

ECEN 667

Power System Stability

Lecture 21: Power System Stabilizers

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Announcements



- By Nov 20th read the following two papers
 - K. Huang, M. Xiong, Y. Liu and K. Sun, "A Heterogeneous Multiscale Method for Efficient Simulation of Power Systems With Inverter-Based Resources," in *IEEE Transactions on Power Systems*, vol. 40, no. 5, pp. 4292-4306, Sept. 2025.
 - M. Xiong *et al.*, "EMT-TS Hybrid Simulation for Large Power Grids Considering IBR-Driven Dynamics," *IECON 2024 - 50th Annual Conference of the IEEE Industrial Electronics Society*, Chicago, IL, USA, 2024, pp. 1-6.
- HW #5 is on the website, due Nov 20th at 8 AM.
- **Exam 2 will be Tuesday, December 2nd, 2025**

Damping Oscillations: Power System Stabilizers (PSSs)



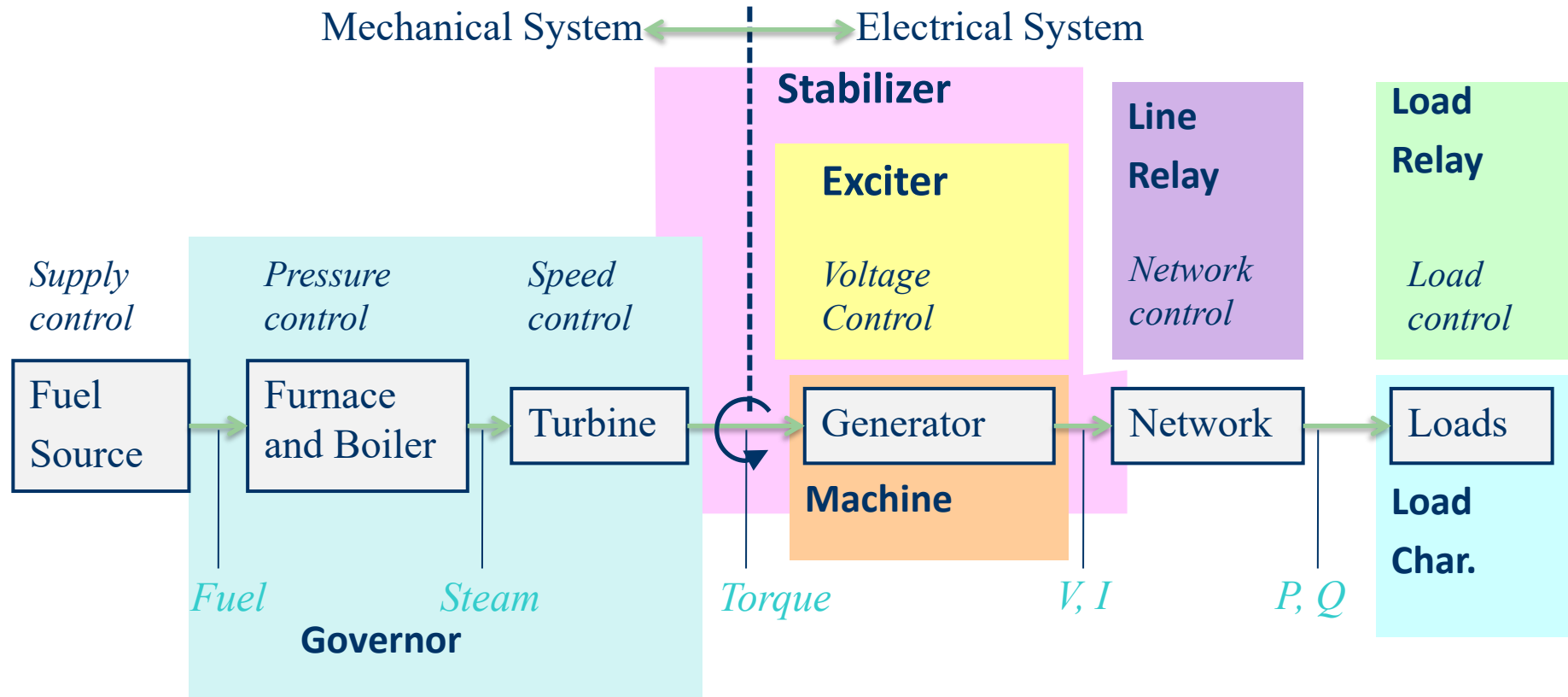
- A PSS adds a signal to the excitation system to improve damping
 - A common signal is proportional to the generator's speed; other inputs, such as like power, voltage or acceleration, can be used
 - The signal is usually measured locally (e.g. from the shaft)
- Both local modes and inter-area modes 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

Stabilizer References



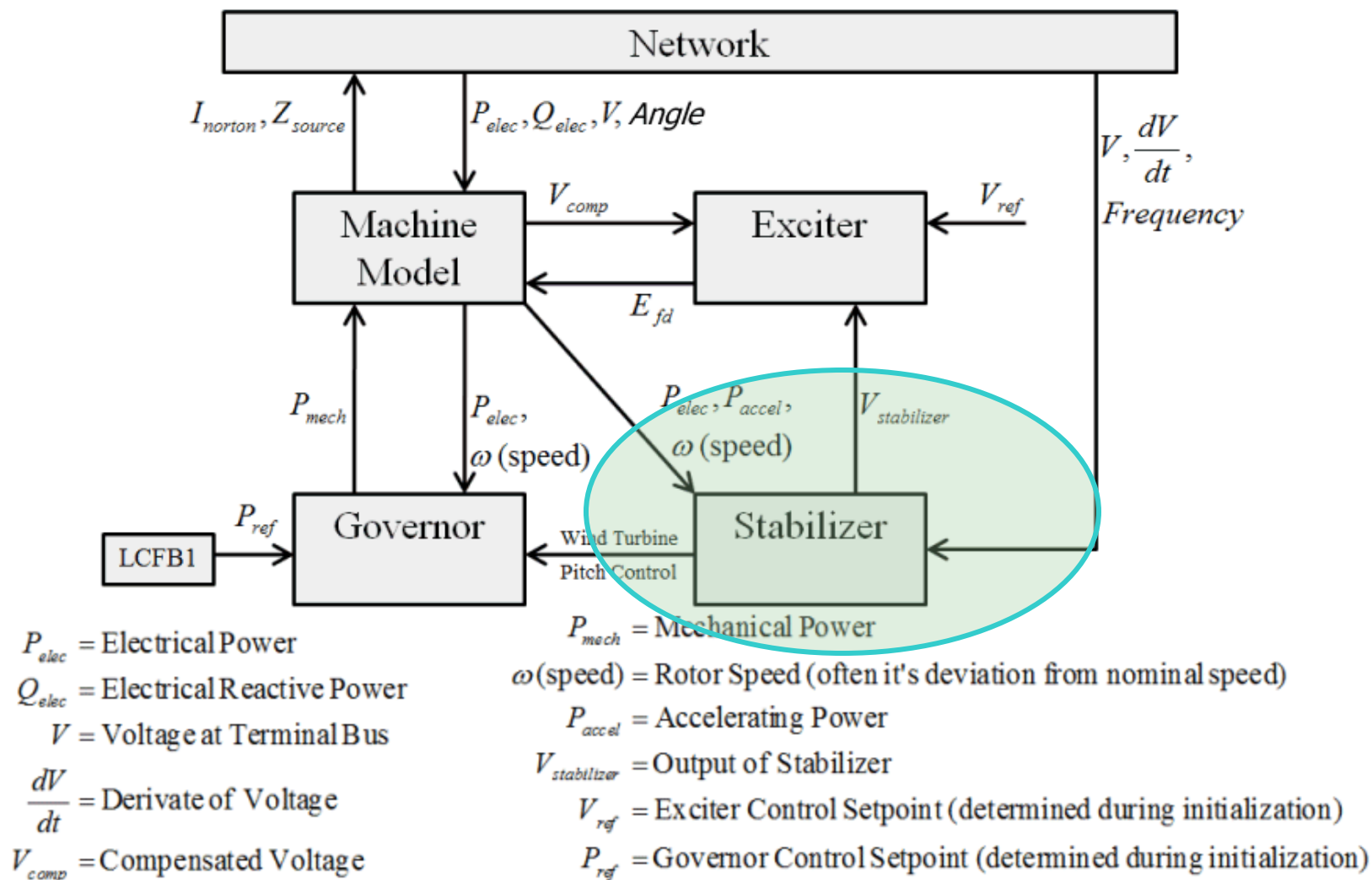
- A few references on power system stabilizers
 - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part I: General Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3017-3024, June 1981.
 - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers 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



Classic Block Diagram of a System with a PSS

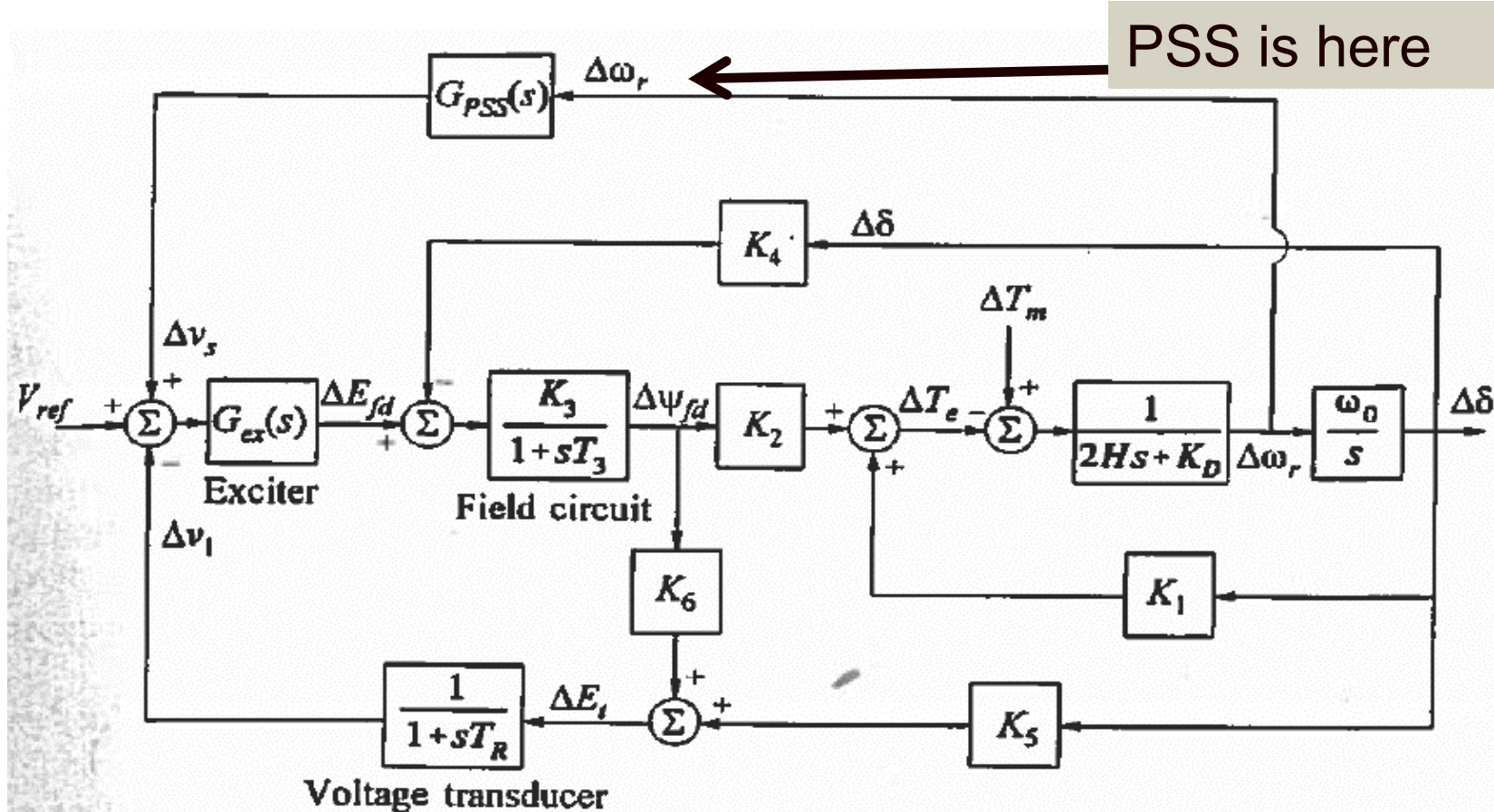


Figure 12.13 Block diagram representation with AVR and PSS

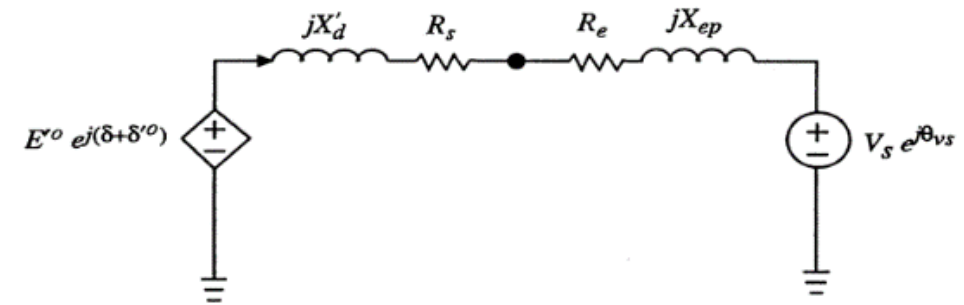
PSS Basics



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

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

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



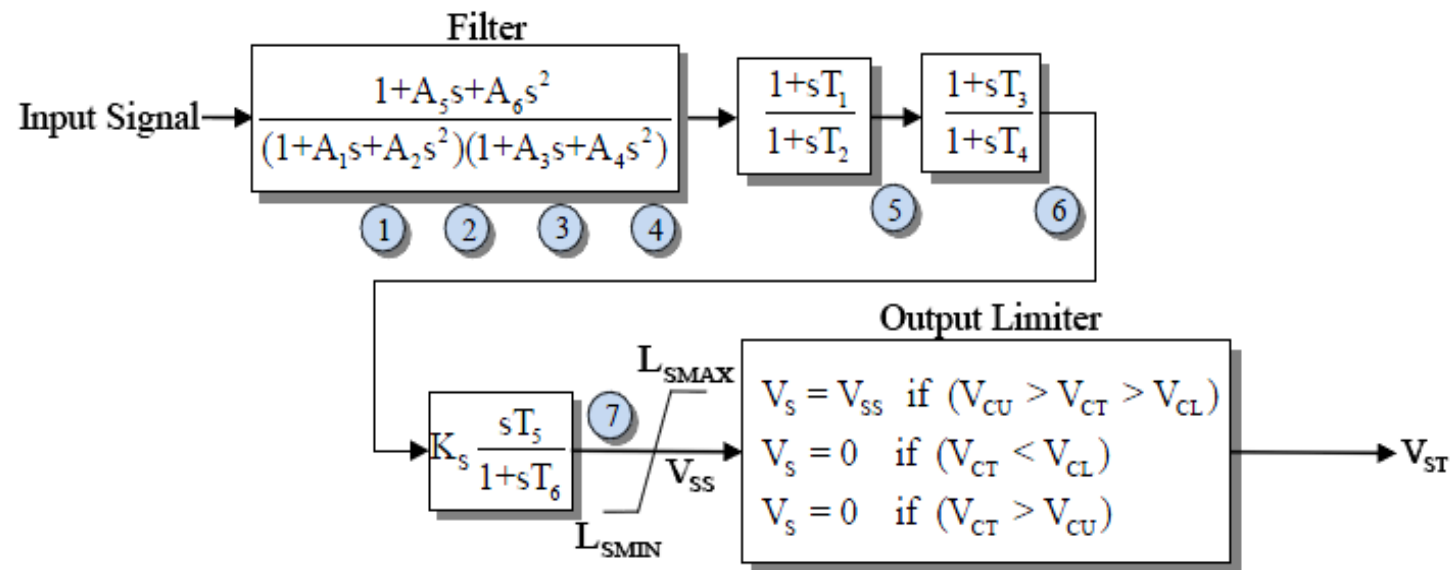
- Assume internal voltage has an additional component

$$E' = E'_{org} + K\Delta\omega$$
- This can add additional damping if $\sin(\delta)$ is positive
- In a real system there is delay, which requires compensation

Example PSS



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



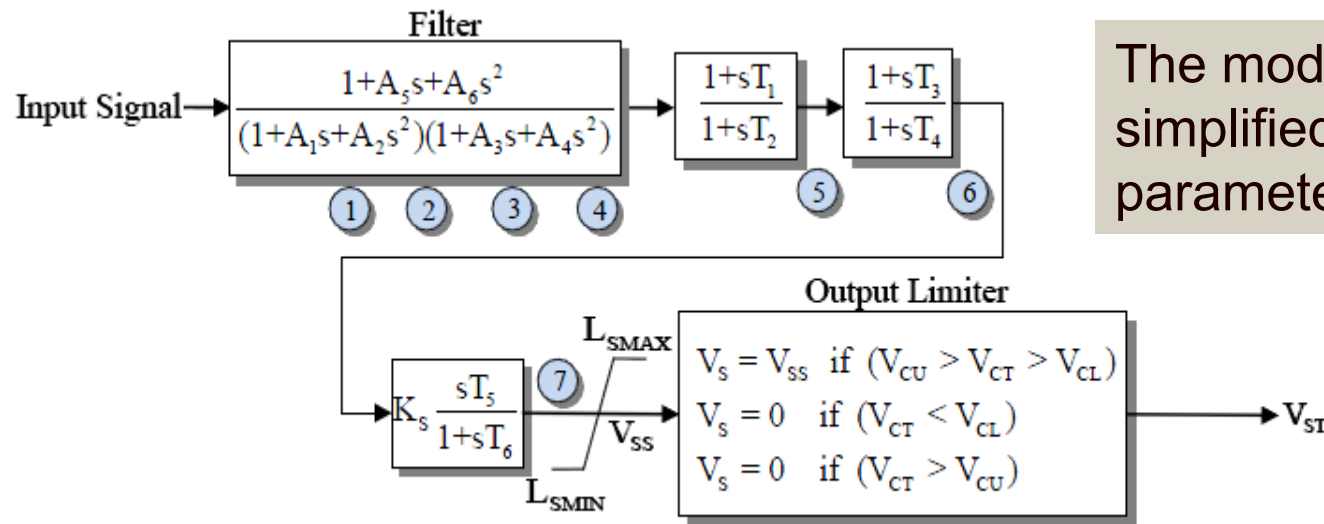
The model can be simplified by setting some parameters to zero

V_{ST} is an input into the exciter

Example PSS, 2



- An example single input stabilizer is shown below (IEEEEST)
 - 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 IEEEEST Stabilizer and STAB1

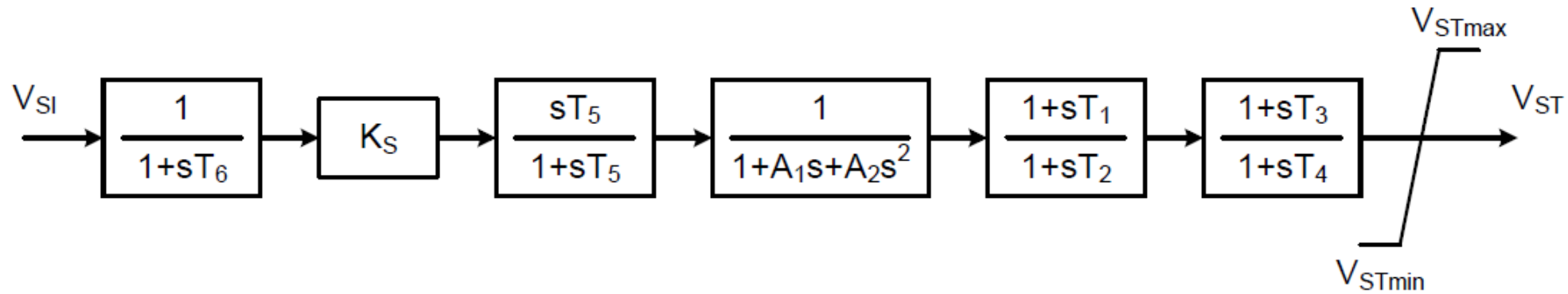


Figure 31 —Type PSS1A single-input power system stabilizer

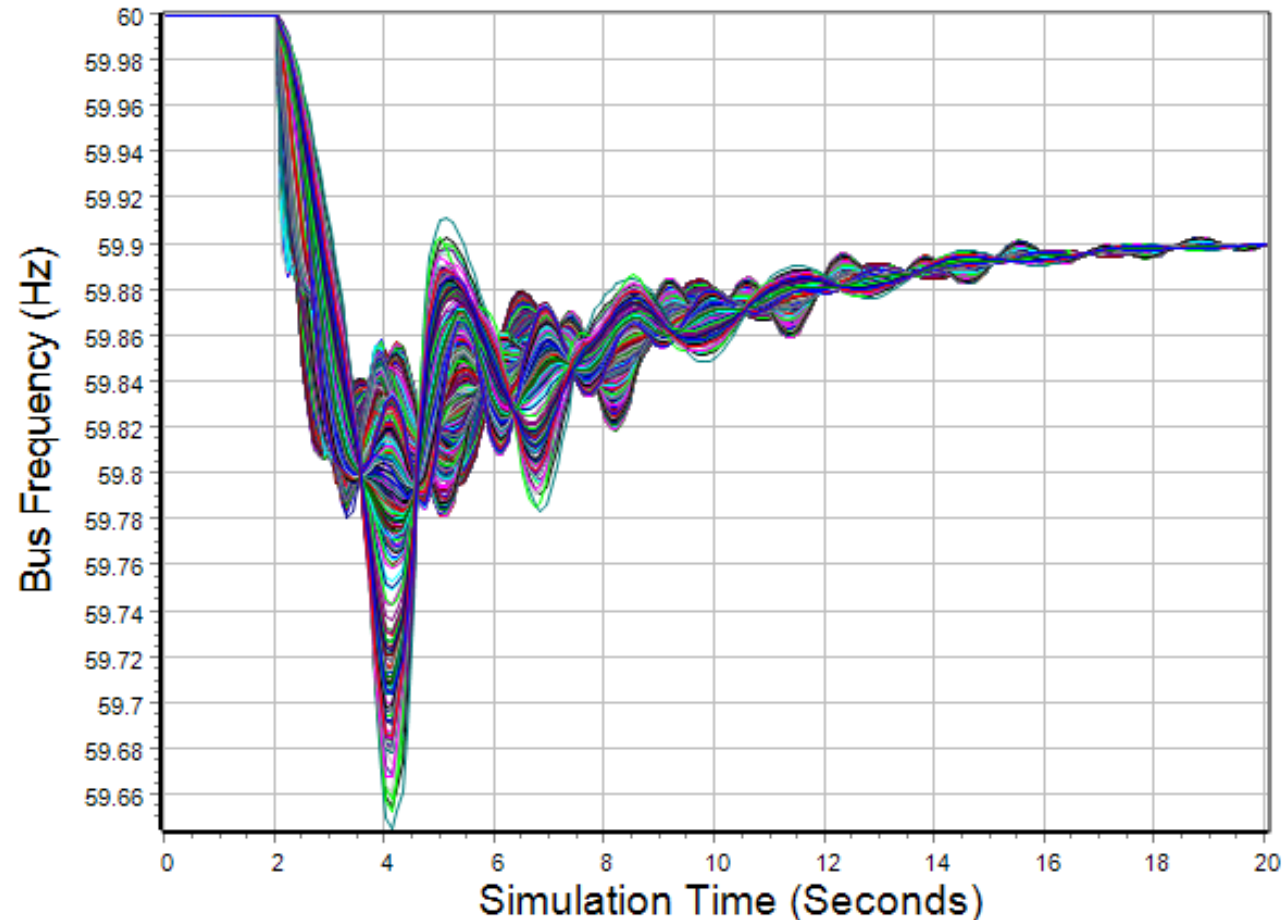
IEEE Std 421.5 describes the common stabilizers

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)

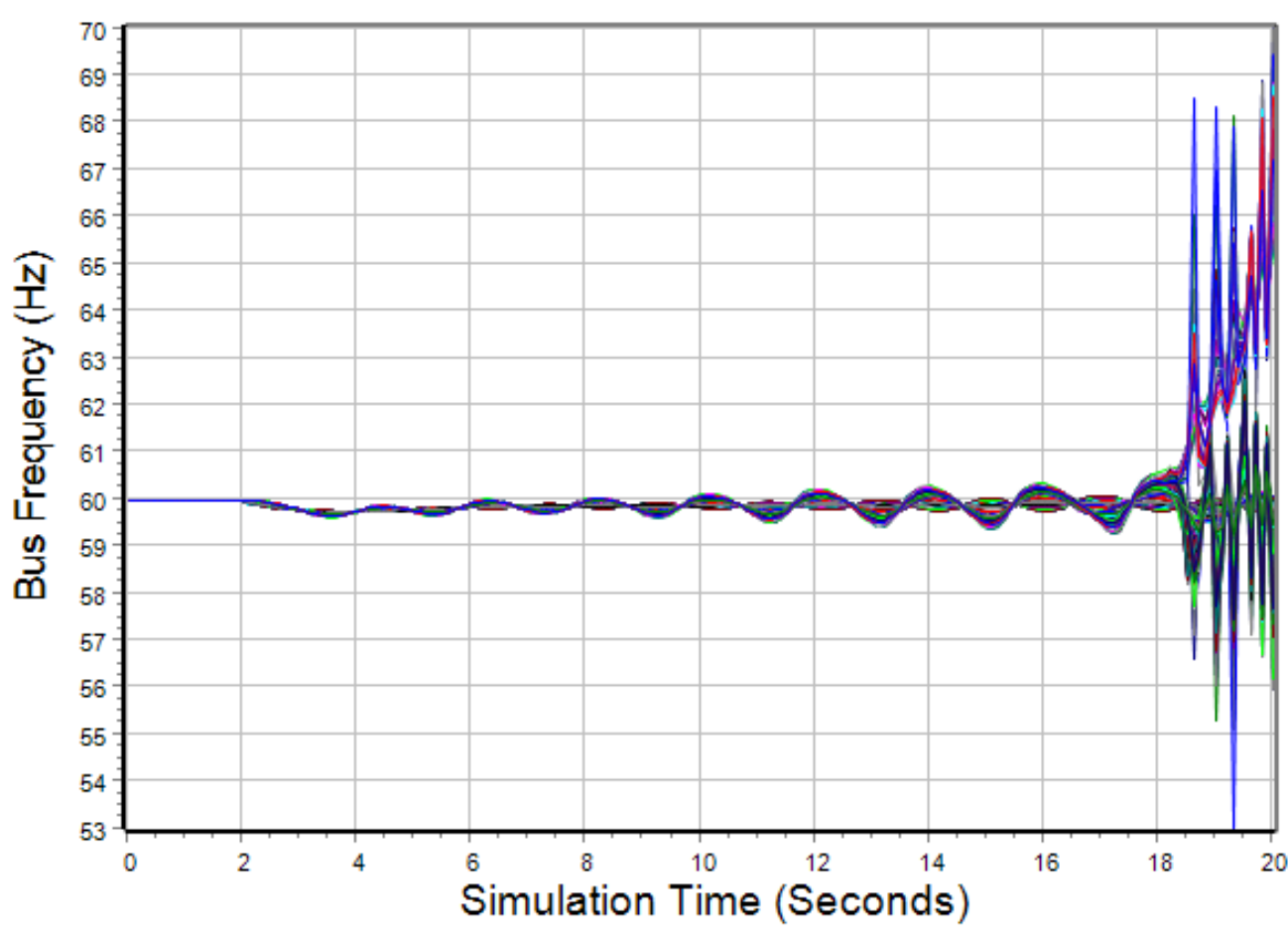
Results are given for the previous generator drop contingency



2000 Bus System Results Without Stabilizers



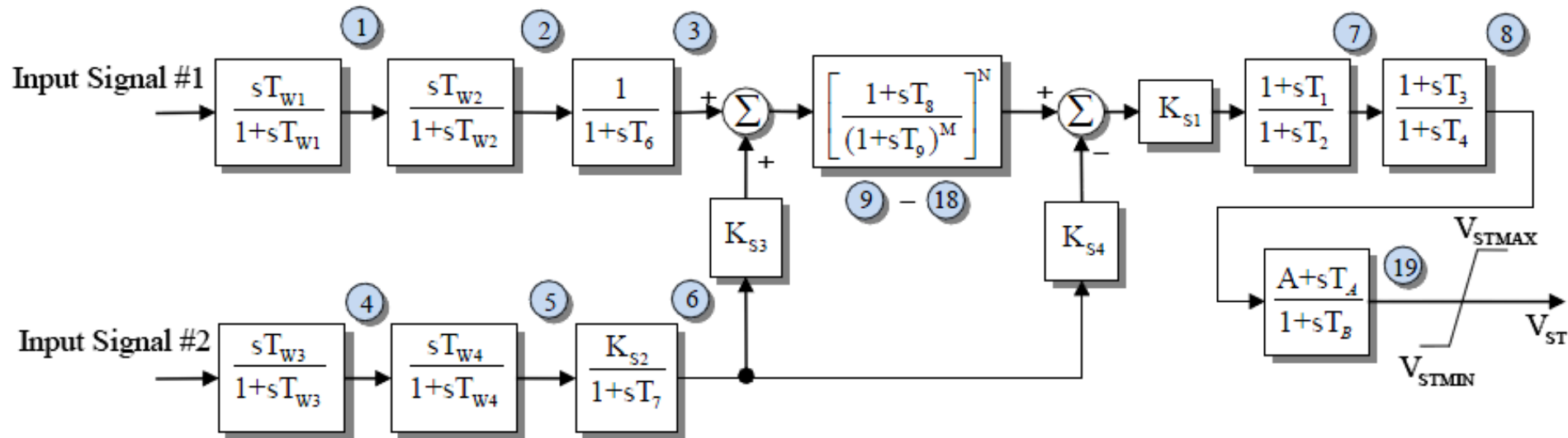
- Clearly the case is unstable; note the change in scale



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



In addition to exciters, IEEE Std 421.5 describes the common stabilizers

Washout Filters and Lead-Lag Compensators



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

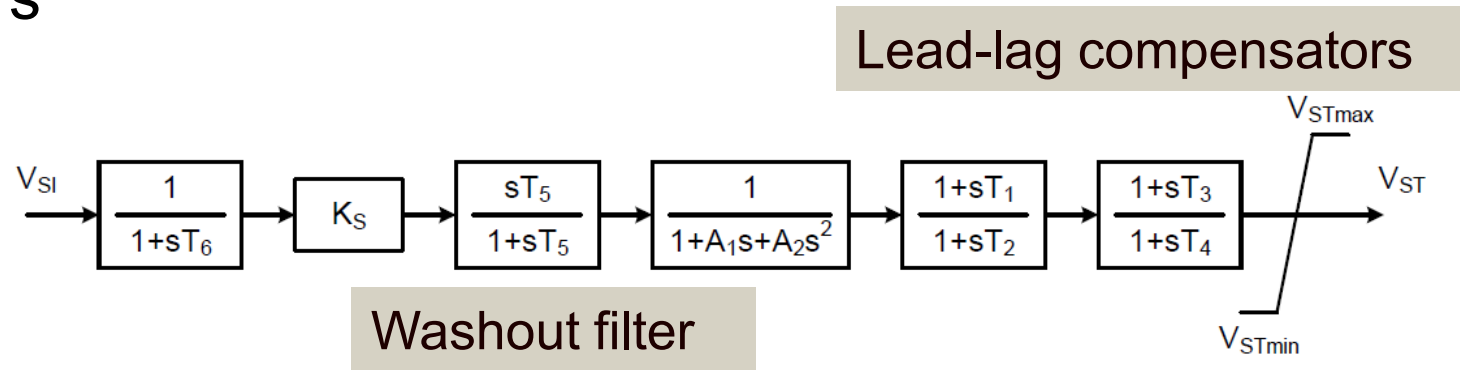


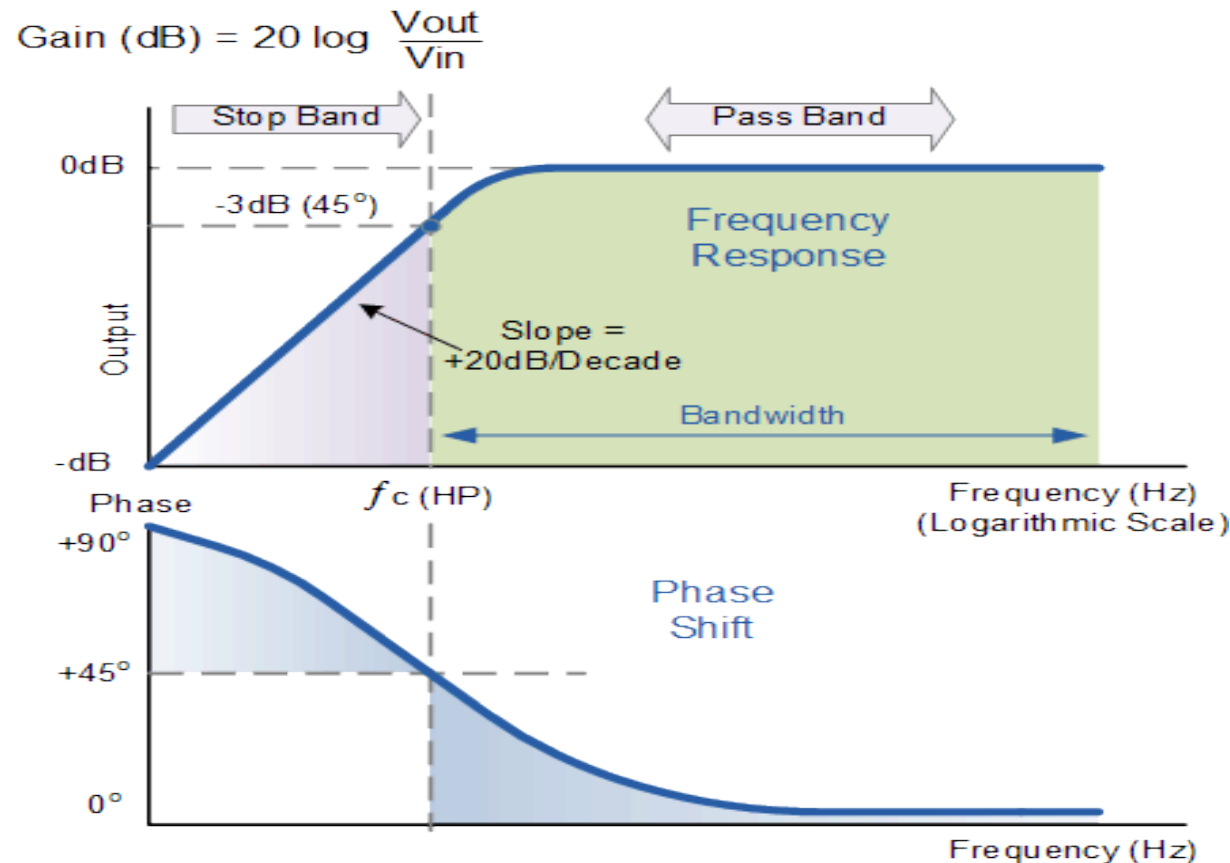
Figure 31 —Type PSS1A single-input power system stabilizer

- 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 ($1/\sqrt{2}$)

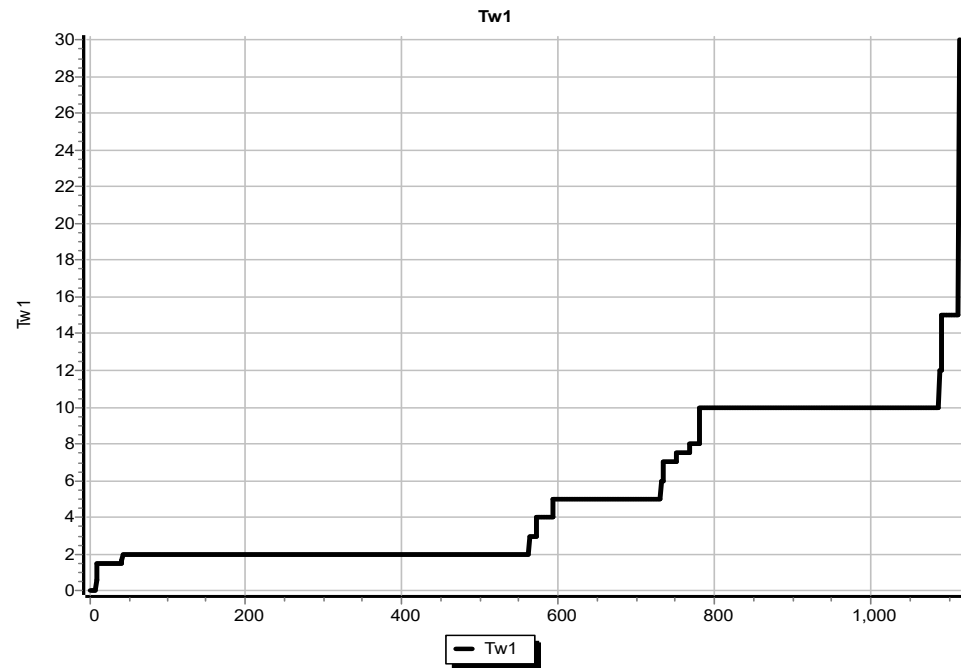
A larger T value shifts the breakpoint to lower frequencies; at $T=10$ the breakpoint frequency is 0.016 Hz

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

Washout Parameter Variation



- The PSS2A is the most common stabilizer in both the EI and WECC cases. Plots show the variation in TW1 for EI (left) and WECC cases (right); for both the x-axis is the number of PSS2A stabilizers sorted by TW1, and the y-axis is TW1 in seconds



Lead-Lag Compensators



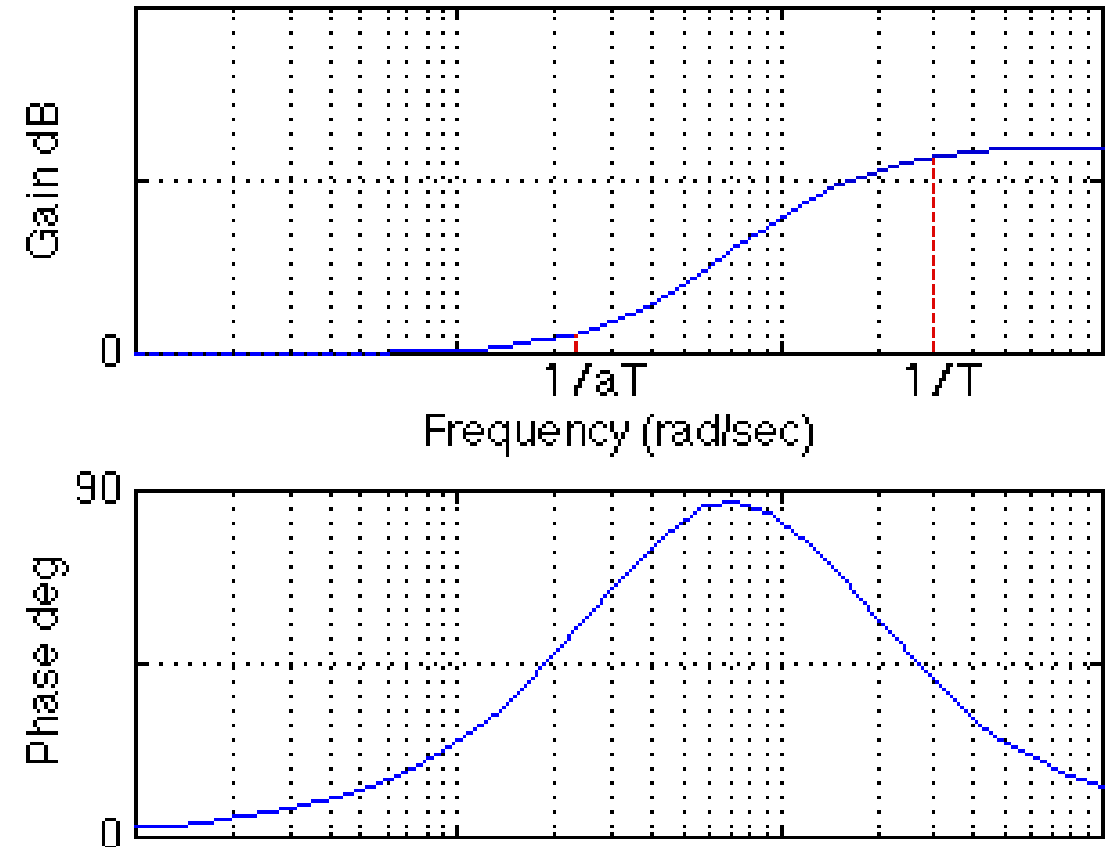
- For a lead-lag compensator of the below form with $a \leq 1$ (equivalently $a \geq 1$)

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

- 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

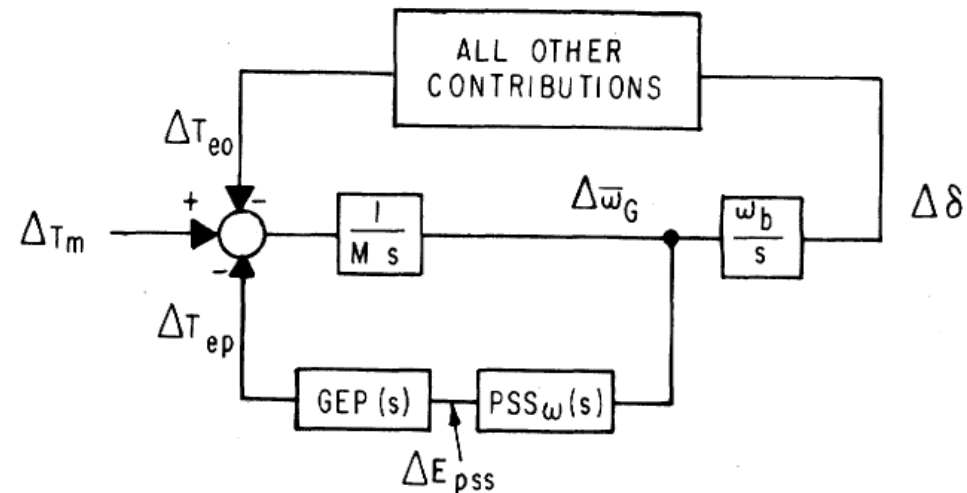


Image Source: Figure 1 from Larsen, 1981, Part 1

Stabilizer Design, 2



- T6 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; T5 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

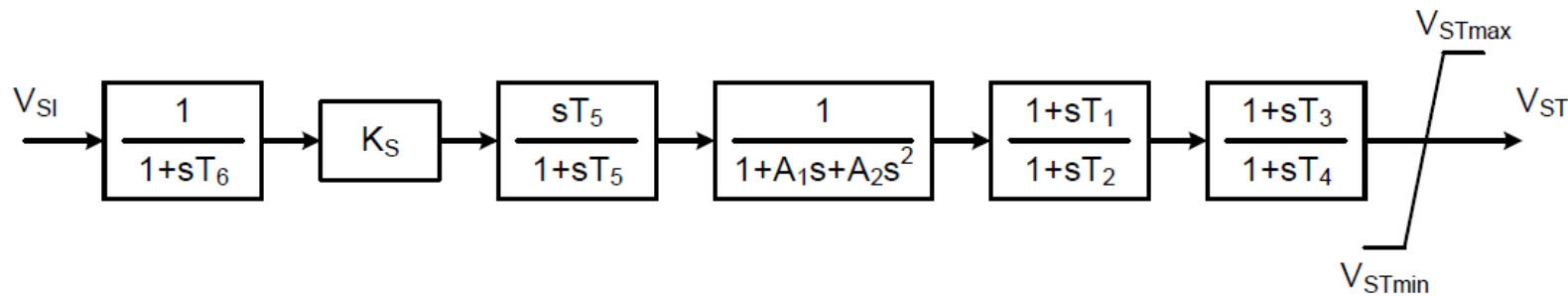


Figure 31 —Type PSS1A single-input power system stabilizer

Image Source:
EEE Std 421.5-2016

Stabilizer Design Values



- With a washout filter value of $T5 = 10$ at 0.1 Hz ($s = j0.2\pi = j0.63$) the gain is 0.987; with $T5 = 1$ 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 $T1=T3$ and $T2=T4$

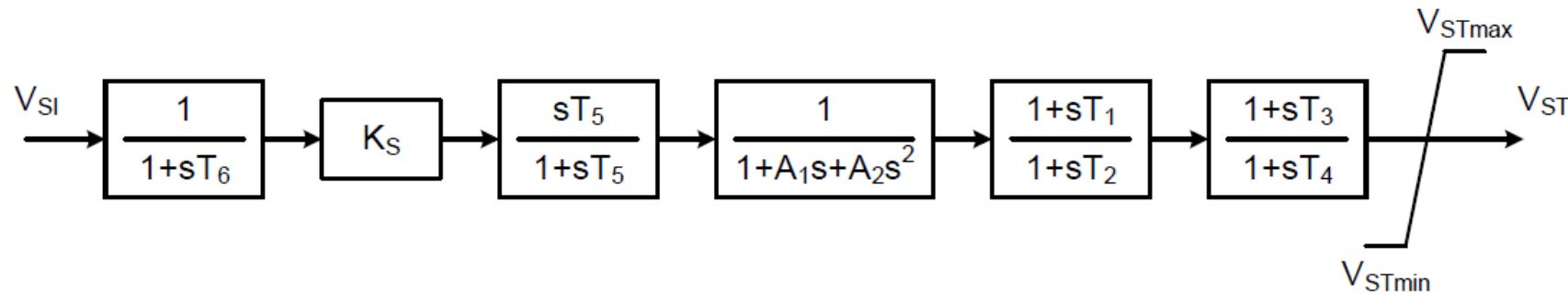


Figure 31 —Type PSS1A single-input power system stabilizer

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

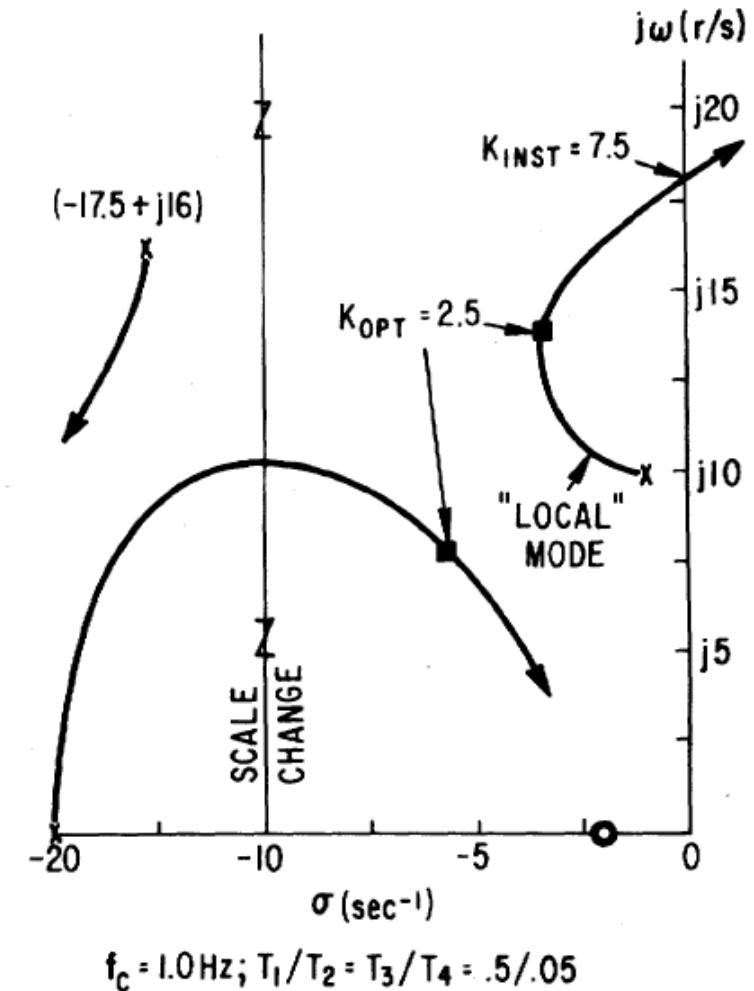
Stabilizer Design Tuning Criteria



- 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

- A practical method is to find K_{INST} , then set K_{OPT} as about $1/3$ to $1/2$ of this value



Stabilizer Design Tuning

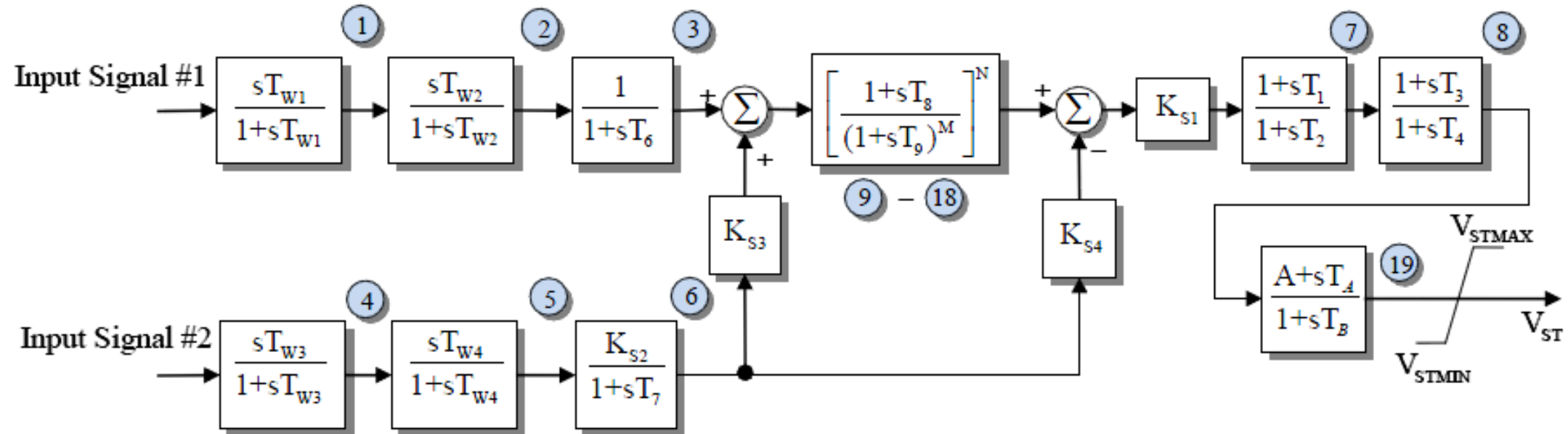


- Basic approach is to provide enhanced damping at desired frequencies; the challenge is power systems can experience many different types of oscillations, ranging from the high frequency local modes to the slower (< 1.0 Hz usually) inter-area modes
- Usually the PSS should be set to compensate the phase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

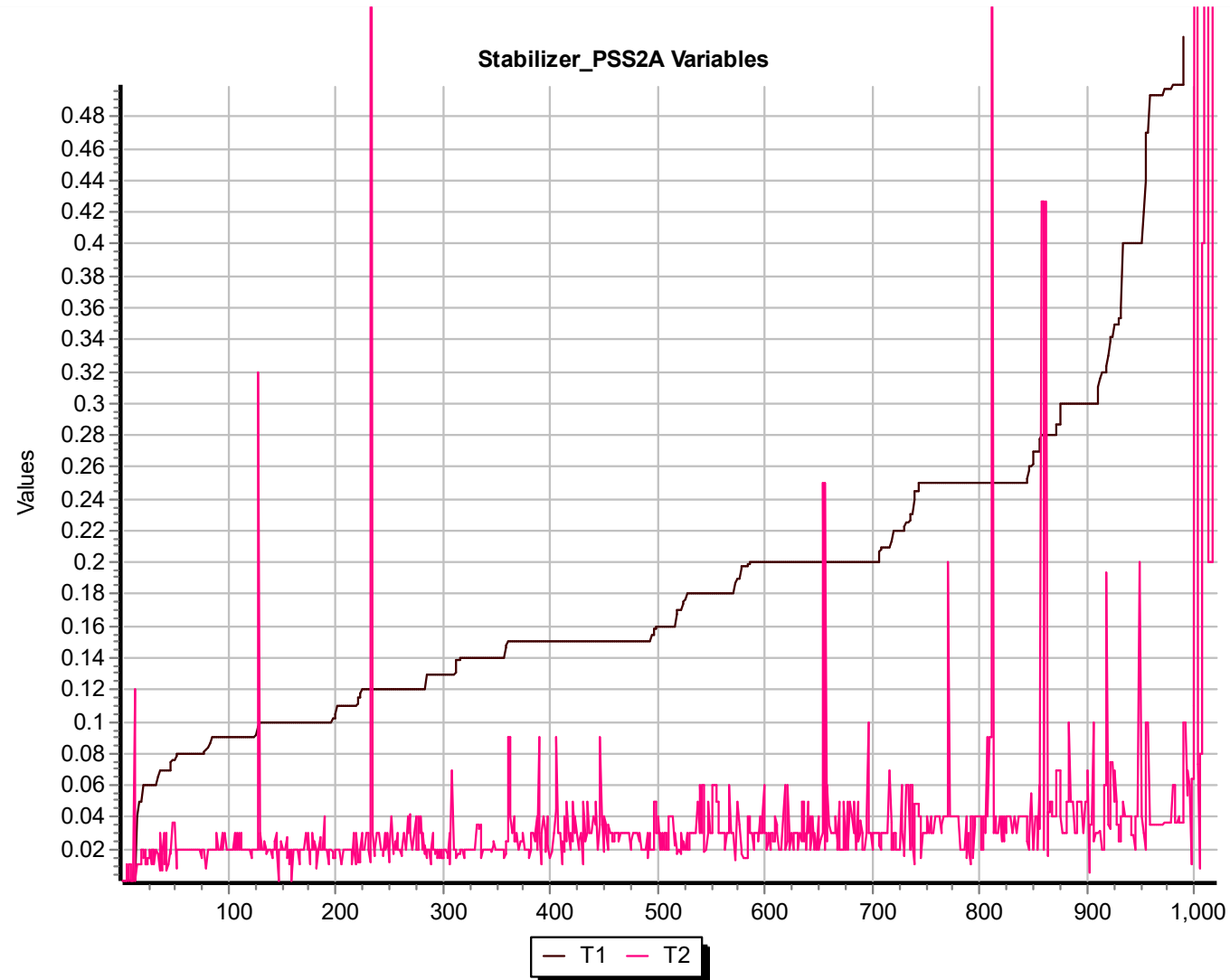
PSS2A Example Values



- Based on about 1000 WECC PSS2A models
 - T1=T3 about 64% of the time and T2=T4 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



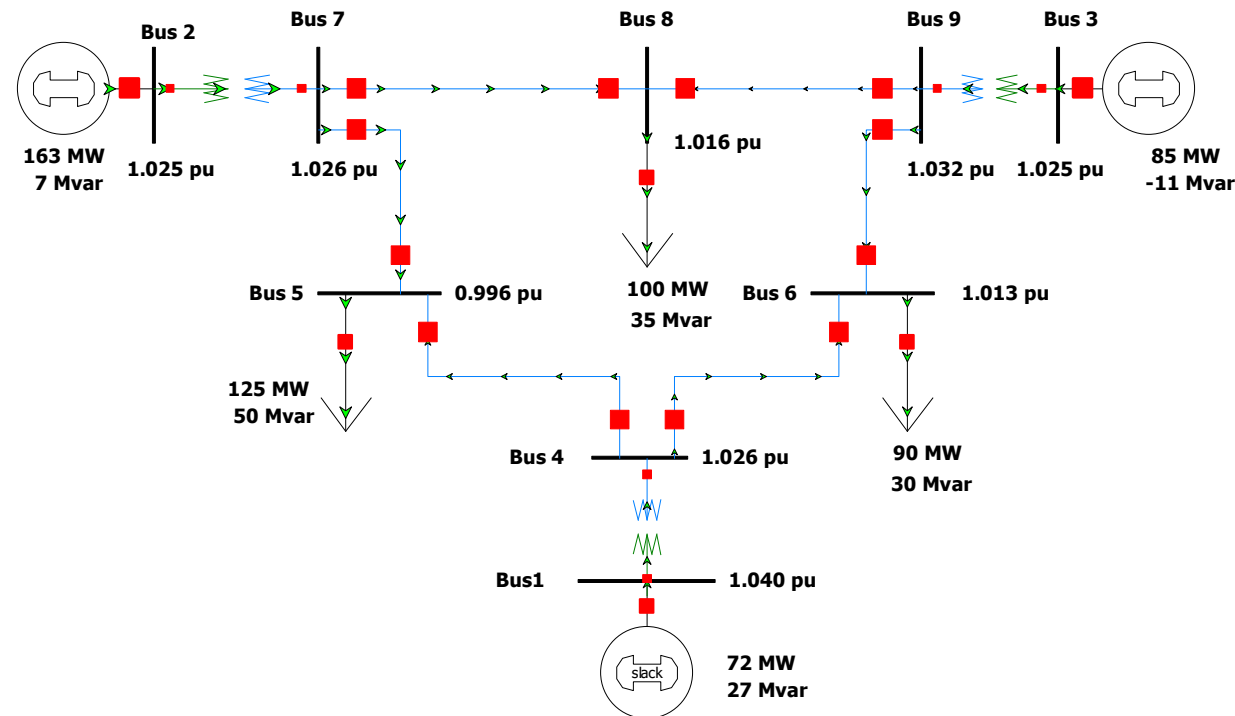
Example T1 and T2 Values



PSS Tuning Example



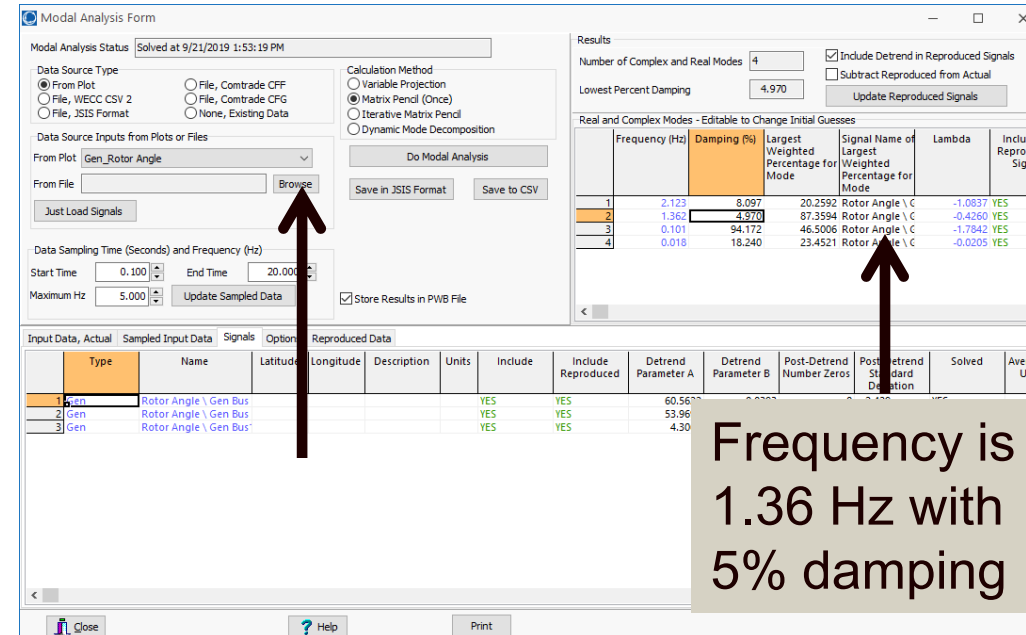
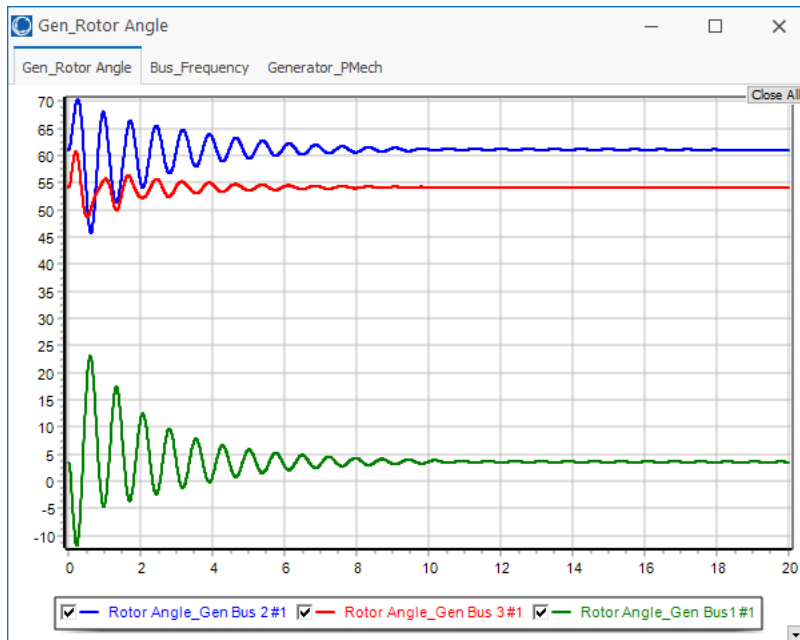
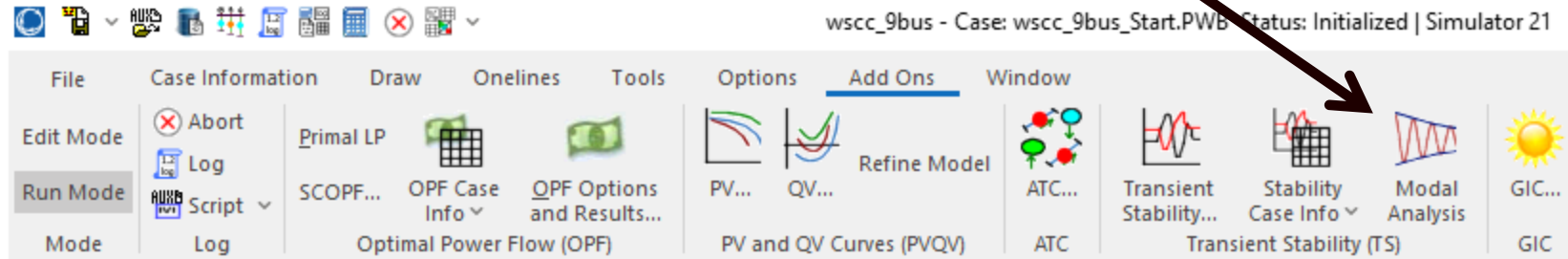
- Open the case wscs_9bus_Start, apply the default dynamics contingency of a self-clearing fault at Bus 8.
- Use Modal Analysis to determine the major modal frequency and damping



PSS Example: Getting Initial Frequency, Damping



- The Modal Analysis button provides quick access



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

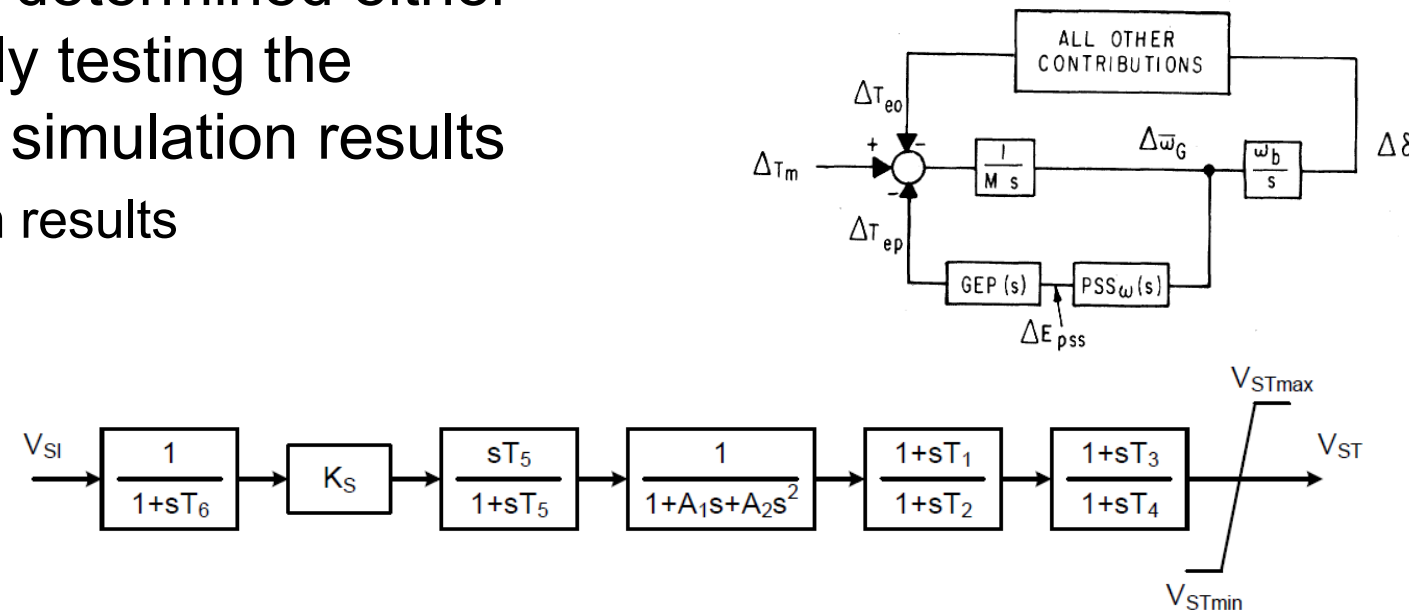


Figure 31 —Type PSS1A single-input power system stabilizer

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 wsc_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 Find By Number
Bus Name: Bus 2 Find By Name
ID: 1 Find ...
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)

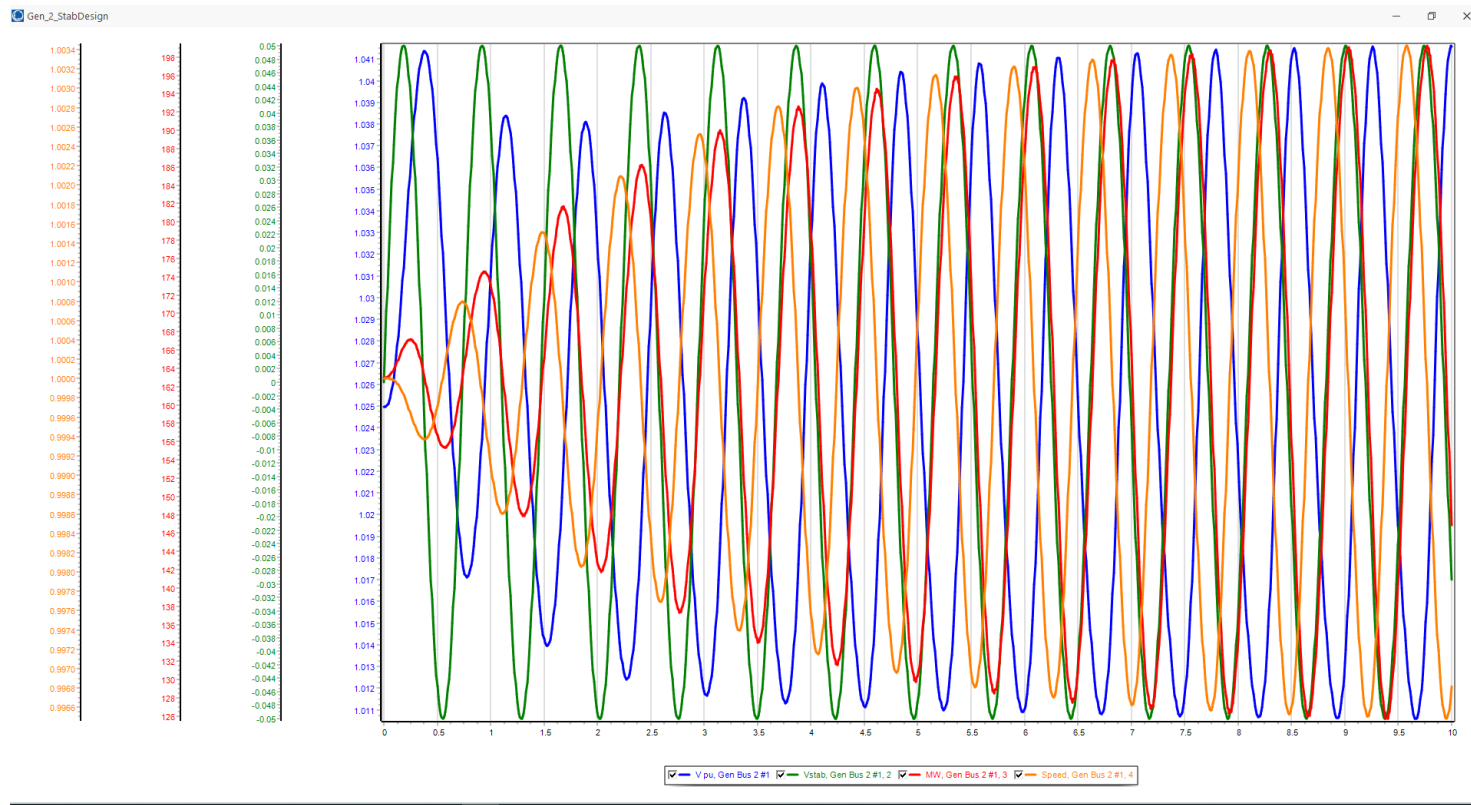
Power and Voltage Control Costs OPF Faults Owners, Area, etc. Custom Stability
Machine Models Exciters Governors Stabilizers Other Models Step-up Transformer Terminal and State
Insert Delete Gen MVA Base: 250.0 Show Block Diagram Create VCurve
Type: SIGNALSTAB ☐ Active (only one may be active) Set to Defaults
Parameters
PU values shown/entered using device base of 250.0 MVA
DoRamp: 0 dVolt4: 0.00000
StartTime: 0.00000 dVolt5: 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
OK Save Save to Aux Cancel Help Print

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

Modal Analysis Mode Details

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

Transfer Results from Selected Column to Object Custom Floating Point Field

Custom Floating Point Field 1 Transfer Results

	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

Close

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

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

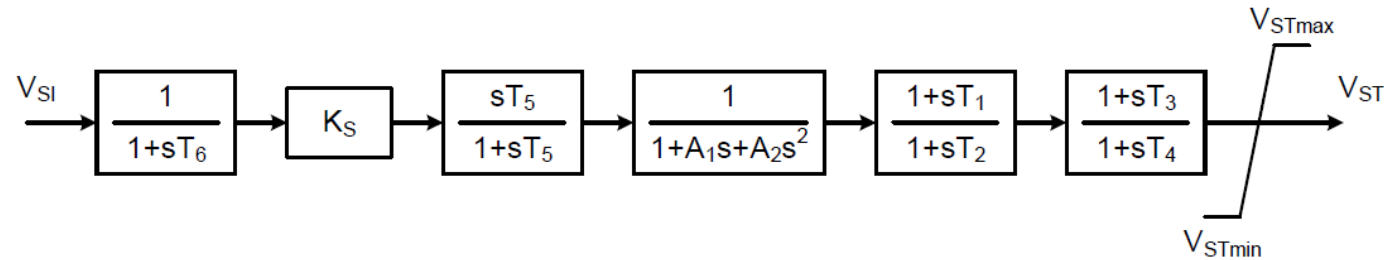
- In our example with $\phi = 50^\circ$ then

$$\frac{1 - \sin \phi}{1 + \sin \phi} = 0.132, T_1 = 0.321, T_2 = \alpha T_1 = 0.042$$

PSS Tuning Example: 1.36 Hz Lead-Lag Values, 2



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

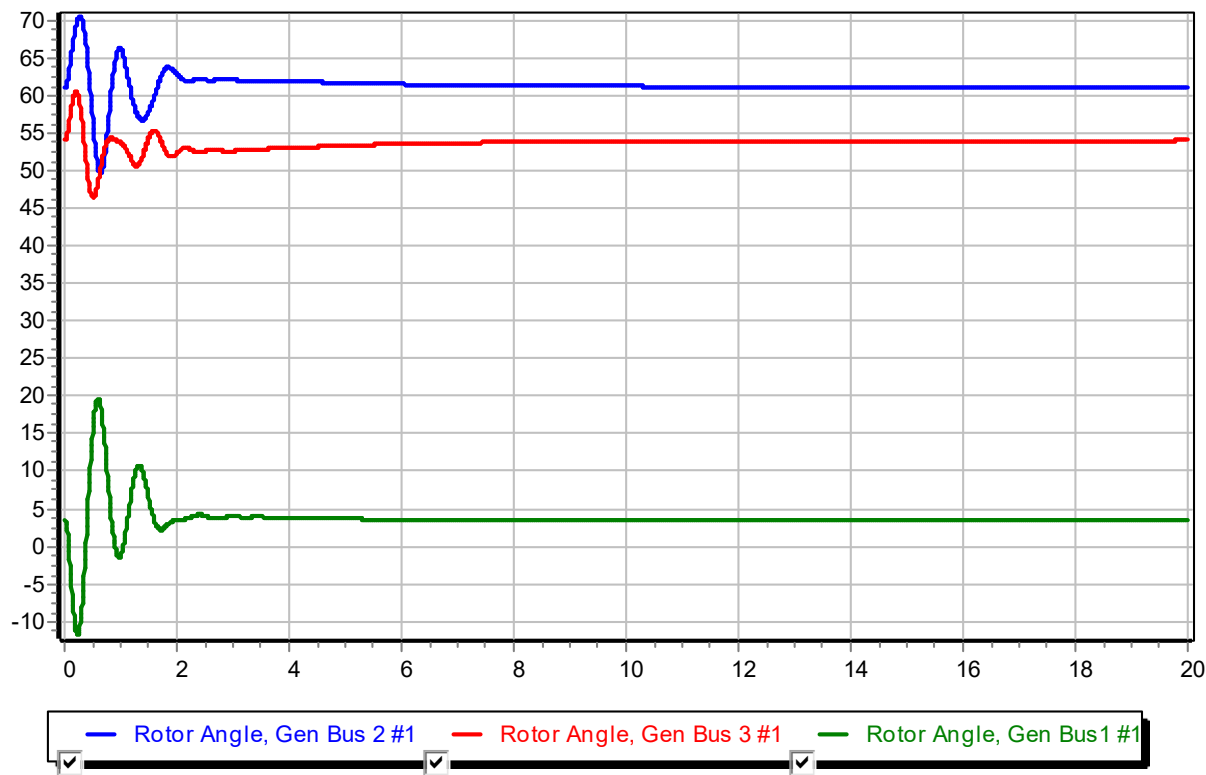


- The last step is to determine K_s . This is done by finding the value of K_s at just causes instability (i.e., K_{INST}), and then setting K_s to about 1/3 of this value
 - Instability is easiest to see by plotting the output (V_{ST}) value for the stabilizer

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

Modal Analysis Mode Details

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

Transfer Results from Selected Column to Object Custom Floating Point Field

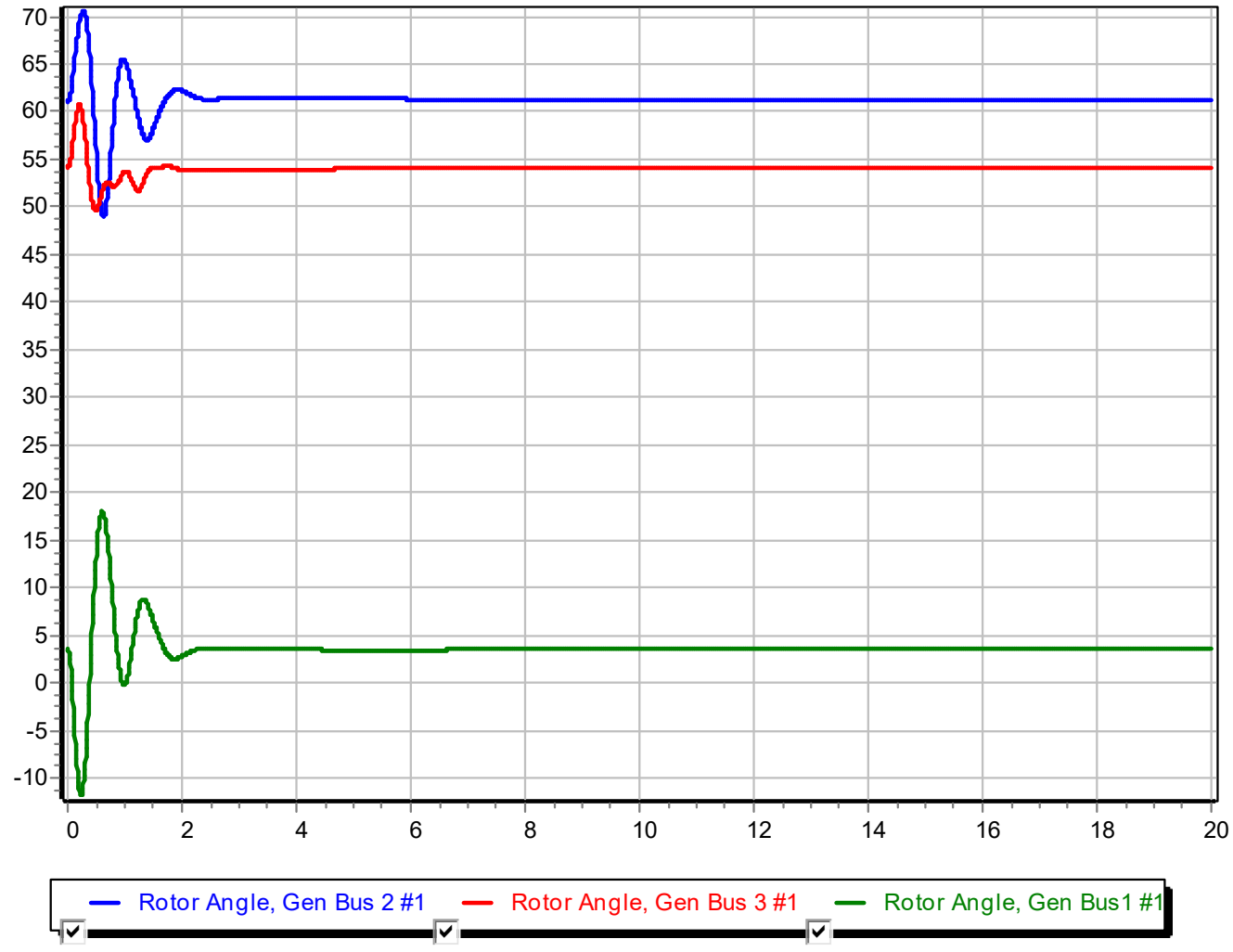
Custom Floating Point Field 1 Transfer Results

	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

Close

- The values are $a = 0.283$, $T1=0.22$, $T2=0.062$, KS for the verge of instability is 36, so KS optimal is 12.

PSS Tuning Example: Final Solution

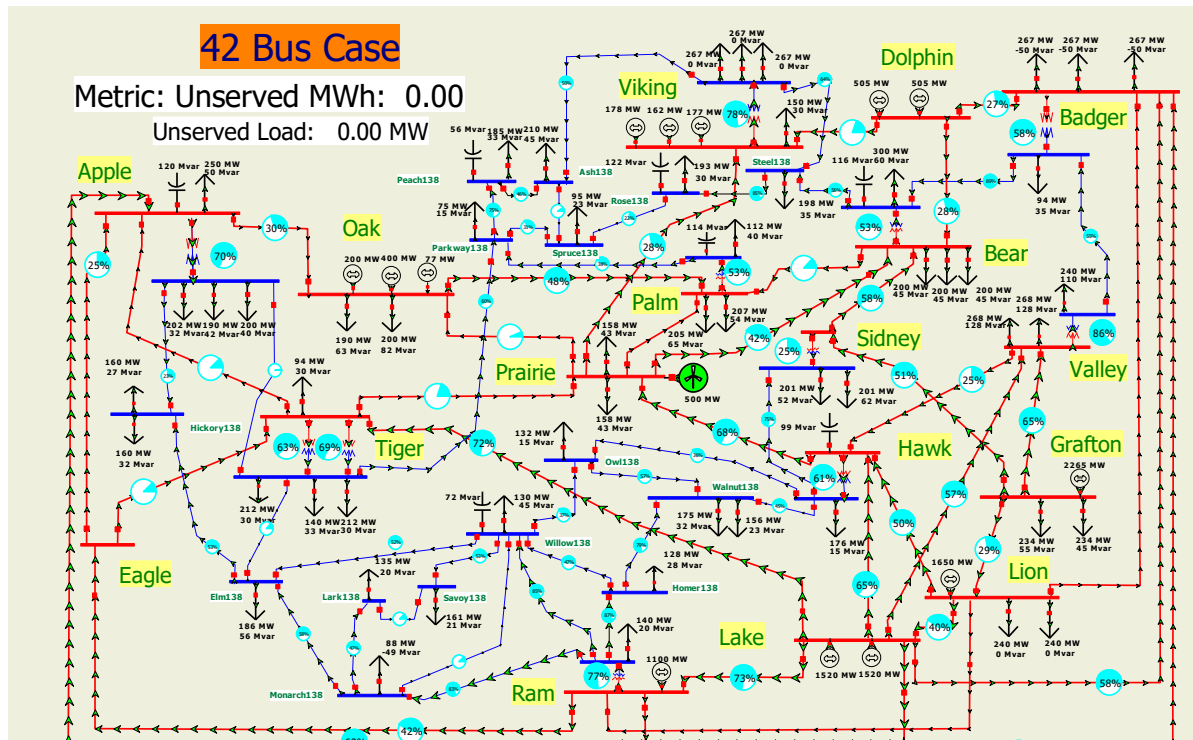


With stabilizers at buses 2 and 3 the damping has been increased to 25.7%

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

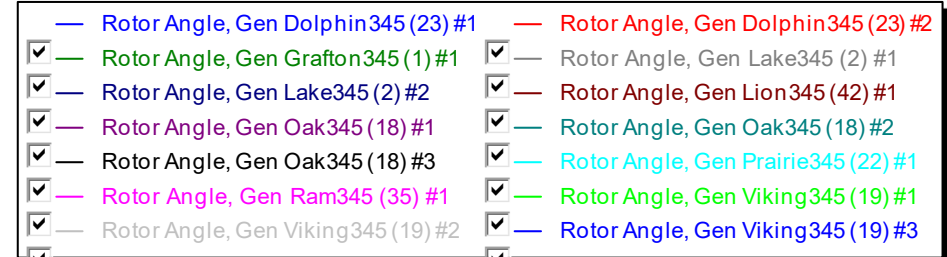
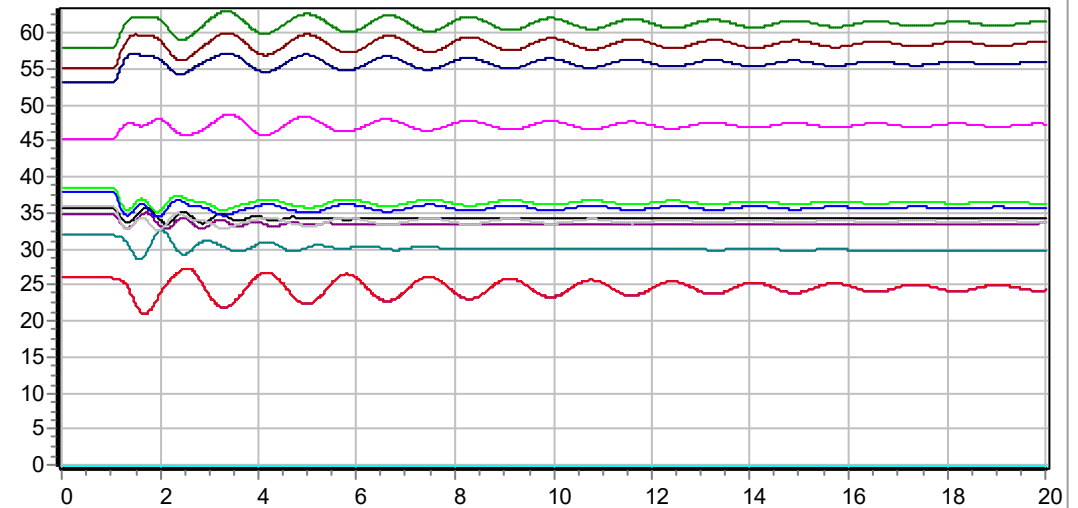
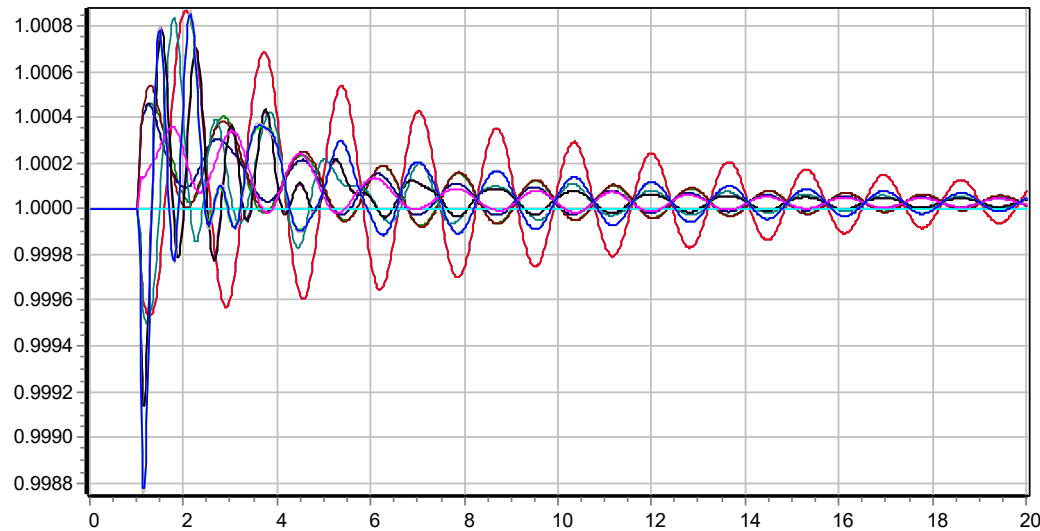


The starting case name is **Bus42_PSS**

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: Quantified Using Modal Analysis



Modal Analysis Form

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

Data Source Type

- ☒ From Plot
- ☐ File, Comtrade CFF
- ☐ File, WECC CSV 2
- ☐ File, Comtrade CFG
- ☐ File, J3IS Format
- ☐ None, Existing Data

Data Source Inputs from Plots or Files

From Plot: Gen_Speed

From File: Browse

Just Load Signals

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 3.000 End Time: 14.000

Maximum Hz: 5.000 Update Sampled Data

Calculation Method

- ☐ Variable Projection
- ☐ Matrix Pencil (Once)
- ☒ Iterative Matrix Pencil
- ☐ Dynamic Mode Decomposition

Do Modal Analysis

Save in J3IS Format Save to CSV

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

Update Reproduced Signals

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 Reproduced Signal
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 Re	-0.4338	YES
4	0.605	2.890	2.634	Speed \ Gen Re	-0.1098	YES
5	0.056	60.018	52.188	Speed \ Gen Re	-0.2222	YES
6	0.000	-100.000	12.3306	Speed \ Gen Re	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	Average Unsolved
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	YES	1.0001	-0.0000	0	0.000	YES	
13 Gen	Speed \ Gen Viking345					YES	YES	1.0001	-0.0000	0	0.000	YES	
14 Gen	Speed \ Gen Viking345					YES	YES	1.0001	-0.0000	0	0.000	YES	

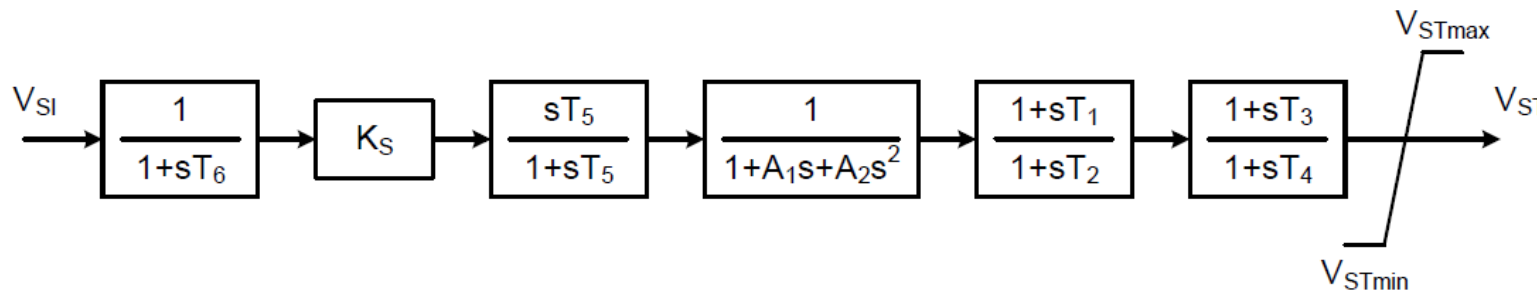
Close ? Help Print

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 $a = 0.72$; 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.



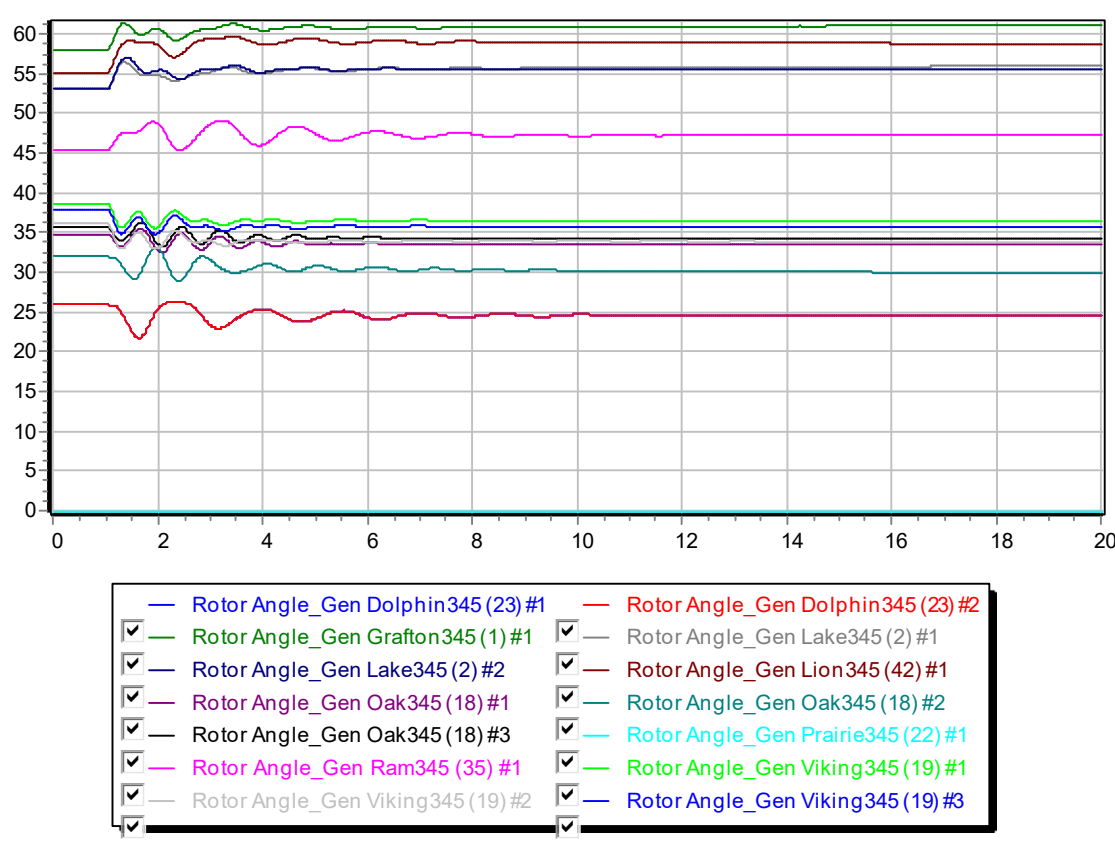
The case with the test signal is **Bus42_PSS_Test**

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