Oscillations and Power System Stabilizers

PowerWorld Corporation
2001 S. First St, Suite 203
Champaign, IL 61820
http://www.powerworld.com
info@powerworld.com
217 384 6330

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Oscillations

- An oscillation is just a repetitive motion that can be either undamped, positively damped (decaying with time) or negatively damped (growing with time)
- If the oscillation can be written as a sinusoid then

$$e^{\alpha t}\left(a\cos\left(\omega t\right)+b\sin\left(\omega t\right)\right)=e^{\alpha t}C\cos\left(\omega t+\theta\right)$$

$$\text{where } C=\sqrt{A^2+B^2} \text{ and } \theta=\tan\left(\frac{-b}{a}\right)$$

- And the damping ratio is defined as (see Kundur 12.46)

$$\xi=\frac{-\alpha}{\sqrt{\alpha^2+\omega^2}}$$

The percent damping is just the damping ratio multiplied by 100; goal is sufficiently positive damping

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Power System Oscillations

- Power systems can experience a wide range of oscillations, ranging from highly damped and high frequency switching transients to sustained low frequency (< 2 Hz) inter-area oscillations affecting an entire interconnect
- Types of oscillations include
  - Transients: Usually high frequency and highly damped
  - Local plant: Usually from 1 to 5 Hz
  - Inter-area oscillations: From 0.15 to 1 Hz
  - Slower dynamics: Such as AGC, less than 0.15 Hz
  - Subsynchronous resonance: 10 to 50 Hz (less than synchronous)

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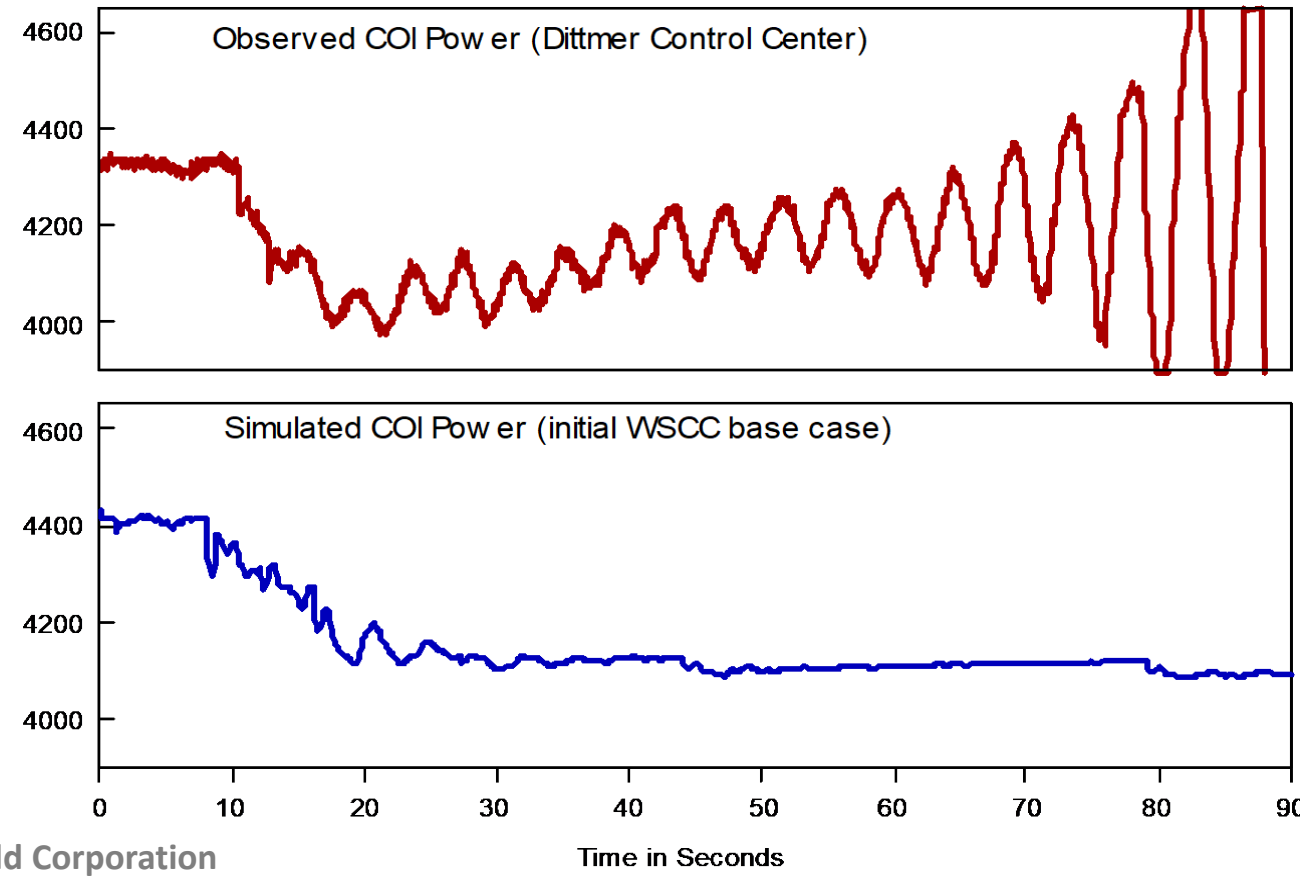
Example Oscillations

- The below graph shows an oscillation that was observed during a 1996 WECC Blackout



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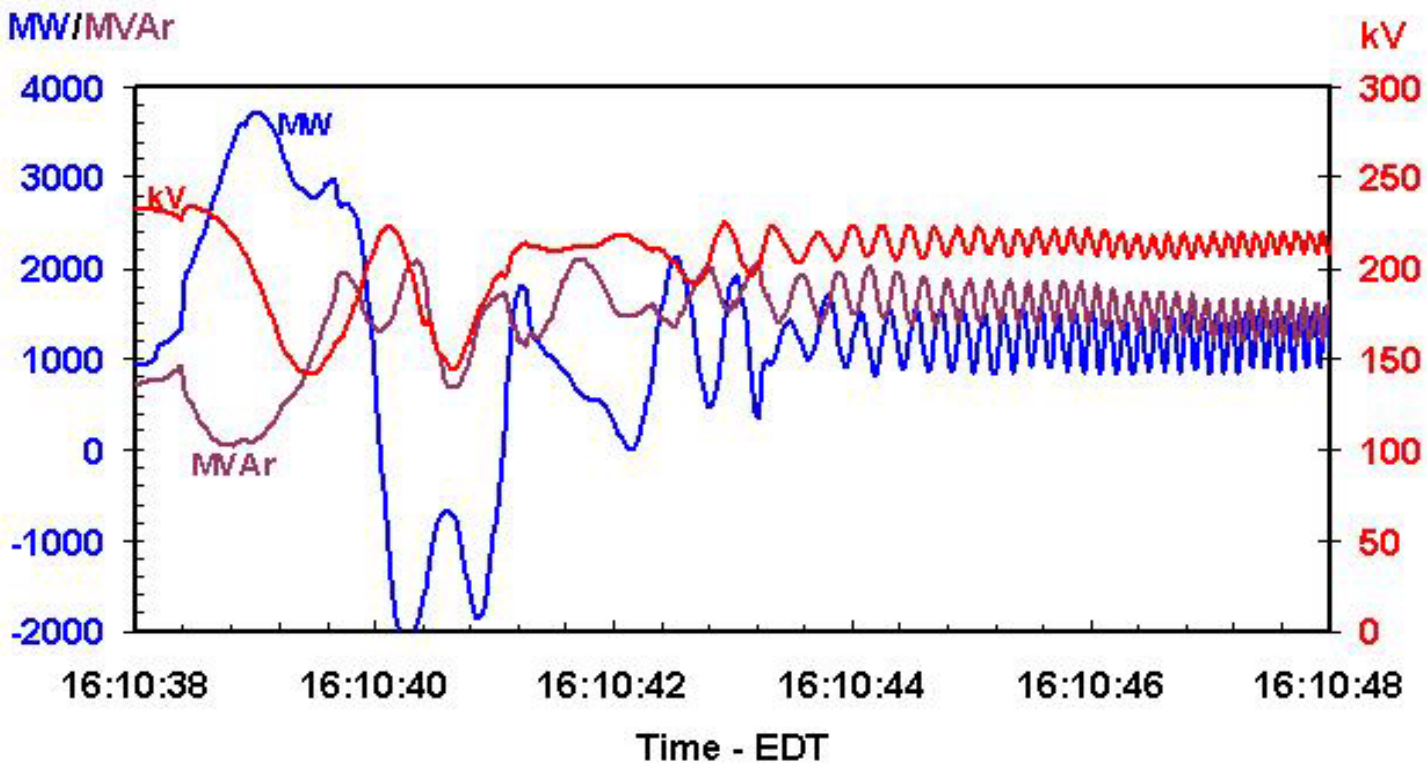
Example Oscillations

- The below graph shows oscillations on the Michigan/Ontario Interface on 8/14/03



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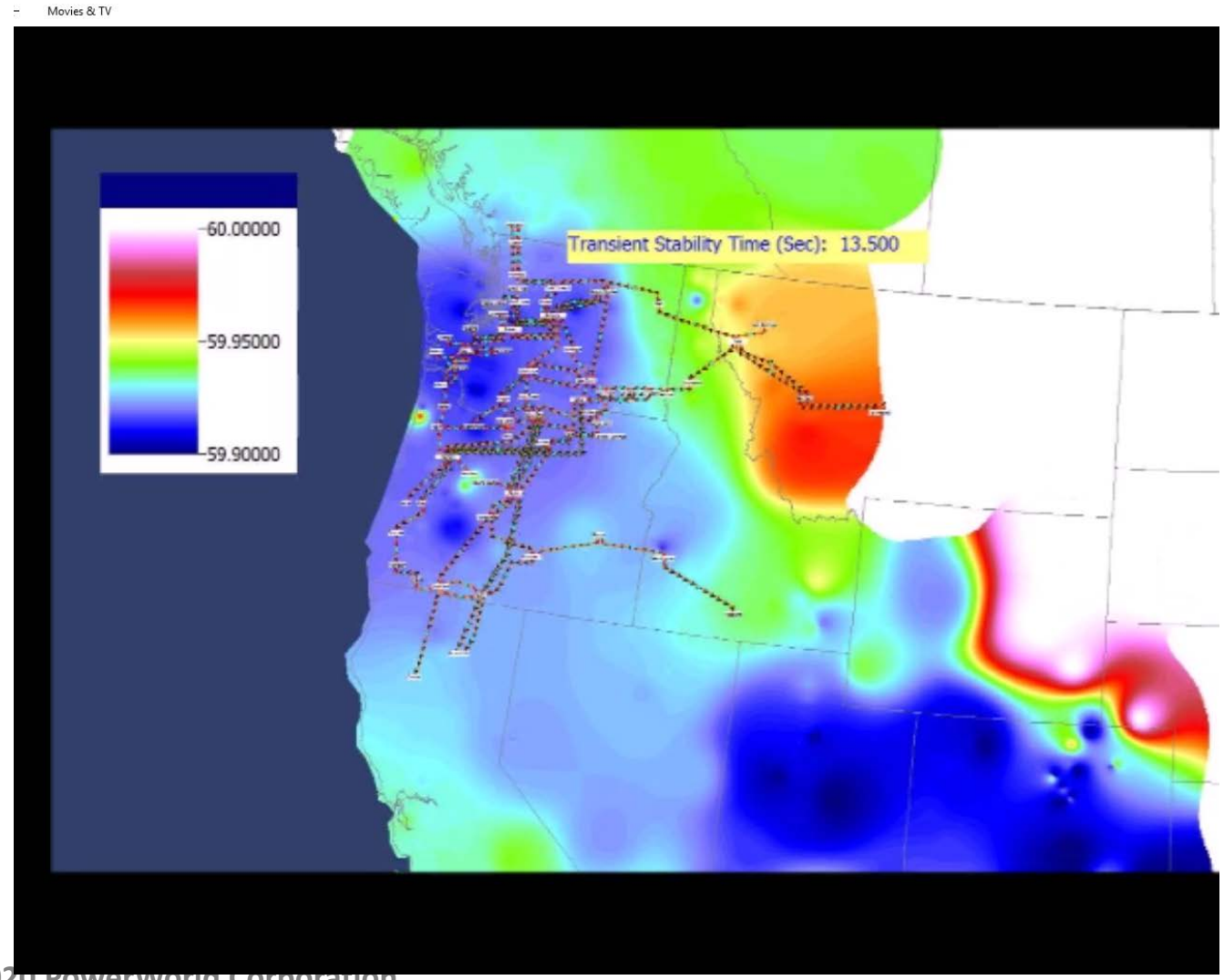
Fictitious System Oscillation



Movie shows an example of sustained oscillations in an equivalent system

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Forced Oscillations in WECC (from [1])

- Summer 2013 24 hour data: 0.37 Hz oscillations observed for several hours. Confirmed to be forced oscillations at a hydro plant from vortex effect.
- 2014 data: Another 0.5 Hz oscillation also observed. Source points to hydro unit as well. And 0.7 Hz. And 1.12 Hz. And 2 Hz.
- Resonance is possible when a system mode is poorly damped and close. Resonance can be observed in model simulations

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

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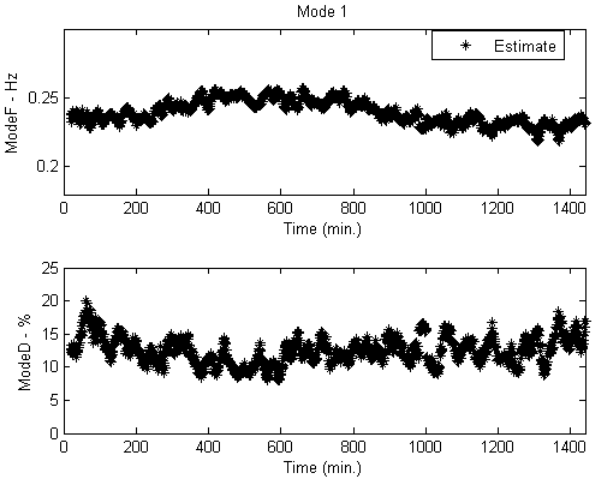
Inter-Area Modes in the WECC

- The dominant inter-area modes in the WECC have been well studied
- A good reference paper is D. Trudnowski, "Properties of the Dominant Inter-Area Modes in the WECC Interconnect," 2012
  - Four well known modes are NS Mode A (0.25 Hz), NS Mode B (or Alberta Mode), (0.4 Hz), BC Mode (0.6 Hz), Montana Mode (0.8 Hz)

Below figure from paper shows NS Mode A On May 29, 2012



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Resonance with Interarea Mode [1]

- Resonance effect high when:
  - Forced oscillation frequency near system mode frequency
  - System mode poorly damped
  - Forced oscillation location near the two distant ends of mode
- Resonance effect medium when
  - Some conditions hold
- Resonance effect small when
  - None of the conditions holds

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015 http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

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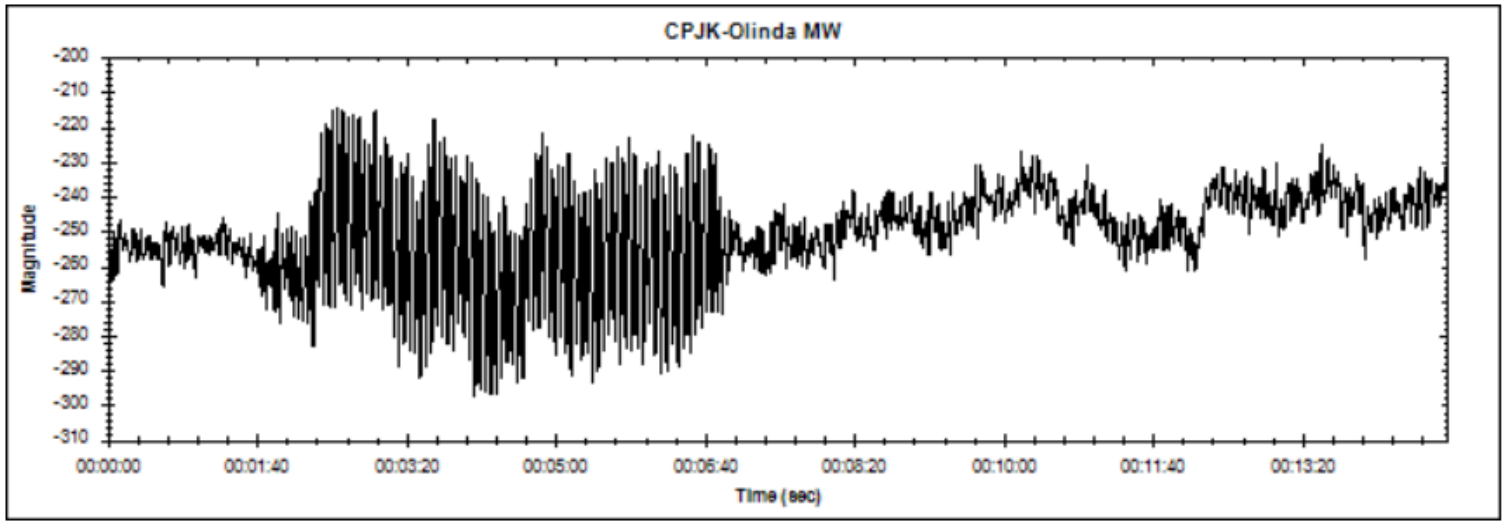
Medium Resonance on 11/29/2005



- 20 MW 0.26 Hz Forced Oscillation in Alberta Canada
- 200 MW Oscillations on California-Oregon Inter-tie
- System mode 0.27 Hz at 8% damping
- Two out of the three conditions were true.

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

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An On-line Oscillation Detection Tool

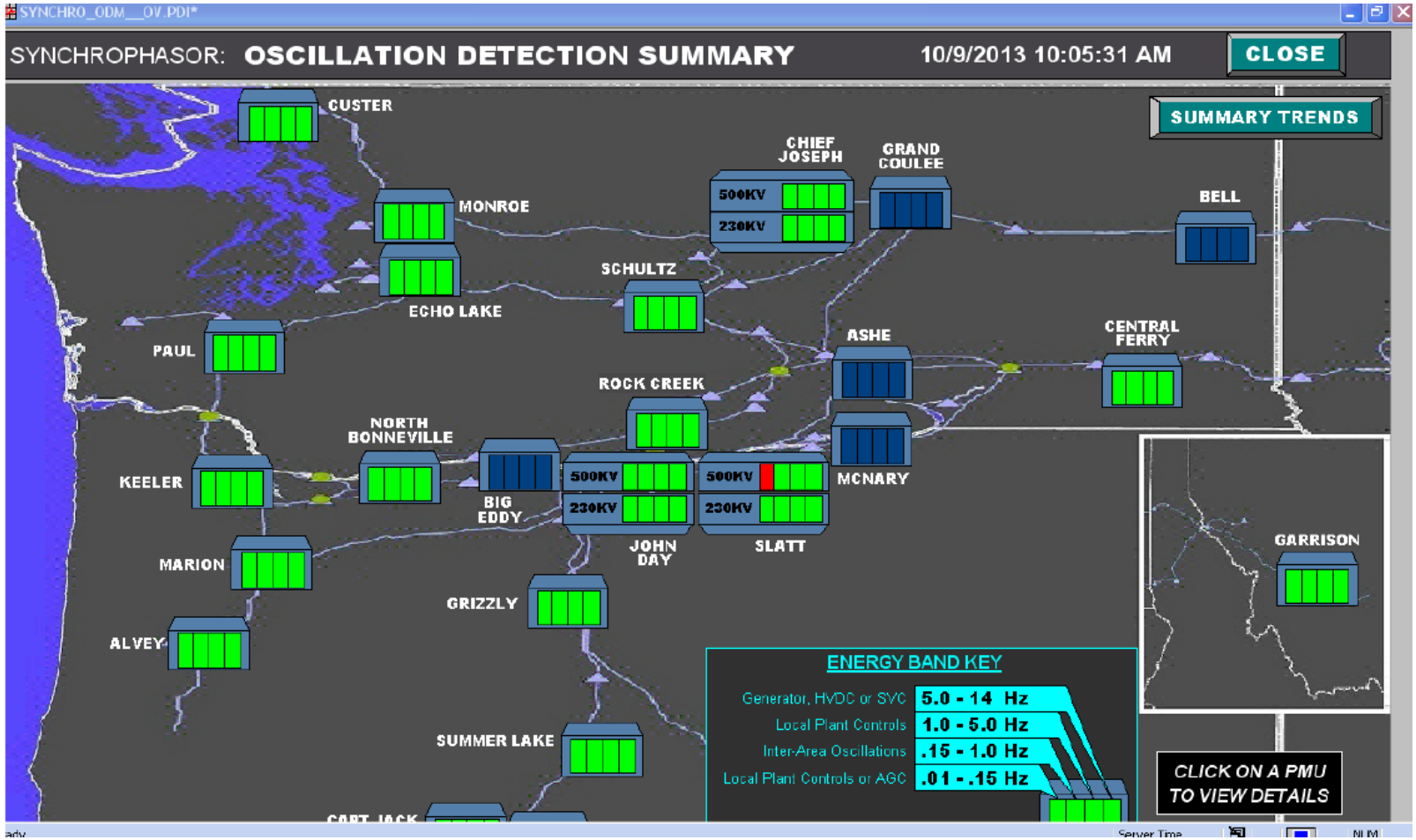

Image source: WECC Joint Synchronized Information Subcommittee Report, October 2013

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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

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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

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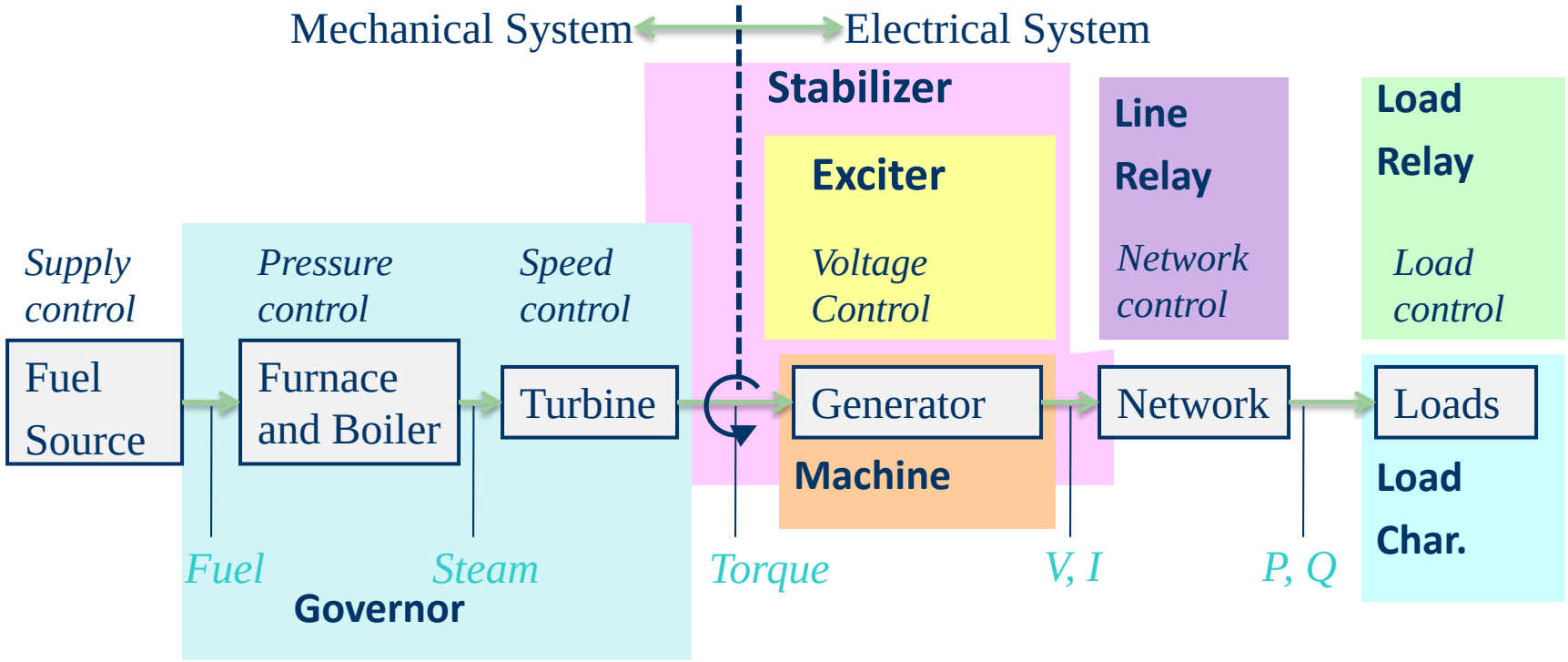
Dynamic Models in the Physical Structure



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

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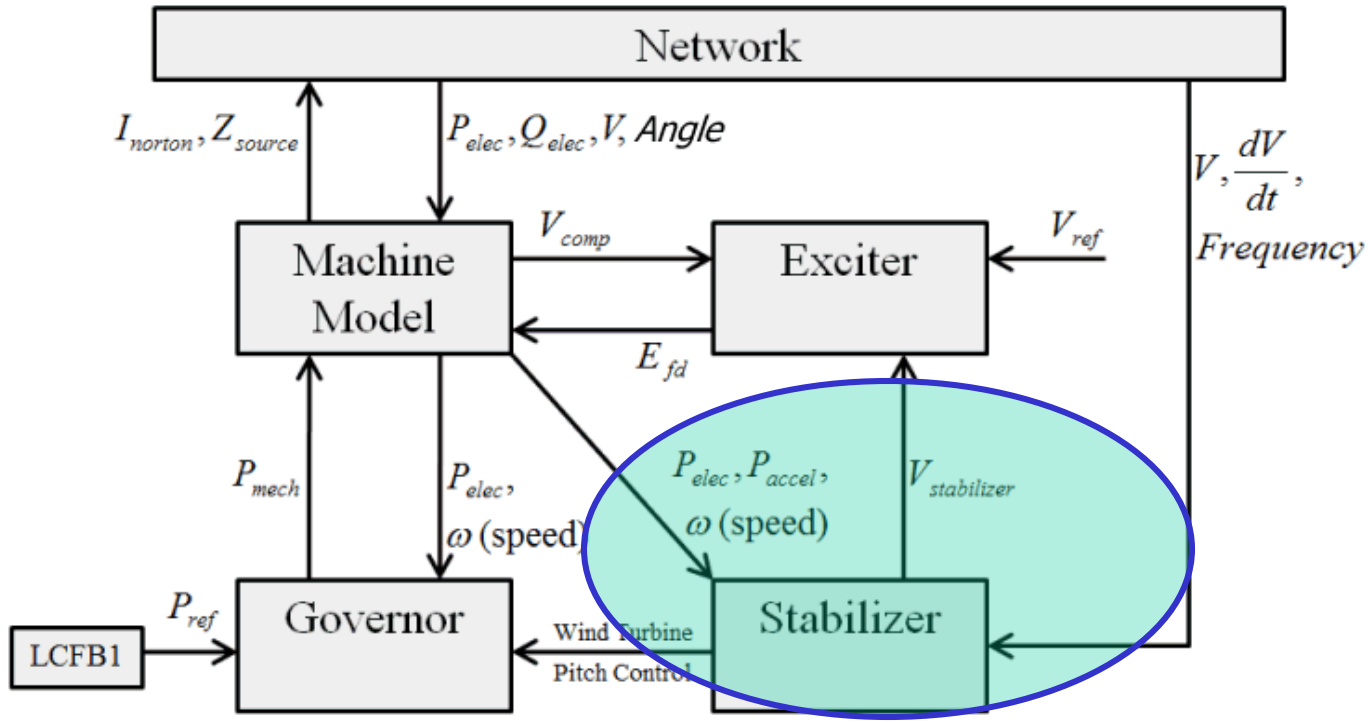
Power System Stabilizer (PSS) Models



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)

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Classic Block Diagram of a System with a PSS

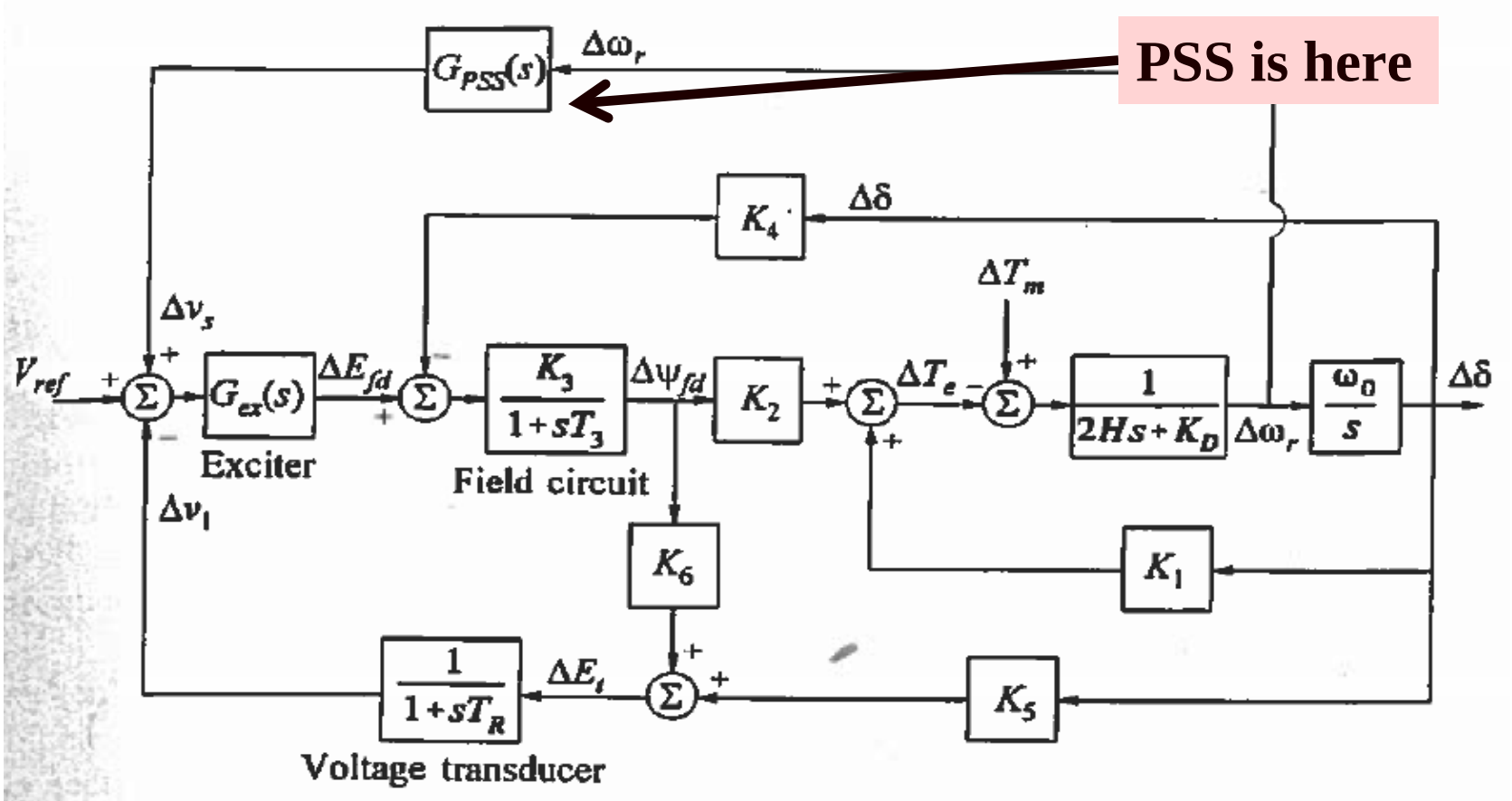

Figure 12.13 Block diagram representation with AVR and PSS

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

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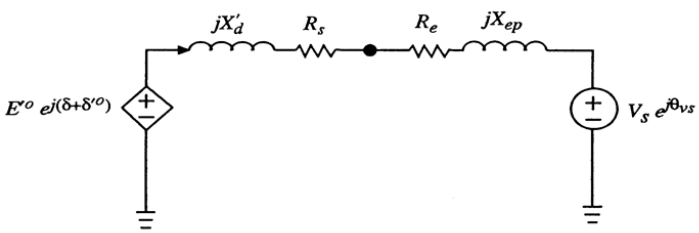
PSS Basics

- 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

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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

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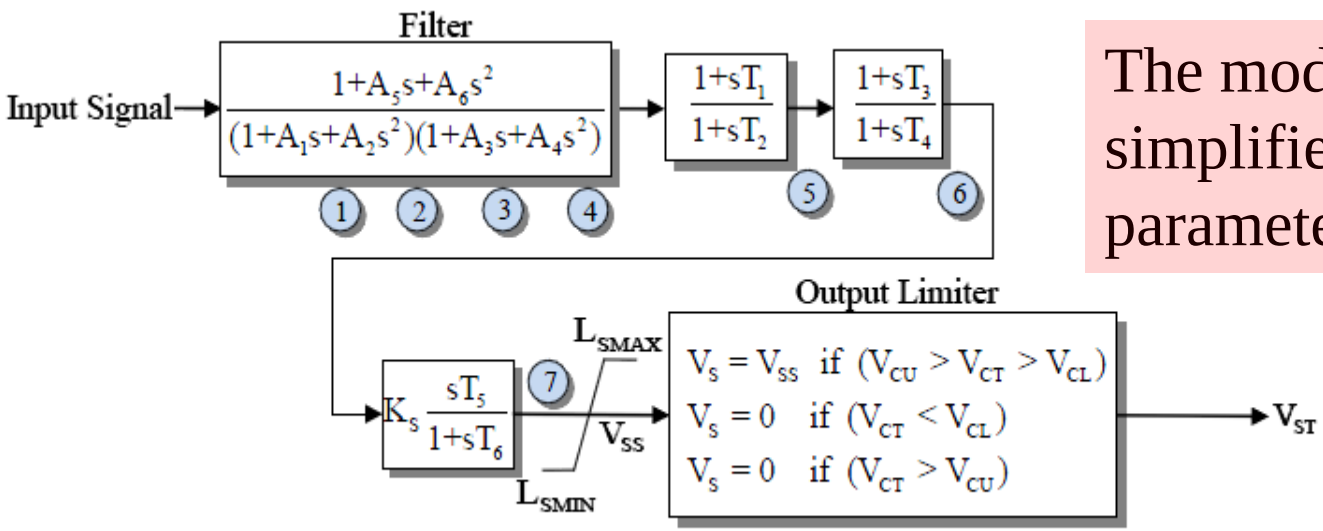
Example PSS

- 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



The model can be simplified by setting parameters to zero

V_{ST} is an input into the exciter

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Another Single Input PSS

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

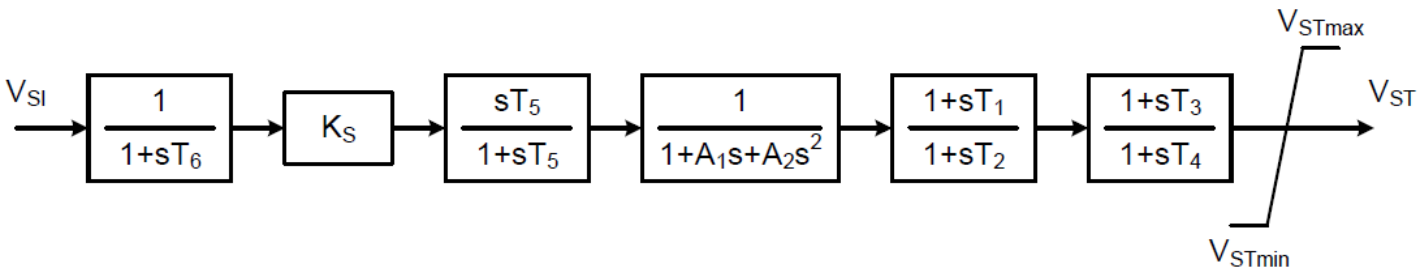

Figure 31 —Type PSS1A single-input power system stabilizer

IEEE Std 421.5 describes the common stabilizers

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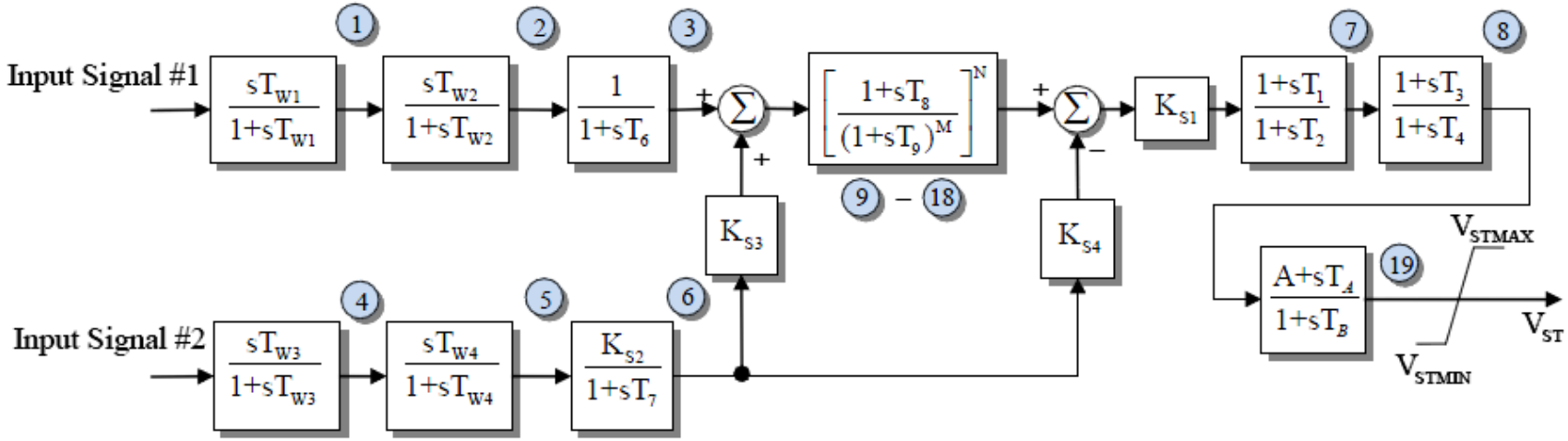
Example Dual Input PSS

- 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



IEEE Std 421.5 describes the common stabilizers

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Washout Filters and Lead-Lag Compensators

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

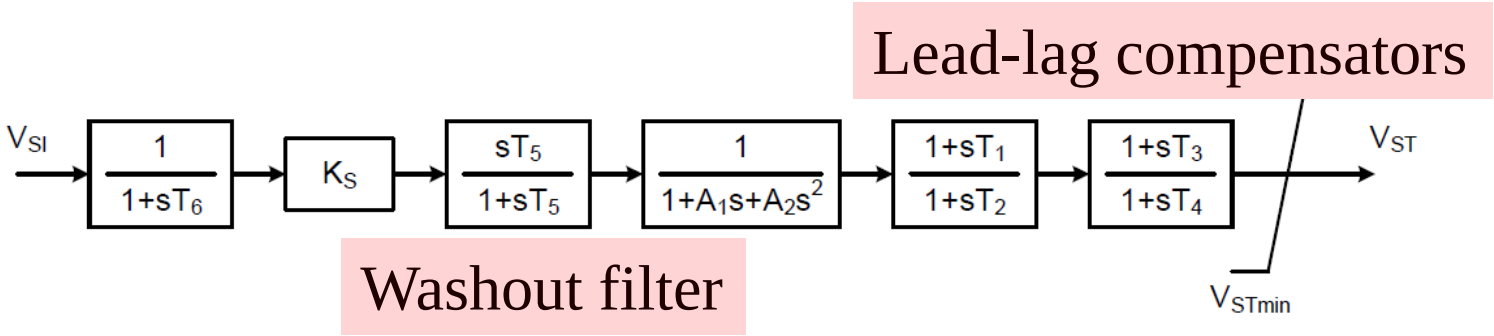

Figure 31 —Type PSS1A single-input power system stabilizer

- 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.

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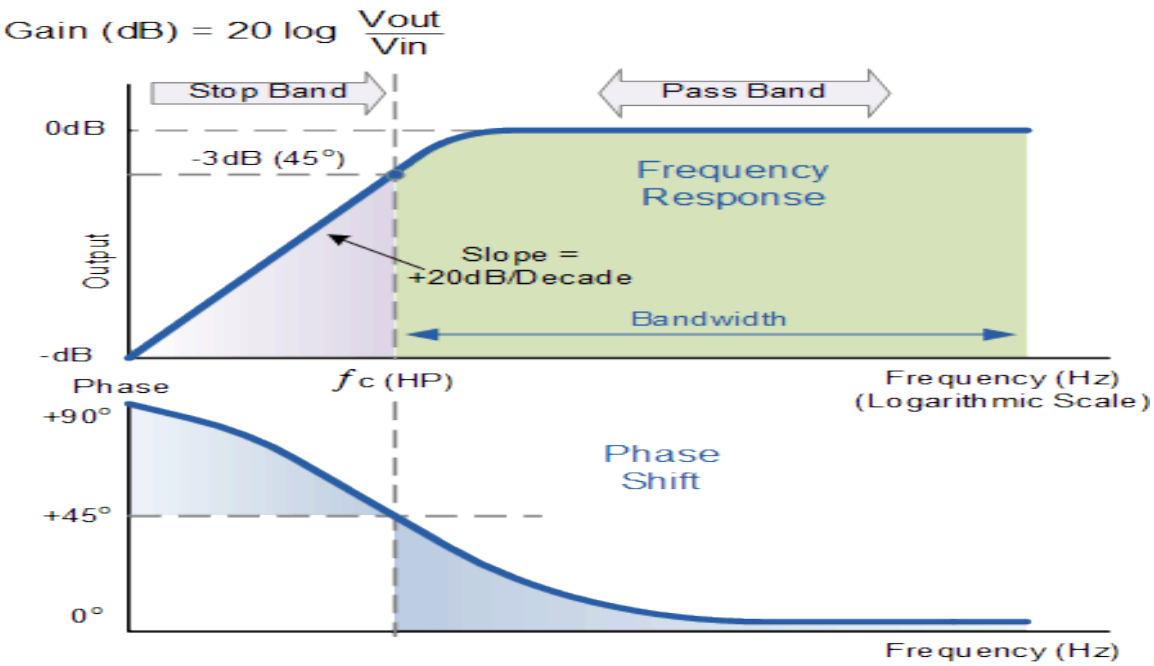
Washout Filter

- 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

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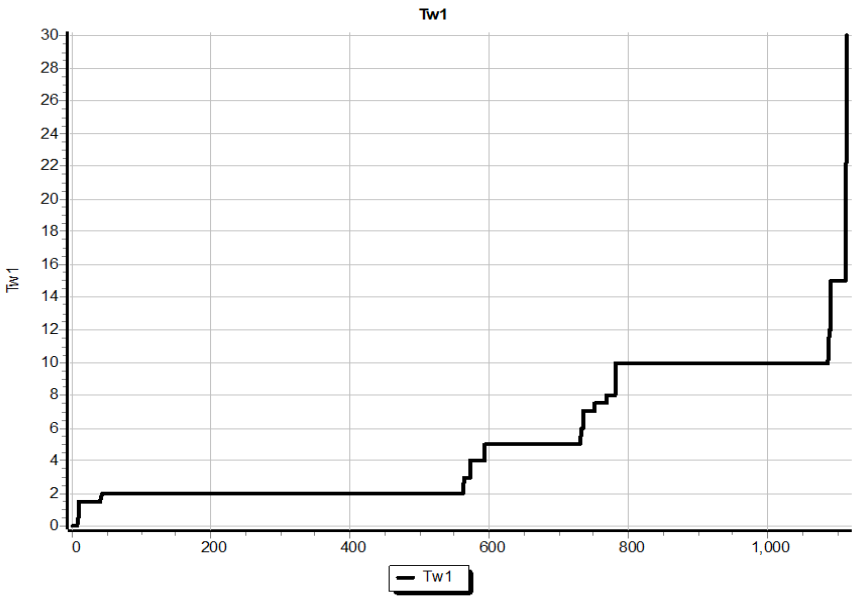
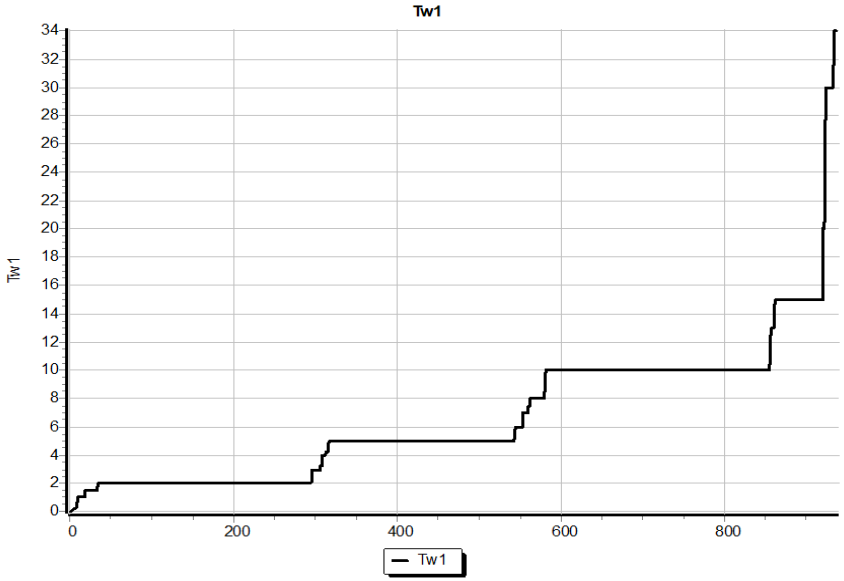
Washout Parameter Variation

- 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





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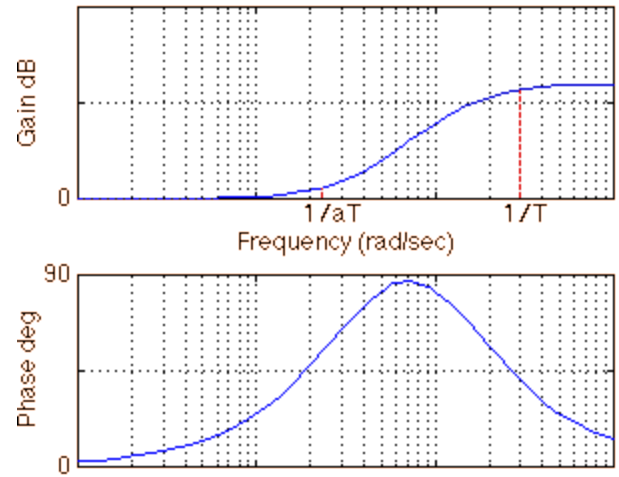
Lead-Lag Compensators

- 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

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

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

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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

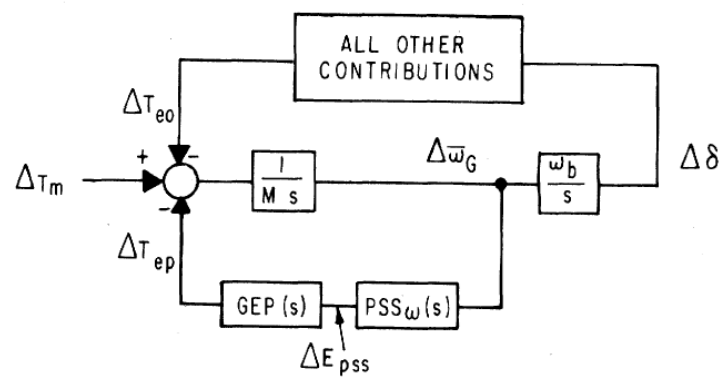

Image Source: Figure 1 from Larsen, 1981, Part 1

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Stabilizer Design

- 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

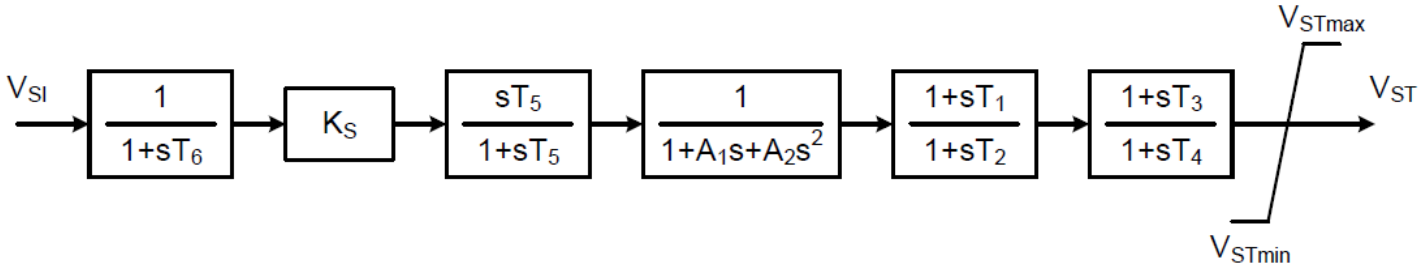

Figure 31 —Type PSS1A single-input power system stabilizer

Image Source: IEEE Std 421.5-2016

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Stabilizer Design Values

- With a washout filter value of T_5 = 10 at 0.1 Hz (s = j0.2π = 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

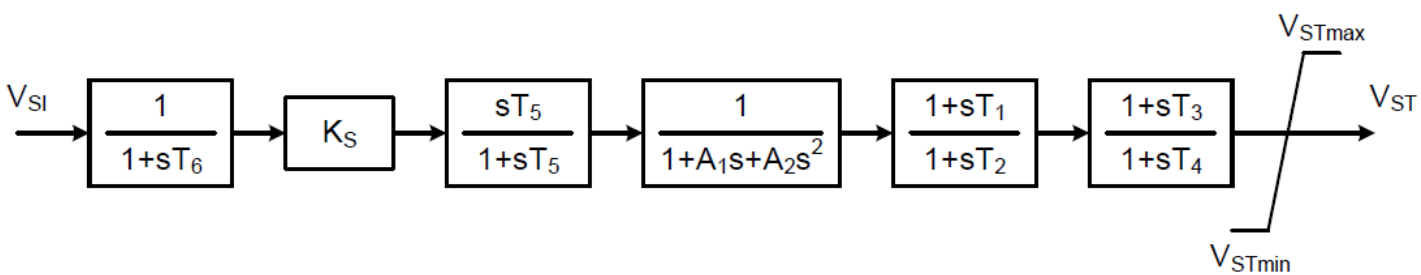

Figure 31—Type PSS1A single-input power system stabilizer

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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

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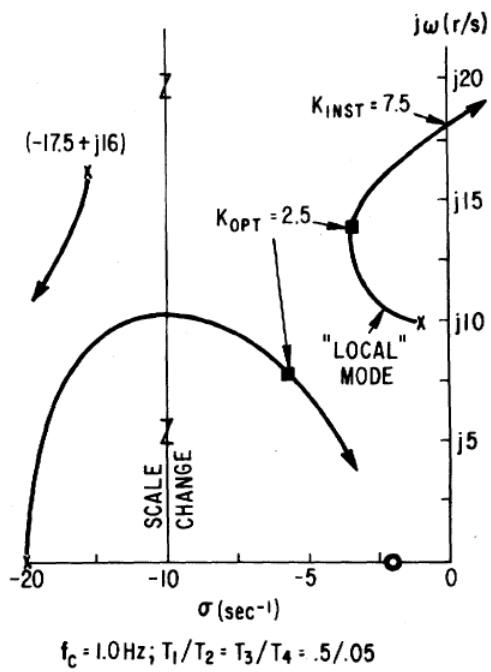
Stabilizer Design Tuning Criteria

- 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

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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

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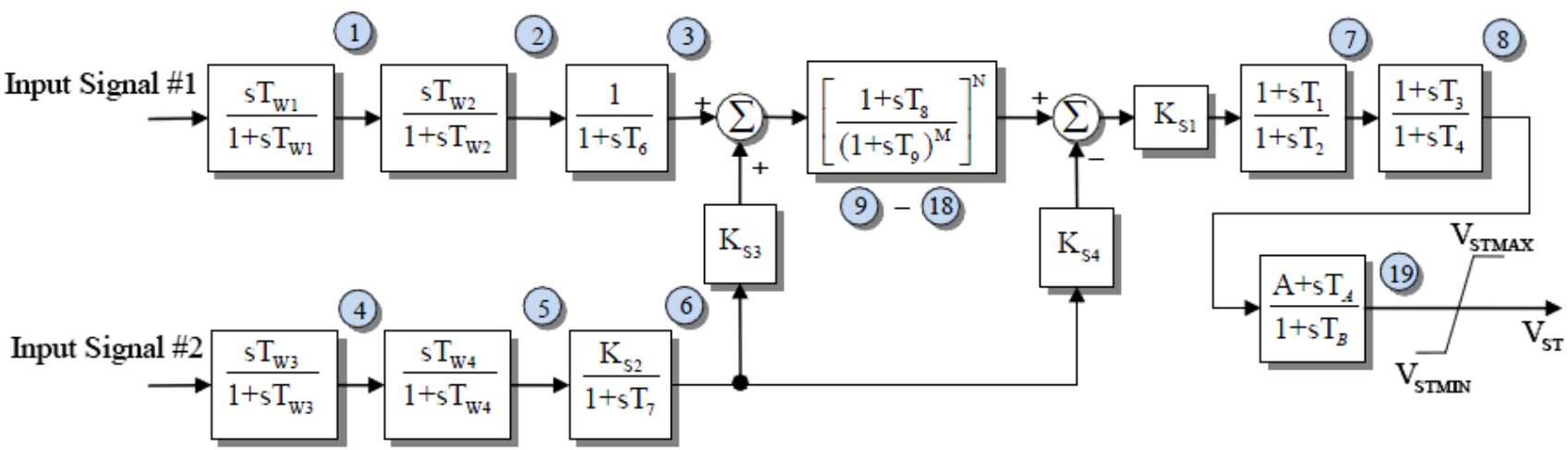
PSS2A Example Values

- 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



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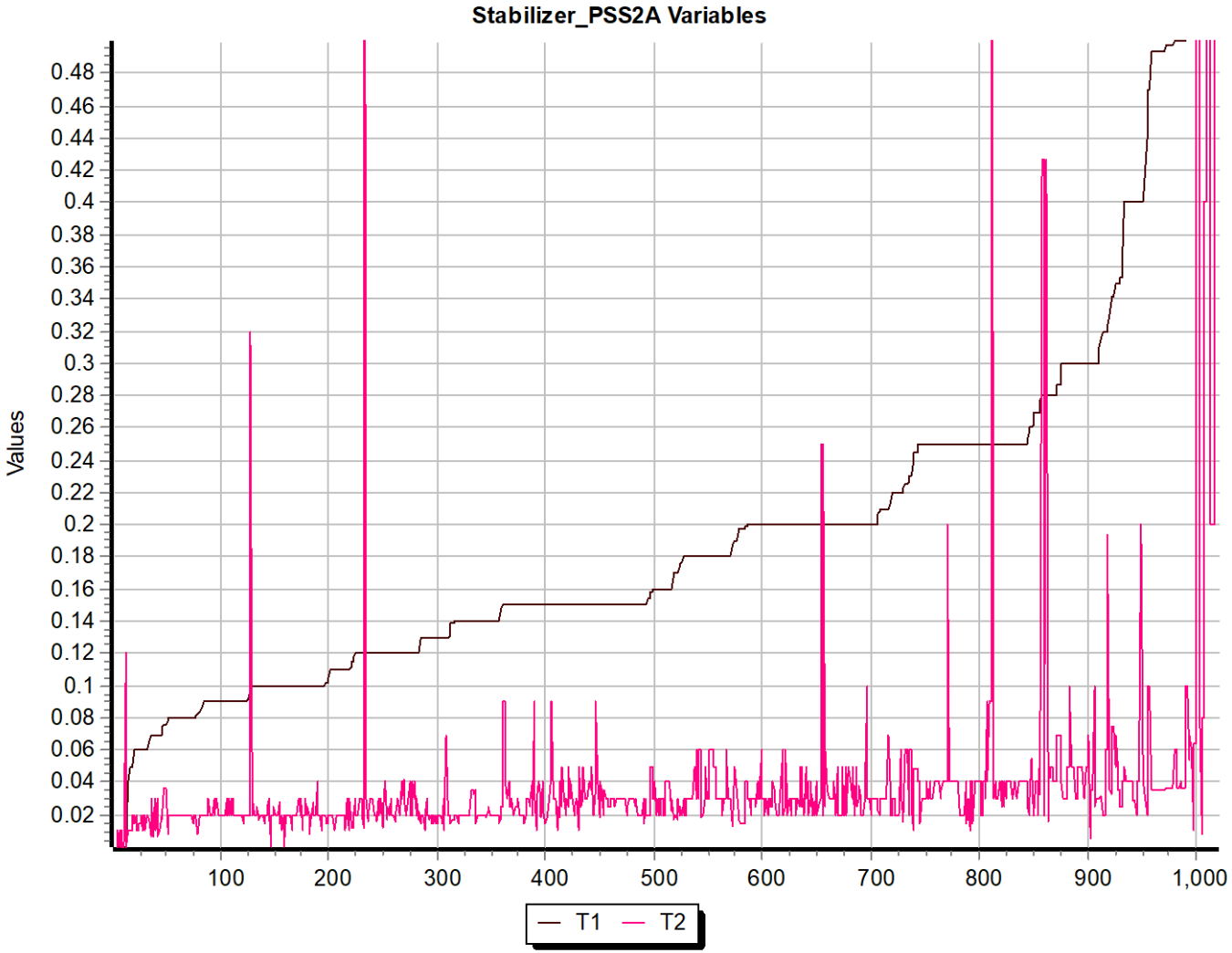
Example T1 and T2 Values



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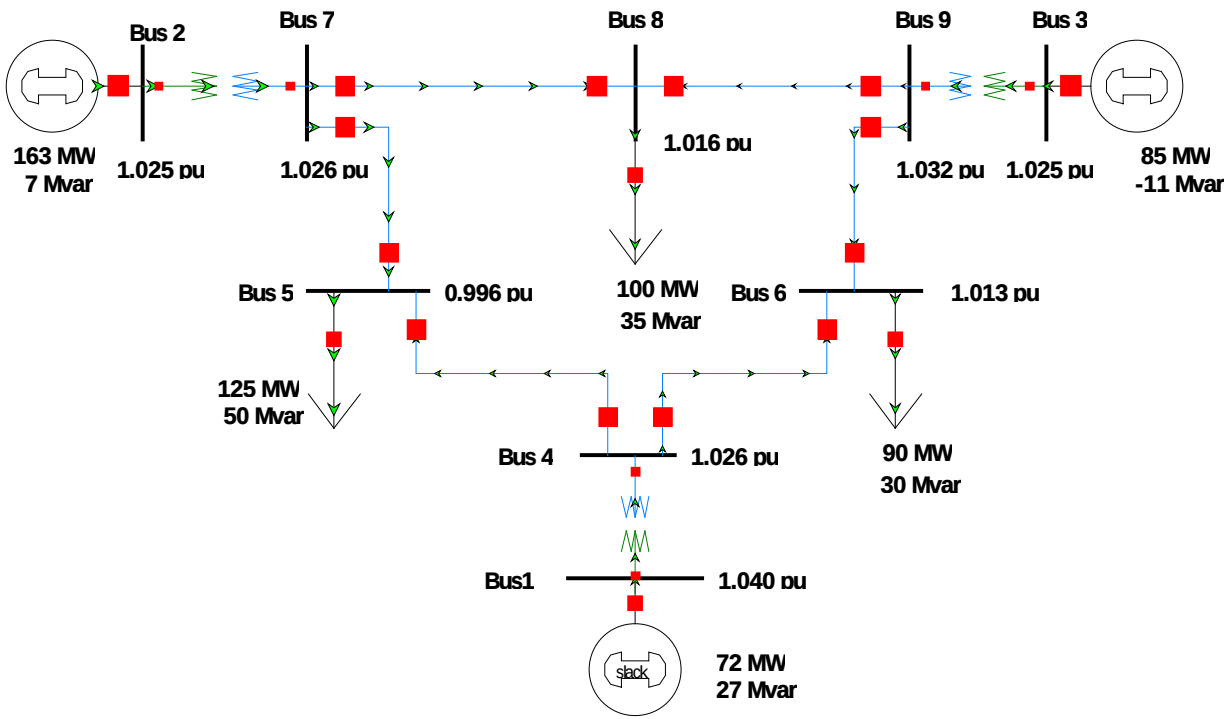
Hands-On PSS Tuning Example

- 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



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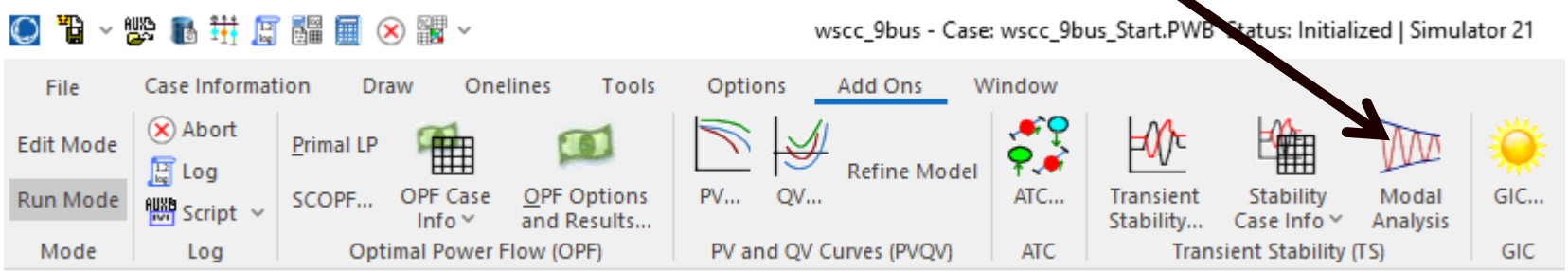
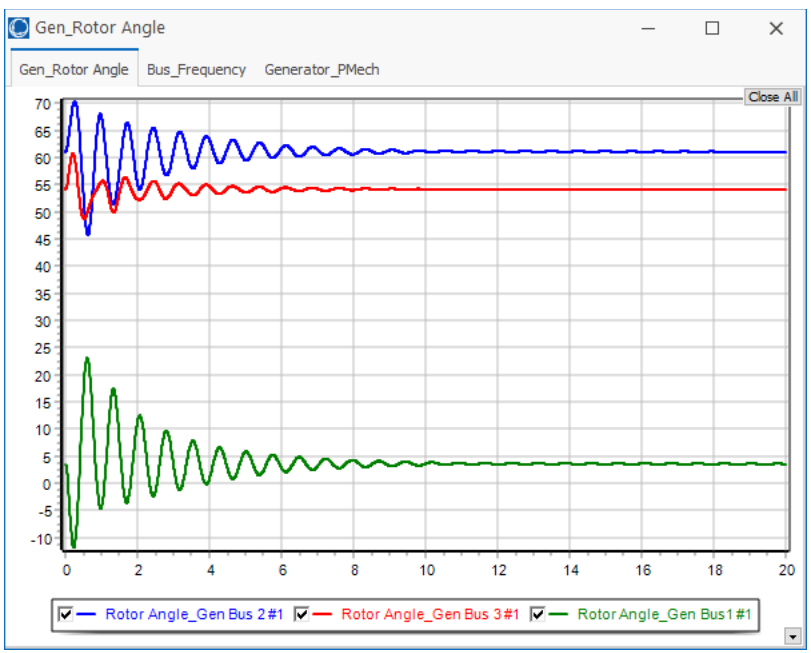
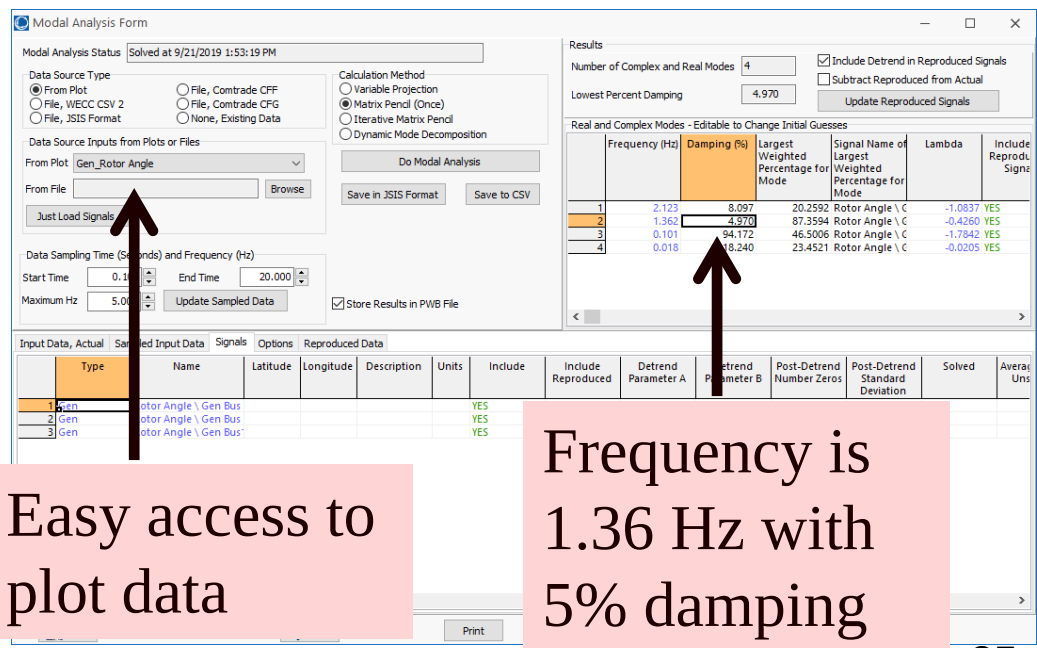
Hands-On PSS Tuning Example: Getting Initial Frequency and Damping

- The new Modal Analysis button provides quick







Easy access to plot data

Frequency is 1.36 Hz with 5% damping

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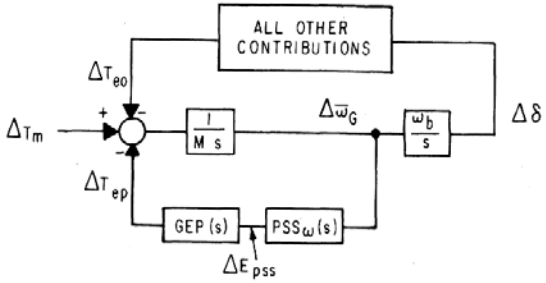
Hands-On PSS Tuning Example: We'll Add PSS1As at Gens 2 and 3

- To increase the generator speed damping, add PSS1A stabilizers using the local shaft speed 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



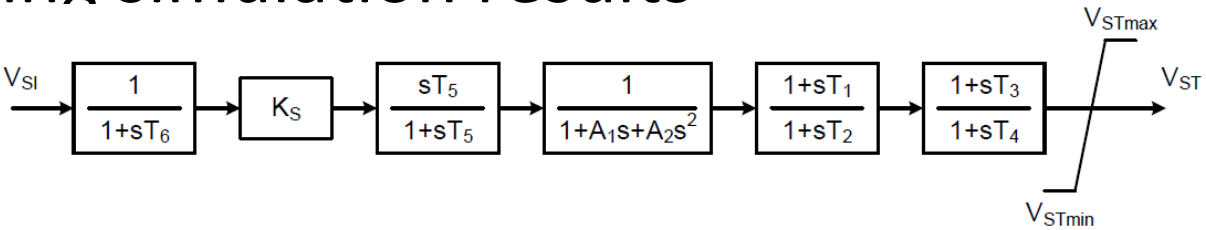


Figure 31 —Type PSS1A single-input power system stabilizer

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Hands-On 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
- Open the case **wscc_9Bus_Stab_Test**
  - This has SignalStab stabilizers modeled at each generator; these models can play in a fixed frequency signal

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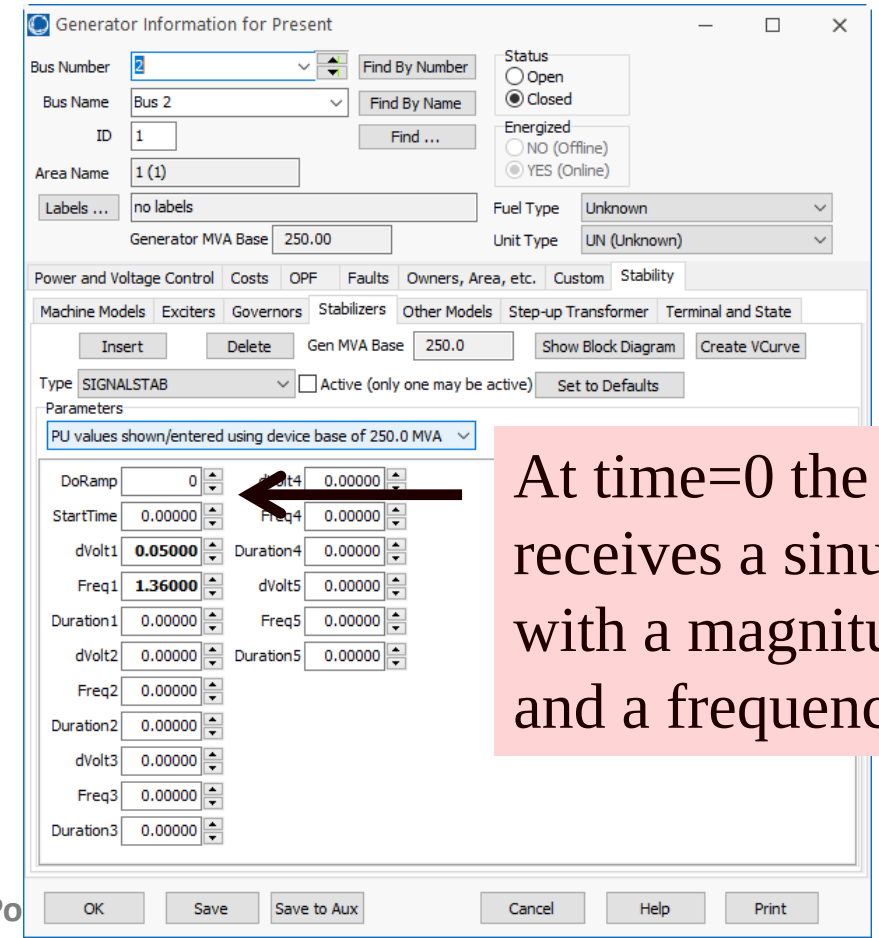
SignalStab Input and Results

- 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

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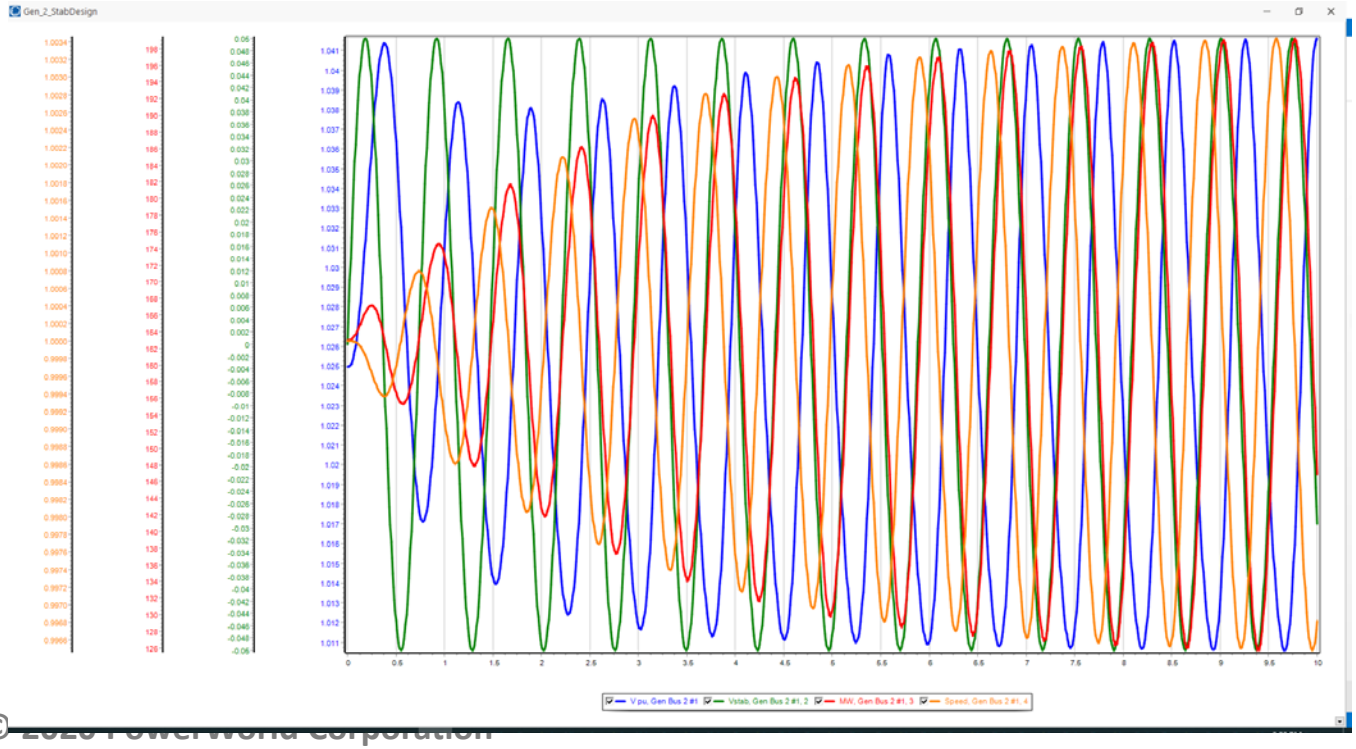
Hands-On PSS Tuning Example: Gen2 Reference Signal Results

- 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

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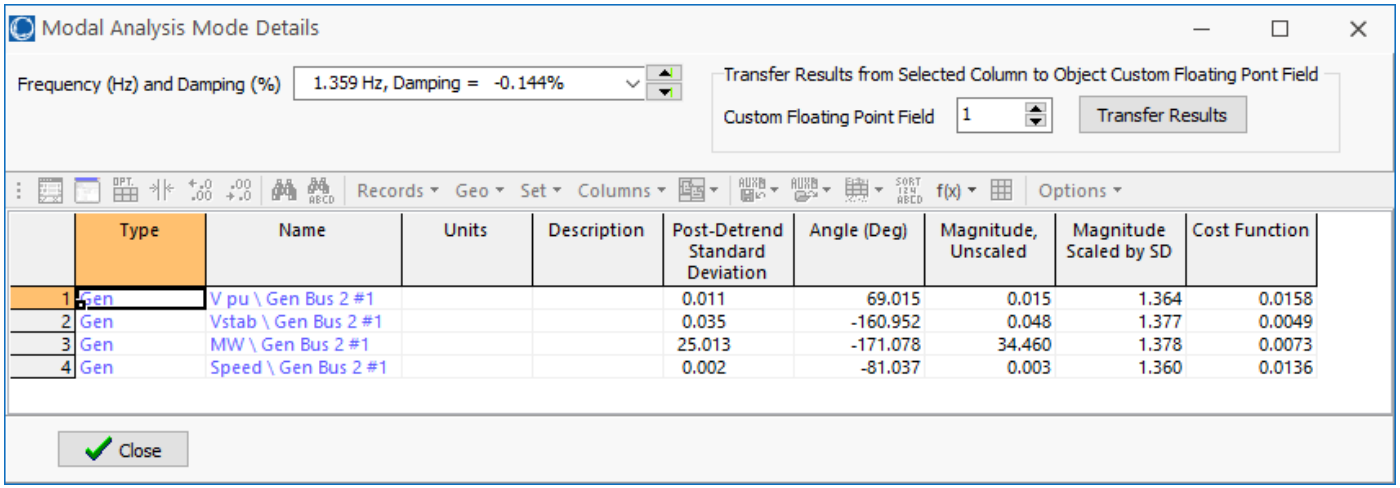
Hands-On PSS Tuning Example: 1.36 Hz Modal Values

- 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

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Hands-On 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 a is

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

- In our example with ϕ = 50° then

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

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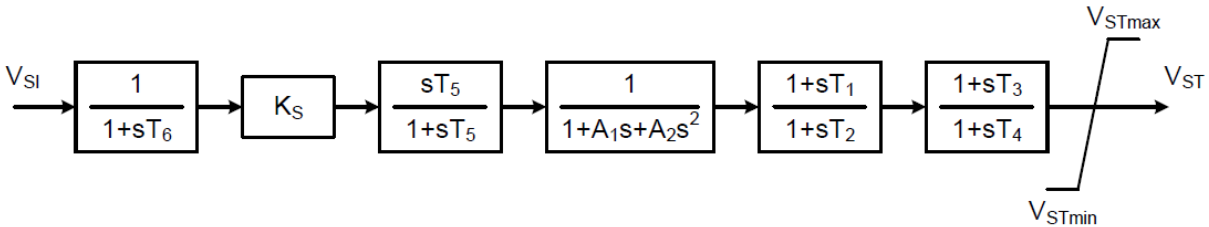
Hands-On PSS Tuning Example: 1.36 Hz Lead-Lag Values

- 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

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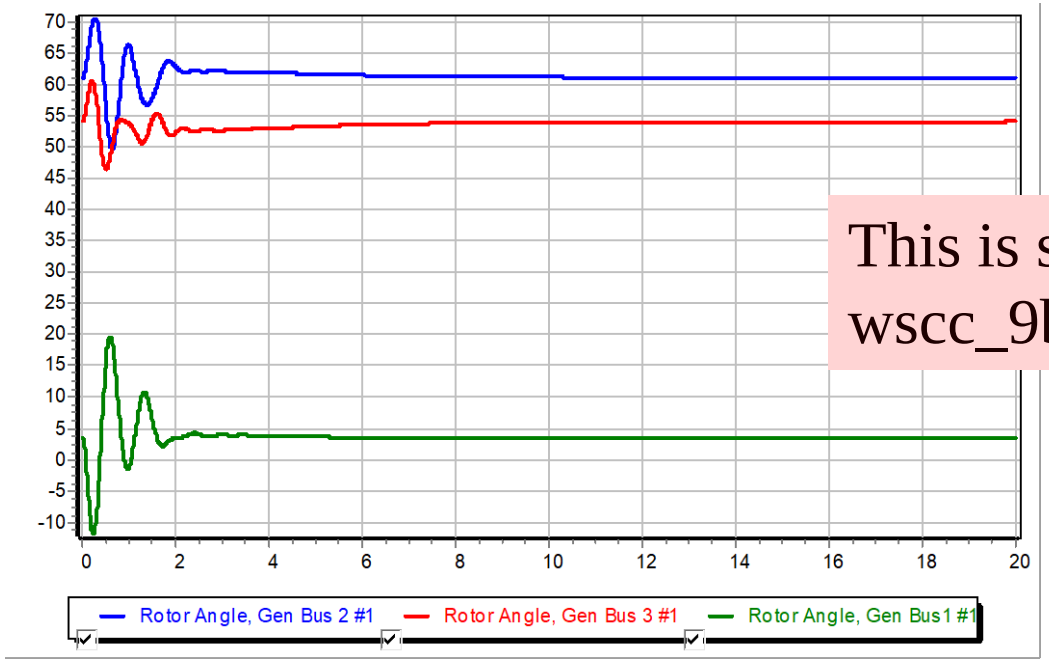
Hands-On PSS Tuning Example: Setting the Values for Gen 2

- 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

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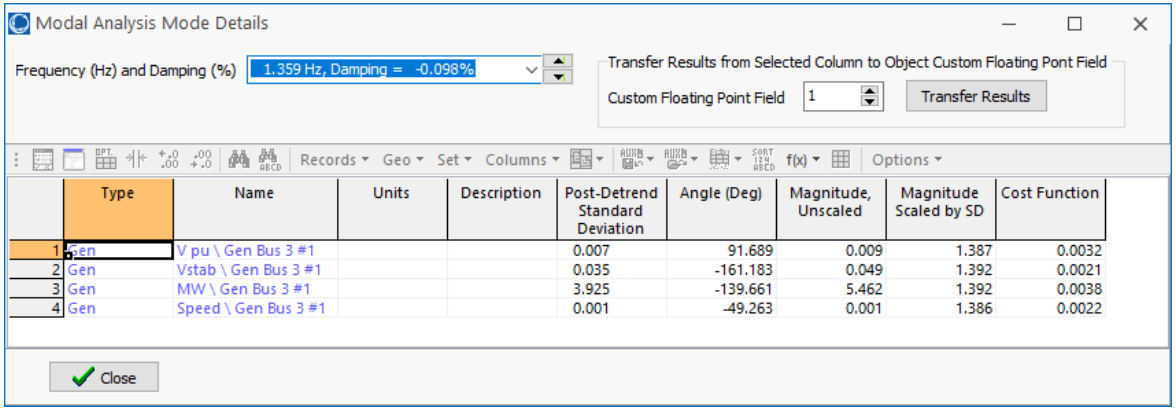
Hands-On PSS Tuning Example: Setting the Values for Gen 3

- 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 α = 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.

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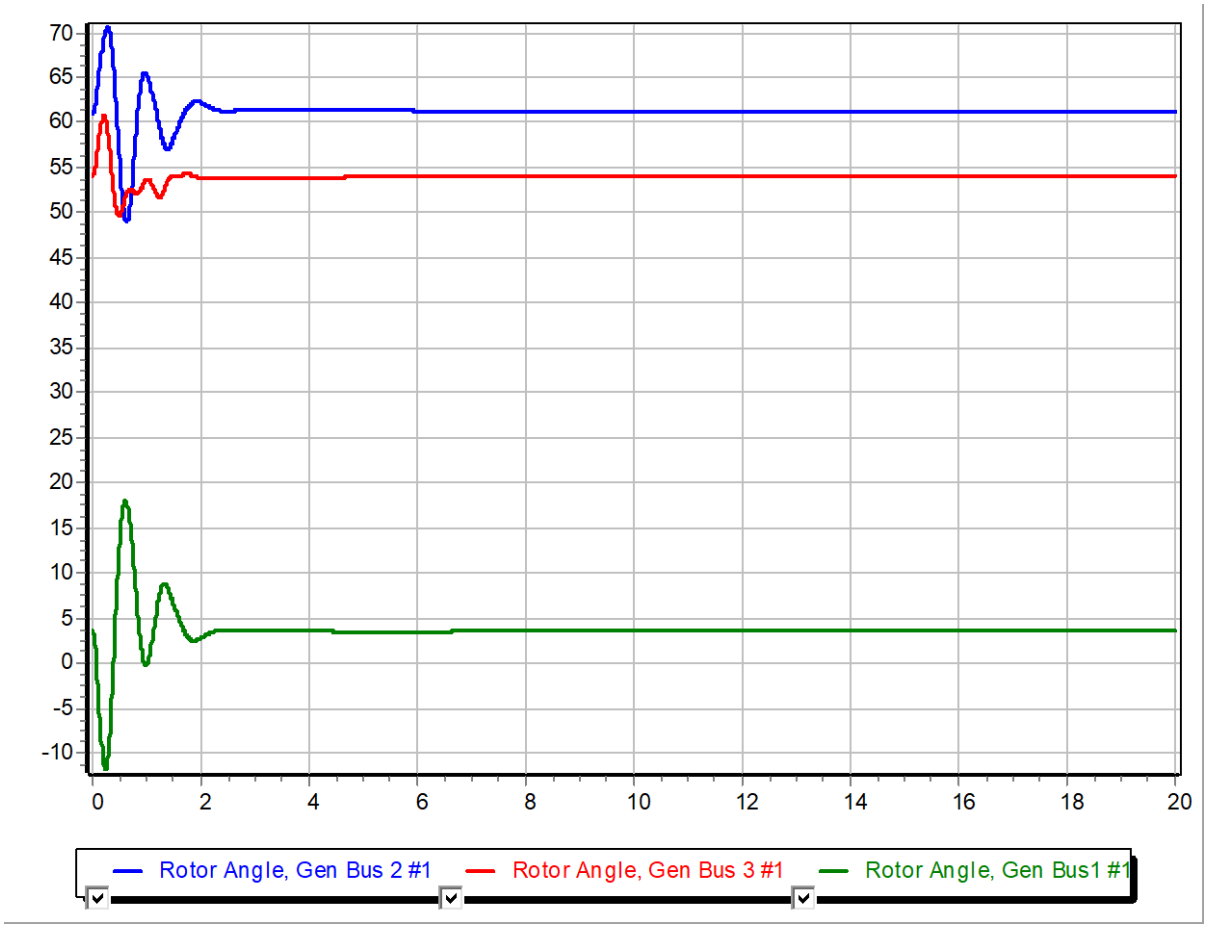
Hands-On PSS Tuning Example: Final Solution



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

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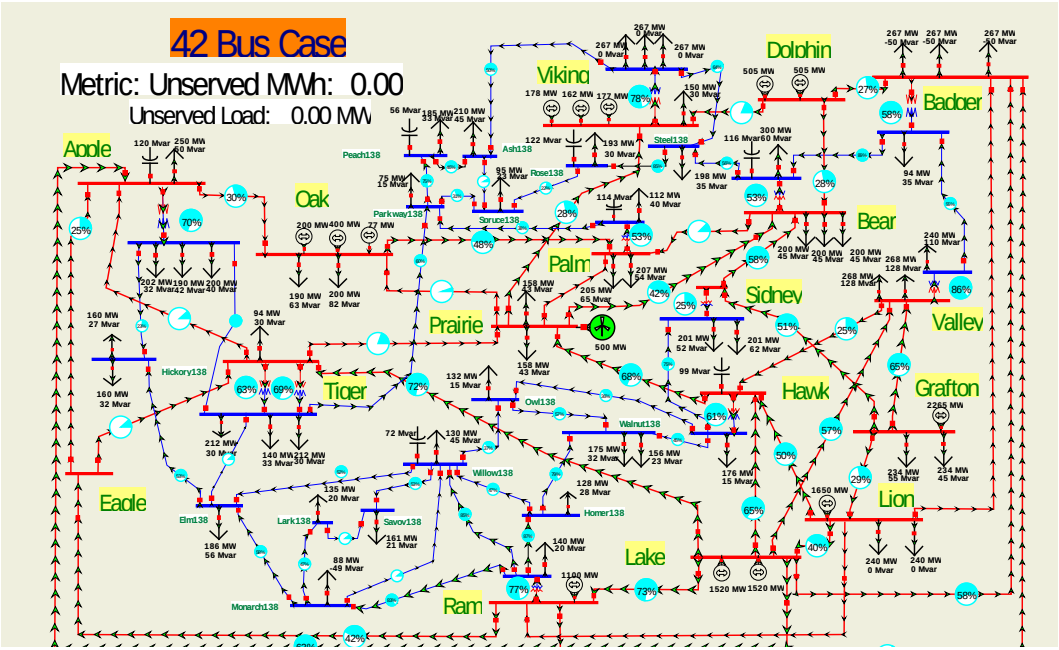
Hands-On Example 2: Adding a PSS to a 42 Bus System

- 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**

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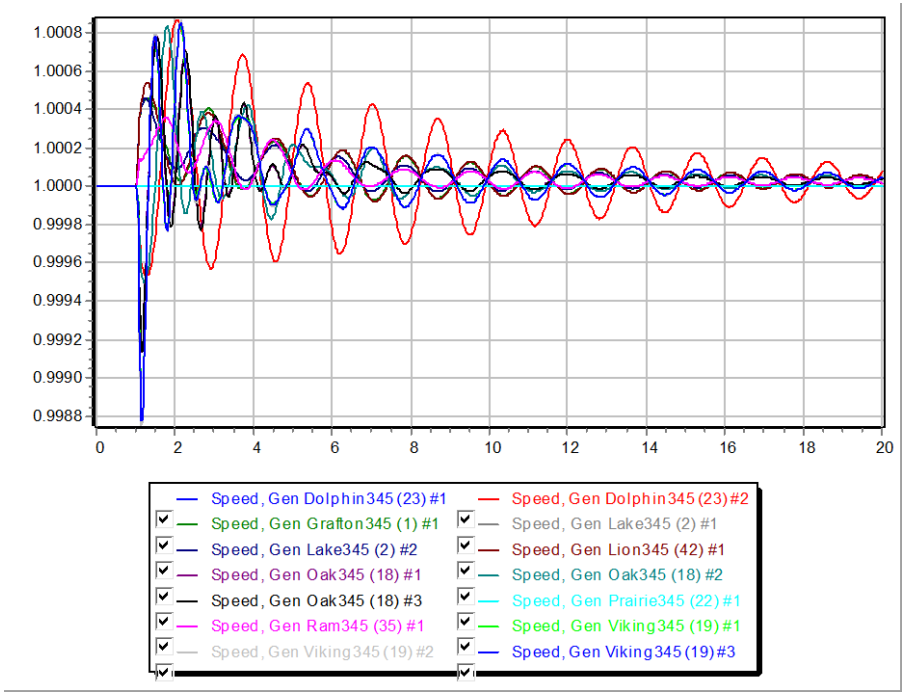
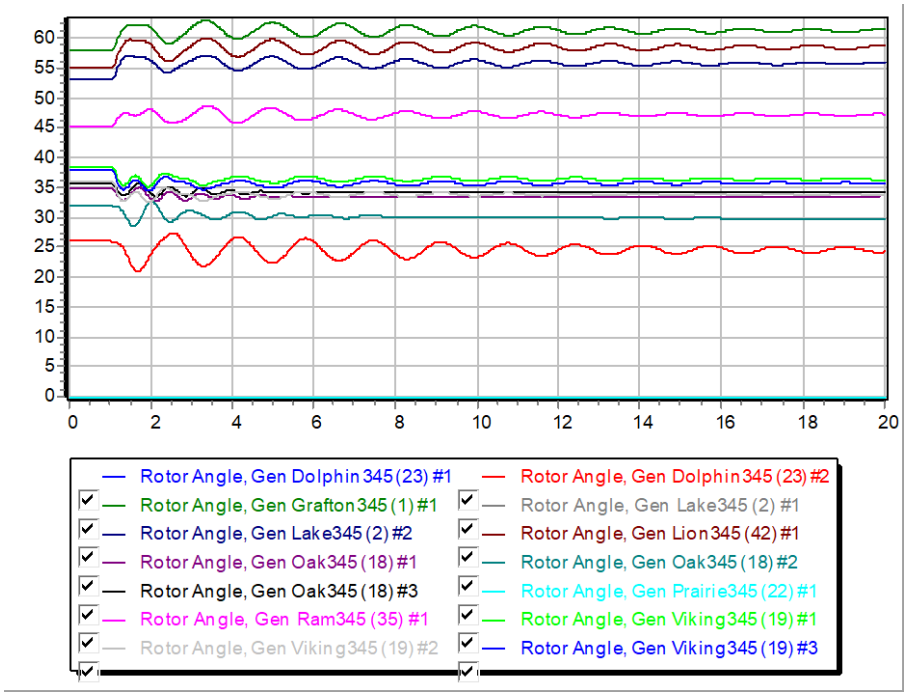
Example 2: Decide Generators to Tune and Frequency

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





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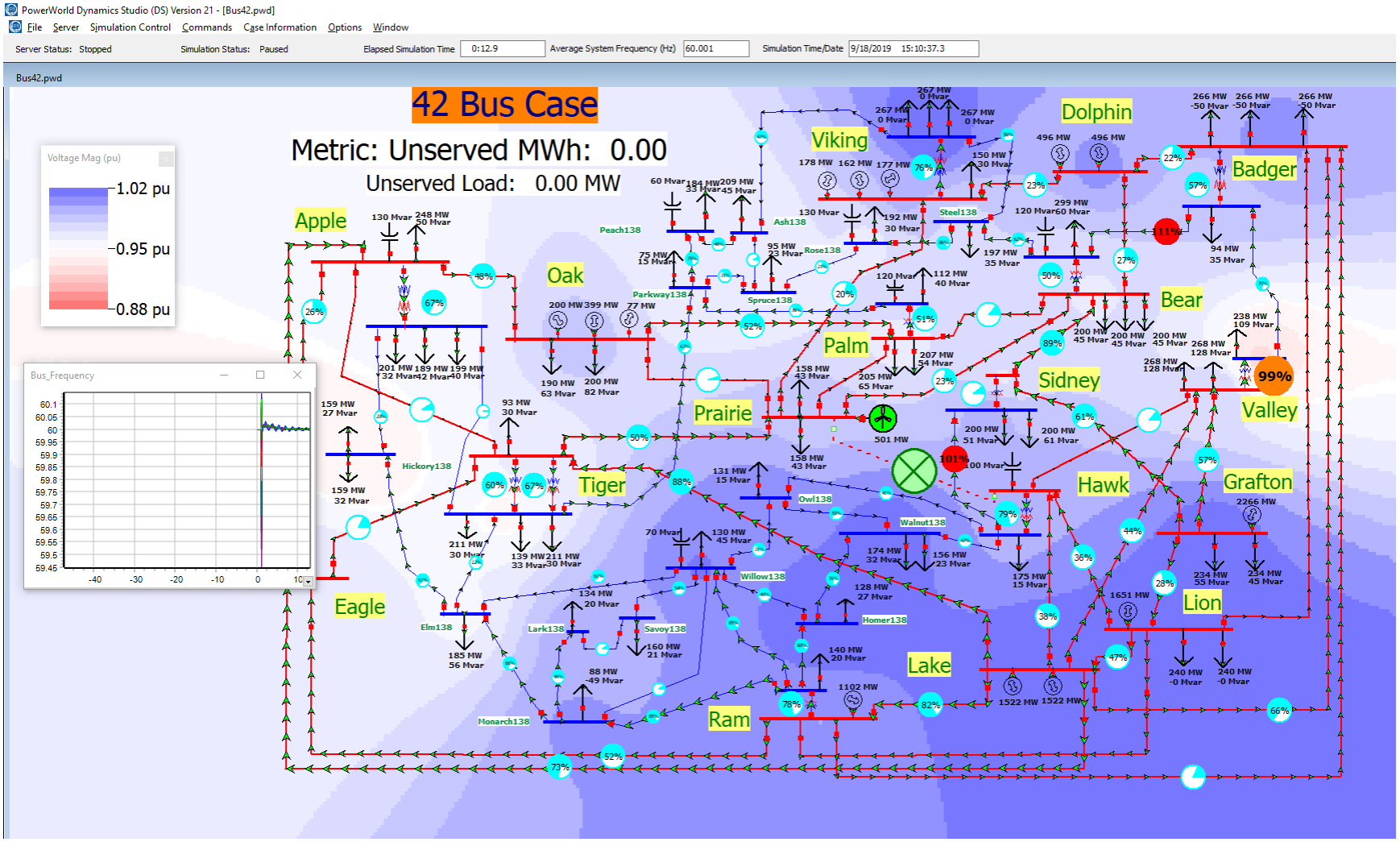
Aside: Visualizing the Disturbance in PowerWorld Dynamics Studio (DS)



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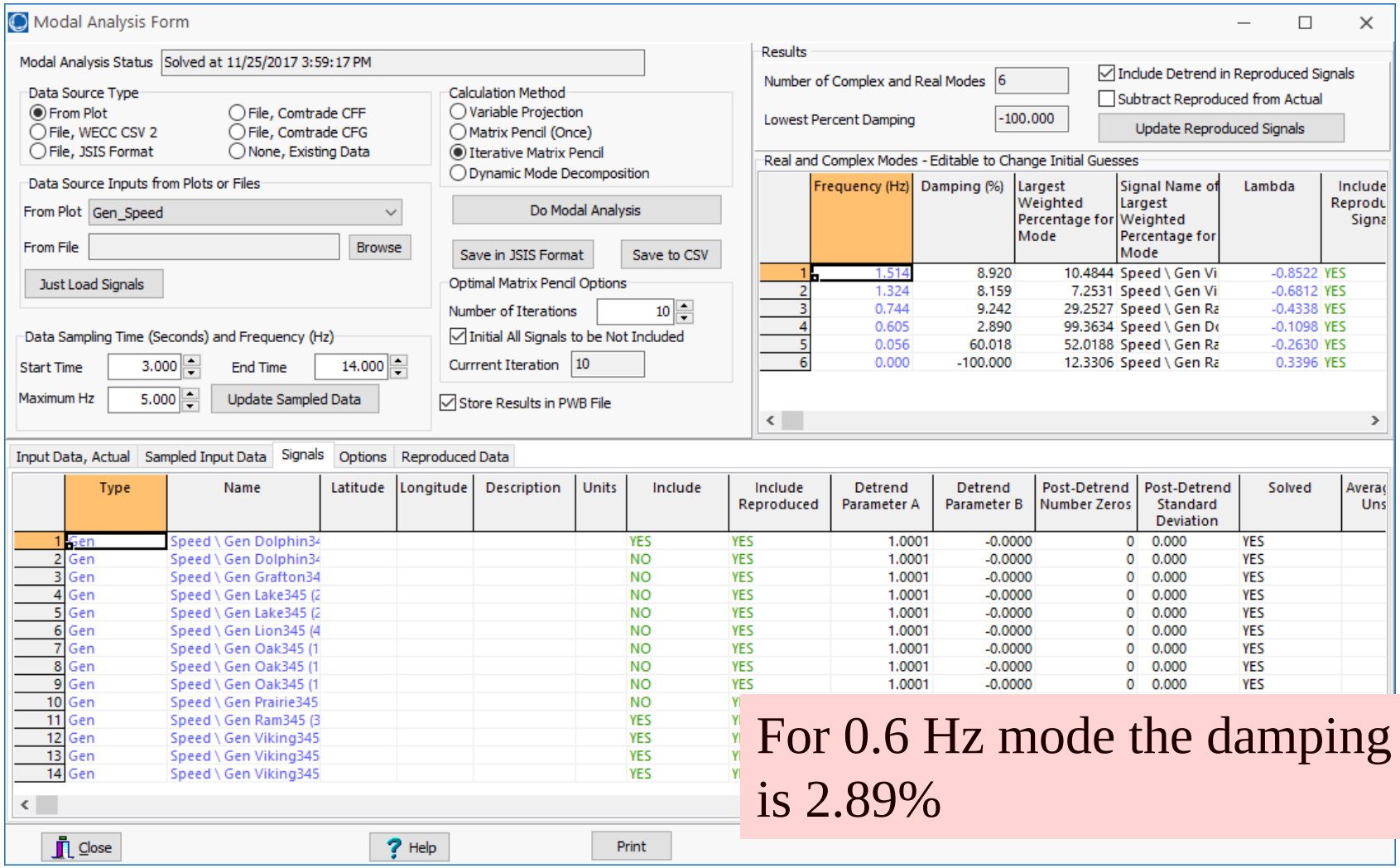
Example 2: Response Quantified Using Modal Analysis



For 0.6 Hz mode the damping is 2.89%

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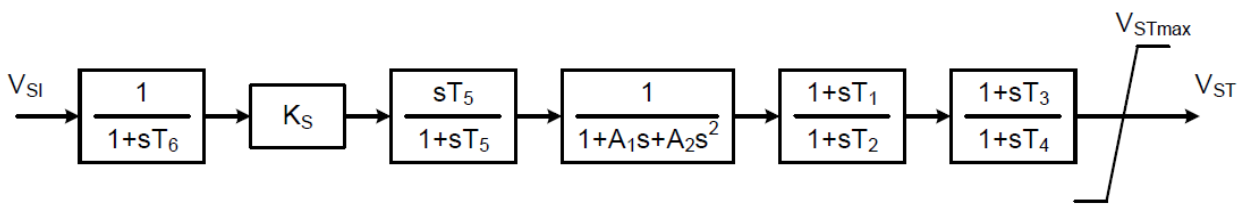
Example 2: Determine Phase Compensation

- 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%

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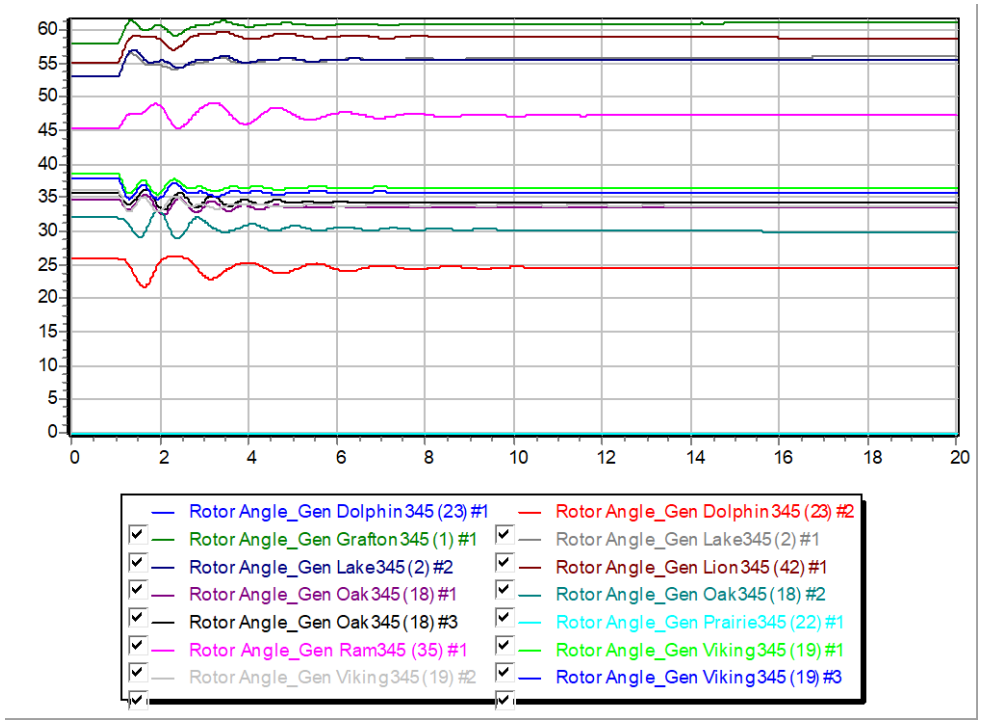
Example 2: Determine Phase Compensation For Several Generators

- 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

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