ECEN 667
Power System Stability

Lecture 23: Inter-Area Modes, Stabilizers

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TEXAS A&M UNIVERSITY

Announcements

- Read Chapters 8 and 9 (8.6 covers stabilizers)
- Homework 6 is due today
- Homework 7 should be done before the second exam
- As noted in the syllabus, the second exam is on Thursday Nov 30, 2023
  - On campus students will take it during class (80 minutes) whereas distance learning students should contact Sanjana.
  - The exam is comprehensive, but emphasizes the material since the first exam; it will be of similar form to the first exam
  - Two 8.5 by 11 inch hand written note sheets are allowed, front and back, as are calculators

Large Grid Inter-Area Modes

- Analyzing the wide-area dynamic respond of electric grids using the concept of modes has been a helpful approach for many years
- In North America much of the work has been done in the WECC, with several identified distinct Inter-Area modes
- Less work has been done on the Eastern Interconnect (EI) and ERCOT, but there are still some identified modes
- Recent research has questioned the extent to which a few distinct modes exist particularly for the EI

A Few North America Grid Oscillation Publications

- There is lots of prior work describing electric grid oscillations. A few examples for North American grid oscillations include
  - F.R. Schleif, J.H. White, “Damping for the Northwest – Southwest Tieline Oscillations – An Analog Study,” IEEE Trans. Power App. & Syst., vol. PAS-85, pp. 1239-1247, Dec. 1966.
  - Interconnection Oscillation Analysis, NERC, July 2019.
  - J. Follum, T. Becejac, R. Huang, "Estimation of Electromechanical Modes of Oscillation in the Eastern Interconnection from Ambient PMU Data," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference, Washington, DC, USA, Feb. 2021.
  - *Modes of Inter-Area Oscillations in the Western Interconnection*, Western Interconnection Modes Review Group, WECC, 2021.
  - R.T. Elliott, D.A. Schoenwald, “Visualizing the Inter-Area Modes of the Western Interconnection,” IEEE PES 2022 General Meeting, Denver, CO, July 2022.
  - J. Follum, N. Nayak, J. Eto, “Online Tracking of Two Dominant Inter-Area Modes of Oscillation in the Eastern Interconnect,” 56th Hawaii International Conference on System Sciences, Lahaina, HI, Jan. 2023.
  - T.J. Overbye, S. Kunkolienkar, F. Safdarian, A. Birchfield, “On the Existence of Dominant Inter-Area Oscillation Modes in the North American Eastern Interconnect Stability Simulations”, 57th Hawaii International Conference on System Sciences, Honolulu, HI, January 2024.

North America Grid Oscillation Modes

- In North American grids there are identified modes that have names, examples include
  - WECC North-South A (NSA): Alberta vs System (0.20 to 0.30 Hz) (10 - 25% damping)
  - WECC North-South B (NSB): Alberta vs BC+N US vs S US (0.35 to 0.45 Hz) (5-10%)
  - WECC East-West A (EWA): Colorado + E. Wyoming vs System (0.35 to 0.45 Hz)
  - WECC British Columbia A (BCA): BC vs N. US vs S. US (0.50 to 0.72 Hz)
  - WECC BCB W. edge vs System vs E. edge (0.60 to 0.72 Hz)
  - Eastern Interconnect (EI) Northeast vs South (NE-S) (0.15 to 0.22 Hz) (10 – 25%)
  - EI Northeast vs Midwest (NE-MW) (0.18 to 0.27 Hz) (10 – 25%)
- If they exist, at a particular operating point a mode will have a frequency, a damping and a shape, with these values changing some as the operating point changes

Do Distinct Inter-Area Modes Exist?

- Since the modes have been observed under many different conditions they have quite a bit of variability in their values. There could be two explanations for this, both of which are consistent with the observed results
  - One explanation: at a particular operating point the North American grids have a few well-defined modes, with each mode having a frequency, damping and shape. As long as a disturbance excites the mode, it should be observed. The goal is to find these modes
  - An alternative explanation: at a particular operating point the North American grids do not have a few well-defined modes. They certainly have oscillation patterns, but the frequency, damping and especially the shapes of these oscillations are disturbance dependent.

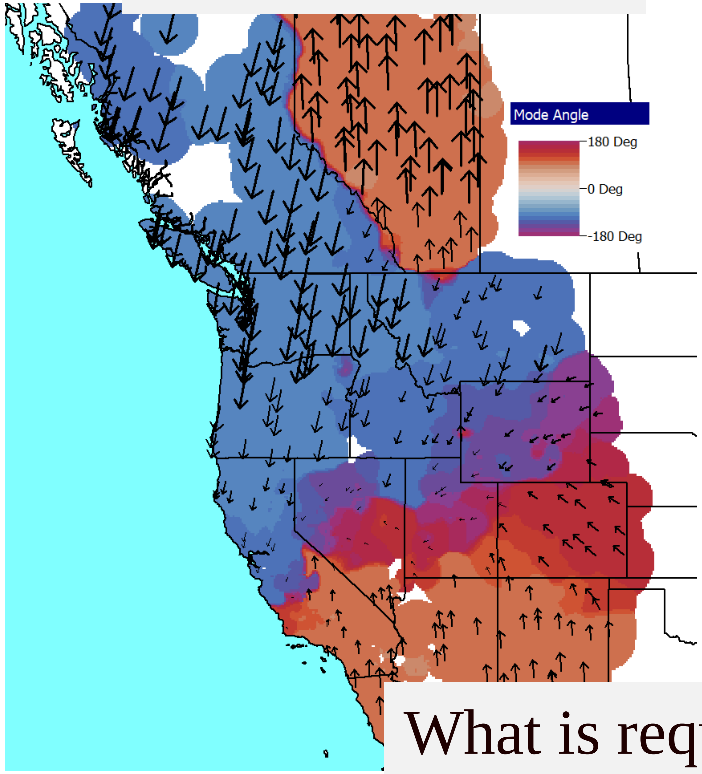
Electric Grids are Non-linear Systems

- Electric grids are non-linear systems, and are likely becoming more non-linear with the rapid growth of inverter-based resources and other controls
  - An increasing number of controls are either operated at limits, or will quickly reach a limit, meaning there might not be a valid linearization
  - Deadbands and other nonlinear controls mean that the grid's response to small perturbations can be quite different than its response to large disturbances
- Hence there is a need to question the degree to which linear analysis techniques can be used to explain the behavior of modern grids
- Even the linear system model has a number of modes that could be interacting
- This questioning is facilitated by recent developments in measurement-based modal analysis

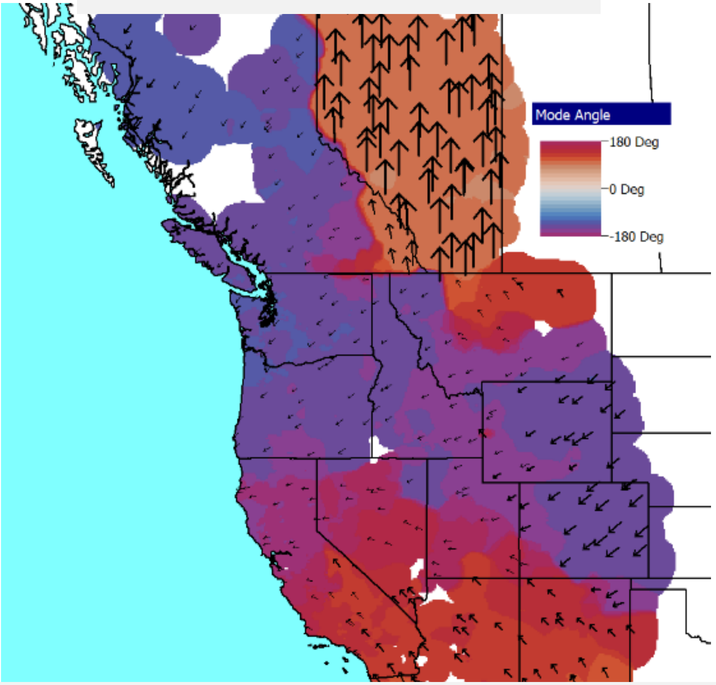
WECC Example 1

- Using a 2022 series, 25,000 bus WECC case at the same operating point for three different disturbances, the below modes are observed

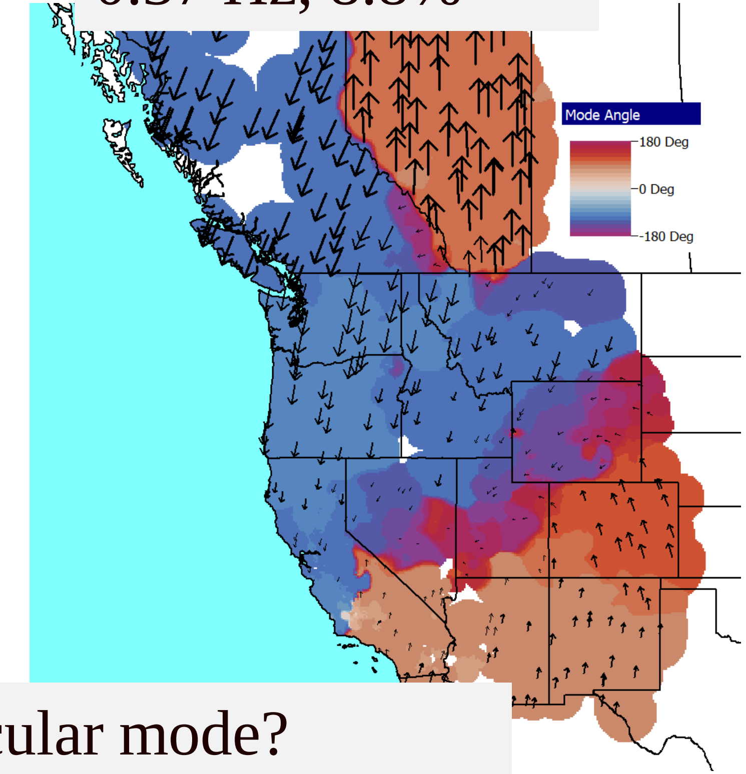
Disturbance A,
0.35 Hz, 12.6%



Disturbance B,
0.34 Hz, 10.0%



Disturbance C,
0.37 Hz, 8.8%

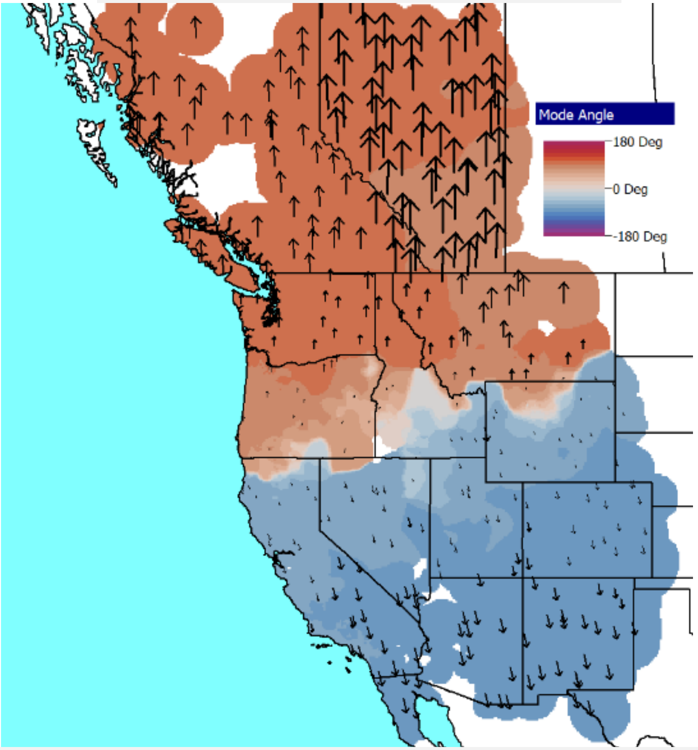


What is required to say the grid has a particular mode?

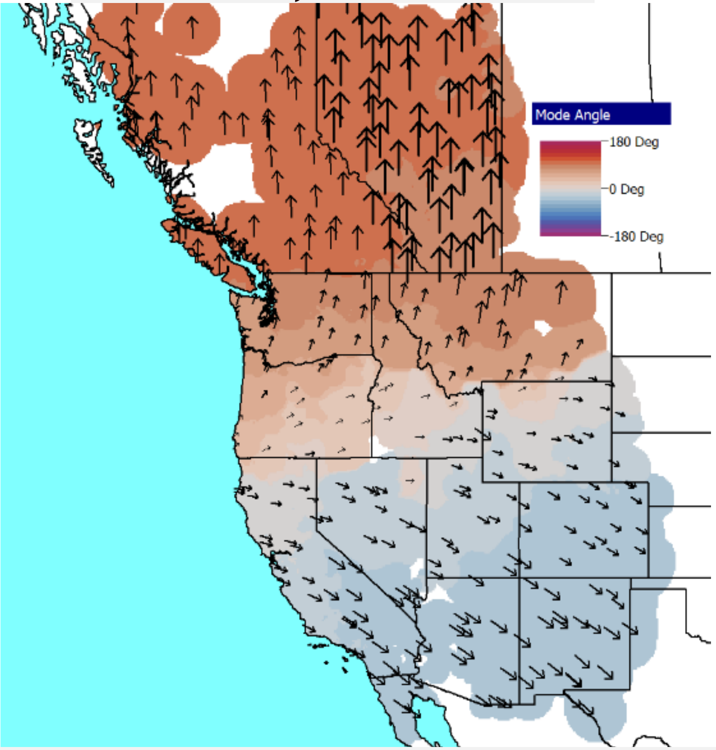
WECC Example 2

- Same operating point as Example 1

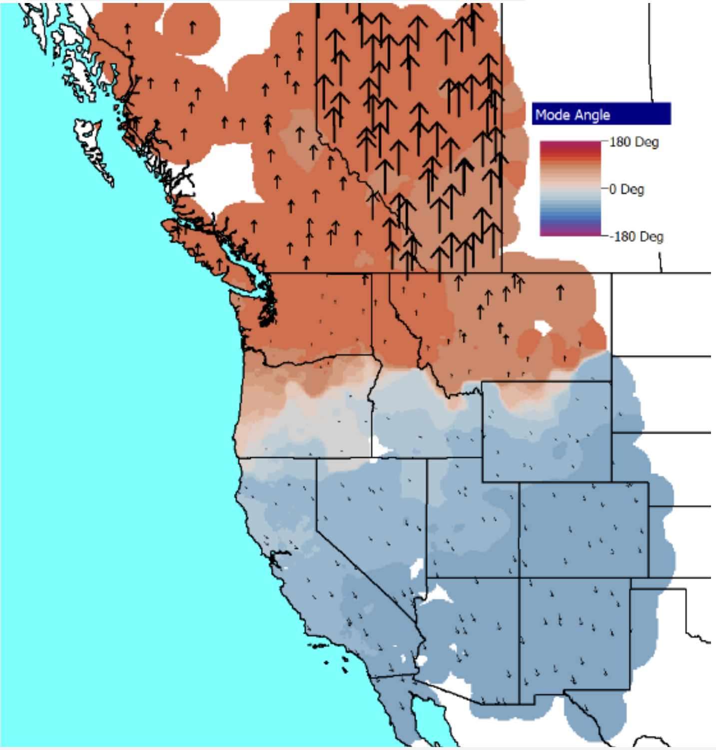
Disturbance A,
0.24 Hz, 15.5%



Disturbance B,
0.23 Hz, 11.6%



Disturbance C,
0.25 Hz, 5.0%



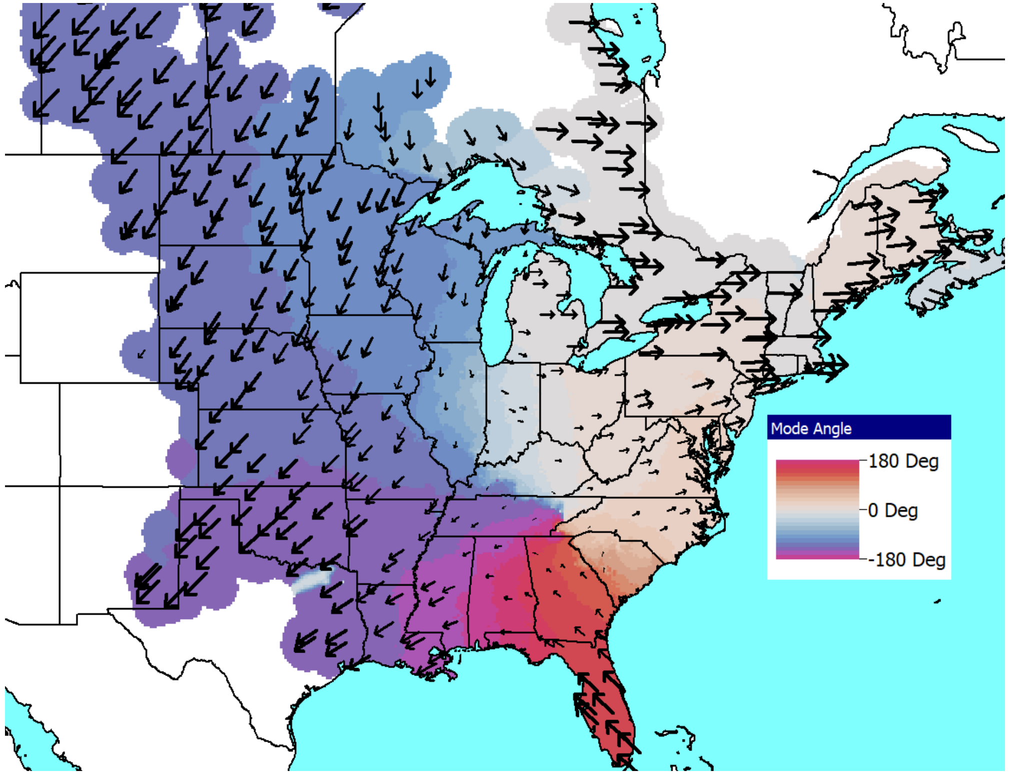
The results for these two examples are showing fairly consistent modes; these are the best observed ones in the WECC simulations

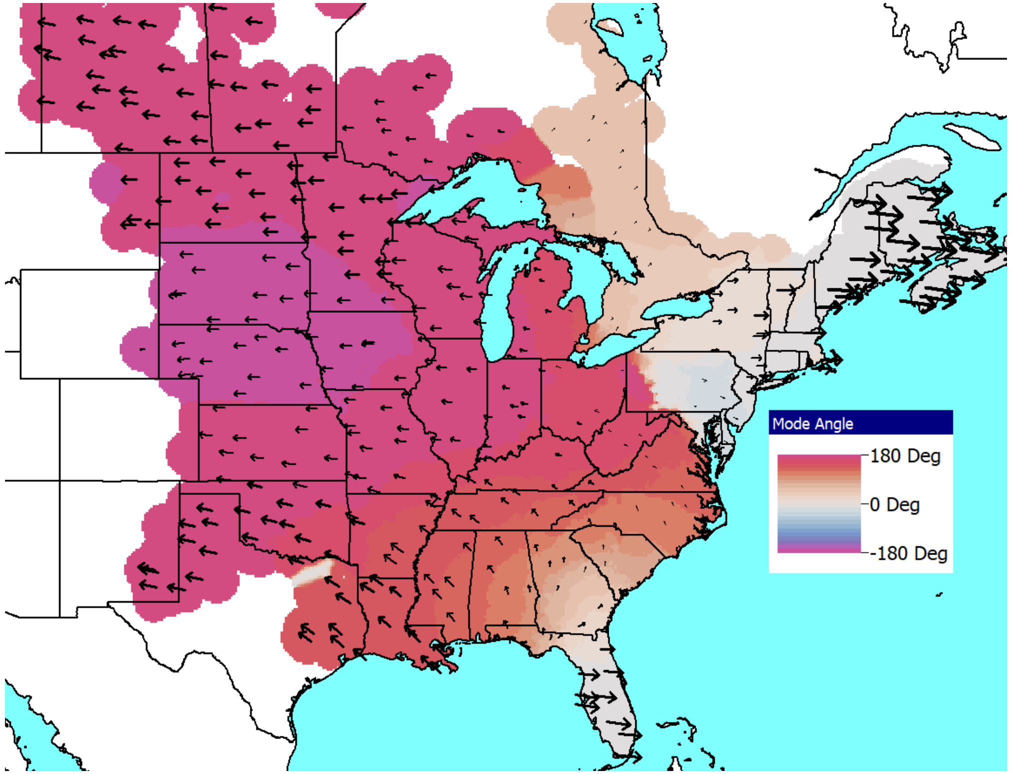
A Particular Focus is on Distinct Mode Existence

- Earlier literature mentions
  - Northeast vs South(NE-S) mode with a frequency of between 0.15 to 0.22 Hz, (10 – 25% damping)
  - Northeast vs Midwest (NE-MW) mode with a frequency of between 0.18 to 0.27 Hz, (10 – 25% damping
- Same procedure as before is used. That is, to apply a series of disturbances to the same operating point, calculate the modes using the IMP, and see if distinct modes are observed
  - The same previous three disturbance types are used

Analysis of Potential 0.27 Hz Mode

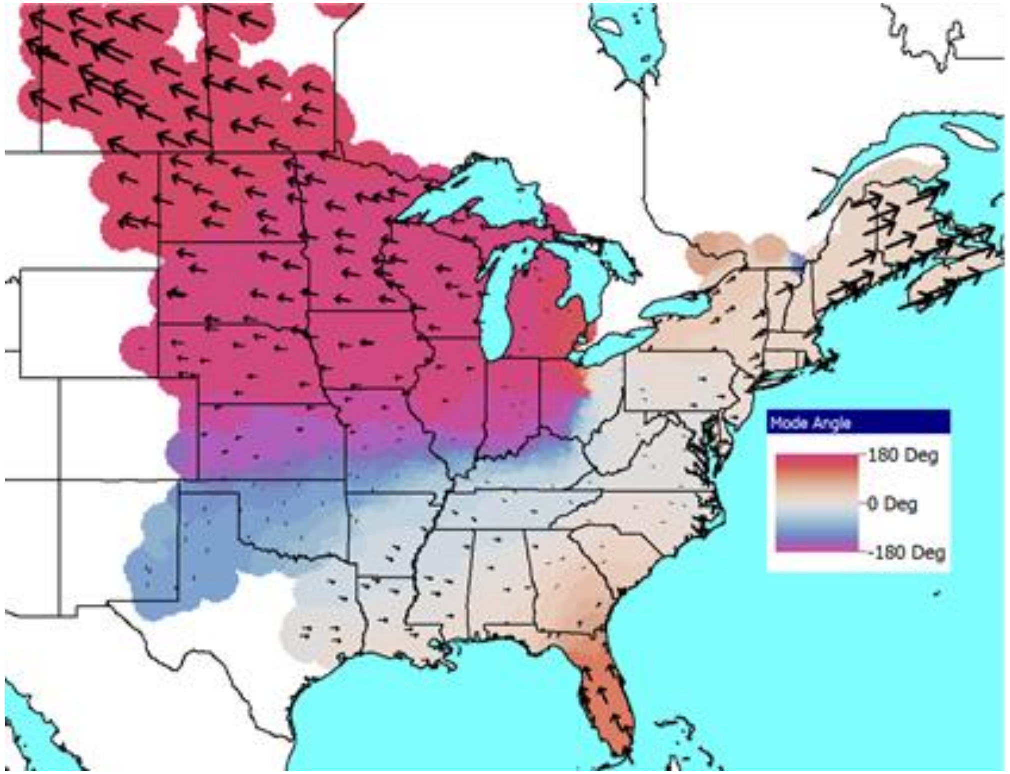
- Left image shows visualization of the 0.27 Hz mode (21.3%), while the right image shows a 0.25 Hz mode (20.2%) that is observed when the disturbance is changed to opening a generator in Nebraska

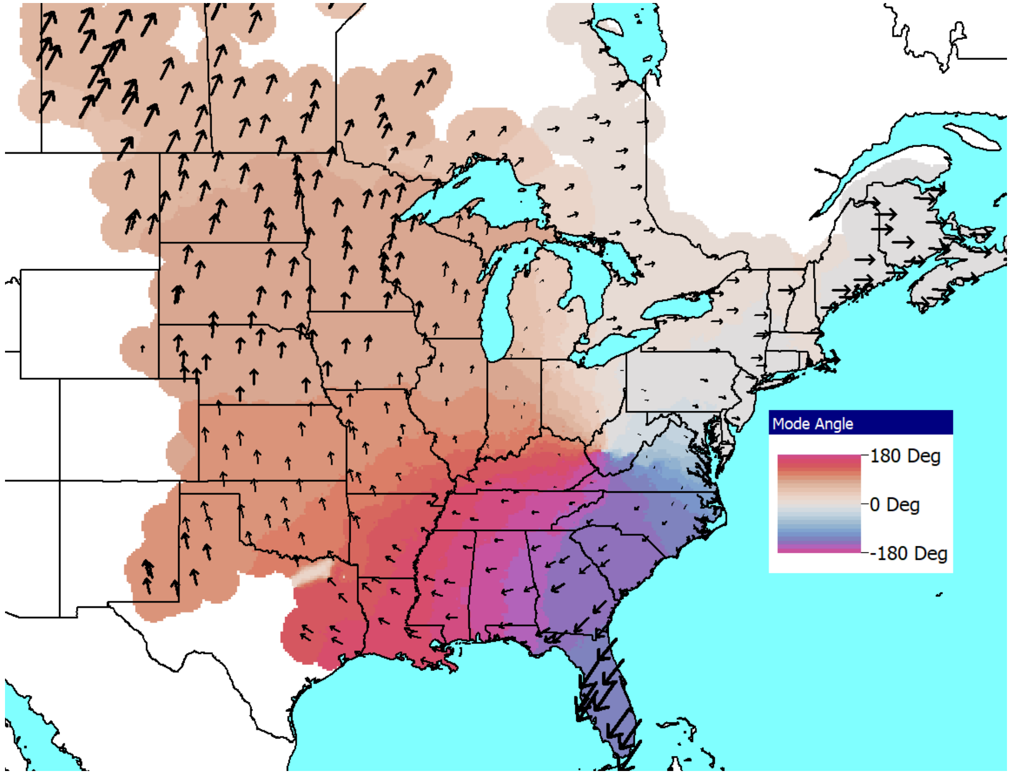




Analysis of Mississippi and Florida

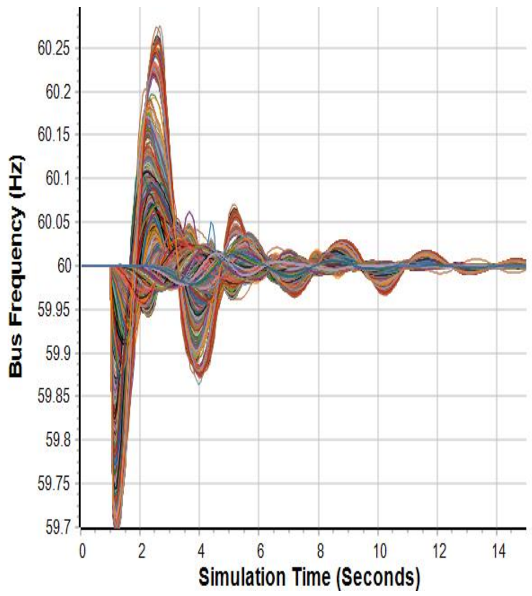
- The same approach is applied to opening large generators in Mississippi (0.25 Hz with 23.5%) and Florida (0.23 Hz with 21.5%)



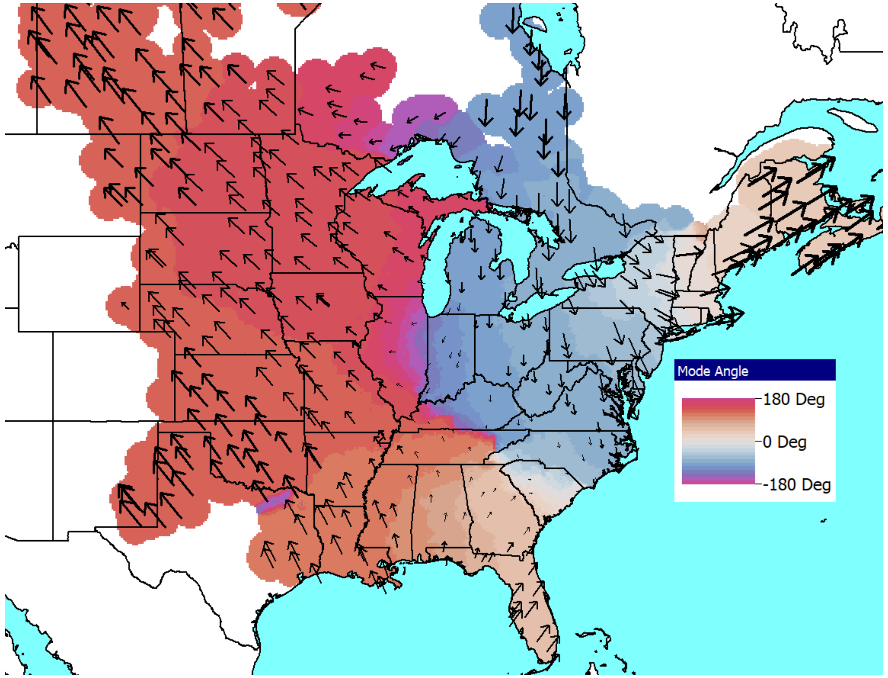


New England, Just Frequency Change

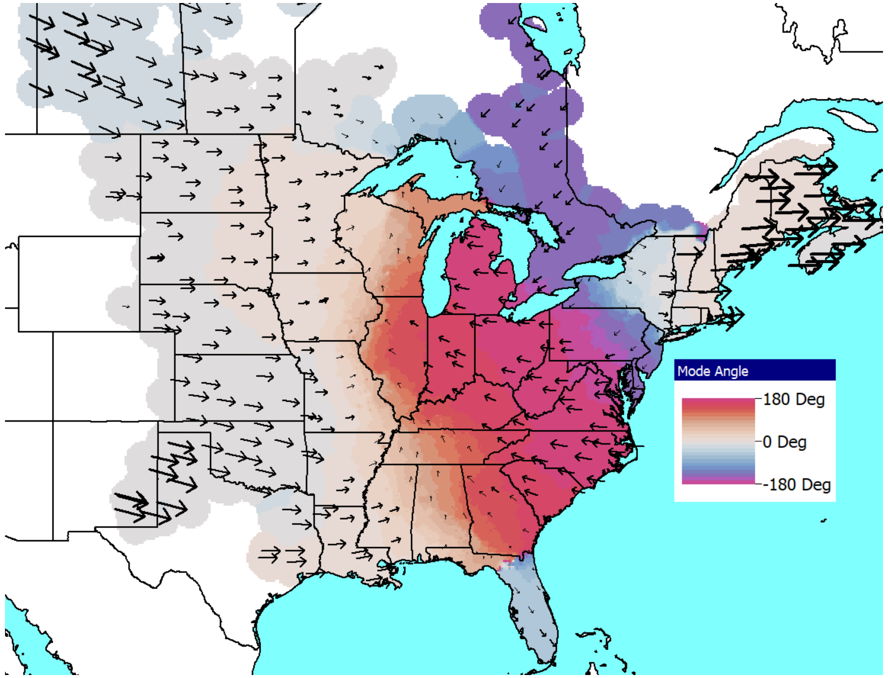
- Since opening generators changes the grid (albeit slightly in such a large grid), the frequency change disturbance can be used



0.22 Hz, 27.1% Damping

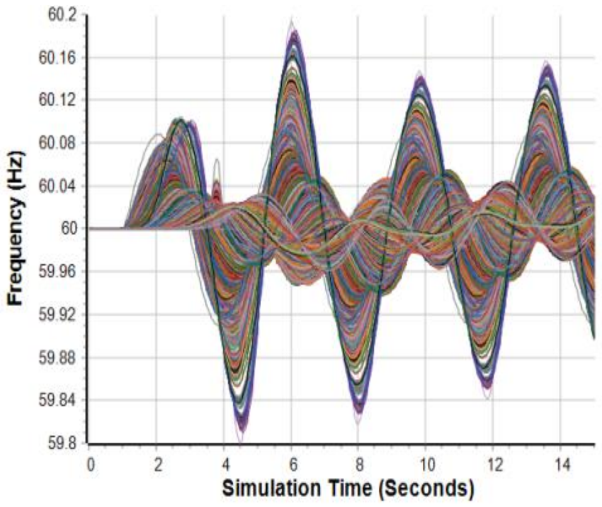


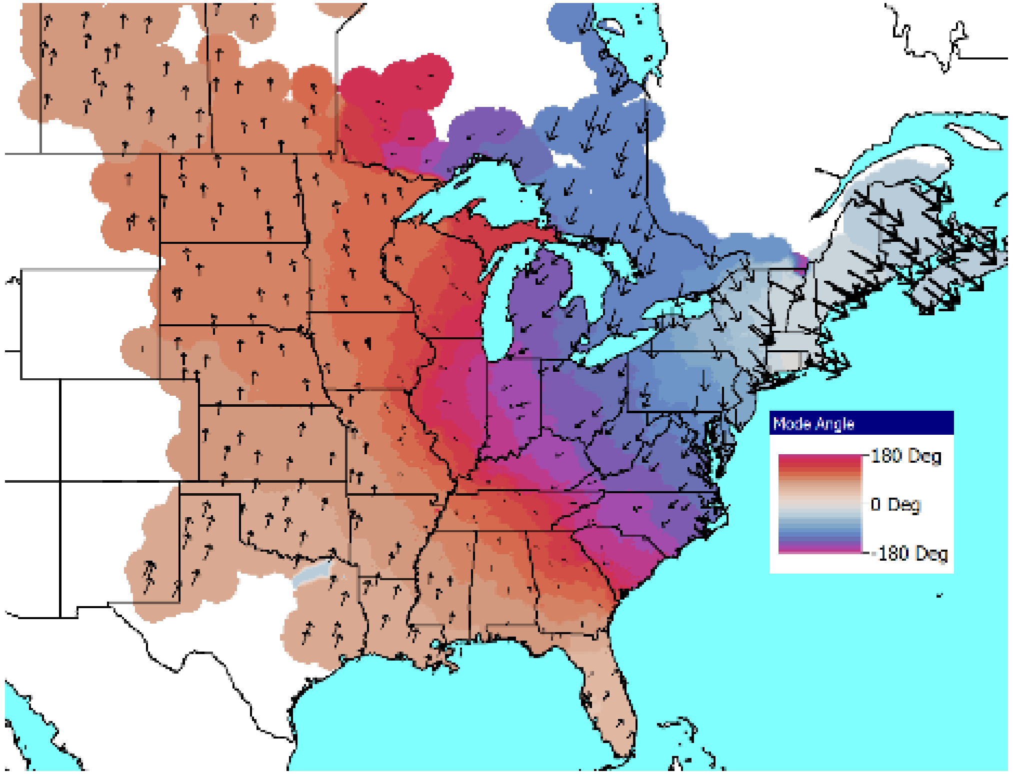
0.35 Hz, 15.0% Damping

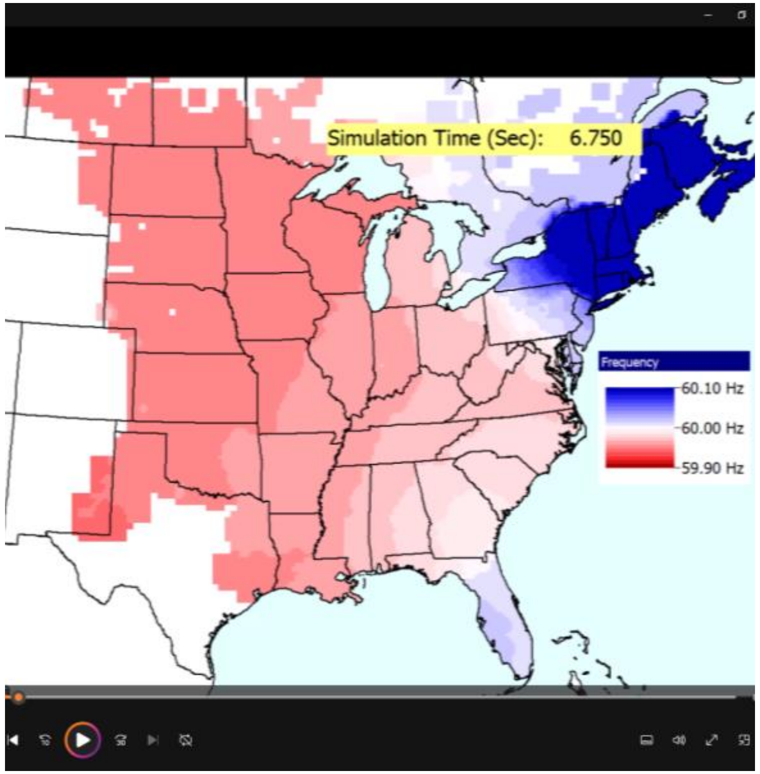


New England 0.27 Hz Forced Oscillation

- The last disturbance is a 0.27 Hz forced oscillation in New England







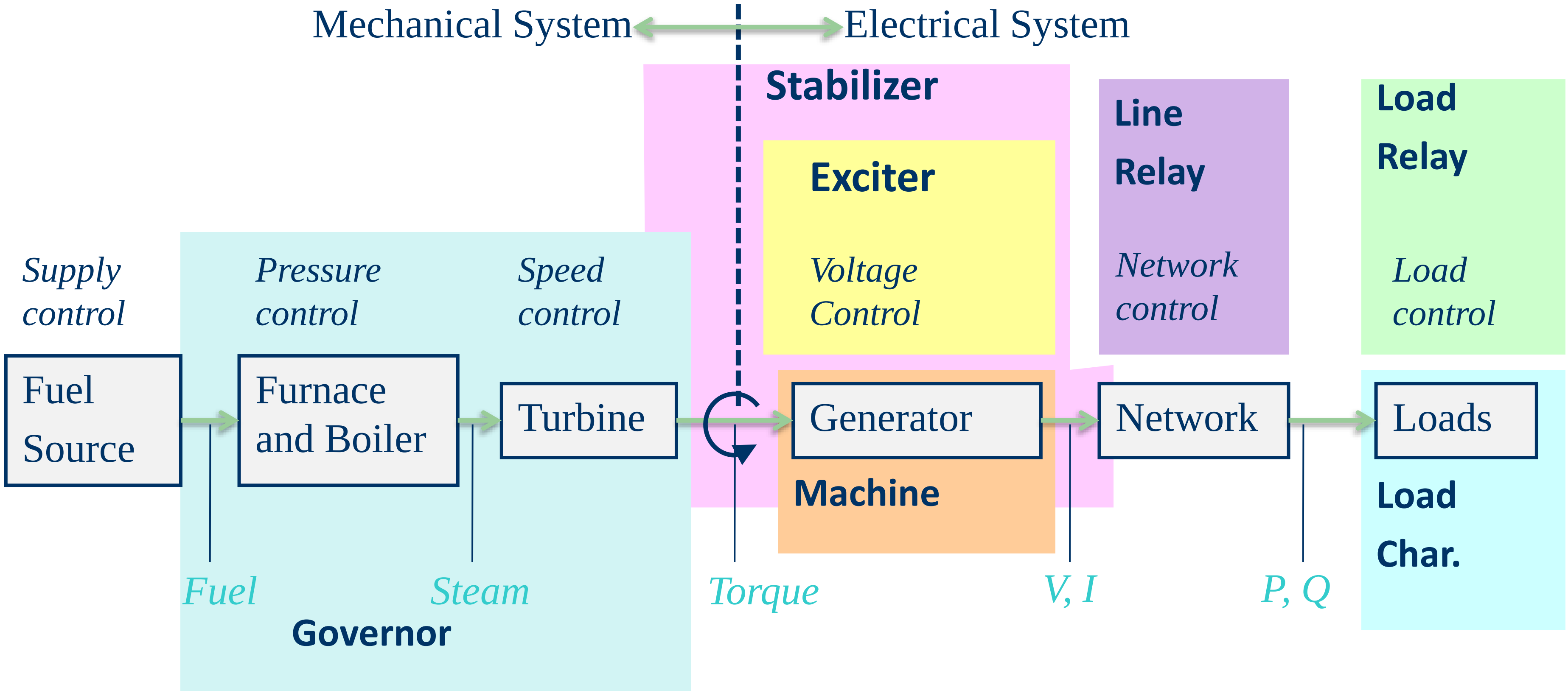
Damping Oscillations: Power System Stabilizers (PSSs)

- 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

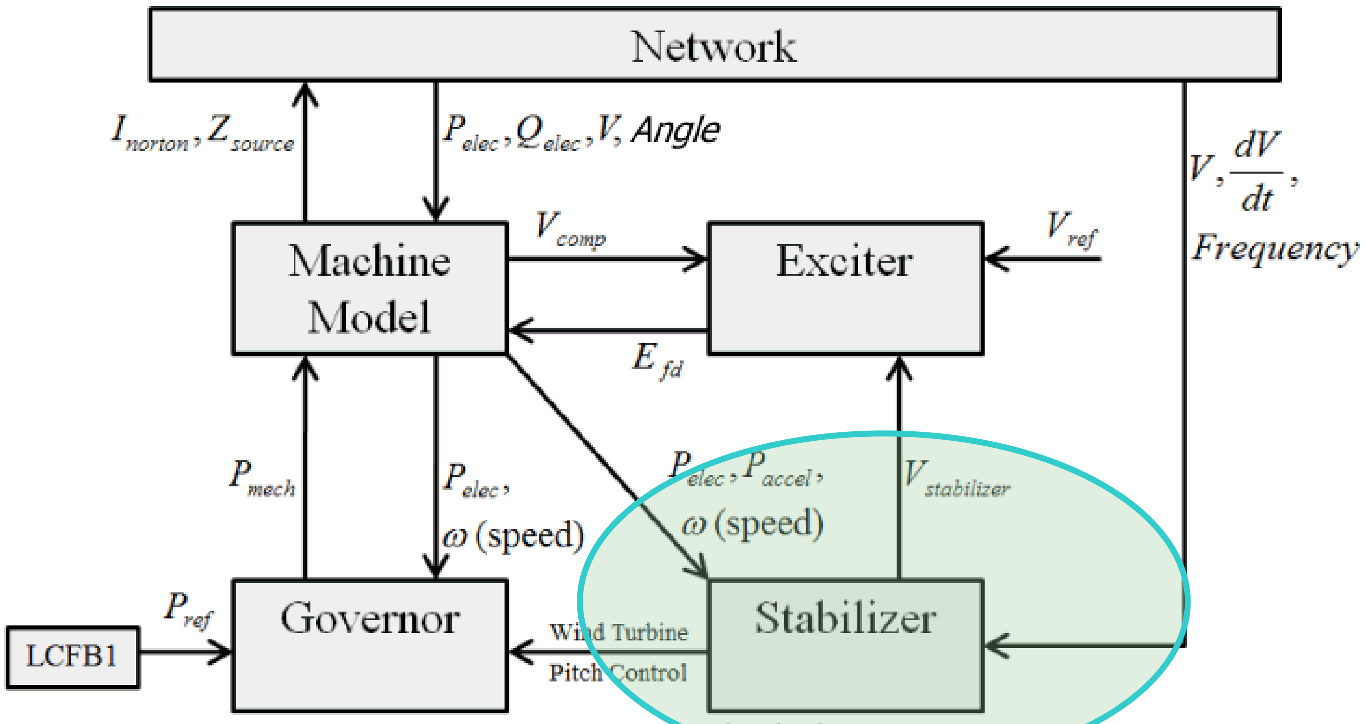
- A few references on power system stabilizers
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part I: General Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3017-3024, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers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



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

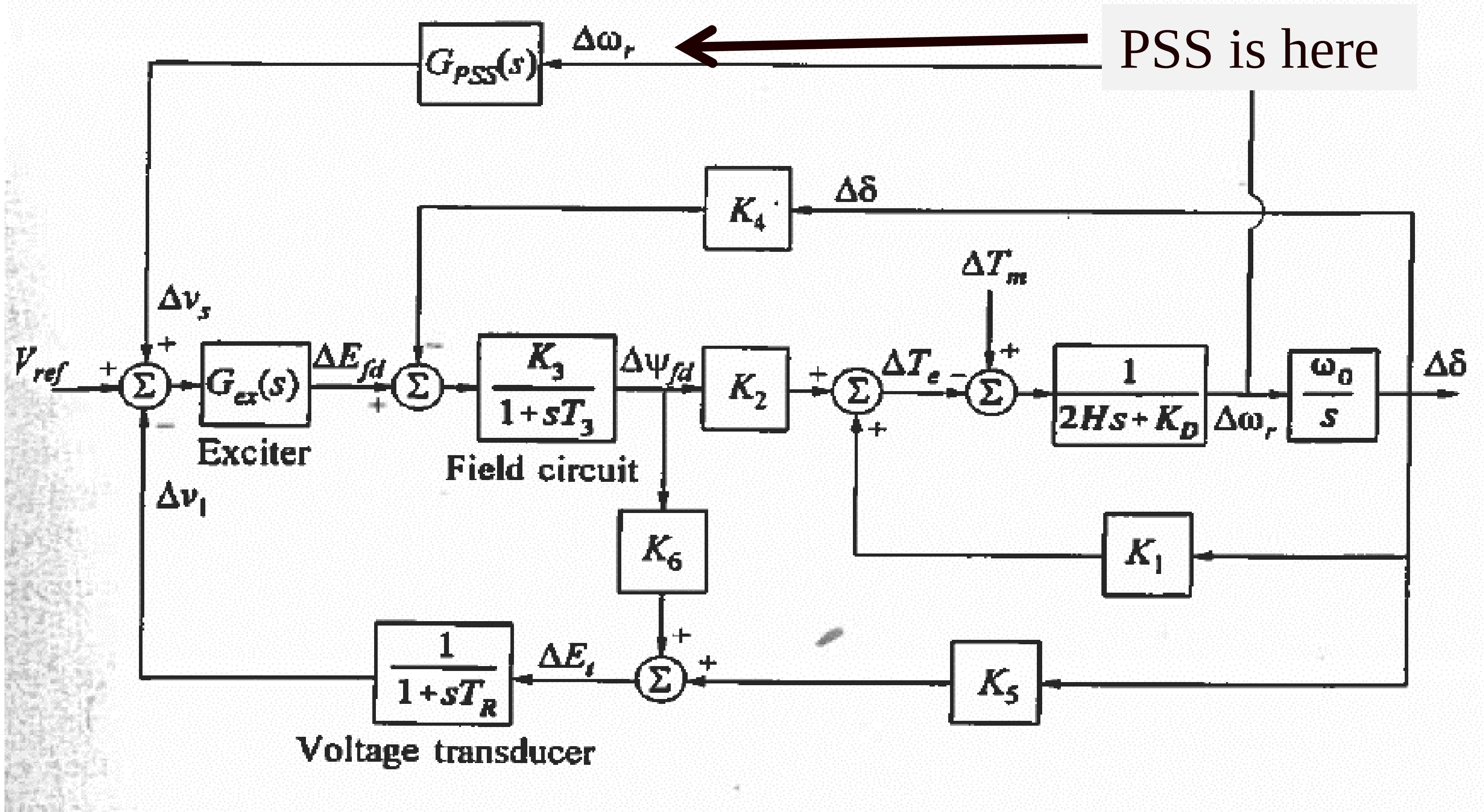


Figure 12.13 Block diagram representation with AVR and PSS

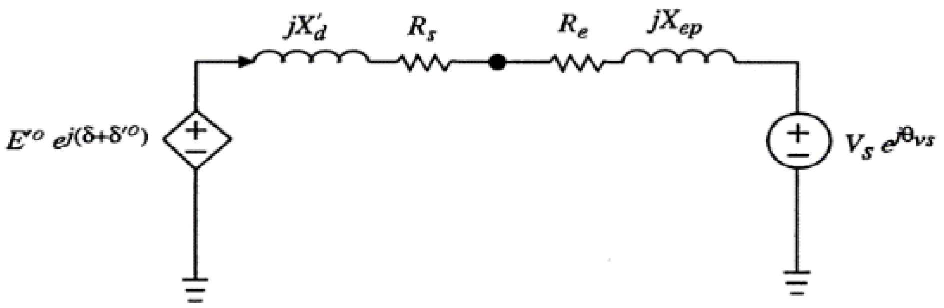
Image Source: Kundur, *Power System Stability and Control*

PSS Basics

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

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

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



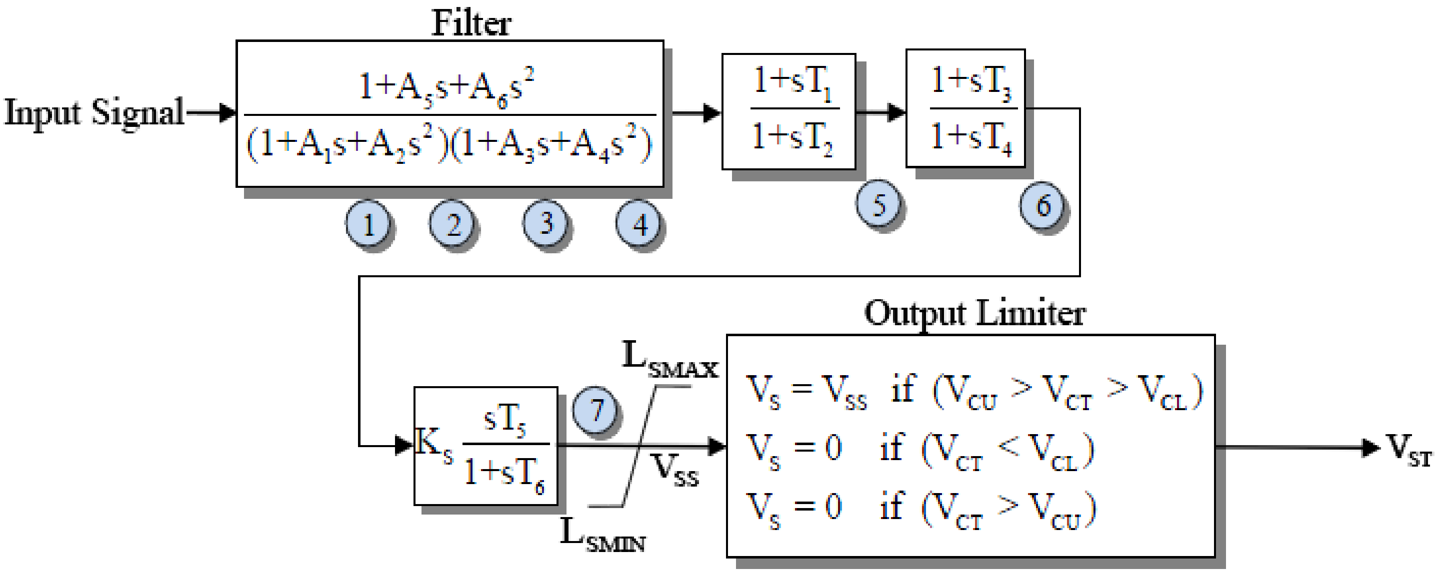
- Assume internal voltage has an additional component

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

- 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

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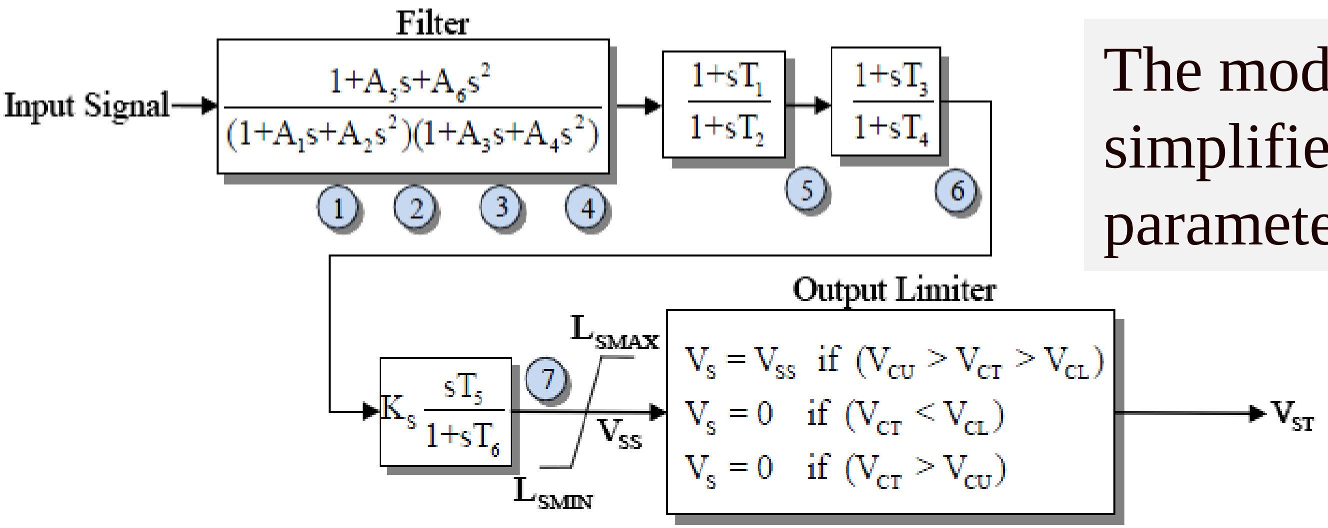


The model can be simplified by setting parameters to zero

V_{ST} is an input into the exciter

Another Single Input PSS

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

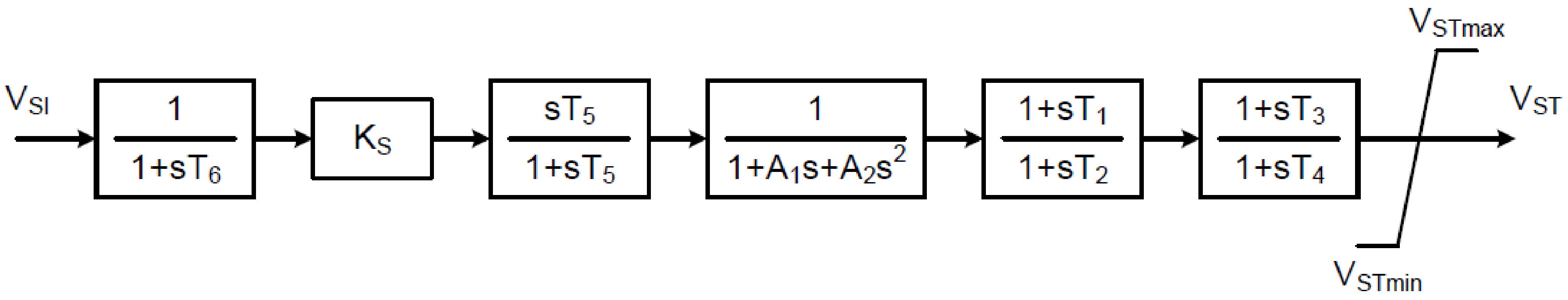


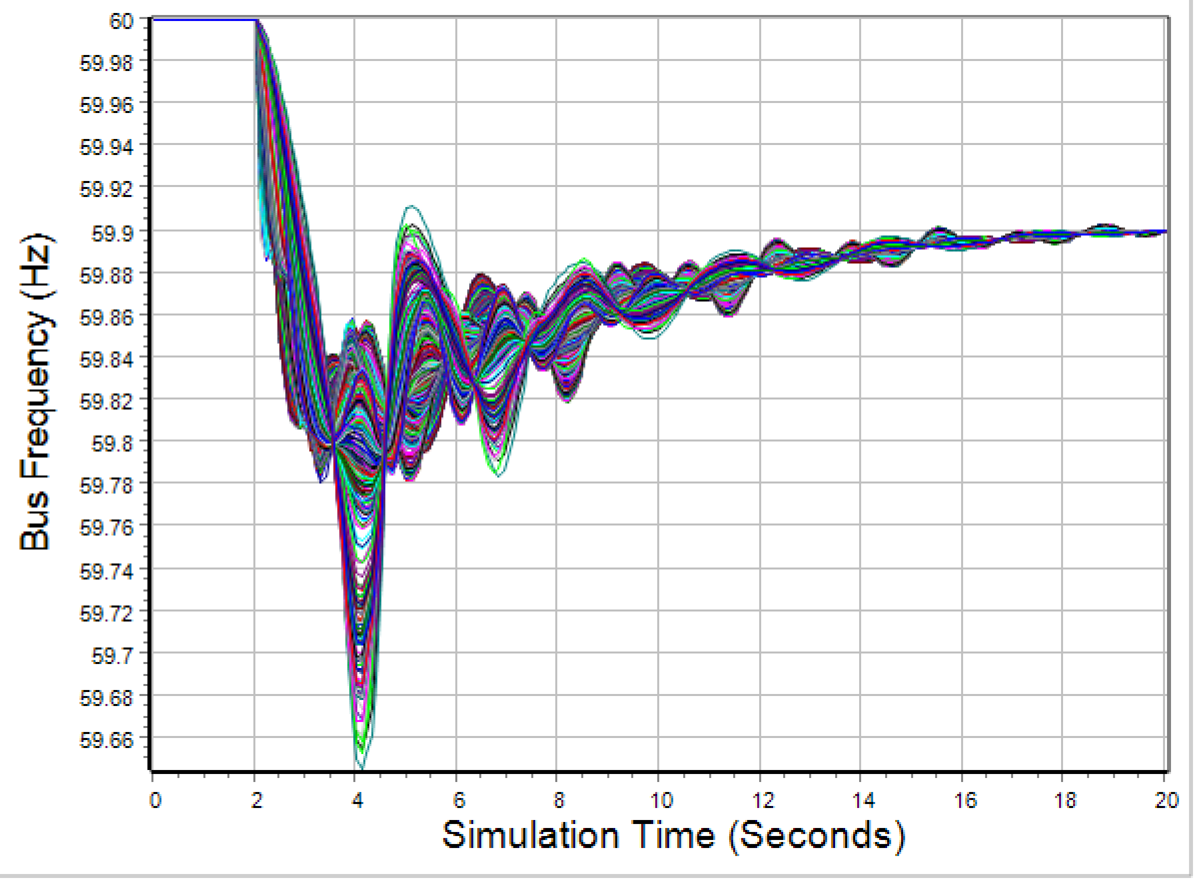
Figure 31 —Type PSS1A single-input power system stabilizer

IEEE Std 421.5 describes the common stabilizers

2000 Bus System Results With Stabilizers

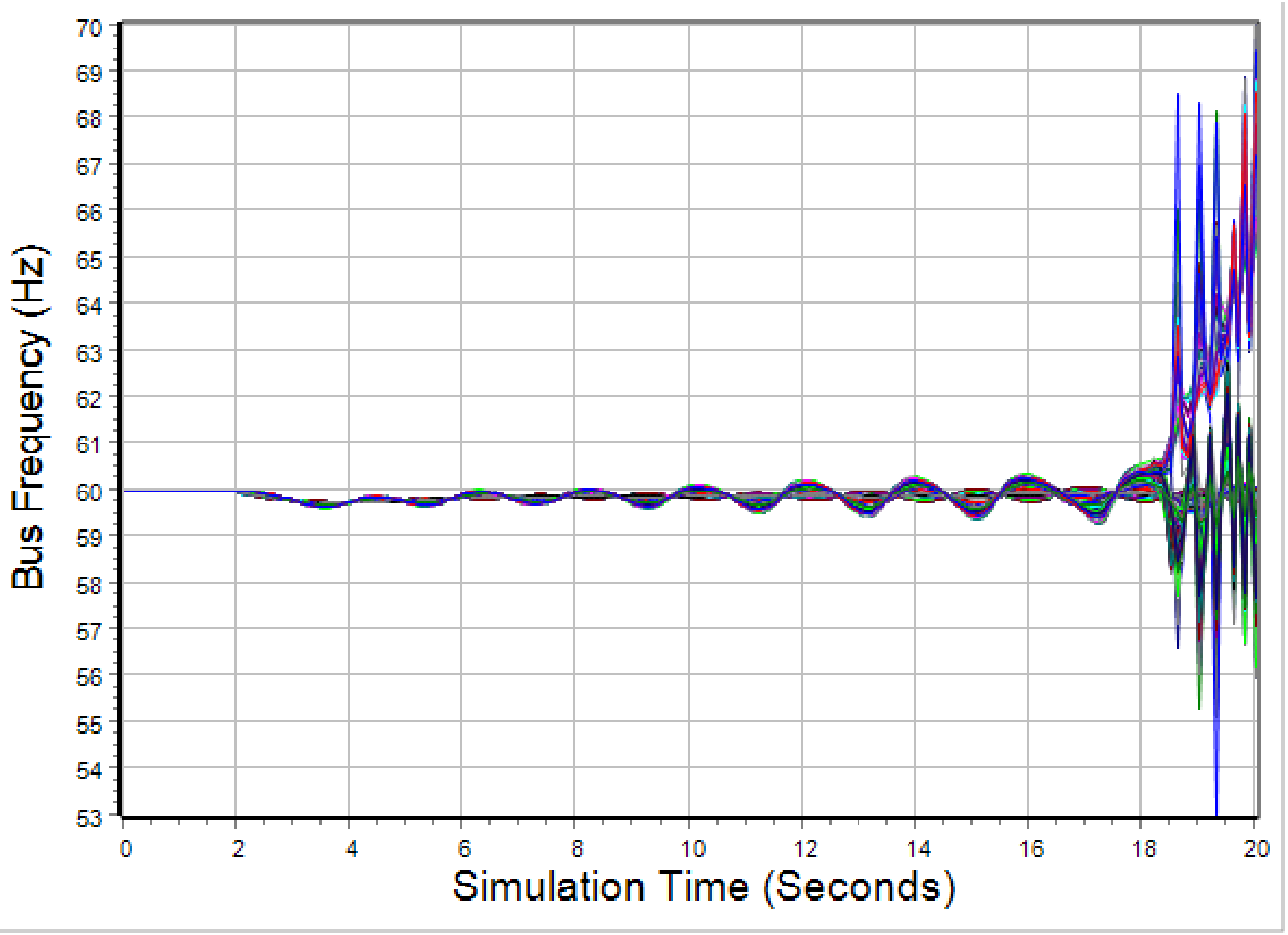
- The case has 334 IEEST stabilizers, all with the same parameters (which would not be the case in a real system)

Results are given for the previous generator drop contingency



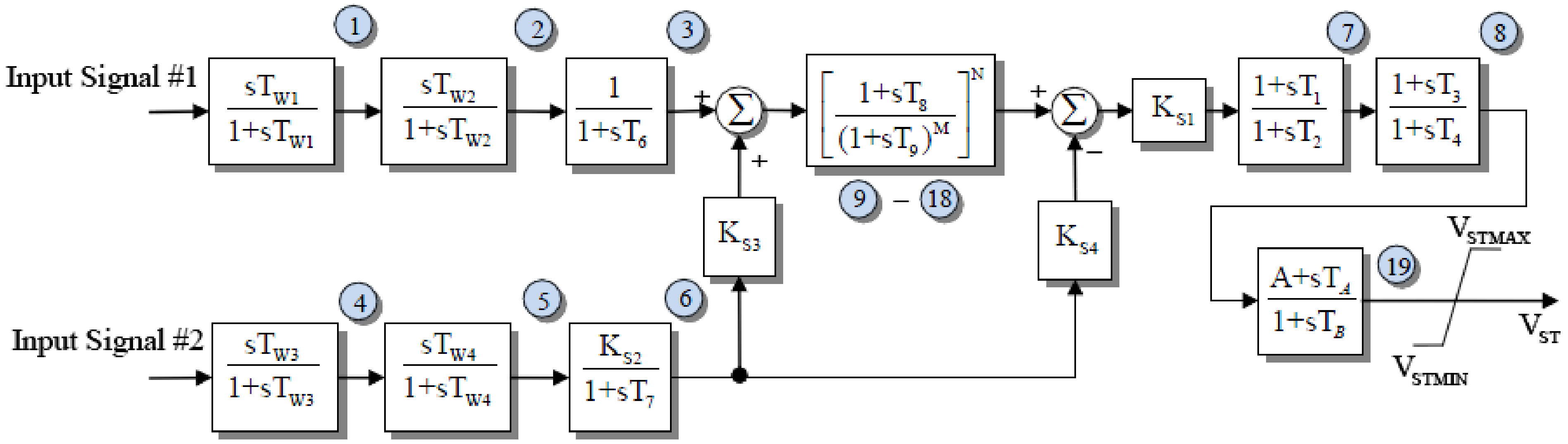
2000 Bus System Results Without Stabilizers

- 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

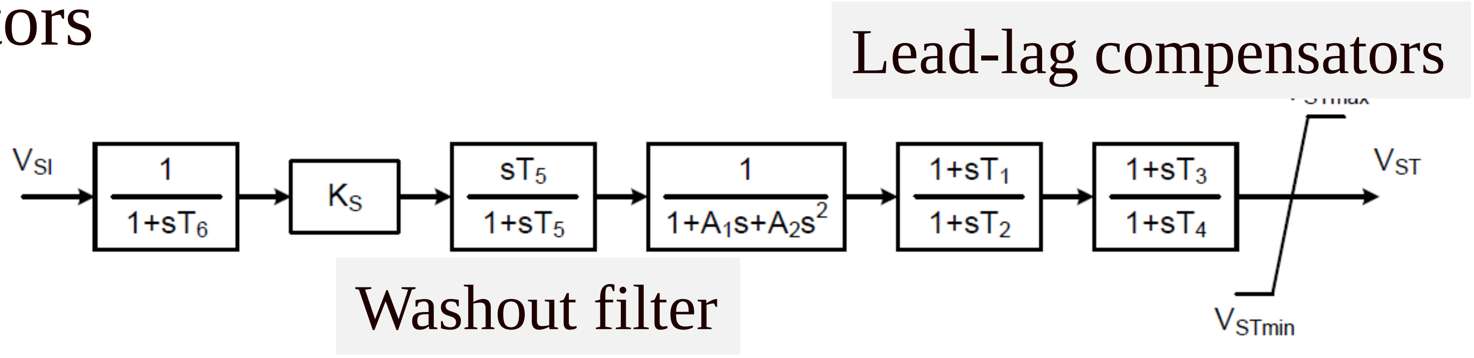
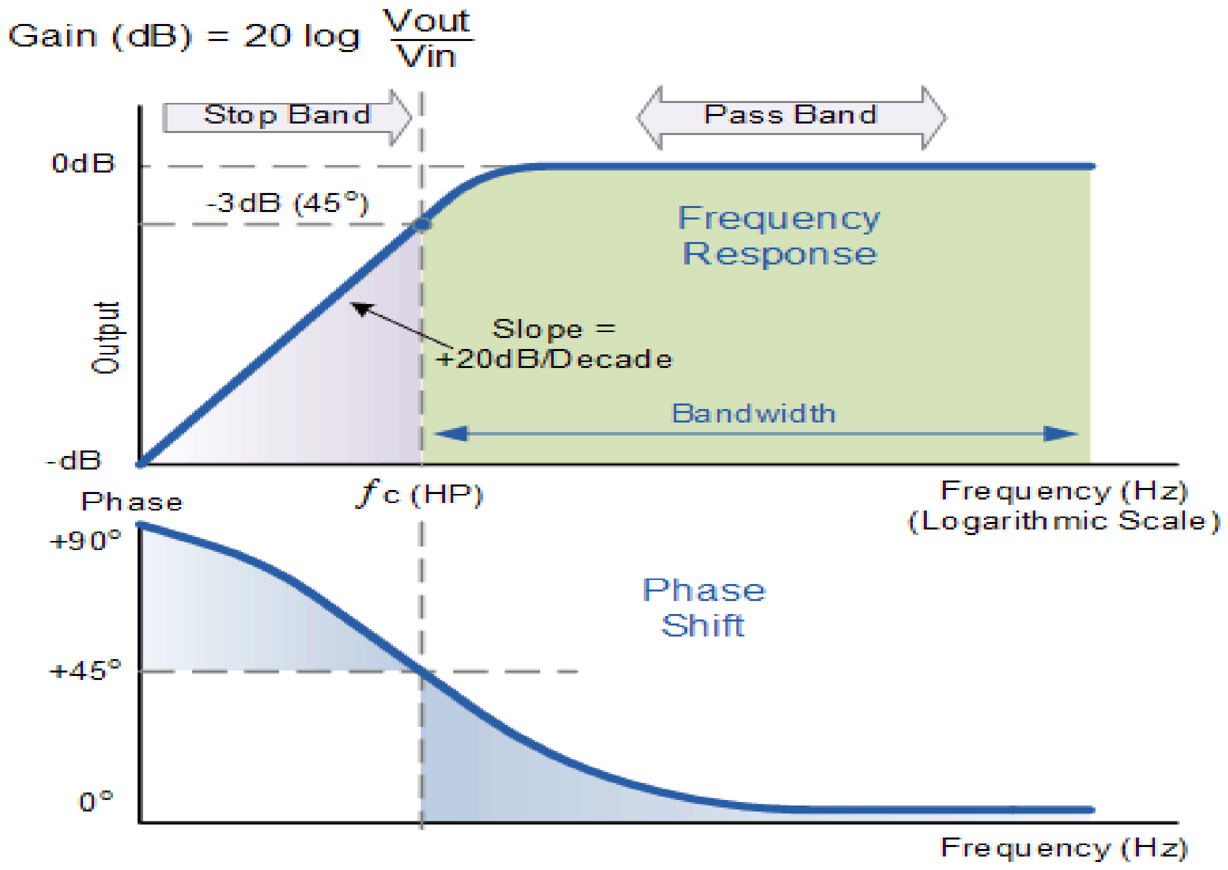


Figure 31 —Type PSS1A single-input power system stabilizer

- 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



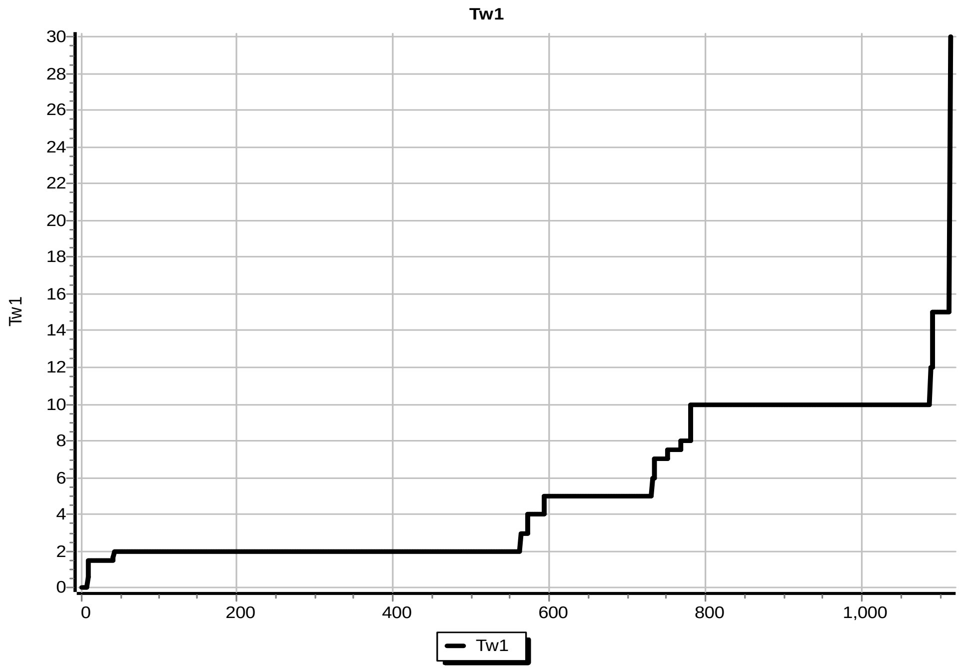
The breakpoint frequency is when the phase shift is 45 degrees and the gain is -3 dB (1/sqrt(2))

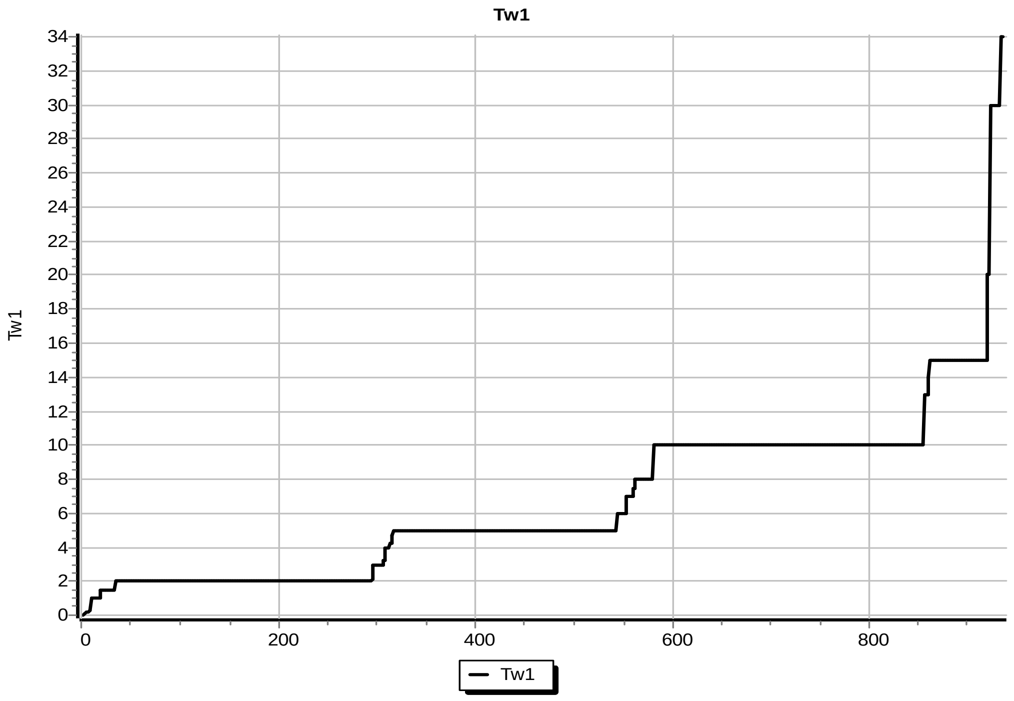
A larger T value shifts the breakpoint to lower frequencies; at T=10 the breakpoint frequency is 0.016 Hz

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 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

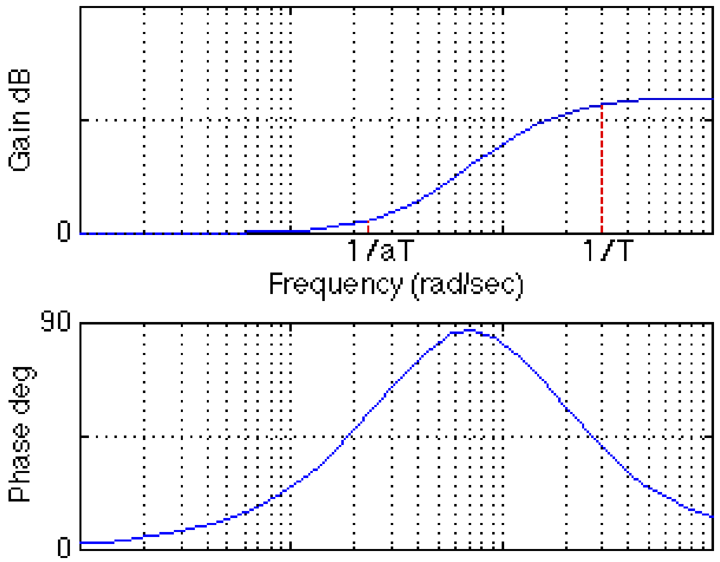




Lead-Lag Compensators

- For a lead-lag compensator of the below form with 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

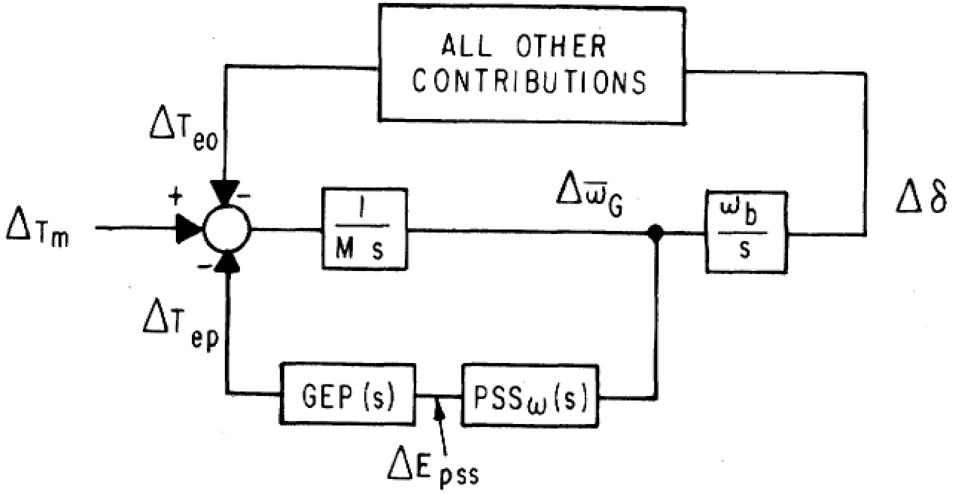


Image Source: Figure 1 from Larsen, 1981, Part 1

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

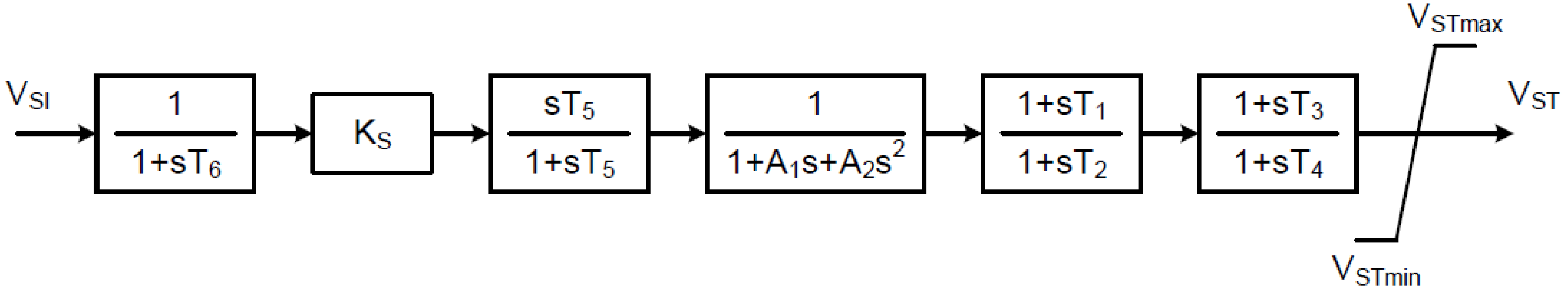


Figure 31 —Type PSS1A single-input power system stabilizer

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 $T_2=T_4$

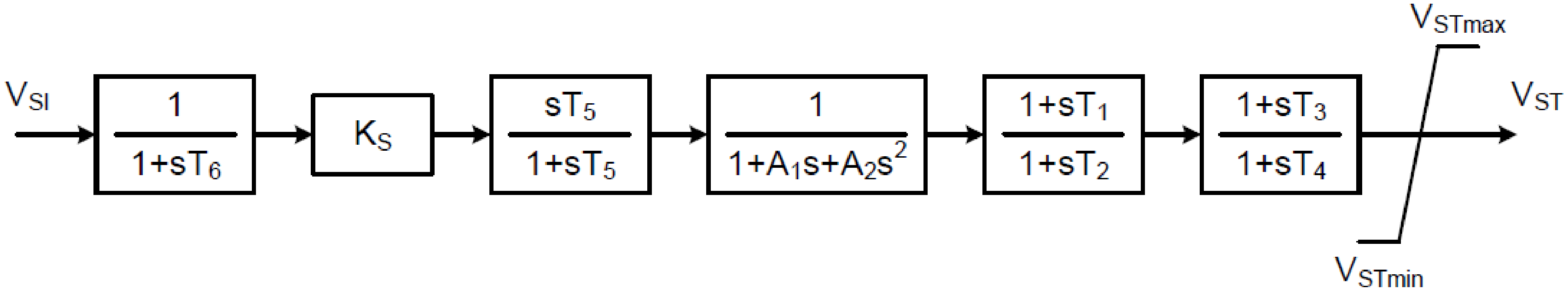


Figure 31 —Type PSS1A single-input power system stabilizer

Stabilizer Design Phase Compensation

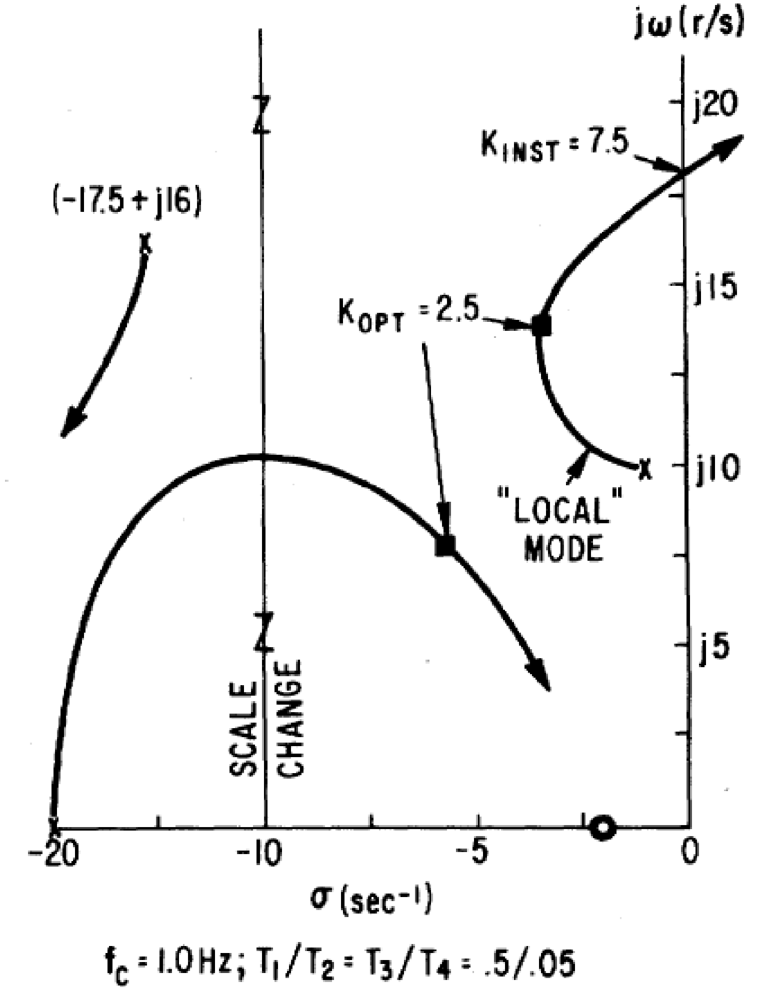
- Goal is to move the eigenvalues further into the left-half plane
- Initial direction the eigenvalues move as the stabilizer gain is increased from zero depends on the phase at the oscillatory frequency
  - If the phase is close to zero, the real component changes significantly but not the imaginary 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

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

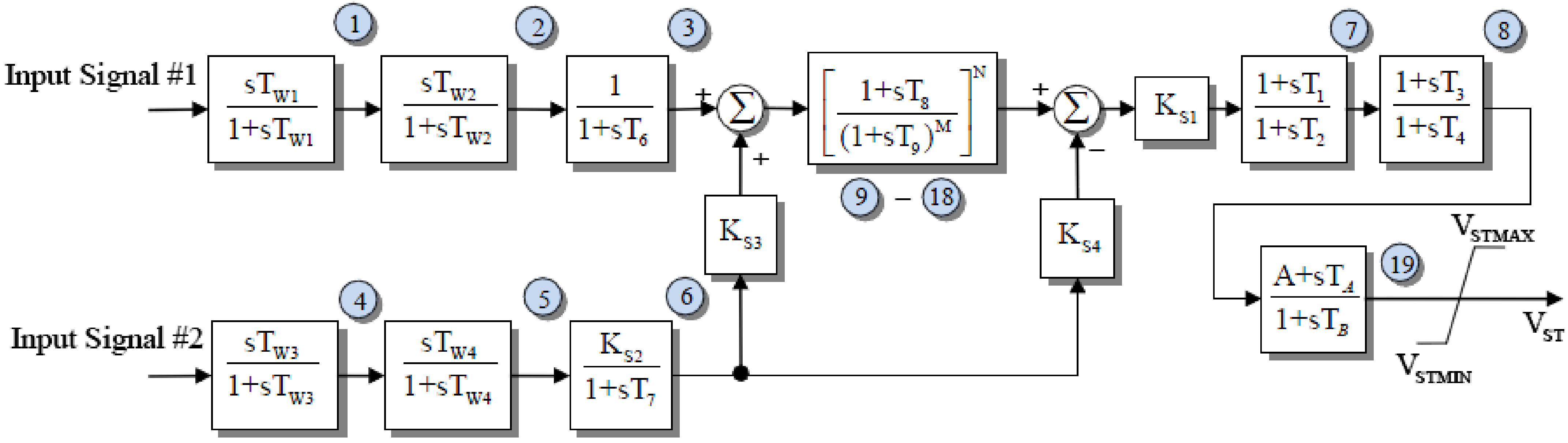


Stabilizer Design Tuning

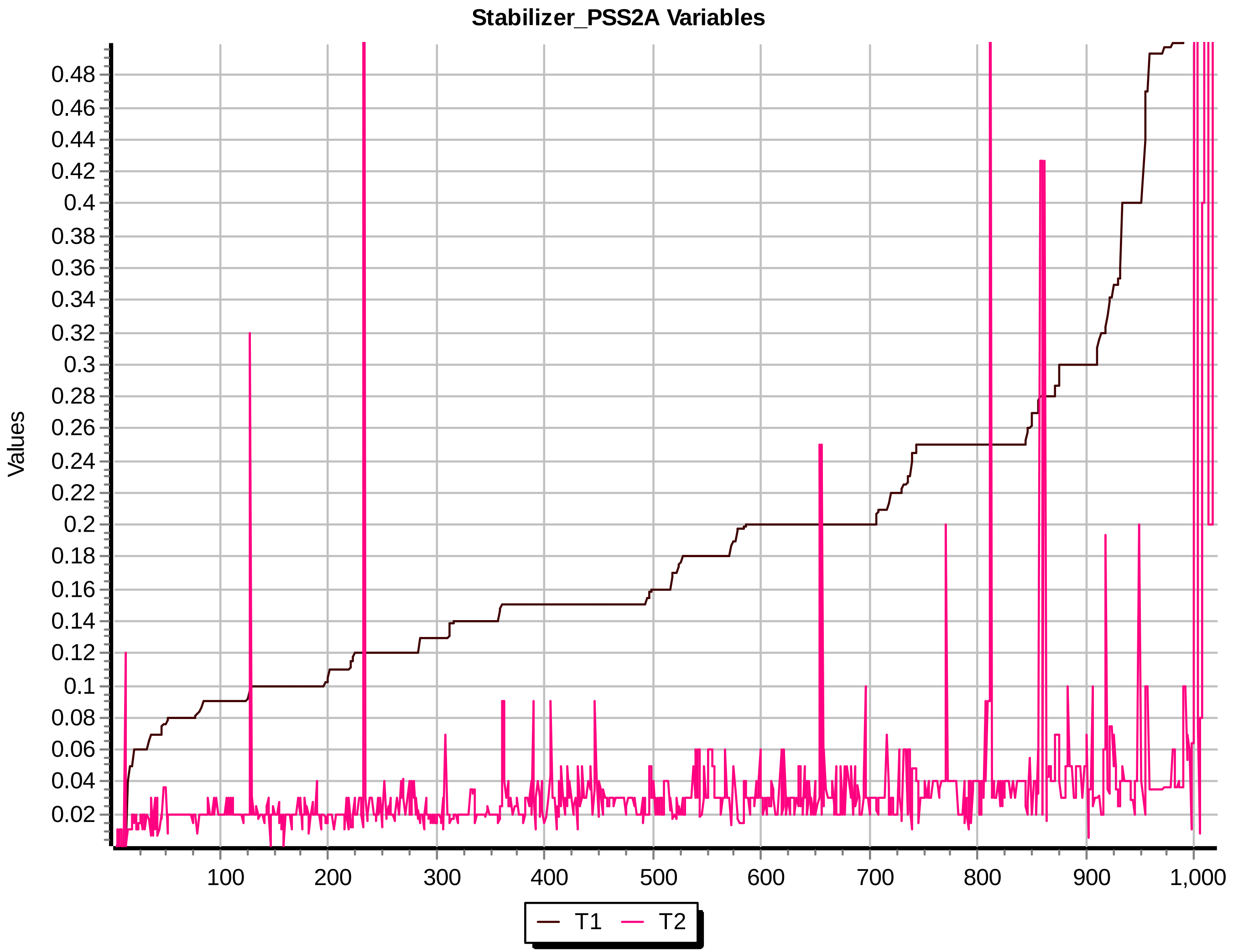
- Basic approach is to provide enhanced damping at desired frequencies; the challenge is power systems can experience many different types of oscillations, ranging from the high frequency local modes to the slower (< 1.0 Hz usually) inter-area modes
- Usually the PSS should be set to compensate the phase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

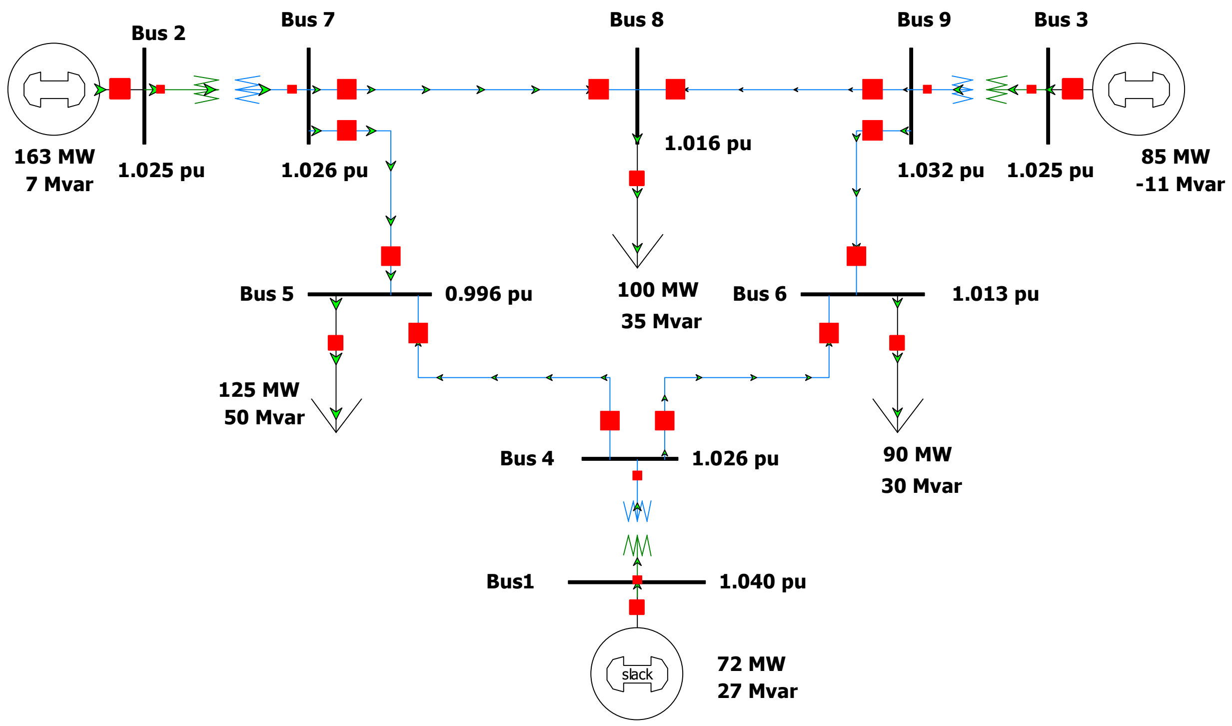


Example T_1 and T_2 Values



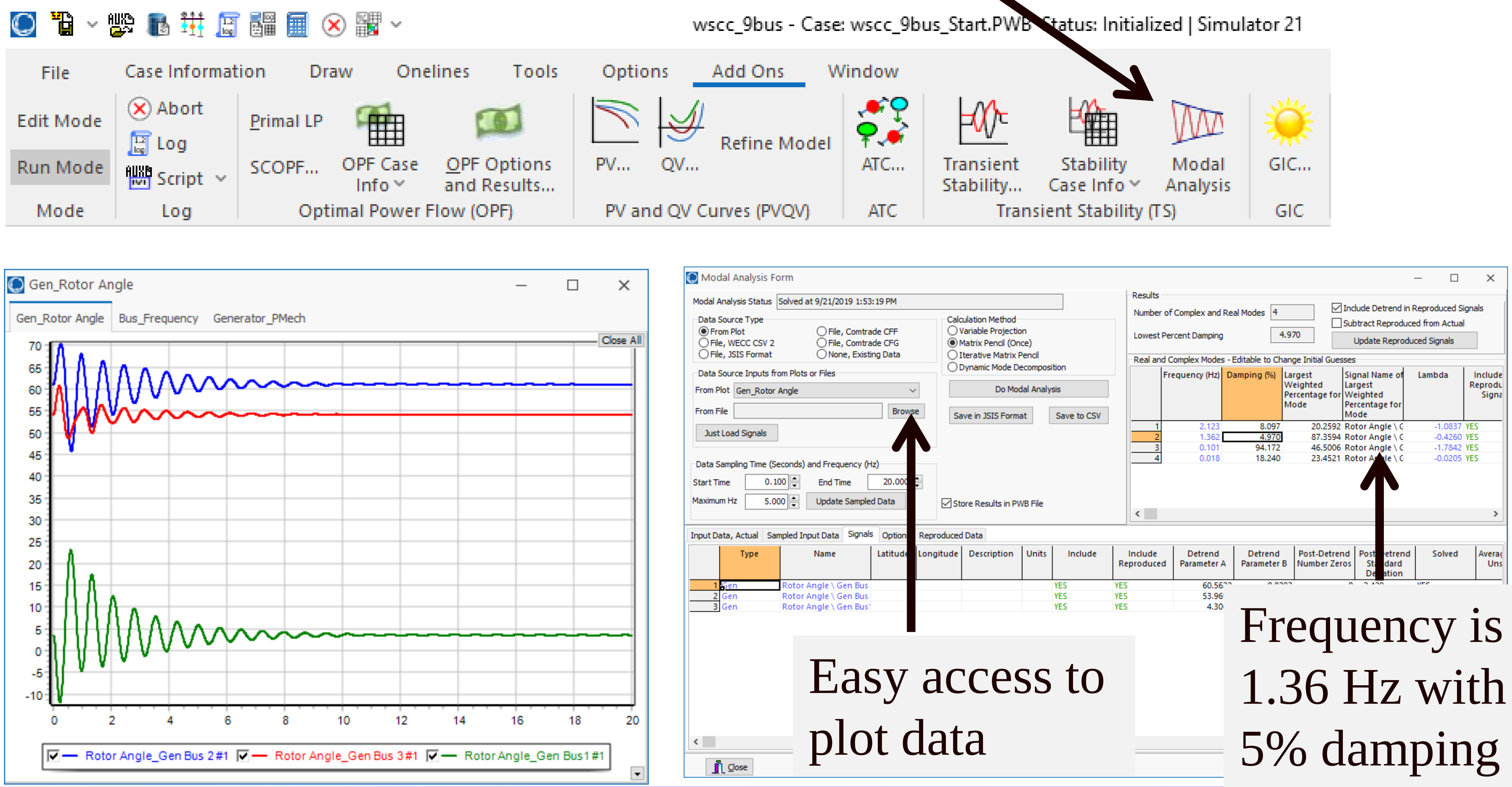
PSS Tuning Example

- 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

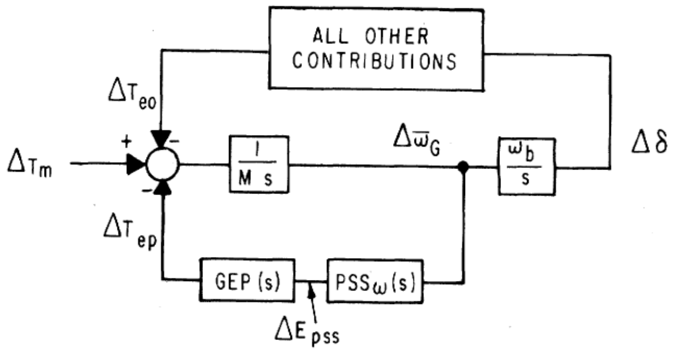


Easy access to plot data

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



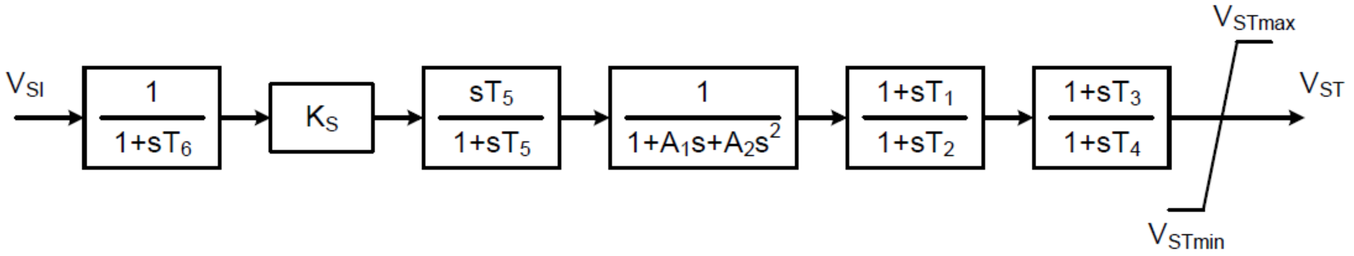


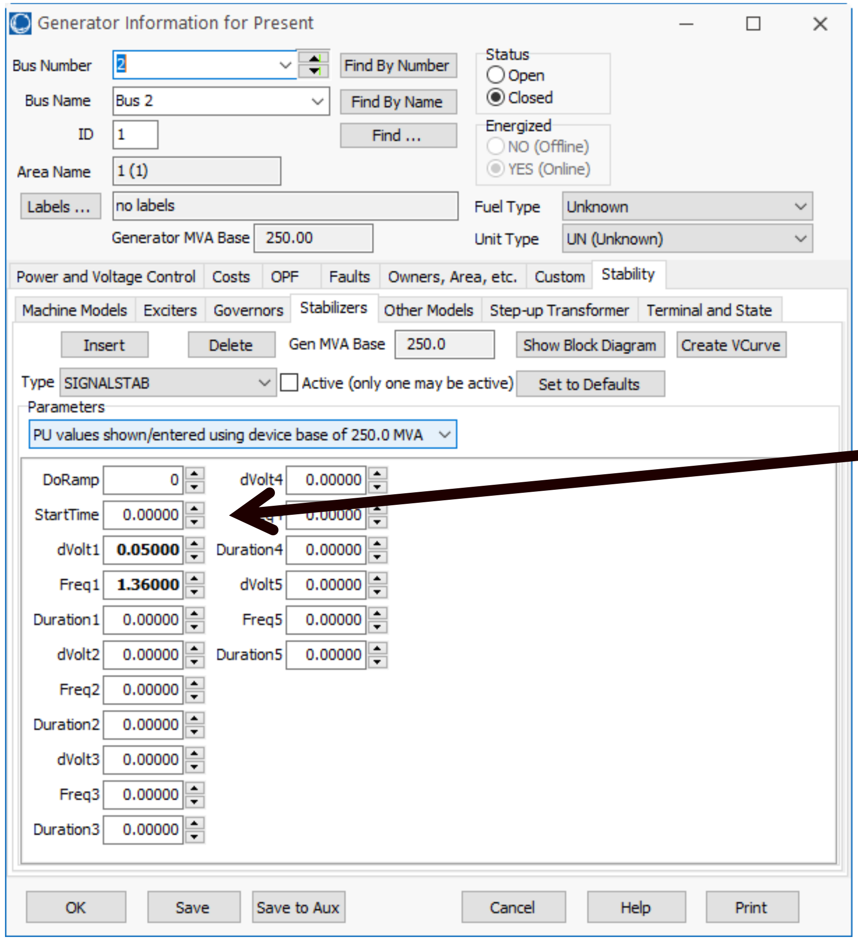
Figure 31 —Type PSS1A single-input power system stabilizer

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

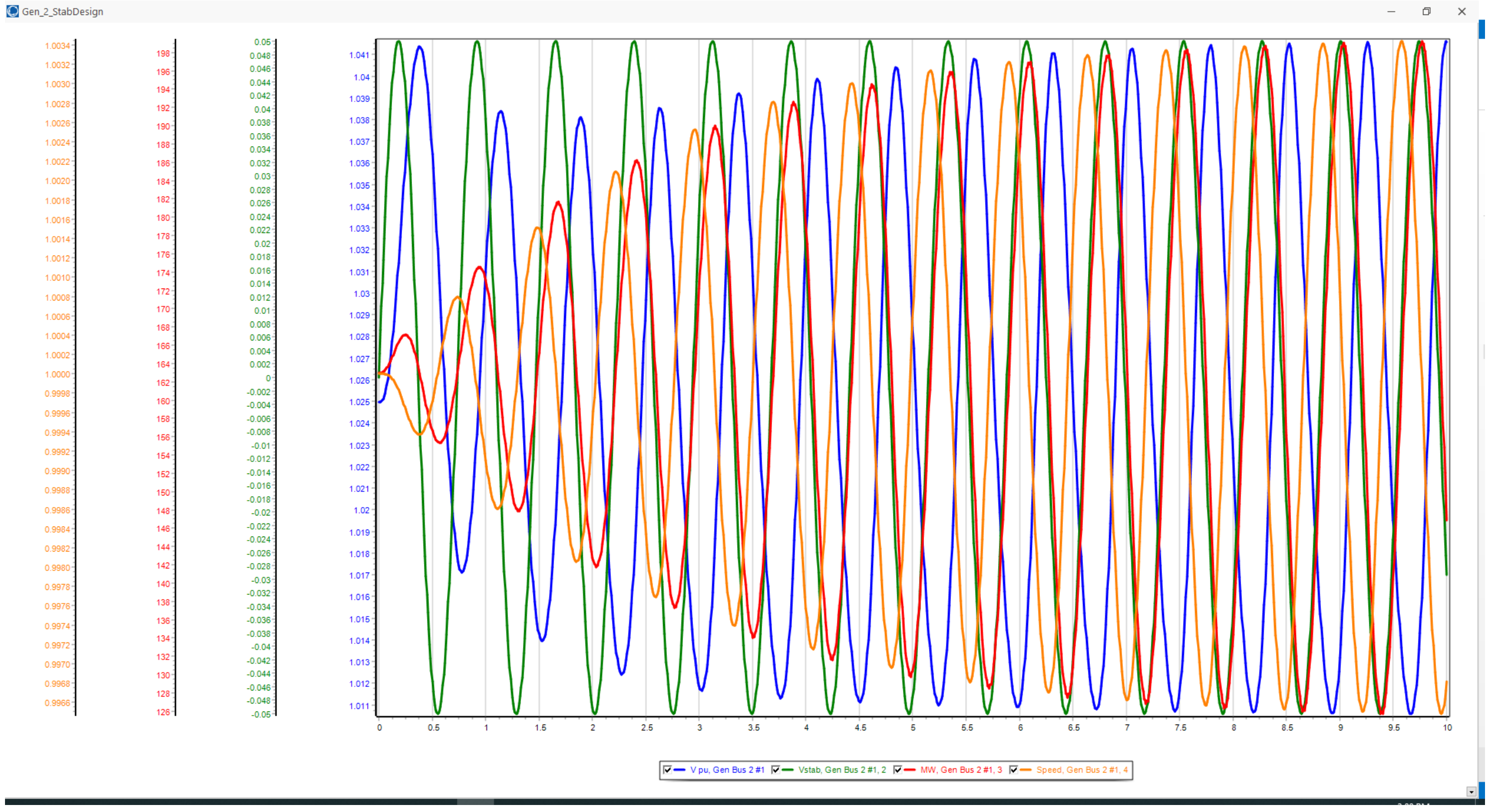
- Enable the SignalStab stabilizer at the bus 2 generator and run the simulation



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

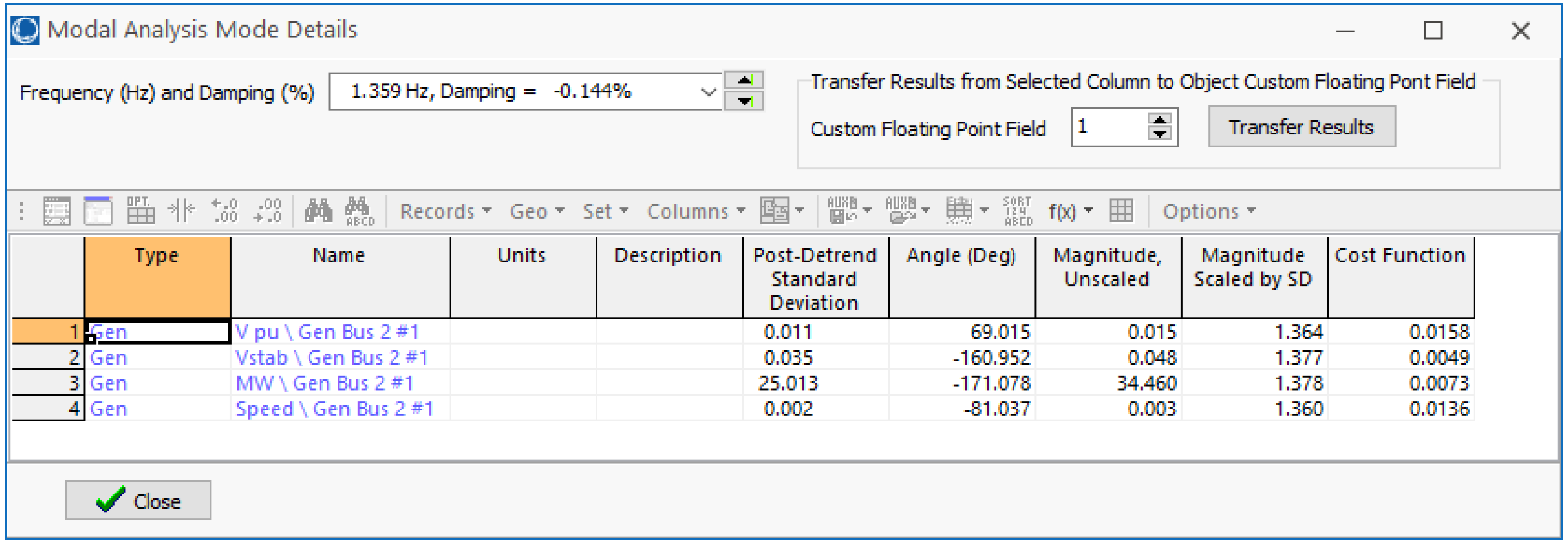
- Graph shows four signals at bus 2, including the stabilizer input and the generator's speed
  - The phase relationships are most important



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

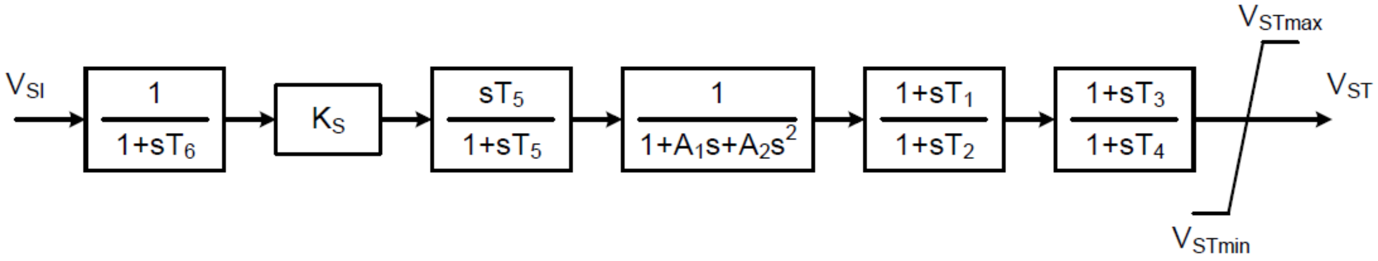
$$\alpha = \frac{1-\sin\phi}{1+\sin\phi}, \; T_1 = \frac{1}{2\pi f\sqrt{\alpha}}$$

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

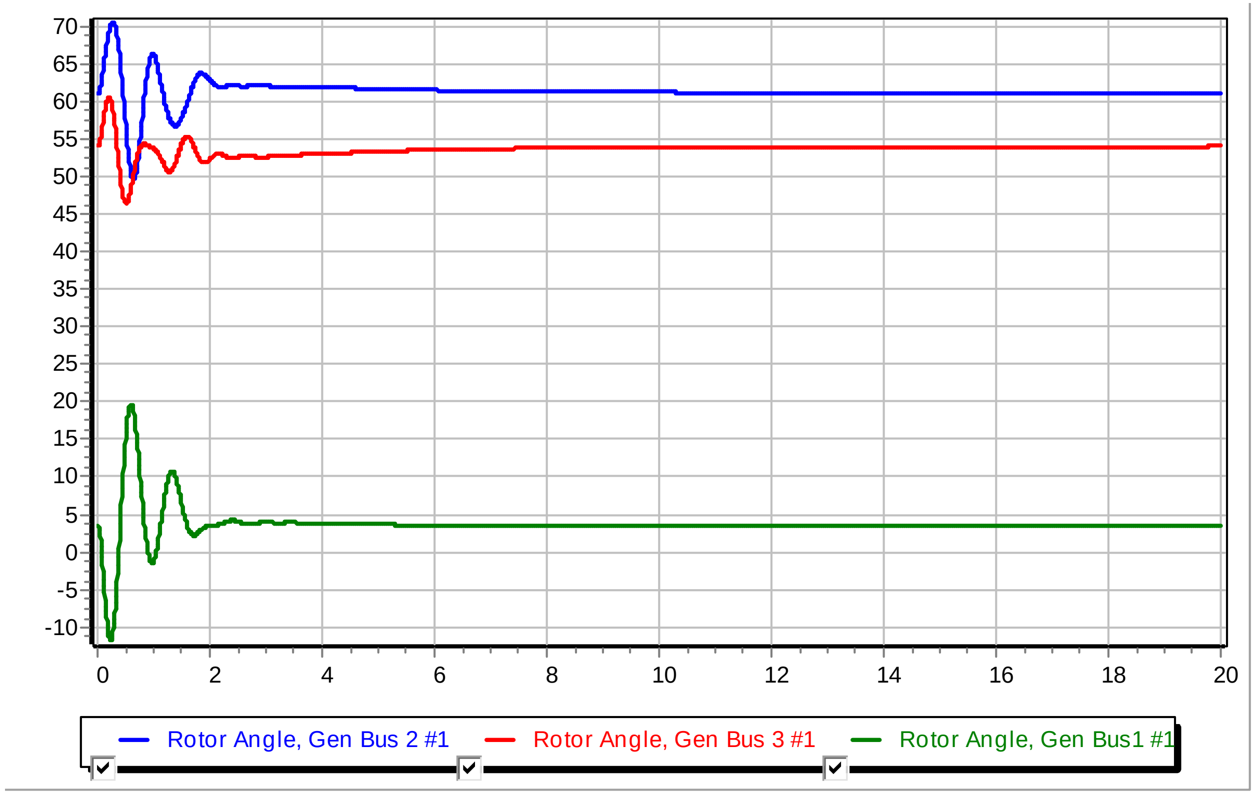
- Hence T_1=T_3=0.321, T_2=T_4=0.042. We'll assumed T_6=0, and T_5=10, and A_1=A_2=0



- 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

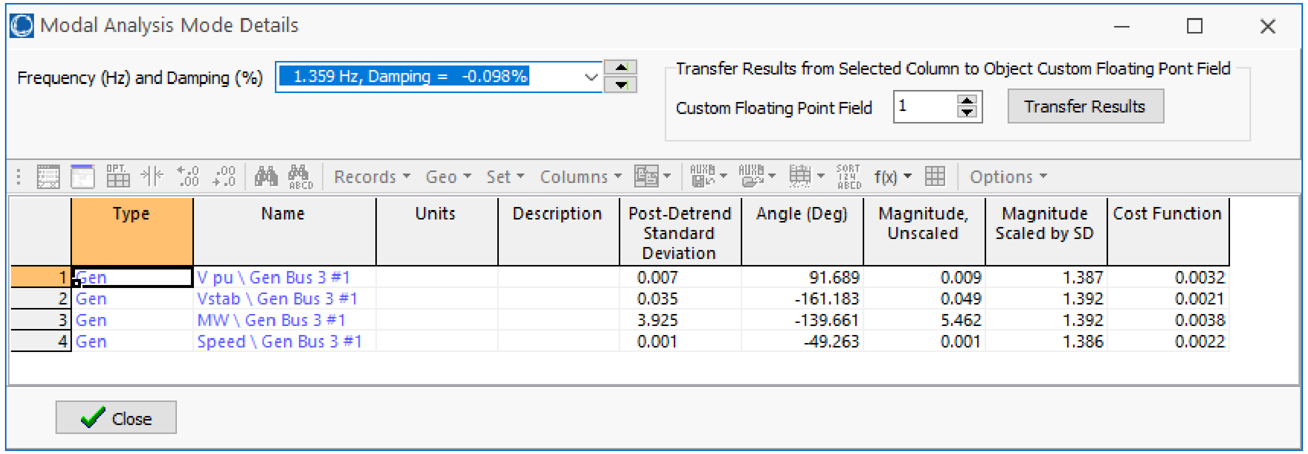
- Instability occurs with KS = 55, hence the optimal value is about 55/3=18.3
- This increases the damping from 5% to about 16.7%



This is saved as case **WSCC_9bus_Stab**

PSS Tuning Example: Setting the Values for Gen 3

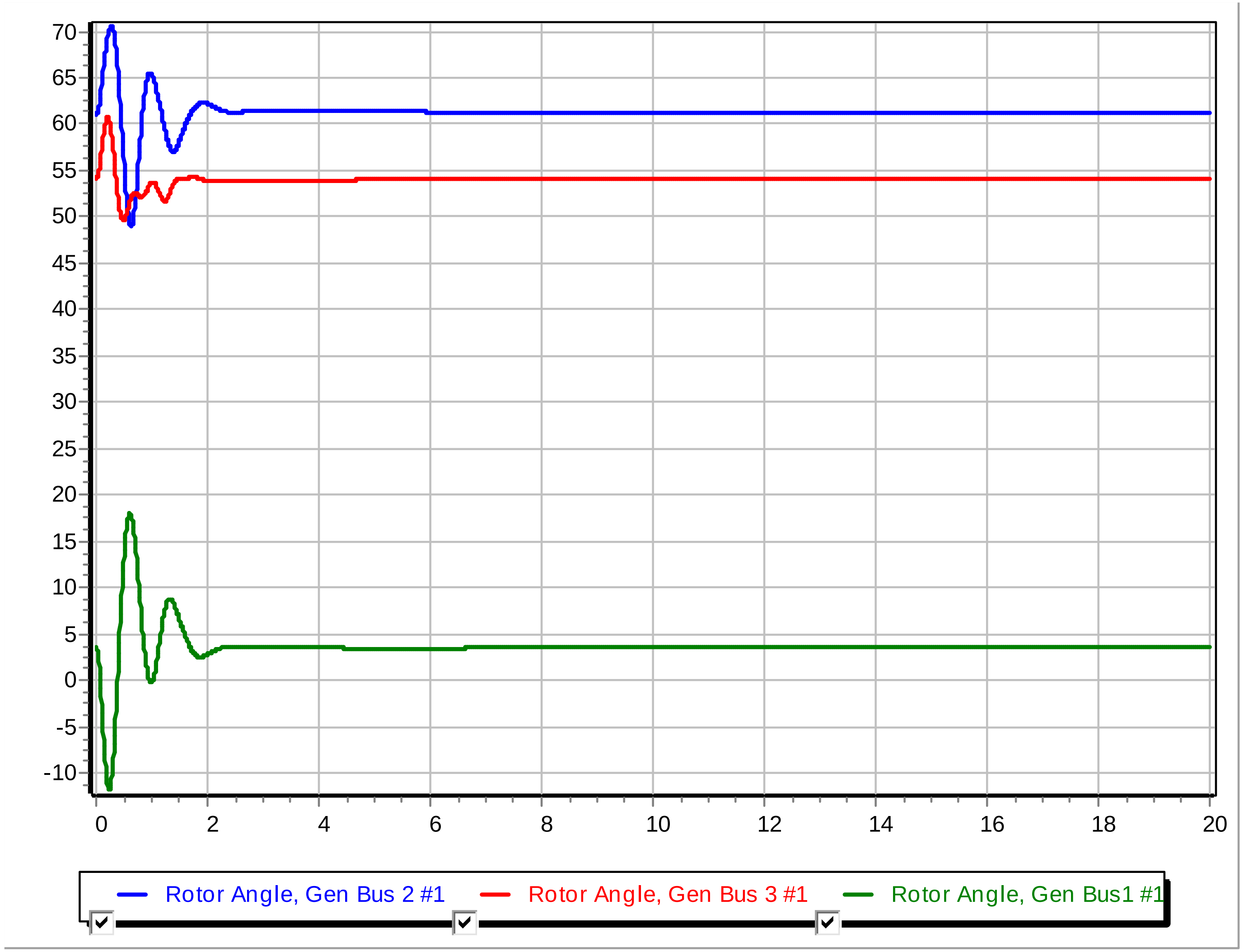
- The procedure can be repeated to set the values for the bus 3 generator, where we need a total of 68 degrees of compensation, or 34 per lead-lag



	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.

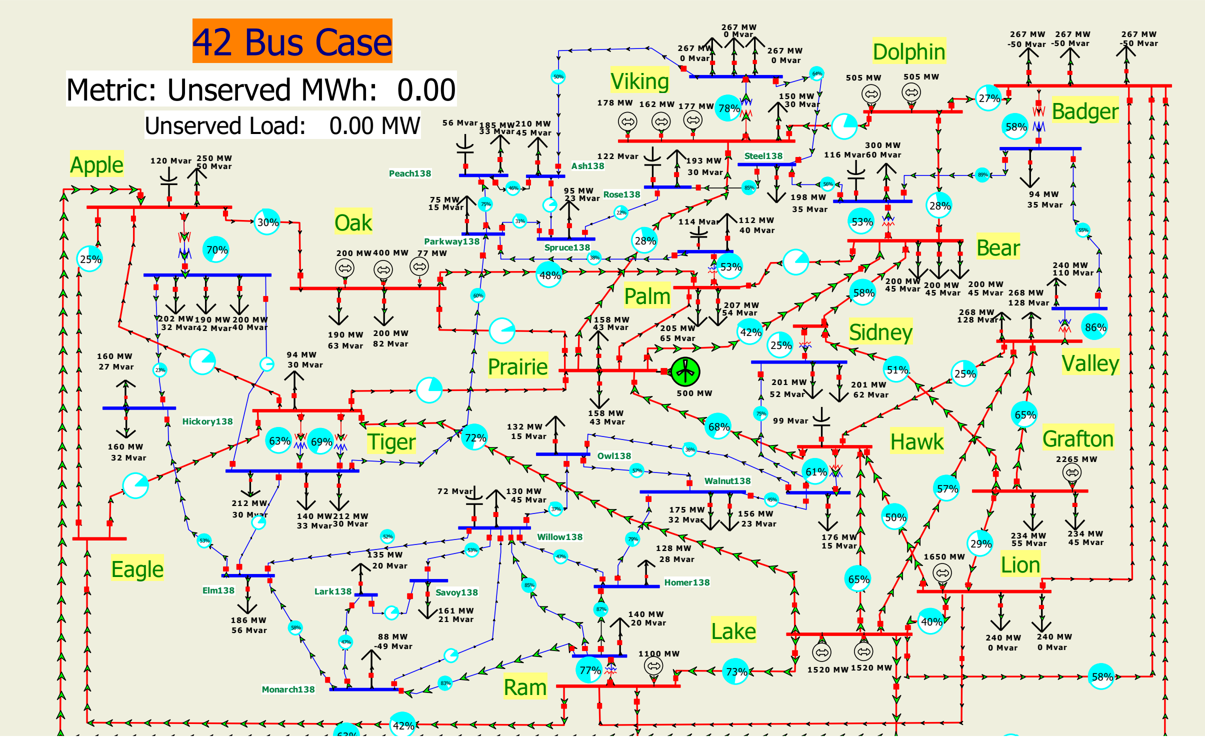
PSS Tuning Example: Final Solution



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

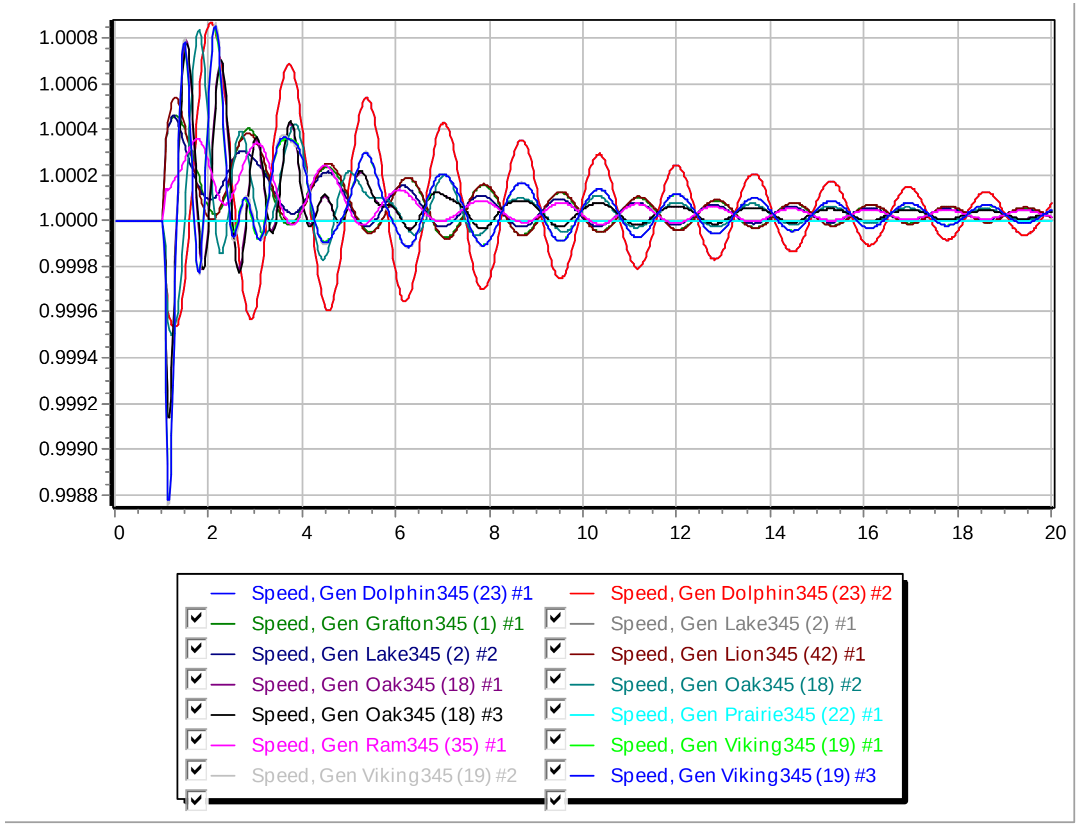
- Goal is to try to improve damping by adding one PSS1A at a large generator at Lion345 (bus 42)
  - Example event is a three-phase fault is applied to the middle of the 345 kV transmission line between Prairie (bus 22) and Hawk (bus 3) with both ends opened at 0.05 seconds

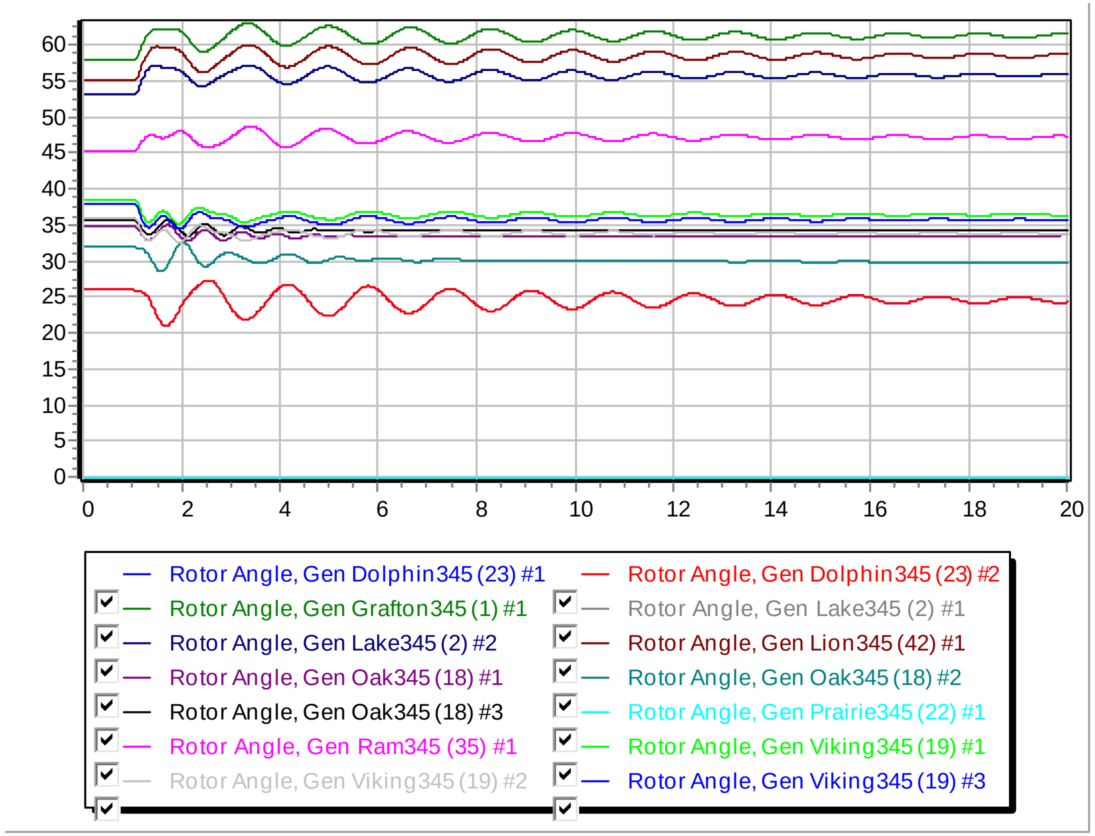


The starting case name is **Bus42_PSS**

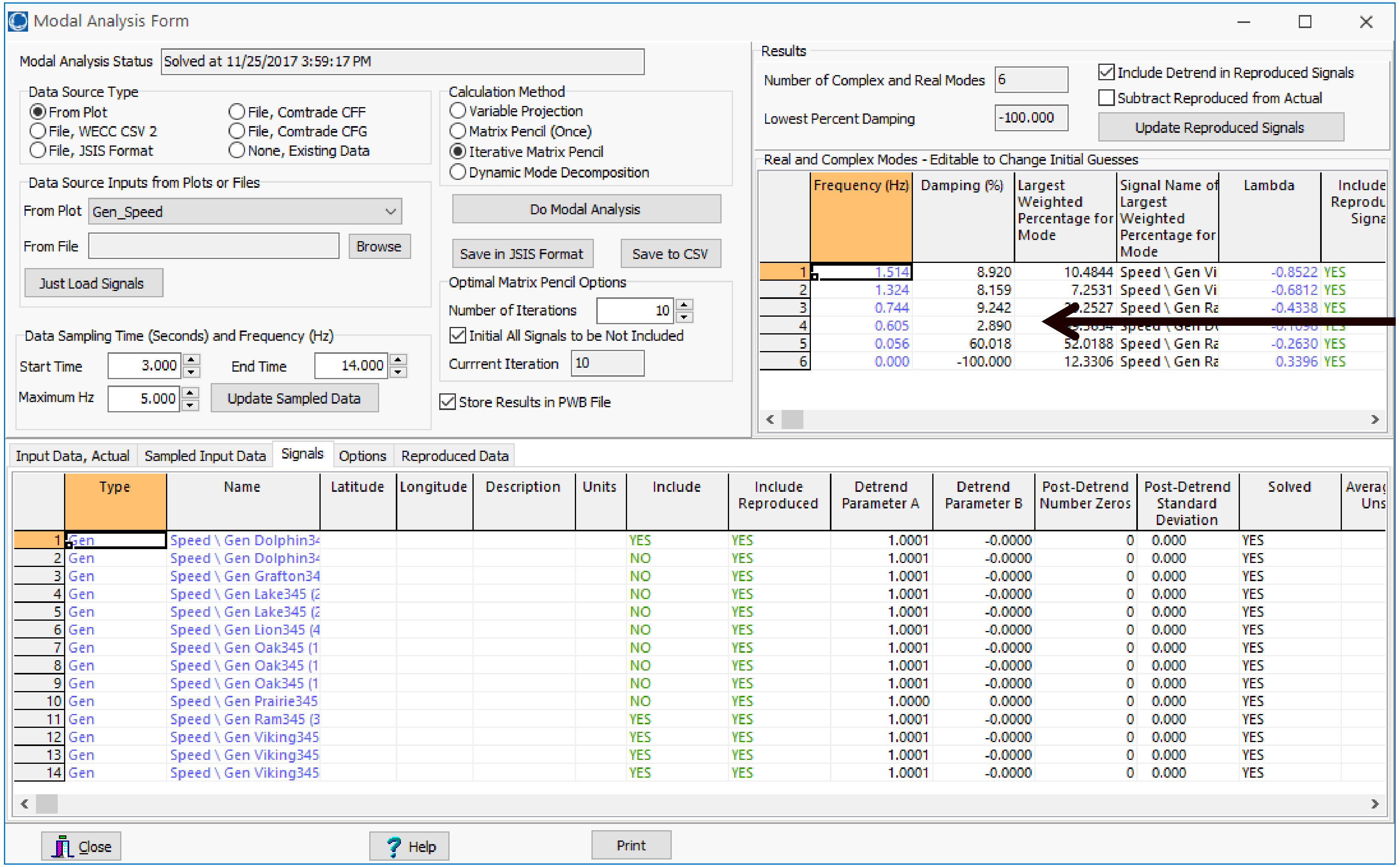
Example 2: Decide Generators to Tune, Frequency

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





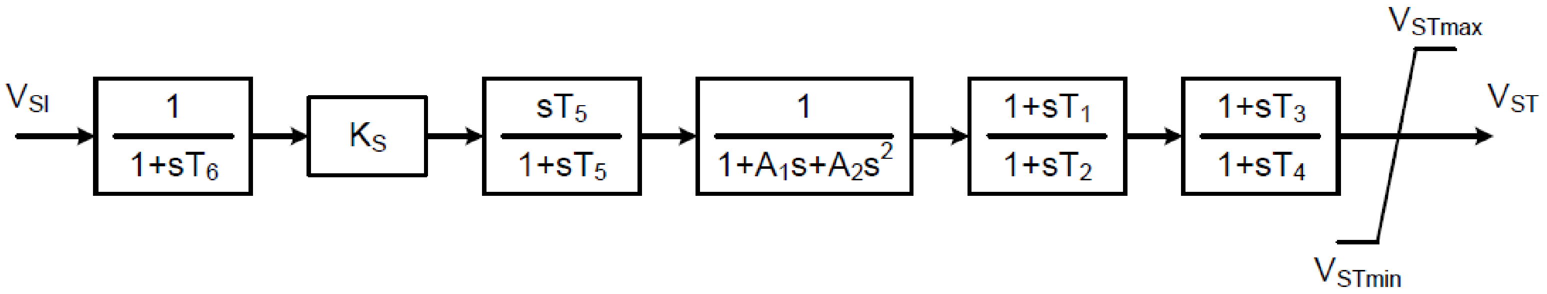
Example 2: Quantified Using Modal Analysis



For 0.6 Hz mode the damping is 2.89%

Example 2: Determine Phase Compensation

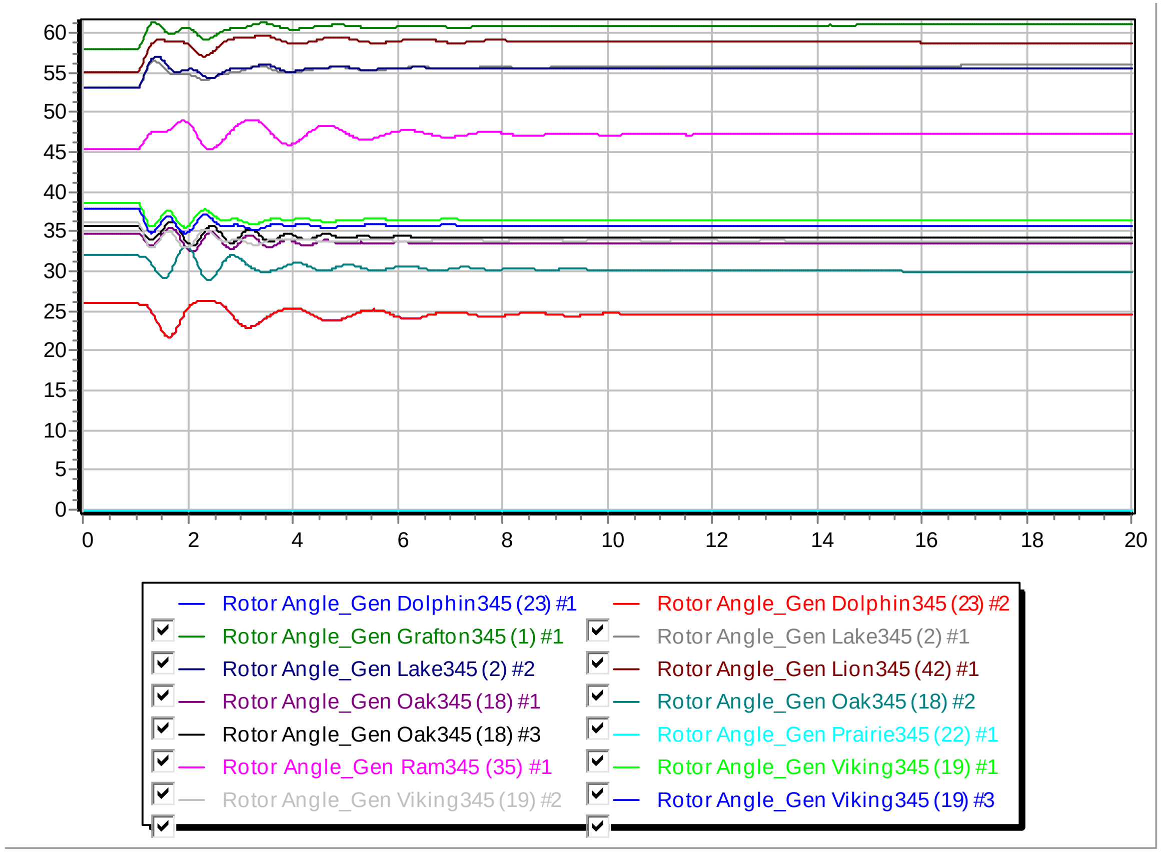
- Using a SignalStabStabilizer at bus 42 (Lion345), the phase lag of the generator's speed, relative to the stabilizer input is 199 degrees; flipping the sign requires phase compensation of 19 degrees or 9.5 per lead-lag
- Values are α = 0.72; for 0.6 Hz, T_1= 0.313, T_2=0.225; set T_3 and T_4 to match;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