ECEN 460
Power System Operation and Control
Spring 2025

Lecture 22: Modal Analysis, Stabilizers
Voltage Stability

Prof. Tom Overbye

Special Guest Lecture Given by Sanjana Kunkolienkar

Dept. of Electrical and Computer Engineering

Texas A&M University

overbye@tamu.edu

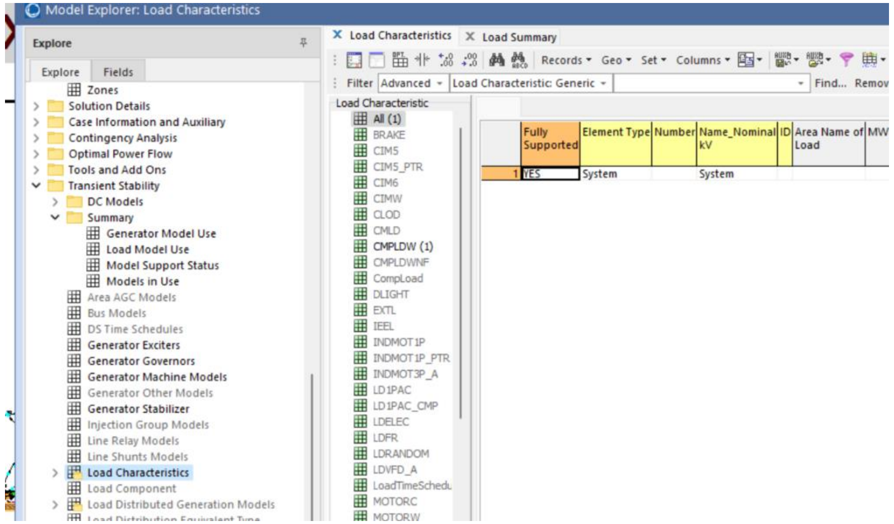
Announcements

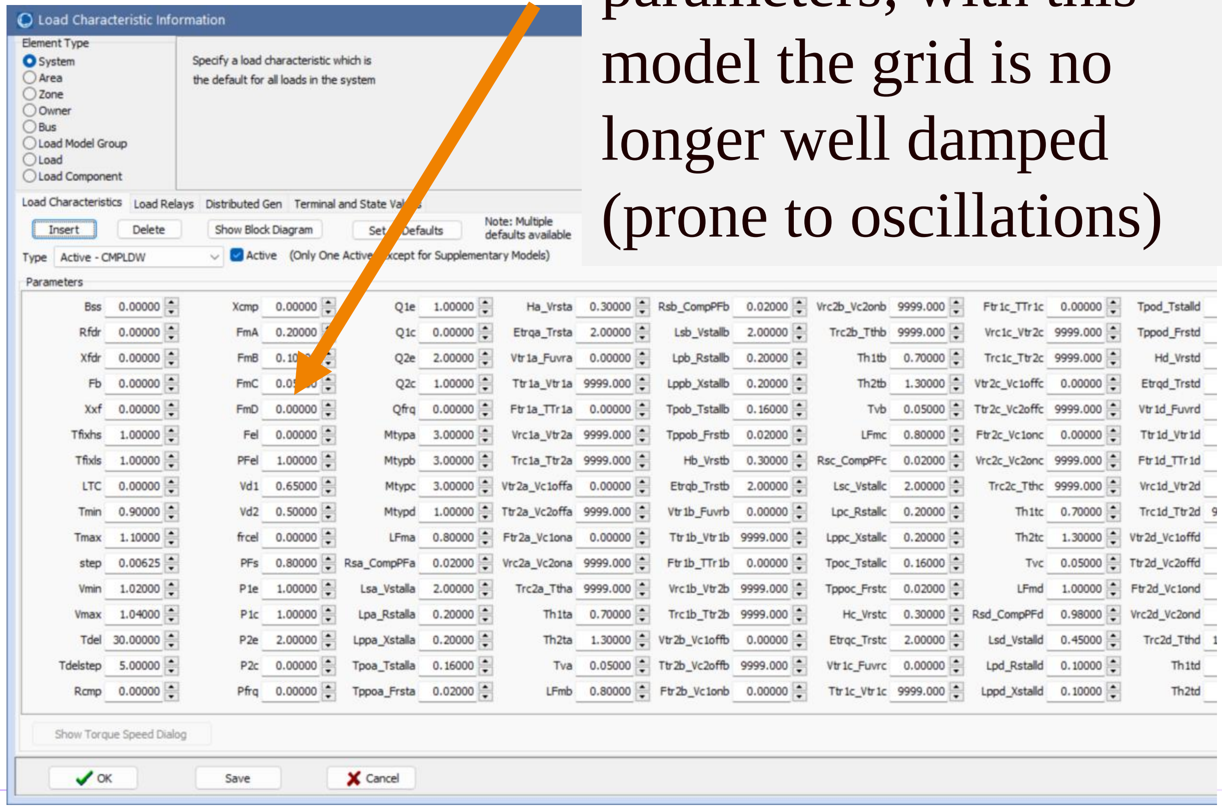
- Please read Chapter 13
- By April 9 do Problem Set A
- Schedule for the rest of the semester is
  - Lab 10 week of April 7 consisting of time for the design groups to meet; all groups need to turn in a brief progress report in lieu of a lab report
  - Lab 3 week of April 14 (optional, ungraded machine lab, Wednesday times only; since Friday is a Reading Day the Friday lab folks can go to a Wednesday lab
  - Lab 11 (project presentations) by the individual teams to their TA before the end of classes (on or before April 29)
  - Exam 2 on Wednesday April 23 during class; similar format to other exam; comprehensive but more emphasis on material since the first exam
  - Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)

Running 2000 Bus Case with Composite Loads

- Show Texas2000_CMPLDW; this is the previous 2000 bus case with the CMPLDW model applied to all loads
- To see and modify the parameters in the Model Explorer select **Transient Stability, Load Characteristics**

Run the generator drop scenario varying these parameters; with this model the grid is no longer well damped (prone to oscillations)



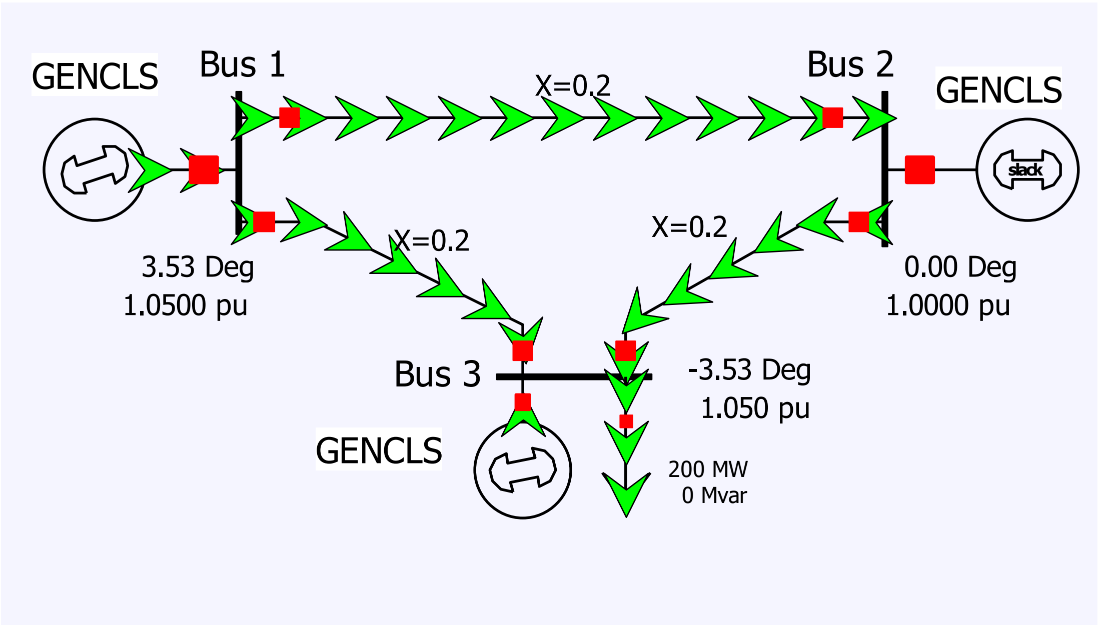


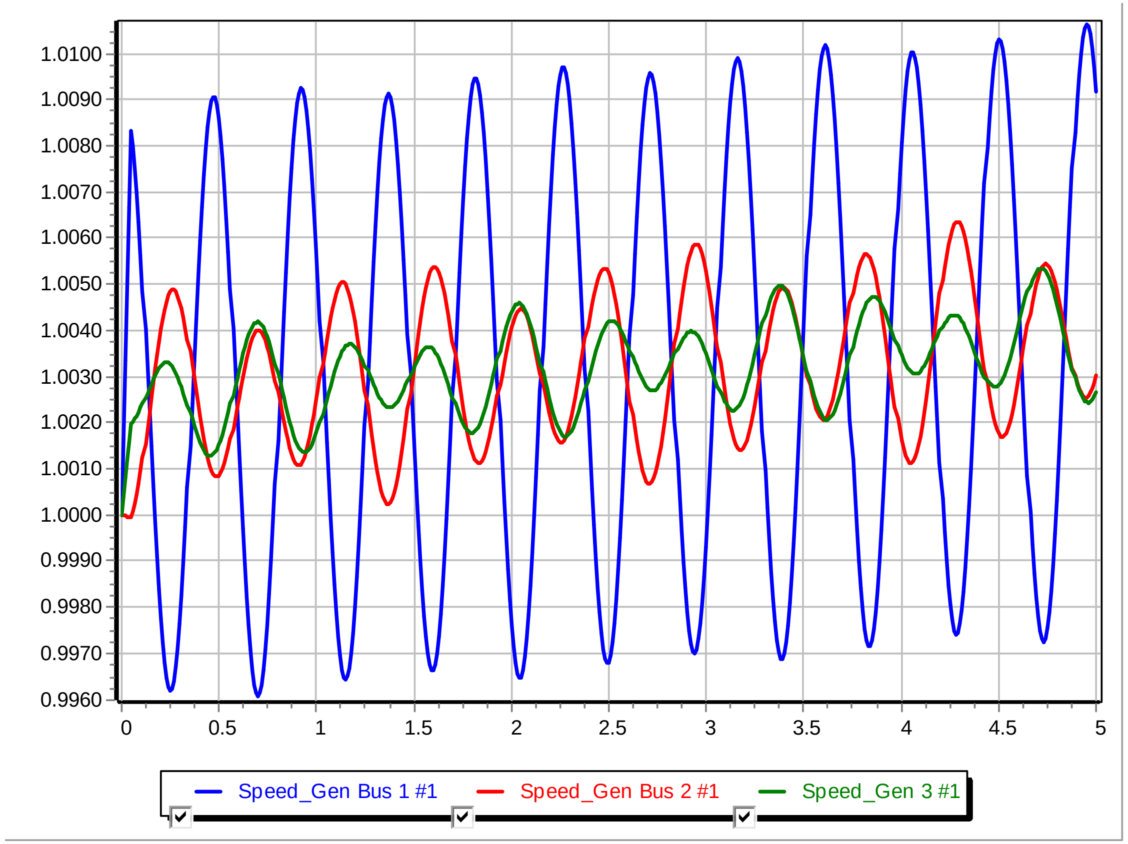
Modal Analysis in PowerWorld

- Goal is to make modal analysis easy to use, and easy to visualize the results
- Provided tool can be used with either transient stability results or actual system signals (e.g., from PMUs)
- Three ways to access in PowerWorld
  - From the Modal Analysis button (in **Add-Ons**)
  - On the Transient Stability Analysis form left menu, **Modal Analysis** (right below SMIB Eigenvalues)
  - By right-clicking on a transient stability or plot case information display, and selecting **Modal Analysis Selected Columns** or **Modal Analysis All Columns**

Modal Analysis: Three Generator Example

- A short fault at t=0 gets the below three generator case oscillating with multiple modes (mostly clearly visible for the red and the green curve)



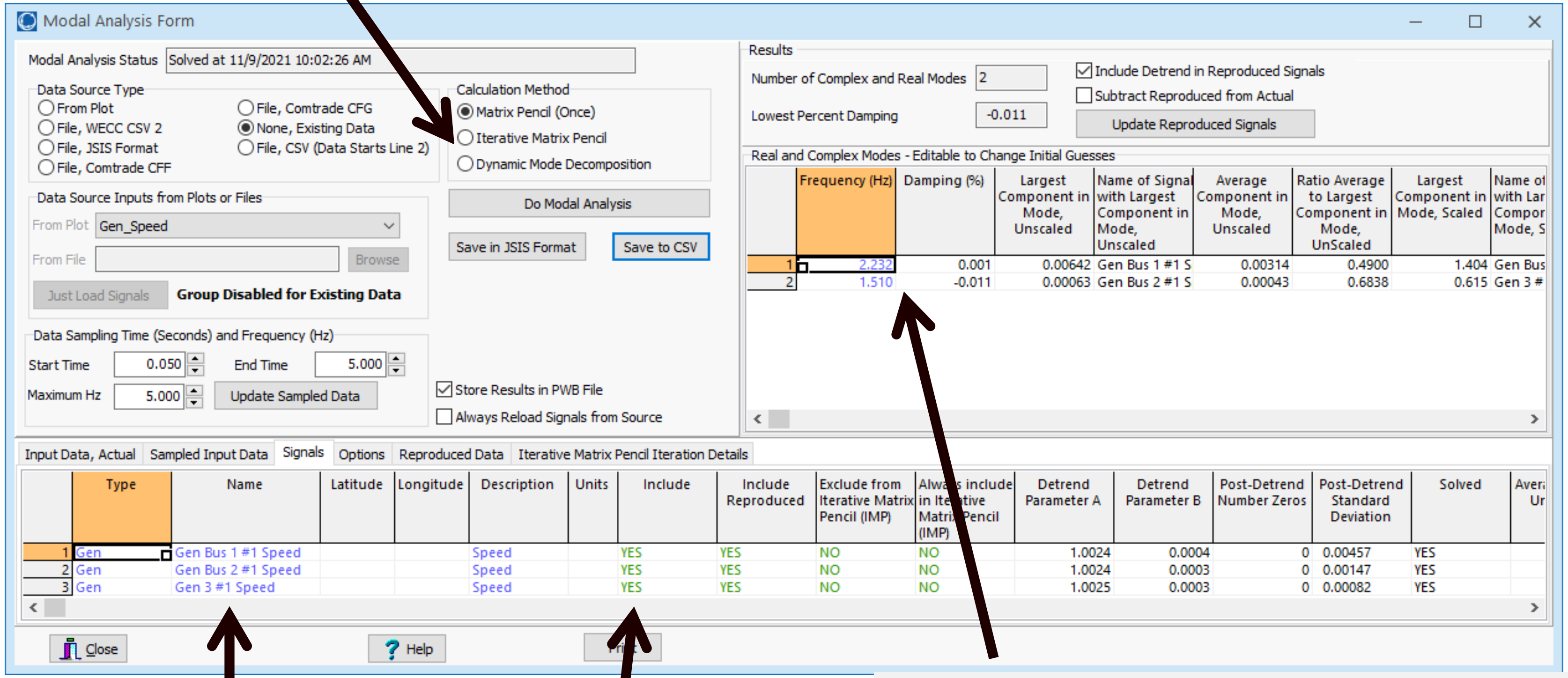


Modal Analysis: Three Generator Example

- Open the case **B3_CLS_UnDamped**
  - This system has three classical generators without damping; the default event is a self clearing fault at bus 1
- Run the transient stability for 5 seconds
- To do modal analysis, on the Transient Stability page select Results from RAM, view just the generator speed fields, right-click and select **Modal Analysis All Columns**
  - This display the Modal Analysis Form

Modal Analysis Form

First click on **Do Modal Analysis** to run the modal analysis



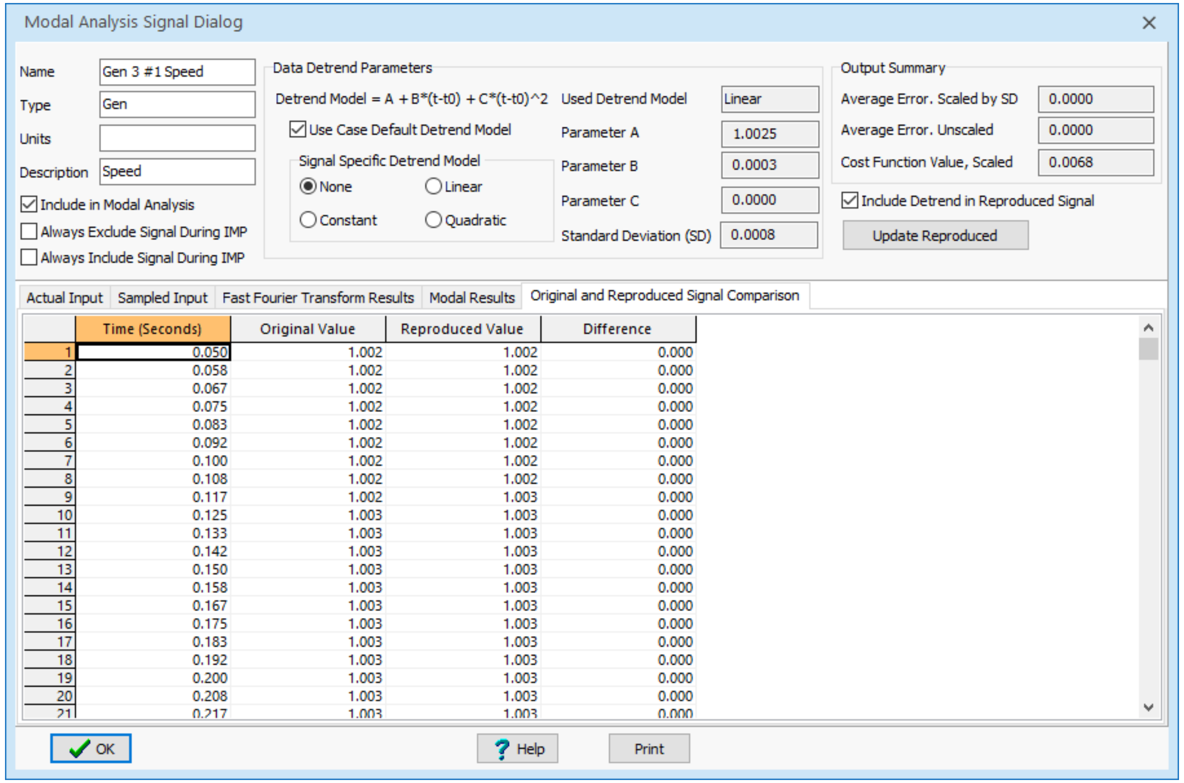
Right-click on signal to view its dialog

Signals to include

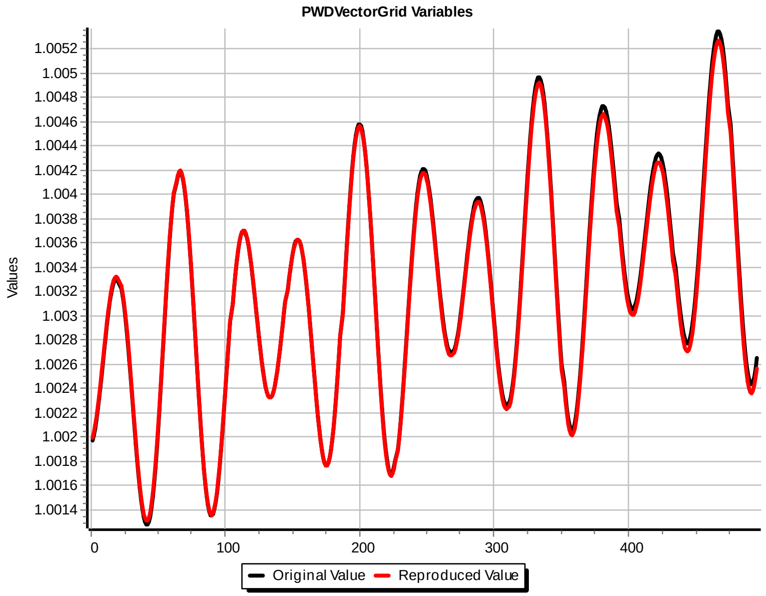
Key results are shown in the upper-right of the form. There are two main modes, one at 2.23Hz and one at 1.51; both have very little damping.

Three Generator Example: Signal Dialog

- The **Signal Dialog** provides details about each signal, including its modal components and a comparison between the original and reproduced signals (example for gen 3)

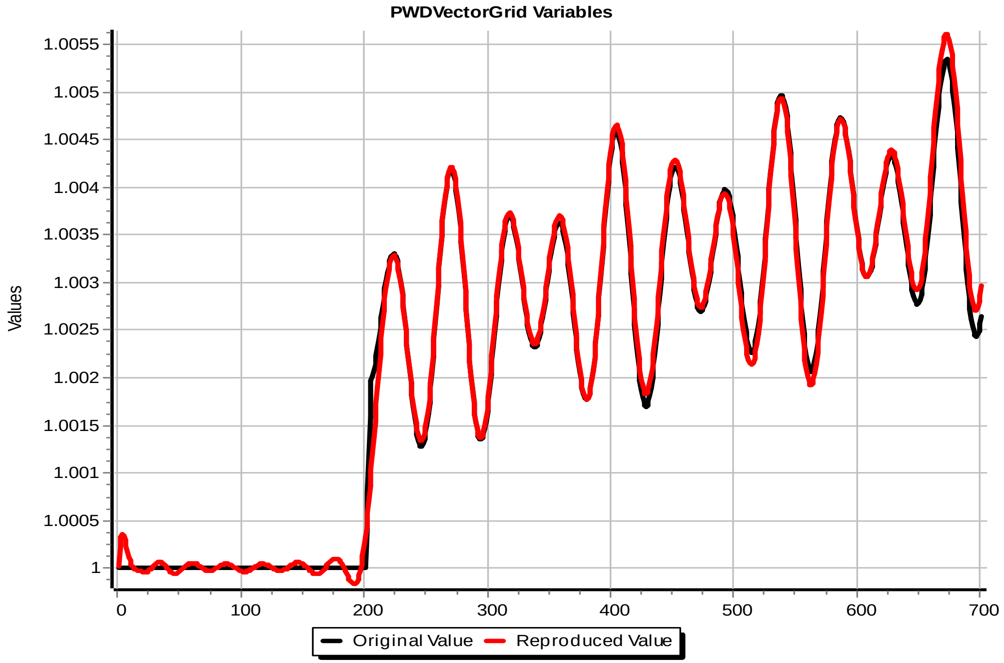


Plotting the original and reproduced signals shows a near exact match



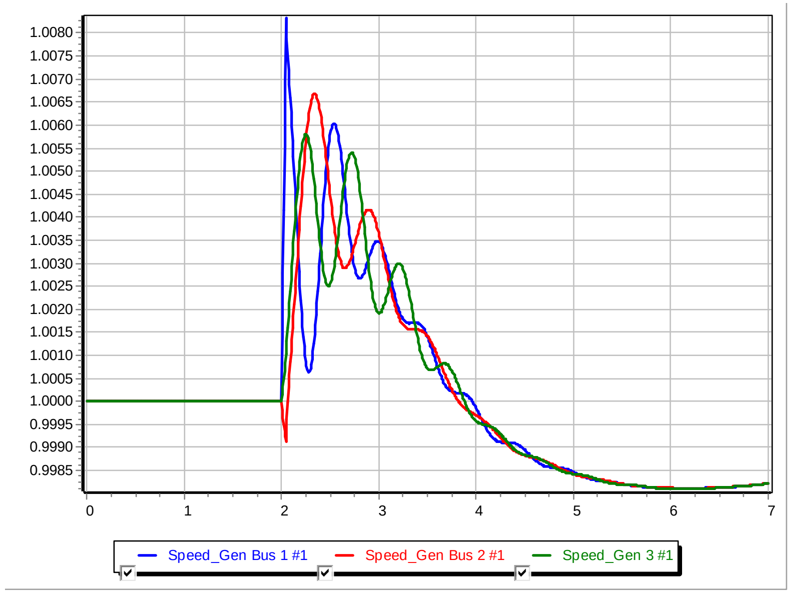
Caution: Setting Time Range Incorrectly Can Result in Unexpected Results!

- Assume the system is run with no disturbance for two seconds, and then the fault is applied and the system is run for a total of seven seconds (five seconds post-fault)
  - The incorrect approach would be to try to match the entire signal; rather just match from after the fault
  - Trying to match the full signal between 0 and 7 seconds required eleven modes!
  - By default the **Modal Analysis Form** sets thedefault start time to immediately after the last event



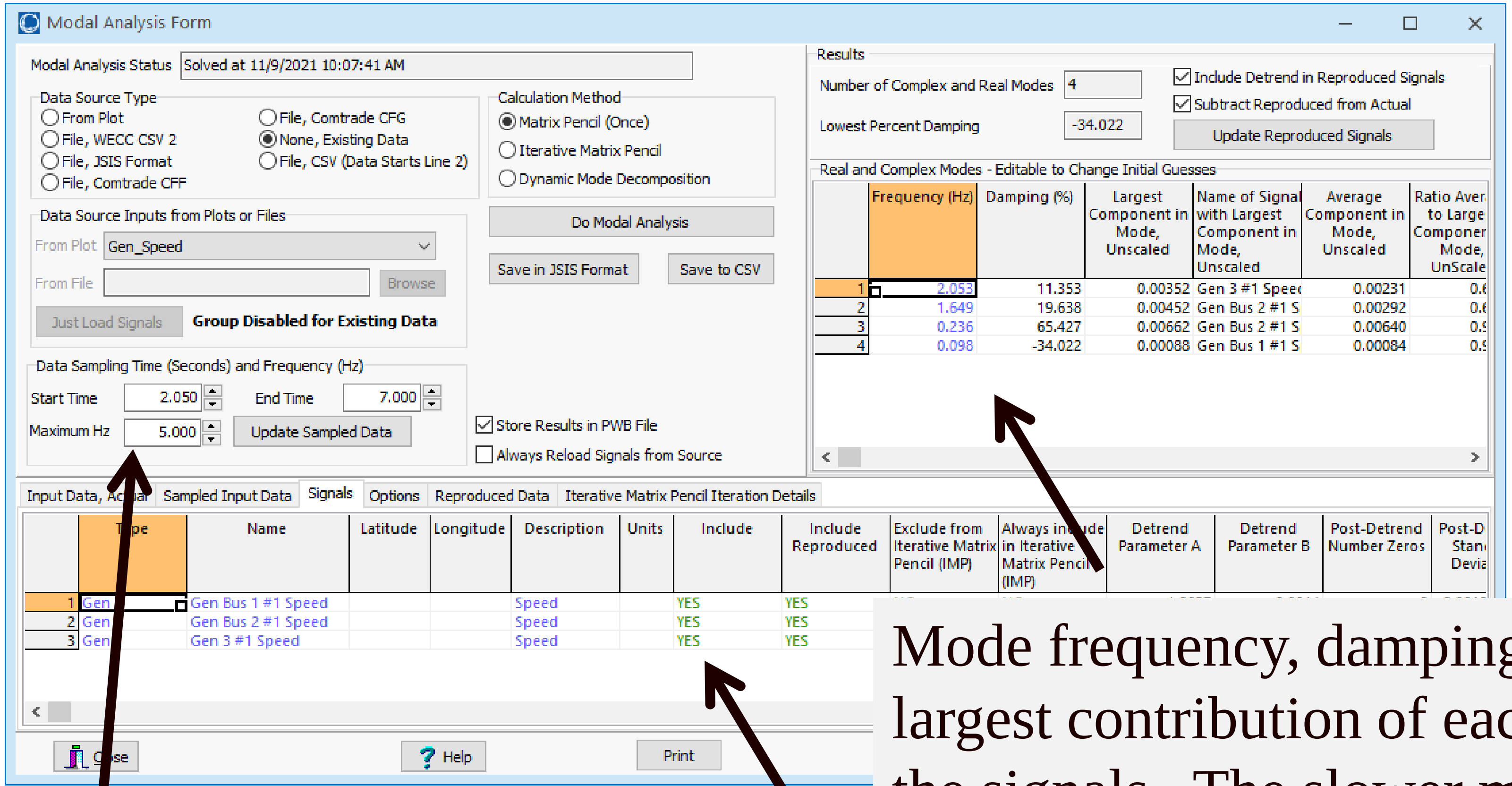
GENROU Example with Damping

- Open the case **B3_GENROU**, which changes the GENCLS to GENROU models, adding damping
  - Also each has an EXST1 exciter and a TGOV1 governor
  - The simulation runs for seven seconds, with the fault occurring at two seconds; modal analysis is done from the time the fault is cleared until the end of the simulation.



The image shows the generator speeds. The initial rise in the speed is caused by the load dropping during the fault, causing a power mismatch; this is corrected by the governors. Note the system now has damping; modal analysis tells us how much.

GENROU Example with Damping

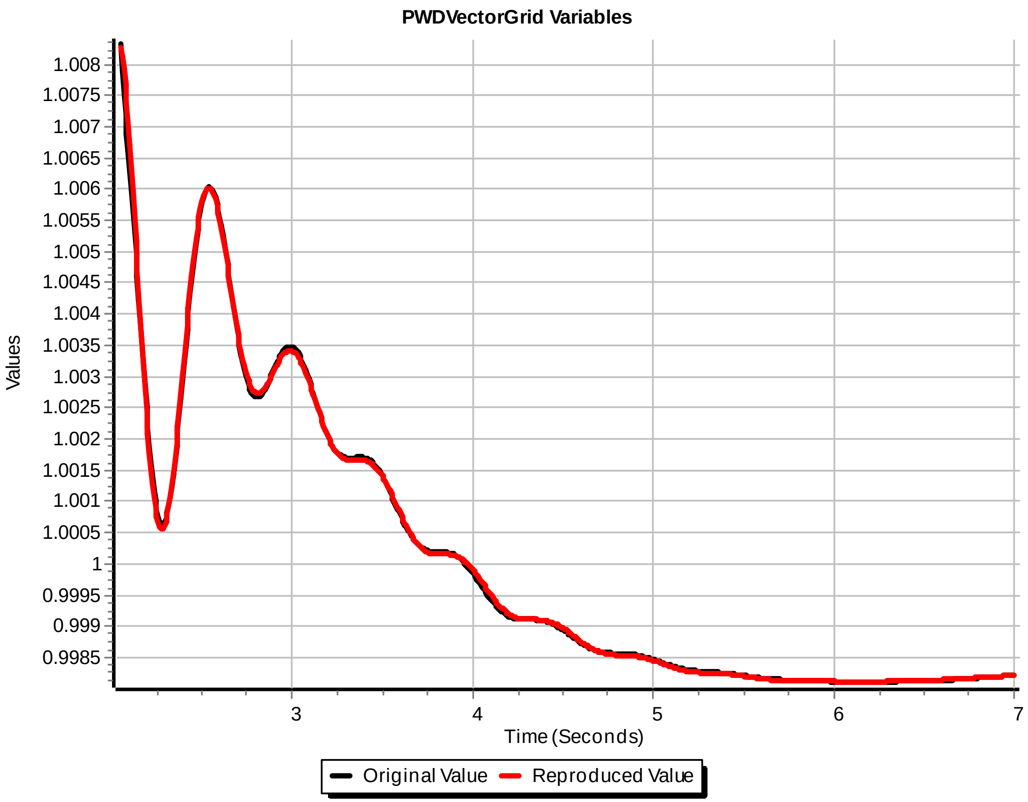


Mode frequency, damping, and largest contribution of each mode in the signals. The slower mode is associated with the governors.

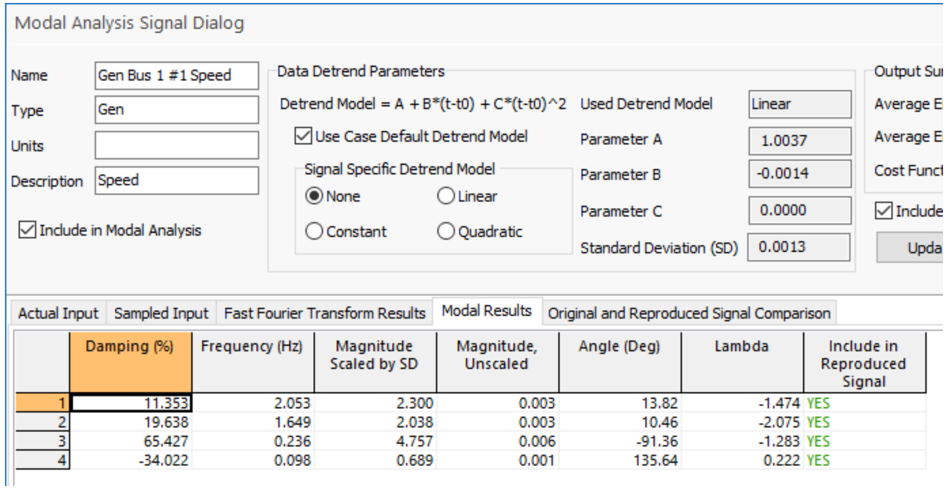
Start time default value

GENROU Example with Damping

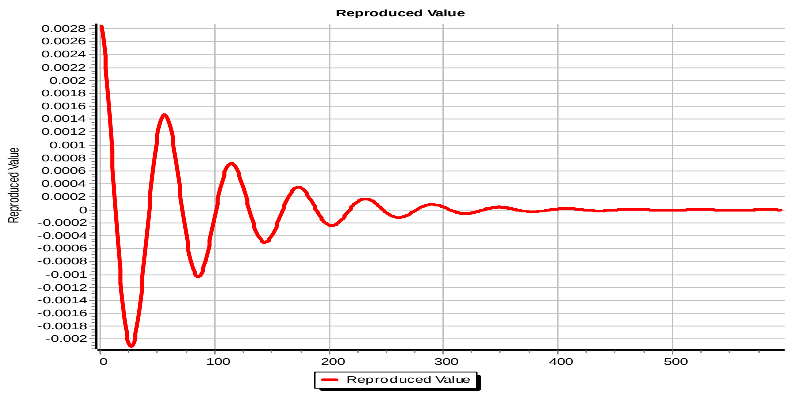
- Left image show how well the speed for generator 1 is approximated by the modes



More signal details



	Damping (%)	Frequency (Hz)	Magnitude Scaled by SD	Magnitude, Unscaled	Angle (Deg)	Lambda	Include in Reproduced Signal
1	11.353	2.053	2.300	0.003	13.82	-1.474	YES
2	19.638	1.649	2.038	0.003	10.46	-2.075	YES
3	65.427	0.236	4.757	0.006	-91.36	-1.283	YES
4	-34.022	0.098	0.689	0.001	135.64	0.222	YES



Just the 2.05 Hz mode

Dealing with Multiple Signals

- When there are many signals, usually they are at least somewhat correlated, so we do not need to include all the signals in the calculation of α.
- Based on the previous quick calculation of $\mathbf{b}_k$, we can determine how well the signals match the α.
- A natural algorithm for improving is to include the signals that do not match α well. That is, have high residuals.
- This gave rise to what is called the Iterative Matrix Pencil algorithm.

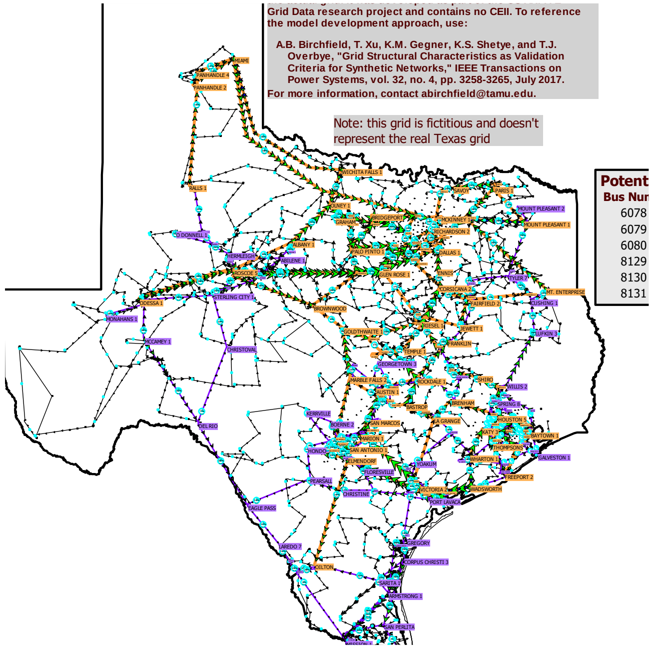
Iterative Matrix Pencil Method

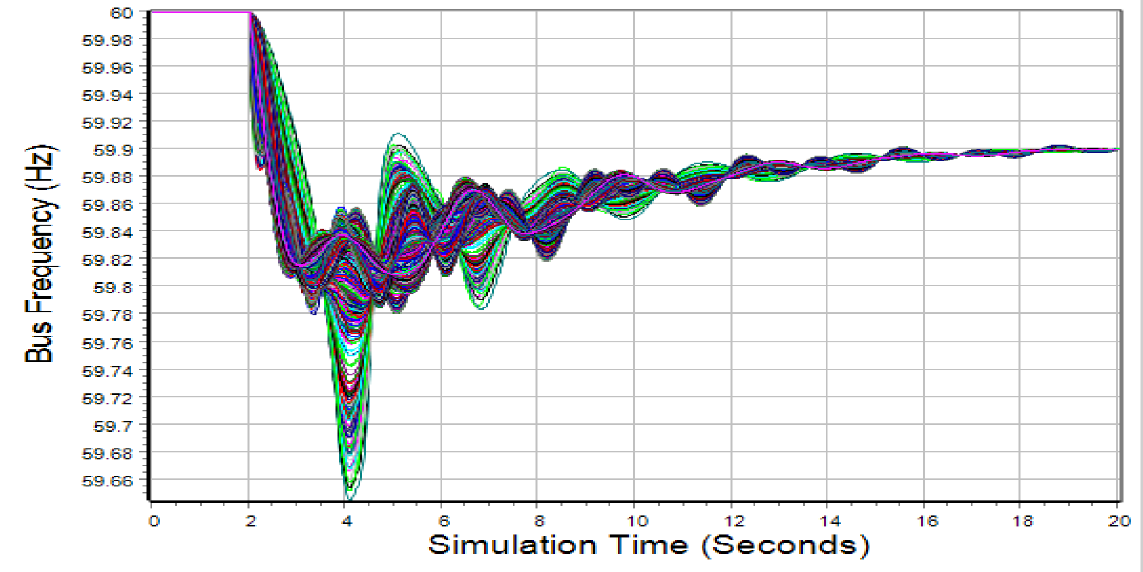
- When there are a large number of signals the iterative matrix pencil method works by
  - Selecting an initial signal to calculate the α vector
  - Quickly calculating the **b** vectors for all the signals, and getting a cost function for how closely the reconstructed signals match their sampled values
  - Selecting a signal that has a high cost function, and repeating the above adding this signal to the algorithm to get an updated α

An open access paper describing this is W. Trinh, K.S. Shetye, I. Idehen, T.J. Overbye, "Iterative Matrix Pencil Method for Power System Modal Analysis," *Proc. 52nd Hawaii International Conference on System Sciences*, Wailea, HI, January 2019; available at scholarspace.manoa.hawaii.edu/handle/10125/59803

Texas 2000 Bus Synthetic Grid Example

- For this example we'll again use the Texas 2000 bus grid, saved as **TSGC_2000_GenDrop**
- Use the Iterative Matrix Pencil Method to examine its modes
  - The contingency is the loss of two large generators (at bus 7098 and 7099)

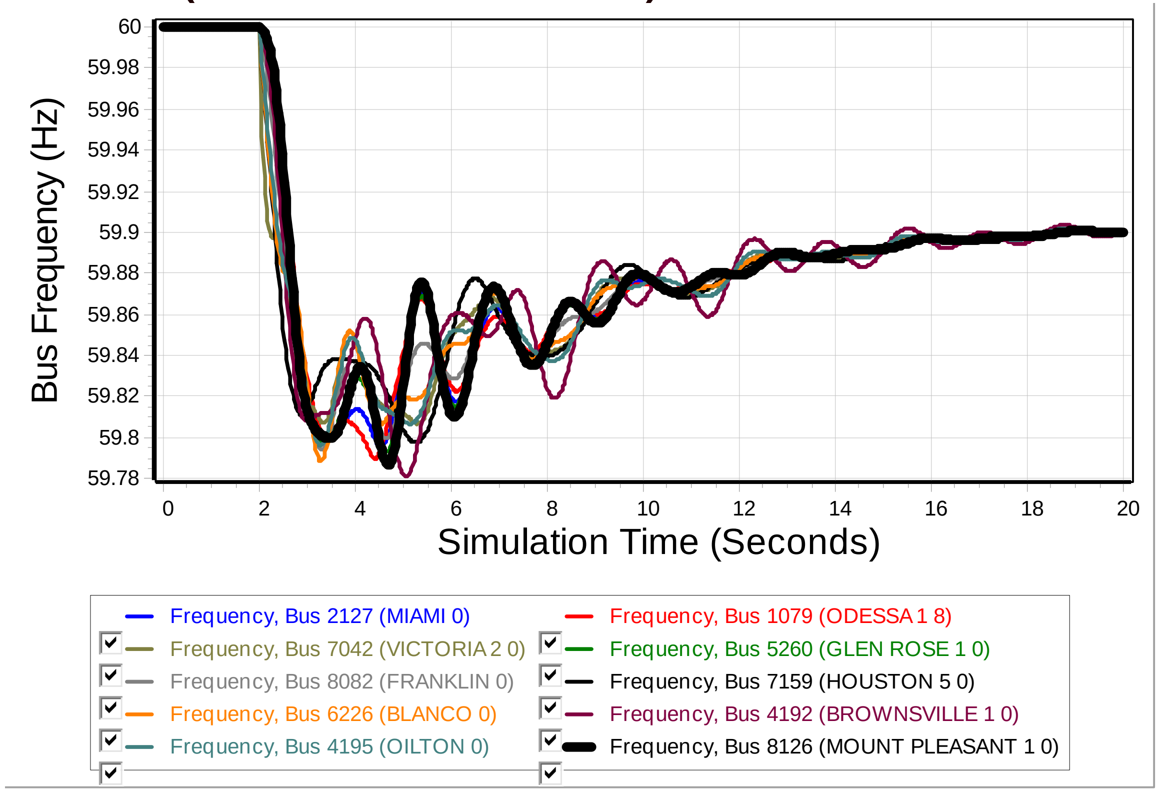




The measurements will be the frequencies at all 2000 buses

2000 Bus System Example, Initially Just One Signal

- Initially our goal is to understand the modal frequencies and their damping
- First we'll consider just one of the 2000 signals; arbitrarily I selected bus 8126 (Mount Pleasant)



Some Initial Considerations

- The input is a dynamics study running using a ½ cycle time step; data was saved every 3 steps, so at 40 Hz
  - The contingency was applied at time = 2 seconds
- We need to pick the portion of the signal to consider and the sampling frequency
  - Because of the underlying SVD, the algorithm scales with the cube of the number of time points (in a single signal)
- I selected between 2 and 17 seconds
- I sampled at ten times per second (so a total of 150 samples)

2000 Bus System Example, One Signal

- The results from the Matrix Pencil Method are

Number of Complex and Real Modes: 6

Lowest Percent Damping: 10.137

☑ Include Detrend in Reproduced Signals

☐ Subtract Reproduced from Actual

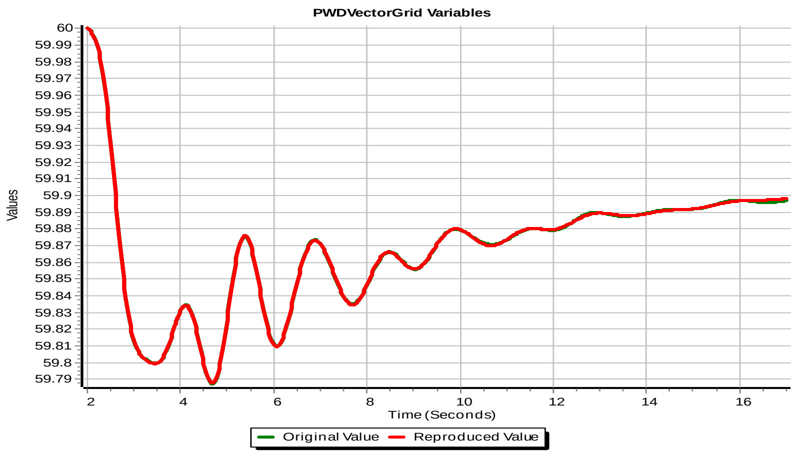
Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Component Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambda	Include in Reproduced Signal
1	0.383	32.011	0.44275	Bus 1073 (ODE!	12.224	Bus 7310 (WHA	-0.8136	YES
2	0.670	24.191	0.38466	Bus 2120 (PARI!	11.549	Bus 8078 (MT. E	-1.0490	YES
3	0.665	10.705	0.23093	Bus 2115 (PARI!	6.801	Bus 2115 (PARI!	-0.4501	YES
4	0.312	14.397	0.16911	Bus 1073 (ODE!	4.954	Bus 7310 (WHA	-0.2855	YES
5	0.971	10.137	0.08179	Bus 1051 (MON	2.551	Bus 6147 (SAN /	-0.6215	YES
6	0.052	41.828	0.04603	Bus 1074 (ODE!	1.063	Bus 3035 (CHEF	-0.1506	YES

Calculated mode information

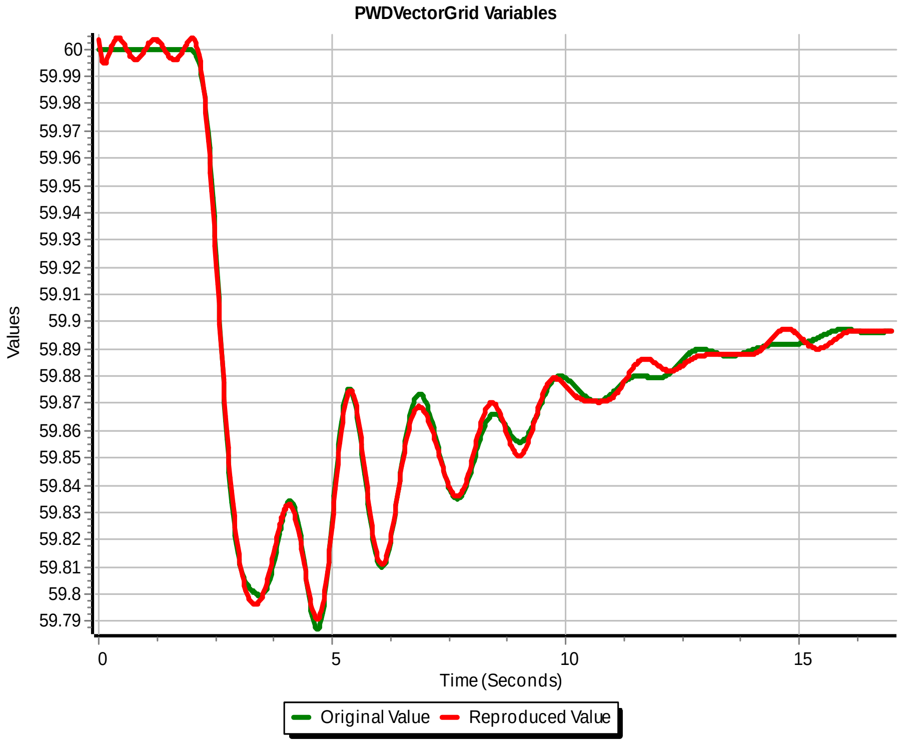
Verification of results



Some Observations

- These results are based on the consideration of just one signal
- The start time **should** be at or after the event!

If it isn't then…



The results show the algorithm trying to match the first two flat seconds; this should not be done!!

Results

Number of Complex and Real Modes: 8

Lowest Percent Damping: -100.000

☑ Include Detrend in Reproduced Signals

☐ Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Component Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambda	R
1	0.000	100.000	0.93636	Bus 1073 (ODE!	14.030	Bus 1077 (ODE!	-1.6801	YE!
2	0.240	44.396	0.82180	Bus 1073 (ODE!	12.073	Bus 1077 (ODE!	-0.7473	YE!
3	0.025	84.809	0.43068	Bus 4026 (CHRI	8.463	Bus 4026 (CHRI	-0.2476	YE!
4	0.408	4.729	0.10932	Bus 1073 (ODE!	1.587	Bus 1073 (ODE!	-0.1213	YE!
5	0.645	6.111	0.09142	Bus 2115 (PARI!	1.694	Bus 2115 (PARI!	-0.2482	YE!
6	0.751	6.110	0.05556	Bus 4192 (BROV	1.042	Bus 4192 (BROV	-0.2887	YE!
7	0.954	3.484	0.02405	Bus 1051 (MON	0.397	Bus 6147 (SAN /	-0.2089	YE!
8	0.000	-100.000	0.01406	Bus 4026 (CHRI	0.276	Bus 4026 (CHRI	0.0565	YE!

2000 Bus System Example, Two Signals

With two signals

- [x] Include Detrend in Reproduced Signals
- [ ] Subtract Reproduced from Actual

Number of Complex and Real Modes: 9

Lowest Percent Damping: 7.359

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Component in Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambd
1	2.266	17.168	0.04028	Bus 7329 (NEW	1.730	Bus 7307 (WHA	-2
2	1.413	21.844	0.10763	Bus 4030 (FANN	4.475	Bus 4030 (FANN	-1
3	0.958	7.359	0.04666	Bus 6147 (SAN	1.801	Bus 6147 (SAN	-0
4	0.701	11.705	0.21220	Bus 1051 (MON	5.762	Bus 8077 (MT. E	-0
5	0.630	13.361	0.20903	Bus 2120 (PARIS	6.350	Bus 4192 (BROV	-0
6	0.352	36.405	0.44679	Bus 1051 (MON	13.024	Bus 7311 (WHA	-0
7	0.322	14.403	0.19570	Bus 1073 (ODES	5.372	Bus 7311 (WHA	-0
8	0.000	100.000	0.09305	Bus 1051 (MON	1.767	Bus 1051 (MON	-0
9	0.064	36.756	0.02993	Bus 1073 (ODES	1.182	Bus 7307 (WHA	-0

With one signal

- [x] Include Detrend in Reproduced Signals
- [ ] Subtract Reproduced from Actual

Number of Complex and Real Modes: 6

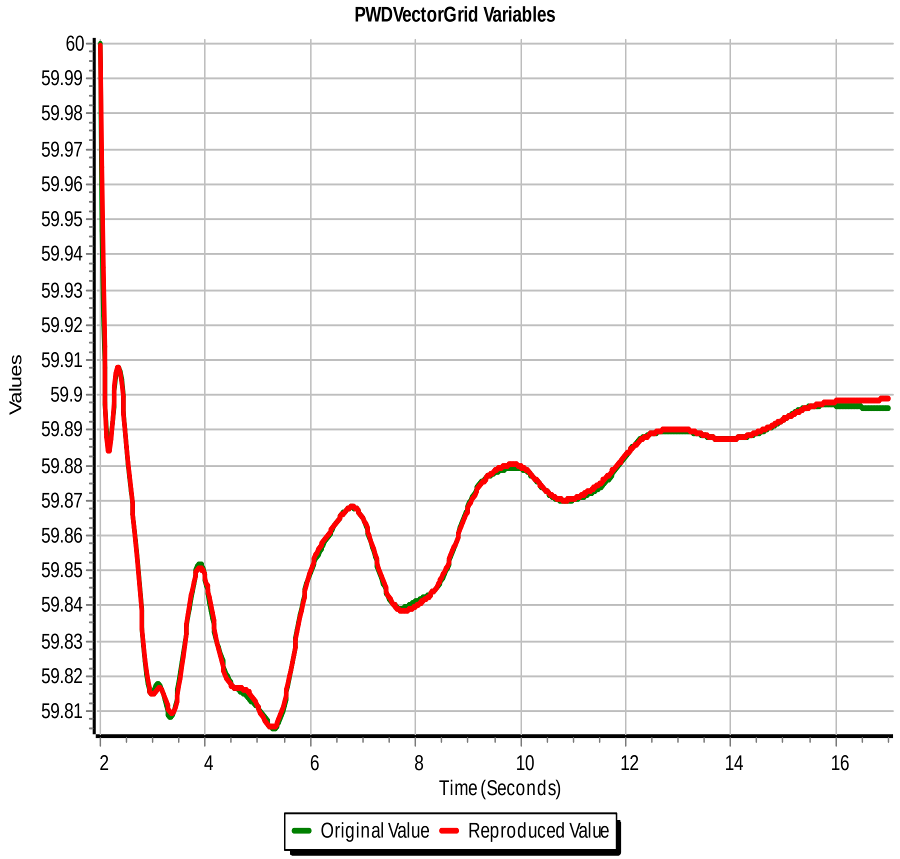
Lowest Percent Damping: 10.137

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Component Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambd
1	0.383	32.011	0.44275	Bus 1073 (ODES	12.224	Bus 7310 (WHA	-0
2	0.670	24.191	0.38466	Bus 2120 (PARIS	11.549	Bus 8078 (MT. E	-1
3	0.665	10.705	0.23093	Bus 2115 (PARIS	6.801	Bus 2115 (PARIS	-0
4	0.312	14.397	0.16911	Bus 1073 (ODES	4.954	Bus 7310 (WHA	-0
5	0.971	10.137	0.08179	Bus 1051 (MON	2.551	Bus 6147 (SAN	-0
6	0.052	41.828	0.04603	Bus 1074 (ODES	1.063	Bus 3035 (CHER	-0

The new match on the bus that was previously worst (Bus 7061) is now quite good!



2000 Bus System Example, Iterative Matrix Pencil

- The Iterative Matrix Pencil intelligently adds signals until a specified number is met
  - Doing ten iterations takes about four seconds

Number of Complex and Real Modes: 11

Lowest Percent Damping: 6.082

☑ Include Detrend in Reproduced Signals

☐ Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%	Largest Component in Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambda	Include in Reproduced Signal
1	0.631	6.082	0.10313	Bus BROWNSVI	3.292	Bus BROWNSVI	-0.2415	YES
2	0.959	7.068	0.04897	Bus SAN ANTOI	1.890	Bus SAN ANTOI	-0.4269	YES
3	1.364	7.246	0.03780	Bus ODESSA 1	1.420	Bus CHRISTINE	-0.6228	YES
4	0.593	7.897	0.07205	Bus BROWNSVI	2.300	Bus BROWNSVI	-0.2949	YES
5	1.602	8.562	0.04887	Bus FANNIN 2 F	2.032	Bus FANNIN 2 F	-0.8650	YES
6	0.732	11.936	0.21348	Bus MONAHAN	4.054	Bus MONAHAN	-0.5529	YES
7	0.324	14.207	0.19906	Bus ODESSA 1	5.268	Bus WHARTON	-0.2917	YES
8	0.324	39.346	0.55936	Bus MONAHAN	12.994	Bus WHARTON	-0.8722	YES
9	0.060	39.972	0.03815	Bus ODESSA 1	1.196	Bus POINT COM	-0.1645	YES
10	0.964	57.683	0.61264	Bus ODESSA 1	18.504	Bus POINT COM	-4.2760	YES
11	0.000	100.000	0.59650	Bus ODESSA 1	14.434	Bus WHARTON	-2.5257	YES

Takeaways So Far

- Modal analysis can be quickly done on a large number of signals
  - Computationally is an $O(N^3)$ process for one signal, where N is the number of sample points; it varies linearly with the number of included signals
  - The number of sample points can be automatically determined from the highest desired frequency (the Nyquist-Shannon sampling theory requires sampling at twice the highest desired frequency)
  - Determining how all the signals are manifested in the modes is quite fast!!

Visualizing the Modes

- If the grid has embedded geographic coordinates, the contributions for the mode to each signal can be readily visualized utilizing geographic data views (GDVs)

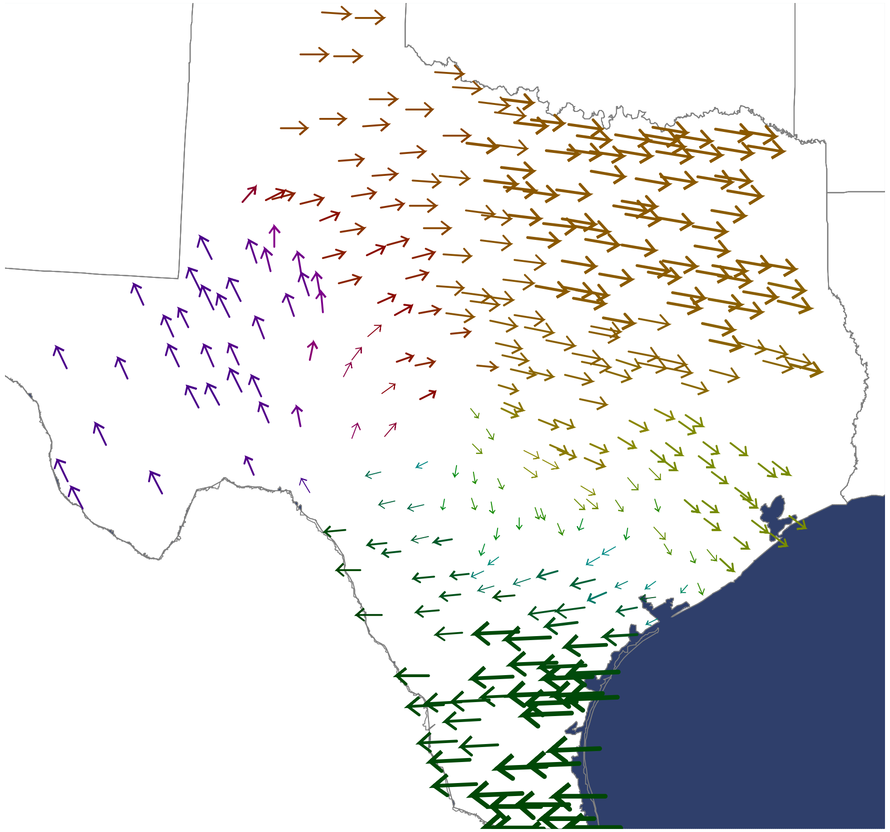
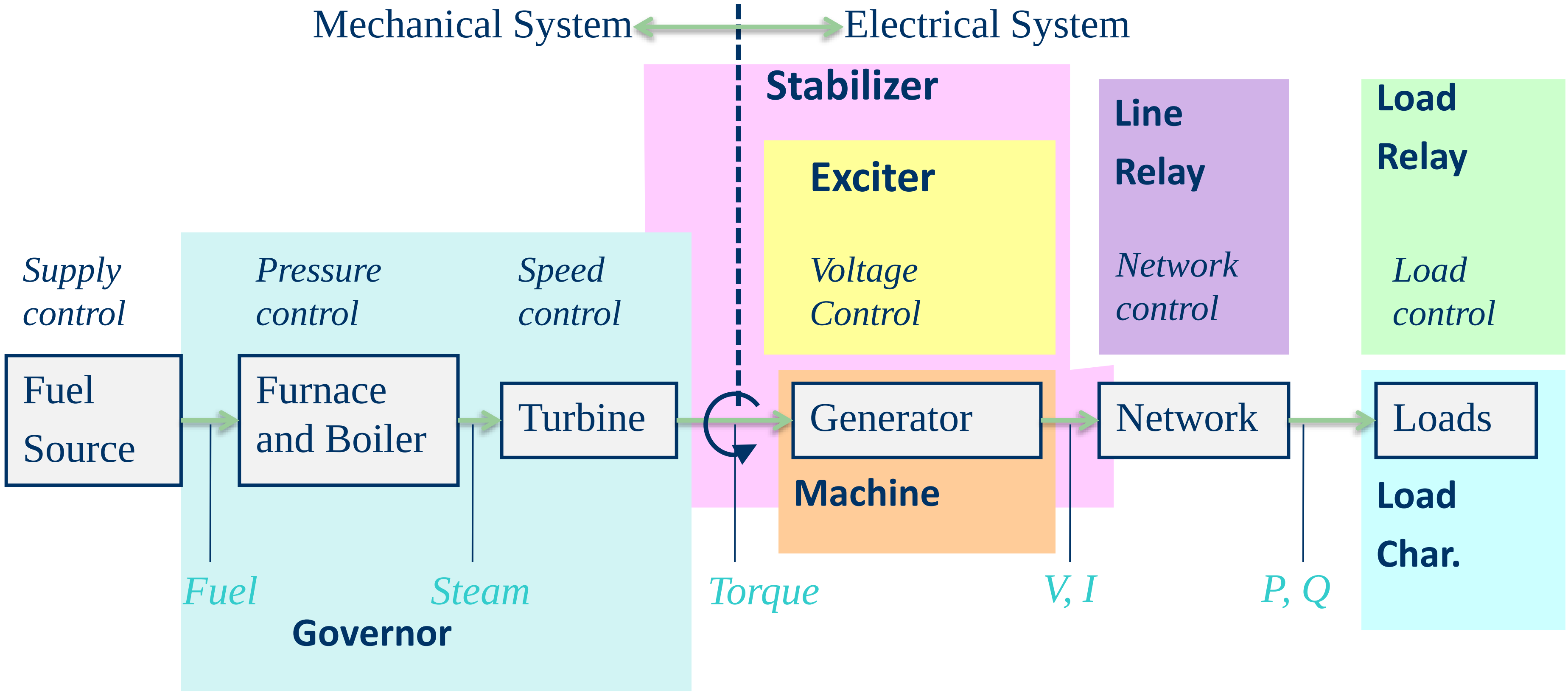


Image shows the magnitudes of the components for the 0.63 Hz mode; the display was pruned to only show some of the values

Damping Oscillations: Power System Stabilizers (PSSs)

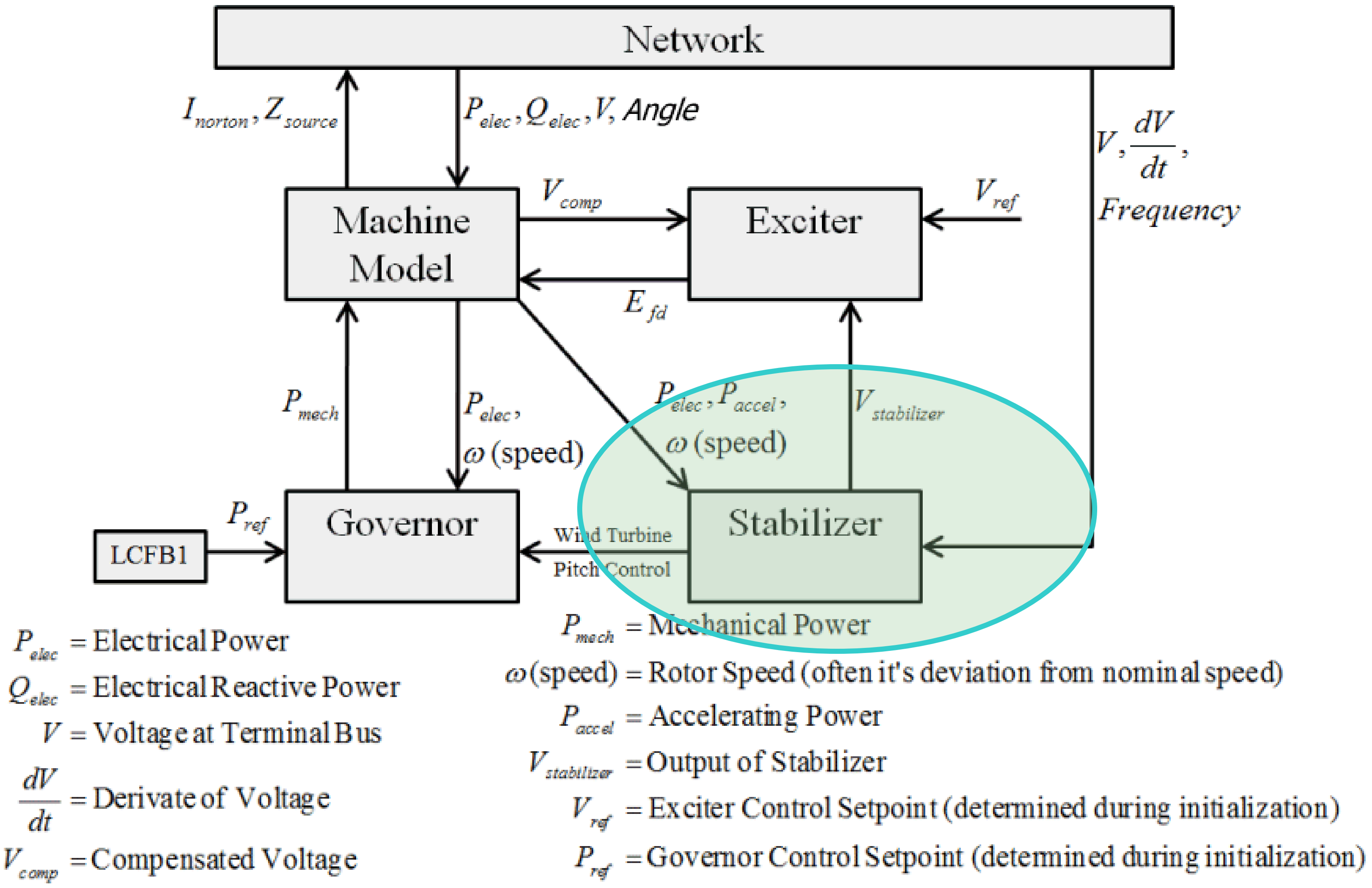
- A PSS adds a signal to the excitation system to improve damping
  - A common signal is proportional to the generator's speed; other inputs, such as like power, voltage or acceleration, can be used
  - The signal is usually measured locally (e.g. from the shaft)
- Both local modes and inter-area modes can be damped.
- Regular tuning of PSSs is important
- Fully considering power system stabilizers can get quite involved
  - Here we'll just focus on covering the basics, and doing a simple PSS design. The goal is providing insight and tools that can help power system engineers understand the PSS models, determine whether there is likely bad data, understand the basic functionality, and do simple planning level design

Dynamic Models in the Physical Structure



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Power System Stabilizer (PSS) Models



PSSs Regulations

- On ERCOT PSSs are required on all synchronous generators greater than 10 MW installed after January 2008
  - If a generator has a PSS then they need to be kept in-service; they also need to be tuned to help damp out oscillations between 0.2 to 2 Hz.
- WECC requires PSSs for synchronous generators connected to the bulk electric grid, and has a number specific requires associated with PSS values (see NERC VAR-501-WECC-3.1)

Classic Block Diagram of a System with a PSS

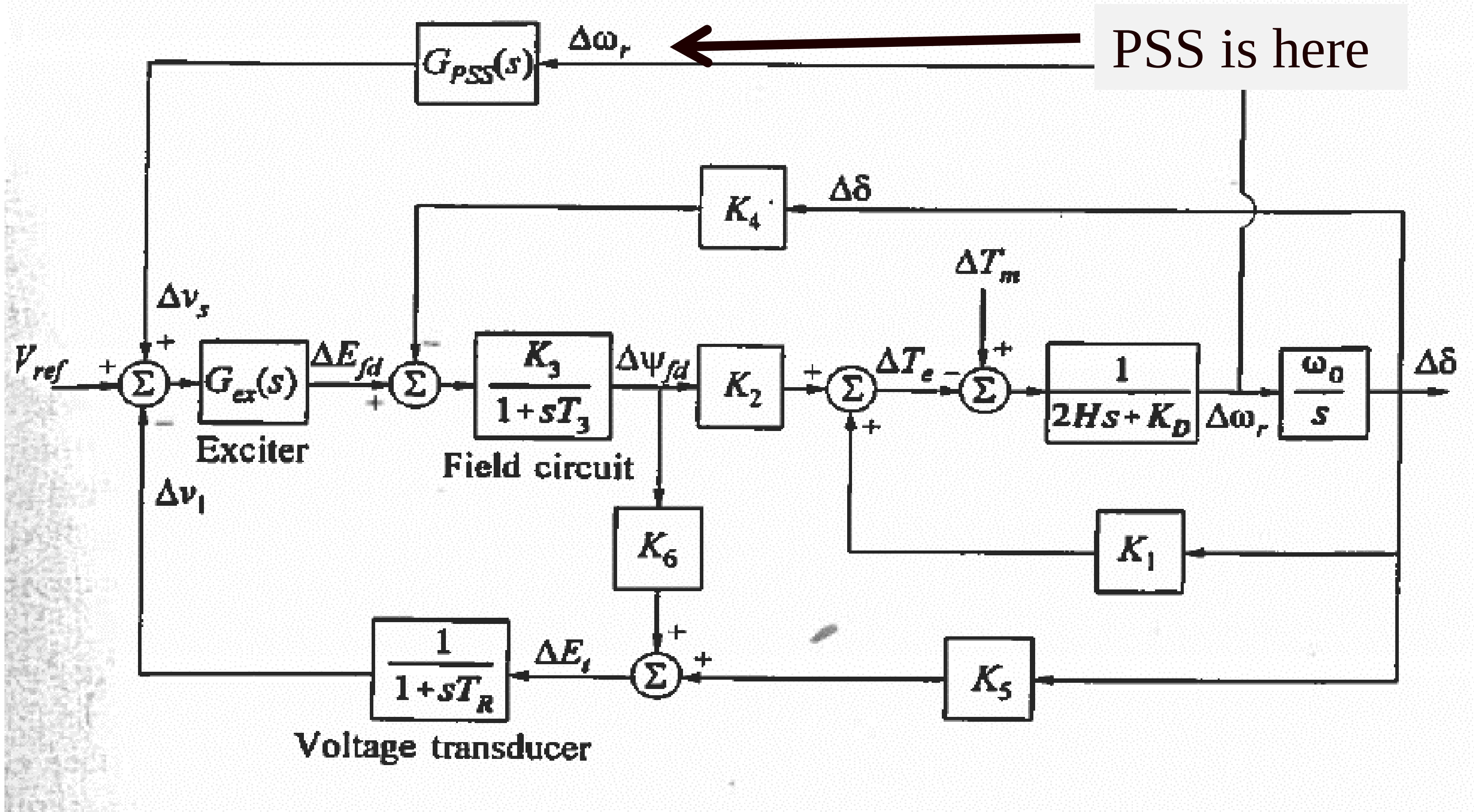


Figure 12.13 Block diagram representation with AVR and PSS

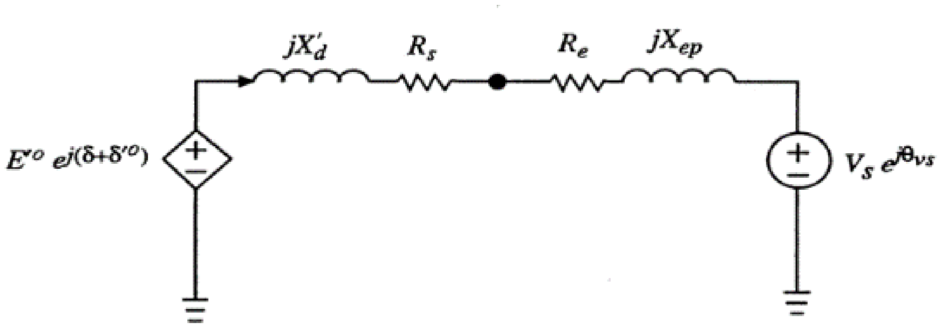
Image Source: Kundur, *Power System Stability and Control*

PSS Basics

- Stabilizers can be motivated by considering a classical model supplying an infinite bus

$$\frac{d\delta}{\mathrm{dt}} = \omega - \omega_s = \Delta\omega$$

$$\frac{2H}{\omega_0}\frac{d\Delta\omega}{dt} = T_M^0 - \frac{E'V_s}{X_d' + X_{ep}}\sin(\delta) - D\Delta\omega$$



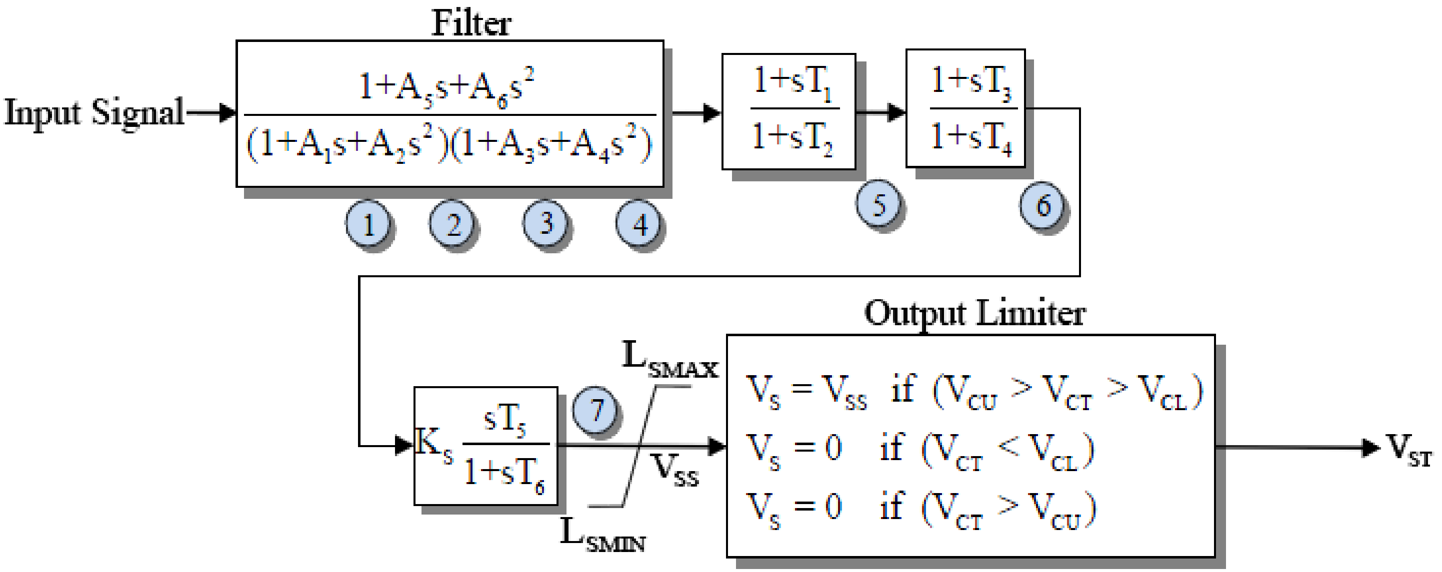
- Assume internal voltage has an additional component

$$E' = E'_{org} + K\Delta\omega$$

- This can add additional damping if sin(δ) is positive
- In a real system there is delay, which requires compensation

Example PSS

- An example single input stabilizer is shown below (IEEEST)
  - The input is usually the generator shaft speed deviation, but it could also be the bus frequency deviation, generator electric power or voltage magnitude



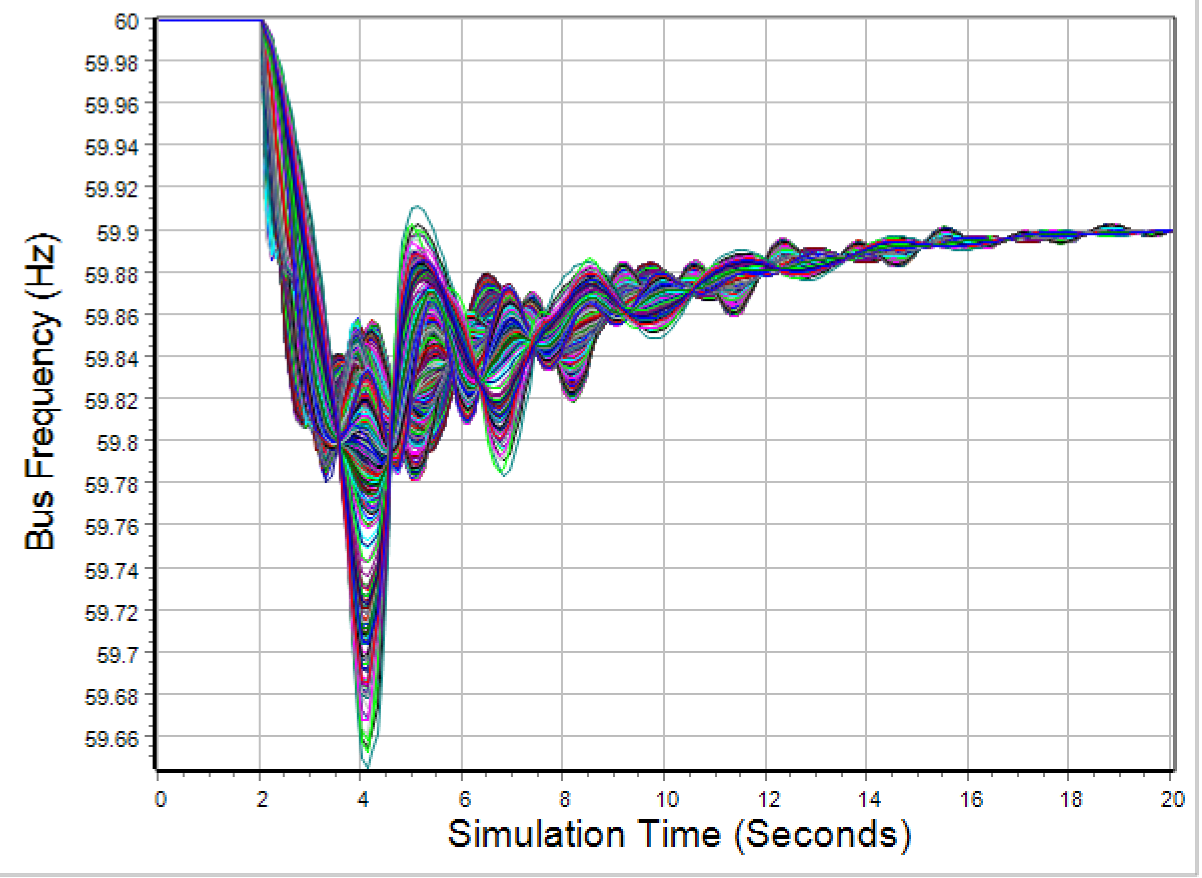
The model can be simplified by setting some parameters to zero

V_{ST} is an input into the exciter

2000 Bus System Results With Stabilizers

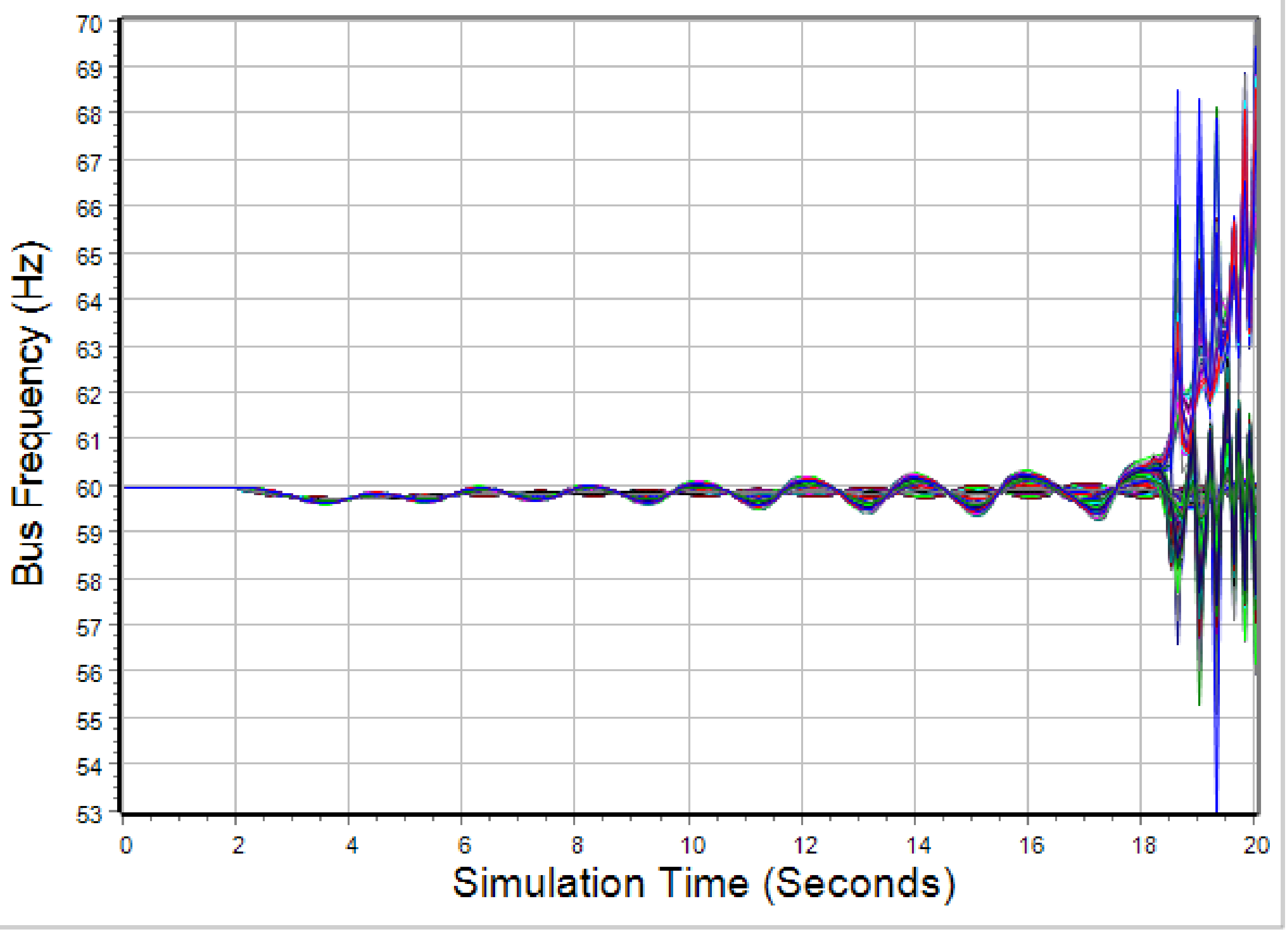
- The case has 334 IEEST stabilizers, all with the same parameters (which would not be the case in a real system)

Results are given for the previous generator drop contingency



2000 Bus System Results Without Stabilizers

- Clearly the case is unstable; note the change in scale



Washout Filters and Lead-Lag Compensators

- Two common attributes of PSSs are washout filters and lead-lag compensators

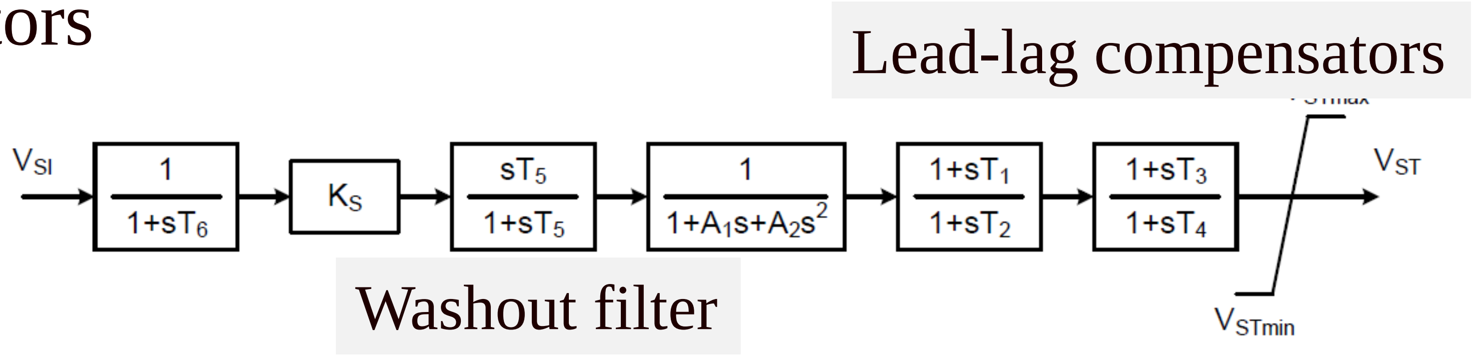
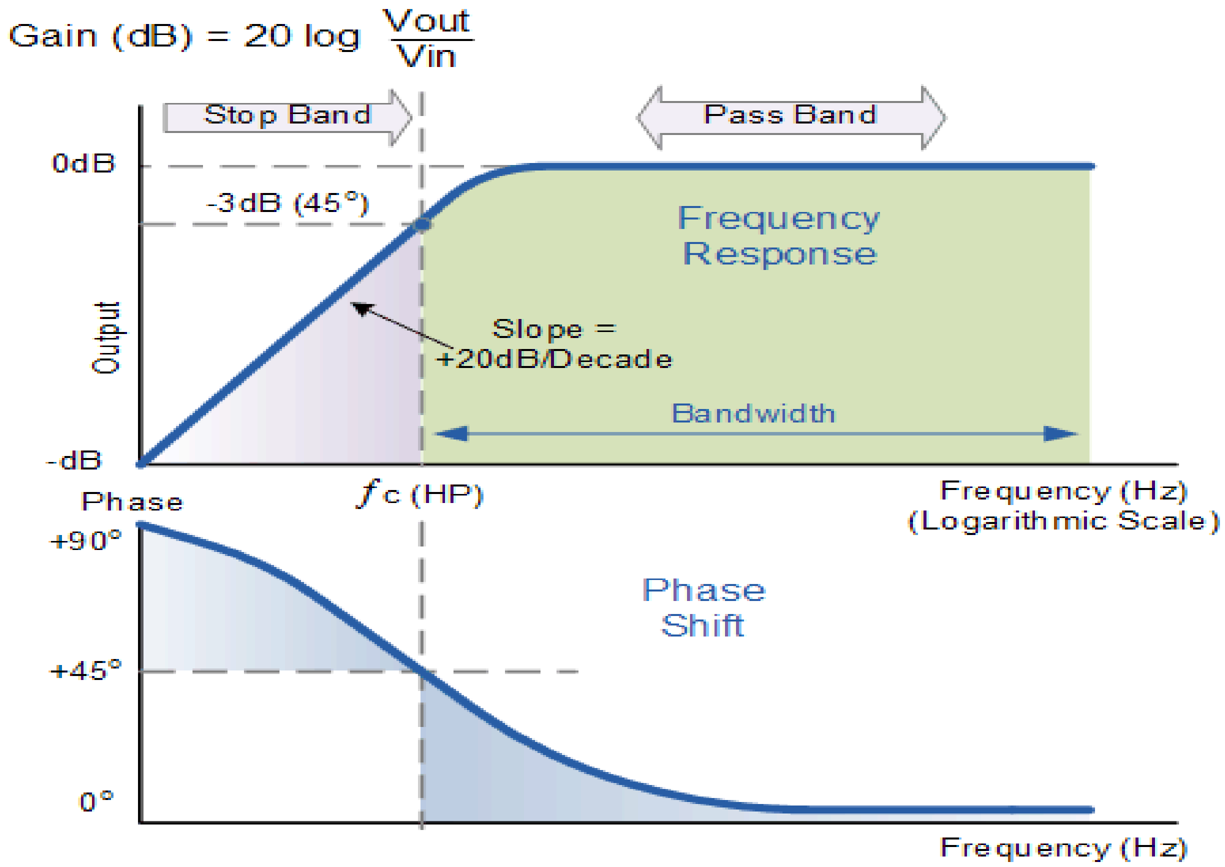


Figure 31 —Type PSS1A single-input power system stabilizer

- Since PSSs are associated with damping oscillations, they should be immune to slow changes. These low frequency changes are "washed out" by the washout filter; this is a type of high-pass filter.

Washout Filter

- The filter changes both the magnitude and angle of the signal at low frequencies



The breakpoint frequency is when the phase shift is 45 degrees and the gain is -3 dB (1/sqrt(2))

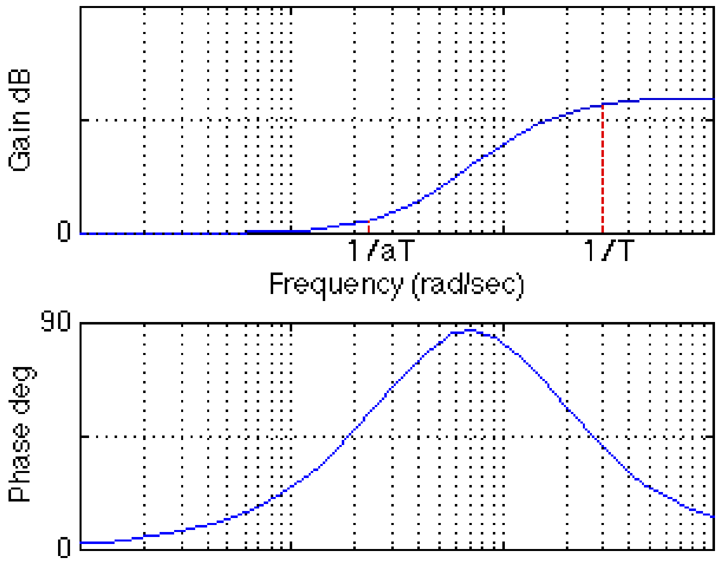
A larger T value shifts the breakpoint to lower frequencies; at T=10 the breakpoint frequency is 0.016 Hz

Image Source: www.electronics-tutorials.ws/filter/filter_3.html

Lead-Lag Compensators

- For a lead-lag compensator of the below form with α <= 1 (equivalently a >= 1)

$$\frac{1+sT_1}{1+sT_2} = \frac{1+sT_1}{1+s\alpha T_1} = \frac{1+asT}{1+sT}$$



- There is no gain or phase shift at low frequencies, a gain at high frequencies but no phase shift
- Equations for a design maximum phase shift α at a frequency f are given

$$\alpha = \frac{1-\sin\phi}{1+\sin\phi}, \; T_1 = \frac{1}{2\pi f\sqrt{\alpha}}$$

$$\sin\phi = \frac{1-\alpha}{1+\alpha}$$

Stabilizer Design

- As noted by Larsen, the basic function of stabilizers is to modulate the generator excitation to damp generator oscillations in frequency range of about 0.2 to 2.5 Hz
  - This requires adding a torque that is in phase with the speed variation; this requires compensating for the gain and phase characteristics of the generator, excitation system, and power system (GEP(s))
  - We need to compensate for the phase lag in the GEP
- The stabilizer input is often the shaft speed

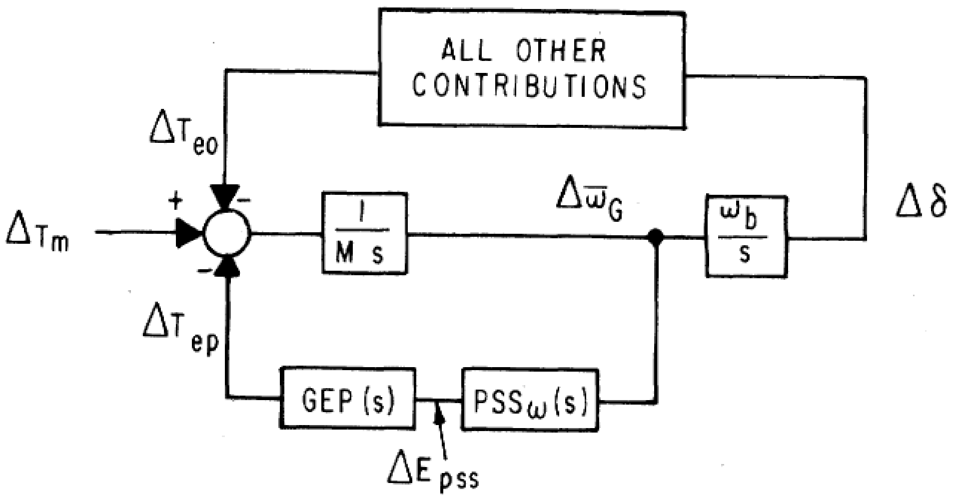


Image Source: Figure 1 from Larsen, 1981, Part 1

Stabilizer Design

- T_6 is used to represent measurement delay; it is usually zero (ignoring the delay) or a small value (< 0.02 sec)
- The washout filter removes low frequencies; T_5 is usually several seconds (with an average of say 5)
  - Some guidelines say less than ten seconds to quickly remove the low frequency component
  - Some stabilizer inputs include two washout filters

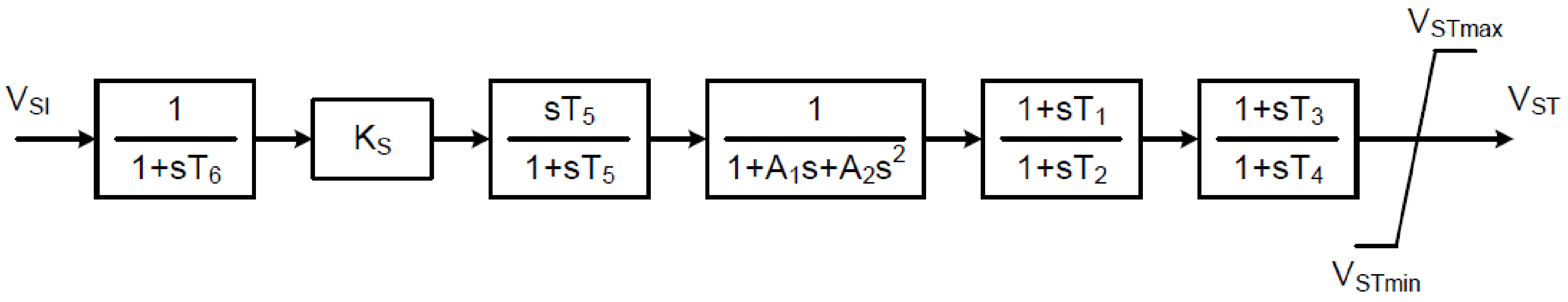


Figure 31 —Type PSS1A single-input power system stabilizer

Image Source:
EEE Std 421.5-2016

Stabilizer Design Values

- With a washout filter value of T_5 = 10 at 0.1 Hz (s = $j0.2\pi$ = j0.63) the gain is 0.987; with T_5 = 1 at 0.1 Hz the gain is 0.53
- Ignoring the second order block, the values to be tuned are the gain, K_s, and the time constants on the two lead-lag blocks to provide phase compensation
  - We'll assume T_1=T_3 and T_2=T_4

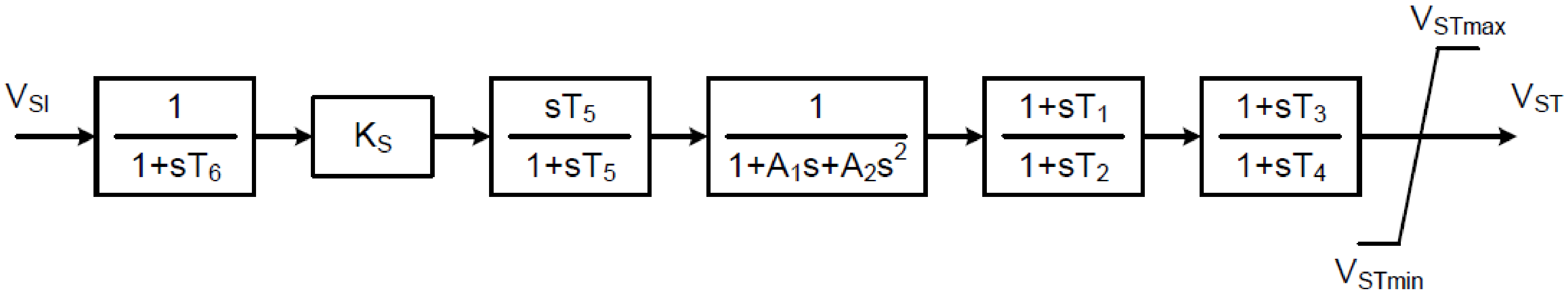


Figure 31—Type PSS1A single-input power system stabilizer

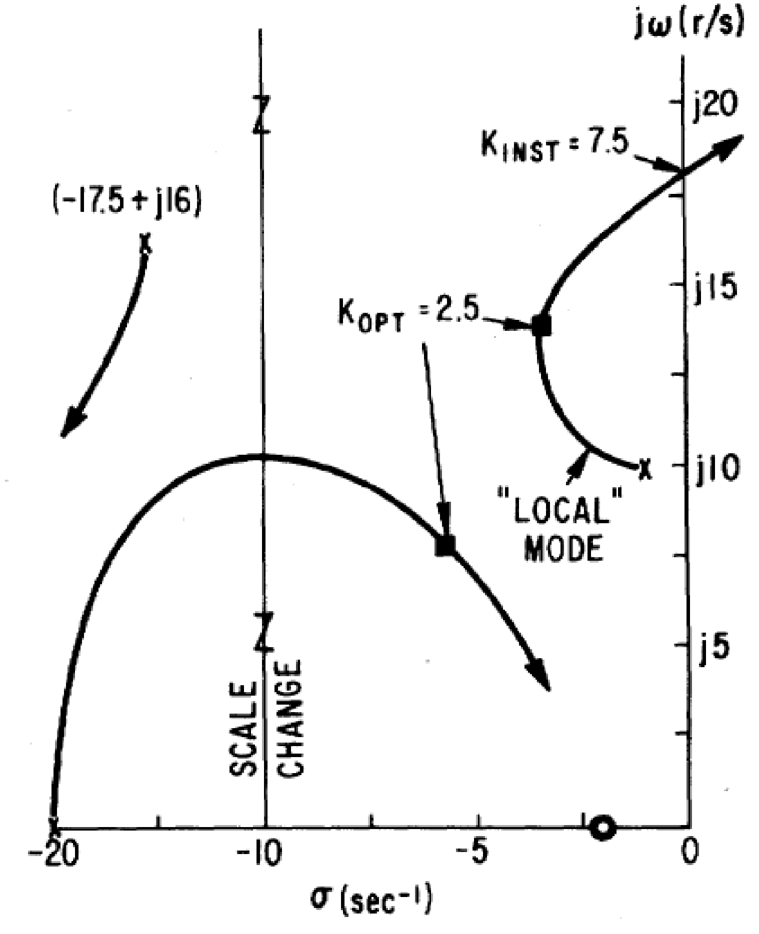
Stabilizer Design Phase Compensation

- Goal is to move the eigenvalues further into the left-half plane
- Initial direction the eigenvalues move as the stabilizer gain is increased from zero depends on the phase at the oscillatory frequency
  - If the phase is close to zero, the real component changes significantly but not the imaginary component
  - If the phase is around -45° then both change about equally
  - If the phase is close to -90° then there is little change in the real component but a large change in the imaginary component

Stabilizer Design Tuning Criteria

- Eigenvalues moves as K_s increases

K_{OPT} is where the damping is maximized; K_{INST} is the gain at which sustained oscillations or an instability occur



f_c = 1.0 Hz; $T_1/T_2 = T_3/T_4$ = .5/.05

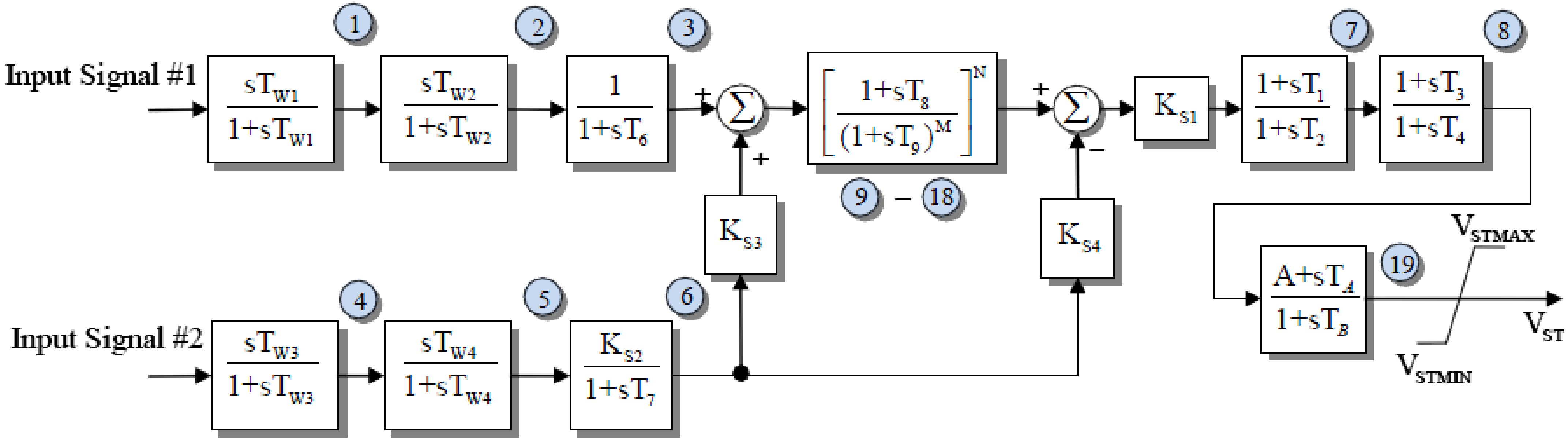
- A practical method is to find K_{INST}, then set K_{OPT} as about 1/3 to ½ of this value

Stabilizer Design Tuning

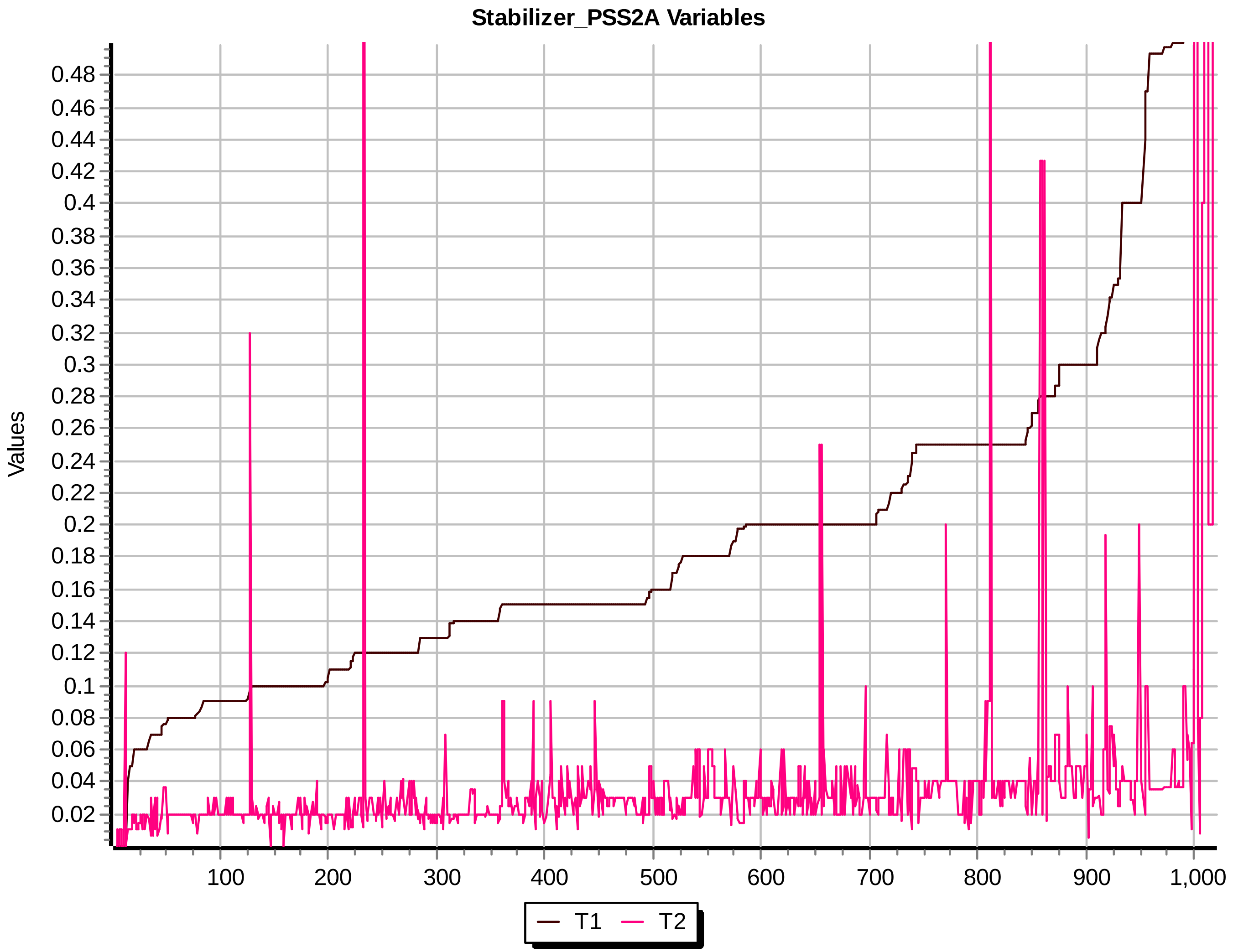
- Basic approach is to provide enhanced damping at desired frequencies; the challenge is power systems can experience many different types of oscillations, ranging from the high frequency local modes to the slower (< 1.0 Hz usually) inter-area modes
- Usually the PSS should be set to compensate the phase so there is little phase lag at inter-area frequencies
  - This can get modified slightly if there is a need for local stability enhancement
- An approach is to first set the phase compensation, then tune the gain; this should be done at full output

PSS2A Example Values

- Based on about 1000 WECC PSS2A models
  - T_1=T_3 about 64% of the time and T_2=T_4 about 69% of the time
  - The next page has a plot of the T1 and T2 values; the average T1/T2 ratio is about 6.4

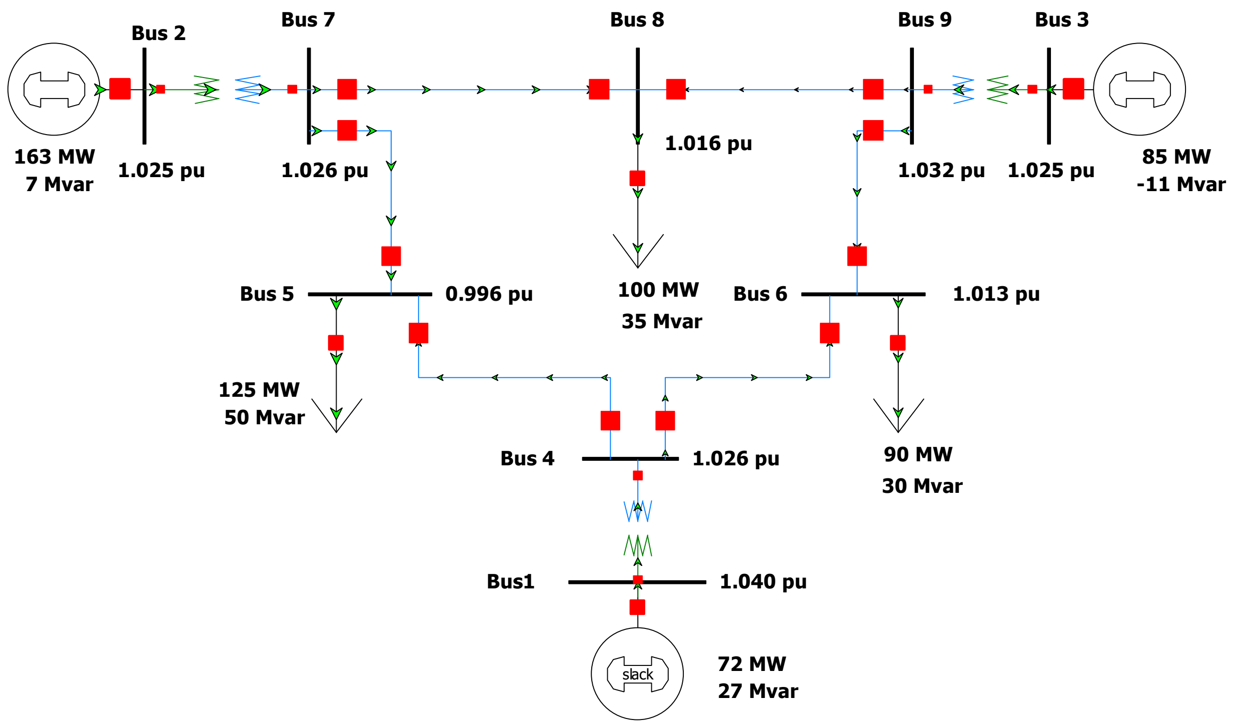


Example T_1 and T_2 Values



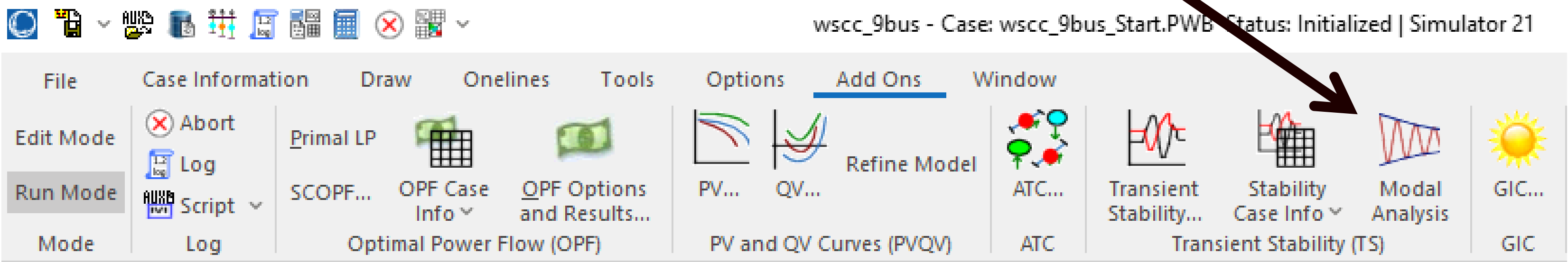
PSS Tuning Example

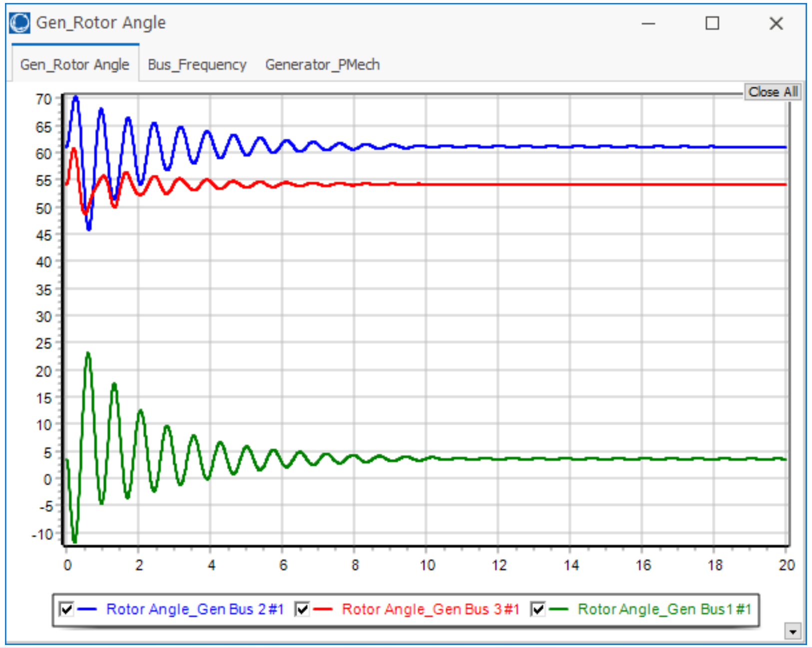
- Open the case **wscc_9bus_Start**, apply the default dynamics contingency of a self-clearing fault at Bus 8.
- Use Modal Analysis to determine the major modal frequency and damping

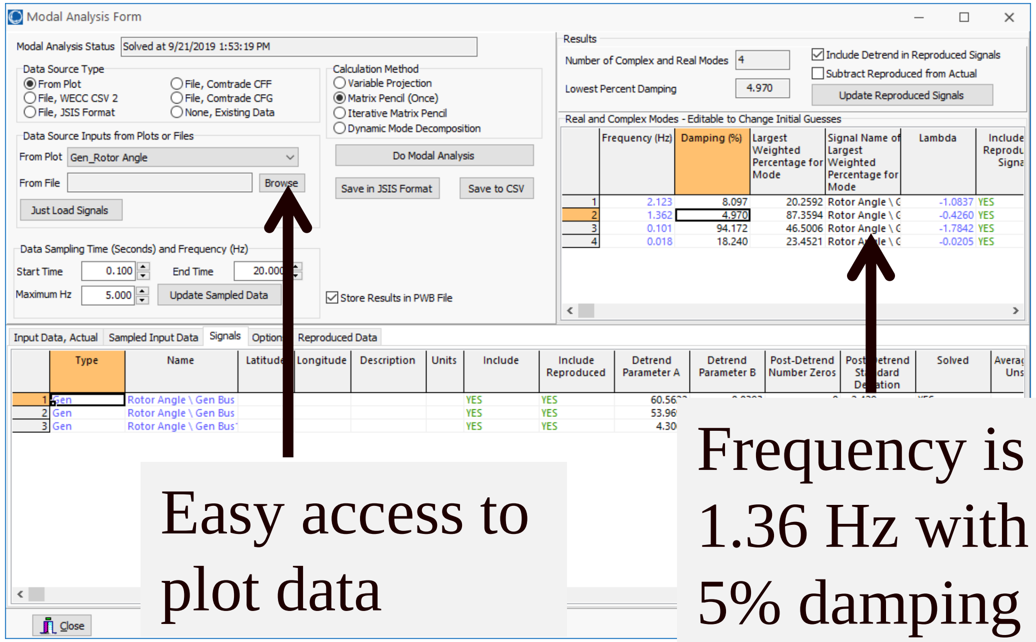


PSS Example: Getting Initial Frequency, Damping

- The **Modal Analysis** button provides quick access





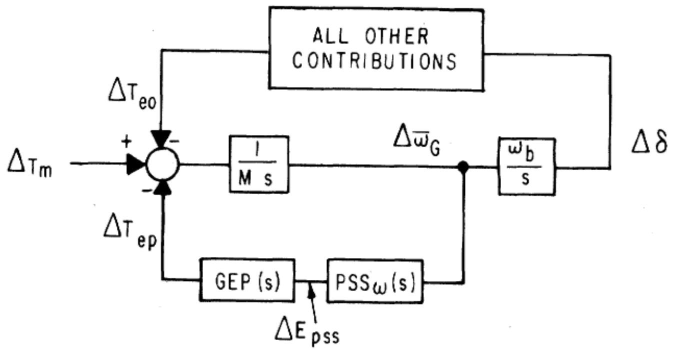


Easy access to plot data

Frequency is 1.36 Hz with 5% damping

PSS Tuning Example: Add PSS1As at Gens 2 and 3

- To increase the generator speed damping, we'll add PSS1A stabilizers using the local shaft speed as an input
- First step is to determine the phase difference between the PSS output and the PSS input; this is the value we'll need to compensate
- This phase can be determined either analytically, actually testing the generator or using simulation results
  - We'll use simulation results



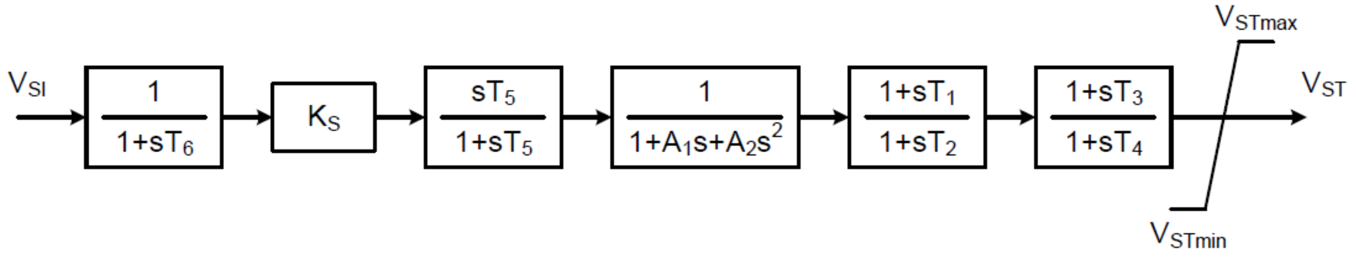


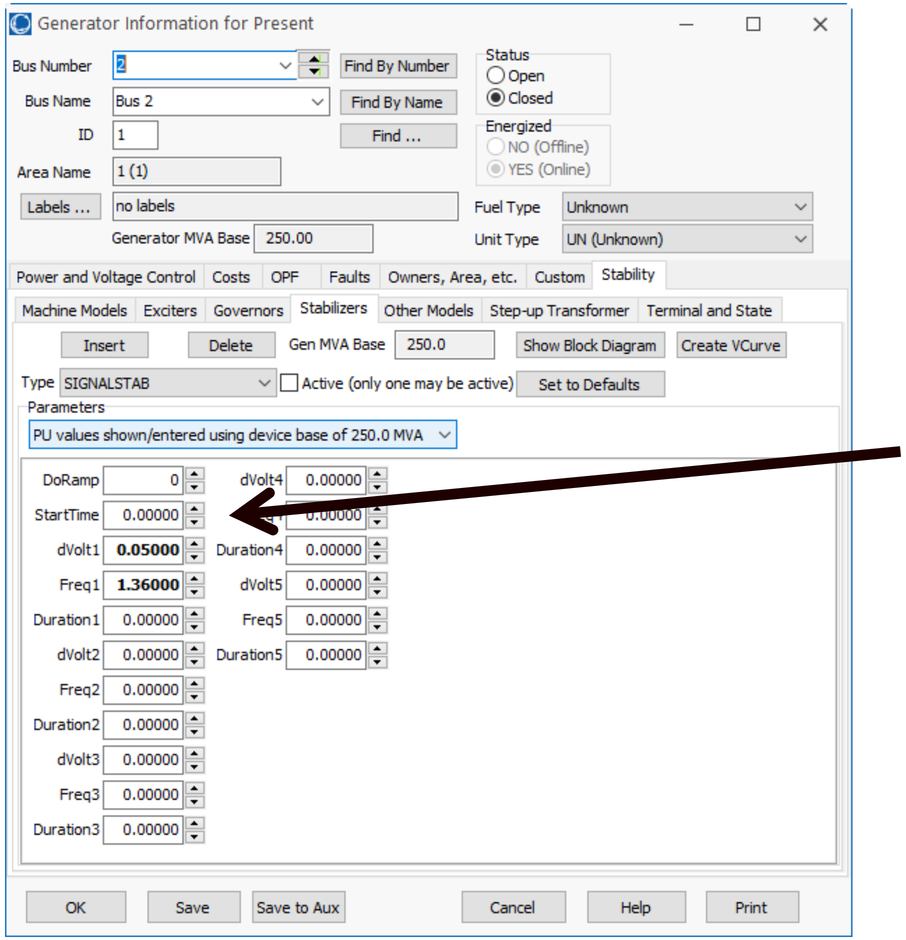
Figure 31 —Type PSS1A single-input power system stabilizer

PSS Example: Using Stabilizer Reference Signals

- PowerWorld now allows reference sinusoidals to be easily played into the stabilizer input
  - This should be done at the desired modal frequency
- Modal analysis can then be used to quickly determine the phase delay between the input and the signal we wish to damp
- Open the case **wscc_9Bus_Stab_Test**
  - This has SignalStab stabilizers modeled at each generator; these models can play in a fixed frequency signal

SignalStab Input and Results

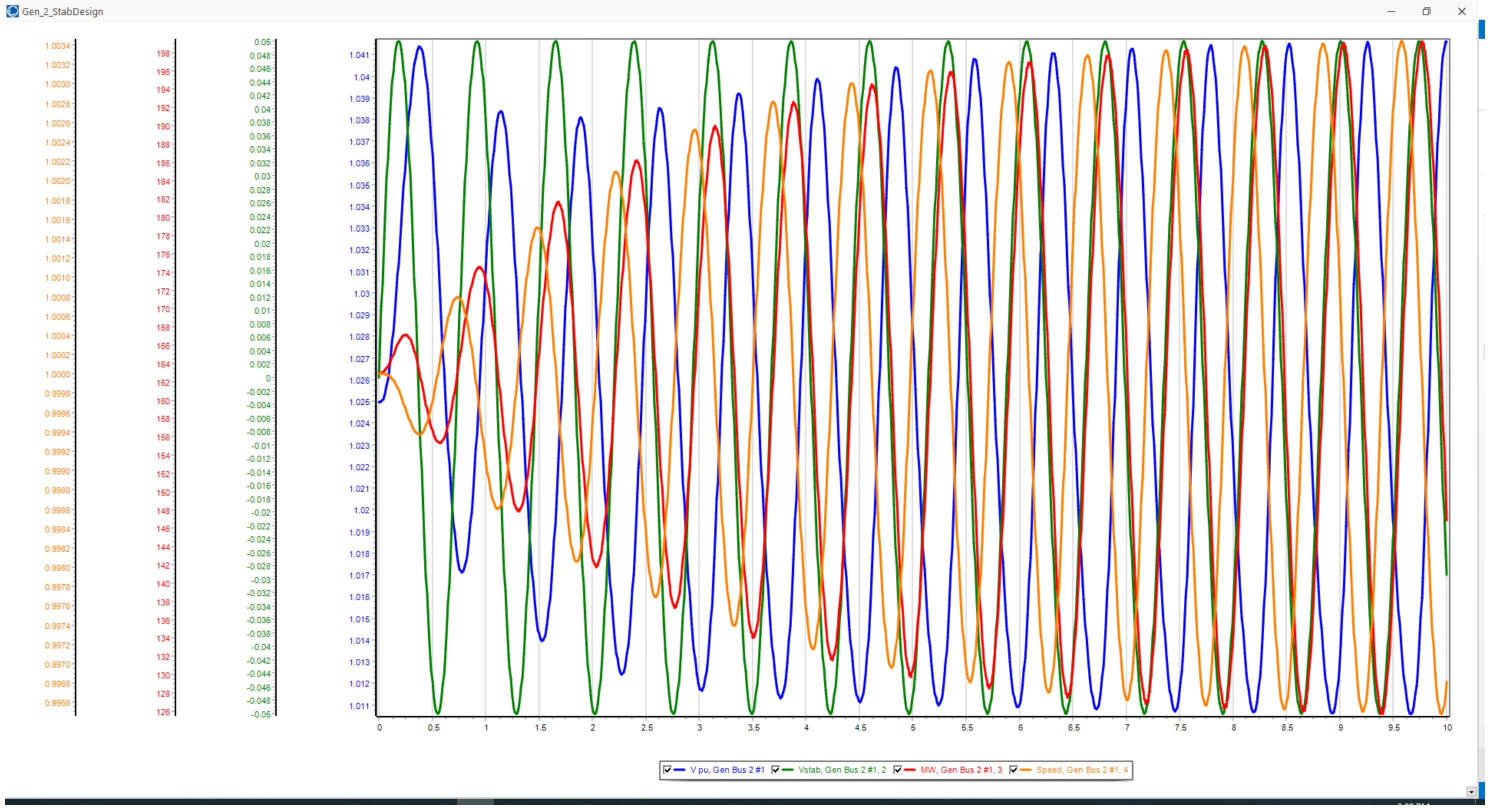
- Enable the SignalStab stabilizer at the bus 2 generator and run the simulation



At time=0 the stabilizer receives a sinusoidal input with a magnitude of 0.05 and a frequency of 1.36 Hz

PSS Example: Gen2 Reference Signal Results

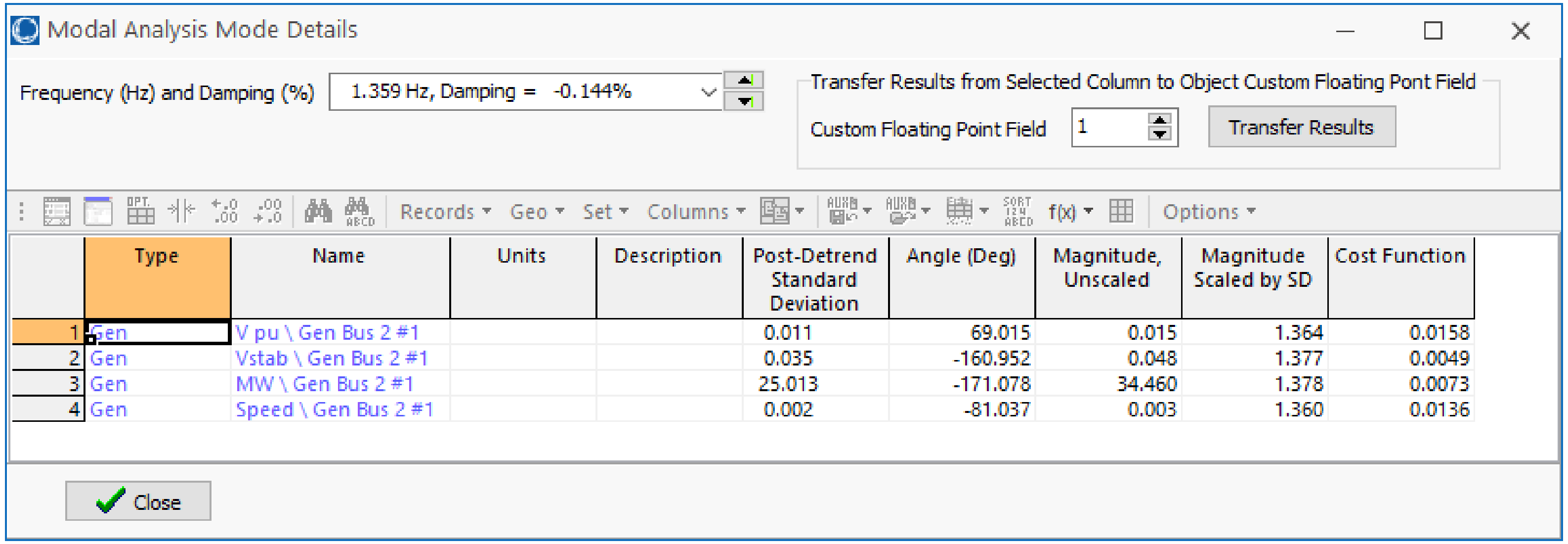
- Graph shows four signals at bus 2, including the stabilizer input and the generator's speed
  - The phase relationships are most important



Use modal analysis to determine the exact phase values for the 1.36 Hz mode; analyze the data between 5 and 10 seconds

PSS Tuning Example: 1.36 Hz Modal Values

- The change in the generator's speed is driven by the stabilizer input sinusoid, so it will be lagging. The below values show is lags by (-161+360) – (-81.0) = 280 degrees
  - Because we want to damp the speed not increased it, subtract off 180 degrees to flip the sign. So we need 100 degrees of compensation; with two lead-lags it is 50 degrees each



	Type	Name	Units	Description	Post-Detrend Standard Deviation	Angle (Deg)	Magnitude, Unscaled	Magnitude Scaled by SD	Cost Function
1	Gen	V pu \ Gen Bus 2 #1			0.011	69.015	0.015	1.364	0.0158
2	Gen	Vstab \ Gen Bus 2 #1			0.035	-160.952	0.048	1.377	0.0049
3	Gen	MW \ Gen Bus 2 #1			25.013	-171.078	34.460	1.378	0.0073
4	Gen	Speed \ Gen Bus 2 #1			0.002	-81.037	0.003	1.360	0.0136

PSS Tuning Example: 1.36 Hz Lead-Lag Values

In designing a lead-lag of the form

$$\frac{1+sT_1}{1+sT_2} = \frac{1+sT_1}{1+s\alpha T_1}$$

to have a specified phase shift of ϕ at a frequency f the value of α is

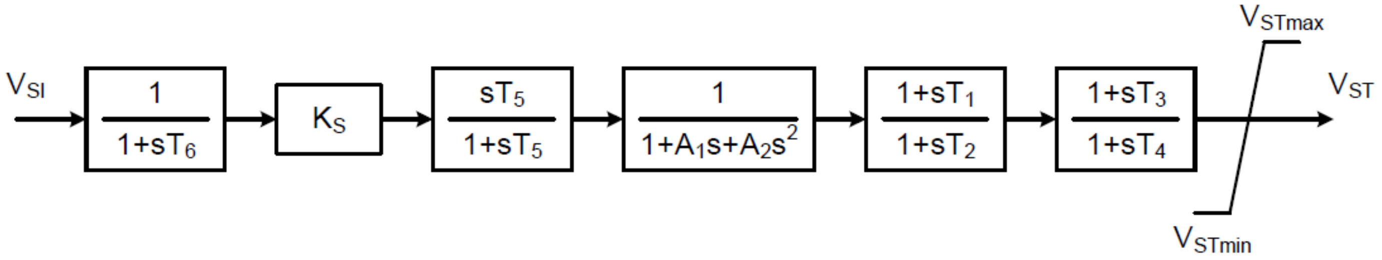
$$\alpha = \frac{1-\sin\phi}{1+\sin\phi},\ T_1 = \frac{1}{2\pi f\sqrt{\alpha}}$$

In our example with $\phi = 50°$ then

$$\frac{1-\sin\phi}{1+\sin\phi} = 0.132,\ T_1 = 0.321,\ \mathrm{T}_2 = \alpha T_1 = 0.042$$

PSS Tuning Example: 1.36 Hz Lead-Lag Values

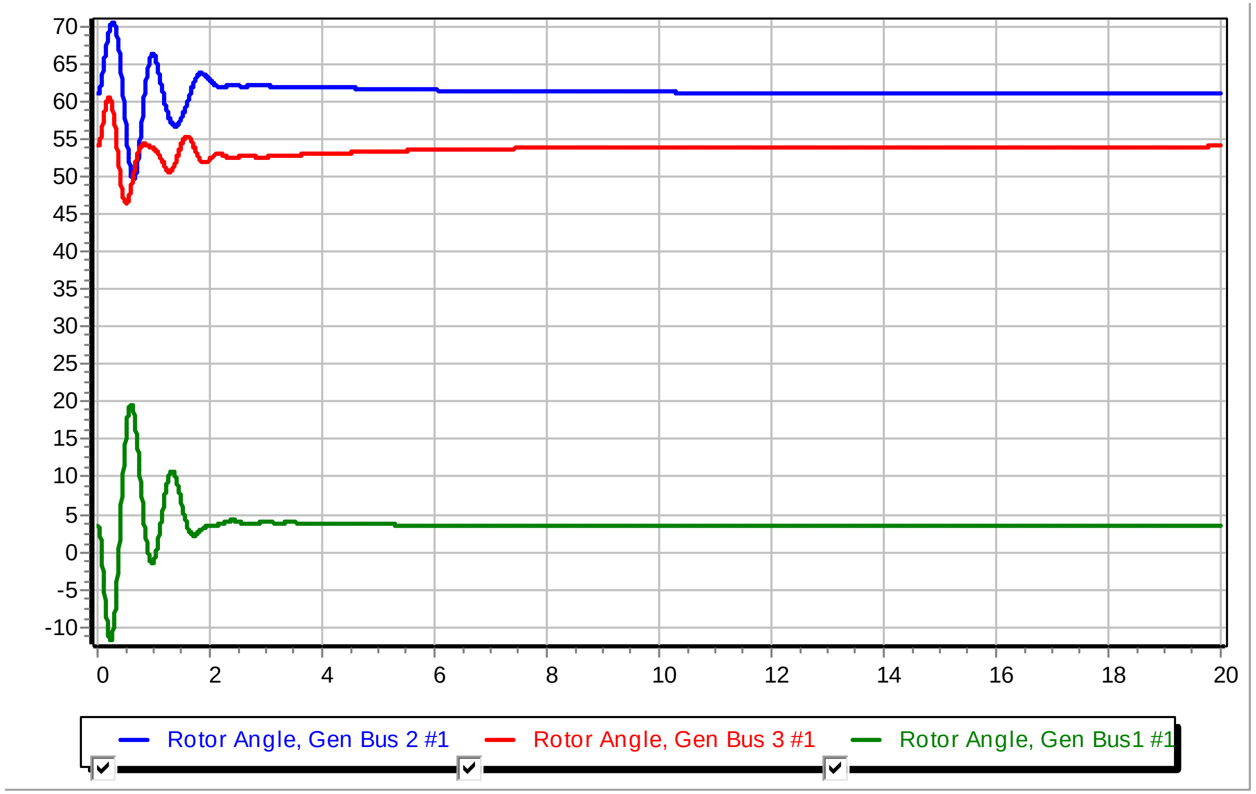
- Hence $T_1=T_3=0.321$, $T_2=T_4=0.042$. We'll assumed $T_6=0$, and $T_5=10$, and $A_1=A_2=0$



- The last step is to determine K_s. This is done by finding the value of K_s at just causes instability (i.e., K_{INST}), and then setting K_s to about 1/3 of this value
  - Instability is easiest to see by plotting the output (V_{ST}) value for the stabilizer

PSS Tuning Example: Setting the Values for Gen 2

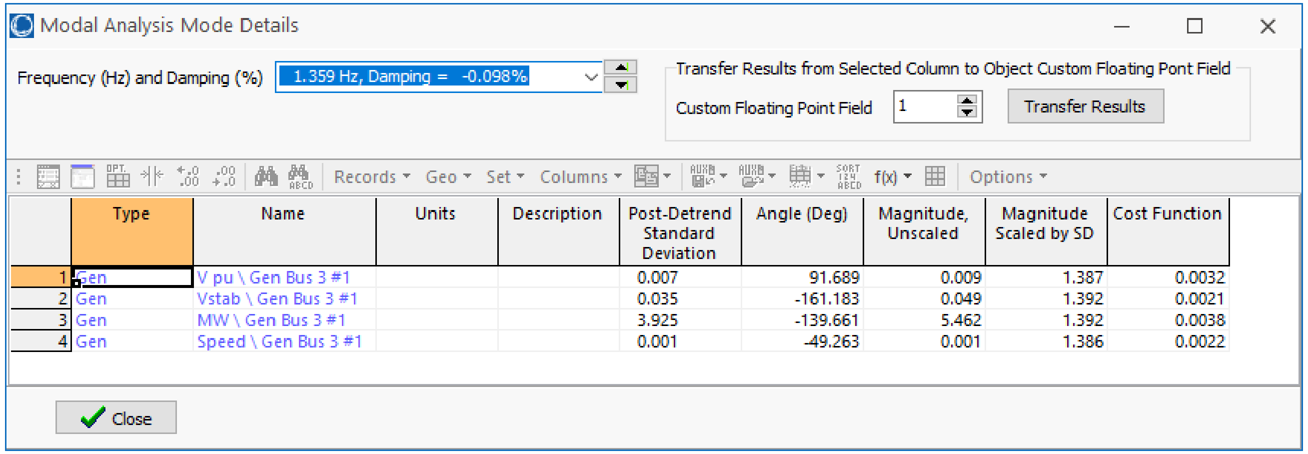
- Instability occurs with KS = 55, hence the optimal value is about 55/3=18.3
- This increases the damping from 5% to about 16.7%



This is saved as case **WSCC_9bus_Stab**

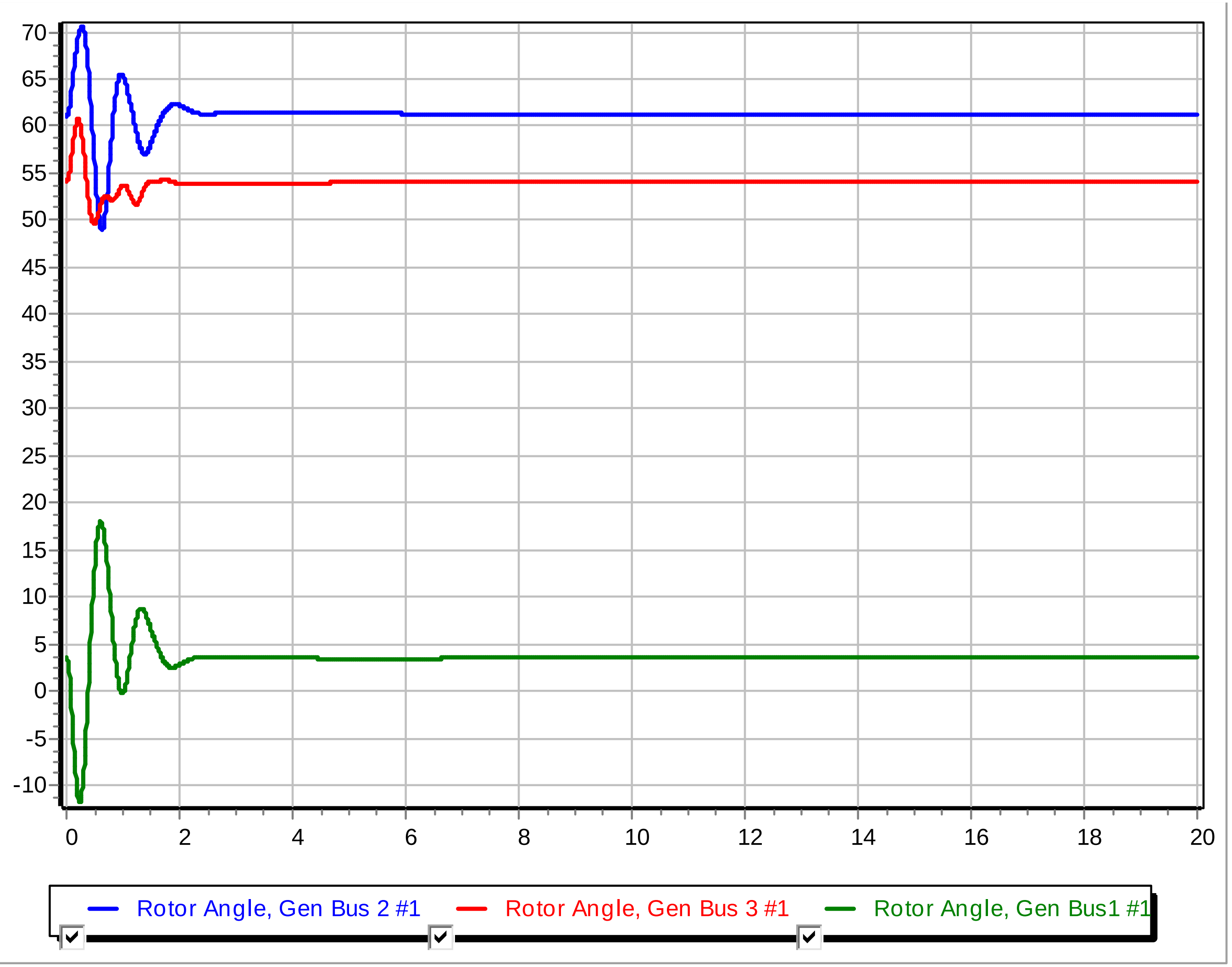
PSS Tuning Example: Setting the Values for Gen 3

- The procedure can be repeated to set the values for the bus 3 generator, where we need a total of 68 degrees of compensation, or 34 per lead-lag



- The values are $\alpha = 0.283$, T_1=0.22, T_2=0.062, K_S for the verge of instability is 36, so K_S optimal is 12.

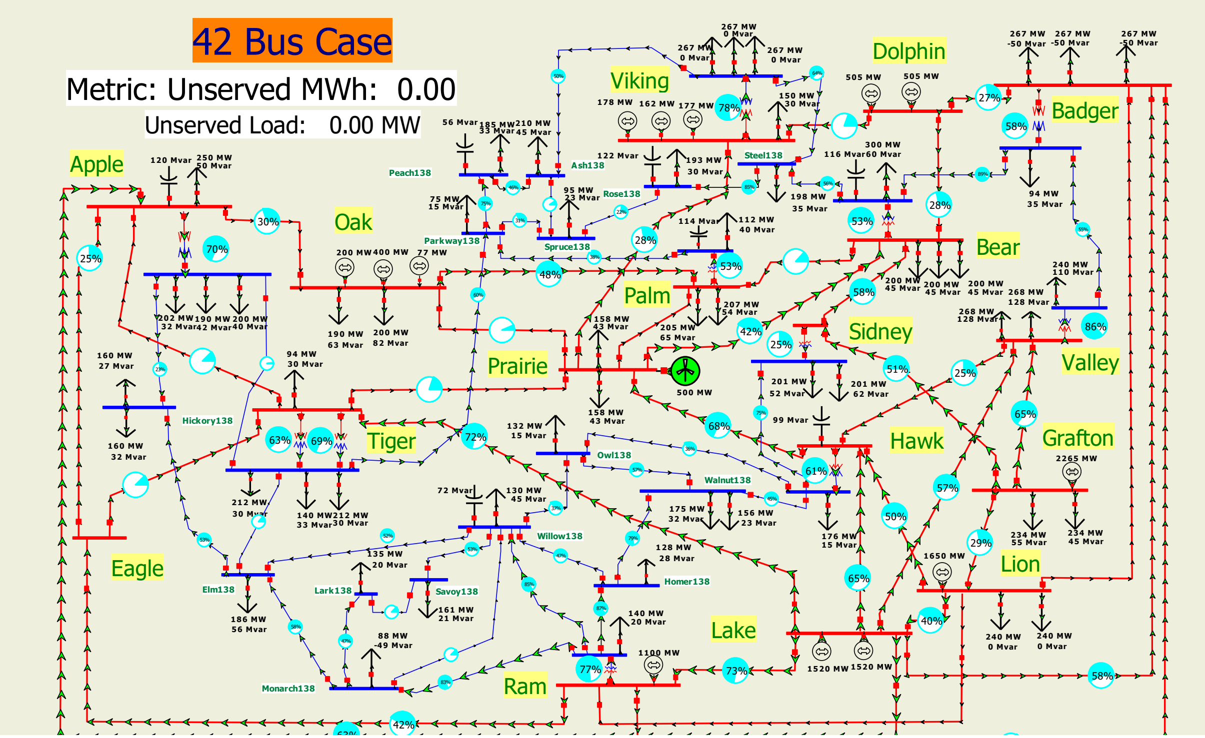
PSS Tuning Example: Final Solution



With stabilizers at buses 2 and 3 the damping has been increased to 25.7%

Example 2: Adding a PSS to a 42 Bus System

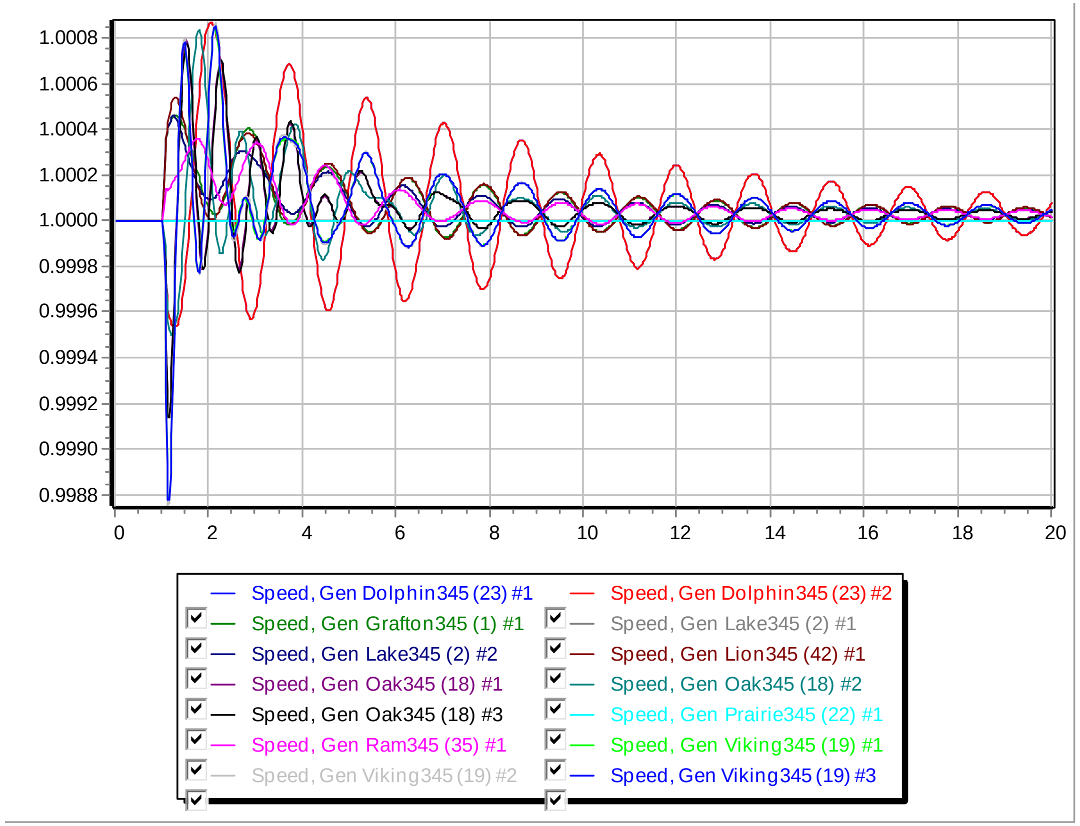
- Goal is to try to improve damping by adding one PSS1A at a large generator at Lion345 (bus 42)
  - Example event is a three-phase fault is applied to the middle of the 345 kV transmission line between Prairie (bus 22) and Hawk (bus 3) with both ends opened at 0.05 seconds

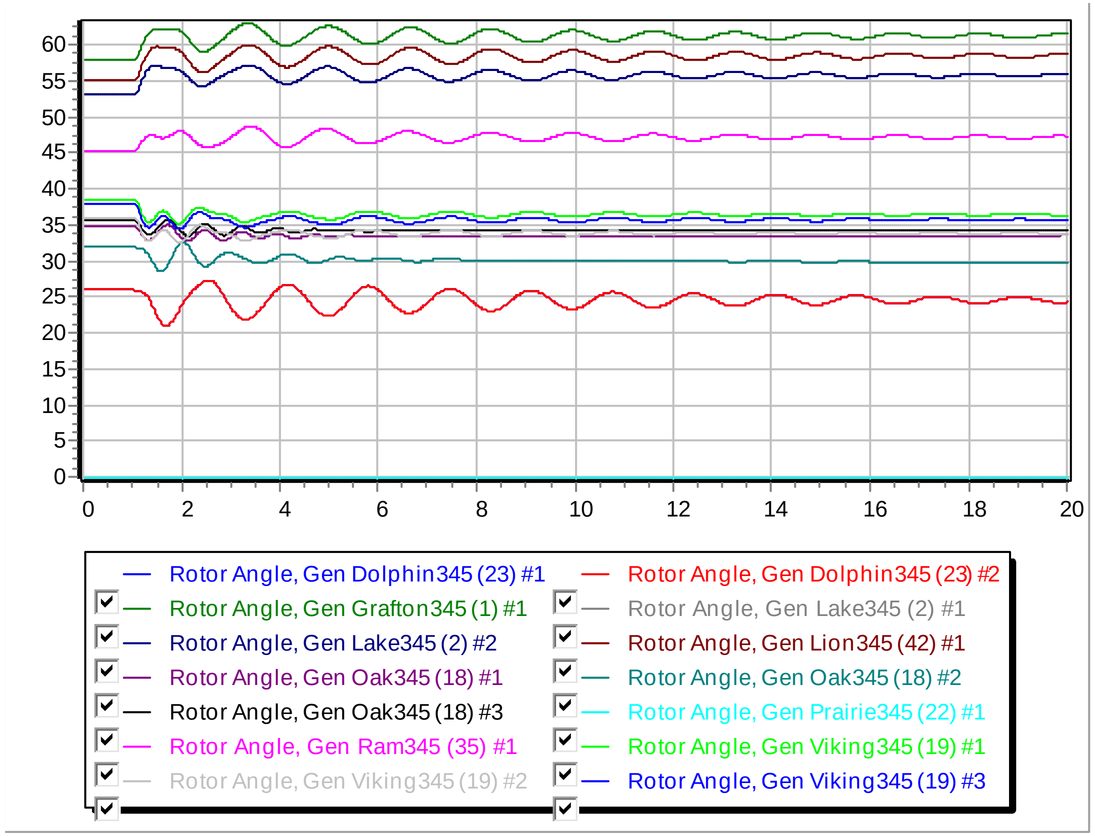


The starting case name is **Bus42_PSS**

Example 2: Decide Generators to Tune, Frequency

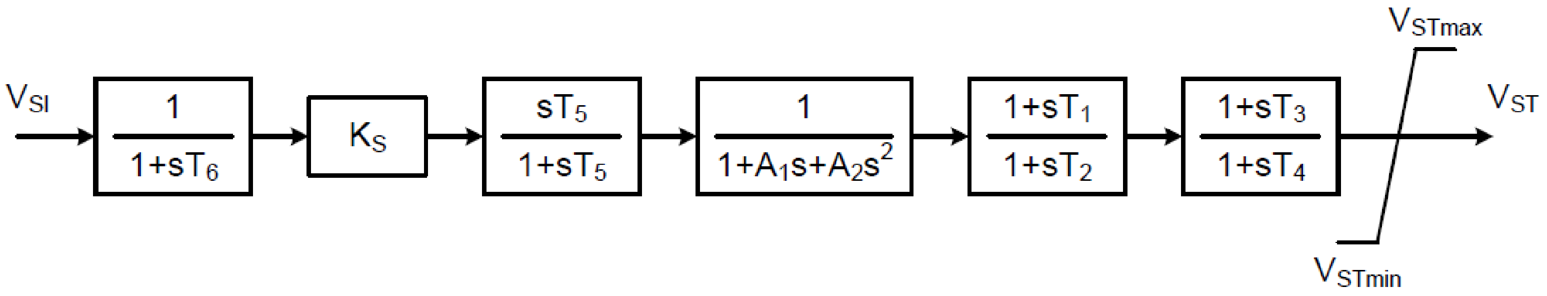
- Generator speeds and rotor angles are observed to have a poorly damped oscillation around 0.6 Hz.





Example 2: Determine Phase Compensation

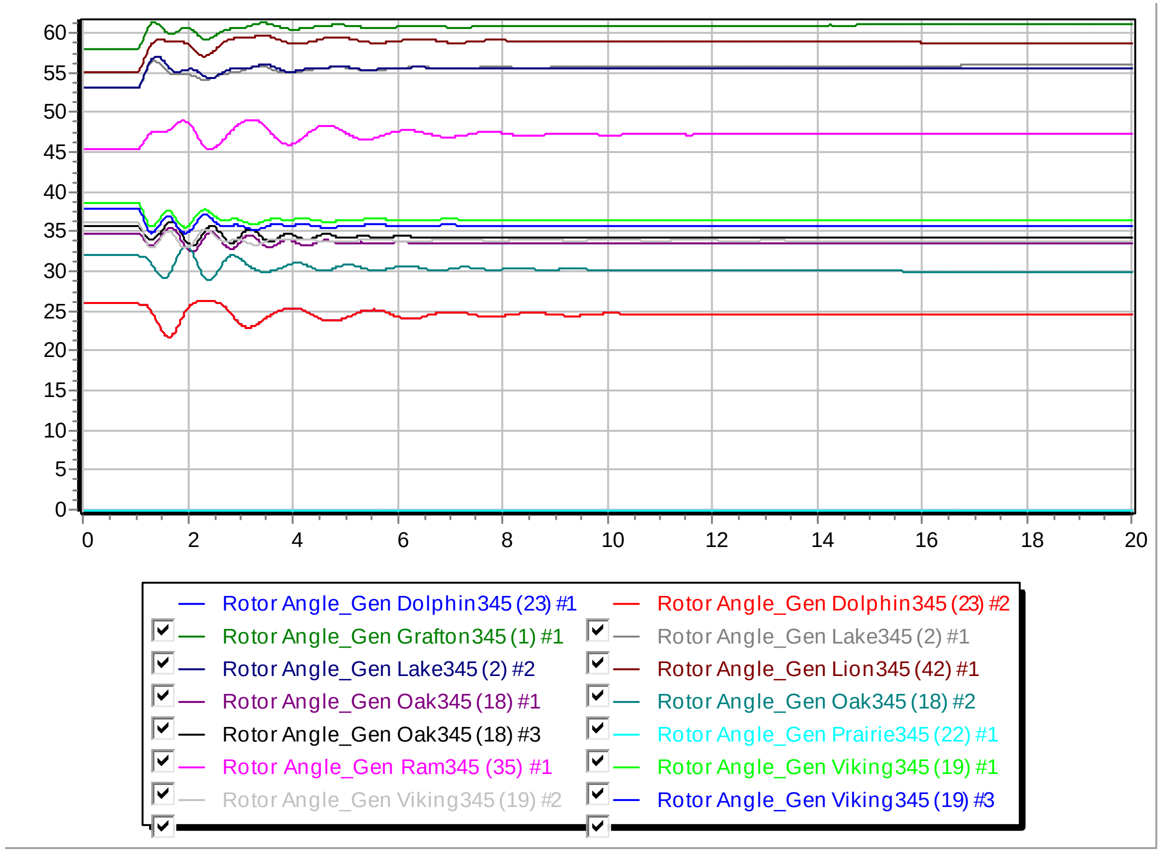
- Using a SignalStabStabilizer at bus 42 (Lion345), the phase lag of the generator's speed, relative to the stabilizer input is 199 degrees; flipping the sign requires phase compensation of 19 degrees or 9.5 per lead-lag
- Values are $\alpha = 0.72$; for 0.6 Hz, $T_1 = 0.313$, $T_2 = 0.225$; set T_3 and T_4 to match; gain at instability is about 450, so the gain is set to 150.



The case with the test signal is **Bus42_PSS_Test**
Adding this single stabilizer increases the damping to 4.24%

Example 2: Determine Phase Compensation for the Other Gens

- Adding and tuning three more stabilizers (at Grafton345 and the two units at Lake345) increases the damping to 8.16%



However, these changes are impacting modes in other areas of the system

Power System Voltage Stability

- **Voltage Stability**: The ability to maintain system voltage so that both power and voltage are controllable. System voltage responds as expected (i.e., an increase in load causes proportional decrease in voltage).
- **Voltage Instability**: Inability to maintain system voltage. System voltage and/or power become uncontrollable. System voltage does not respond as expected.
- **Voltage Collapse**: Process by which voltage instability leads to unacceptably low voltages in a significant portion of the system. Typically results in loss of system load.

Power System Stability Terms

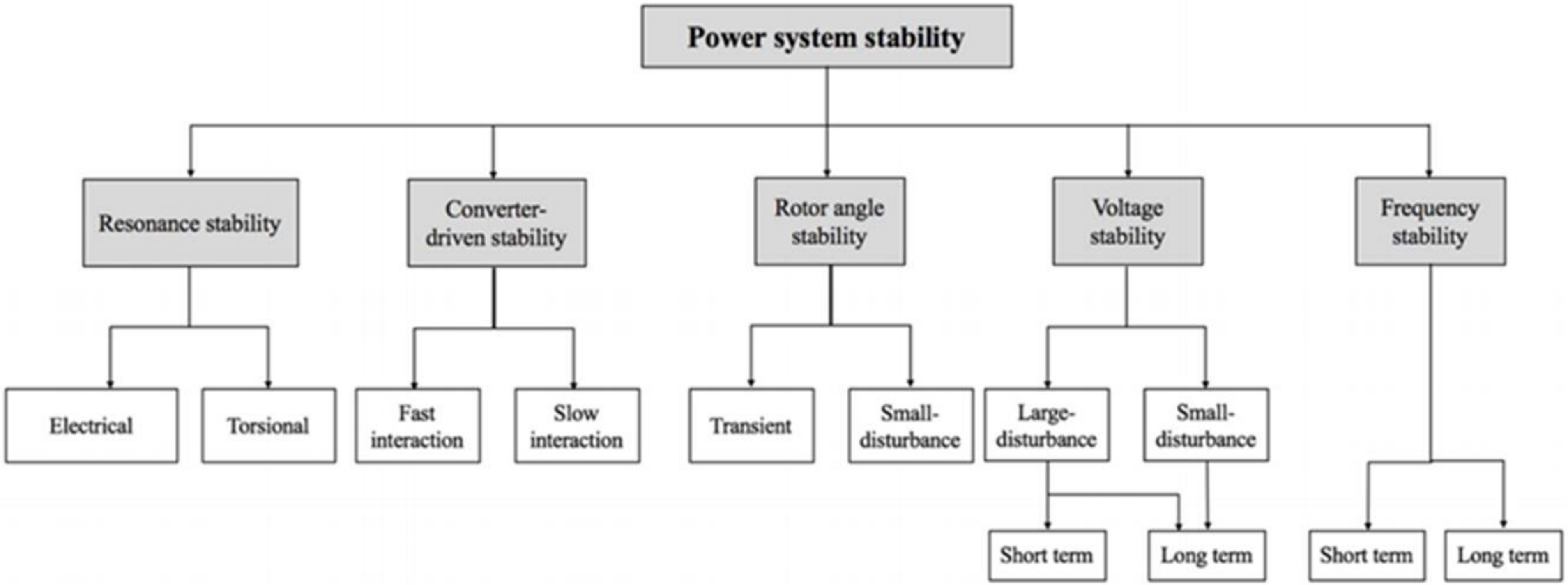
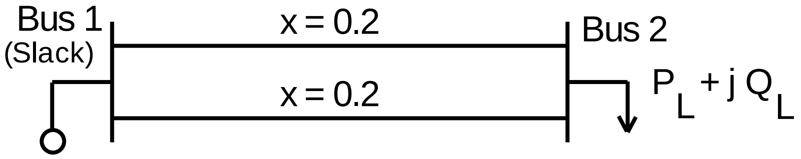


Fig. 4. Classification of power system stability

[a] IEEE/PES Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", PES-TR77, April 2020

Small Disturbance Voltage Stability

- Small disturbance voltage stability can be assessed using a power flow (maximum loadability)
- Depending on the assumed load model, the power flow can have multiple (or no solutions)
- PV curve is created by plotting power versus voltage



Assume V_{slack}=1.0

$$P_L - BV \sin\theta = 0$$

$$Q_L + BV\cos\theta - BV^2 = 0$$

Where B is the line susceptance =-10,
$V\angle\theta$ is the load voltage

Small Disturbance Voltage Stability

- Question: how do the power flow solutions vary as the load is changed?
- A Solution: Calculate a series of power flow solutions for various load levels and see how they change
- Power flow Jacobian

$$\mathbf{J}(\theta,V) = \begin{bmatrix} -BV\cos\theta & -B\sin\theta \\ -BV\sin\theta & B\cos\theta - 2BV \end{bmatrix}$$

$$\det \mathbf{J}(\theta,V) = VB^2\left(2V\cos\theta - \cos^2\theta - \sin^2\theta\right)$$

$$\text{Singular when } \left(2V\cos\theta - 1\right) = 0$$

Maximum Loadability: Singular Power Flow Jacobian

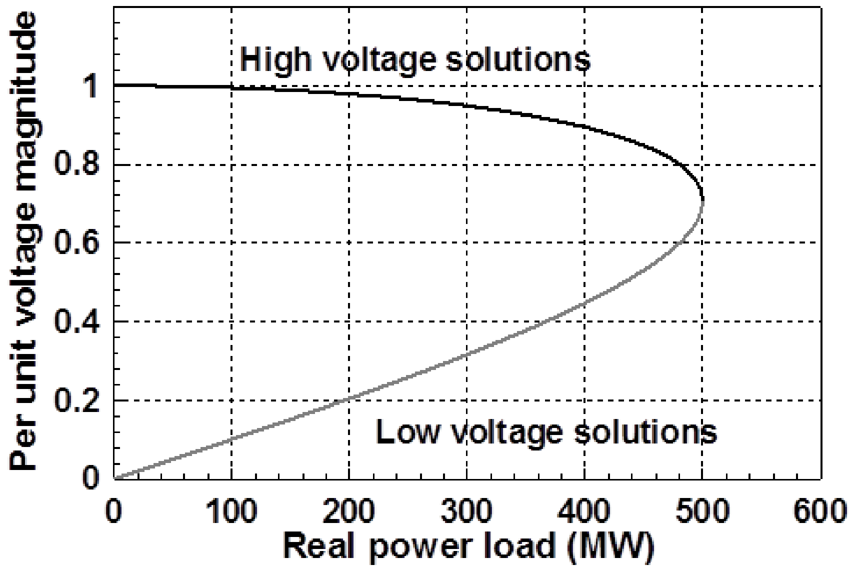
- An important paper considering this was by Sauer and Pai from *IEEE Trans. Power Systems* in Nov 1990, "Power system steady-state stability and the load-flow Jacobian"
- Other earlier papers were looking at the characteristics of multiple power flow solutions
- Work with the power flow optimal multiplier around the same time had shown that optimal multiplier goes to zero as the power flow Jacobian becomes singular
- The power flow Jacobian depends on the assumed load model (we'll see the impact in a few slides)

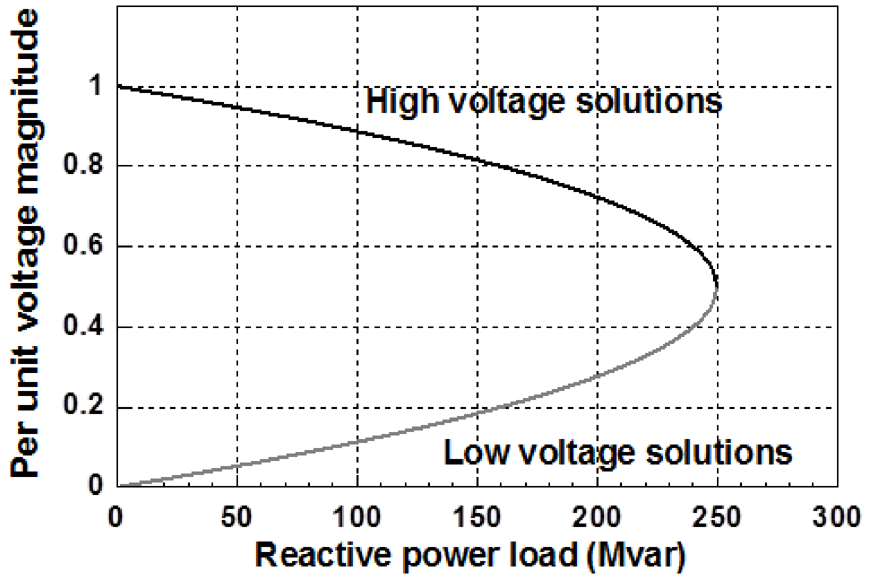
Bifurcations

- In general, bifurcation is the division of something into two branches or parts
- For a dynamic system, a bifurcation occurs when small changes in a parameter cause a new quality of motion of the dynamic system
- Two types of bifurcation are considered for voltage stability
  - Saddle node bifurcation is the disappearance of an equilibrium point for parameter variation; for voltage stability it is two power flow solutions coalescing with parameter variation
  - Hopf bifurcation is cause by two eigenvalues crossing into the right-half plane

PV and QV Curves

- PV curves can be traced by plotting the voltage as the real power is increased; QV curves as reactive power is increased
  - At least for the upper portion of the curve
- Two bus example PV and QV curves

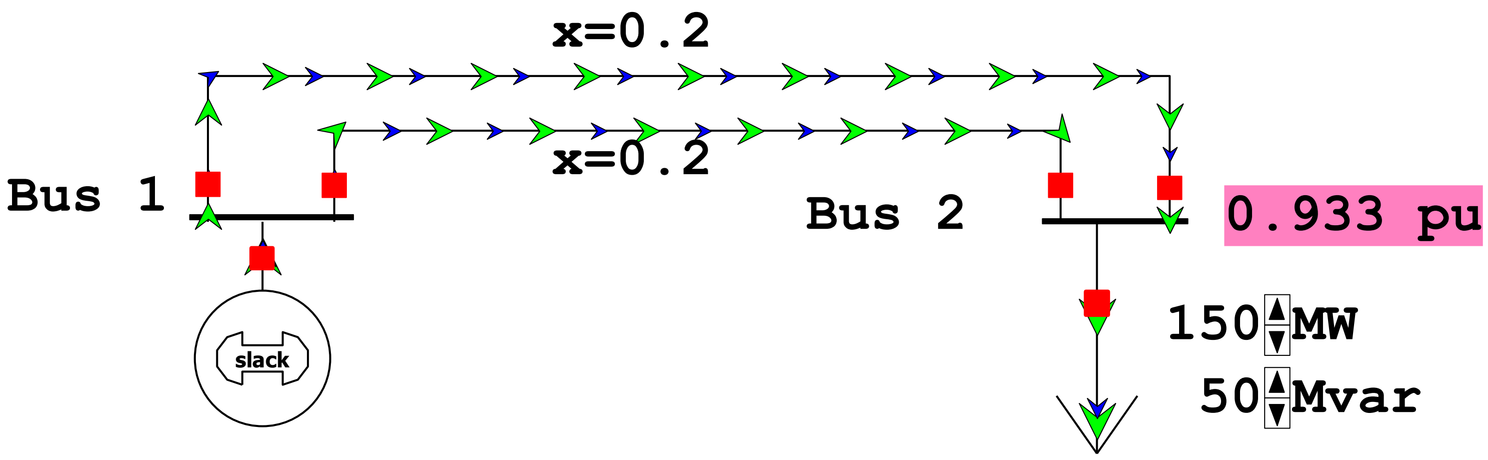


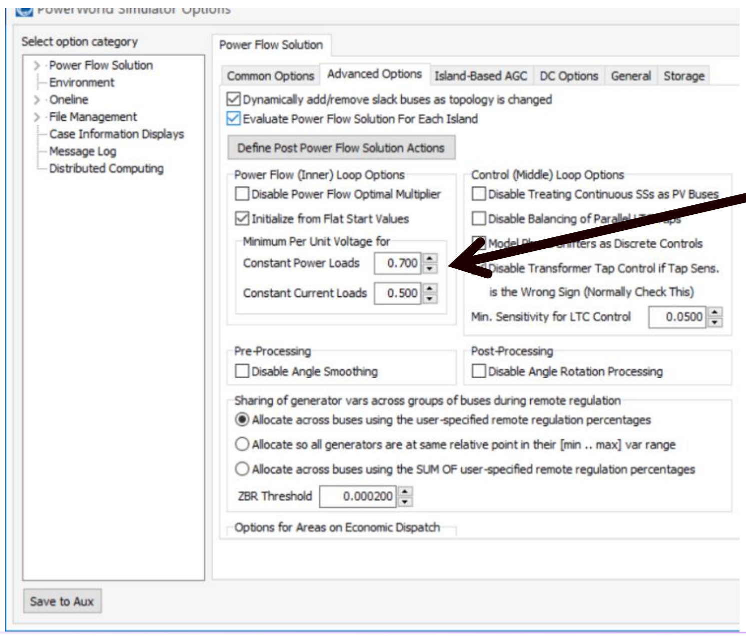


Small Disturbance Voltage Collapse

- At constant frequency (e.g., 60 Hz) the complex power transferred down a transmission line is $S=VI^*$
  - V is phasor voltage, I is phasor current
  - This is the reason for using a high voltage grid
- Line real power losses are given by RI^2 and reactive power losses by XI^2
  - R is the line's resistance, and X its reactance; for a high voltage line X >> R
- Increased reactive power tends to drive down the voltage, which increases the current, which further increases the reactive power losses

PowerWorld Two Bus Example

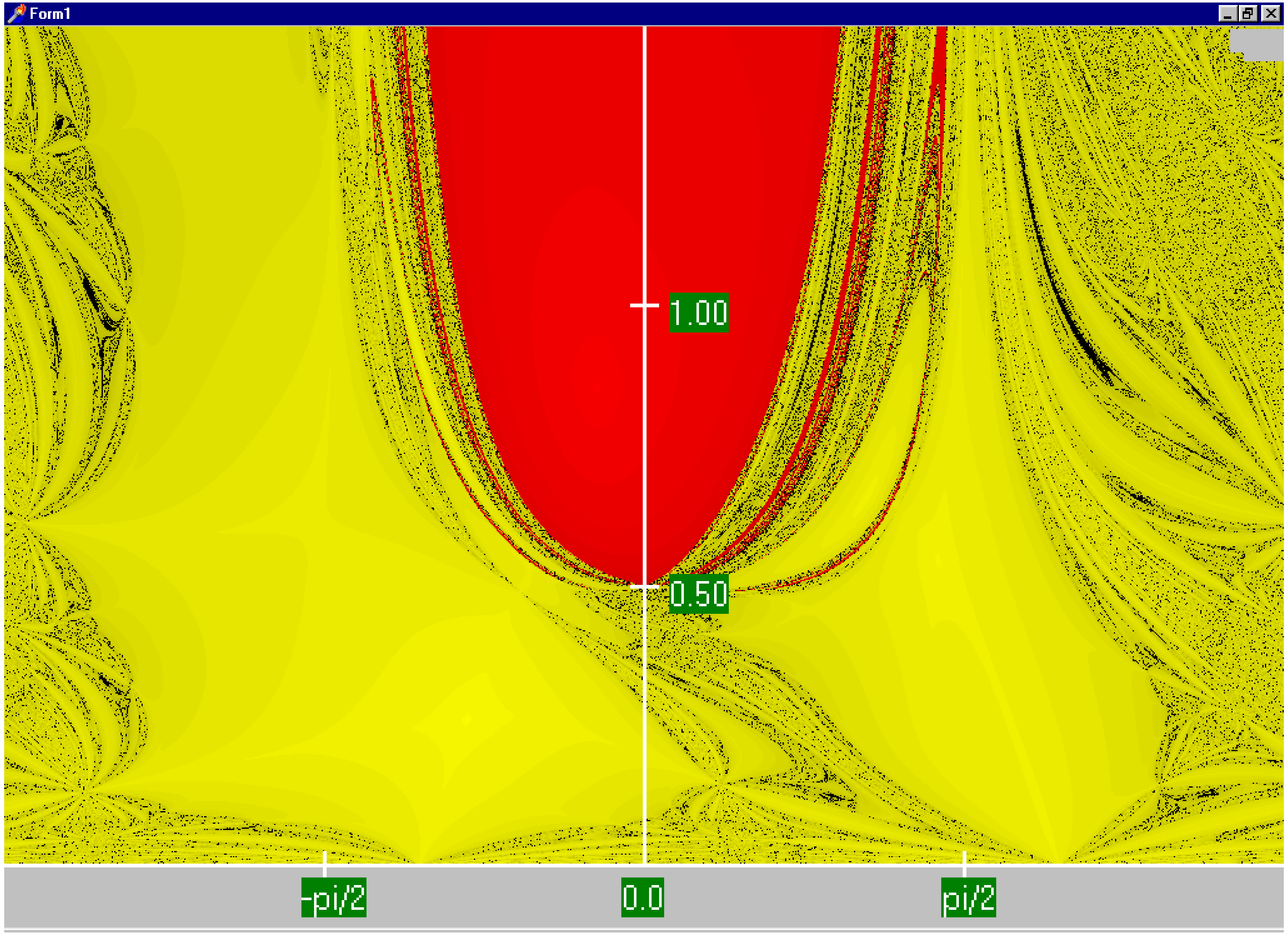




Commercial power flow software usually auto converts constant power loads at low voltages; set these fields to zero to disable this conversion

Case is **Bus2_PV**

Power Flow Region of Convergence

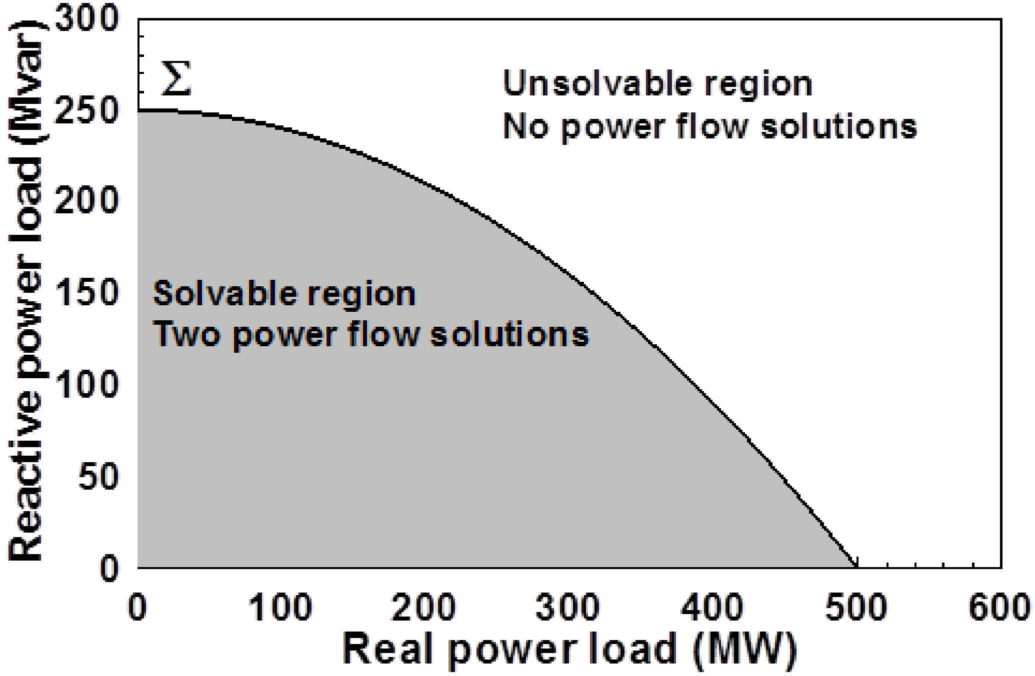


Convergence regions with P=100 MW, Q=0 Mvar

Load Parameter Space Representation

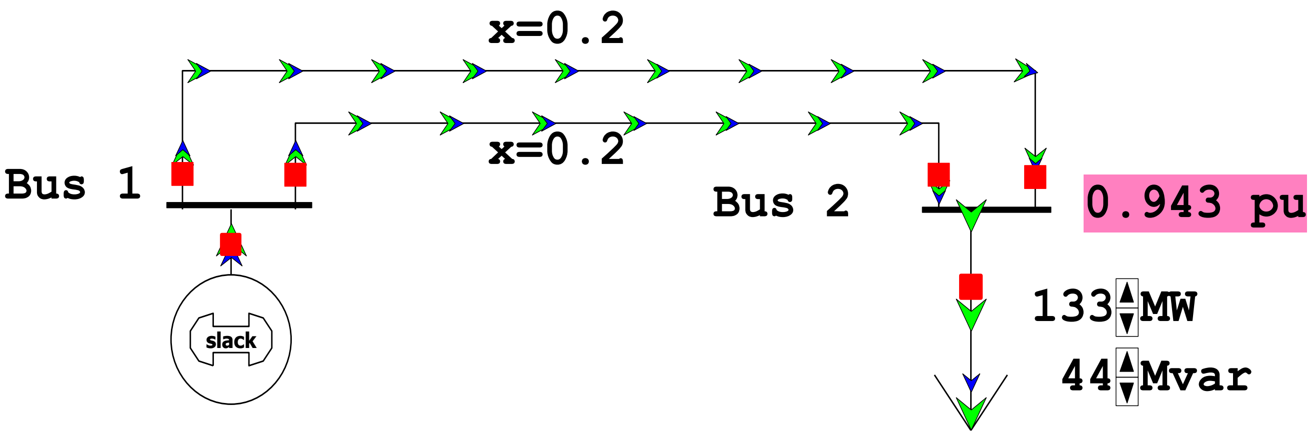
- With a constant power model there is a maximum loadability surface, Σ
  - Defined as point in which the power flow Jacobian is singular
  - For the lossless two bus system it can be determined as

$$-\frac{P_L^2}{B}+Q_L+\frac{1}{4}B=0$$



Load Model Impact

- With a static load model regardless of the voltage dependency the same PV curve is traced
  - But whether a point of maximum loadability exists depends on the assumed load model
    - If voltage exponent is > 1 then multiple solutions do not exist (see B.C. Lesieutre, P.W. Sauer and M.A. Pai "Sufficient conditions on static load models for network solvability," NAPS 1992, pp. 262-271)



Change the load to constant impedance; hence it becomes a linear model

Application: Conservation Voltage Reduction (CVR)

- If the “steady-state” load has a true dependence on voltage, then a change (usually a reduction) in the voltage should result in a total decrease in energy consumption
- If an “optimal” voltage could be determined, then this could result in a net energy savings
- Some challenges are 1) the voltage profile across a feeder is not constant, 2) the load composition is constantly changing, 3) a decrease in power consumption might result in a decrease in useable output from the load, and 4) loads are dynamic and an initial decrease might be balanced by a later increase

CVR Issues

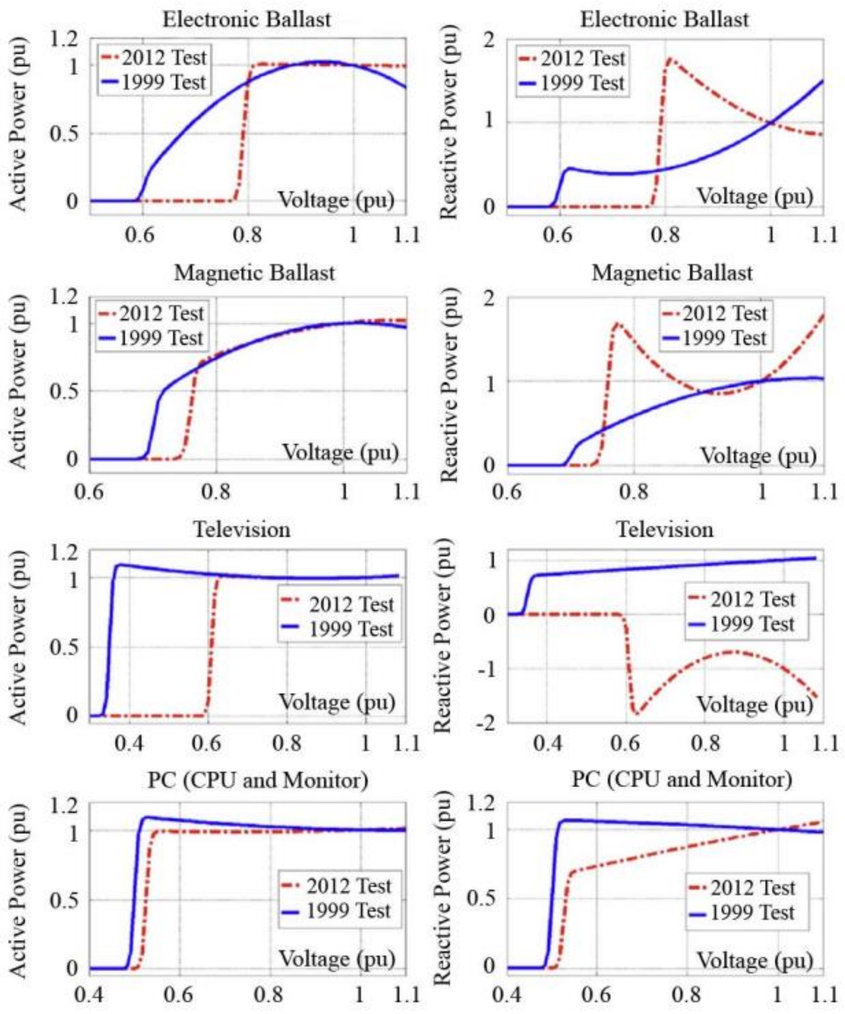
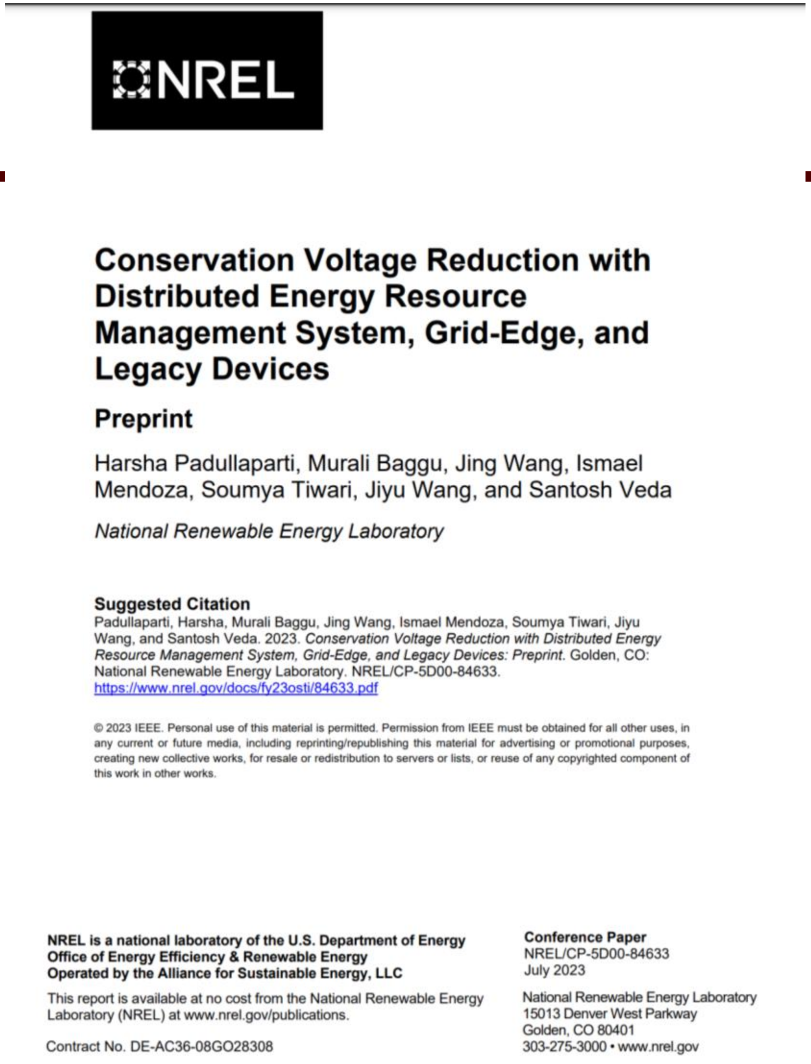


Fig. 4. Comparison of active and reactive powers between old and new appliances.



NREL

Conservation Voltage Reduction with Distributed Energy Resource Management System, Grid-Edge, and Legacy Devices

Preprint

Harsha Padullaparti, Murali Baggu, Jing Wang, Ismael Mendoza, Soumya Tiwari, Jiyu Wang, and Santosh Veda

National Renewable Energy Laboratory

Suggested Citation
Padullaparti, Harsha, Murali Baggu, Jing Wang, Ismael Mendoza, Soumya Tiwari, Jiyu Wang, and Santosh Veda. 2023. *Conservation Voltage Reduction with Distributed Energy Resource Management System, Grid-Edge, and Legacy Devices: Preprint.* Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-84633. https://www.nrel.gov/docs/fy23osti/84633.pdf

© 2023 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-84633
July 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

The gist of the 2023 NREL paper is distributed generation (like PV) can help with CVR through better feeder voltage regulation

Figure 4 from A, Bokhari, et. al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," *IEEE Trans. Power Delivery*, June. 2014

Dynamic Load Response

- As first reported in the below paper, following a change in voltage there will be a dynamic load response
  - Residential supply voltage should be between 114 and 126 V
- If there is a heating load the response might be on the order of ten minutes
- Longer term issues can also come into play

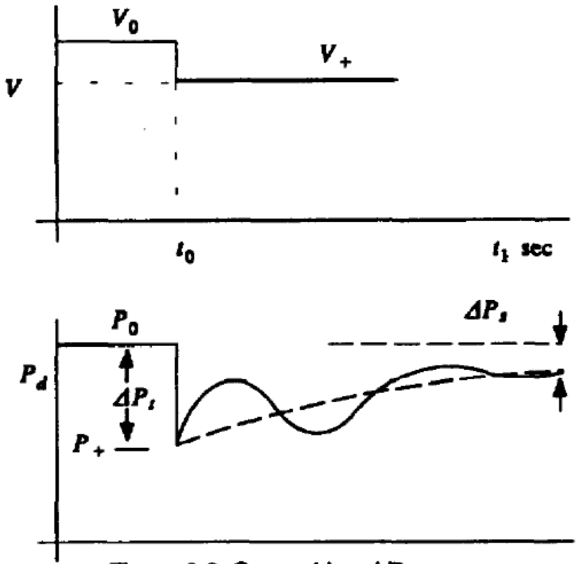


Figure 2.2 General Load Response

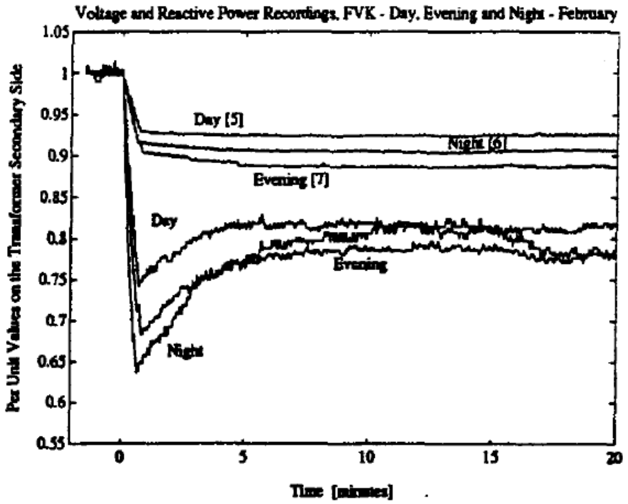
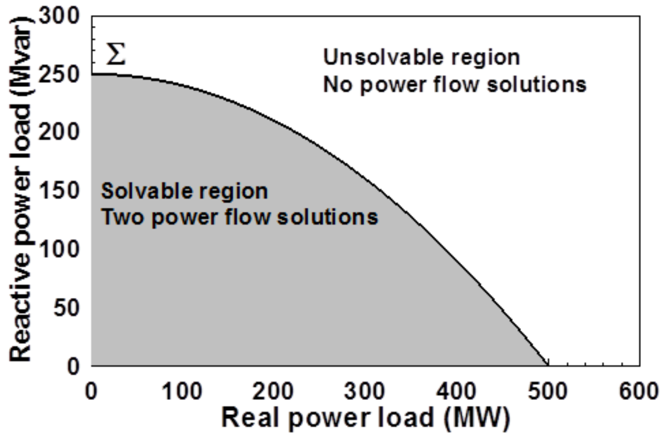


Figure 4.4b. Voltage and reactive power recordings after a voltage reduction in FVK: February: day, evening and night. The number of tap-changer steps used for the ramp is shown in brackets.

Useful paper and figure reference: D. Karlsson, D.J. Hill, “Modeling and Identification of Nonlinear Dynamic Loads in Power Systems,” IEEE. Trans. on Power Systems, Feb 1994, pp. 157-166

Determining a Metric to Voltage Collapse

- The goal of much of the voltage stability work was to determine an easy way to calculate a metric (or metrics) of the current operating point to voltage collapse
  - PV and QV curves (or some combination) can determine such a metric along a particular path
  - Goal was to have a path independent metric. The closest boundary point was considered, but this could be quite misleading if the system was not going to move in that direction



  - Any linearization about the current operating point (i.e., the Jacobian) does not consider important nonlinearities like generators hitting their reactive power limits

Assessing Voltage Margin Using PV and QV Curve Analysis

- A common method for assessing the distance in parameter space to voltage instability (or an undesirable voltage profile) is to trace how the voltage magnitudes vary as the system parameters (such as the loads) are changed in a specified direction
  - If the direction involves changing the real power (P) this is known as a PV curve; if the change is with the reactive power (Q) then this is a QV curve
- PV/QV curve analysis can be generalized to any parameter change, and can include the consideration of contingencies

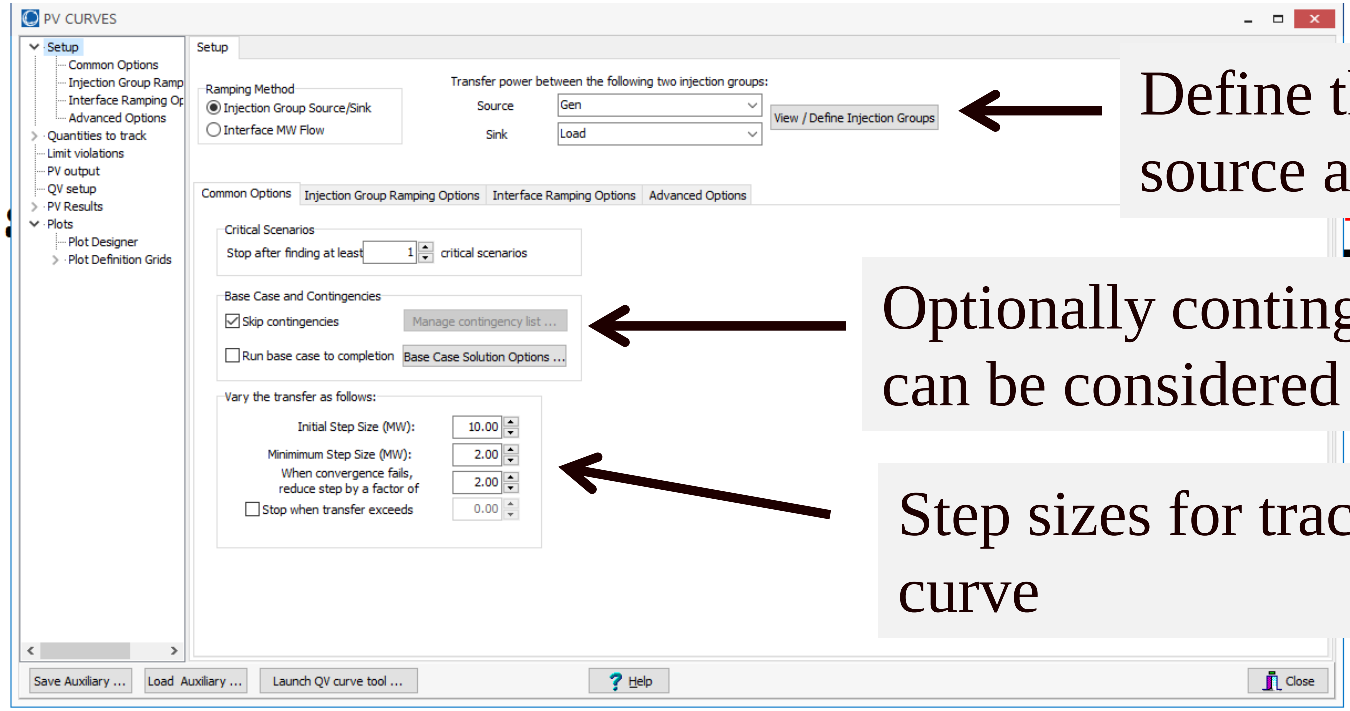
PV and QV Analysis in PowerWorld

- Requires setting up what is known in PowerWorld as an injection group
  - An injection group specifies a set of objects, such as generators and loads, that can inject or absorb power
  - Injection groups can be defined by selecting **Case Information, Aggregation, Injection Groups**
- The PV and/or QV analysis then varies the injections in the injection group, tracing out the PV curve
- This allows optional consideration of contingencies
- The PV tool can be displayed by selecting **Add-Ons, PV**

This has already been done in the **Bus2_PV** case

PV and QV Analysis in PowerWorld: Two Bus Example

- Setup page defines the source and sink and step size



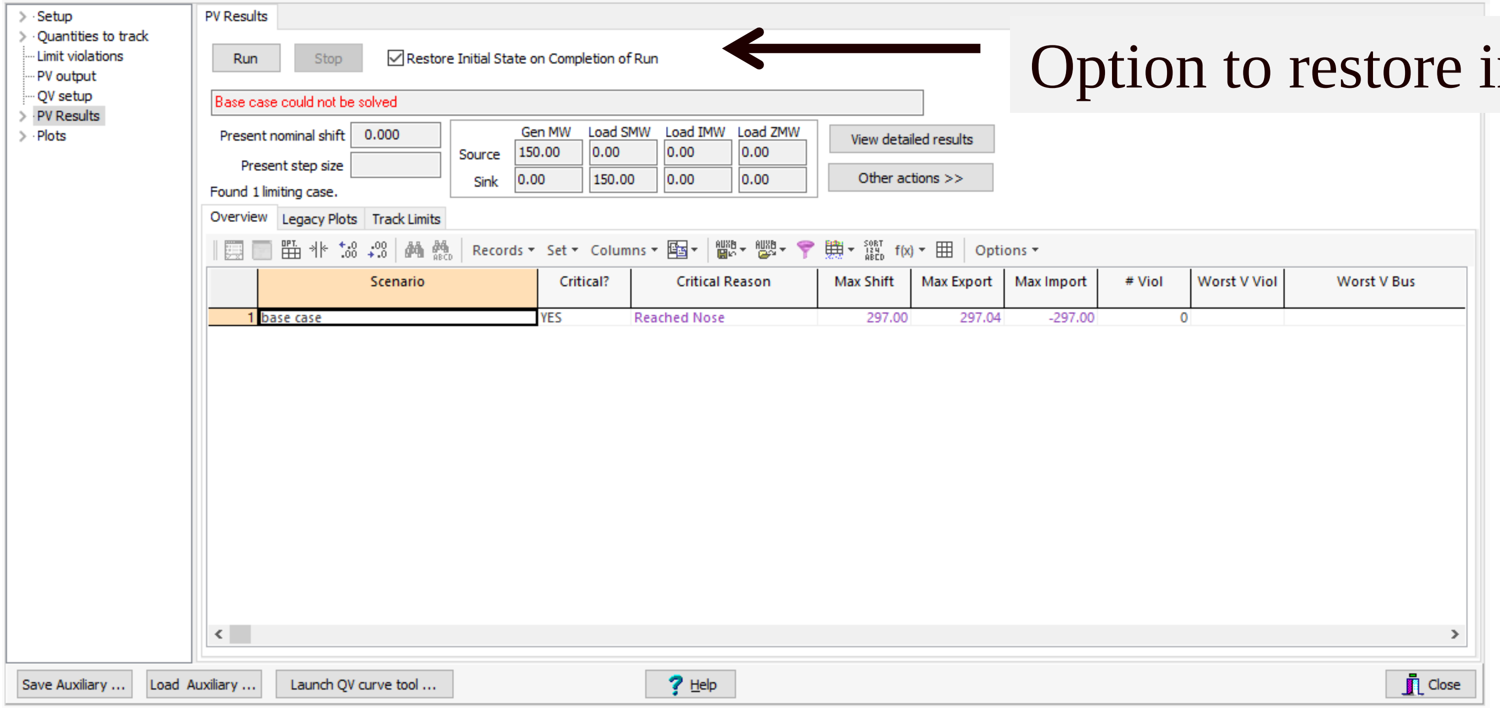
Define the source and sink

Optionally contingencies can be considered

Step sizes for tracing the curve

PV and QV Analysis in PowerWorld: Two Bus Example

- The PV Results Page does the actual solution
  - Plots can be defined to show the results
    - This should be done beforehand
  - **Other Actions, Restore initial state** restores the pre-study state

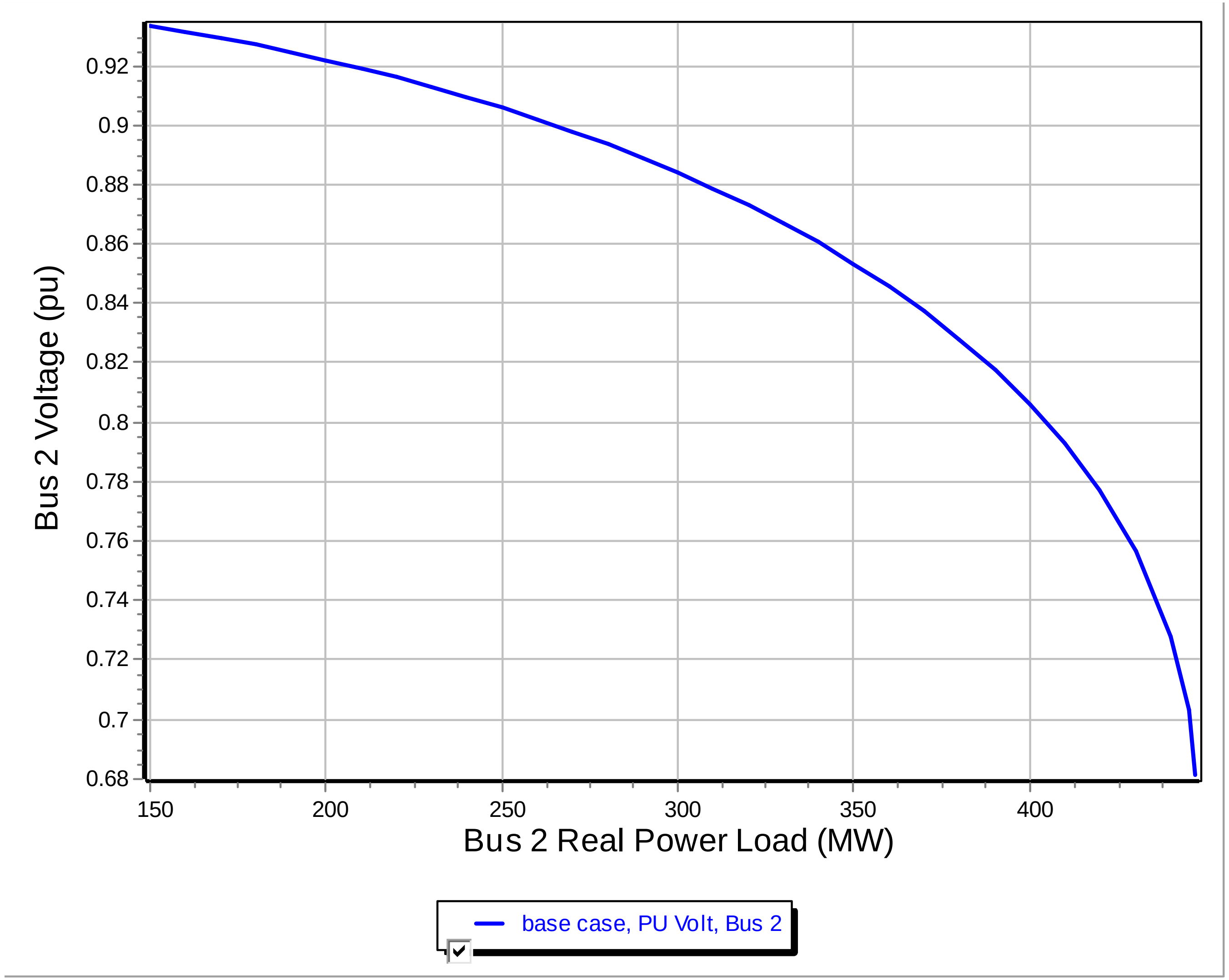


Option to restore initial state

Click the **Run** button to run the PV analysis;

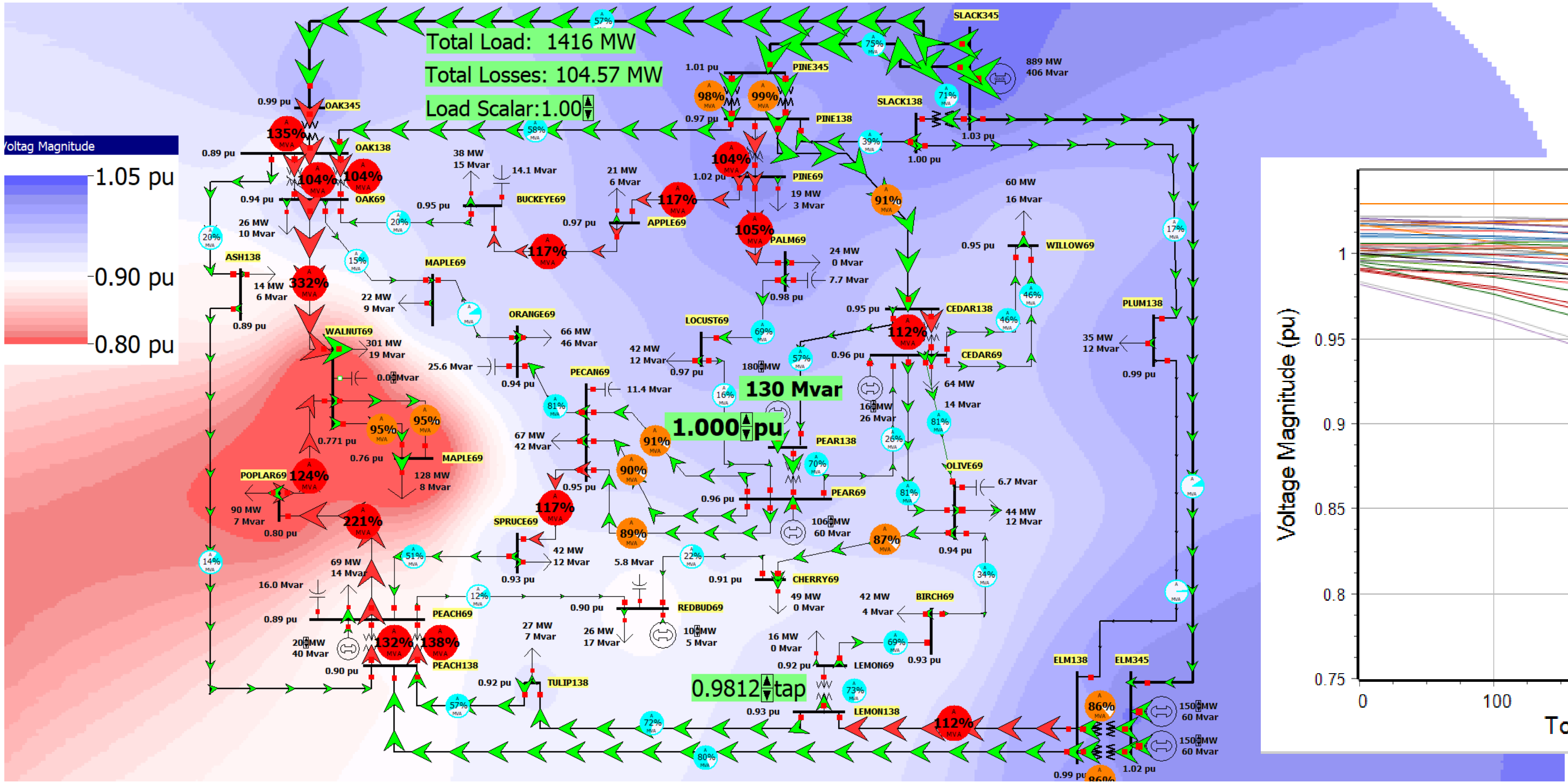
Check the **Restore Initial State on Completion of Run** to restore the pre-PV state (by default it is not restored)

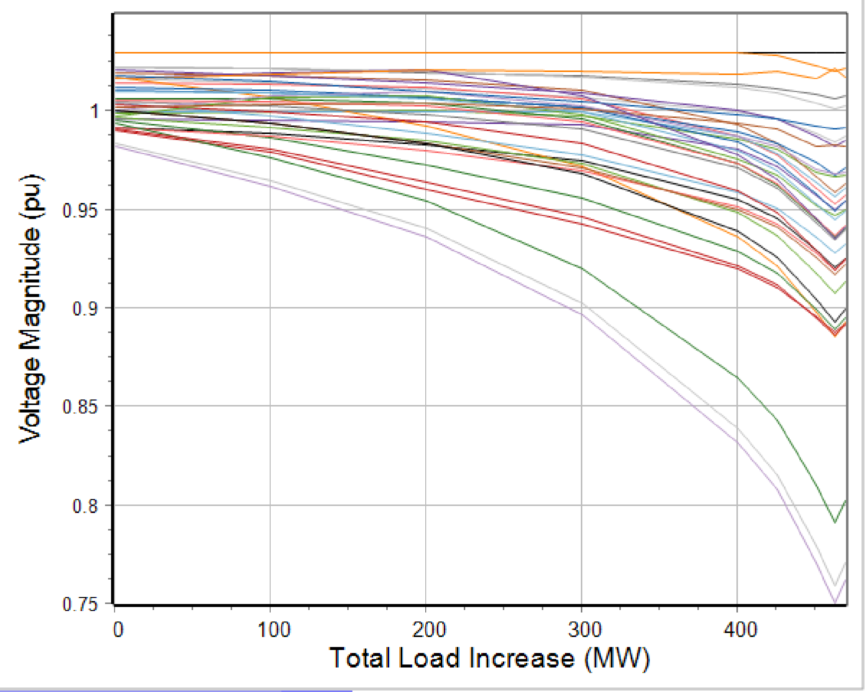
PV and QV Analysis in PowerWorld: Two Bus Example



To restore the starting case, on the **PV Results** page select **Other Actions, Restore Initial State**

PV and QV Analysis in PowerWorld: 37 Bus Example





Usually other limits also need to be considered in doing a realistic PV analysis; example case is **Bus37_PV**

Shorter Term Dynamics

- On a shorter time-scale (minutes down to seconds) voltage stability is impacted by controls hitting limits (such as the action of generator over excitation limiters), the movement of voltage control devices (such as LTC transformers) and load dynamics
  - Motor stalling can have a major impact
- The potential for voltage instability can be quantified by looking at the amount and duration of voltage dips following an event

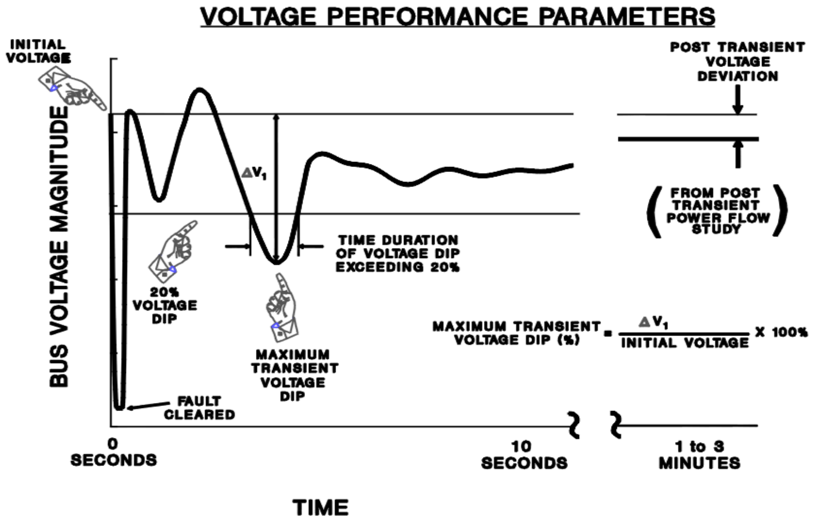


Image from WECC Planning and Operating Criteria

Fault Induced Delayed Voltage Recovery (FIDVR)

- FIDVR is a situation in which the system voltage remains significantly reduced for at least several seconds following a fault (at either the transmission or distribution level)
  - It is most concerning in the high voltage grid, but found to be unexpectedly prevalent in the distribution system
- Stalled residential air conditioning units are a key cause of FIDVR – they can stall within the three cycles needed to clear a fault

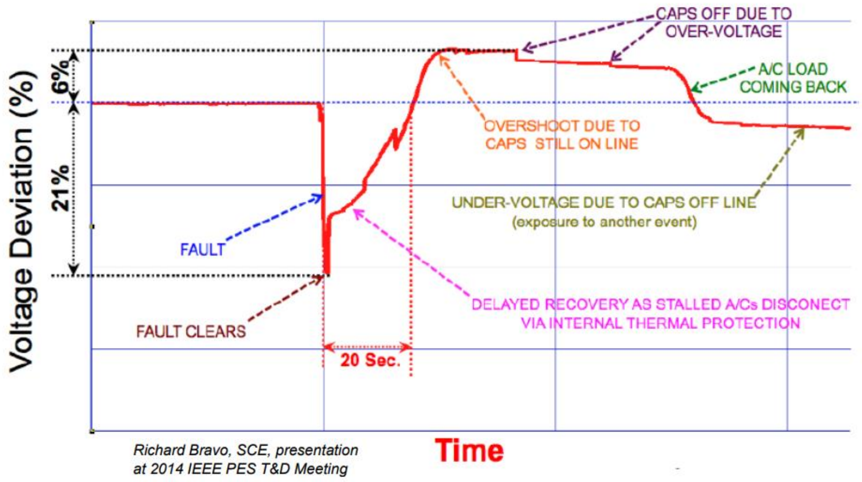


Image Source: NERC, Fault Induced Delayed Voltage Recovery (FIDVR) Advisory, July 2015