ECEN 667
Power System Stability

Lecture 6: Stability Overview with PowerWorld Simulator

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Announcements

- Start reading Chapter 3
- Homework 1 is due today
- Homework 2 is assigned today and due on Thursday Sept 13.

Aside: Ionized Air as a Conductor

An Interesting Video of an Uncleared Fault

- The below video shows an event from September 2, 2022 in the Netherlands (Flevoland province) in which a transmission line fault was not cleared. Note the sag and smoke (steam?) coming from the line
- https://nos.nl/video/2443017-explosies-en-rokende-kabels-bij-verdeelstation-in-dronten

Review of Phasors

Goal of phasor analysis is to simplify the analysis of constant frequency ac systems

$$v(t) = V_{max} \cos(\omega t + \theta_V)$$
$$i(t) = I_{max} \cos(\omega t + \theta_I)$$

Root Mean Square (RMS) voltage of sinusoid

$$\sqrt{\frac{1}{T}\int_0^T v(t)^2 dt} = \frac{V_{max}}{\sqrt{2}}$$

Phasor Representation

Euler's Identity: $e^{j\theta} = \cos\theta + j\sin\theta$

Phasor notation is developed by rewriting using Euler's identity

$$v(t) = \sqrt{2}\left|V\right|\cos(\omega t + \theta_V)$$

$$v(t) = \sqrt{2}\left|V\right|\mathrm{Re}\left[e^{j(\omega t+\theta_V)}\right]$$

(Note: $\left|V\right|$ is the RMS voltage)

Phasor Representation, cont'd

The RMS, cosine-referenced voltage phasor is:

$$V = |V| e^{j\theta_V} = |V| \angle \theta_V$$

$$v(t) = \text{Re} \sqrt{2}\, V e^{j\omega t} e^{j\theta_V}$$

$$V = |V| \cos\theta_V + j|V| \sin\theta_V$$

$$I = |I| \cos\theta_I + j|I| \sin\theta_I$$

Advantages of Phasor Analysis

Device	**Time Analysis**	**Phasor**
Resistor	$v(t) = Ri(t)$	$V = RI$
Inductor	$v(t) = L\frac{di(t)}{dt}$	$V = j\omega LI$
Capacitor	$\frac{1}{C}\int_0^t i(t)dt + v(0)$	$V = \frac{1}{j\omega C}I$

$$Z \quad = \quad \text{Impedance} = R + jX = |Z|\angle\phi$$

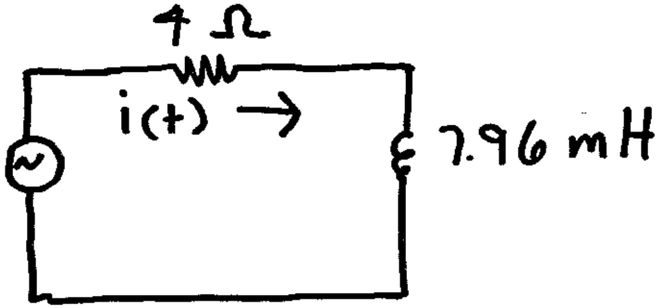
$$R \quad = \quad \text{Resistance}$$

$$X \quad = \quad \text{Reactance}$$

$$|Z| \quad = \quad \sqrt{R^2 + X^2} \qquad \phi = \arctan\left(\frac{X}{R}\right)$$

(Note: Z is a complex number but not a phasor)

RL Circuit Example



$$V(t) = \sqrt{2}\,100\cos(\omega t + 30°)$$

$$f = 60\text{Hz}$$

$$\text{R} = 4\Omega \qquad X = \omega L = 3$$

$$|Z| = \sqrt{4^2 + 3^2} = 5 \quad \phi = 36.9°$$

$$I = \frac{V}{Z} = \frac{100\angle 30°}{5\angle 36.9°}$$

$$= 20\angle -6.9° \text{ Amps}$$

$$\text{i(t)} = 20\sqrt{2}\cos(\omega t - 6.9°)$$

Complex Power

Power

$$p(t) = v(t)\, i(t)$$

$$\text{v(t)} = V_{\max}\cos(\omega t + \theta_V)$$

$$i(\text{t}) = I_{\max}\cos(\omega t + \theta_I)$$

$$\cos\alpha\cos\beta = \frac{1}{2}[\cos(\alpha - \beta) + \cos(\alpha + \beta)]$$

$$p(t) = \frac{1}{2}V_{\max}I_{\max}[\cos(\theta_V - \theta_I) +$$

$$\cos(2\omega t + \theta_V + \theta_I)]$$

Complex Power, cont'd

Average Power

$$p(t) = \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)]$$

$$P_{avg} = \frac{1}{T} \int_0^T p(t)dt$$

$$= \frac{1}{2} V_{\max} I_{\max} \cos(\theta_V - \theta_I)$$

$$= |V||I| \cos(\theta_V - \theta_I)$$

Power Factor Angle = $\phi = \theta_V - \theta_I$

Complex Power

$$S = |V||I|[\cos(\theta_V - \theta_I) + j\sin(\theta_V - \theta_I)]$$

$$= P + jQ$$

(Note: S is a complex number but not a phasor)

$$= V\,I^*$$

P = Real Power (W, kW, MW)

Q = Reactive Power (var, kvar, Mvar)

S = 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

Complex Power, cont'd

Relationships between real, reactive and complex power

$$P = |S| \cos\phi$$

$$Q = |S| \sin\phi = \pm |S| \sqrt{1 - pf^2}$$

Example: A load draws 100 kW with a leading pf of 0.85. What are ϕ (power factor angle), Q and $|S|$?

$$\phi = -\cos^{-1} 0.85 = -31.8°$$

$$|S| = \frac{100 kW}{0.85} = 117.6 \text{ kVA}$$

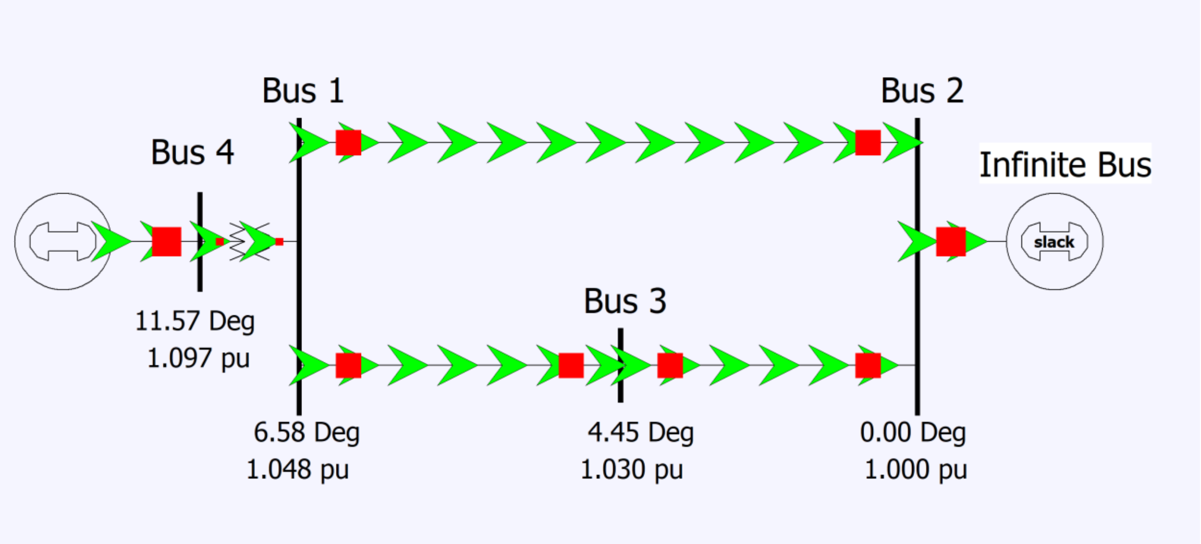
$$Q = 117.6 \sin(-31.8°) = -62.0 \text{ kVar}$$

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.

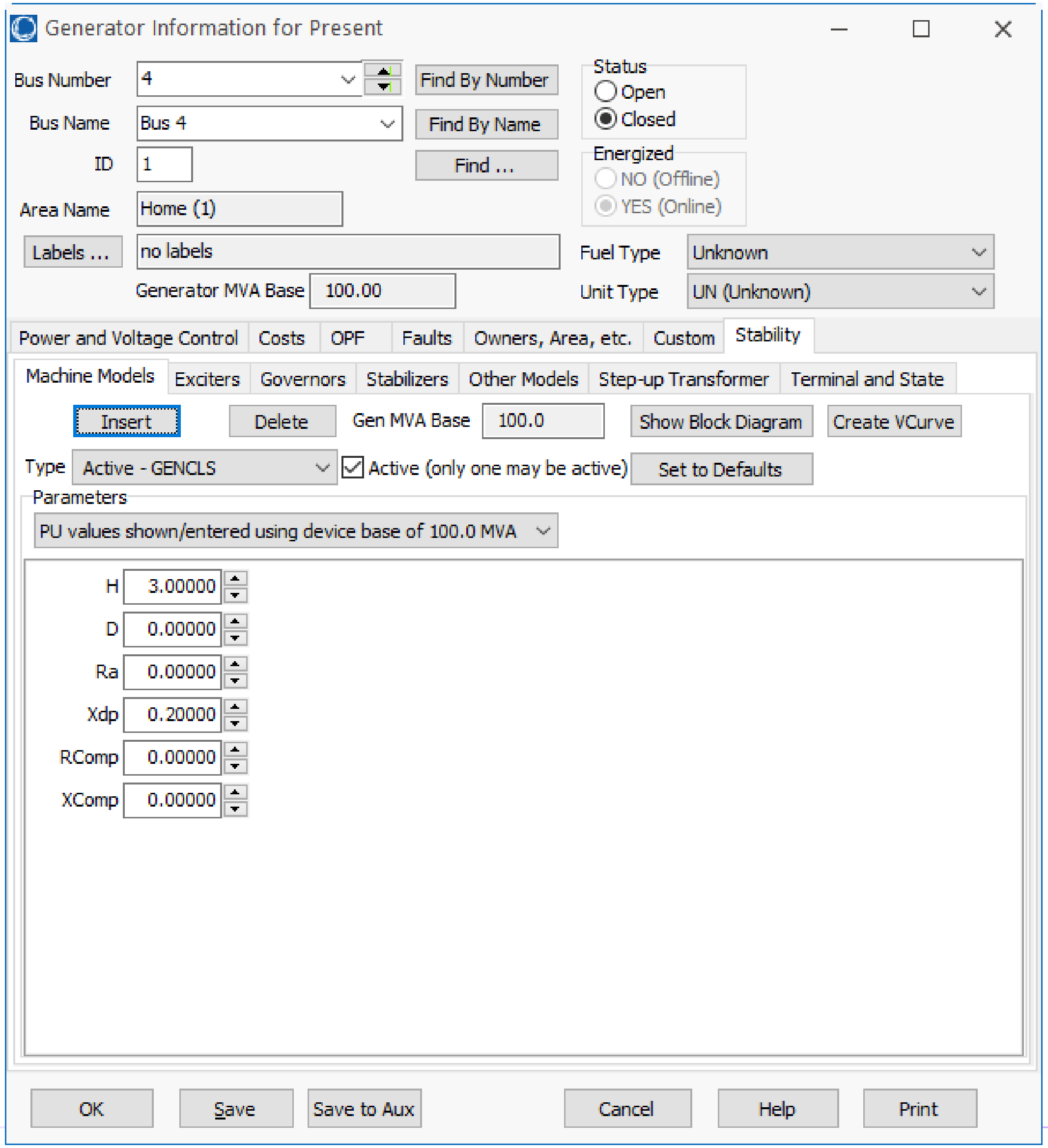
First Example Case

- 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



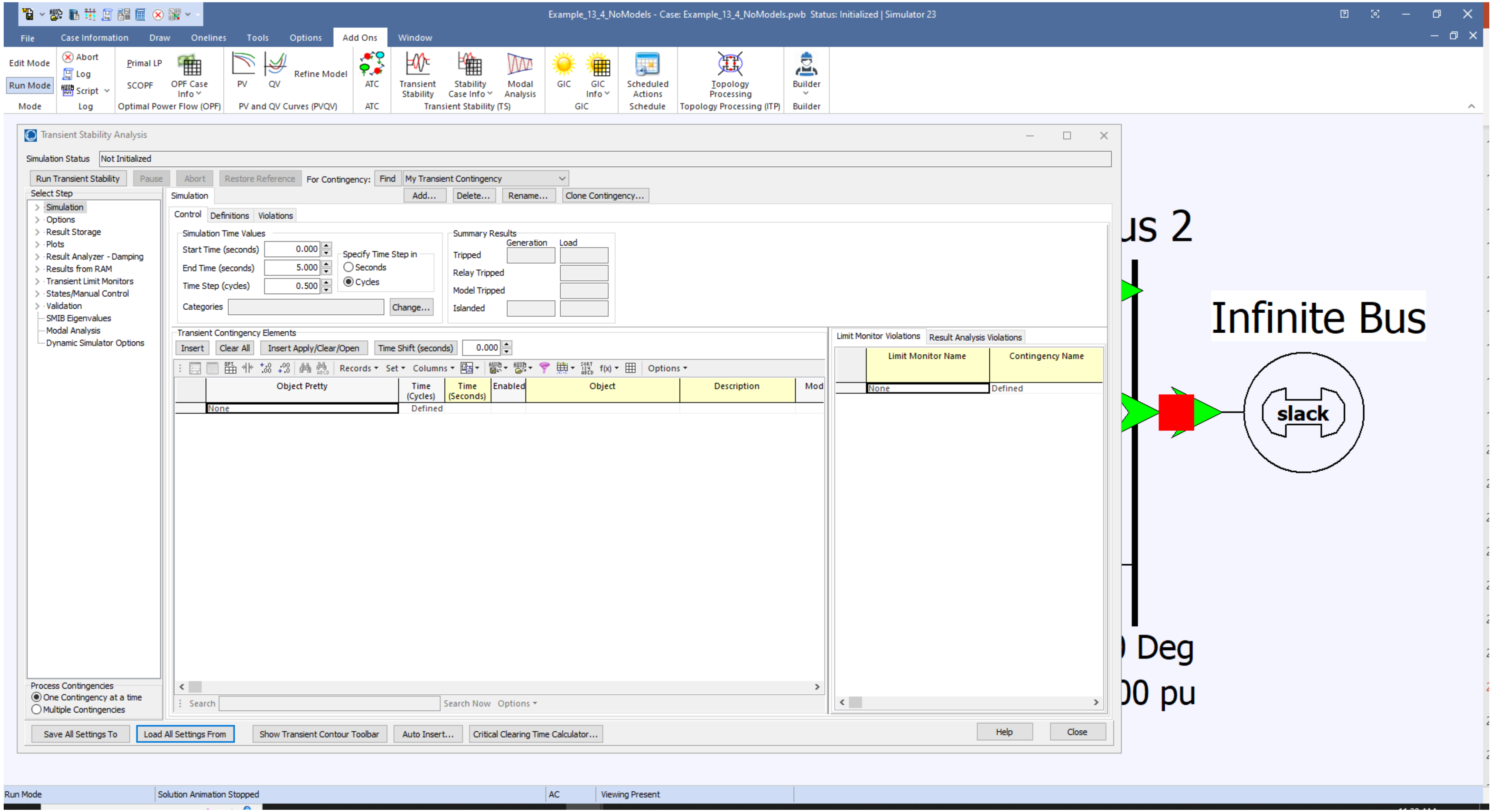
The GENCLS model represents the machine dynamics as a fixed voltage magnitude behind a transient impedance Ra + jXdp.

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 they should be saved
  - **Plots**: Used to plot results
  - **Results**: Used to view the results (actual numbers, not plots)

Transient Stability Overview Form



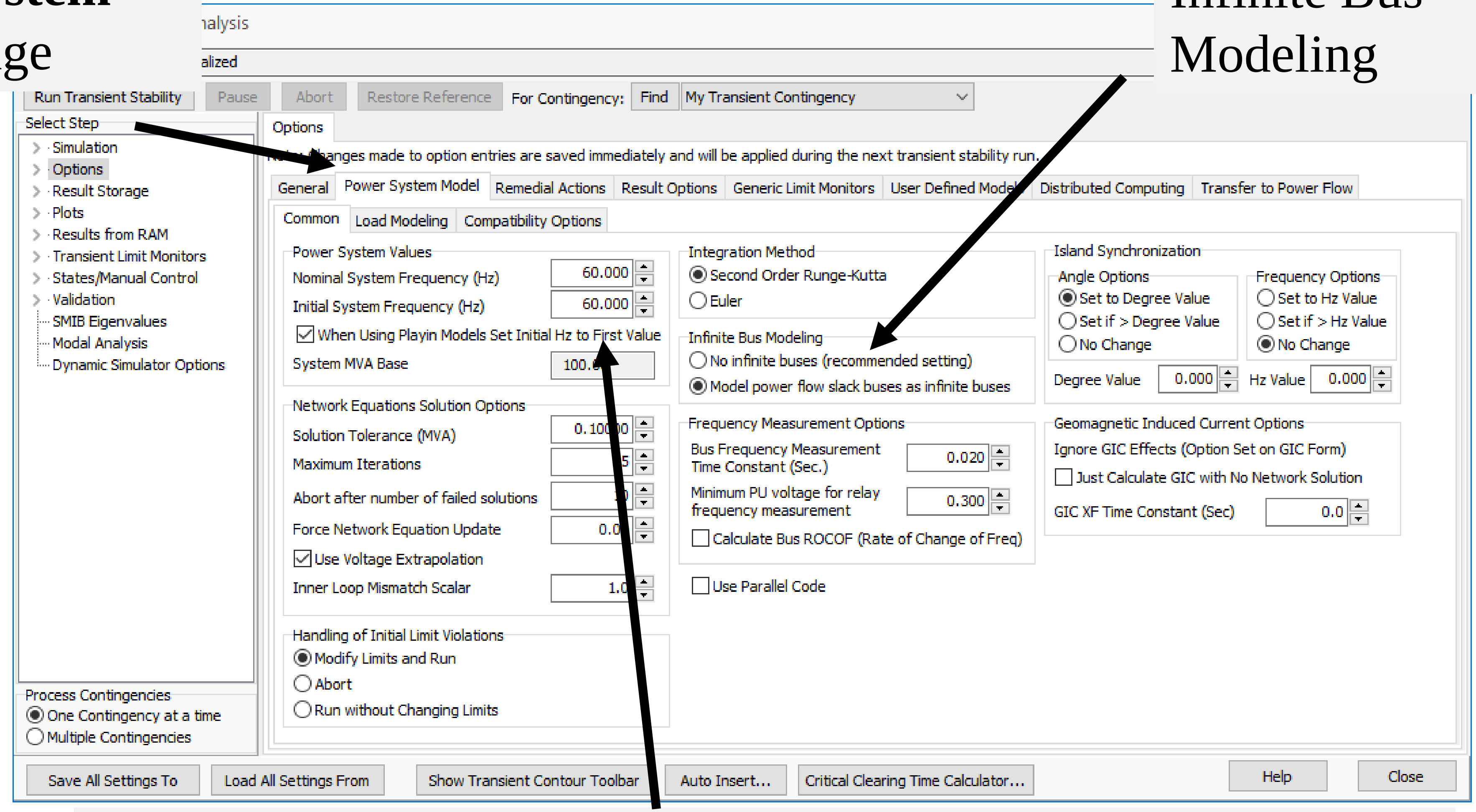
Infinite Bus Modeling

- 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.

Transient Stability Options Page

Power System Model Page

Infinite Bus Modeling



This page is also used to specify the nominal system frequency

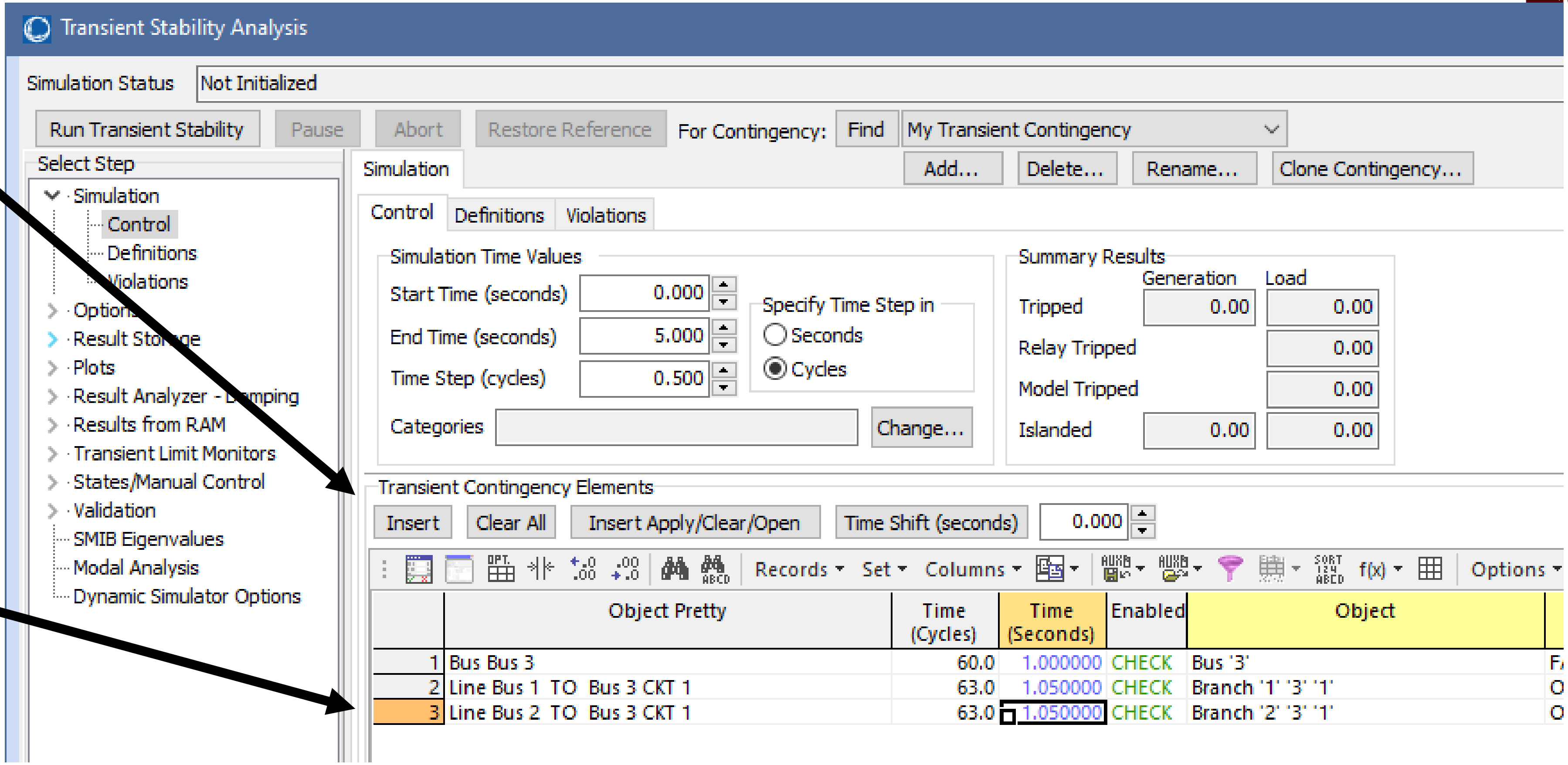
Specifying the Contingency Event

- The grid is pushed away from its equilibrium by a disturbance, known as a contingency; an example would be lightning hitting a transmission line
- 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 sec, and clearing at 1.05 sec
  - 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.

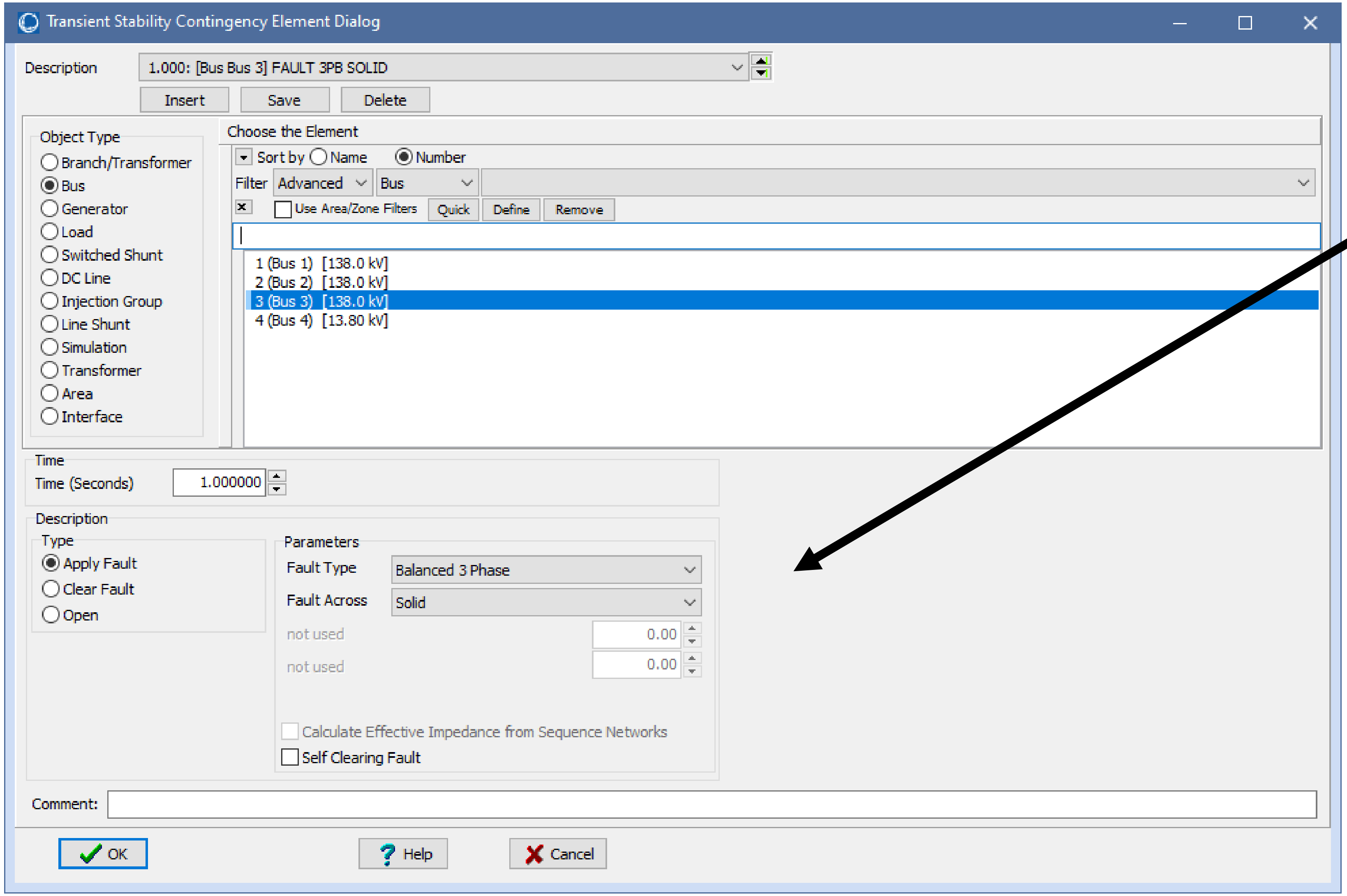
Inserting Transient Stability Contingency Elements

Click to insert new elements

Summary of all elements in the contingency, and the time of each action



Event Contingency Dialog



Available element type will vary with different objects

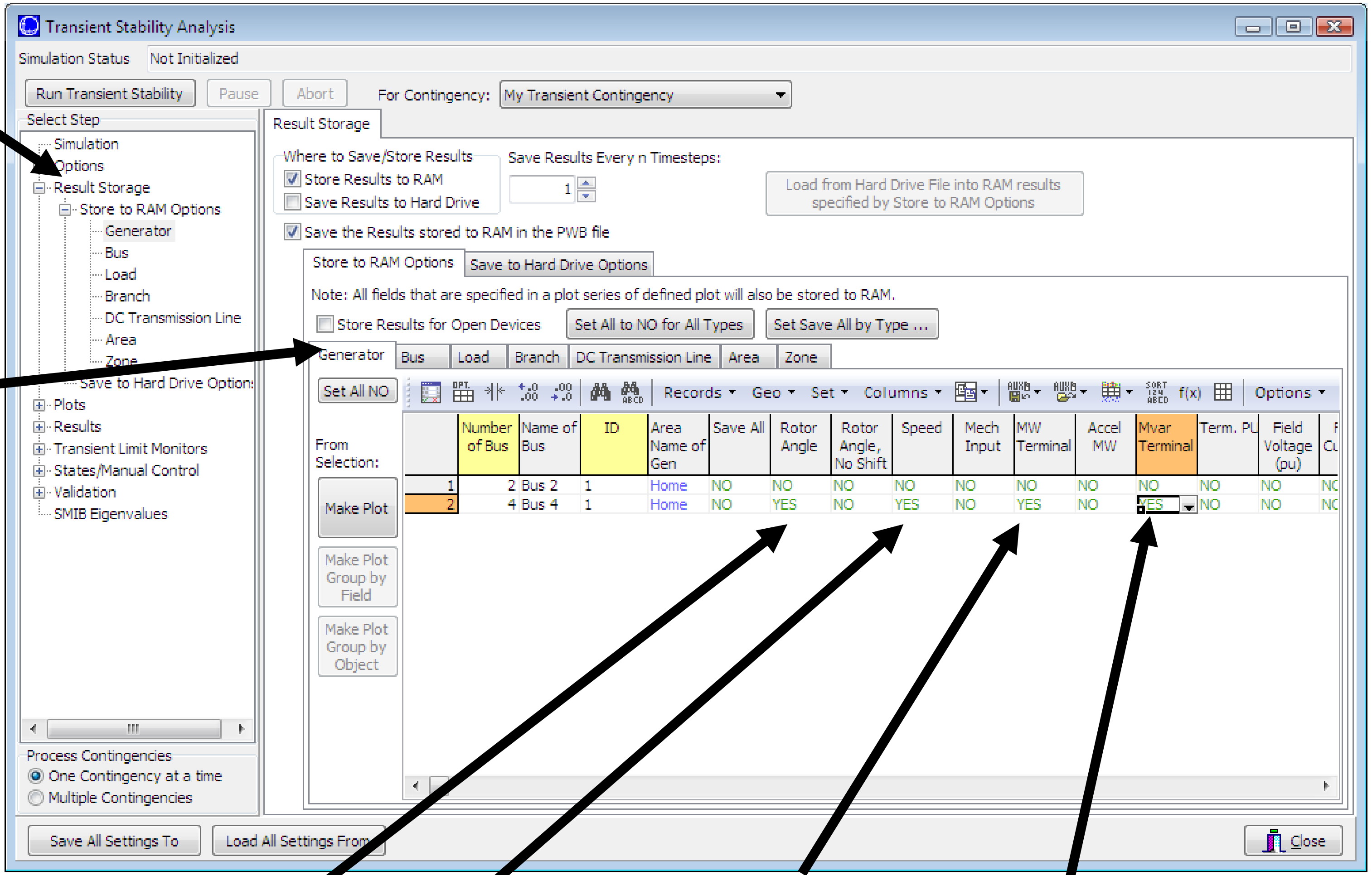
Determining the Results to View

- 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

Generator Tab



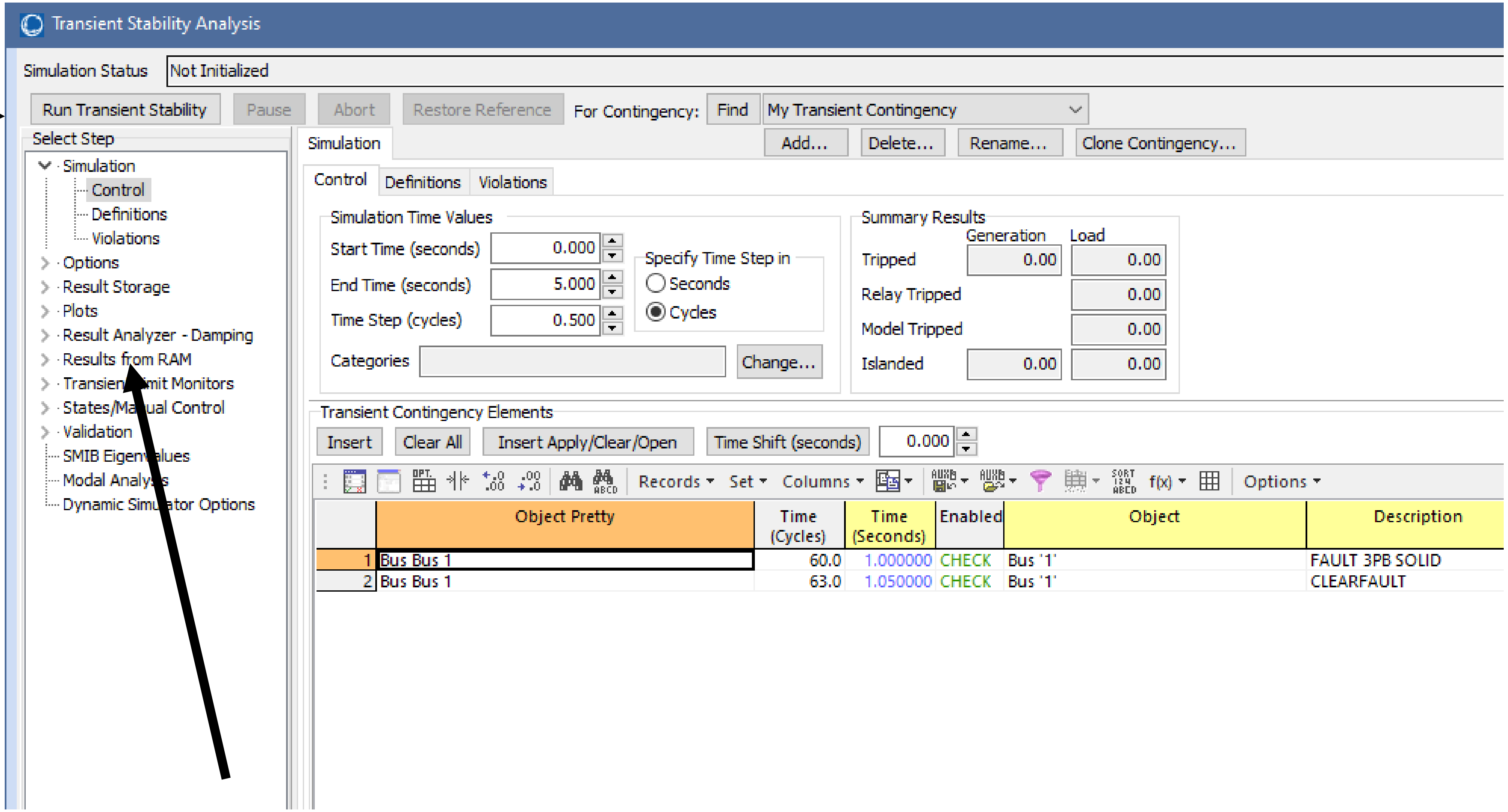
Double Click on Fields (which sets them to yes) to Store Their Values

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



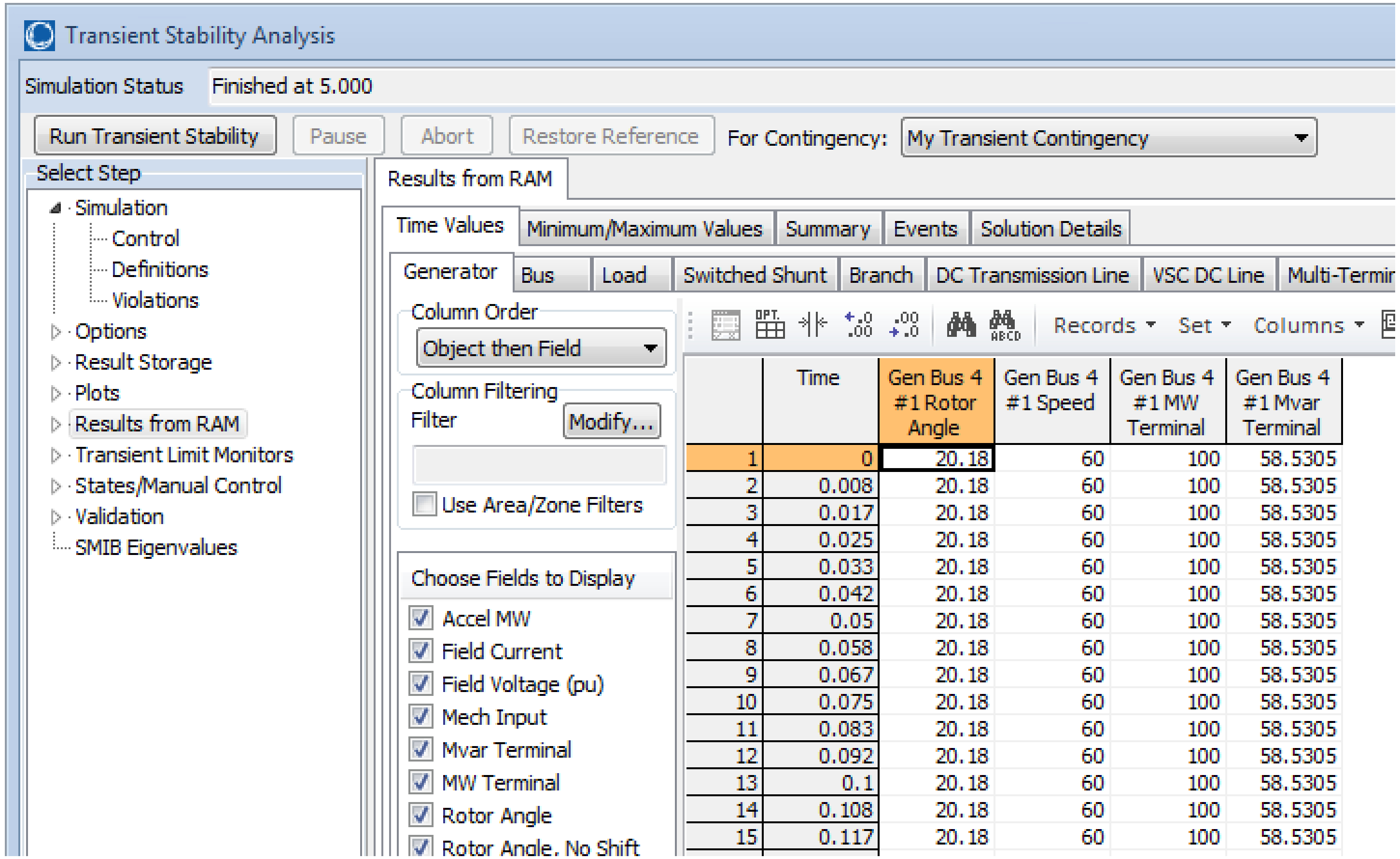
Once the contingency runs the **Results from RAM** page may be opened

Transient Stability Results

- Once the transient stability run finishes, the **Results from RAM** 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**

Results: Time Values

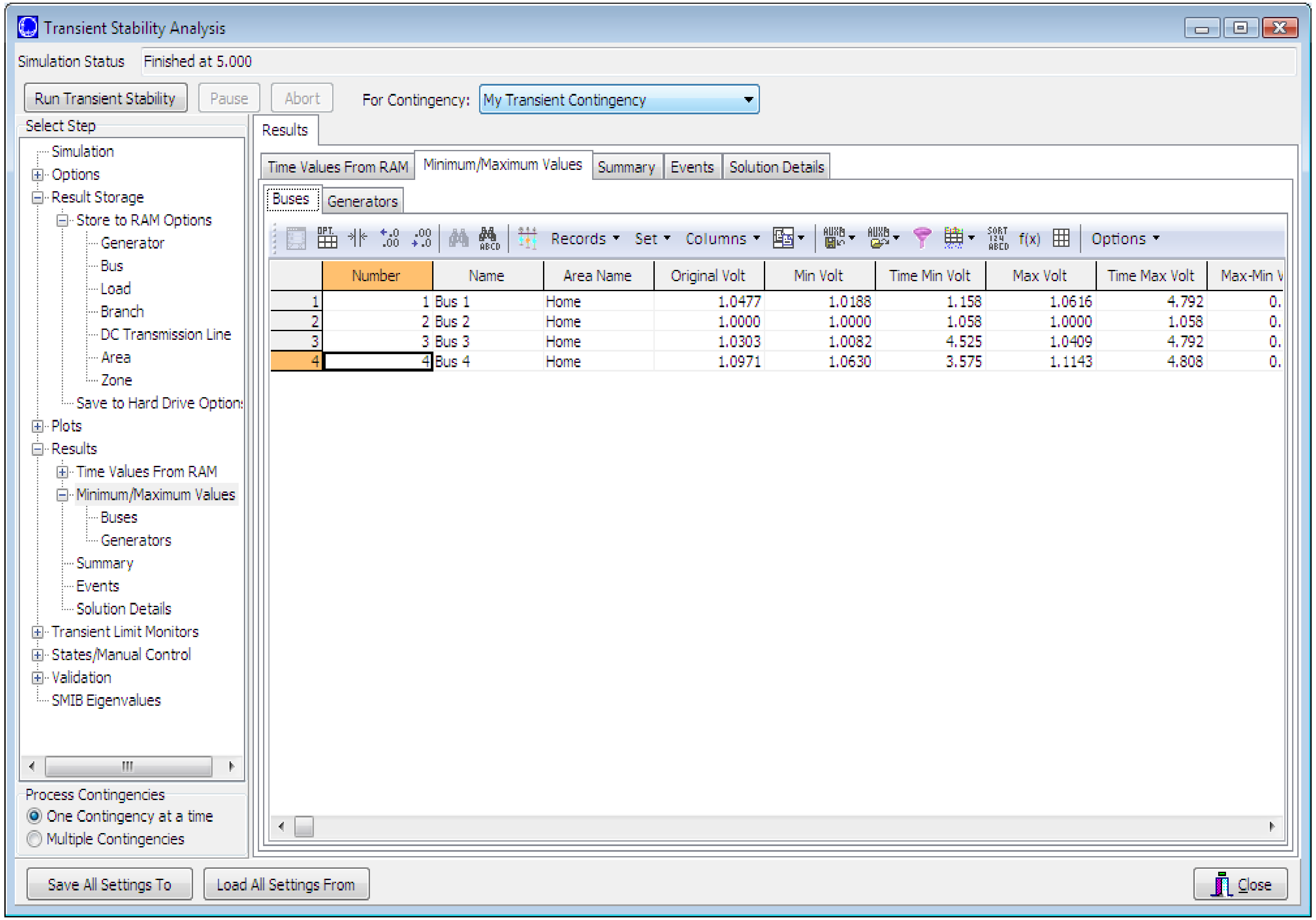
Lots of options are available for showing and filtering the results.



By default the results are shown for each time step. Results can be saved saved every "n" timesteps using an option on the Results Storage Page

Results: Minimum and Maximum Values

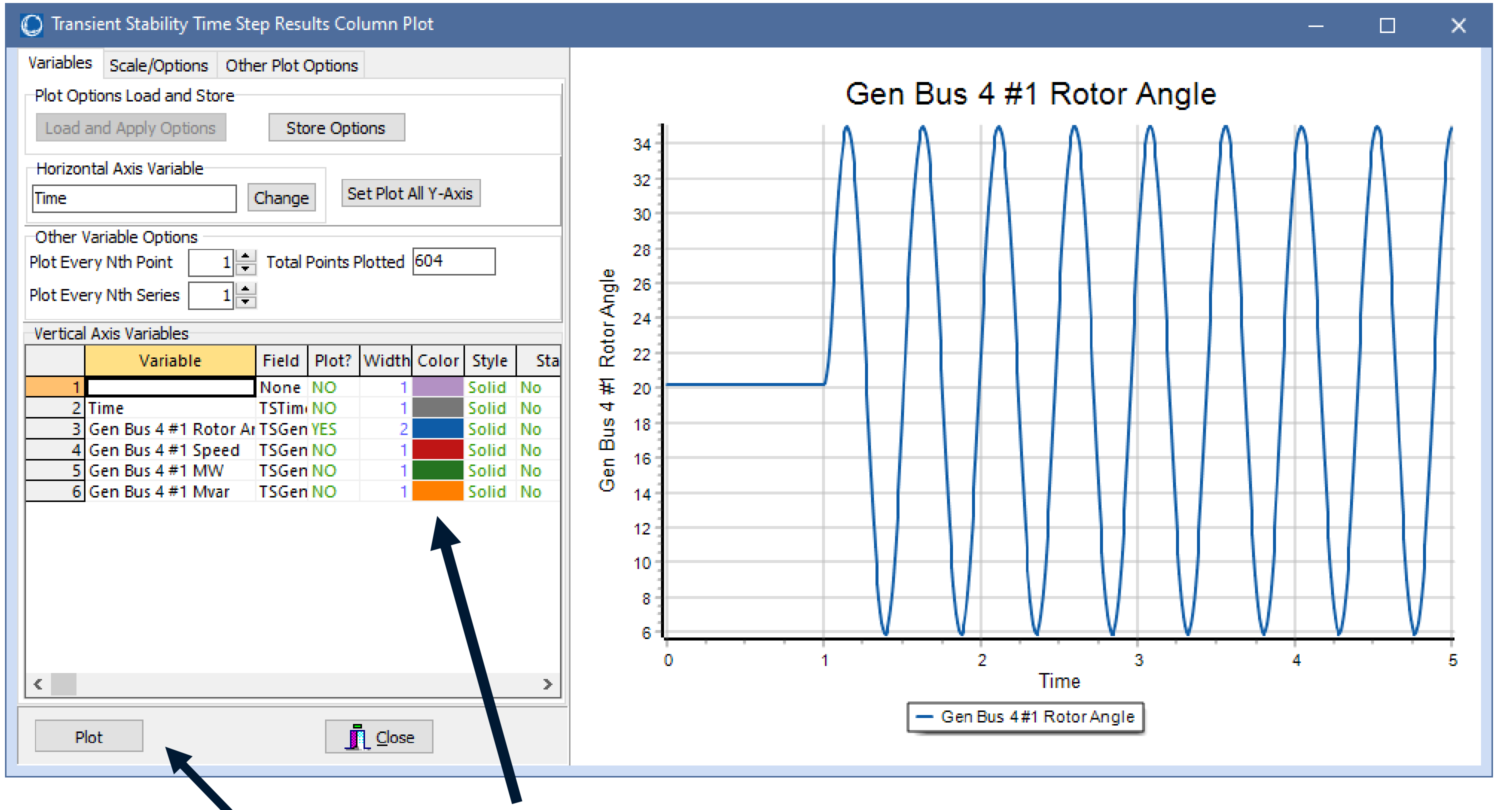
Minimum and maximum values are available for all generators and buses



Quickly Plotting Results

- Time value results can be quickly plotted by using the standard case information display plotting capability.
  - Right-click on the desired column
  - Select **Plot Columns**
  - Use the **Column Plot Dialog** to customize the results.
  - Right-click on the plot to save, copy or print it.
- More comprehensive plotting capability is provided using the Transient Stability **Plots** page; this will be discussed later.

Generator 4 Rotor Angle Column Plot



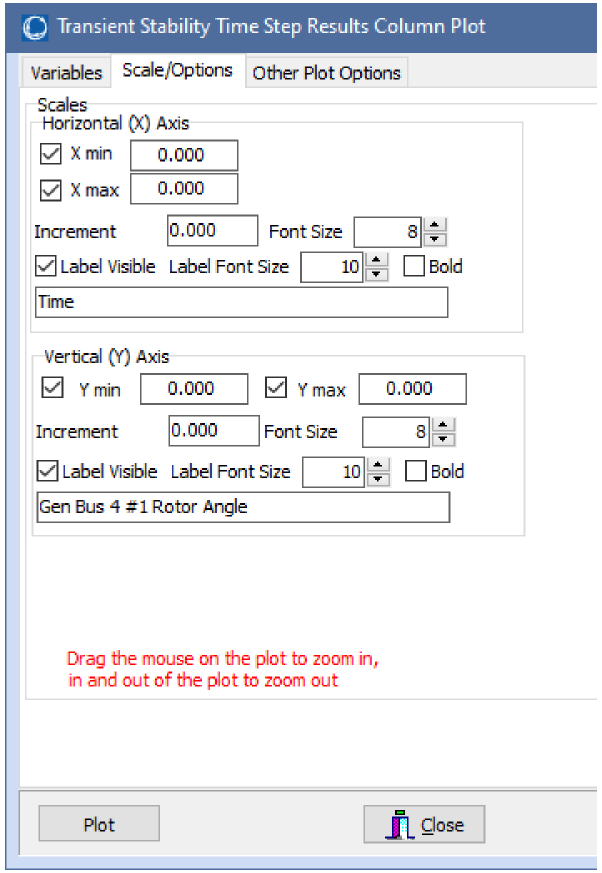
Notice that the result is undamped; damping is provided by damper windings

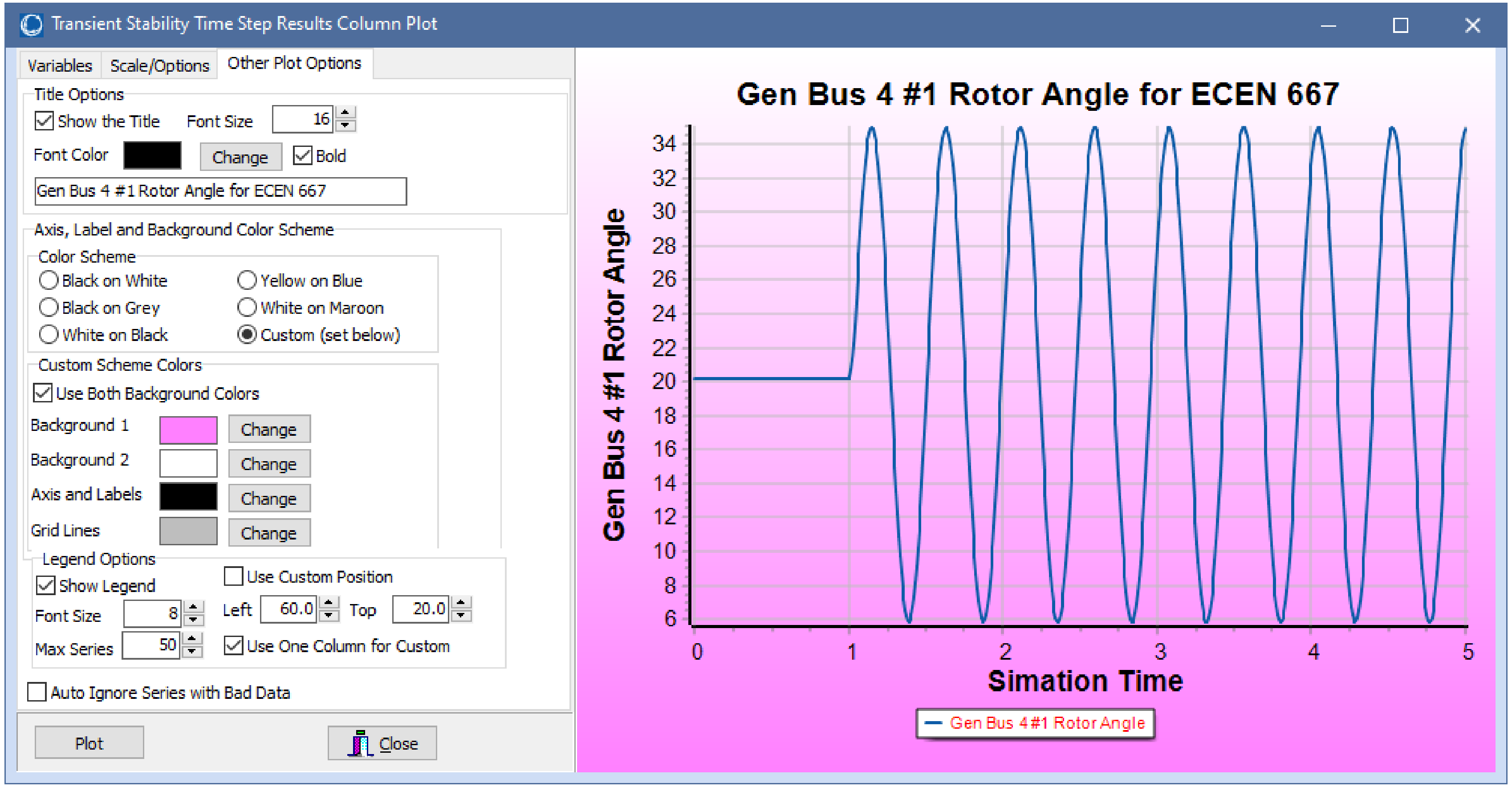
Change line color here And re-plot by clicking here

Starting the event at t = 1.0 seconds allows for verification of an initially stable operating point. The small angle oscillation indicates the system is stable, although undamped.

Column Plots Option Page

- The Column Plot page has recently been enhanced to provide more options, so good plots can be quickly made for papers and presentations



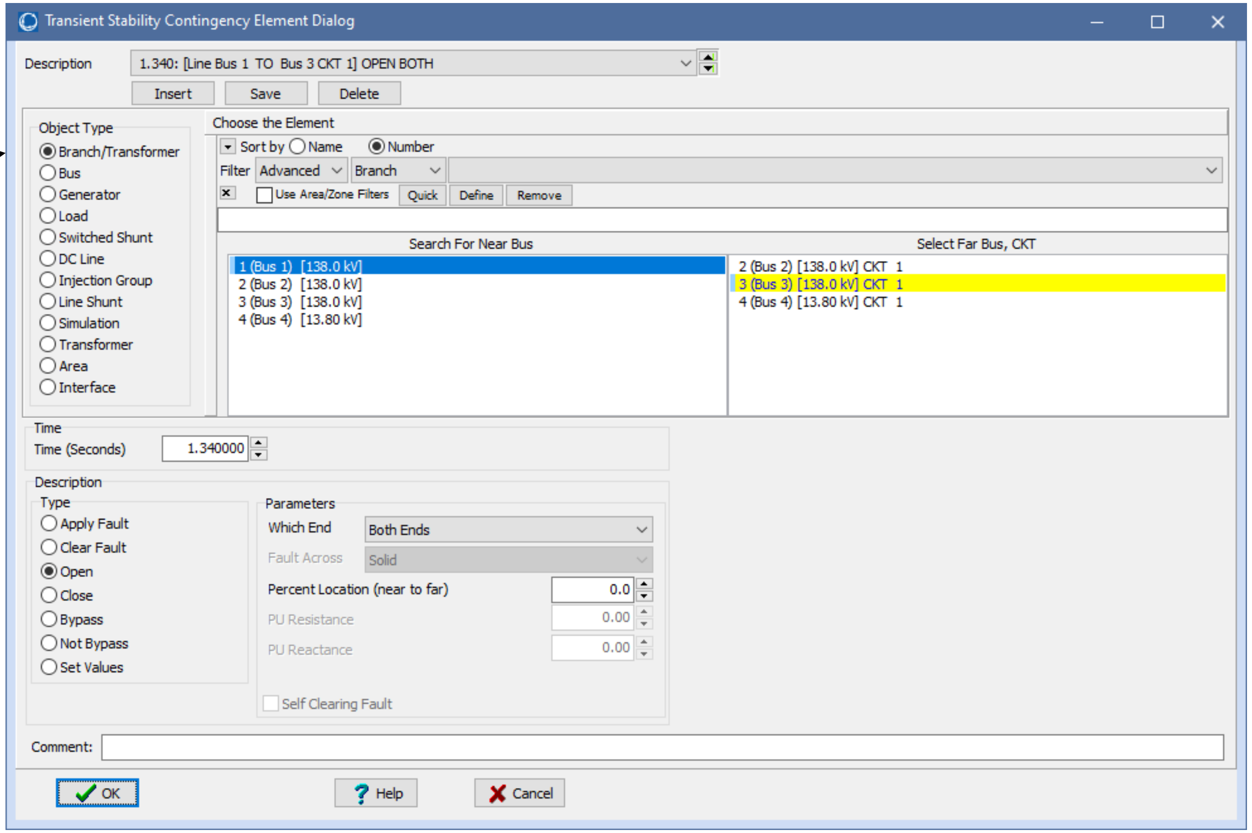


Changing the Case

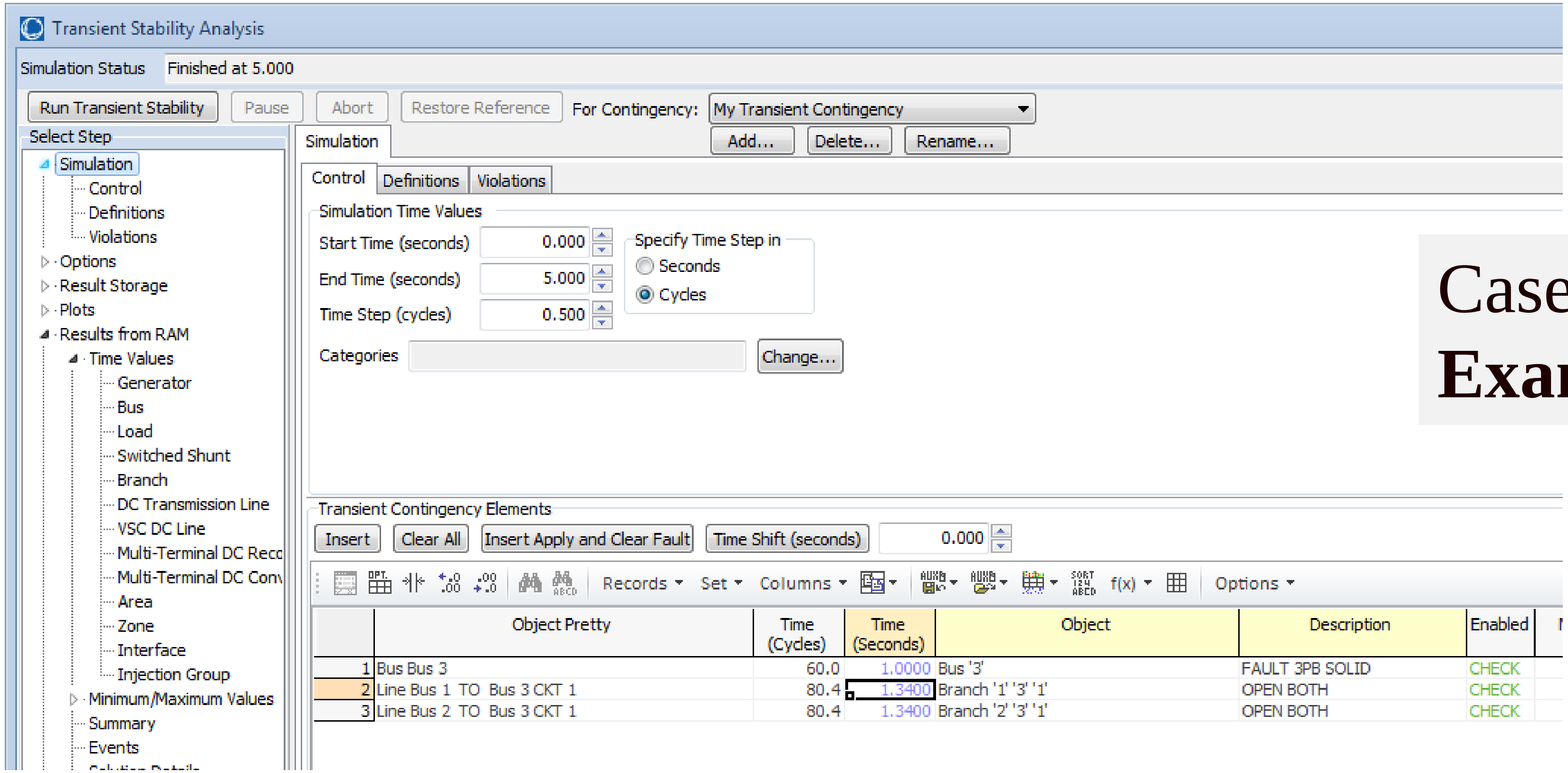
- PowerWorld Simulator allows for easy modification of the study system. As a next example we will duplicate example 13.4 from earlier editions of the Glover/Overbye/Birchfield/Sarma *Power System Analysis and Design* book.
- Back on the one-line, right-click on the generator and use the **Stability/Machine Models** page to change the Xdp field from 0.2 to 0.3 per unit.
- On the **Transient Stability Simulation** page, change the contingency to be a solid three phase fault at Bus 3, cleared by opening both the line between buses 1 and 3 and the line between buses 2 and 3 at time = 1.34 seconds.

Changing the Contingency Elements

Change object type to AC Line/Transformer, select the right line, and change the element type to "Open".



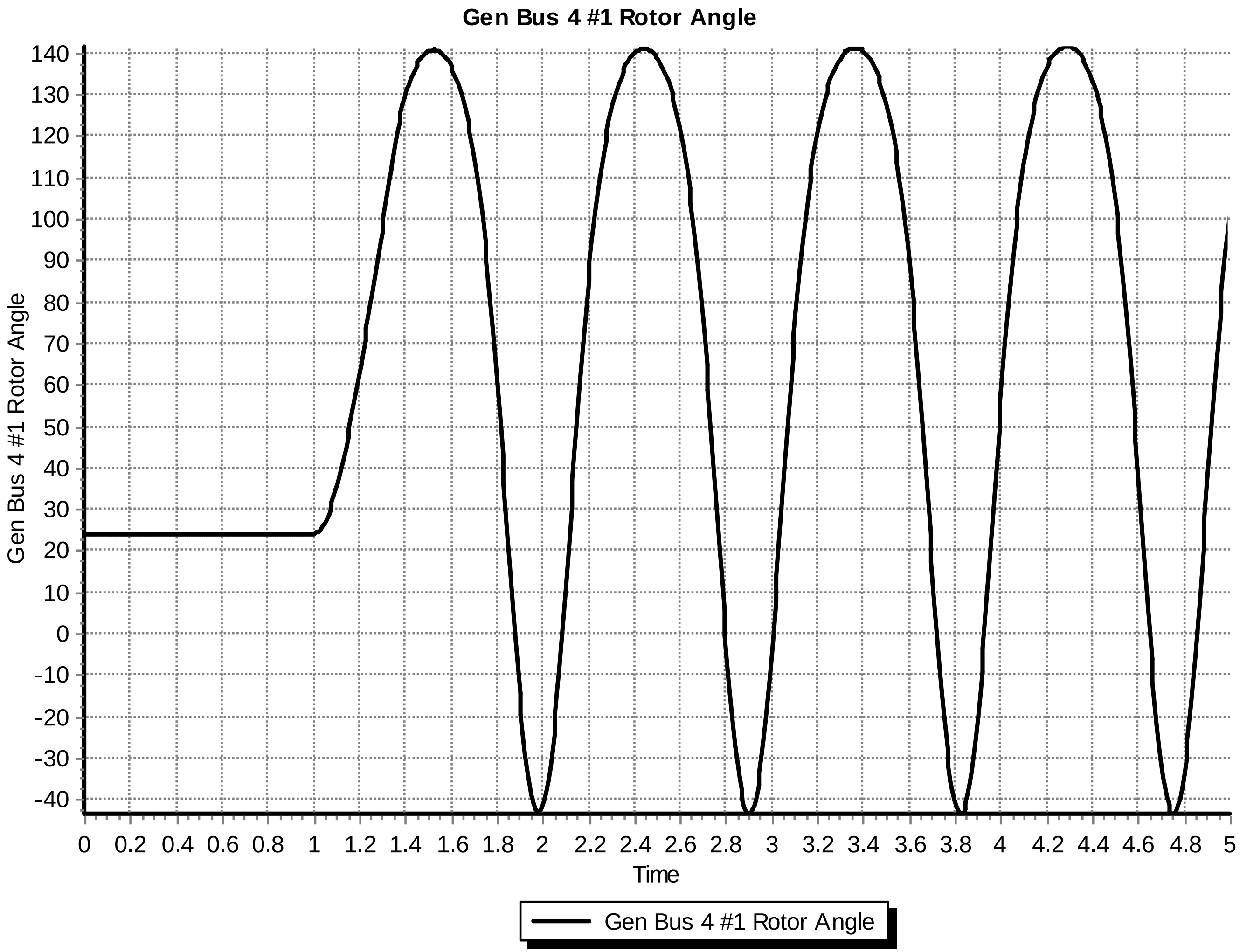
Changing the Contingency Elements



Case Name:
Example_13_4_Bus3Fault

Contingency Elements displays should eventually look like this. Note fault is at bus 3, not at bus 1

Results: On Verge of Instability

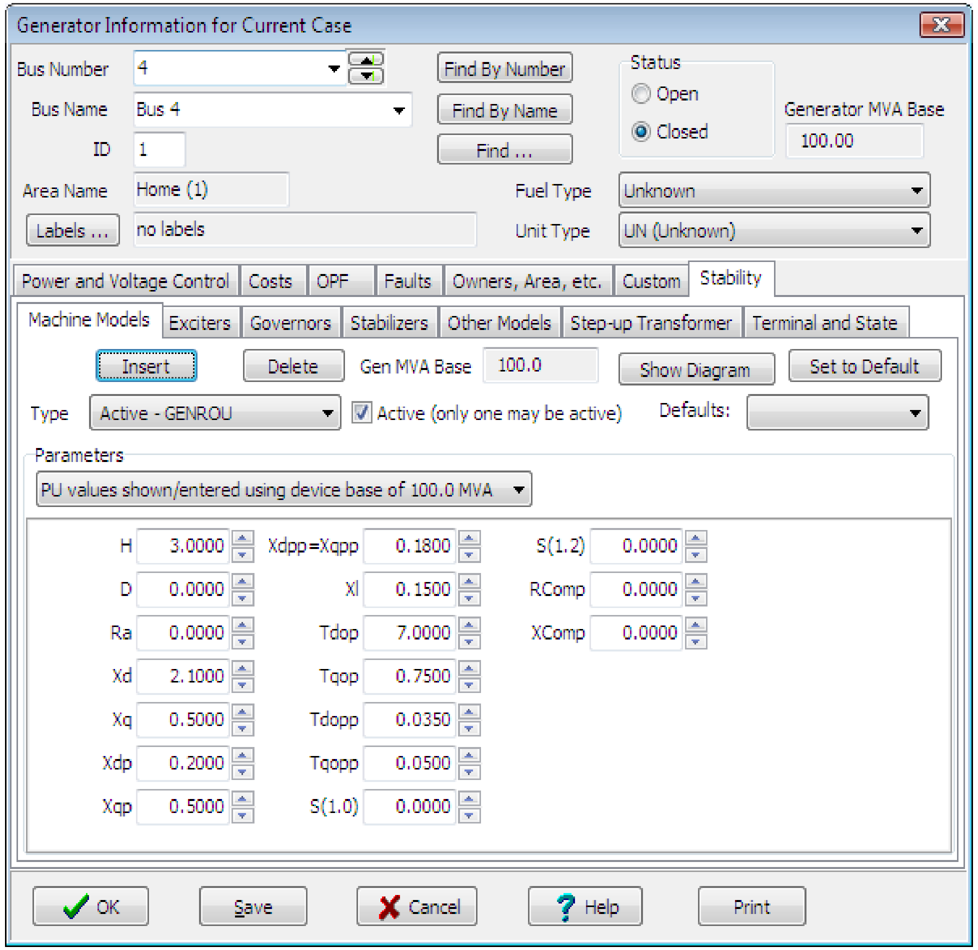


Also note that the oscillation frequency has decreased

A More Realistic Generator Model

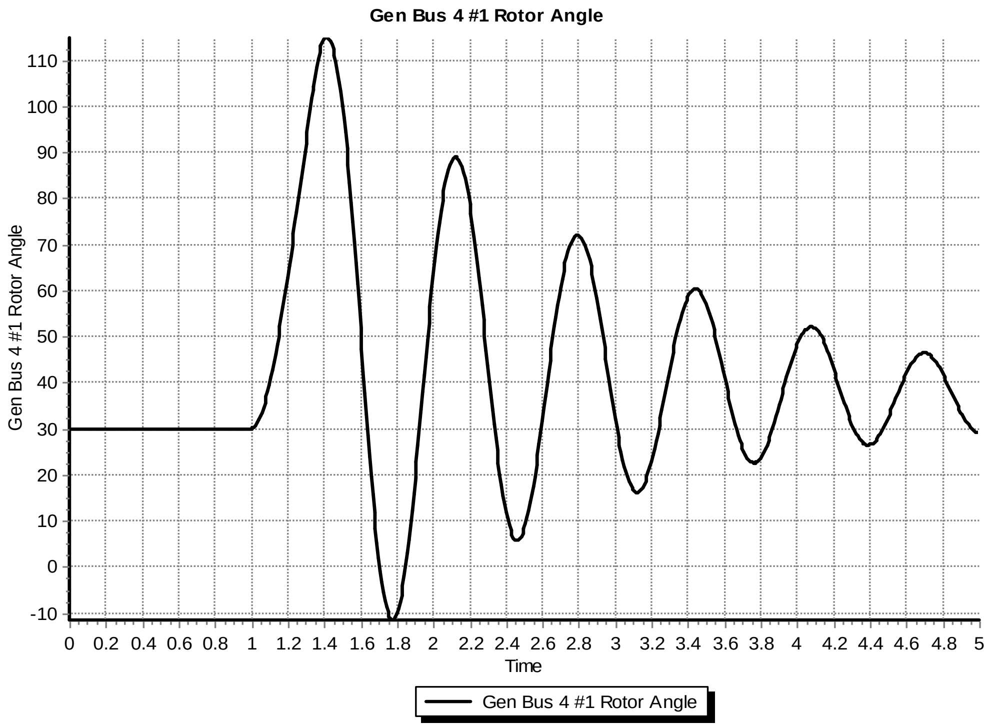
- The classical model is considered in section 5.6 of the book, as the simplest but also the hardest to justify
  - Had been widely used, but is not rapidly falling from use
- PowerWorld Simulator includes a number of much more realistic models that can be easily used
  - Coverage of these models is beyond the scope of this intro
- To replace the classical model with a detailed solid rotor, subtransient model, go to the generator dialog **Machine Models**, click **Delete** to delete the existing model, select **Insert** to display the **Model Type** dialog and select the **GENROU** model; accept the defaults.

GENROU Model



The GENROU model provides a good approximation for the behavior of a synchronous generator over the dynamics of interest during a transient stability study (up to about 10 Hz). It is used to represent a solid rotor machine with three damper windings.

Repeat of Example 13.1 with GENROU



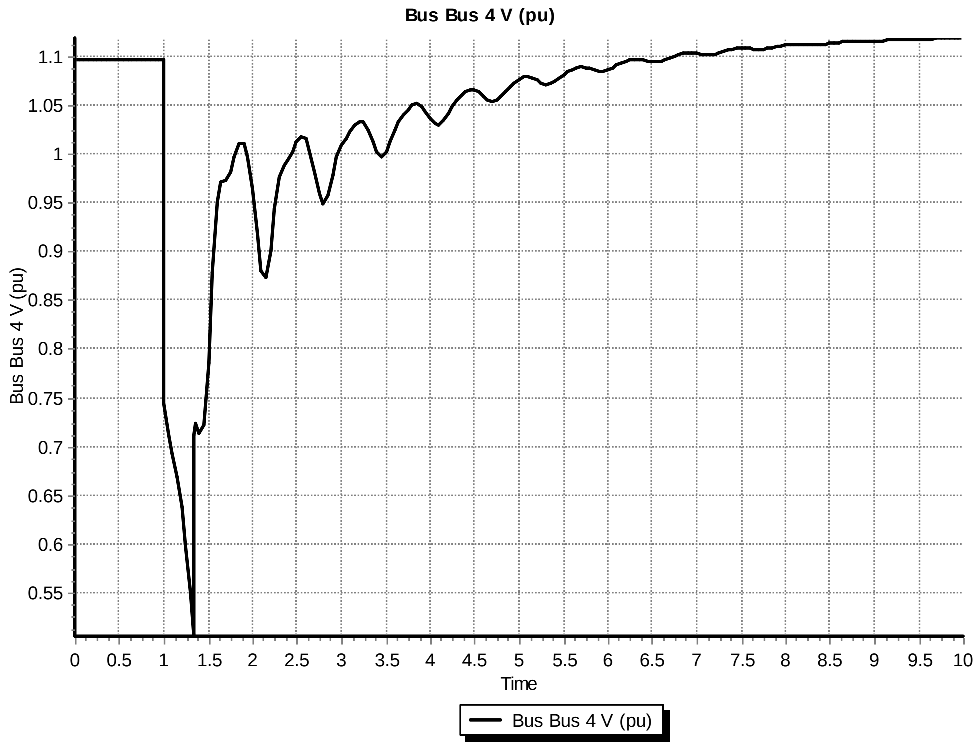
This plot repeats the previous example with the bus 3 fault. The generator response is now damped due to the damper windings included in the GENROU model. Case is saved in examples as **Example_13_4_GENROU**.

Saving Results Every n Timesteps

- Before moving on it will be useful to save some additional fields. On the Transient Stability Analysis form select the “Result Storage” page. Then on the Generator tab toggle the generator 4 “Field Voltage” field to Yes. On the Bus tab toggle the bus 4 “V (pu)” field to Yes.
- At the top of the “Result Storage” page, change the “Save Results Every n Timesteps” to 6.
  - PowerWorld Simulator allows you to store as many fields as desired. On large cases one way to save on memory is to save the field values only every n timesteps with 6 a typical value (i.e., with a ½ cycle time step 6 saves 20 values per second)

Plotting Bus Voltage

- Change the end time to 10 seconds on the "Simulation" page, and rerun the previous. Then on "Results" page, "Time Values from RAM", "Bus", plot the bus 4 per unit voltage. The results are shown below.



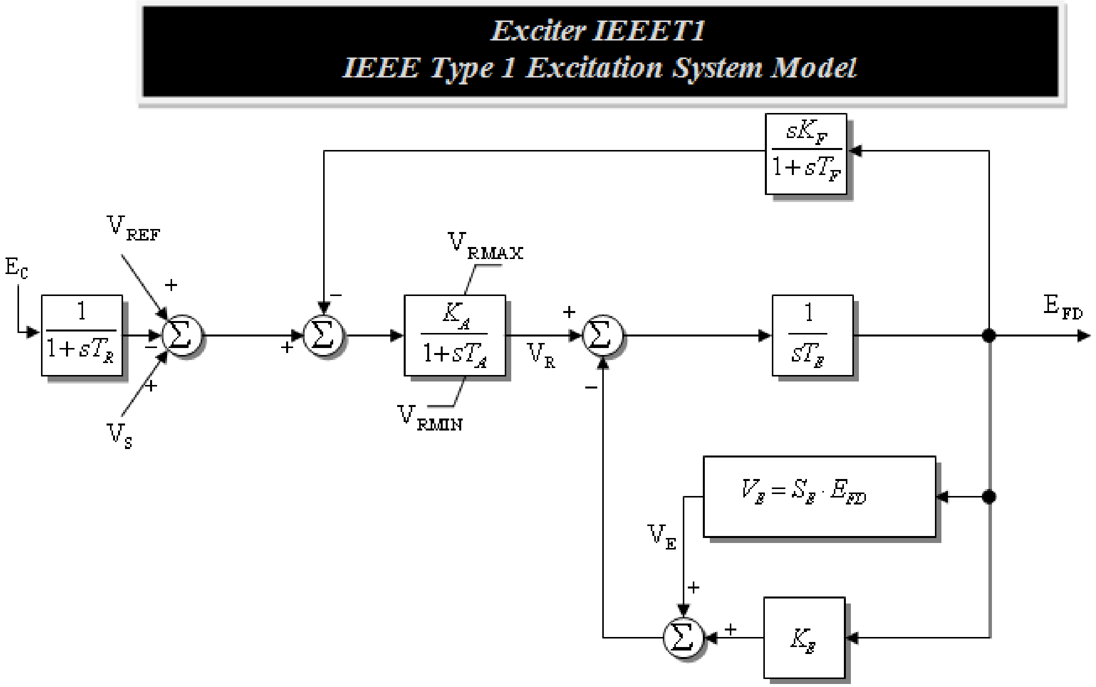
Notice following the fault the voltage does not recover to its pre-fault value. This is because we have not yet modeled an exciter.

Adding a Generator Exciter

- The purpose of the generator excitation system (exciter) is to adjust the generator field current to maintain a constant terminal voltage.
- PowerWorld Simulator includes many different types of exciter models. One simple exciter is the IEEET1. To add this exciter to the generator at bus 4 go to the generator dialog, “Stability” tab, “Exciters” page. Click Insert and then select IEEET1 from the list. Use the default values.
- Exciters will be covered in the first part of Chapter 4

IEEET1 Exciter

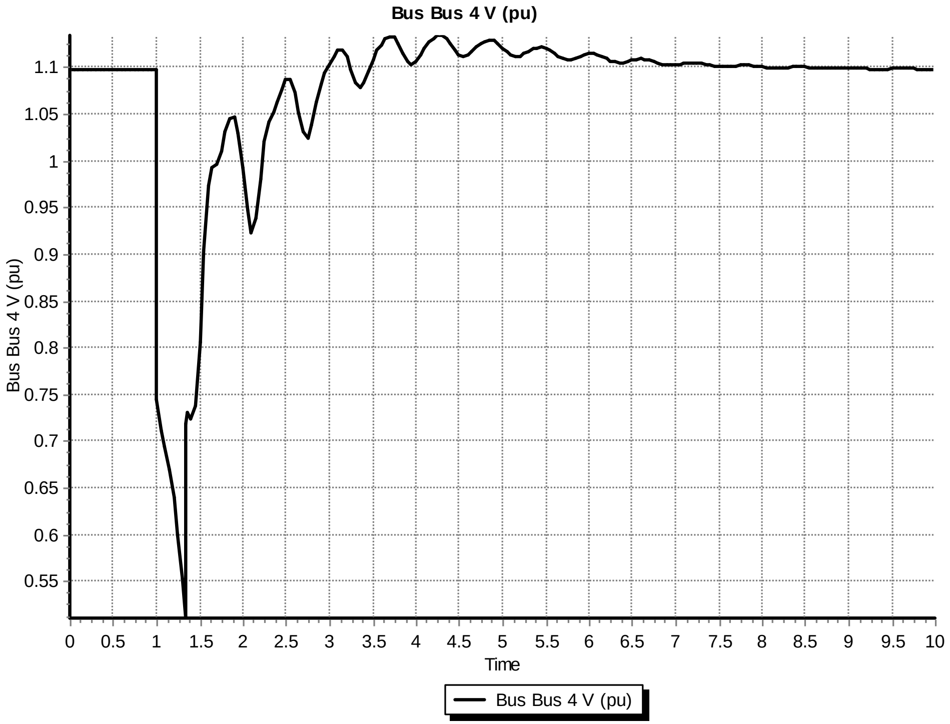
- Once you have inserted the IEEET1 exciter you can view its block diagram by clicking on the "Show Diagram" button. This opens a PDF file in Adobe Reader to the page with that block diagram. The block diagram for this exciter is also shown below.



The input to the exciter, E_C,is usually the terminal voltage. The output, E_{FD}, is the machine field voltage.

Voltage Response with Exciter

- Re-do the run. The terminal time response of the terminal voltage is shown below. Notice that now with the exciter it returns to its pre-fault voltage.



Case Name: **Example_13_4_GenROU_IEEET1**