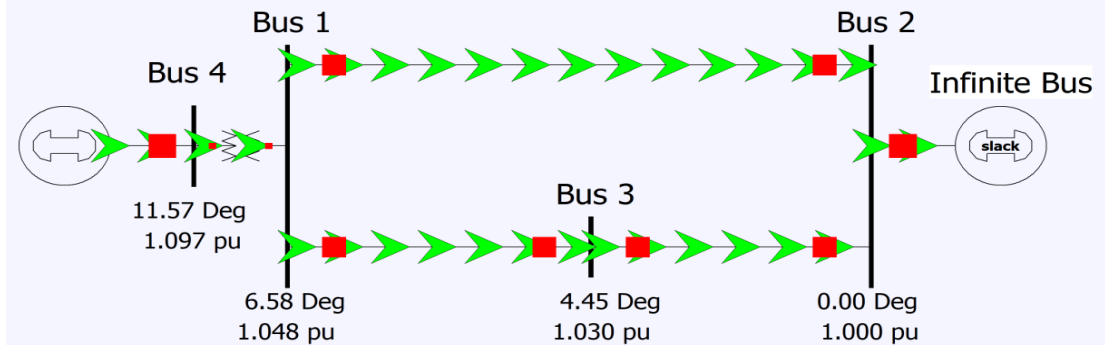
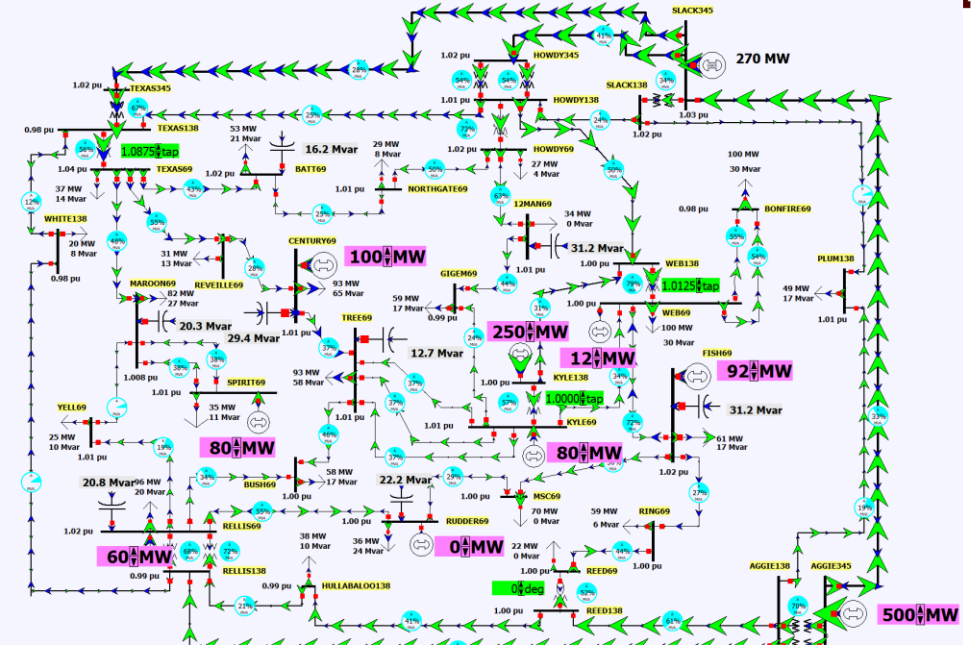


Power System One-line Diagrams



We will be using these a lot in 667

Aggieland Power and Light



A More Detailed Oneline (Single Line) Diagram

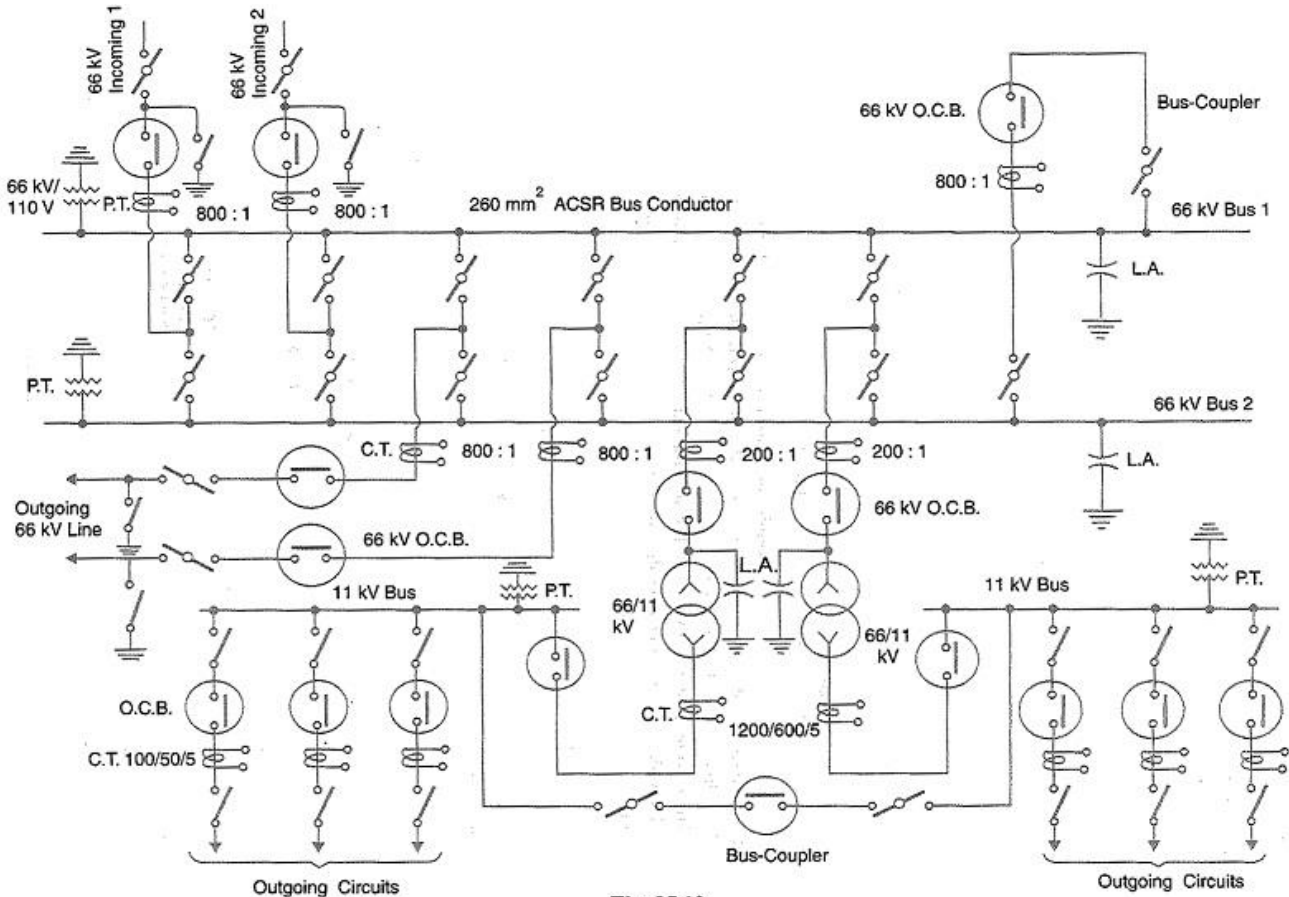
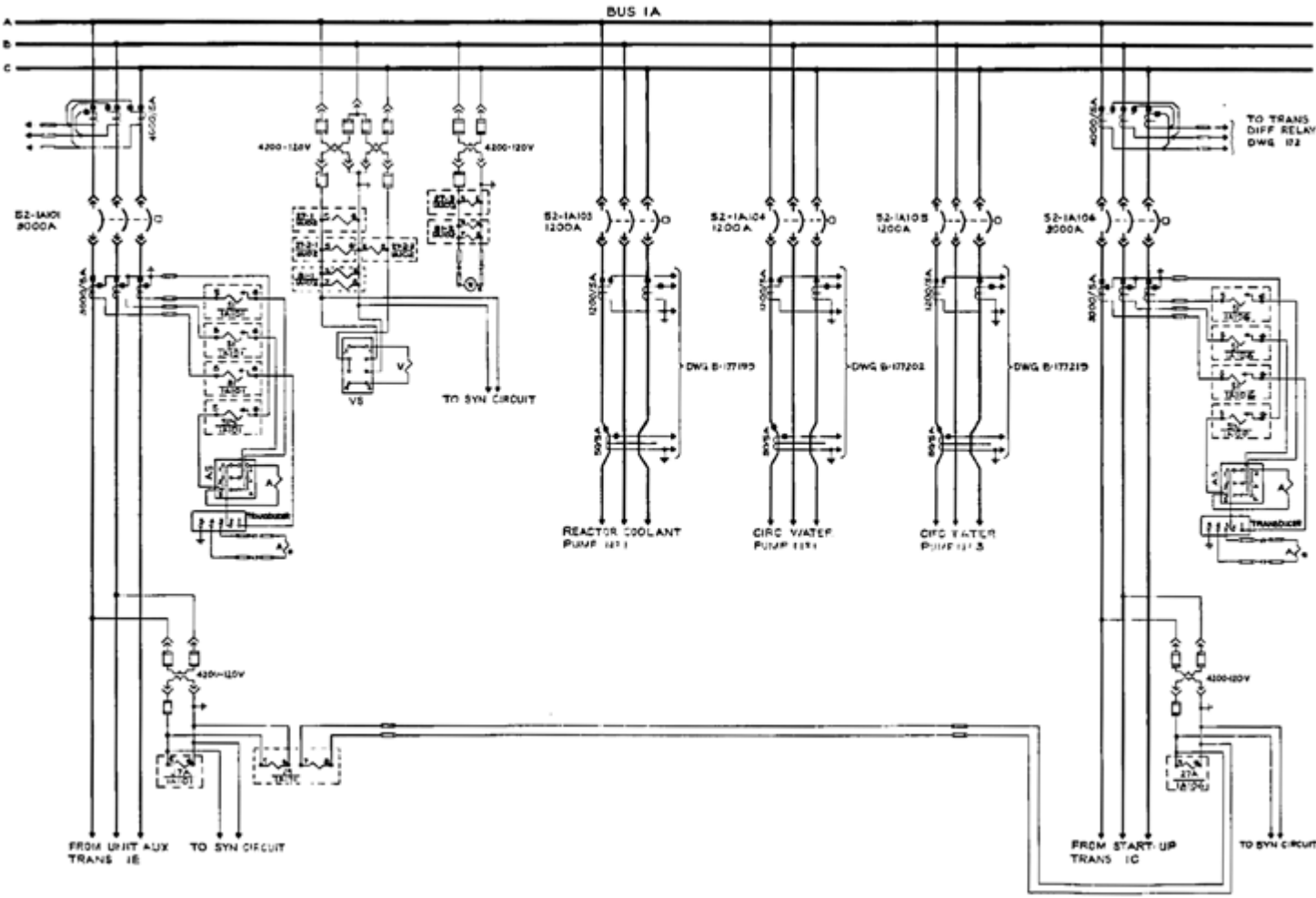


Fig. 25.10

Mostly we won't get into this level of detail in 667

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

Three Line Diagram



We won't be using these in 667

Quick Review of Symmetric Components



- In 667 we won't use symmetrical components much but it is a key concept so I will briefly cover them
- Much of power system dynamic analysis is done assuming the system is operated balanced, three-phase
- However, we need to briefly consider unbalanced system operation, which certainly can occur during faults
 - The most common fault is a single line-to-ground (SLG) fault, whereas three-phase faults are uncommon
- Such systems can be analyzed using symmetrical components

Symmetric Components



- The key idea of symmetrical component analysis is to decompose the system into three sequence networks. The networks are then coupled only at the point of the unbalance (i.e., the fault)
- The three sequence networks are known as the
 - positive sequence (this is the one for balanced systems)
 - negative sequence
 - zero sequence
- Presented in paper by Charles L. Fortescue in 1918 (most important 20th century power paper)

Heydt, G. T.; Venkata, S. S.; Balijepalli, N. (October 24, 2000). "[High Impact Papers in Power Engineering, 1900-1999](#)" *Proceedings 2000 North American Power Symposium, vol. 1, October 2000*. North American Power Symposium (NAPS). Waterloo, Ontario.

Positive, Negative and Zero Sequence Sets



- The positive sequence sets have three phase currents/voltages with equal magnitude, with phase b lagging phase a by 120° , and phase c lagging phase b by 120°
- The negative sequence sets have three phase currents/voltages with equal magnitude, with phase b **leading** phase a by 120° , and phase c **leading** phase b by 120°
- Zero sequence sets have three values with equal magnitude and angle

Symmetrical Component Conversion



- Voltages and currents can be easily transformed between their phase and sequence values

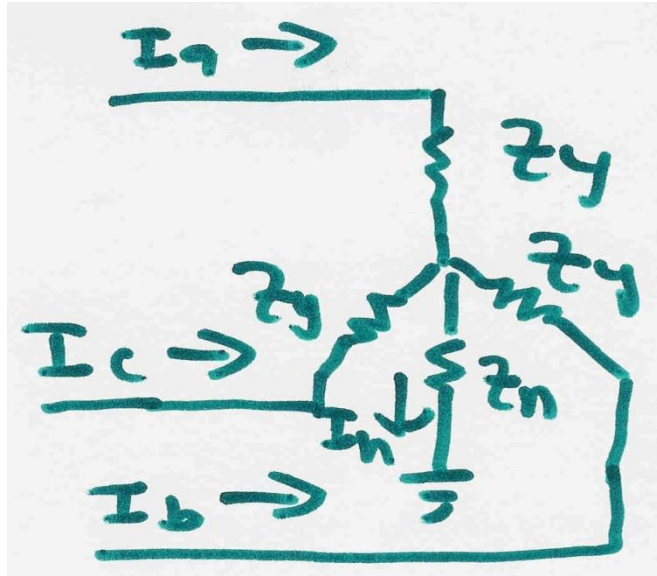
Define the symmetrical components transformation matrix

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \quad \text{With } \alpha = 1 \angle 120^\circ$$

$$\text{Then } \mathbf{I} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \mathbf{A} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \mathbf{A} \begin{bmatrix} I^0 \\ I^+ \\ I^- \end{bmatrix} = \mathbf{A} \mathbf{I}_s$$

Symmetrical Components to Decouple Unbalanced Networks

- Consider the following wye-connected load:



$$I_n = I_a + I_b + I_c$$

$$V_{ag} = I_a Z_y + I_n Z_n$$

$$V_{ag} = (Z_y + Z_n)I_a + Z_n I_b + Z_n I_c$$

$$V_{bg} = Z_n I_a + (Z_y + Z_n)I_b + Z_n I_c$$

$$V_{cg} = Z_n I_a + Z_n I_b + (Z_y + Z_n)I_c$$

$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} Z_y + Z_n & Z_n & Z_n \\ Z_n & Z_y + Z_n & Z_n \\ Z_n & Z_n & Z_y + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Symmetrical Components to Decouple Unbalanced Networks



$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \begin{bmatrix} Z_y + Z_n & Z_n & Z_n \\ Z_n & Z_y + Z_n & Z_n \\ Z_n & Z_n & Z_y + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\mathbf{V} = \mathbf{Z} \mathbf{I} \quad \mathbf{V} = \mathbf{A} \mathbf{V}_s \quad \mathbf{I} = \mathbf{A} \mathbf{I}_s$$

$$\mathbf{A} \mathbf{V}_s = \mathbf{Z} \mathbf{A} \mathbf{I}_s \quad \rightarrow \quad \mathbf{V}_s = \mathbf{A}^{-1} \mathbf{Z} \mathbf{A} \mathbf{I}_s$$

$$\mathbf{A}^{-1} \mathbf{Z} \mathbf{A} = \mathbf{Z}_s = \begin{bmatrix} Z_y + 3Z_n & 0 & 0 \\ 0 & Z_y & 0 \\ 0 & 0 & Z_y \end{bmatrix}$$

Use of Symmetrical Components



- Sequence models can be derived for lines, transformers, generators and loads
- During normal operation only the positive sequence network is excited
- The sequence networks get coupled because of the unbalances caused by faults
- Usually we only analyze the positive sequence network; unbalanced faults can be modeled by compensated positive sequence values

Power System Overvoltages



- Line switching can cause transient overvoltages
 - Resistors (200 to 800 Ω) are preinserted in EHV circuit breakers to reduce overvoltages, and subsequently shorted
- Common overvoltage cause is lightning strikes
 - Lightning strikes themselves are quite fast, with rise times of 1 to 20 μ s, with a falloff to $\frac{1}{2}$ current within less than 100 μ s
 - Peak current is usually less than 100kA
 - Shield wires above the transmission line greatly reduce the current that gets into the phase conductors
 - EMTP studies can show how these overvoltage propagate down the line

Insulation Coordination



- Insulation coordination is the process of correlating electric equipment insulation strength with expected overvoltages
- The expected overvoltages are time-varying, with a peak value and a decay characteristic
- Transformers are particularly vulnerable
- Surge arrestors are placed in parallel (phase to ground) to cap the overvoltages
 - They have high impedance during normal voltages, and low impedance during overvoltages; airgap devices have been common, though gapless designs are also used

Stability Simulation Overview



- In next several lectures we'll be deriving models used primarily in time-domain stability analysis (covering from cycles to dozens of seconds)
- Goal is to provide a good understanding of 1) the theoretical foundations, 2) applications and 3) some familiarity the commercial packages
- Next several slides provide an overview using PowerWorld Simulator
 - Learning by doing!
- Background on modeling power systems is given in my 460 or 615 slides, both of which can be accessed from my website
 - <https://overbye.engr.tamu.edu/course-2/>

PowerWorld Simulator



- Class will make extensive use of PowerWorld Simulator. If you do not have a copy of v23, the free 42 bus student version is available for download at <http://www.powerworld.com/gloveroverbyesarma>
- Start getting familiar with this package, particularly the power flow basics. Stability aspects will be covered in class
- Free training material is available at <http://www.powerworld.com/training/online-training>

PowerWorld Simulator History



- I started developing the power flow code that would become PowerWorld in 1987 on an 8088 computer with 128 kB of RAM and a 360 KB floppy drive, later also with a 3.5 inch 720 KB floppy drive
 - I improved this code throughout graduate school
 - I also developed windows code for a power system dynamics short course in 1993
- PowerWorld was born in 1994 through the merging of these two code sets, originally to teach power system operators to utility industry non-technicals.
- PowerWorld as a company was formed in 1996; the first commercial version was 4.0; current release is Version is 23
- The goal of PowerWorld Simulator (Simulator) is to make power system analysis as easy as possible

Power Flow and Dynamics Introduction



- The most common power system analysis tool is the power flow (also known as the load flow) with digital algorithms dating back to the 1950's
 - Power flow tells how the power flows in a network assuming a balanced three-phase system (known as positive sequence)
 - It is also used to calculate all bus (node) voltages and all currents
 - Power flow is a steady-state analysis tool
- Due to constant power models the power flow is a nonlinear analysis technique
- A nice history of the power flow is given in an insert by Alvarado and Thomas in T.J. Overbye, J.D. Weber, “Visualizing the Electric Grid,” *IEEE Spectrum*, Feb 2001
- Power flow is used to initialize dynamic simulations

Newton-Raphson Power Flow Algorithm



- Most common technique for solving the power flow problem is to use the Newton-Raphson algorithm
 - Classic paper is W.F. Tinney and C.E. Hart, “Power Flow Solution by Newton’s Method,” *IEEE Power App System*, Nov 1967

General form of problem: Find an \mathbf{x} such that

$$\mathbf{f}(\hat{\mathbf{x}}) = 0$$

- Key idea behind Newton-Raphson is to use sequential linearization
- In the power flow \mathbf{f} is the power balance equations and \mathbf{x} is the voltage angles and magnitudes

Power Balance Equations at Bus i



- The power balance equations are used to specify that at every bus in a grid, the sum of the power into the bus must be zero

$$\begin{aligned} S_i &= P_i + jQ_i = V_i \sum_{k=1}^n Y_{ik}^* V_k^* = \sum_{k=1}^n |V_i| |V_k| e^{j\theta_{ik}} (G_{ik} - jB_{ik}) \\ &= \sum_{k=1}^n |V_i| |V_k| (\cos \theta_{ik} + j \sin \theta_{ik}) (G_{ik} - jB_{ik}) \end{aligned}$$

Resolving into the real and imaginary parts

$$P_i = \sum_{k=1}^n |V_i| |V_k| (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) = P_{Gi} - P_{Di}$$

$$Q_i = \sum_{k=1}^n |V_i| |V_k| (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}) = Q_{Gi} - Q_{Di}$$

Per Unit 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

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

- Power engineers using give voltages in per unit (e.g., 1.02 per unit [pu], as opposed to the actual voltage

Slack (or Reference) Bus



- In the power flow we can not arbitrarily specify S at all buses because total generation must equal total load + total losses
- We also need an angle reference bus
- To solve these problems we define one bus as the slack bus; this bus has a fixed voltage magnitude and angle, and a varying real/reactive power injection
- The slack bus will not be needed in dynamic simulations though we will still need an angle reference

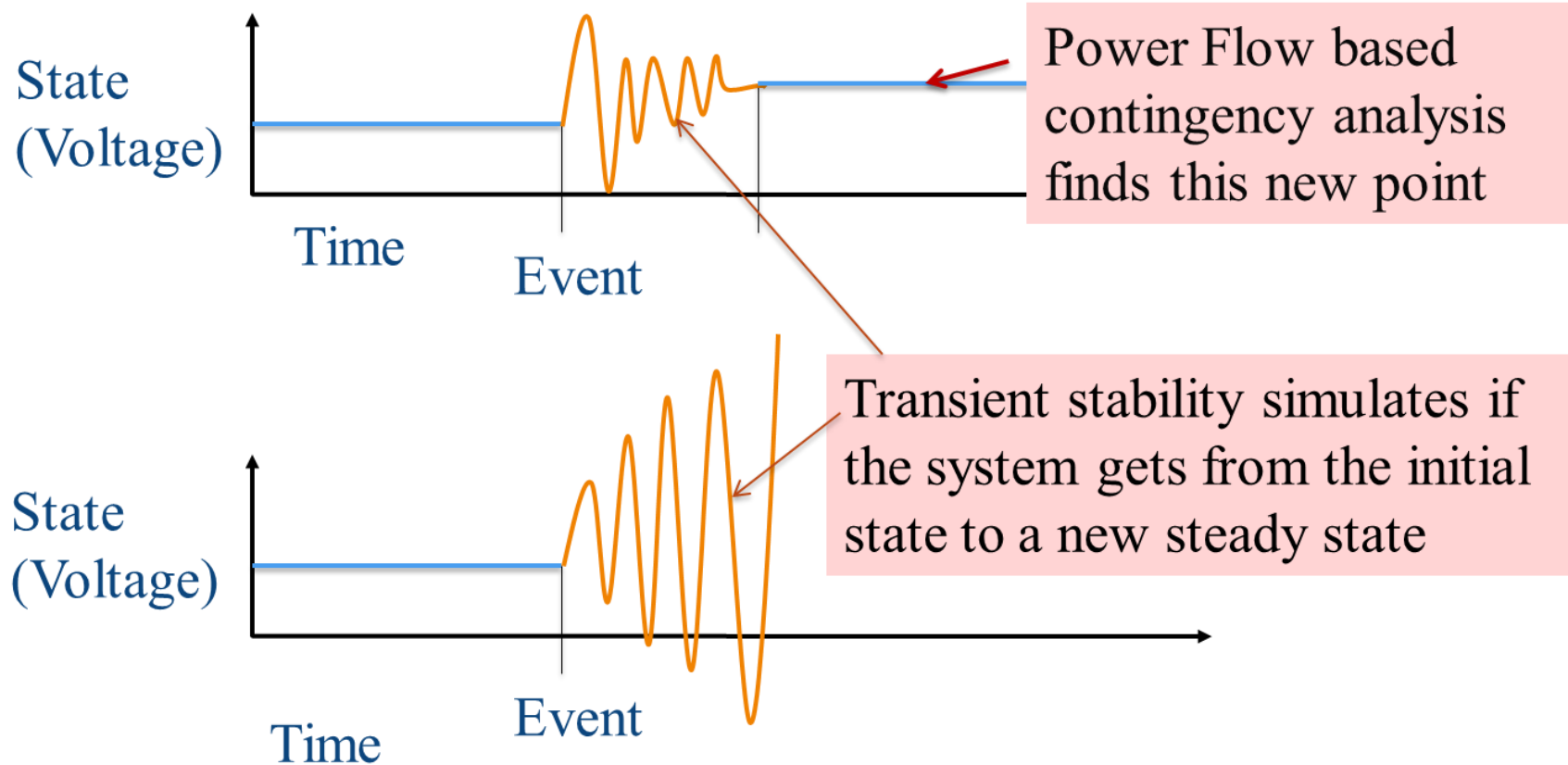
Three Traditional Types of Power Flow Buses



- There are three traditional types of power flow buses
 - Load (PQ) at which P/Q are fixed; iteration solves for voltage magnitude and angle.
 - Slack at which the voltage magnitude and angle are fixed; iteration solves for P/Q injections
 - Generator (PV) at which P and $|V|$ are fixed; iteration solves for voltage angle and Q injection
- In dynamic simulations there will no longer be slack and PV buses

Power Flow and Dynamics

- Power flow characterizes quasi-static equilibrium points in which the system frequency is nominal (e.g., 60 Hz)



Power Flow and Dynamics



- Power flow determines quasi-steady state solution and provides the dynamics initial conditions
- Transient stability is used to determine whether following a contingency the power system returns to a steady-state operating point
 - Goal is to solve a set of differential and algebraic equations,
 $\frac{dx}{dt} = f(x,y)$
 $g(x,y) = 0$
 - Starts in steady-state; hopefully returns to steady-state.
 - Models reflect the transient stability time frame (up to dozens of seconds), with some values assumed to be slow enough to hold constant while others are still fast enough to treat as algebraic

Power Flow to Transient Stability



- With PowerWorld Simulator a power flow case can be quickly transformed into a transient stability case
 - This requires the addition of at least one dynamic model
- PowerWorld Simulator supports hundreds of different dynamic models. ECEN 667 covers the major ones, with more being continually add
 - Default values are provided for most models allowing easy experimentation
 - Creating a new transient stability case from a power flow case would usually only be done for training/academic purposes; for commercial studies the dynamic models from existing datasets would be used.

First Example Case



- Open the case Example_13_4_NoModels

- Cases are on the class website

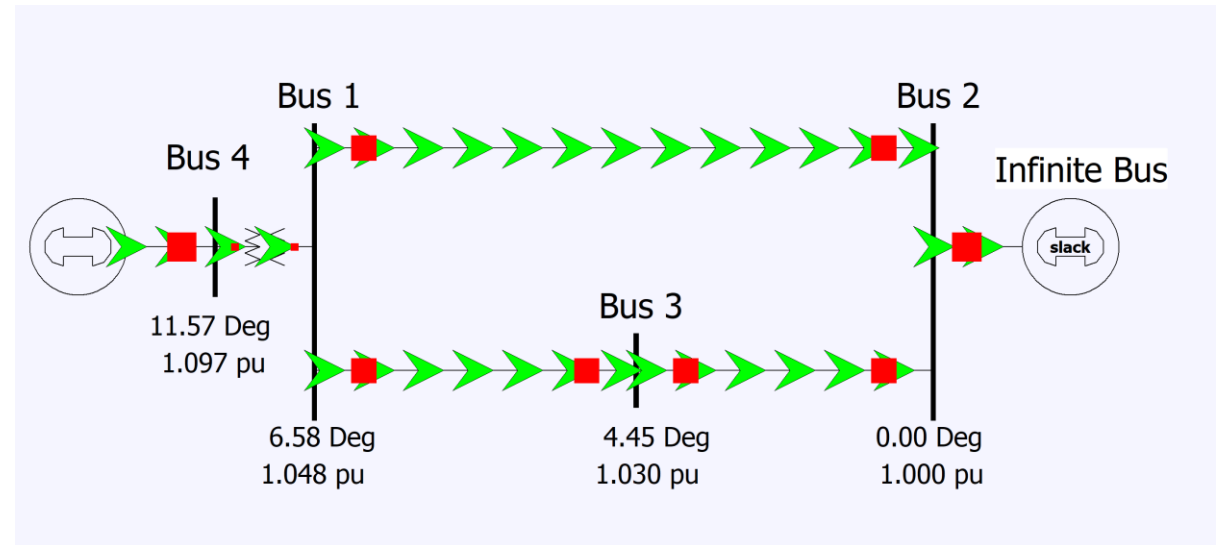
- Add a dynamic generator model to an existing “no model” power flow case by:

- In run mode, right-click on the generator symbol for bus 4, then

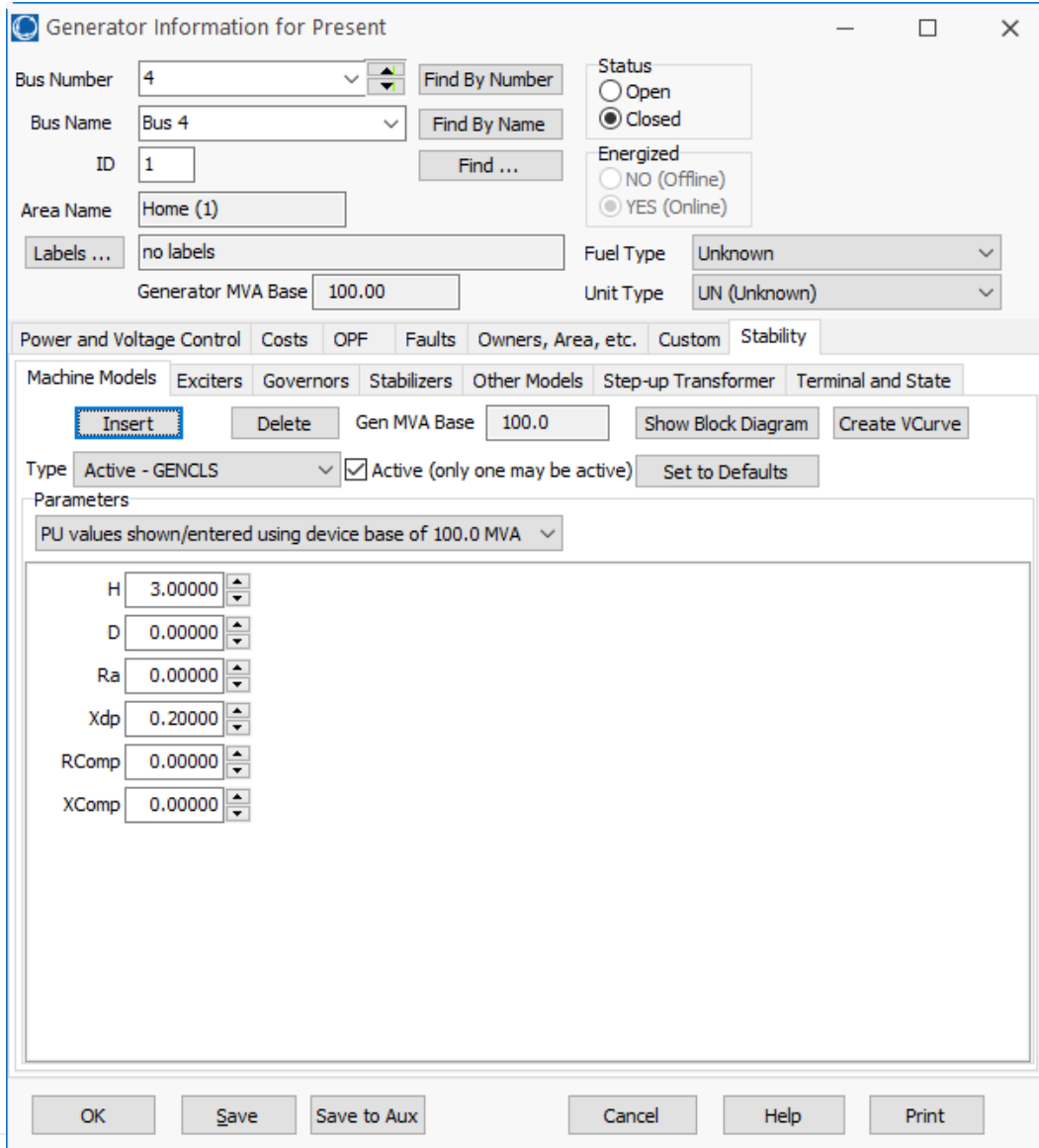
select **Generator Information Dialog**” from the local menu

- This displays the **Generator Information Dialog**, select the **Stability** tab to view the transient stability models; none are initially defined.

- Select the **Machine Models** tab to enter a dynamic machine model for the generator at bus 4. Click **Insert** to enter a machine model. From the Model Type list select **GENCLS**, which represents a simple “Classical” machine model. Use the default values. Values are per unit using the generator MVA base



Adding a Machine Model



Generator Information for Present

Bus Number: 4 (Find By Number)
Bus Name: Bus 4 (Find By Name)
ID: 1 (Find ...)
Area Name: Home (1)
Labels: no labels
Generator MVA Base: 100.00

Status:
 Open
 Closed

Energized:
 NO (Offline)
 YES (Online)

Fuel Type: Unknown
Unit Type: UN (Unknown)

Power and Voltage Control | Costs | OPF | Faults | Owners, Area, etc. | Custom | Stability

Machine Models | Exciters | Governors | Stabilizers | Other Models | Step-up Transformer | Terminal and State

Insert | Delete | Gen MVA Base: 100.0 | Show Block Diagram | Create VCurve

Type: Active - GENCLS Active (only one may be active) | Set to Defaults

Parameters
PU values shown/entered using device base of 100.0 MVA

H	3.00000
D	0.00000
Ra	0.00000
Xdp	0.20000
RComp	0.00000
XComp	0.00000

OK | Save | Save to Aux | Cancel | Help | Print

The GENCLS model represents the machine dynamics as a fixed voltage magnitude behind a transient impedance $R_a + jX_{dp}$.

Press **Ok** when done to save the data and close the dialog

Transient Stability Form Overview



- Most of the PowerWorld Simulator transient stability functionality is accessed using the **Transient Stability Analysis Form**. To view this form, from the ribbon select **Add Ons, Transient Stability**
- Key pages of form for quick start examples (listed under Select Step)
 - **Simulation** page: Used for specifying the starting and ending time for the simulation, the time step, defining the transient stability fault (contingency) events, and running the simulation
 - **Options**: Various options associated with transient stability
 - **Result Storage**: Used to specify the fields to save and where they should be saved
 - **Plots**: Used to plot results
 - **Results**: Used to view the results (actual numbers, not plots)

Transient Stability Overview Form



Simulation Status: Not Initialized

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find My Transient Contingency

Simulation Time Values: Start Time (seconds): 0.000, End Time (seconds): 5.000, Time Step (cycles): 0.500

Summary Results: Tripped, Relay Tripped, Model Tripped, Isolated

Object Pretty	Time (Cycles)	Time (Seconds)	Enabled	Object	Description	Mod
None	Defined					

Limit Monitor Name	Contingency Name
None	Defined

Bus 2

Infinite Bus

slack

Deg

00 pu

Infinite Bus Modeling



- Before doing the first transient stability run, it is useful to discuss the concept of an infinite bus. As noted earlier, in the power flow an infinite bus is assumed to have a fixed voltage magnitude and angle; hence its frequency is also fixed at the nominal value
 - In real systems infinite buses obviously do not exist, but they can be a useful concept when learning about transient stability.
 - By default PowerWorld Simulator does NOT treat the slack bus as an infinite bus, but does provide this as an option.
 - For this first example we will use the option to treat the slack bus as an infinite bus. To do this select “Options” from the “Select Step” list. This displays the option page. Select the “Power System Model” tab, and then set Infinite Bus Modeling to “Model the power flow slack bus(es) as infinite buses” if it is not already set to do so.