ECEN 667
Power System Stability

Lecture 25: Power System Stabilizers

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Announcements

- Read Chapter 9
- Homework 6 is due on Tuesday December 3
- Final is at scheduled time here (December 9 from1pm to 3pm)

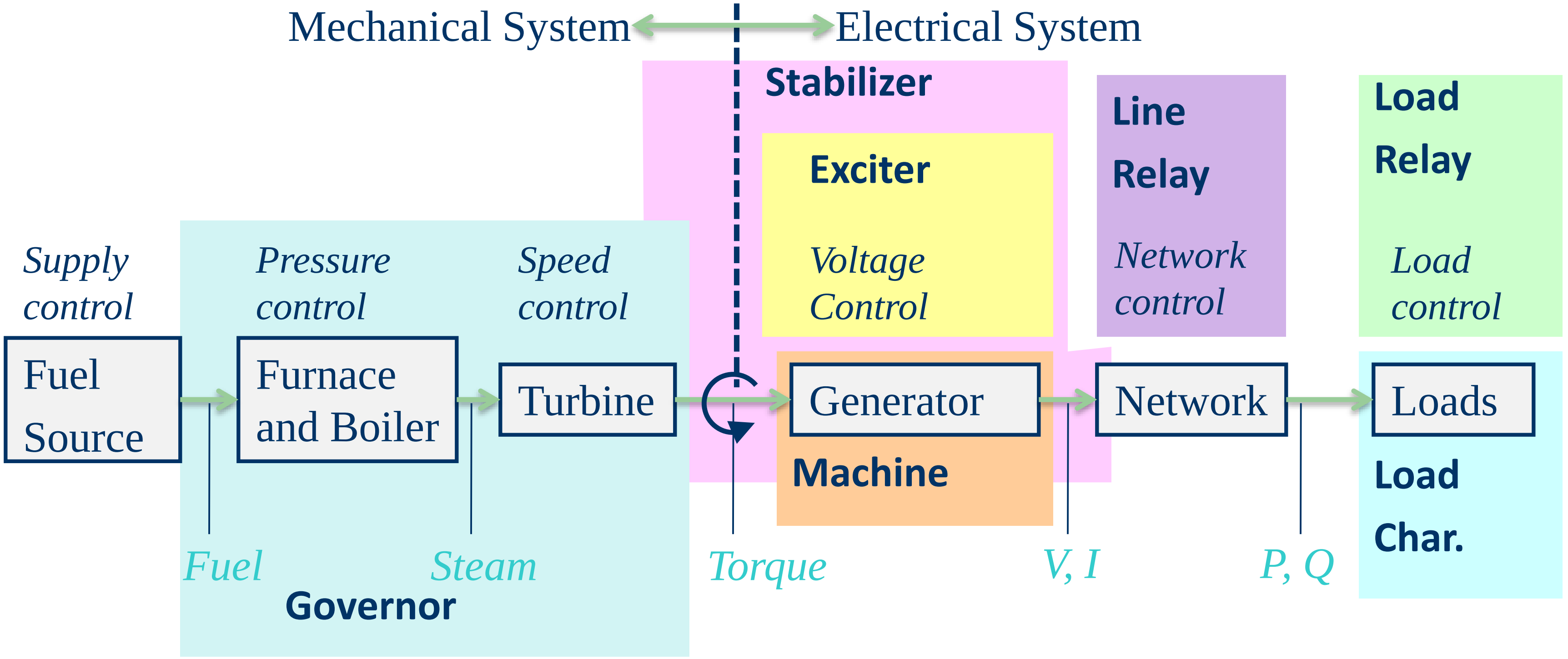
Damping Oscillations: Power System Stabilizers (PSSs)

- A PSS adds a signal to the excitation system to improve the generator’s 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

Stabilizer References

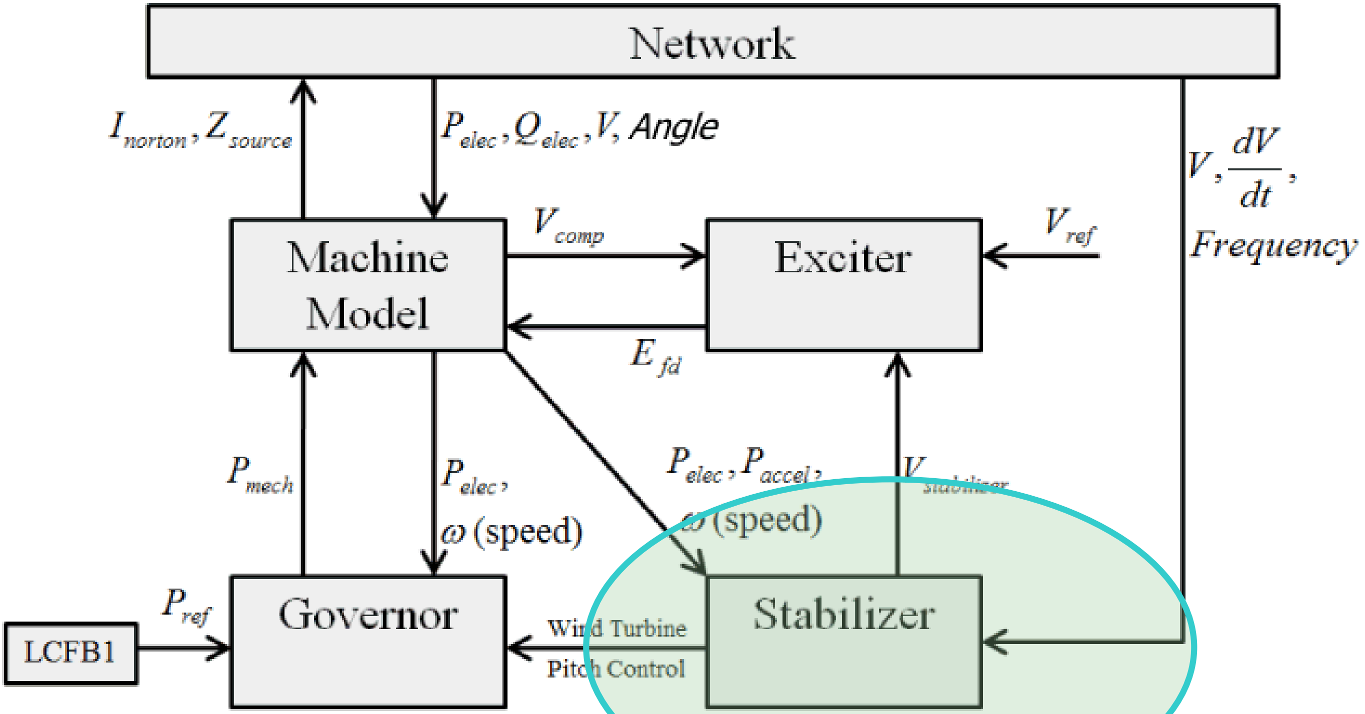
- A few references on power system stabilizers
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part I: General Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3017-3024, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part II: Performance Objectives and Tuning Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3025-3033, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part III: Practical Considerations," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3034-3046, June 1981.
  - *Power System Coherency and Model Reduction*, Joe Chow Editor, Springer, 2013

Dynamic Models in the Physical Structure



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

Power System Stabilizer (PSS) Models



P_{elec} = Electrical Power

Q_{elec} = Electrical Reactive Power

V = Voltage at Terminal Bus

$\frac{dV}{dt}$ = Derivate of Voltage

V_{comp} = Compensated Voltage

P_{mech} = Mechanical Power

ω(speed) = Rotor Speed (often it's deviation from nominal speed)

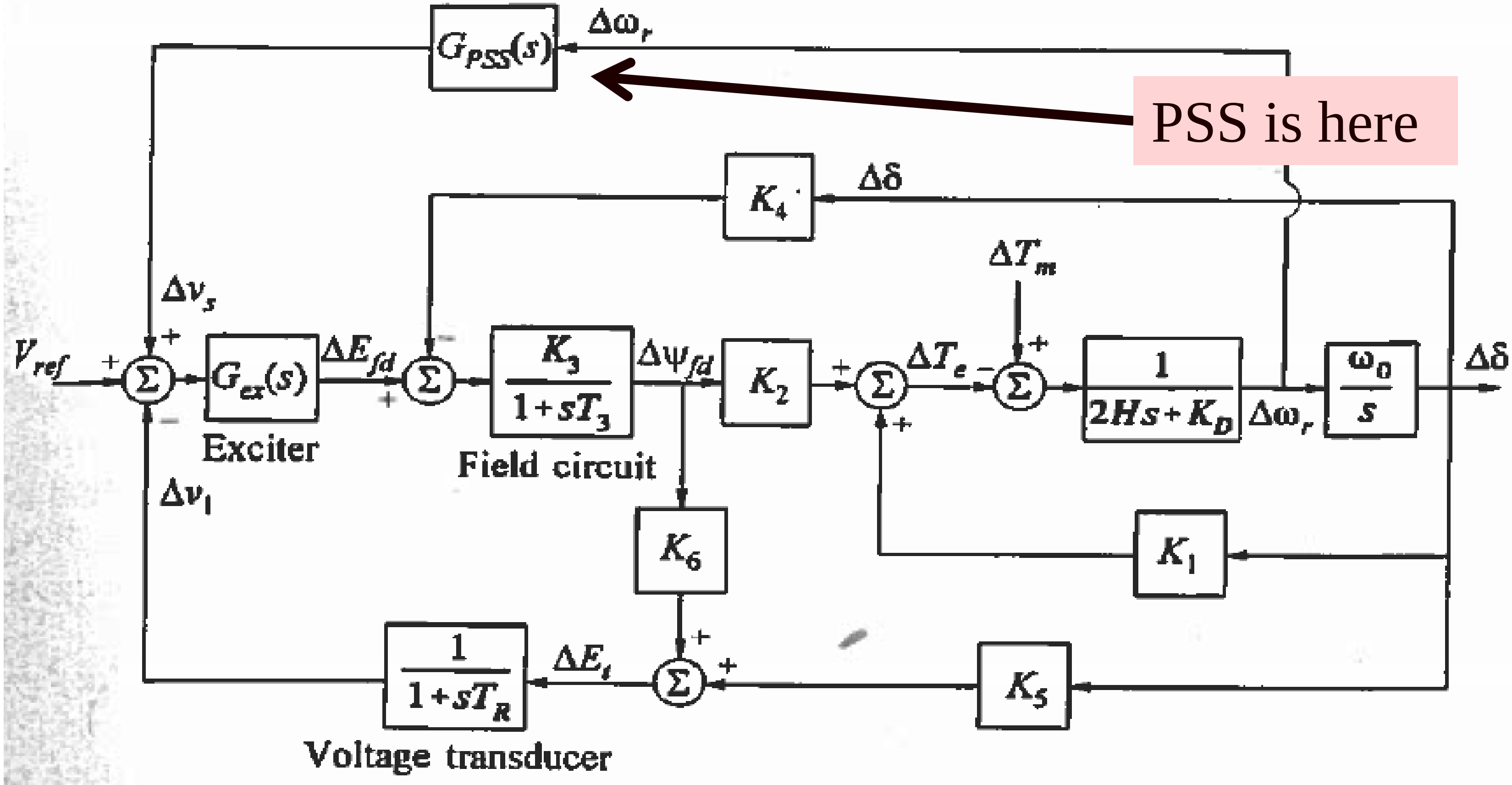
P_{accel} = Accelerating Power

$V_{stabilizer}$ = Output of Stabilizer

V_{ref} = Exciter Control Setpoint (determined during initialization)

P_{ref} = Governor Control Setpoint (determined during initialization)

Classic Block Diagram of a System with a PSS



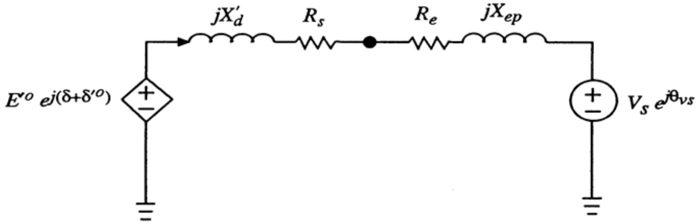
PSS is here

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

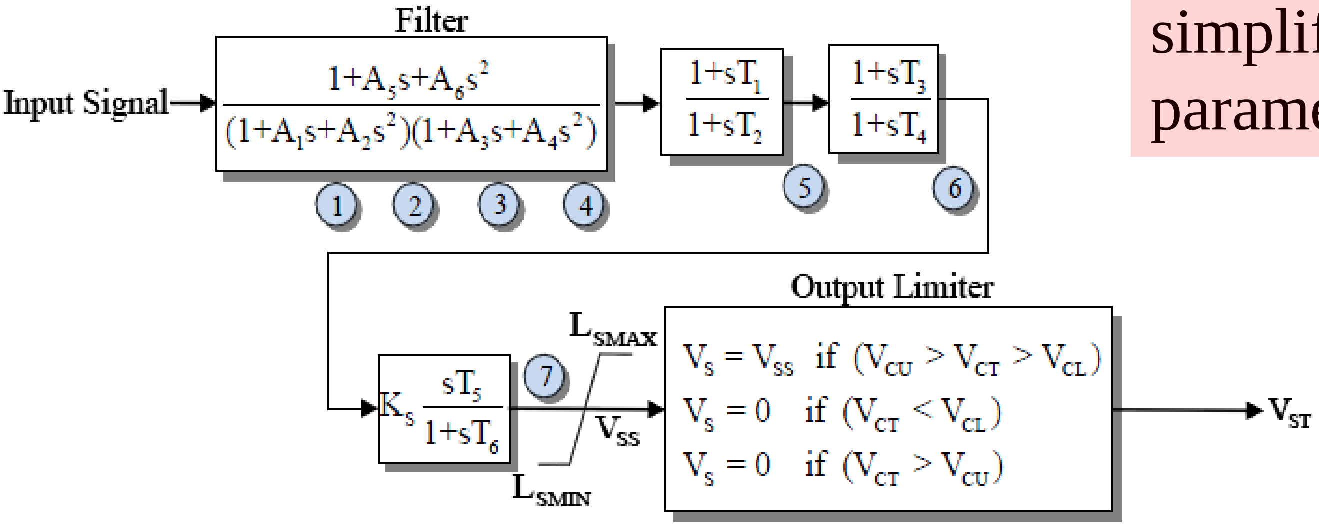
PSS Focus Here

- 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

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 parameters to zero



V_{ST} is an input into the exciter

Another Single Input PSS

- The PSS1A is very similar to the IEEEST Stabilizer and STAB1

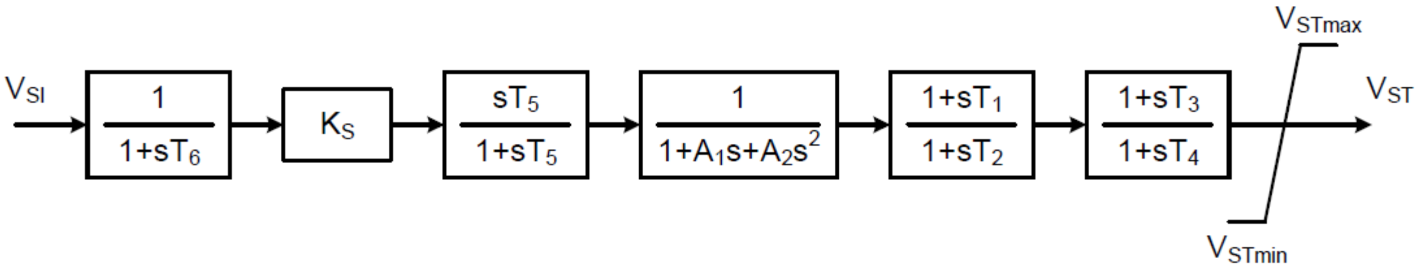
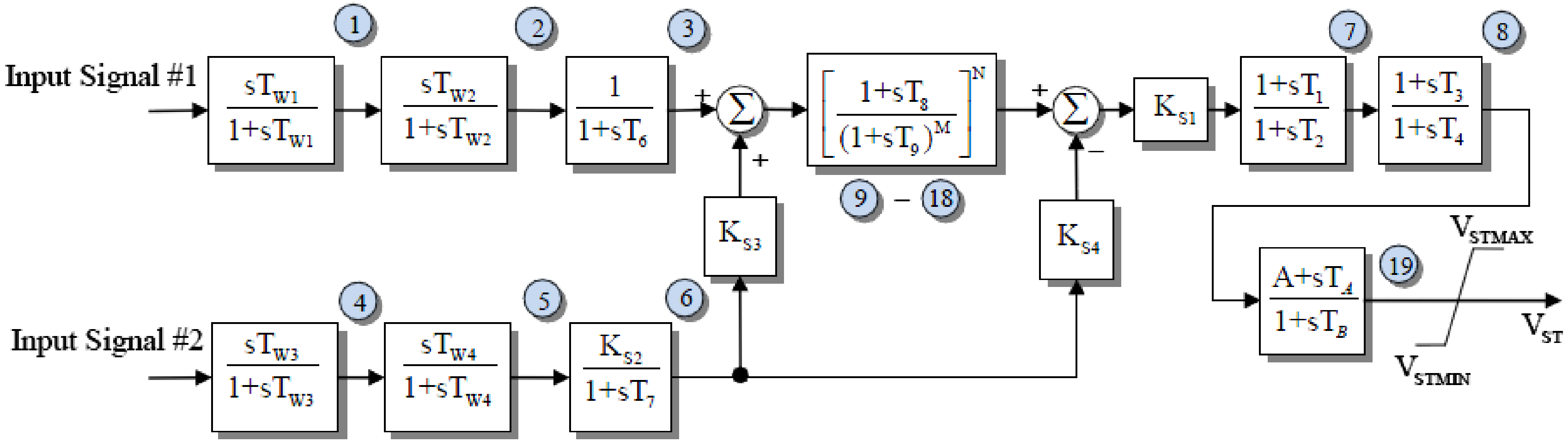


Figure 31 —Type PSS1A single-input power system stabilizer

IEEE Std 421.5 describes the common stabilizers

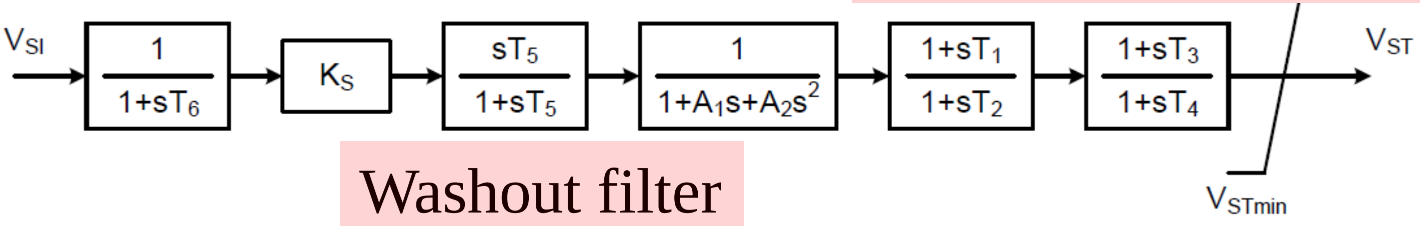
Example Dual Input PSS

- Below is an example of a dual input PSS (PSS2A)
  - Combining shaft speed deviation with generator electric power is common
  - Both inputs have washout filters to remove low frequency components of the input signals



Washout Filters and Lead-Lag Compensators

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



Lead-lag compensators

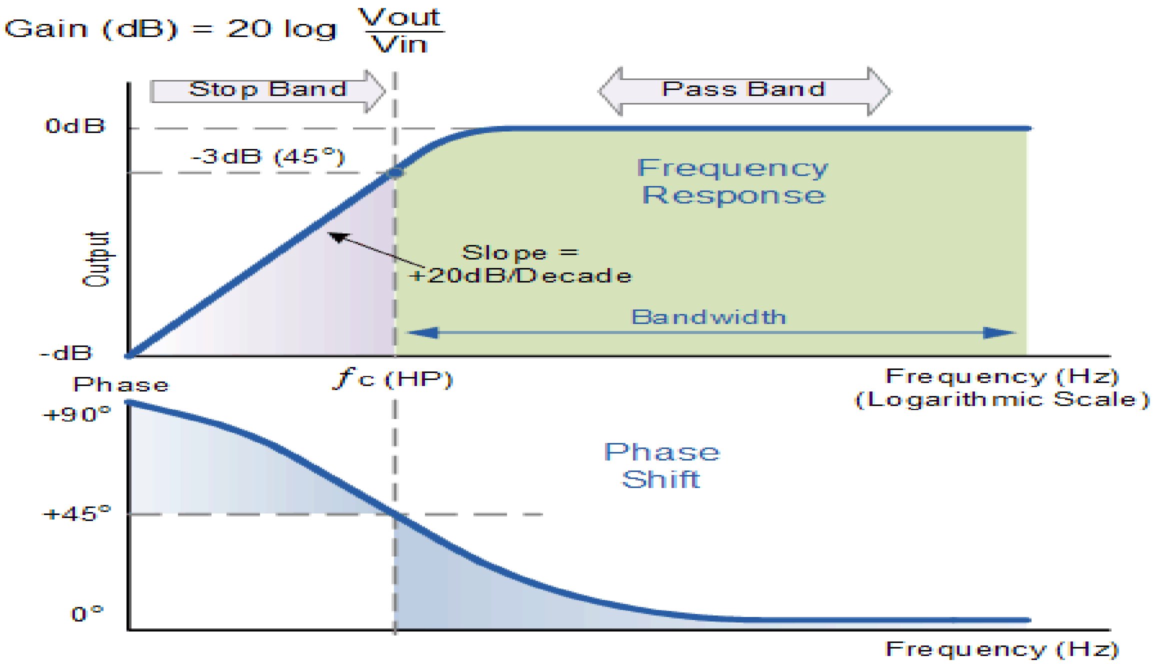
Washout filter

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



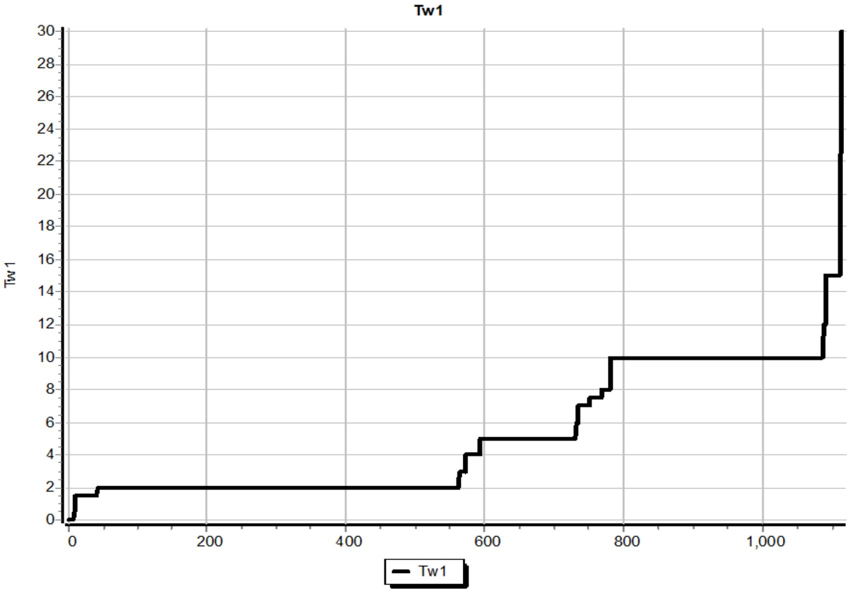
The breakpoint frequency is when the phase shift is 45 degrees and the gain is -3 dB (1/sqrt(2))

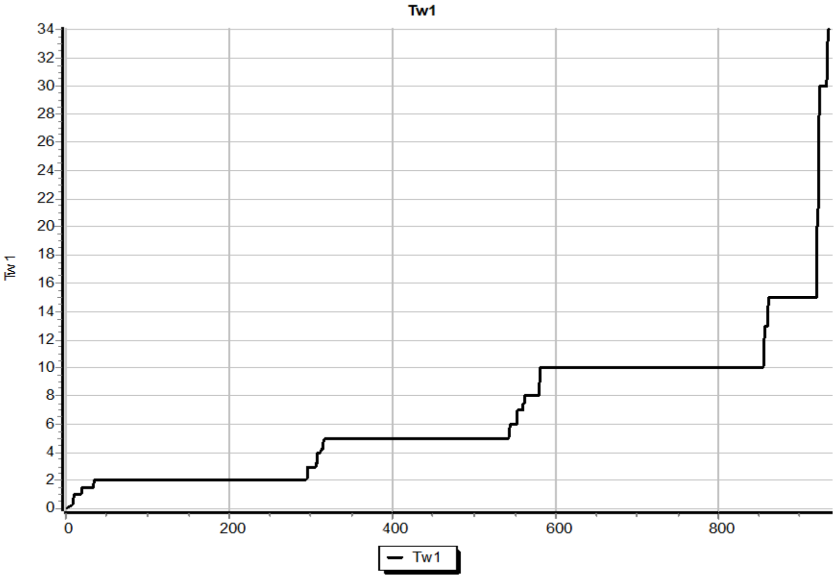
A larger T value shifts the breakpoint to lower frequencies; at T=10 the breakpoint frequency is 0.016 Hz

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

Washout Parameter Variation

- The PSS2A is the most common stabilizer in both the 2015 EI and WECC cases. Plots show the variation in T_{W1} for EI (left) and WECC cases (right); for both the x-axis is the number of PSS2A stabilizers sorted by T_{W1}, and the y-axis is T_{W1} in seconds

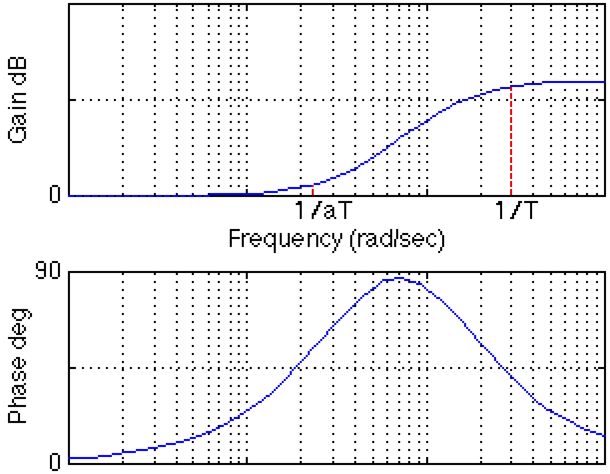




Lead-Lag Compensators

- For a lead-lag compensator of the below form with $\alpha <= 1$ (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

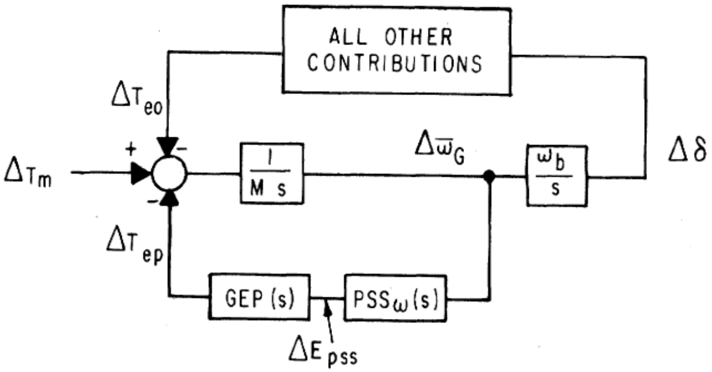


Image Source: Figure 1 from Larsen, 1981, Part 1

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

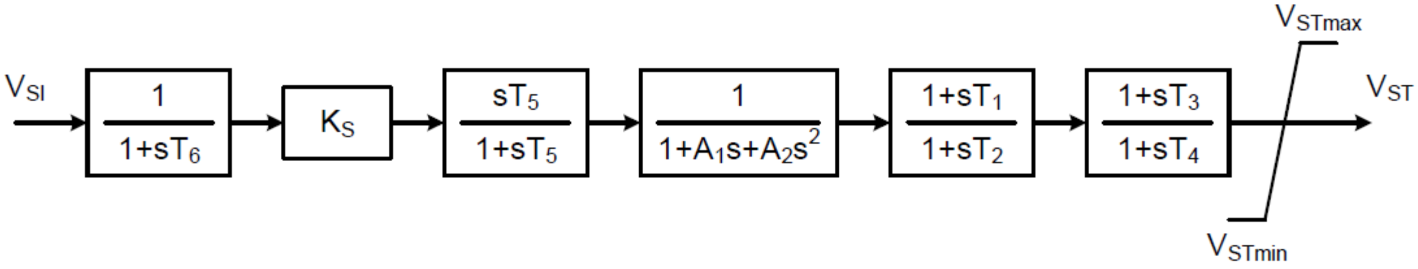


Figure 31 —Type PSS1A single-input power system stabilizer

Image Source: IEEE 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 $T_2=T_4$

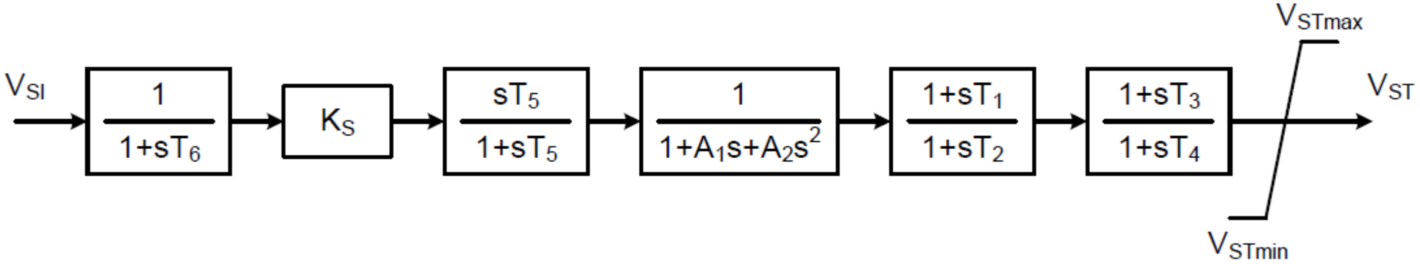


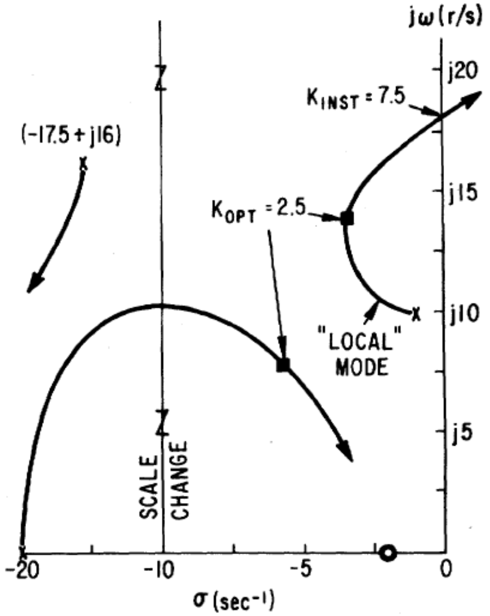
Figure 31 —Type PSS1A single-input power system stabilizer

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



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

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

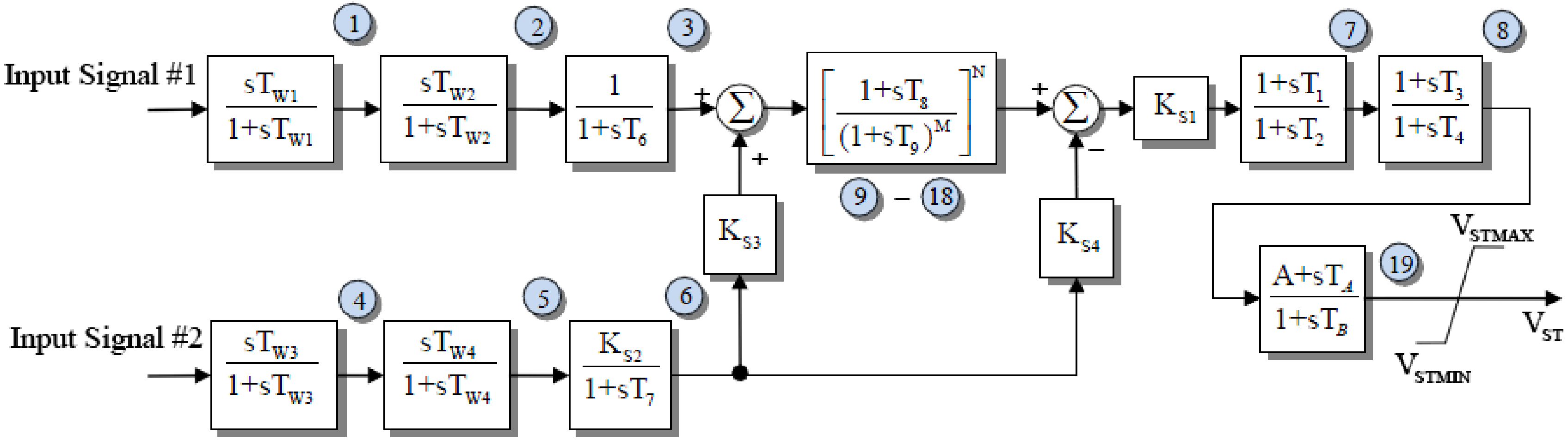
- A practical method is to find K_{INST}, then set K_{OPT} as about 1/3 to ½ of this value

Stabilizer Design Tuning

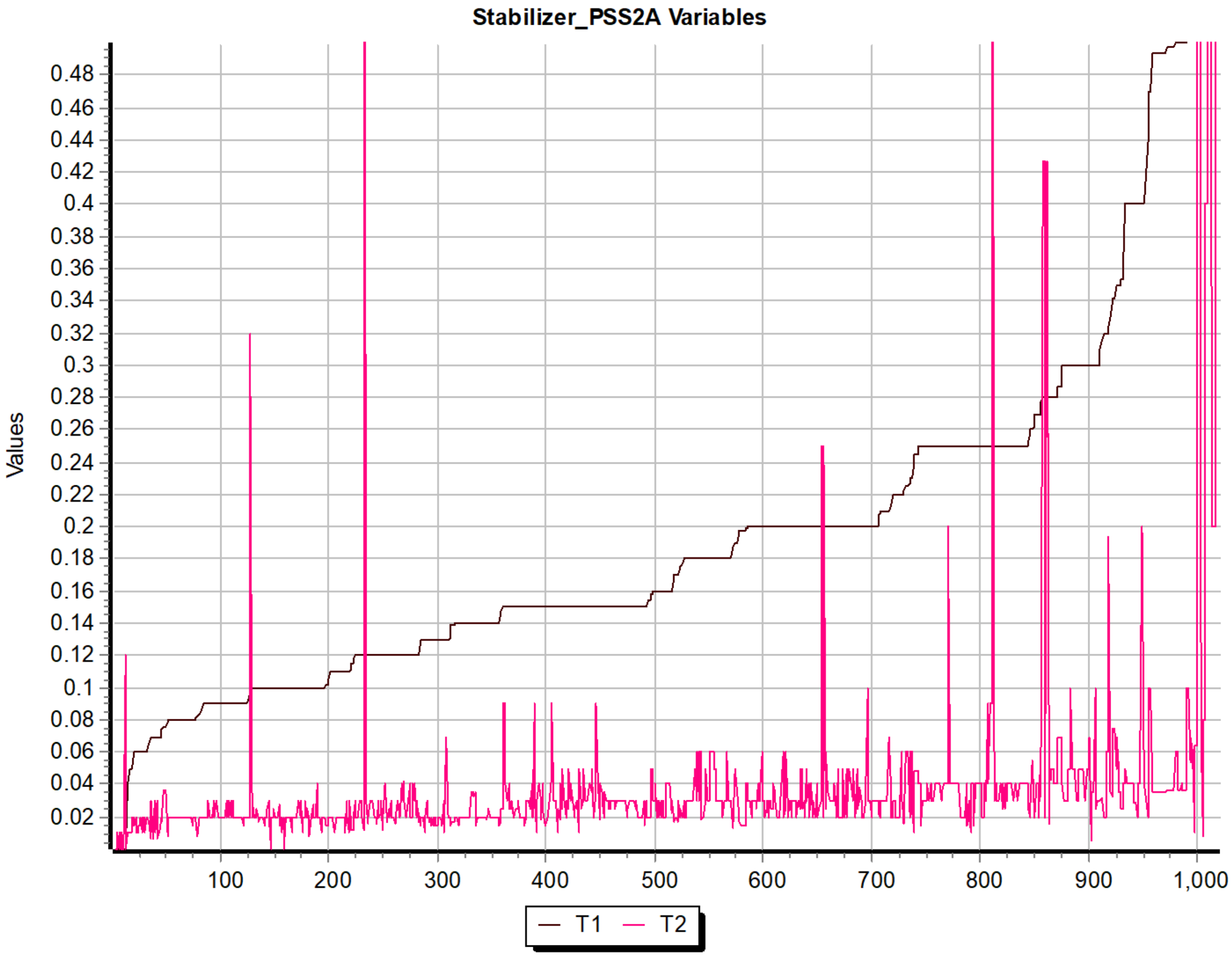
- Basic approach is to provide enhanced damping at desired frequencies; the challenge is power systems can experience many different types of oscillations, ranging from the high frequency local modes to the slower (< 1.0 Hz usually) inter-area modes
- Usually the PSS should be set to compensate the phase 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

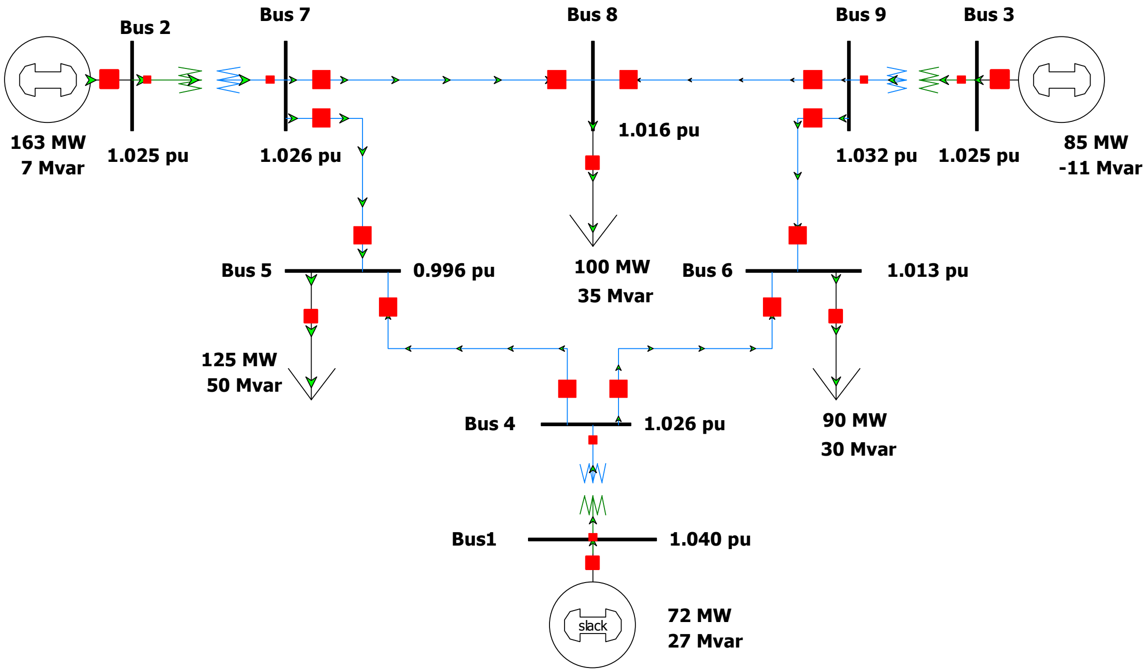


Example T_1 and T_2 Values



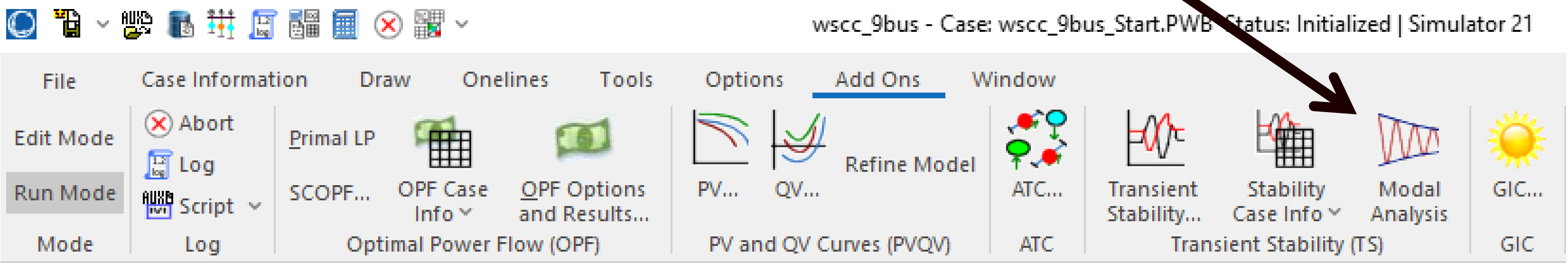
Example

- As an example we'll use the **wscc_9bus_Start** case, and apply the default dynamics contingency of a self-clearing fault at Bus 8.
- Use Modal Analysis to determine the major modal frequency and damping

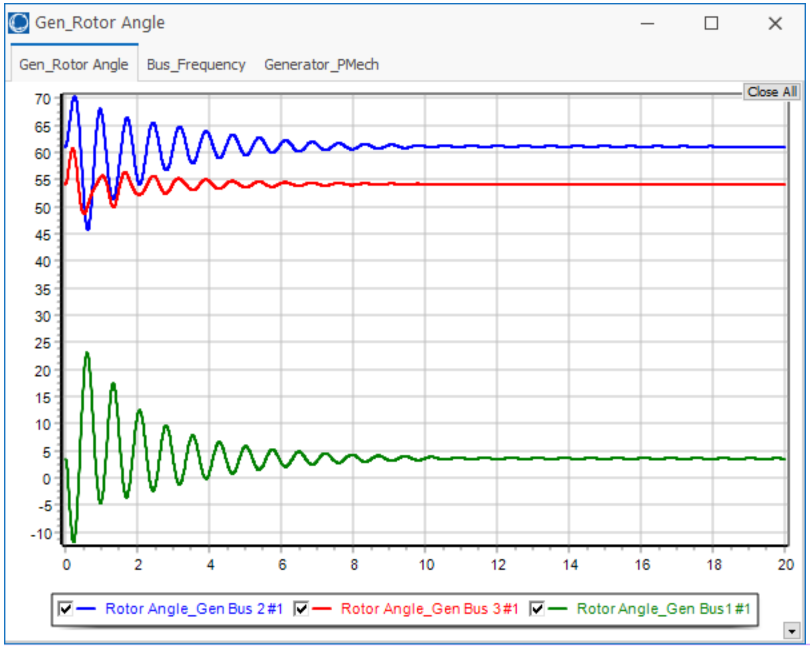


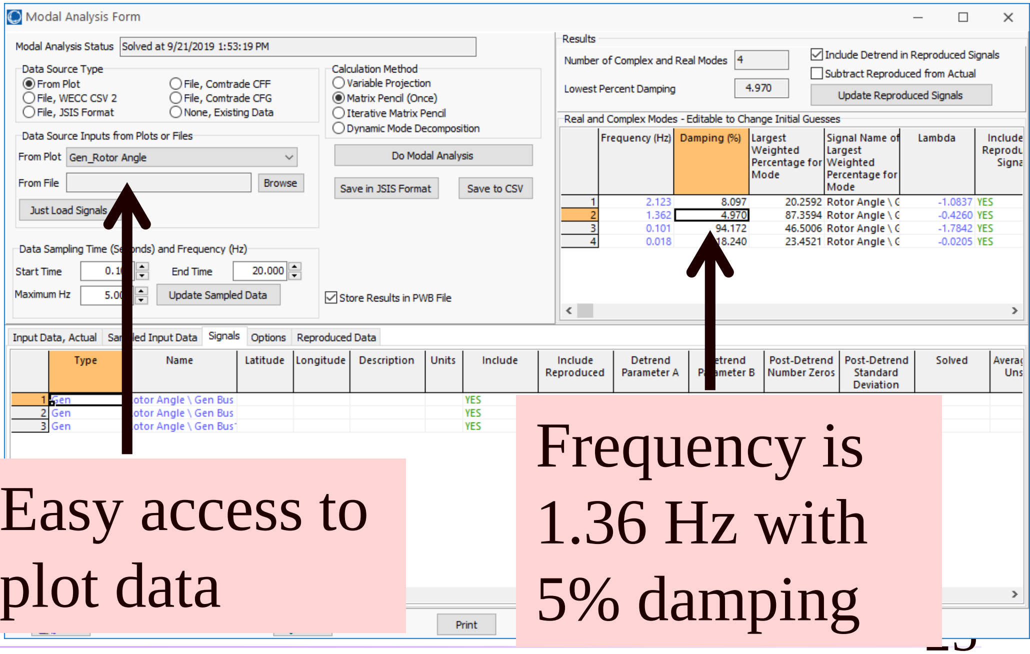
Example: Getting Initial Frequency and Damping

- The new Modal Analysis button provides quick access



wscc_9bus - Case: wscc_9bus_Start.PWB Status: Initialized | Simulator 21





Modal Analysis Form

Modal Analysis Status: Solved at 9/21/2019 1:53:19 PM

Data Source Type
● From Plot
○ File, WECC CSV 2
○ File, JSIS Format
○ File, Comtrade CFF
○ File, Comtrade CFG
○ None, Existing Data

Calculation Method
○ Variable Projection
● Matrix Pencil (Once)
○ Iterative Matrix Pencil
○ Dynamic Mode Decomposition

Data Source Inputs from Plots or Files
From Plot: Gen_Rotor Angle
From File:

Data Sampling Time (Seconds) and Frequency (Hz)
Start Time: 0.1
End Time: 20.000
Maximum Hz: 5.0

☑ Store Results in PWB File

Results
Number of Complex and Real Modes: 4
Lowest Percent Damping: 4.970
☑ Include Detrend in Reproduced Signals
☐ Subtract Reproduced from Actual

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	Include Reprodu Signa
1	2.123	8.097	20.2592	Rotor Angle \ G	-1.0837	YES
2	1.362	4.970	87.3594	Rotor Angle \ G	-0.4260	YES
3	0.101	94.172	46.5006	Rotor Angle \ G	-1.7842	YES
4	0.018	18.240	23.4521	Rotor Angle \ G	-0.0205	YES

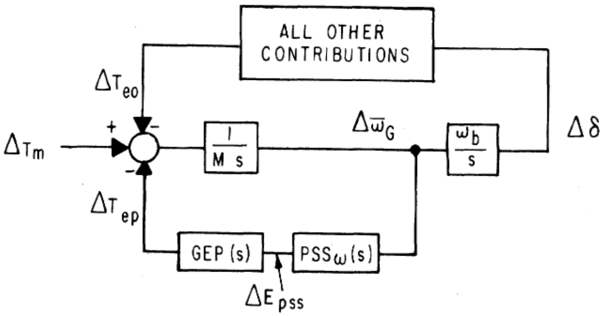
	Type	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Averag Uns
1	Gen	otor Angle \ Gen Bus					YES							
2	Gen	otor Angle \ Gen Bus					YES							
3	Gen	otor Angle \ Gen Bus					YES							

Easy access to plot data

Frequency is 1.36 Hz with 5% damping

PSS Tuning Example: We’ll 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



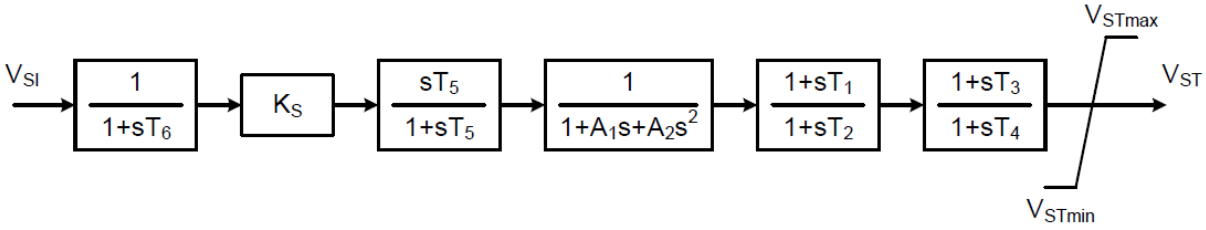


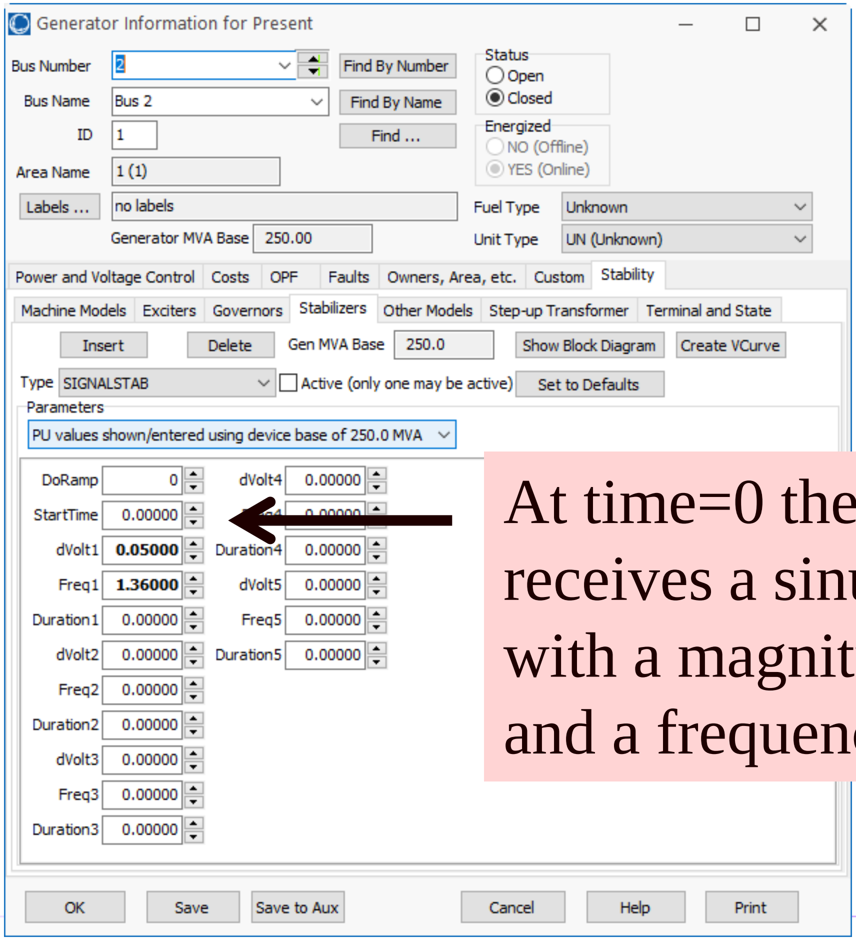
Figure 31 —Type PSS1A single-input power system stabilizer

PSS Tuning 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
- We’ll use the **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



Generator Information for Present

Bus Number: 2
Bus Name: Bus 2
ID: 1
Area Name: 1 (1)
Labels: no labels
Generator MVA Base: 250.00

Status: ○ Open ● Closed
Energized: ○ NO (Offline) ● YES (Online)
Fuel Type: Unknown
Unit Type: UN (Unknown)

Gen MVA Base: 250.0
Type: SIGNALSTAB
☐ Active (only one may be active)

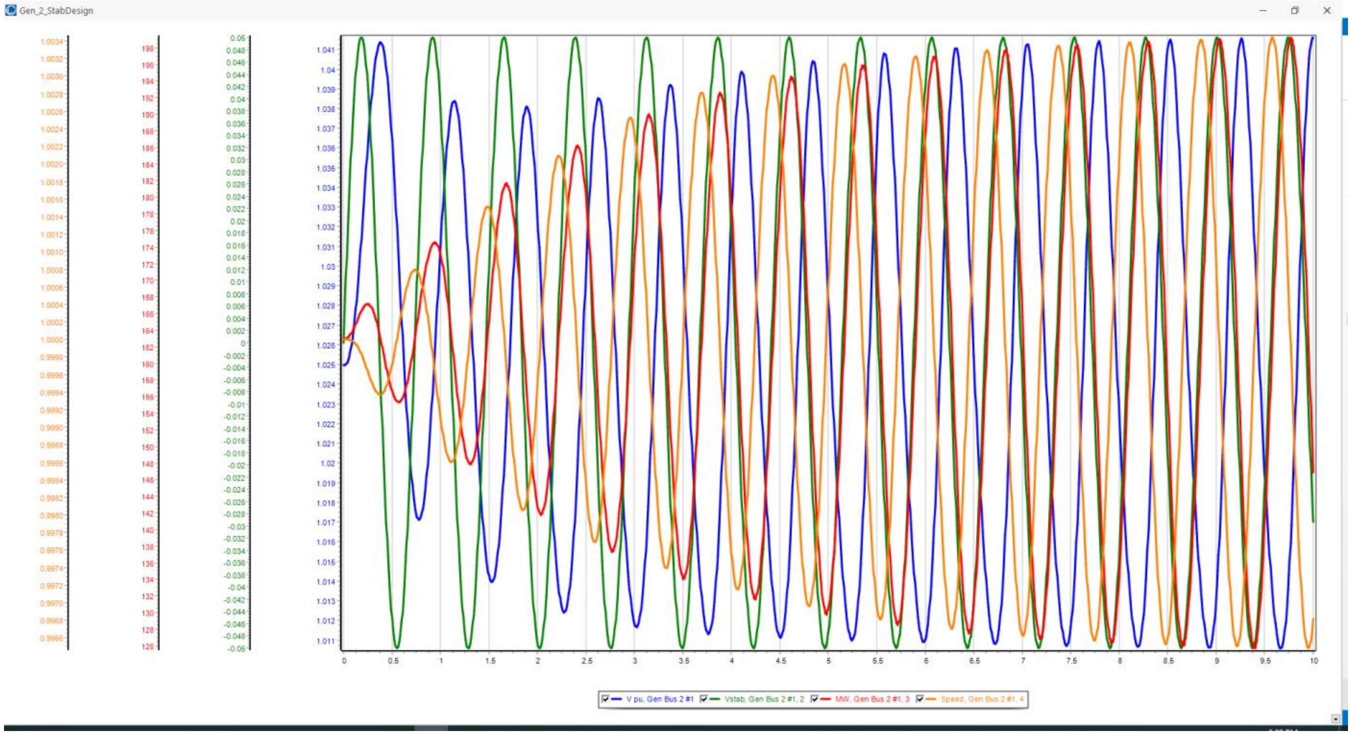
Parameters: PU values shown/entered using device base of 250.0 MVA

DoRamp	0	dVolt4	0.00000
StartTime	0.00000	Freq4	0.00000
dVolt1	**0.05000**	Duration4	0.00000
Freq1	**1.36000**	dVolt5	0.00000
Duration1	0.00000	Freq5	0.00000
dVolt2	0.00000	Duration5	0.00000
Freq2	0.00000		
Duration2	0.00000		
dVolt3	0.00000		
Freq3	0.00000		
Duration3	0.00000		

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

PSS Tuning Example:
Gen2 Reference Signal Results

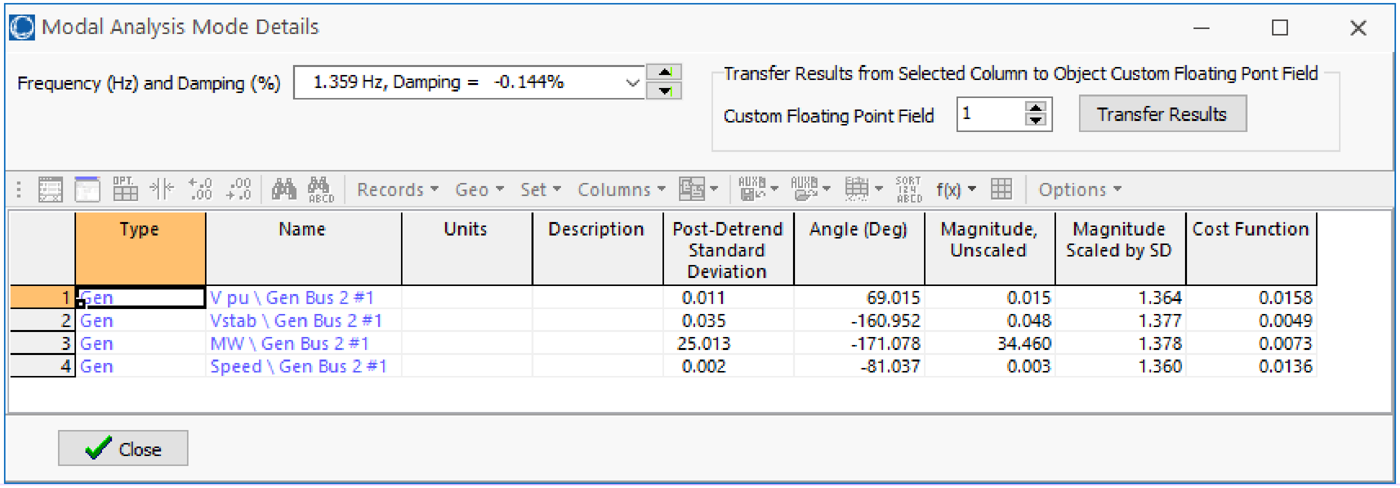
- Graph shows four signals at bus 2, including the stabilizer input and the generator's speed
  - The phase relationships are most important



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



Frequency (Hz) and Damping (%): 1.359 Hz, Damping = -0.144%

Transfer Results from Selected Column to Object Custom Floating Pont Field

Custom Floating Point Field: 1

	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

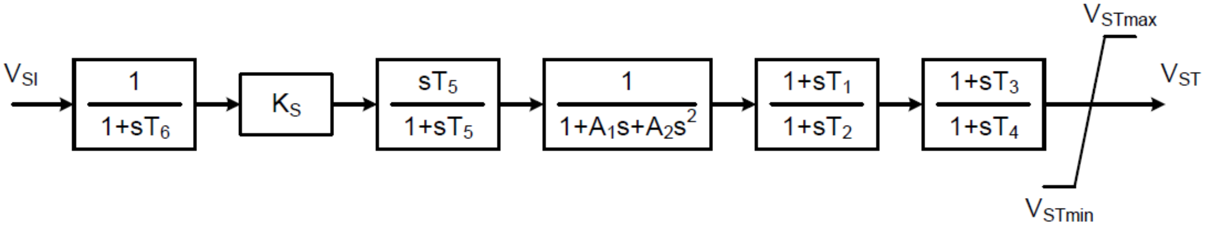
$$\alpha = \frac{1-\sin\phi}{1+\sin\phi},\ T_1 = \frac{1}{2\pi f\sqrt{\alpha}}$$

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

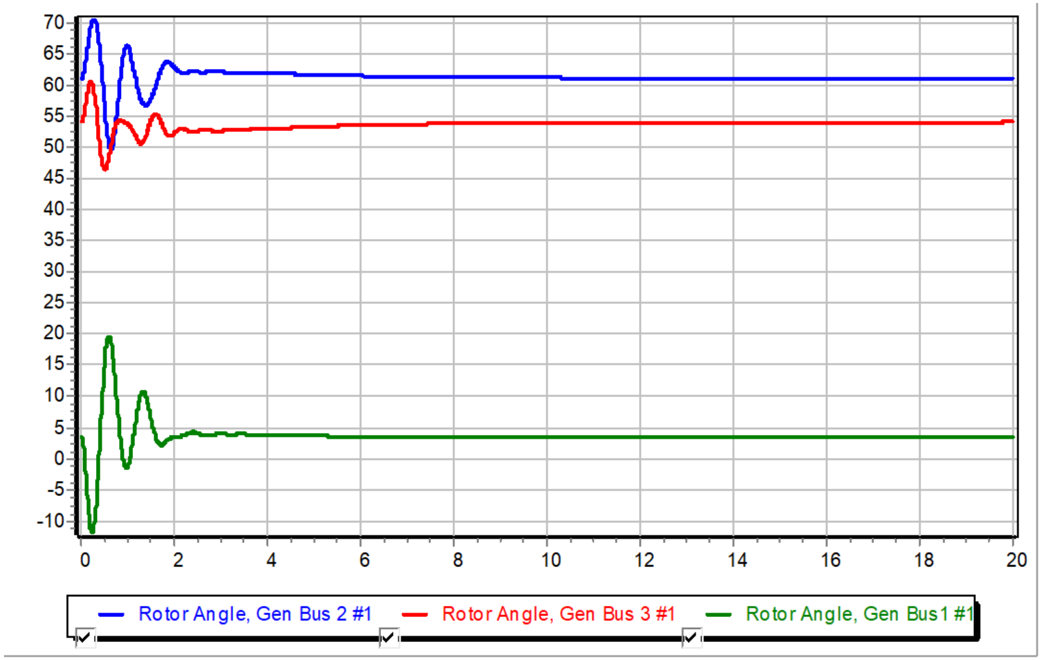
- Hence $T_1=T_3=0.321$, $T_2=T_4=0.042$. We'll assumed $T_6=0$, and $T_5=10$, and $A_1=A_2=0$



- 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

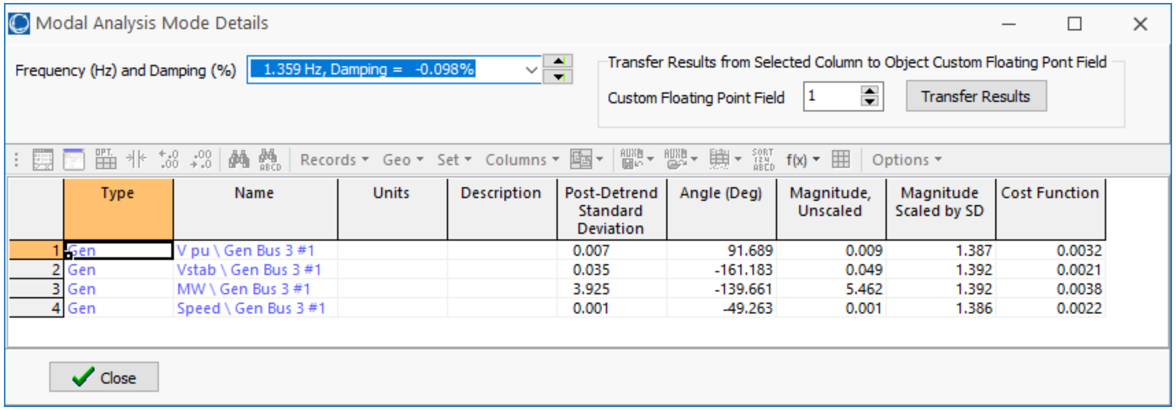
- Instability occurs with $K_S = 55$, hence the optimal value is about 55/3=18.3
- This increases the damping from 5% to about 16.7%



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



Frequency (Hz) and Damping (%): 1.359 Hz, Damping = -0.098%

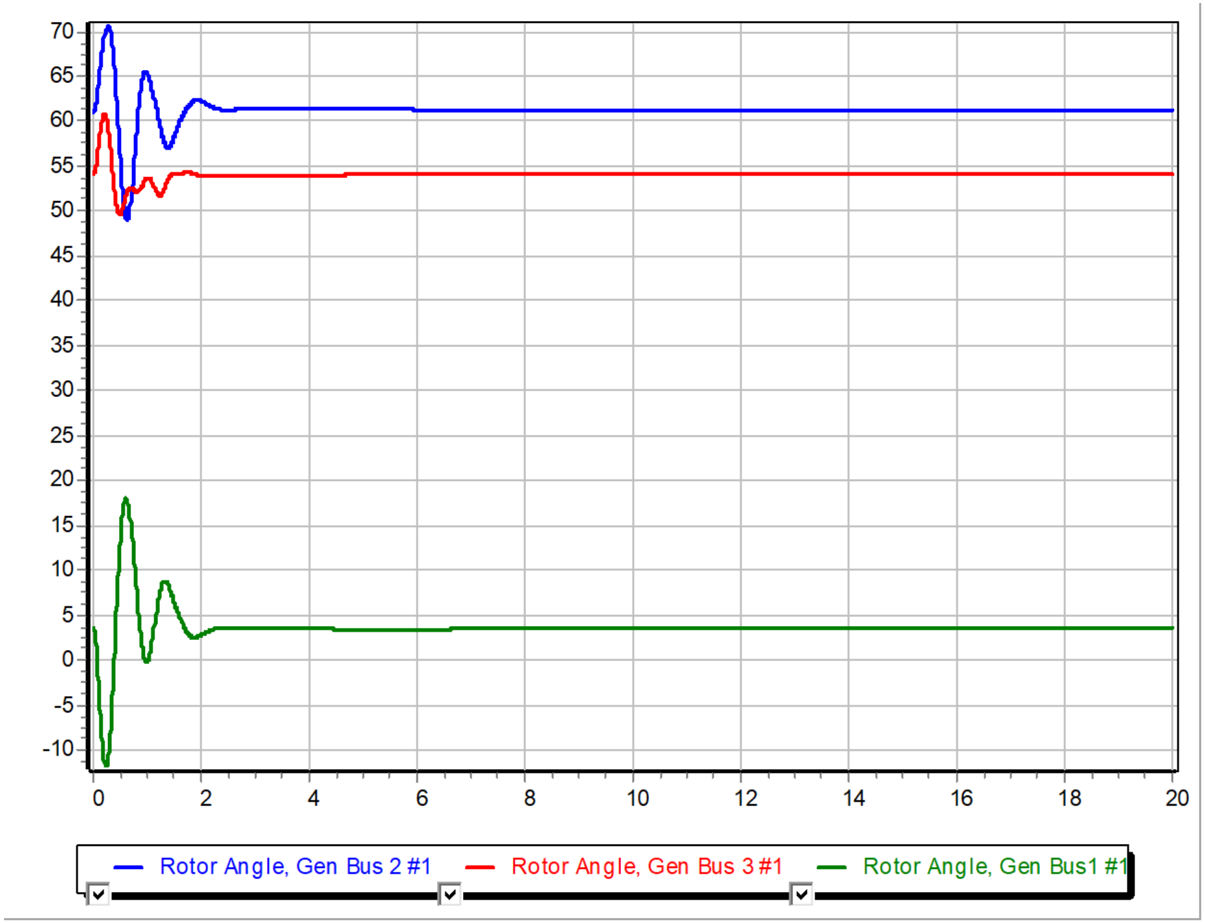
Transfer Results from Selected Column to Object Custom Floating Pont Field

Custom Floating Point Field: 1

	Type	Name	Units	Description	Post-Detrend Standard Deviation	Angle (Deg)	Magnitude, Unscaled	Magnitude Scaled by SD	Cost Function
1	Gen	V pu \ Gen Bus 3 #1			0.007	91.689	0.009	1.387	0.0032
2	Gen	Vstab \ Gen Bus 3 #1			0.035	-161.183	0.049	1.392	0.0021
3	Gen	MW \ Gen Bus 3 #1			3.925	-139.661	5.462	1.392	0.0038
4	Gen	Speed \ Gen Bus 3 #1			0.001	-49.263	0.001	1.386	0.0022

- 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.

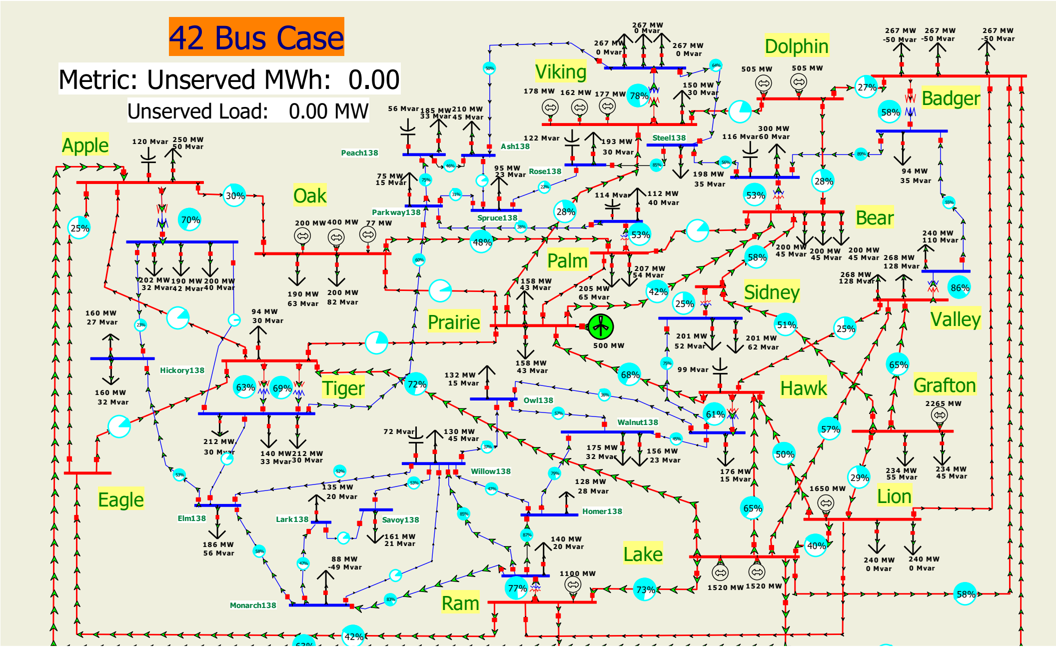
PSS Tuning Example: Final Solution



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

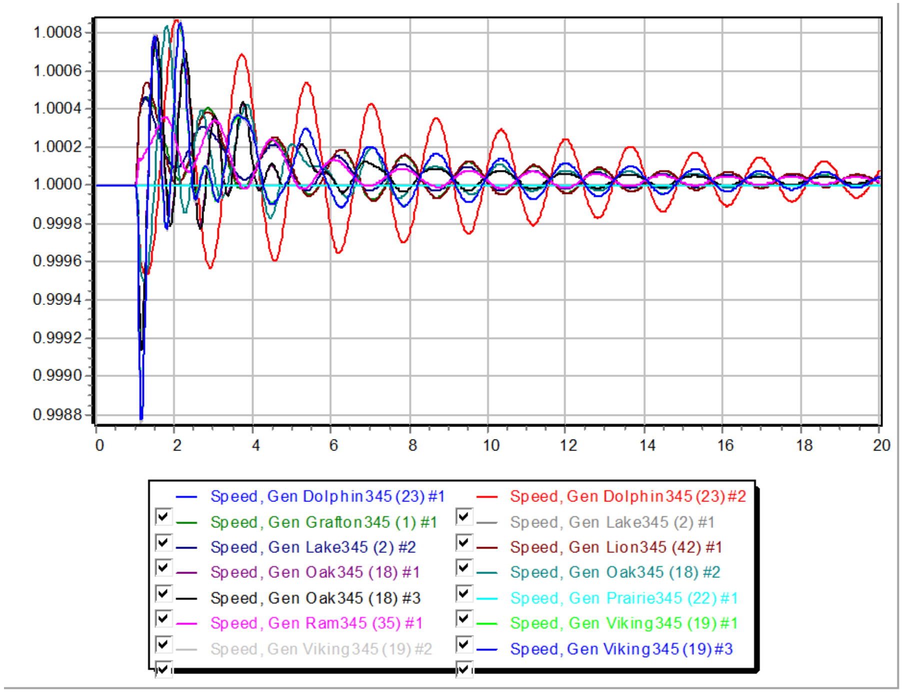
- Goal is to try to improve damping by adding one PSS1A at a large generator at Lion345 (bus 42)
  - Example event is a three-phase fault is applied to the middle of the 345 kV transmission line between Prairie (bus 22) and Hawk (bus 3) with both ends opened at 0.05 seconds

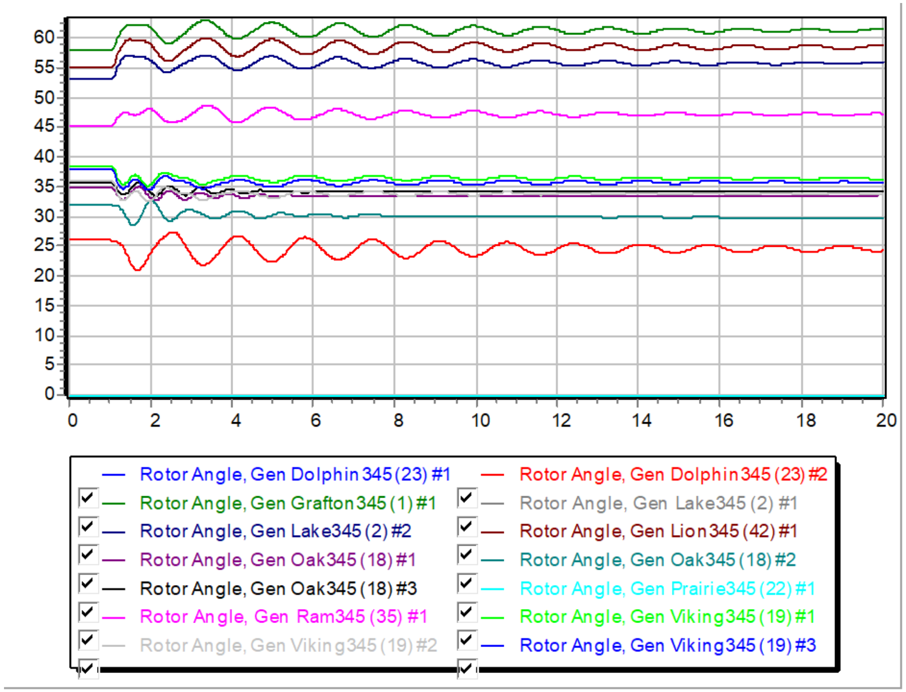


The starting case name is **Bus42_PSS**

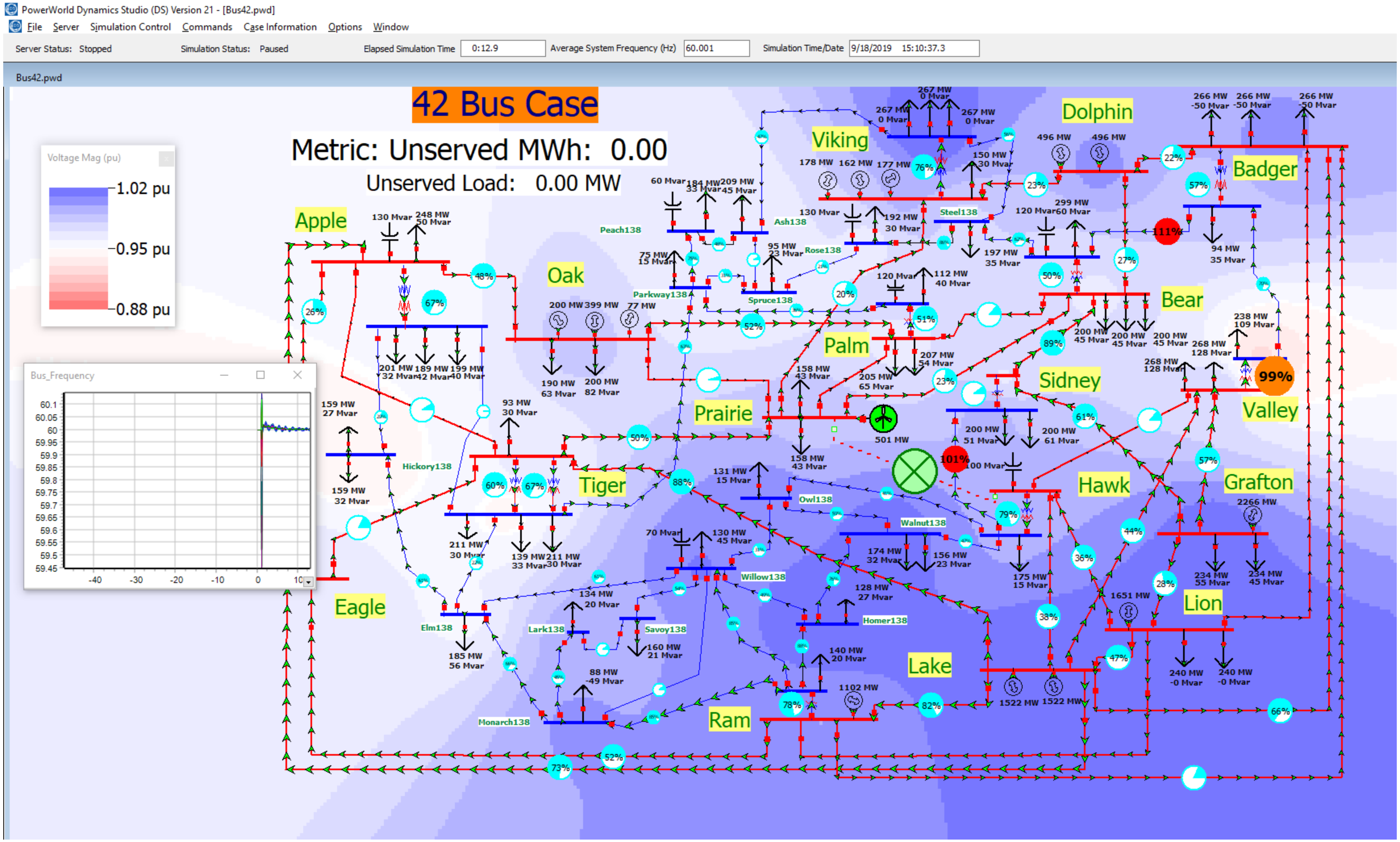
Example 2: Decide Generators to Tune and Frequency

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





Aside: Visualizing the Disturbance in PowerWorld Dynamics Studio (DS)



PowerWorld Dynamics Studio (DS) Version 21 - [Bus42.pwd]

Server Status: Stopped

Simulation Status: Paused

Elapsed Simulation Time: 0:12.9

Average System Frequency (Hz): 60.001

Simulation Time/Date: 9/18/2019 15:10:37.3

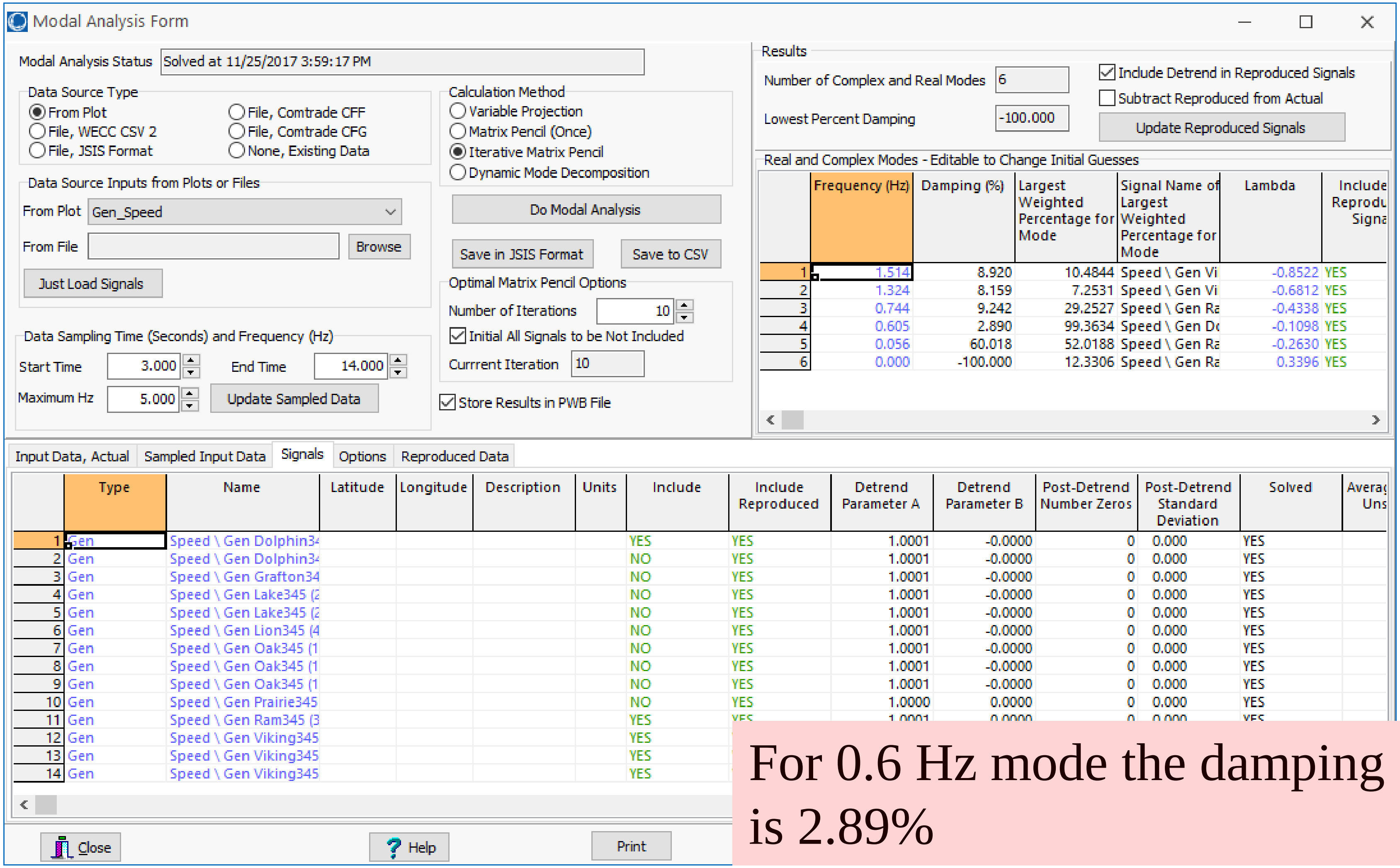
Bus42.pwd

42 Bus Case

Metric: Unserved MWh: 0.00

Unserved Load: 0.00 MW

Example 2: Response Quantified Using Modal Analysis



Modal Analysis Status: Solved at 11/25/2017 3:59:17 PM

Data Source Type
- ● From Plot
- ○ File, WECC CSV 2
- ○ File, JSIS Format
- ○ File, Comtrade CFF
- ○ File, Comtrade CFG
- ○ None, Existing Data

Calculation Method
- ○ Variable Projection
- ○ Matrix Pencil (Once)
- ● Iterative Matrix Pencil
- ○ Dynamic Mode Decomposition

Data Source Inputs from Plots or Files

From Plot: Gen_Speed

From File:

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 3.000

End Time: 14.000

Maximum Hz: 5.000

Optimal Matrix Pencil Options

Number of Iterations: 10

☑ Initial All Signals to be Not Included

Current Iteration: 10

☑ Store Results in PWB File

Results

Number of Complex and Real Modes: 6

Lowest Percent Damping: -100.000

☑ Include Detrend in Reproduced Signals

☐ Subtract Reproduced from Actual

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	Include Reprodu Signa
1	1.514	8.920	10.4844	Speed \ Gen Vi	-0.8522	YES
2	1.324	8.159	7.2531	Speed \ Gen Vi	-0.6812	YES
3	0.744	9.242	29.2527	Speed \ Gen Ra	-0.4338	YES
4	0.605	2.890	99.3634	Speed \ Gen Do	-0.1098	YES
5	0.056	60.018	52.0188	Speed \ Gen Ra	-0.2630	YES
6	0.000	-100.000	12.3306	Speed \ Gen Ra	0.3396	YES

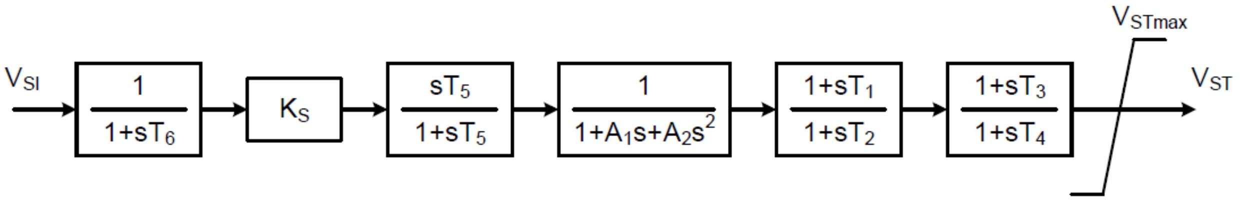
Input Data, Actual | Sampled Input Data | Signals | Options | Reproduced Data

	Type	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Averag Uns
1	Gen	Speed \ Gen Dolphin34					YES	YES	1.0001	-0.0000	0	0.000	YES	
2	Gen	Speed \ Gen Dolphin34					NO	YES	1.0001	-0.0000	0	0.000	YES	
3	Gen	Speed \ Gen Grafton34					NO	YES	1.0001	-0.0000	0	0.000	YES	
4	Gen	Speed \ Gen Lake345 (2					NO	YES	1.0001	-0.0000	0	0.000	YES	
5	Gen	Speed \ Gen Lake345 (2					NO	YES	1.0001	-0.0000	0	0.000	YES	
6	Gen	Speed \ Gen Lion345 (4					NO	YES	1.0001	-0.0000	0	0.000	YES	
7	Gen	Speed \ Gen Oak345 (1					NO	YES	1.0001	-0.0000	0	0.000	YES	
8	Gen	Speed \ Gen Oak345 (1					NO	YES	1.0001	-0.0000	0	0.000	YES	
9	Gen	Speed \ Gen Oak345 (1					NO	YES	1.0001	-0.0000	0	0.000	YES	
10	Gen	Speed \ Gen Prairie345					NO	YES	1.0000	0.0000	0	0.000	YES	
11	Gen	Speed \ Gen Ram345 (3					YES	YES	1.0001	0.0000	0	0.000	YES	
12	Gen	Speed \ Gen Viking345					YES							
13	Gen	Speed \ Gen Viking345					YES							
14	Gen	Speed \ Gen Viking345					YES							

For 0.6 Hz mode the damping is 2.89%

Example 2: Determine Phase Compensation

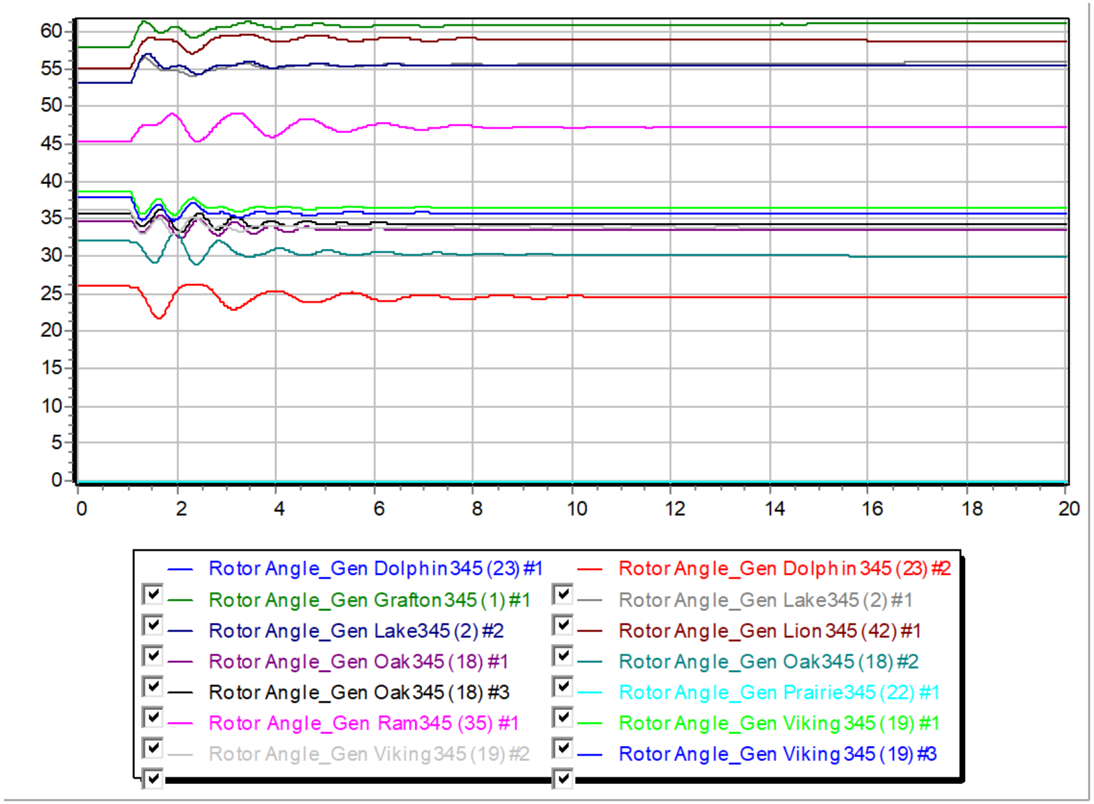
- Using a SignalStabStabilizer at bus 42 (Lion345), the phase lag of the generator's speed, relative to the stabilizer input is 199 degrees; flipping the sign requires phase compensation of 19 degrees or 9.5 per lead-lag
- Values are $\alpha = 0.72$; for 0.6 Hz, $T_1 = 0.313$, $T_2 = 0.225$; set T_3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

- 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