ECEN 667
Power System Stability

Lecture 4: Transient Stability Overview

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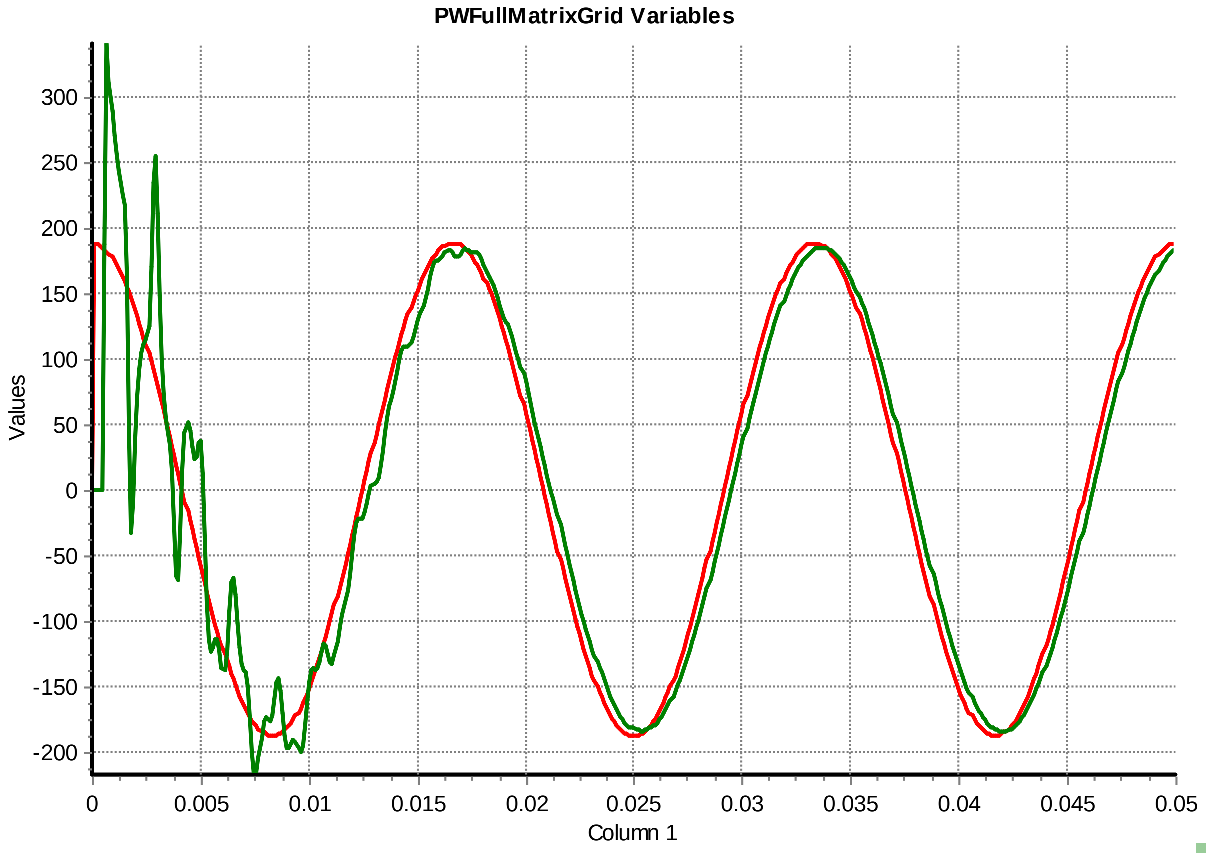
Announcements

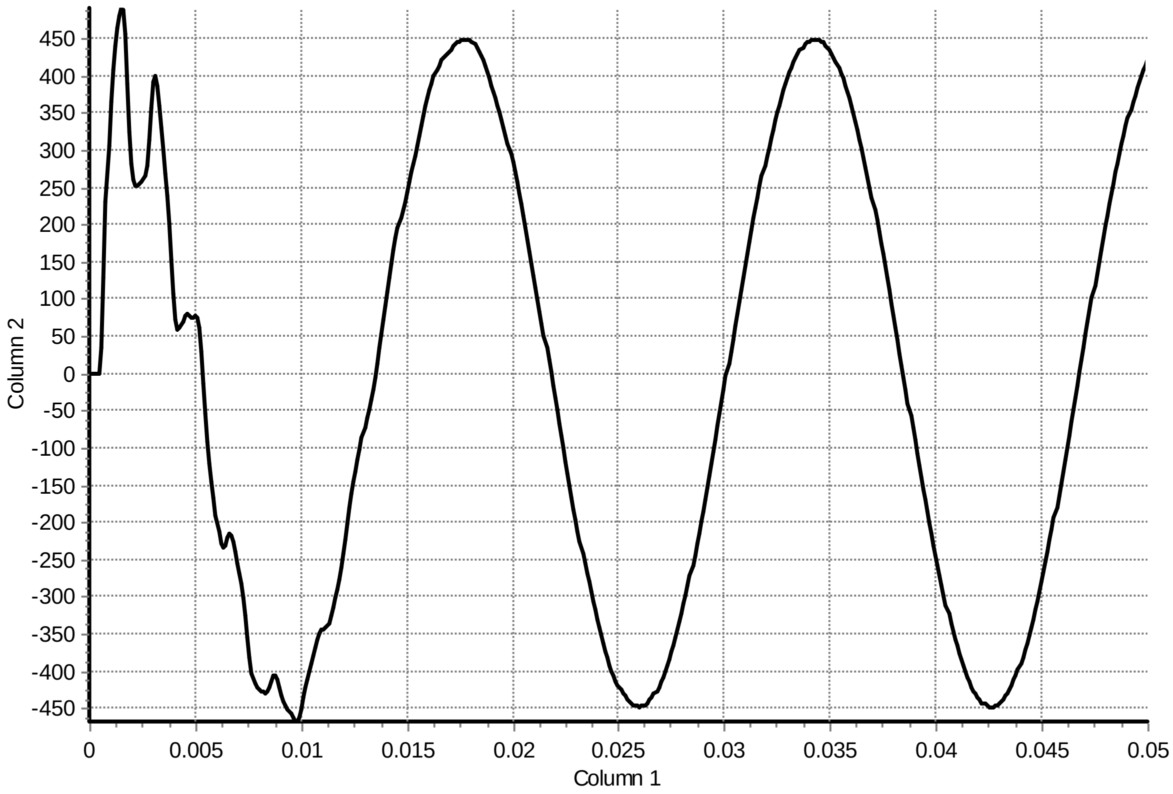
- Start reading Chapter 3
- Homework 1 is due on Thursday

Example 2.1: First Three Cycles



Red is the sending end voltage (in kv), while green is the receiving end voltage. Note the near voltage doubling at the receiving end

Example 2.1: First Three Cycles

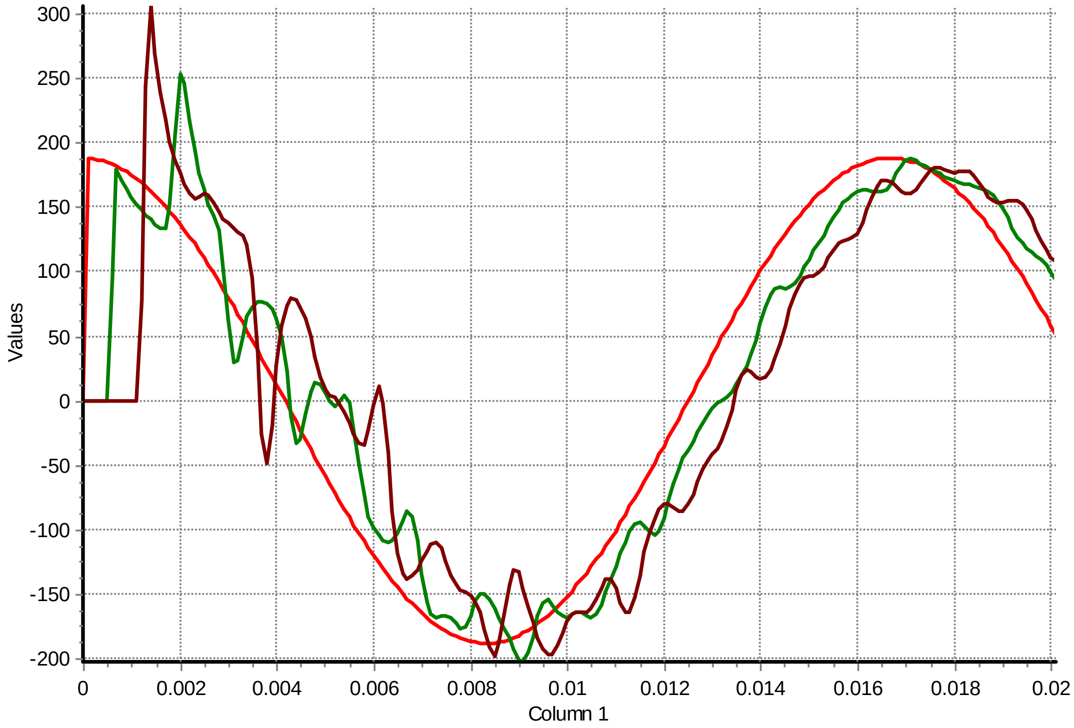


Graph shows the current (in amps) into the RL load over the first three cycles.

To get a **ballpark** value on the expected current, solve the simple circuit assuming the transmission line is just an inductor

$$I_{load,rms} = \frac{230{,}000/\sqrt{3}}{400 + j94.2 + j56.5} = 311\angle -20.6°,$$ hence a peak value of 439 amps

Three Node, Two Line Example

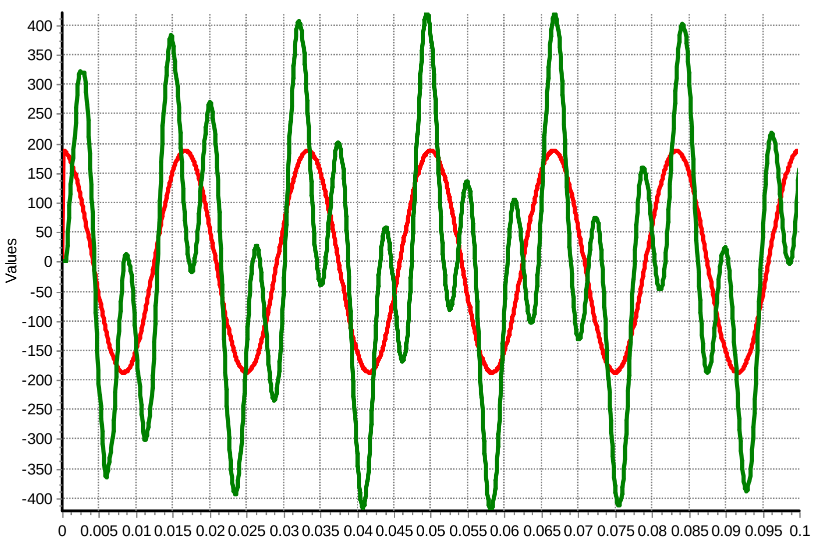


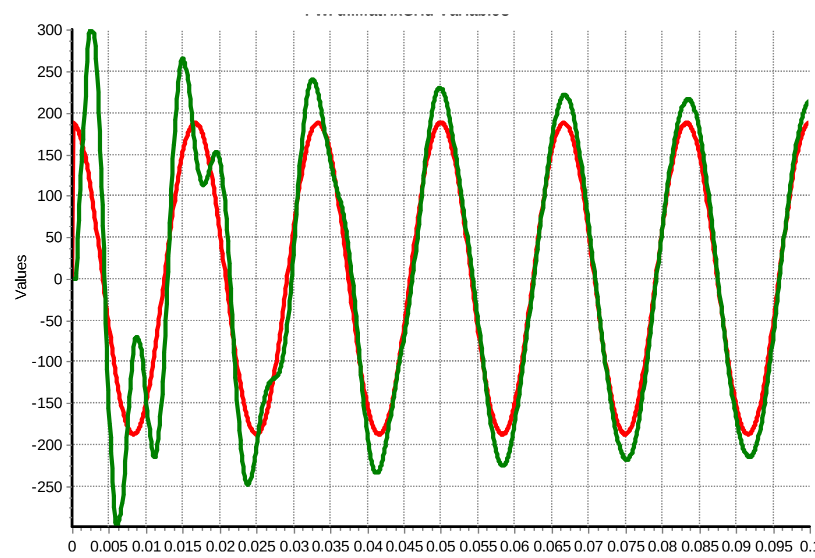
Graph shows the voltages for 0.02 seconds for the Example 2.1 case extended to connect another 120 mile line to the receiving end with an identical load

Note that there is no longer an initial overshoot for the receiving (green) end since wave continues into the second line

Example 2.1 with Capacitance

- Below graph shows example 2.1 except the RL load is replaced by a 5 μF capacitor (about 100 Mvar)
- Graph on left is unrealistic case of resistance in line
- Graph on right has R=0.1 Ω/mile





EMTP Network Solution

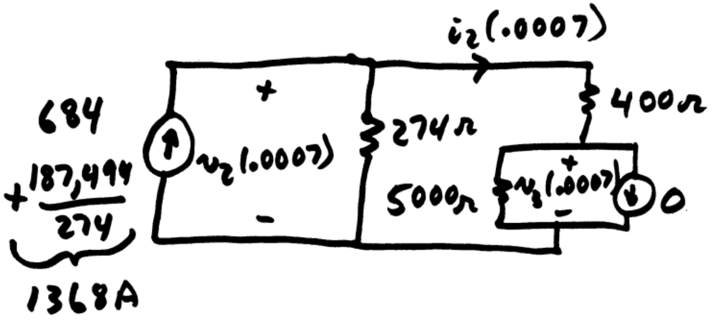
- The EMTP network is represented in a manner quite similar to what is done in the dc power flow or the transient stability network power balance equations or geomagnetic disturbance modeling (GMD)
- Solving set of dc equations for the nodal voltage vector **V** with

  $$\mathbf{V} = \mathbf{G}^{-1}\mathbf{I}$$

  where **G** is the bus conductance matrix and **I** is a vector of the Norton current injections

EMTP Network Solution

- Fixed voltage nodes can be handled in a manner analogous to what is done for the slack bus: just change the equation for node i to $V_i = V_{i,fixed}$
- Because of the time delays associated with the transmission line models **G** is often quite sparse, and can often be decoupled
- Once all the nodal voltages are determined, the internal device currents can be set
  - E.g., in example 2.1 one we know v_2 we can determine v_3



Three-Phase EMTP

- What we just solved was either just for a single phase system, or for a balanced three-phase system
  - That is, per phase analysis (positive sequence)
- EMTP type studies are often done on either balanced systems operating under unbalanced conditions (i.e., during a fault) or on unbalanced systems operating under unbalanced conditions
  - Lightning strike studies
- In this introduction to EMTP will just covered the balanced system case (but with unbalanced conditions)
  - Solved with symmetrical components

Modeling Transmission Lines

- Undergraduate power classes usually derive a per phase model for a uniformly transposed transmission line

$$L = \frac{\mu_0}{2\pi} \ln \frac{D_m}{R_b} = 2\times 10^{-7} \ln \frac{D_m}{R_b} \quad \text{H/m}$$

$$C = \frac{2\pi\varepsilon}{\ln {D_m}/{R_b^c}}$$

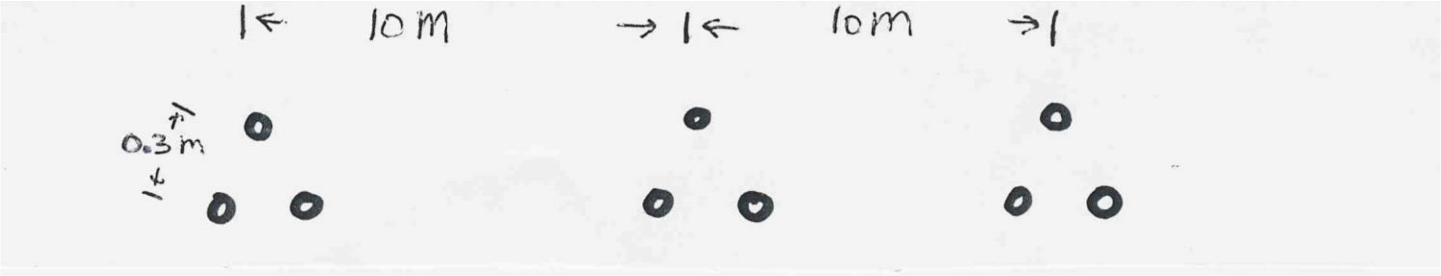
$$\mathrm{D_m} = \left[d_{ab} d_{ac} d_{bc}\right]^{1/3} \qquad R_b = (\mathrm{r}' d_{12} \cdots d_{1n})^{1/n}$$

$$\mathrm{R_b^c} = (r d_{12} \cdots d_{1n})^{1/n} \quad \text{(note r NOT r')}$$

$$\varepsilon \text{ in air } = \varepsilon_o = 8.854\times 10^{-12} \text{ F/m}$$

Modeling Transmission Lines

- Resistance is just the Ω per unit length times the length
- Calculate the per phase inductance and capacitance per km of a balanced 3ϕ, 60 Hz, line with horizontal phase spacing of 10m using three conductor bundling with a spacing between conductors in the bundle of 0.3m. Assume the line is uniformly transposed and the conductors have a 1.5 cm radius and resistance = 0.06 Ω/km



Modeling Transmission Lines

$$D_m = (10 \times 10 \times 20)^{1/3} = 12.6\text{m}$$

$$R_b = (0.78 \times 0.015 \times 0.3 \times 0.3)^{1/3} = 0.102\text{m}$$

$$L = 2 \times 10^{-7} \ln \frac{12.6}{0.102} = 9.63 \times 10^{-7}\text{H/m} = 9.63 \times 10^{-4}\text{H/km}$$

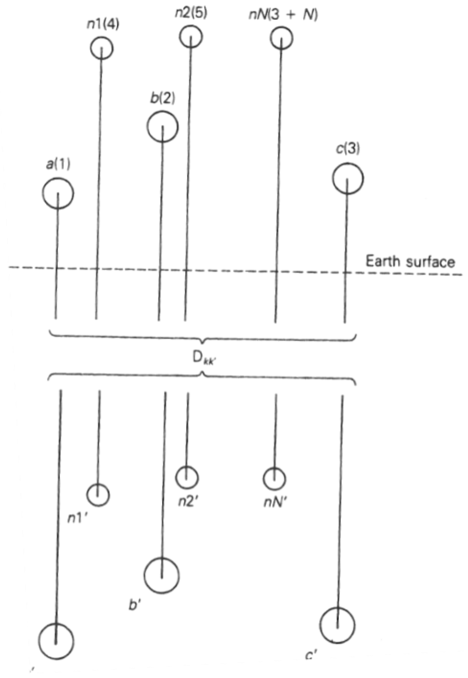
$$R_b^c = (0.015 \times 0.3 \times 0.3)^{1/3} = 0.1105\text{m}$$

$$C = \frac{2\pi \times 8.854 \times 10^{-12}}{\ln 12.6/0,1105} = 1.17 \times 10^{-11}\text{F/m} = 1.17 \times 10^{-8}\text{F/km}$$

- Resistance is 0.06/3=0.02Ω/km
  - Divide by three because three conductors per bundle

Untransposed Lines with Ground Conductors

- To model untransposed lines, perhaps with grounded neutral wires, we use the approach of Carson (from 1926) of modeling the earth return with equivalent conductors located in the ground under the real wires
  - Earth return conductors have the same GMR of their above ground conductor (or bundle) and carry the opposite current
- Distance between conductors is



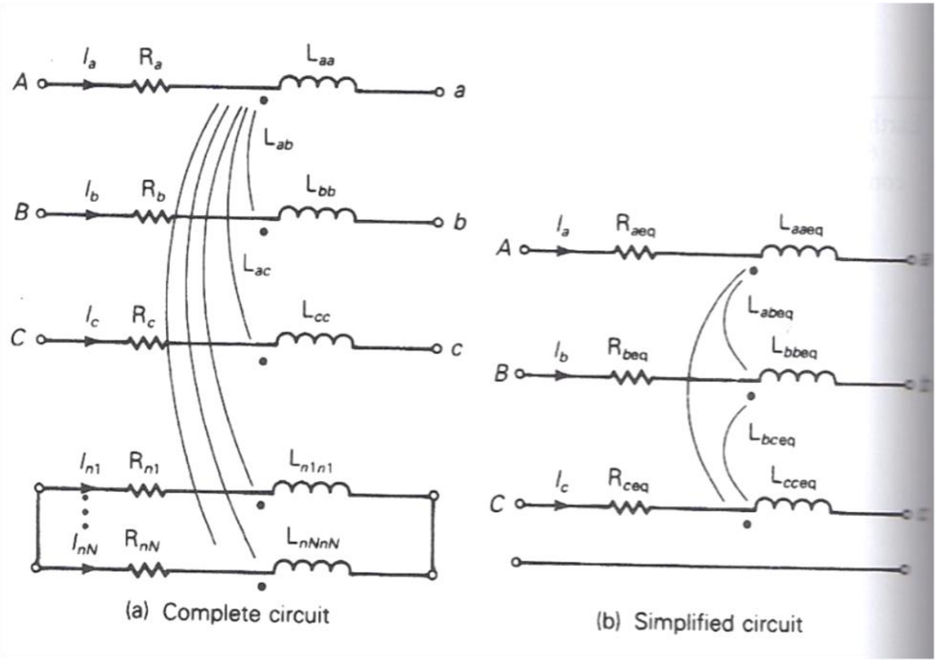
$$D_{kk'} = 658.5\sqrt{\rho / f} \text{ m}$$

where ρ is the earth resistivity in Ω-m

with 100 Ω-m a typical value

Untransposed Lines with Ground Conductors

- The resistance of the equivalent conductors is $R_{k'}=9.869\times10^{-7}\times f$ Ω/m with f the frequency, which is also added in series to the R of the actual conductors
- Conductors are mutually coupled; we'll be assuming three phase conductors and N grounded neutral wires
- Total current in all conductors sums to zero



Untransposed Lines with Ground Conductors

- The relationships between voltages and currents per unit length is

$$\begin{bmatrix} E_{Aa} \\ E_{Bb} \\ E_{Cc} \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \left(\mathbf{R} + j\omega\mathbf{L}\right) \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_{n1} \\ \vdots \\ InN \end{bmatrix}$$

- Where the diagonal resistance are the conductor resistance plus $R_{k'}$ and the off-diagonals are all $R_{k'}$
- The inductances are $L_{km} = 2 \times 10^{-7} \ln\left(\frac{D_{km'}}{D_{km}}\right)$ with D_{kk} just the GMR for the conductor (or bundle)

$D_{kk'}$ is large so $D_{km'} \approx D_{kk'}$

Untransposed Lines with Ground Conductors

- This then gives an equation of the form

$$\begin{bmatrix} E_{Aa} \\ E_{Bb} \\ E_{Cc} \\ \hline 0 \\ \cdots \\ 0 \end{bmatrix} = \left[\begin{array}{ccc|ccc} \multicolumn{3}{c|}{\overbrace{\hphantom{Z_{11} \quad Z_{12} \quad Z_{13}}}^{Z_A}} & \multicolumn{3}{c}{\overbrace{\hphantom{Z_{14} \quad \cdots \quad Z_{1(3+N)}}}^{Z_B}} \\ Z_{11} & Z_{12} & Z_{13} & Z_{14} & \cdots & Z_{1(3+N)} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} & \cdots & Z_{2(3+N)} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} & \cdots & Z_{3(3+N)} \\ \hline Z_{41} & Z_{42} & Z_{43} & Z_{44} & \cdots & Z_{4(3+N)} \\ & & & & & \\ Z_{(3+N)1} & Z_{(3+N)2} & Z_{(3+N)3} & Z_{(3+N)4} & \cdots & Z_{(3+N)(3+N)} \\ \multicolumn{3}{c|}{\underbrace{\hphantom{Z_{11} \quad Z_{12} \quad Z_{13}}}_{Z_C}} & \multicolumn{3}{c}{\underbrace{\hphantom{Z_{14} \quad \cdots \quad Z_{1(3+N)}}}_{Z_D}} \end{array} \right] \begin{bmatrix} I_a \\ I_b \\ I_c \\ \hline I_{n1} \\ I_{nN} \\ \vdots \end{bmatrix}$$

- Which can be reduced to just the phase values

$$\mathbf{E}_p = \left[\mathbf{Z}_A - \mathbf{Z}_B \mathbf{Z}_D^{-1} \mathbf{Z}_C \right] \mathbf{I}_p = \mathbf{Z}_p \mathbf{I}_p$$

- We'll use $\mathbf{Z}_p$ with symmetrical components

Example (from 4.1 in Kersting Book)

- Given a 60 Hz overhead distribution line with the tower configuration (N=1 neutral wire) with the phases using Linnet conductors and the neutral 4/0 6/1 ACSR, determine $\mathbf{Z}_p$ in ohms per mile

  - Linnet has a GMR = 0.0244ft, and R = 0.306Ω/mile
  - 4/0 6/1 ACSR has GMR=0.00814 ft and R=0.592Ω/mile
  - $R_{k'} = 9.869 \times 10^{-7} \times f\ \Omega/m$ is 0.0953 Ω/mile at 60 Hz
  - Phase R diagonal values are 0.306 + 0.0953 = 0.401 Ω/mile
  - Ground is 0.6873 Ω/mile

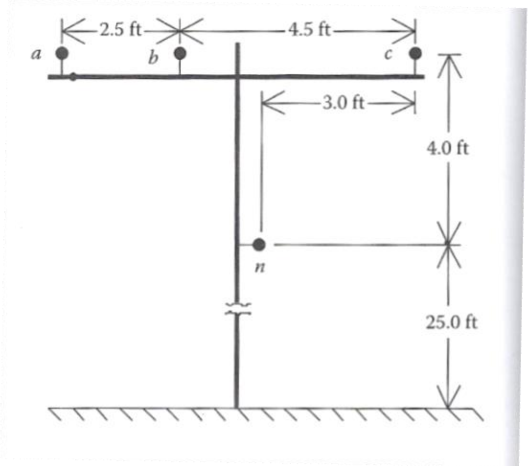


Figure 4.7 from Kersting

Example (from 4.1 in Kersting Book)

- Example inductances are worked with ρ = 100Ω-m

$$D_{kk'} = 658.5\sqrt{100/60}\ m = 850.1m = 2789\ \text{ft}$$

$$L_{km} = 2\times10^{-7}\ln\left(\frac{D_{km'}}{D_{km}}\right) \approx 2\times10^{-7}\ln\left(\frac{D_{kk'}}{D_{km}}\right)$$

- Note at 2789 ft, $D_{kk'}$ is much, much larger than the distances between the conductors, justifying the above assumption

Example (from 4.1 in Kersting Book)

- Working some of the inductance values

$$L_{aa} = 2\times 10^{-7} \ln\left(\frac{2789}{0.0244}\right) = 2.329\times 10^{-6}\ \text{H/m}$$

- Phases a and b are separated by 2.5 feet, while it is 5.66 feet between phase a and the ground conductor

$$L_{ab} = 2\times 10^{-7} \ln\left(\frac{2789}{2.5}\right) = 1.403\times 10^{-6}\ \text{H/m}$$

$$L_{an} = 2\times 10^{-7} \ln\left(\frac{2789}{5.66}\right) = 1.240\times 10^{-6}\ \text{H/m}$$

Even though the distances are worked here in feet, the result is in H/m because of the units on μ_0

Example (from 4.1 in Kersting Book)

- Continue to create the 4 by 4 symmetric **L** matrix
- Then **Z** = **R** + jω**L**
- Partition the matrix and solve $\mathbf{Z}_p = \left[\mathbf{Z}_A - \mathbf{Z}_B \mathbf{Z}_D^{-1} \mathbf{Z}_C\right]$
- The result in Ω/mile is

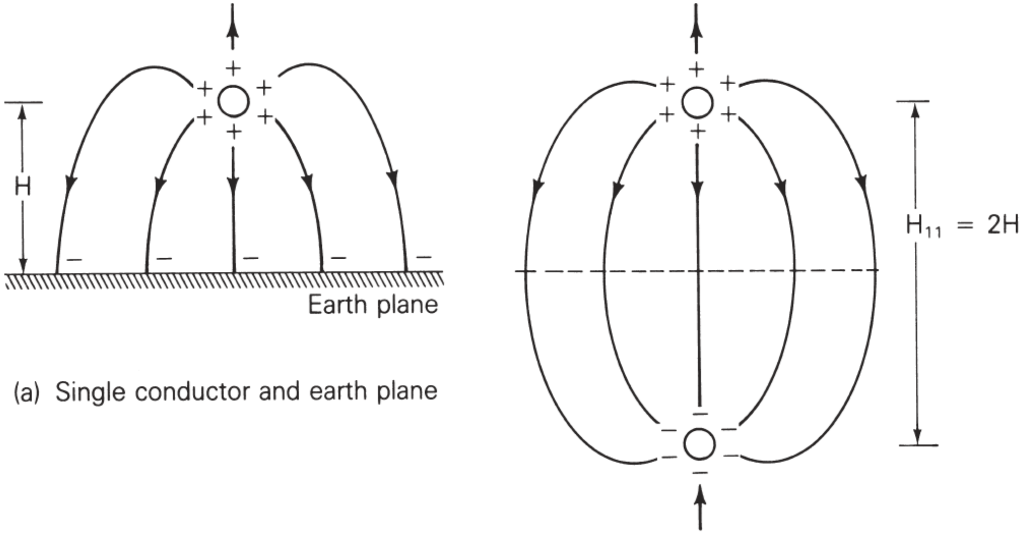
$$\mathbf{Z}_p = \begin{bmatrix} 0.4576 + 1.0780 & 0.1560 + j0.5017 & 0.1535 + j0.3849 \\ 0.1560 + j0.5017 & 0.4666 + j1.0482 & 0.1580 + j0.4236 \\ 0.1535 + j0.3849 & 0.1580 + j0.4236 & 0.4615 + j1.0651 \end{bmatrix}$$

Modeling Line Capacitance

- For capacitance the earth is typically modeled as a perfectly conducting horizontal plane; then the earth plane is replaced by mirror image conductors
  - If conductor is distance H above ground, mirror image conductor is distance H below ground, hence their distance apart is 2H

FIGURE 4.23

Method of images

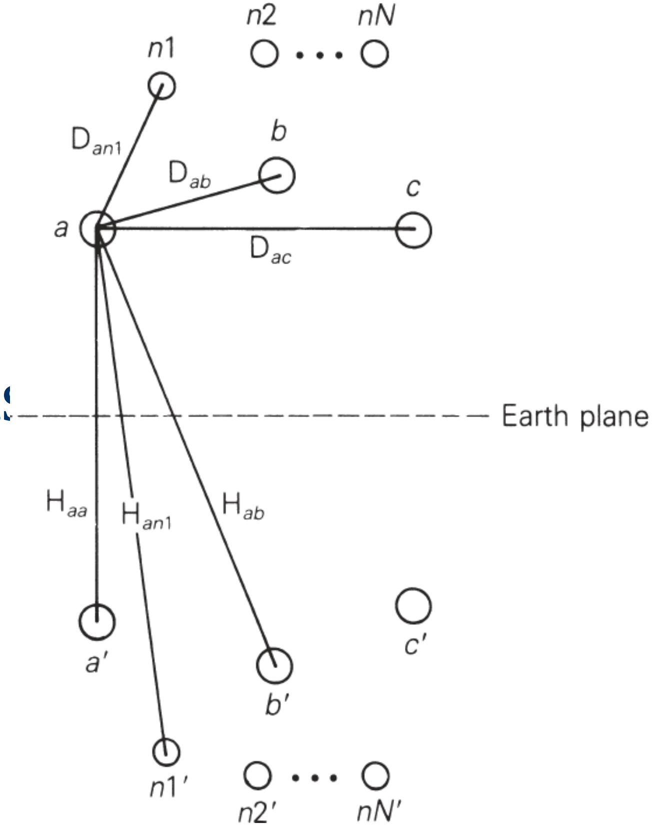


Modeling Line Capacitance

- The relationship between the voltage to neutral and charges are then given as

$$V_{kn} = \frac{1}{2\pi\varepsilon} \sum_{m=a}^{nN} q_m \ln \frac{H_{km}}{D_{km}} = \sum_{m=a}^{nN} q_m P_{km}$$

$$P_{km} = \frac{1}{2\pi\varepsilon} \ln \frac{H_{km}}{D_{km}}$$



- P's are called potential coefficients
- Where D_{km} is the distance between the conductors, H_{km} is the distance to a mirror image conductor and $D_{kk} = R_b^c$

Modeling Line Capacitance

- Then we setup the matrix relationship

$$
\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \\ \hline 0 \\ \vdots \\ 0 \end{bmatrix}
=
\left[\begin{array}{ccc|ccc}
\overbrace{P_{aa} \quad P_{ab} \quad P_{ac}}^{\mathbf{P}_A} & & & \overbrace{P_{an1} \quad \cdots \quad P_{anN}}^{\mathbf{P}_B} & & \\
P_{ba} & P_{bb} & P_{bc} & P_{bn1} & \cdots & P_{bnN} \\
P_{ca} & P_{cb} & P_{cc} & P_{cn1} & \cdots & P_{cnN} \\
\hline
P_{n1a} & P_{n1b} & P_{n1c} & P_{n1n1} & \cdots & P_{n1nN} \\
\vdots & & & & & \\
\underbrace{P_{nNa} \quad P_{nNb} \quad P_{nNc}}_{\mathbf{P}_C} & & & \underbrace{P_{nNn1} \quad \cdots \quad P_{nNnN}}_{\mathbf{P}_D} & &
\end{array}\right]
\begin{bmatrix} q_a \\ q_b \\ q_c \\ \hline q_{n1} \\ \vdots \\ q_{nN} \end{bmatrix}
$$

- And solve

$$\mathbf{V}_p = \left[\mathbf{P}_A - \mathbf{P}_B \mathbf{P}_D^{-1} \mathbf{P}_C\right] \mathbf{Q}_p$$

$$\mathbf{C}_p = \left[\mathbf{P}_A - \mathbf{P}_B \mathbf{P}_D^{-1} \mathbf{P}_C\right]^{-1}$$

Continuing the Previous Example

- In example 4.1, assume the below conductor radii

For the phase conductor $R_b^c = 0.0300$ ft

For the neutral conductor $R_n^c = 0.0235$ ft

- Calculating some values

$$\varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m} = 1.424 \times 10^{-2} \ \mu\text{F/mile}$$

$$P_{aa} = \frac{1}{2\pi\varepsilon_0} \ln\left(\frac{2 \times 29.0}{0.0300}\right) = 11.177 \ln\left(\frac{2 \times 29.0}{0.0300}\right) = 84.57 \text{mile/}\mu\text{F}$$

$$P_{ab} = 11.177 \ln\left(\frac{58.05}{2.5}\right) = 35.15 \text{mile/}\mu\text{F}$$

$$P_{an} = 11.177 \ln\left(\frac{54.148}{5.6569}\right) = 25.25 \text{mile/}\mu\text{F}$$

Continuing the Previous Example

- Solving we get

$$\mathbf{P}_p = \left[\mathbf{P}_A - \mathbf{P}_B \mathbf{P}_D^{-1} \mathbf{P}_C\right] = \begin{bmatrix} 77.12 & 26.79 & 15.84 \\ 26.79 & 75.17 & 19.80 \\ 15.87 & 19.80 & 76.29 \end{bmatrix} \text{ mile/}\mu\text{F}$$

$$\mathbf{C}_p = \left[\mathbf{P}_p\right]^{-1} = \begin{bmatrix} 0.0150 & -0.0049 & -0.0018 \\ -0.0049 & 0.0158 & -0.0030 \\ -0.0018 & -0.0030 & 0.0137 \end{bmatrix} \mu\text{F/mile}$$

Frequency Dependence

- We might note that the previous derivation for **L** assumed a frequency. For steady-state and transient stability analysis this is just the power grid frequency
- As we have seen in EMTP there are a number of difference frequencies present, particularly during transients
  - Coverage is beyond the scope of this class
  - An early paper is J.K. Snelson, "Propagation of Travelling on Transmission Lines: Frequency Dependent Parameters," IEEE Trans. Power App. and Syst., vol. PAS-91, pp. 85-91, 1972

Power System Overvoltages

- Line switching can cause transient overvoltages
  - Resistors (200 to 800Ω) are preinserted in EHV circuit breakers to reduce over voltages, and subsequently shorted
- Common overvoltage cause is lightning strikes
  - Lightning strikes themselves are quite fast, with rise times of 1 to 20 μs, with a falloff to ½ current within less than 100 μs
  - 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

Transient Stability Overview

- In next several lectures we'll be deriving models used primarily in transient 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!

PowerWorld Simulator

- Class will make extensive use of PowerWorld Simulator. If you do not have a copy of v20, 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. Transient stability aspects will be covered in class
- Free training material is available at

http://www.powerworld.com/training/online-training

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 many more than one hundred different dynamic models. These slides cover just a few of them
  - 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.

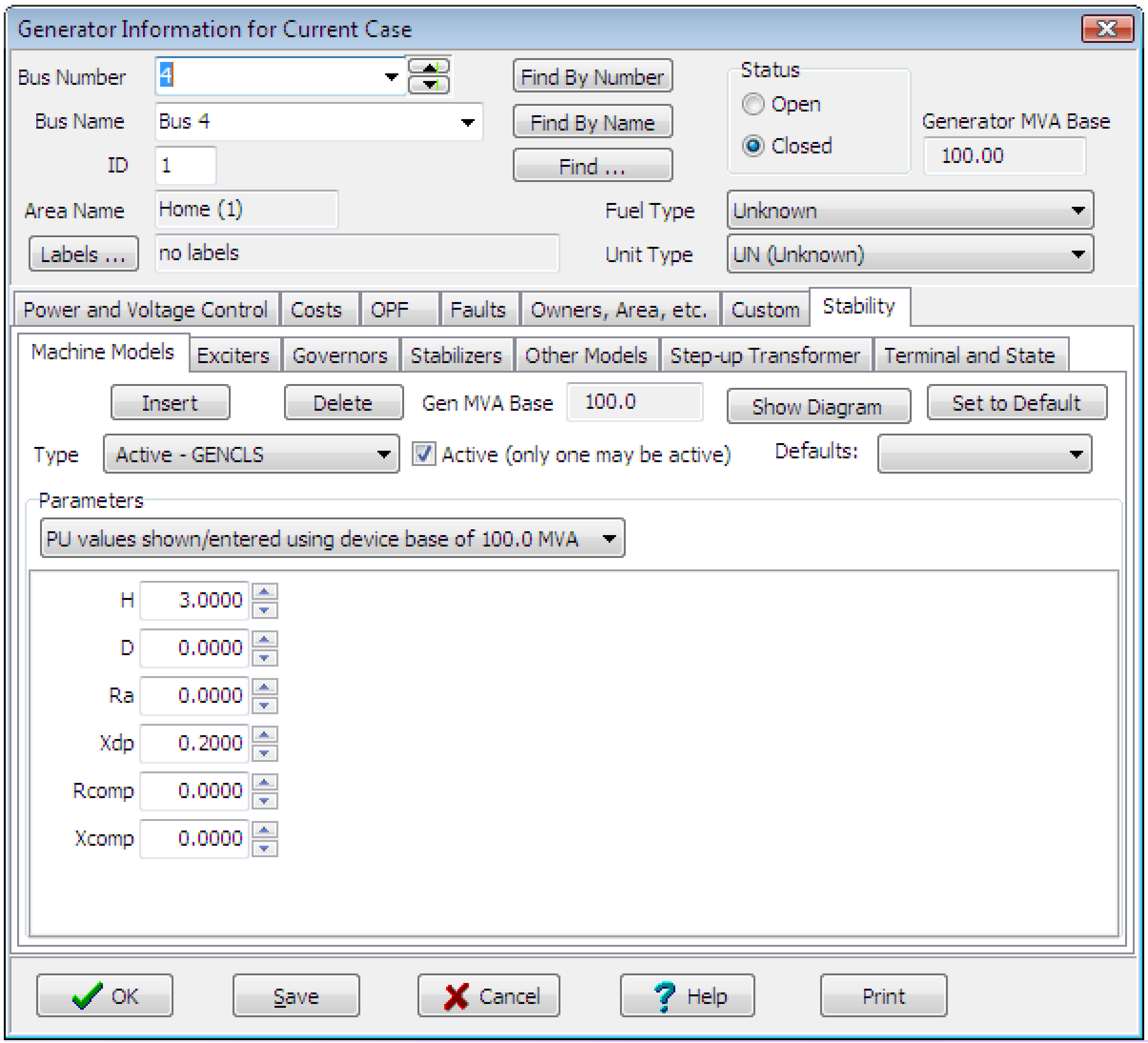
Power Flow vs. Transient Stability

- Power flow determines quasi-steady state solution and provides the transient stability 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, $d\mathbf{x}/dt = \mathbf{f}(\mathbf{x},\mathbf{y}),\ \mathbf{g}(\mathbf{x},\mathbf{y}) = \mathbf{0}$
  - Starts in steady-state, and 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 (LTC tap changing), while others are still fast enough to treat as algebraic (synchronous machine stator dynamics, voltage source converter dynamics).

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



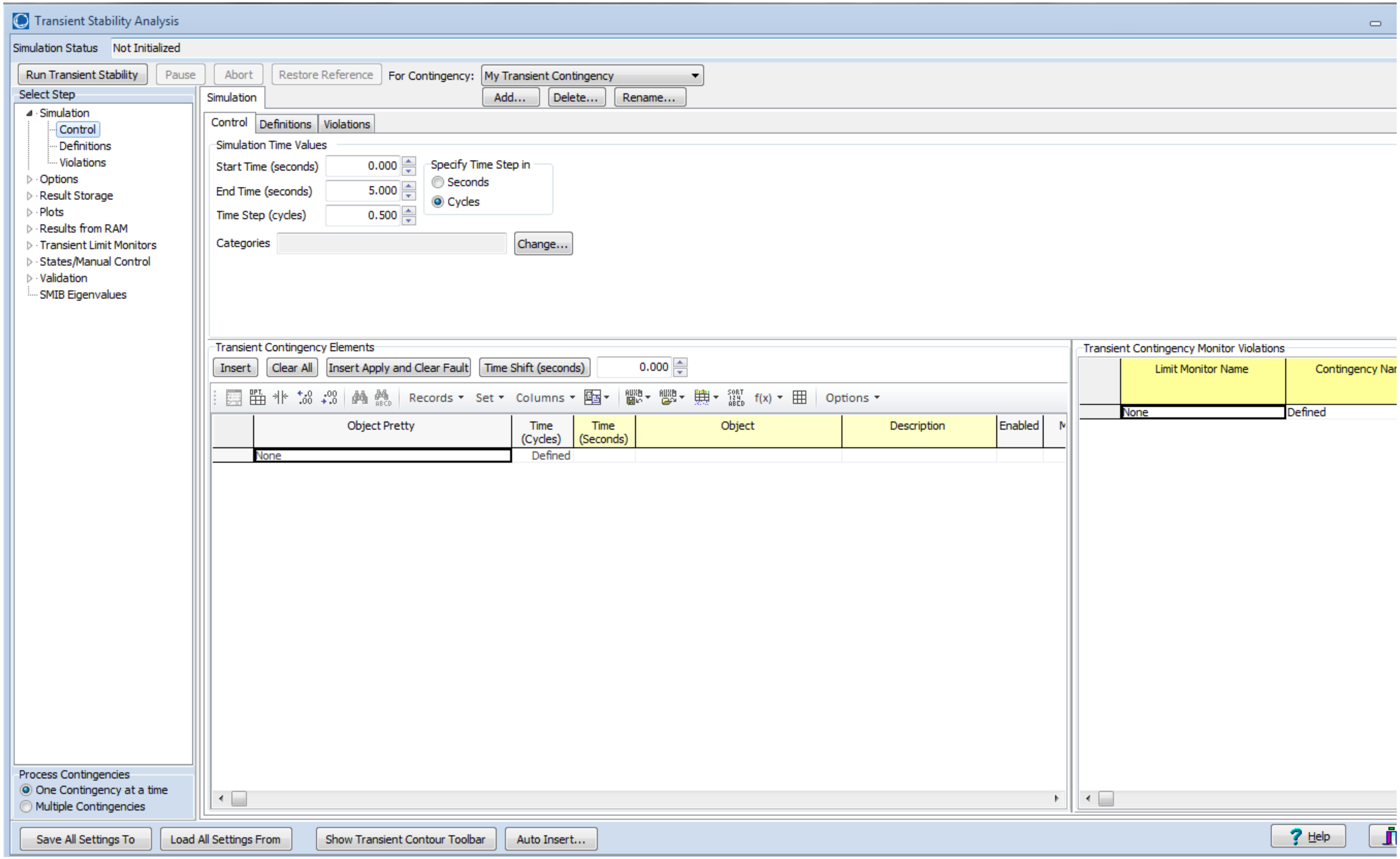
The GENCLS model represents the machine dynamics as a fixed voltage magnitude behind a transient impedance Ra + jXdp.

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
  - Plots: Used to plot results
  - Results: Used to view the results (actual numbers, not plots)

Transient Stability Overview Form



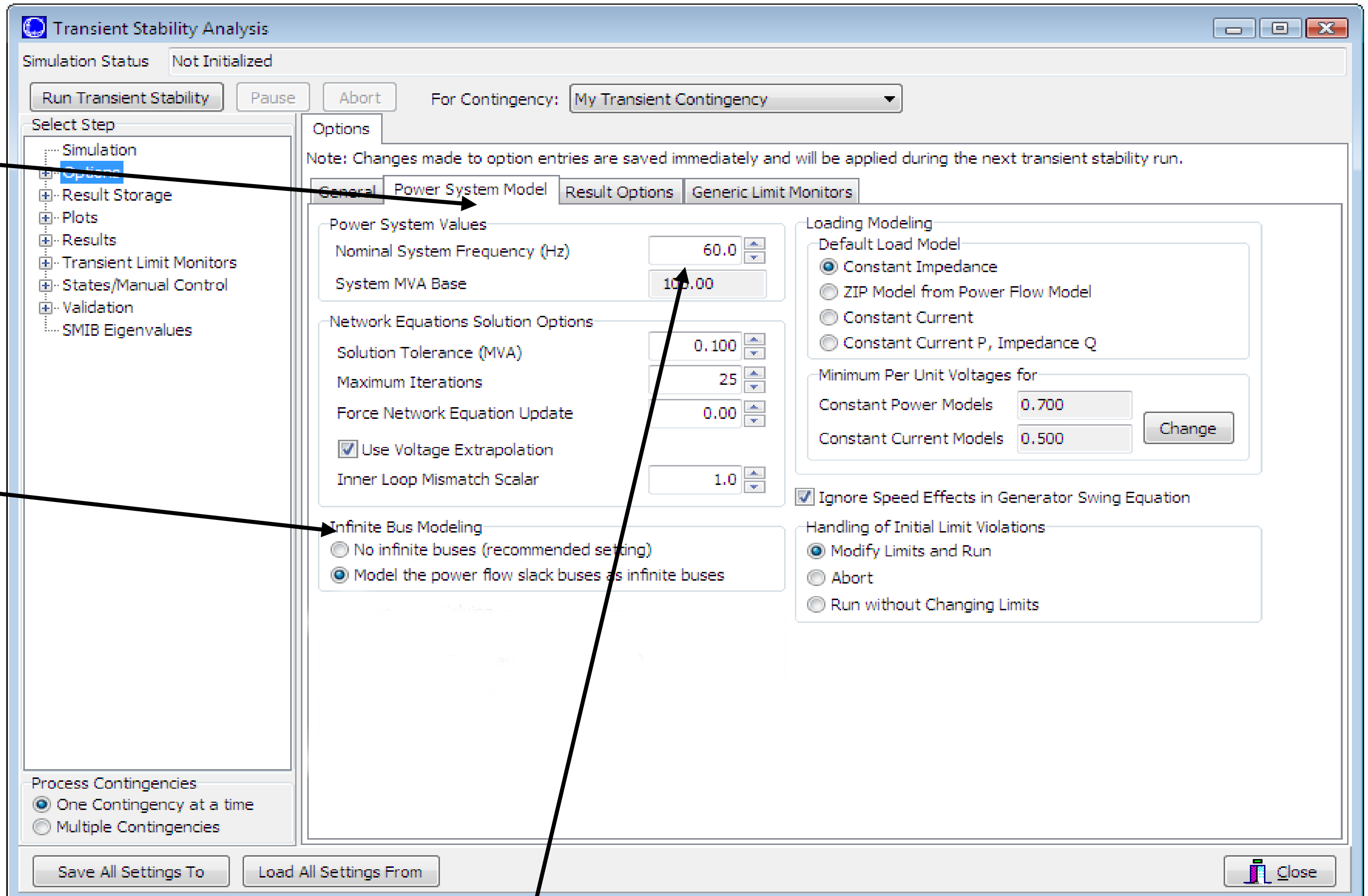
Infinite Bus Modeling

- Before doing our first transient stability run, it is useful to discuss the concept of an infinite bus. 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.

Transient Stability Options Page

Power System Model Page

Infinite Bus Modeling



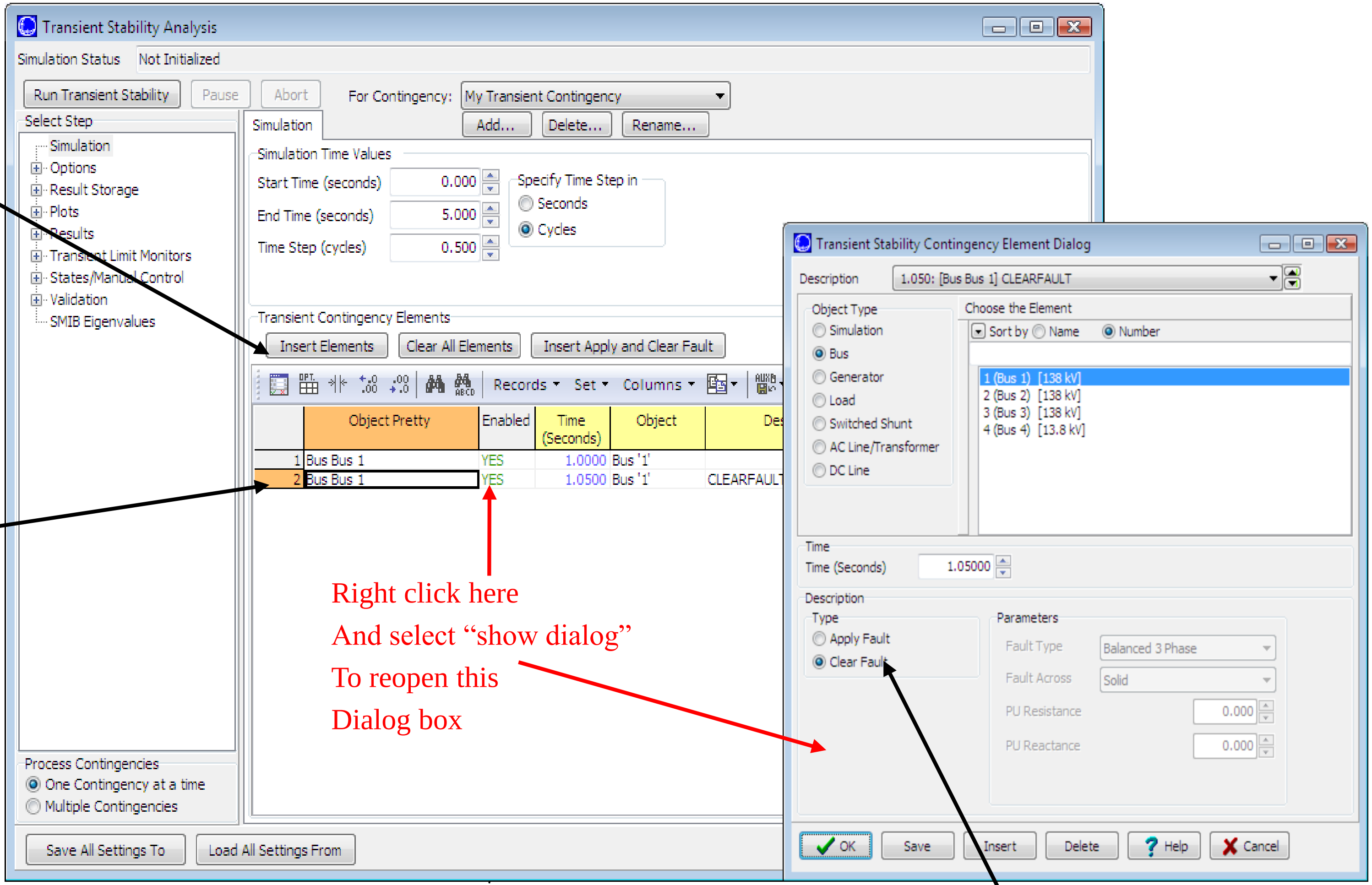
This page is also used to specify the nominal system frequency

Specifying the Contingency Event

- To specify the transient stability contingency go back to the "Simulation" page and click on the "Insert Elements" button. This displays the Transient Stability Contingency Element Dialog, which is used to specify the events that occur during the study.
- Usually start at time > 0 to showcase runs flat
- The event for this example will be a self-clearing, balanced 3-phase, solid (no impedance) fault at bus 1, starting at time = 1.00 seconds, and clearing at time = 1.05 seconds.
  - For the first action just choose all the defaults and select "Insert." Insert will add the action but not close the dialog.
  - For second action change the Time to 1.05 seconds the Type to "Clear Fault." Select "OK," which saves the action and closes the dialog.

Inserting Transient Stability Contingency Elements

Click to insert new elements



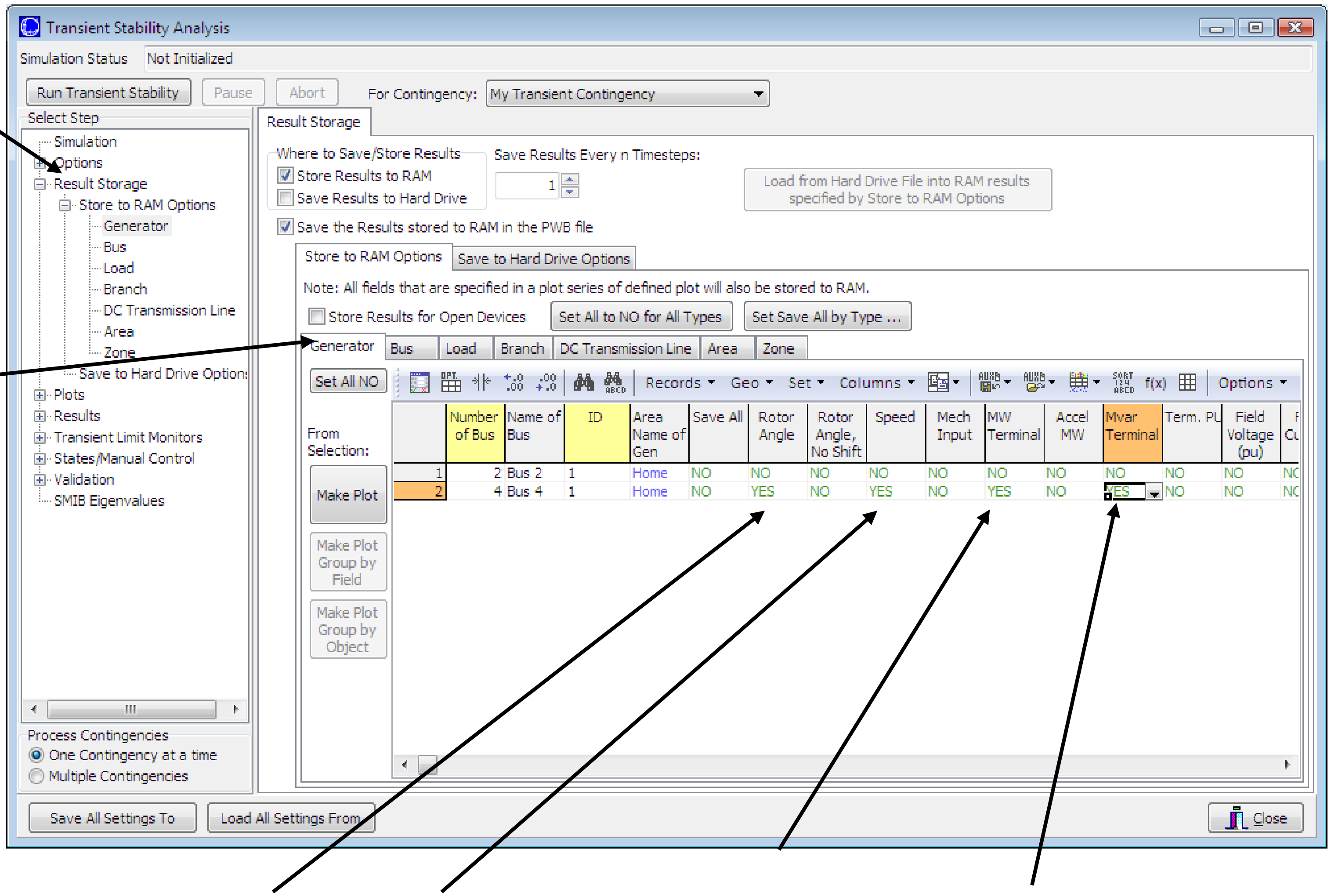
Available element type will vary with different objects

Determining the Results to View

- For large cases, transient stability solutions can generate huge amounts of data. PowerWorld Simulator provides easy ways to choose which fields to save for later viewing. These choices can be made on the "Result Storage" page.
- For this example we'll save the generator 4 rotor angle, speed, MW terminal power and Mvar terminal power.
- From the "Result Storage" page, select the generator tab and double click on the specified fields to set their values to "Yes".

Result Storage Page

Result Storage Page

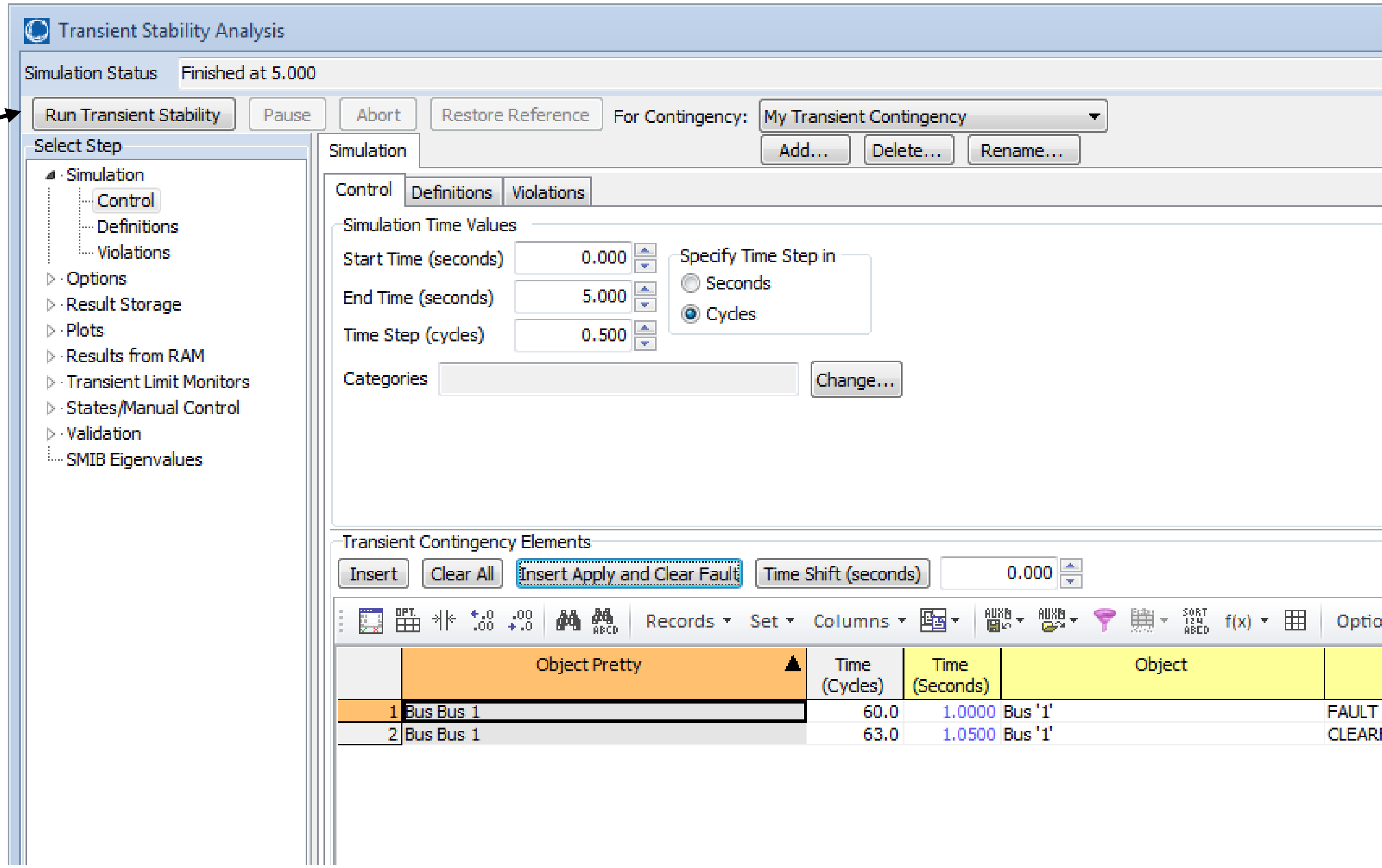


Saving Changes and Doing Simulation

- The last step before doing the run is to specify an ending time for the simulation, and a time step.
- Go to the "Simulation" page, verify that the end time is 5.0 seconds, and that the Time Step is 0.5 cycles
  - PowerWorld Simulator allows the time step to be specified in either seconds or cycles, with 0.25 or 0.5 cycles recommended
- Before doing your first simulation, save all the changes made so far by using the main PowerWorld Simulator Ribbon, select "Save Case As" with a name of "Example_13_4_WithCLSModel_ReadyToRun"
- Click on "Run Transient Stability" to solve.

Doing the Run

Click to run the specified contingency



Once the contingency runs the "Results" page may be opened

Transient Stability Results

- Once the transient stability run finishes, the "Results" page provides both a minimum/maximum summary of values from the simulation, and time step values for the fields selected to view.
- The Time Values and Minimum/Maximum Values tabs display standard PowerWorld Simulator case information displays, so the results can easily be transferred to other programs (such as Excel) by right-clicking on a field and selecting "Copy/Paste/Send"