ECEN 667
Power System Stability

Lecture 24:Stabilizer Design, Measurement Based Modal Analysis

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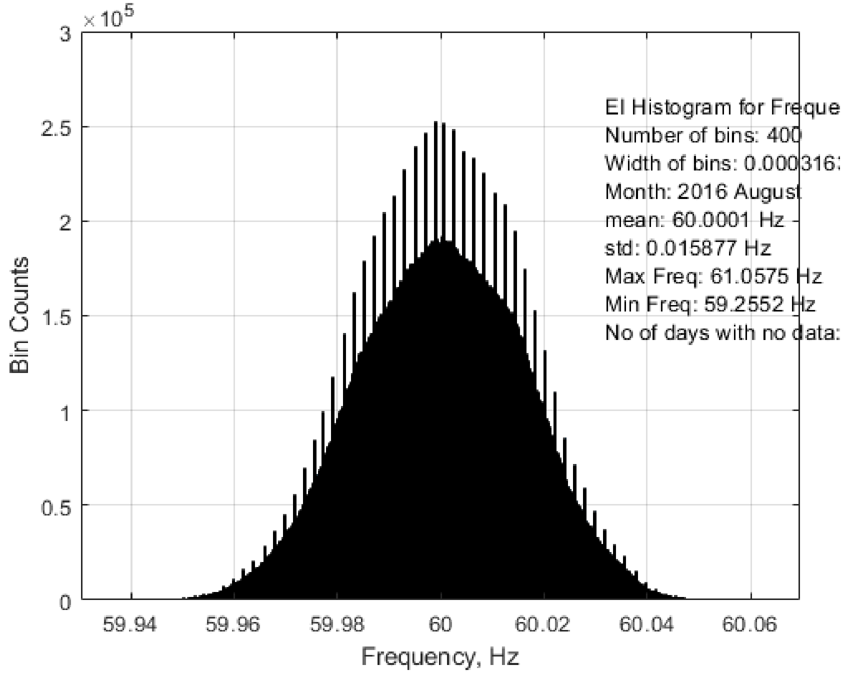
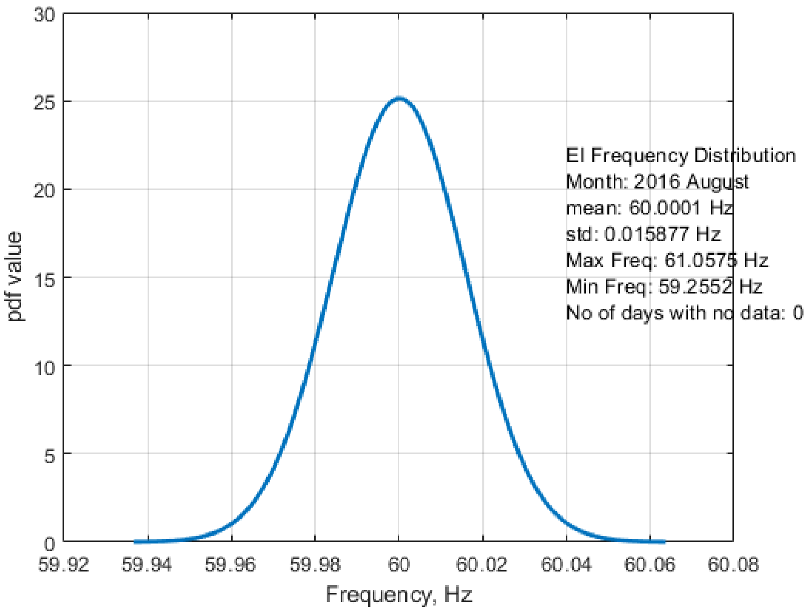
Announcements

- Read Chapter 9
- Homework 7 is posted; due on Thursday Nov 30
- Final is as per TAMU schedule. That is, Friday Dec 8 from 3 to 5pm

Eastern Interconnect Frequency Distribution





Results Provided by Ogbonnaya Bassey using FNET Data

Stabilizer Design

- The following slides give an example of stabilizer design using the below single-input power system stabilizer (type PSS1A from IEEE Std. 421-5)
  - We already considered the theory in lecture 22
  - The PSS1A is very similar to the IEEEST Stabilizer and STAB1

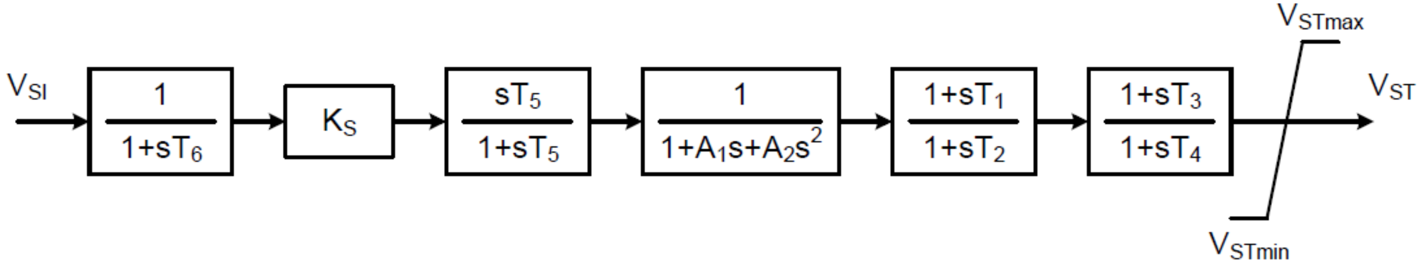


Figure 31 —Type PSS1A single-input power system stabilizer

Image Source: IEEE Std 421.5-2016

Stabilizer References

- Key papers on the example approach are
  - 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.
  - Shin, Jeonghoon & Nam, Su-Chul & Lee, Jae-Gul & Baek, Seung-Mook & Choy, Young-Do & Kim, Tae-Kyun. (2010). A Practical Power System Stabilizer Tuning Method and its Verification in Field Test. Journal of Electrical Engineering and Technology. 5. 400-406.

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 excitation system, generator, and power system
- The stabilizer input is typically shaft speed

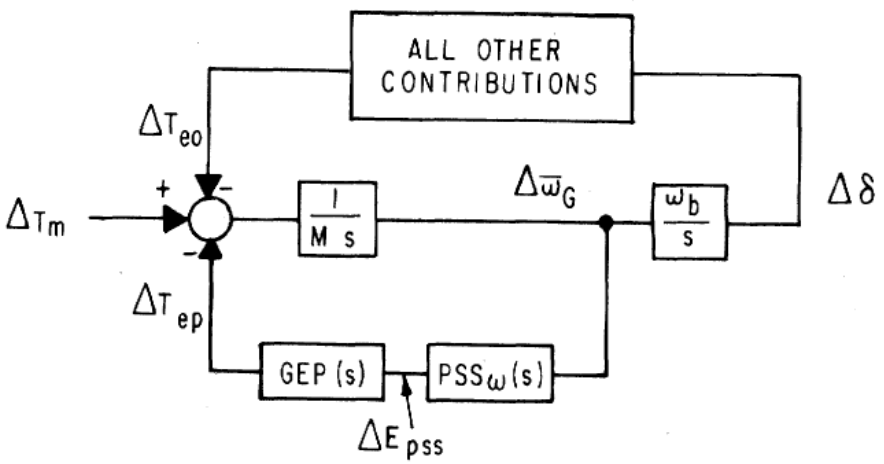


Image Source: Figure 1 from Larsen, 1981, Part 1

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

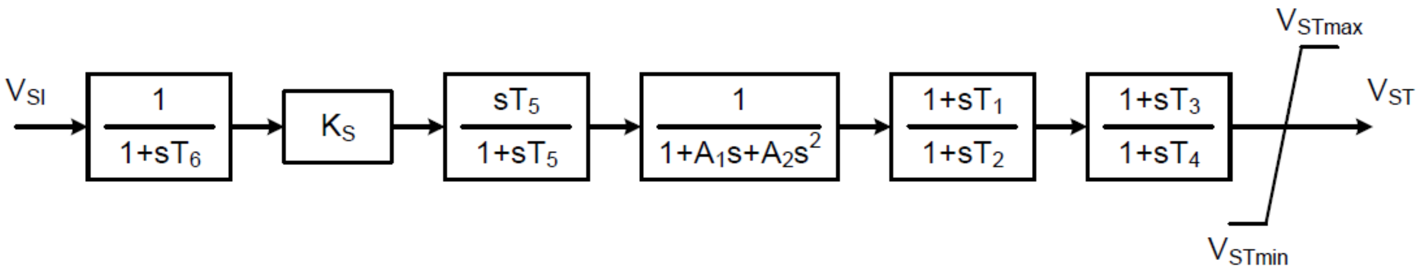
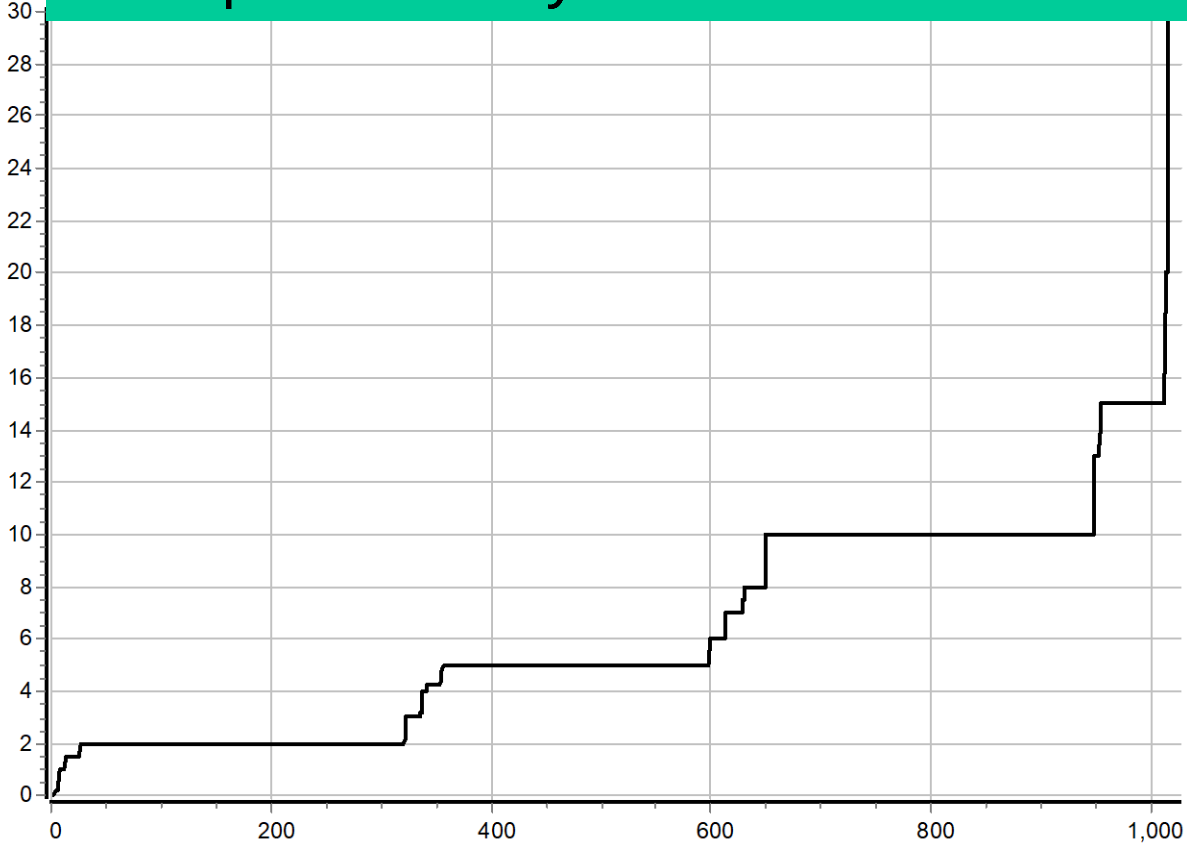


Figure 31 —Type PSS1A single-input power system stabilizer

Image Source: IEEE Std 421.5-2016

Example Washout Filter Values

Graph plots the equivalent of T_5 for an example actual system



With T_5= 10 at 0.1 Hz the gain is 0.987; with T_5= 1 at 0.1 Hz the gain is 0.53

Stabilizer Design

- The Torsional filter is a low pass filter to attenuate the torsional mode frequency
  – We will ignore it here
- Key parameters to be tuned at the gain, K_s, and the time constants on the two lead-lag blocks (to provide the phase compensation)
  – We'll assume $T_1=T_3$ and $T_2=T_4$

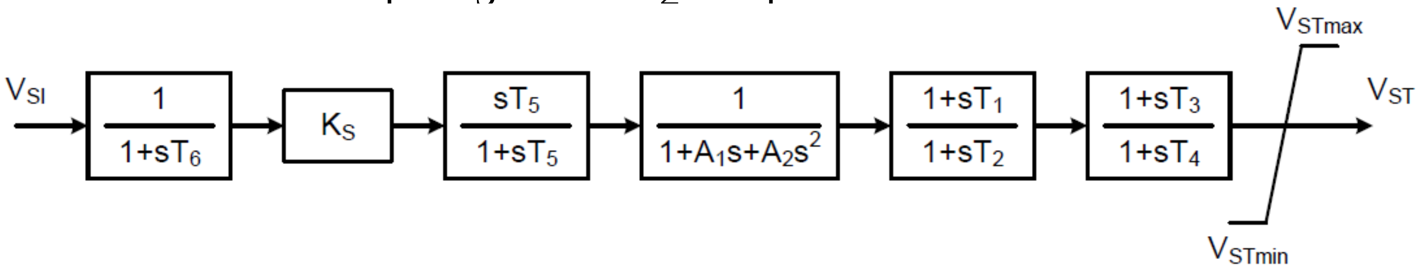


Figure 31—Type PSS1A single-input power system stabilizer

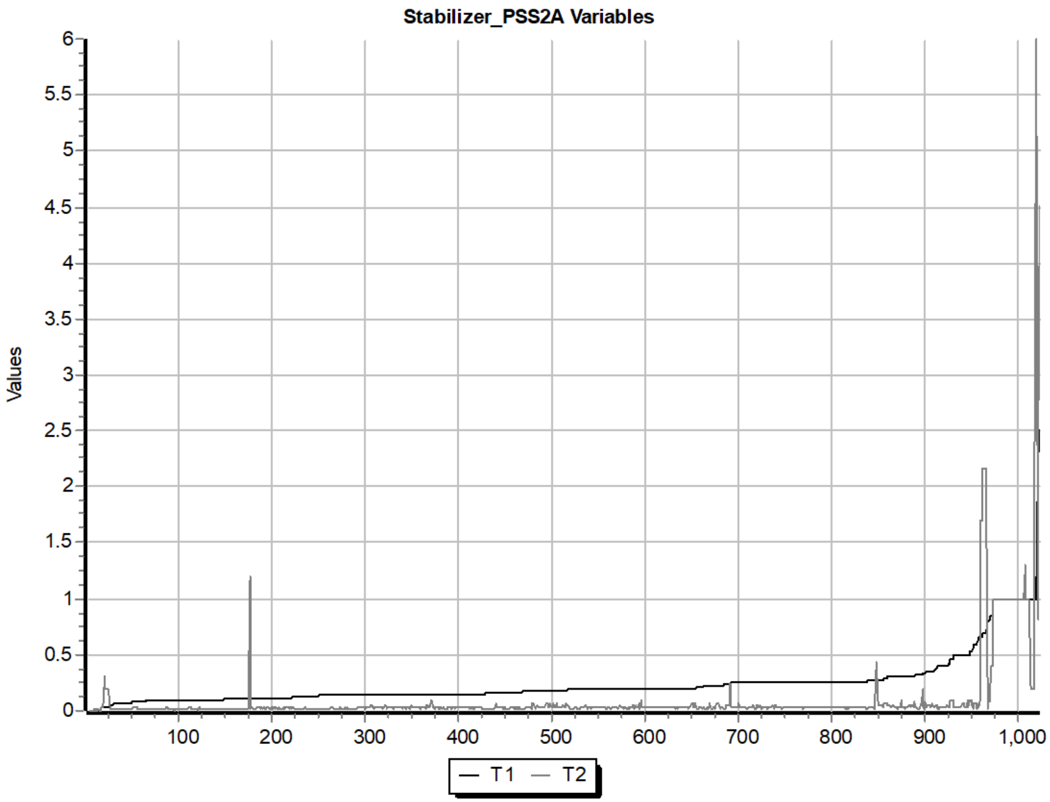
Stabilizer Design Phase Compensation

- 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

- Theoretic tuning criteria:
  - Compensated phase should pass -90^o after 3.5 Hz
  - The compensated phase at the oscillatory frequency should be in the range of [-45^o, 0^o], preferably around -20^o
  - Ratio $(T_1T_3)/(T_2T_4)$ at high frequencies should not be too large
- A peak phase lead provided by the compensator occurs at the center frequency $f_c = 1 \Big/ \left(2\pi\sqrt{T_1T_2}\right)$
  - The peak phase lead increases as ratio T_1/T_2 increases
- A practical method is:
  - Select a reasonable ratio T_1/T_2; select T_1 such that the center frequency is around the oscillatory frequency without the PSS

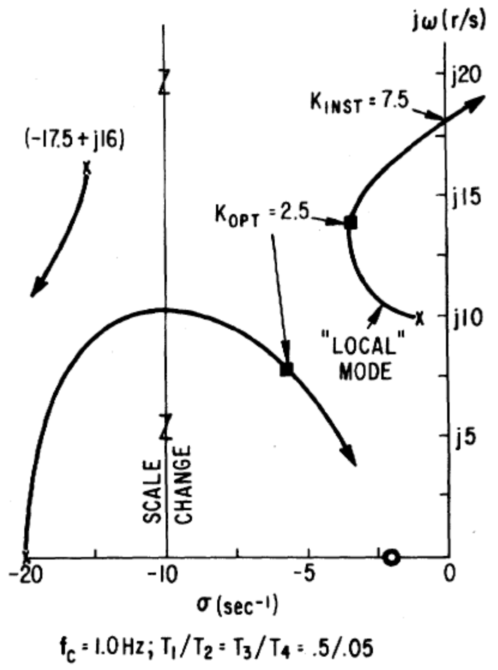
Example T_1 and T_2 Values



The average T_1 value is about 0.25 seconds and T_2 is 0.1 seconds, but most T_2 values are less than 0.05; the average T_1/T_2 ratio is 6.3

Stabilizer Design Tuning Criteria

- Eigenvalues moves as K_s increases

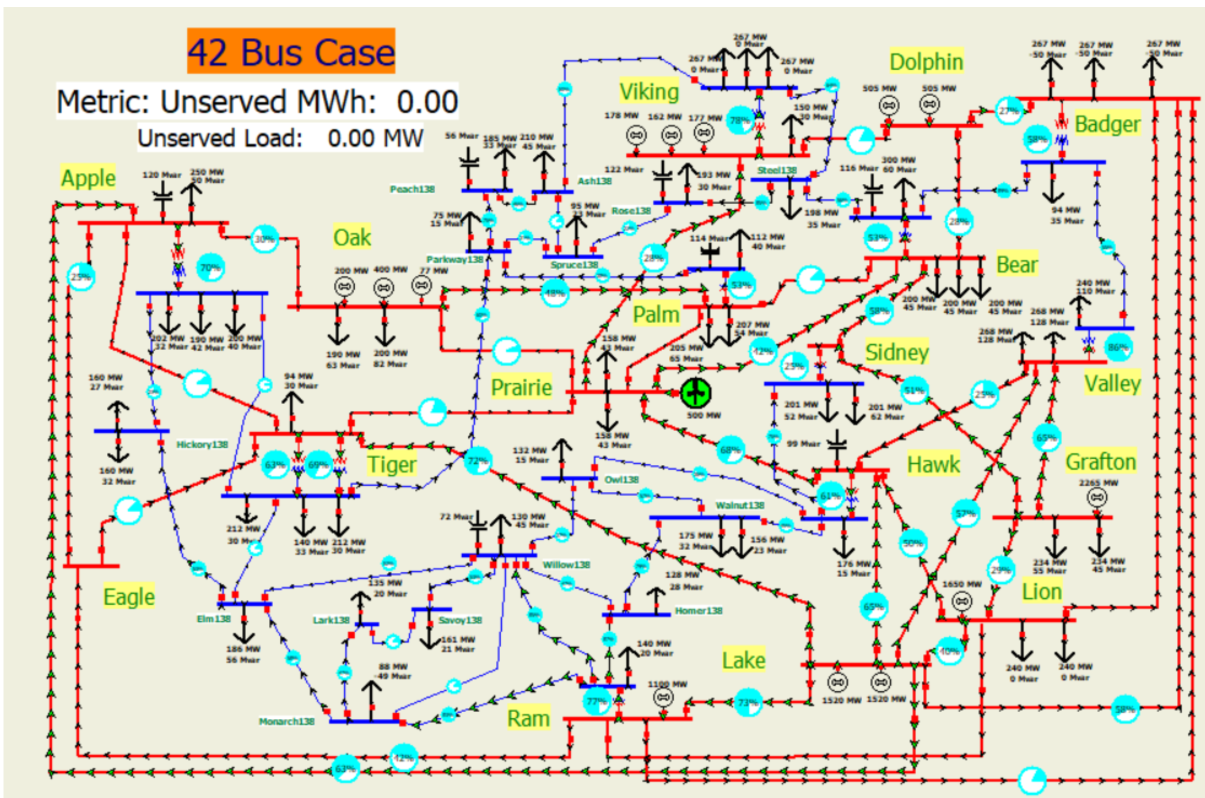


K_{OPT} is where the damping is maximized
K_{INST} is the gain at which sustained oscillations or an instability occur

- A practical method is to find K_{INST}, then set K_{OPT} as about 1/3 or ¼ this value

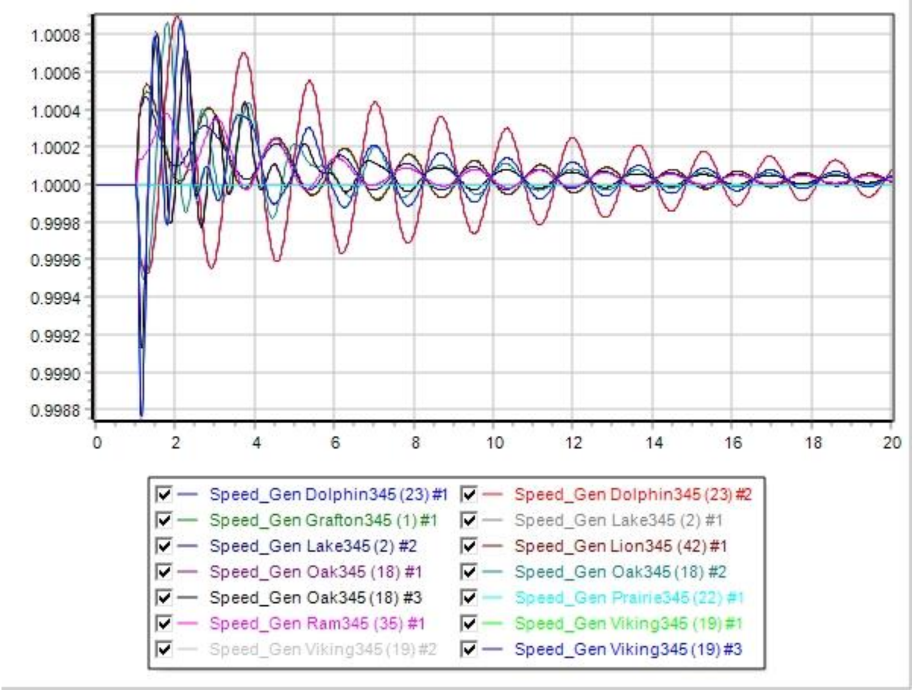
Example with 42 Bus System

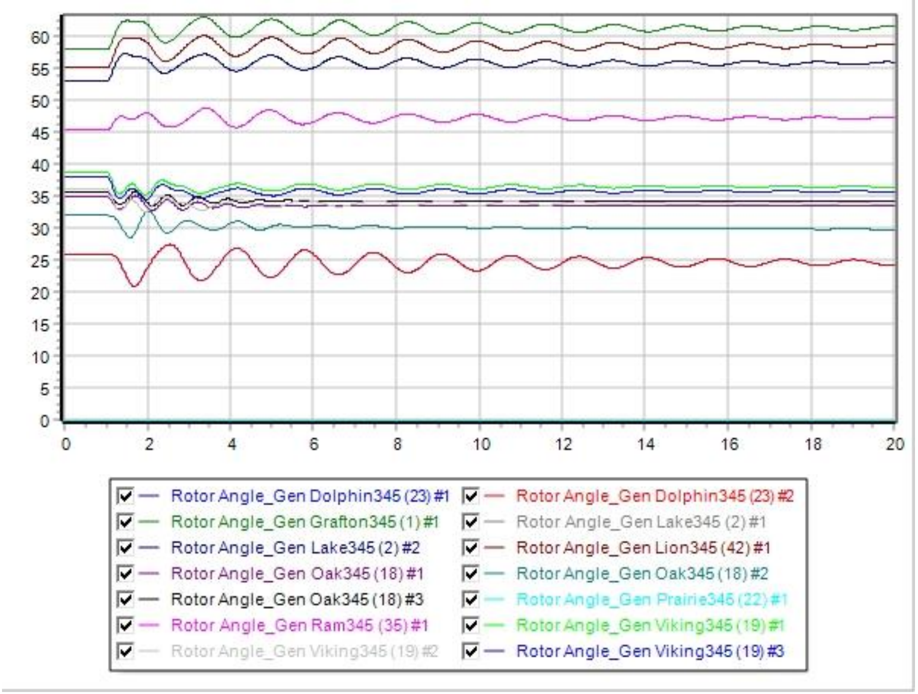
- A three-phase fault is applied to the middle of the 345 kV transmission line between Prairie (bus 22) and Hawk (bus 3) with both ends opened at 0.05 seconds



Step 1: Decide Generators to Tune and Frequency

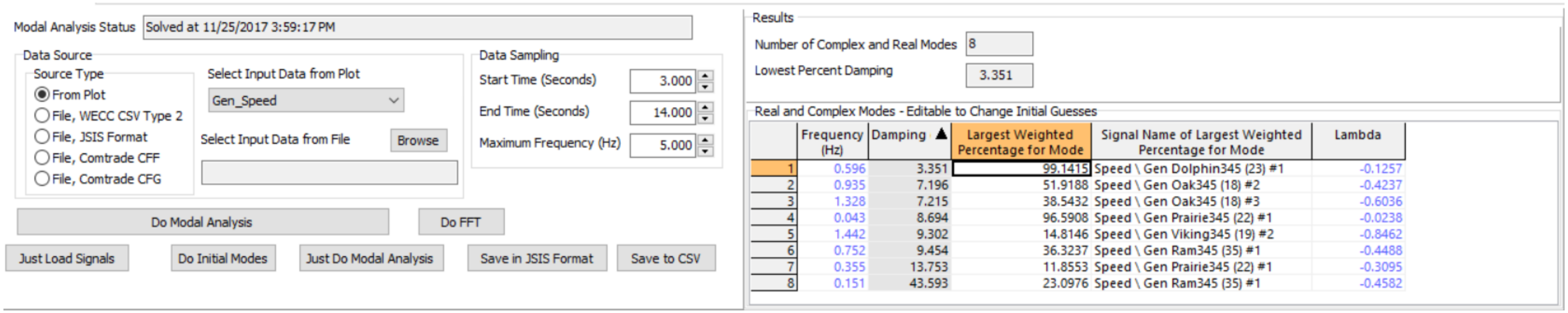
- Generator speeds and rotor angles are observed to have a poorly damped oscillation around 0.6 Hz.





Step 1: Decide Generators to Tune and Frequency

- In addition to interpreting from those plots, a modal analysis tool could assist in finding the oscillation information



- We are going to tune PSS1A models for all generators using the same parameters (doing them individually would be better by more time consuming)

Step 2: Phase Compensation

- Select a ratio of T_1/T_2 to be ten
- Select T_1 so f_c is 0.6 Hz

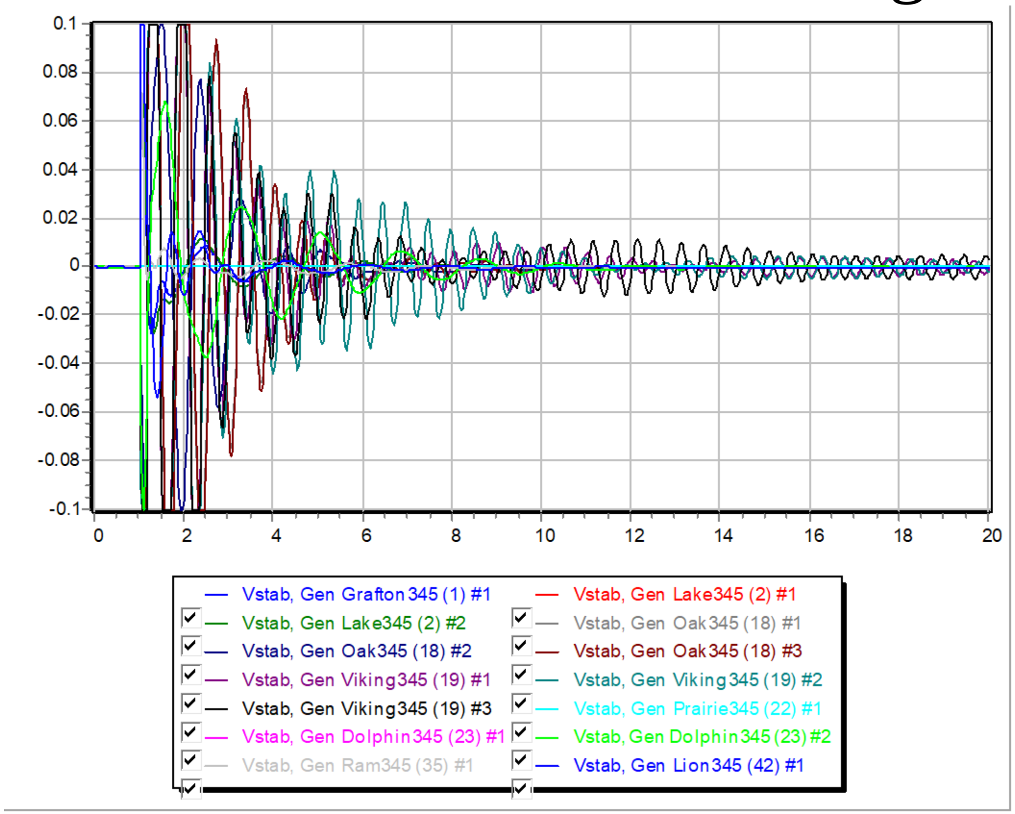
$$f_c = \frac{1}{\left(2\pi\sqrt{T_1 T_2}\right)} = \frac{1}{\left(2\pi\sqrt{T_2 T_2 10}\right)} = \frac{1}{\left(2\pi T_2\sqrt{10}\right)}$$

$$0.6 = \frac{1}{\left(2\pi T_2\sqrt{10}\right)} \rightarrow T_2 = \frac{1}{\left(2\pi \times 0.6 \times \sqrt{10}\right)} = 0.084$$

$$T_1 = 0.84$$

Step 3: Gain Tuning

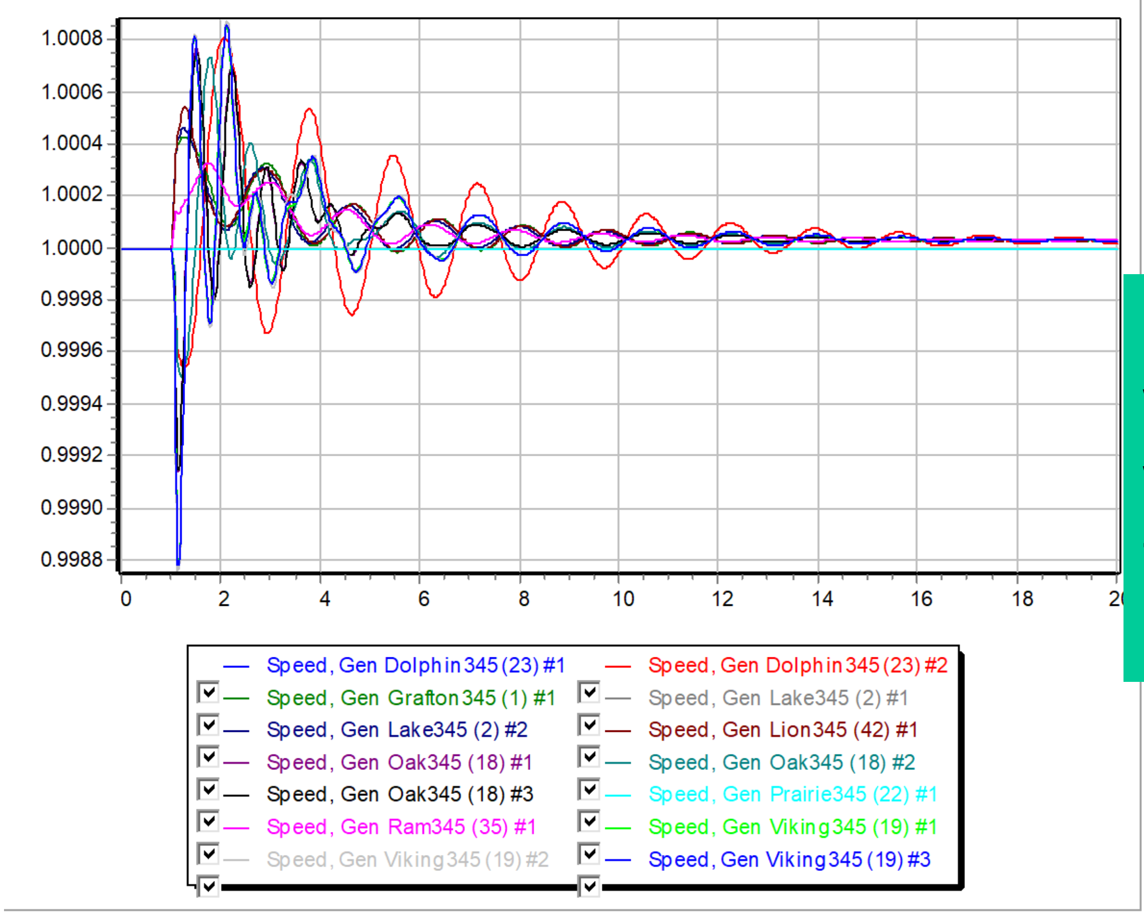
- Find the K_{INST}, which is the gain at which sustained oscillations or an instability occur
- This occurs at about 9 for the gain



Easiest to see the oscillations just by plotting the stabilizer output signal

Step 4: Testing on Original System

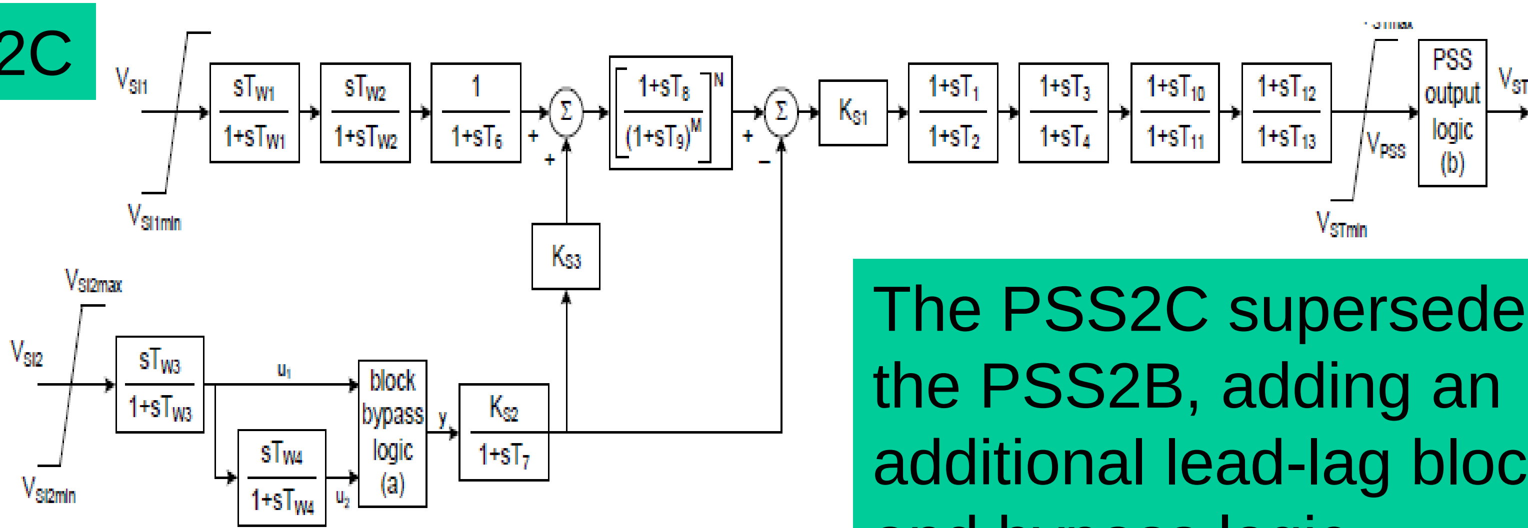
- With gain set to 3



Better tuning would be possible with customizing for the individual generators

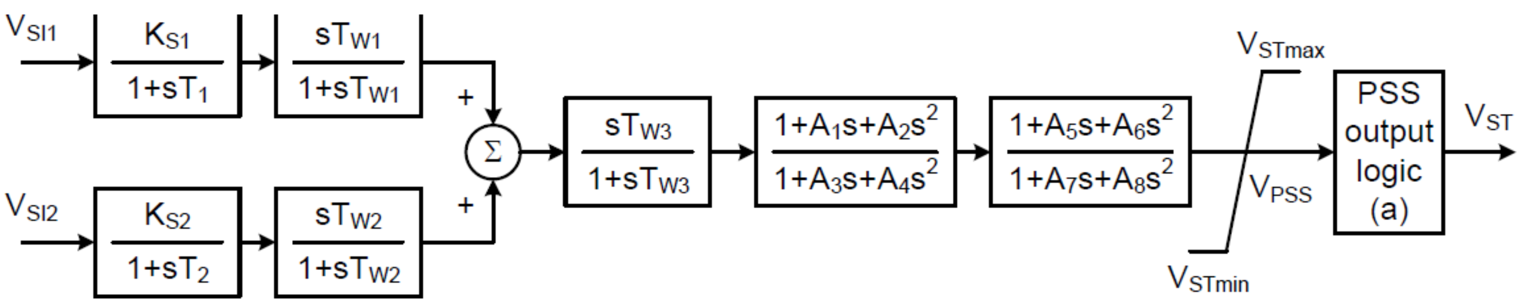
Dual Input Stabilizers

PSS2C



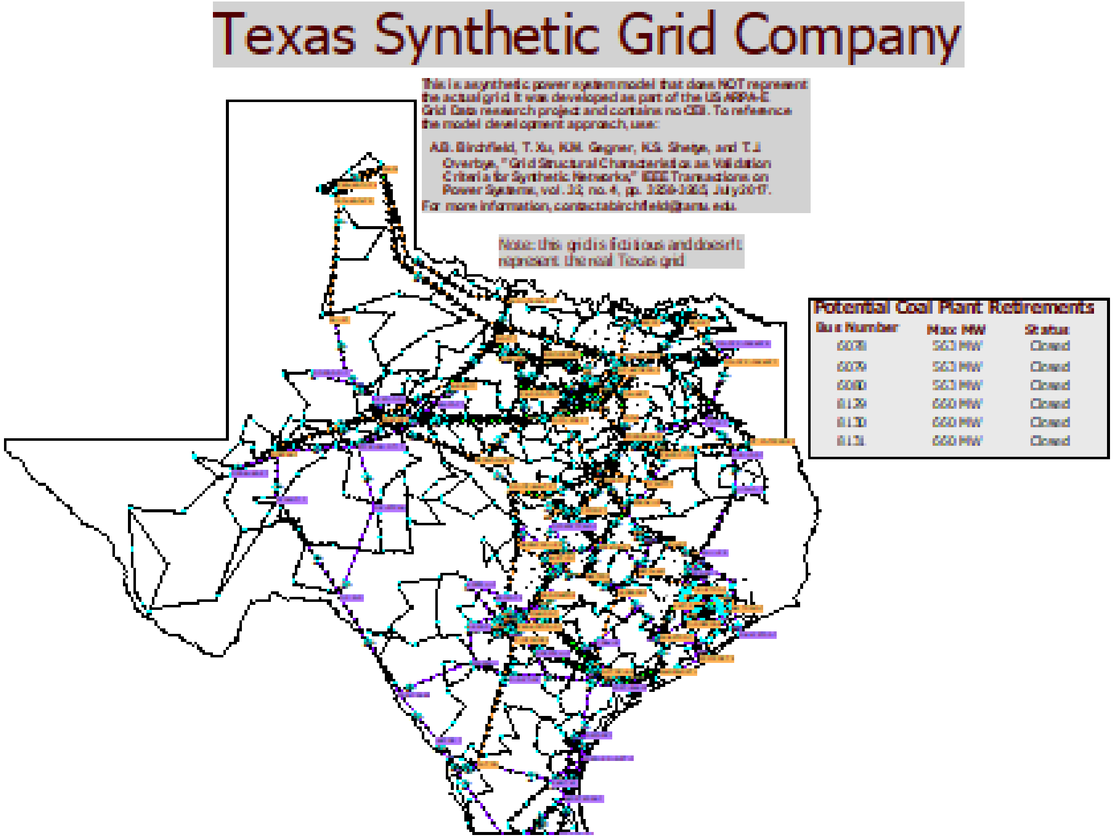
The PSS2C supersedes the PSS2B, adding an additional lead-lag block and bypass logic

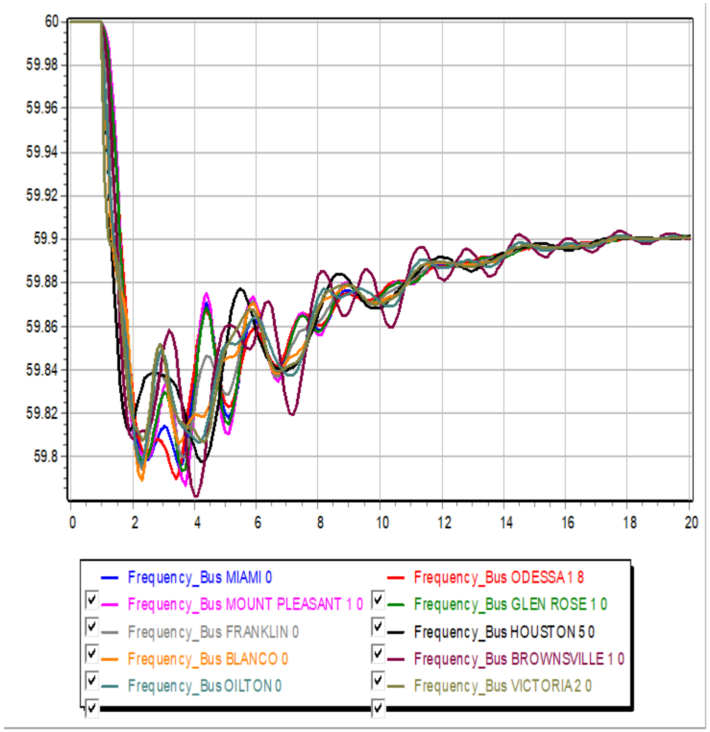
PSS3C



Images Source: IEEE Std 421.5-2016

TSGC 2000 Bus VPM Example

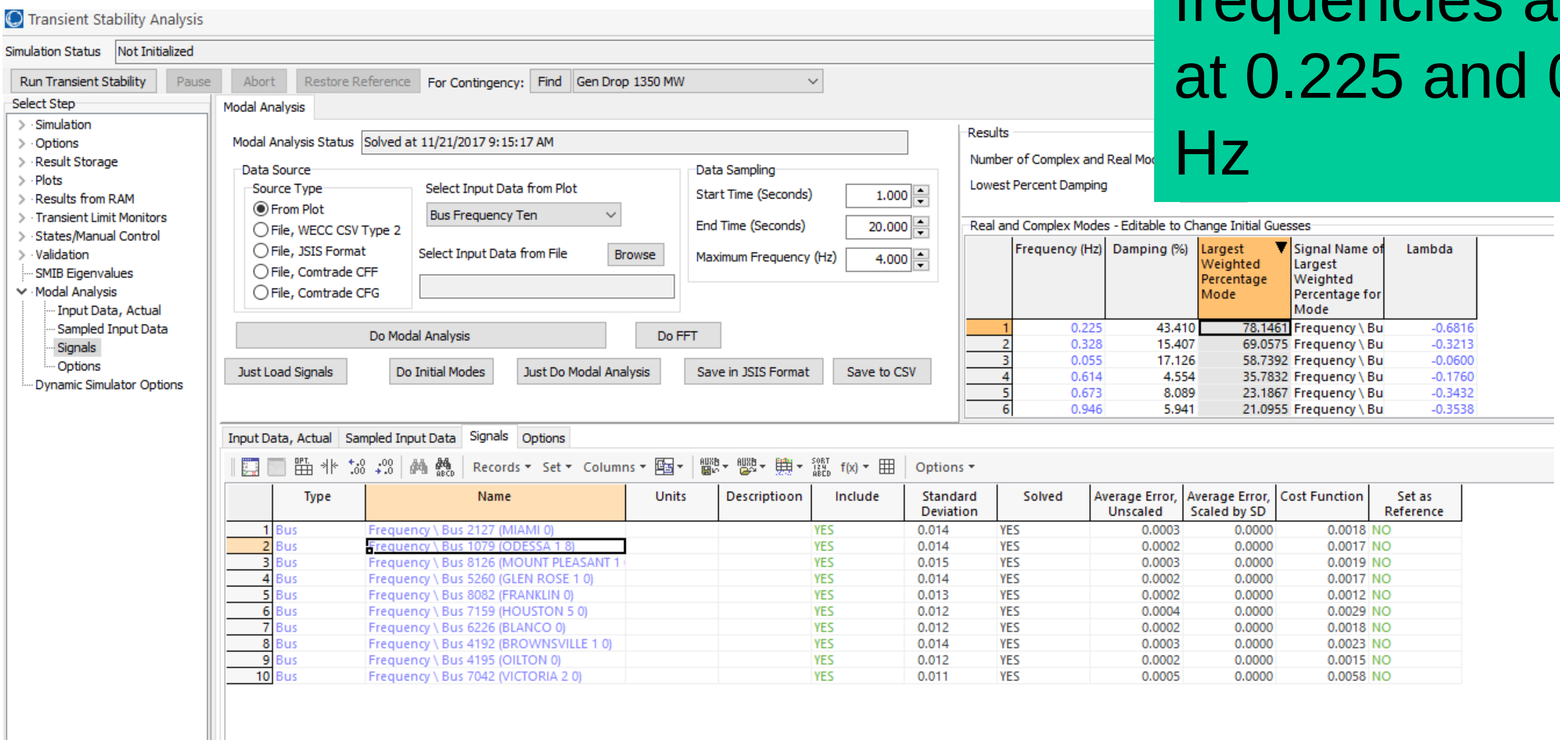




TSGC 2000 Bus Example

- Results obtained with a time period from 1 to 20 seconds, sampling at 4 Hz

Most significant frequencies are at 0.225 and 0.328 Hz

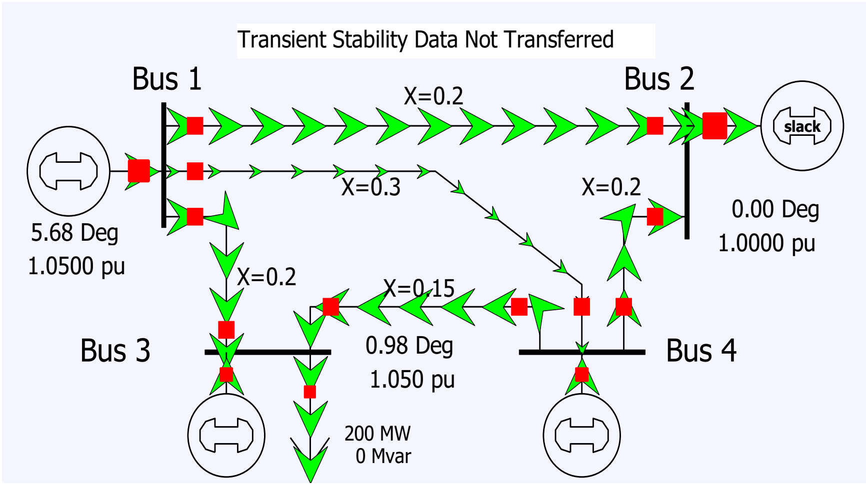


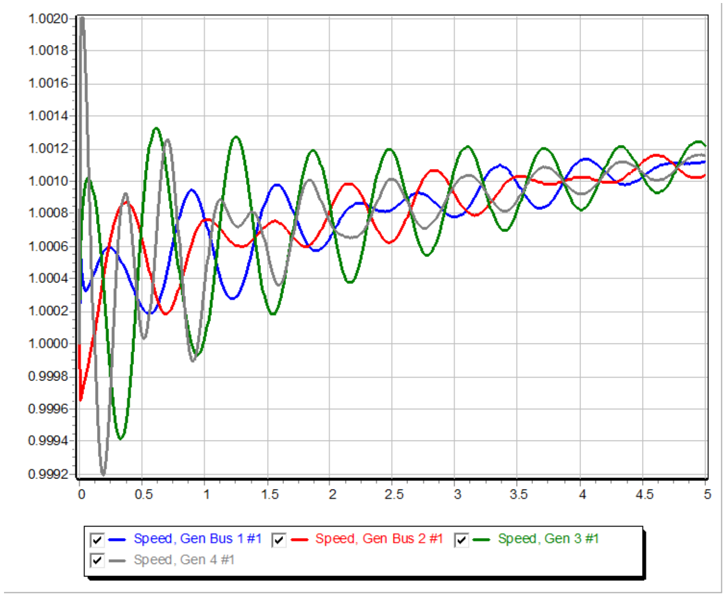
Mode Observability, Shape, Controllability and Participation Factors

- In addition to frequency and damping, there are several other mode characteristics
- Observability tells how much of the mode is in a signal, hence it is associated with a particular signal
- Mode Shape is a complex number that tells the magnitude and phase angle of the mode in the signal (hence it quantifies observability)
- Controllability specifies the amount by which a mode can be damped by a particular controller
- Participation facts is used to quantify how much damping can be provided for a mode by a PSS

Determining Modal Shape Example

- Example uses the four generator system shown below in which the generators are represented by a combination of GENCLS and GENROU. The contingency is a self-clearing fault at bus 1
  - The generator speeds (the signals) are as shown in the right figure

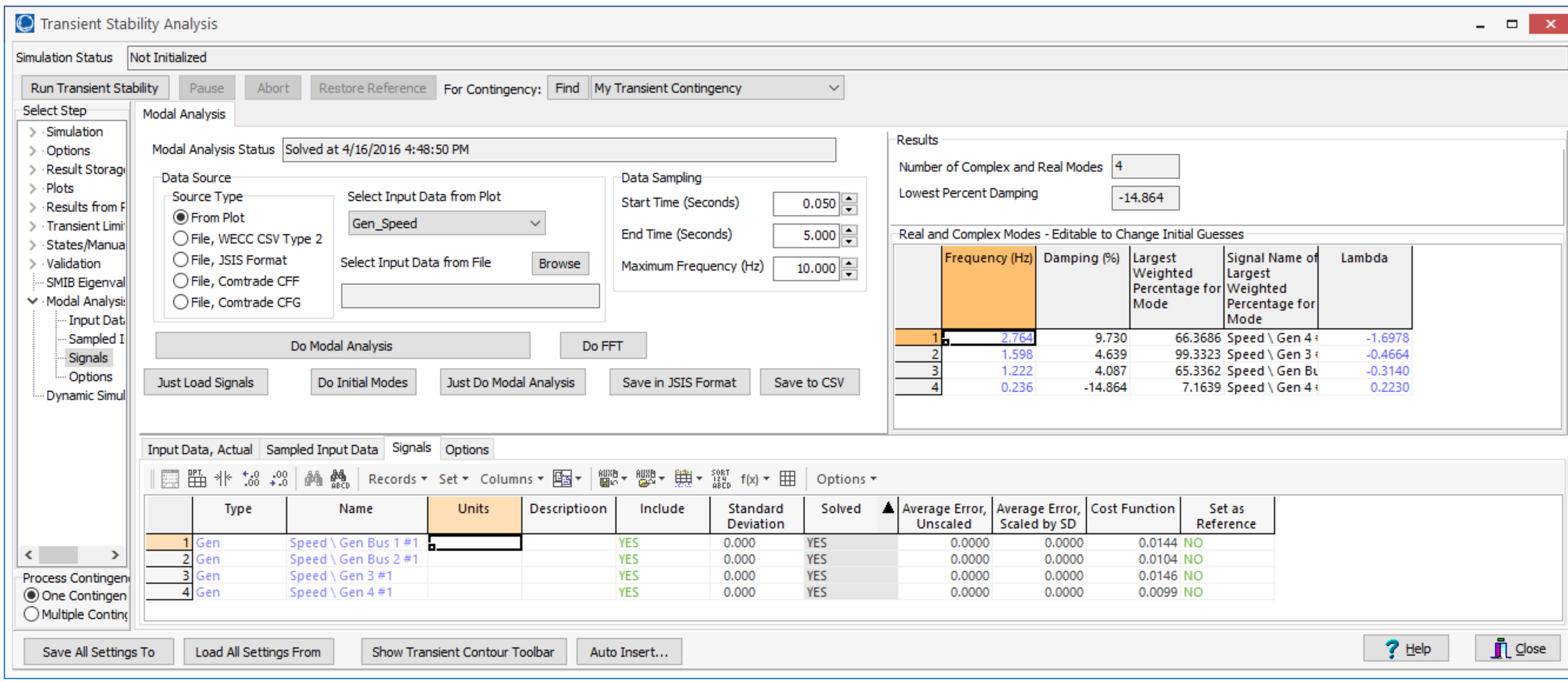




Case is saved as B4_Modes

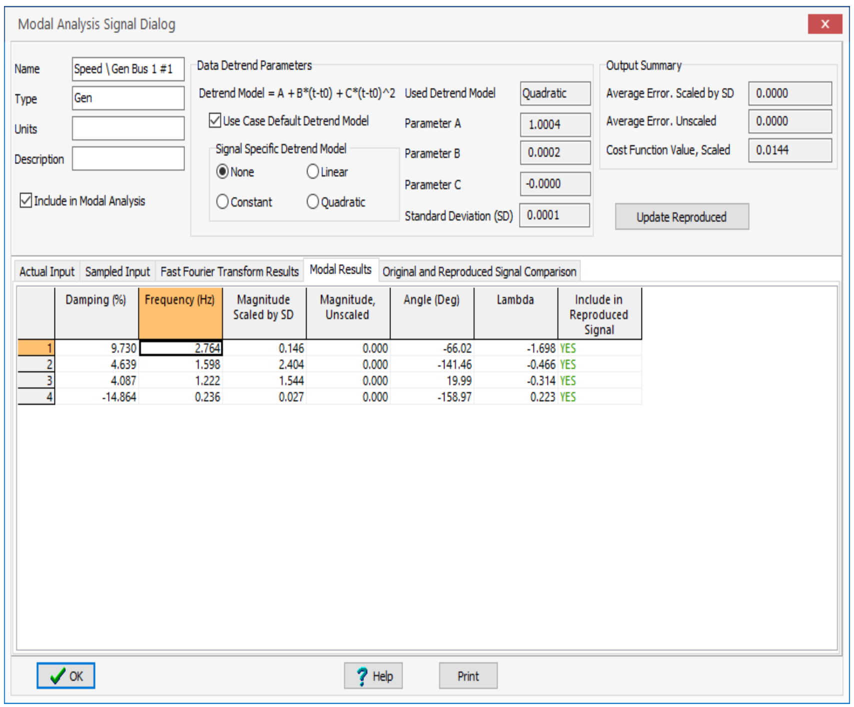
Determining Modal Shape Example

- Example uses the multi-signal VPM to determine the key modes in the signals
  - Four modes were identified, though the key ones were at 1.22, 1.60 and 2.76 Hz

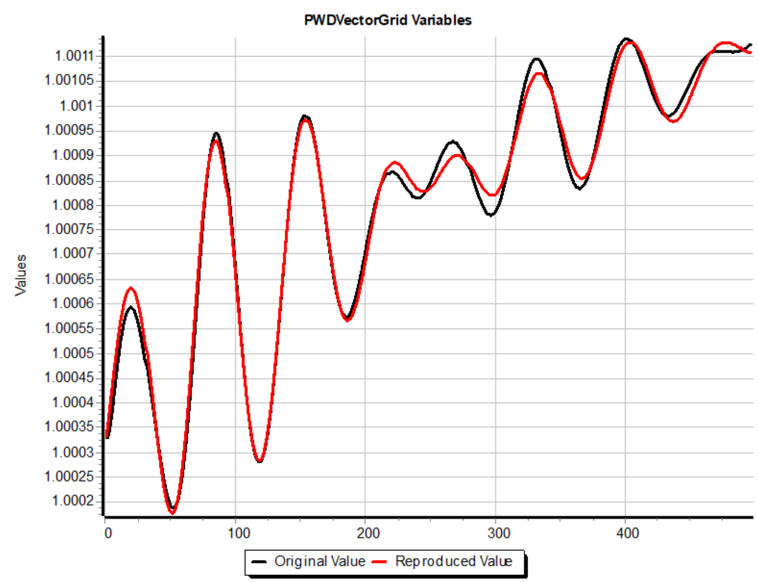


Determining Modal Shape Example

- Information about the mode shape is available for each signal; the mode content in each signal can also be isolated



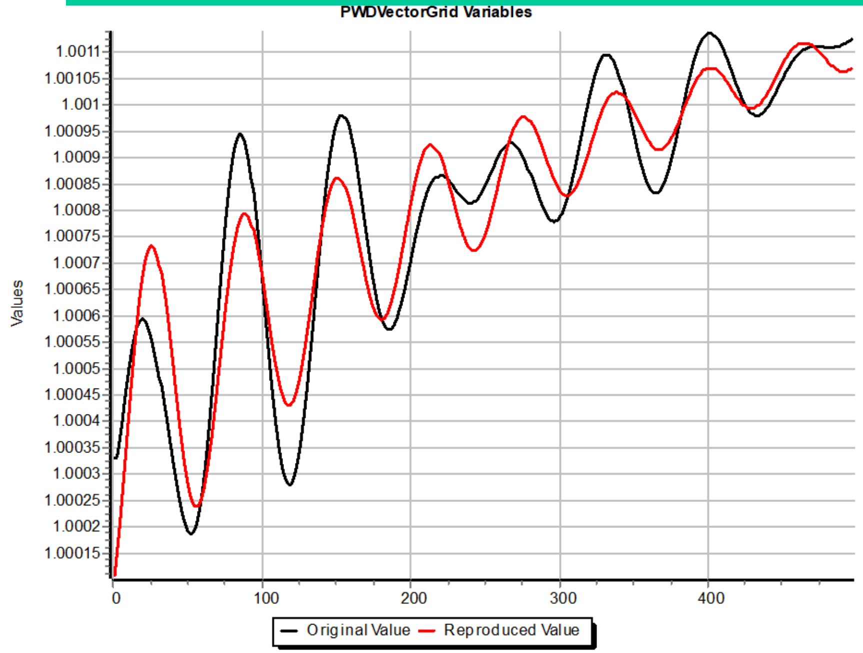
Graph shows original and the reproduced signal



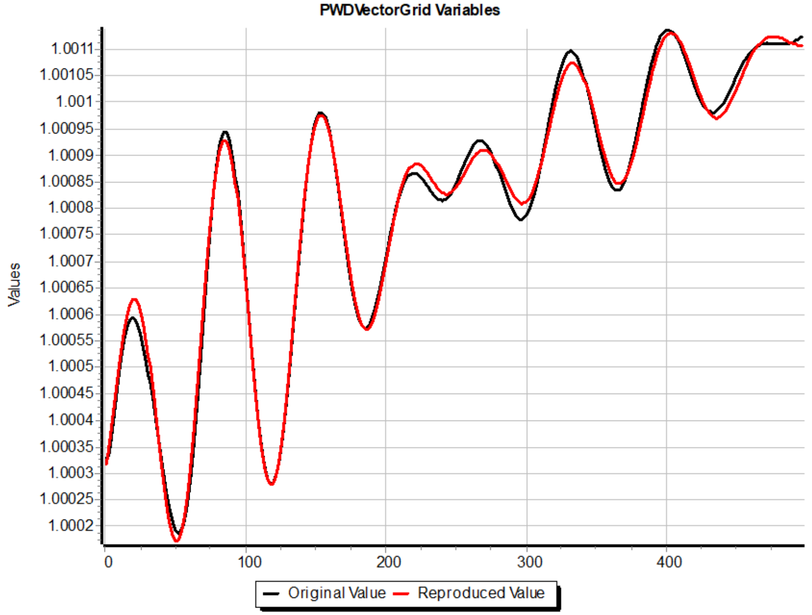
Determining Modal Shape Example

- Graph shows the contribution provided by each mode in the generator 1 speed signal

Reproduced without 1.22 and 2.76 Hz



Reproduced without 2.76 Hz



Modes Shape by Generator (for Speed)

- The table shows the contributions by mode for the different generator speed signals

Mode (Hz)	Gen 1	Gen 2	Gen 3	Gen 4
0.244	0.07	0.082	0.039	0.066
1.22	1.567	1.494	0.097	0.01
1.6	2.367	2.203	2.953	1.639
2.76	0.174	0.378	0.927	4.913

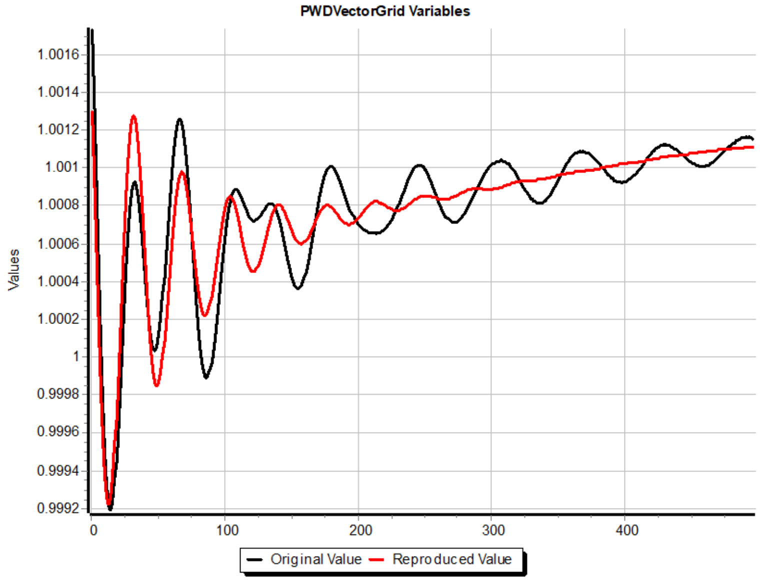
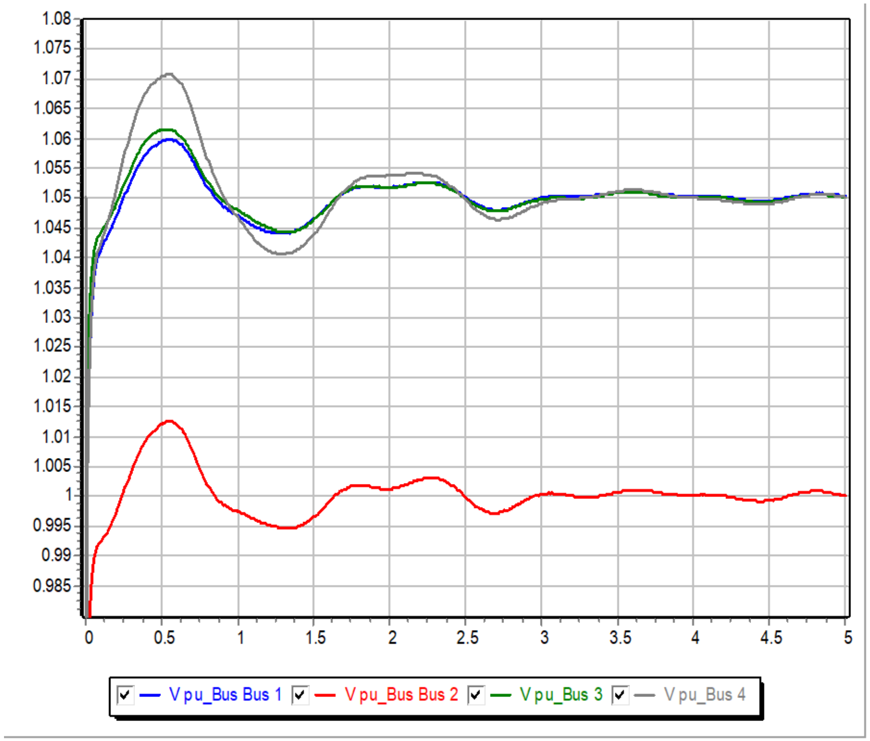
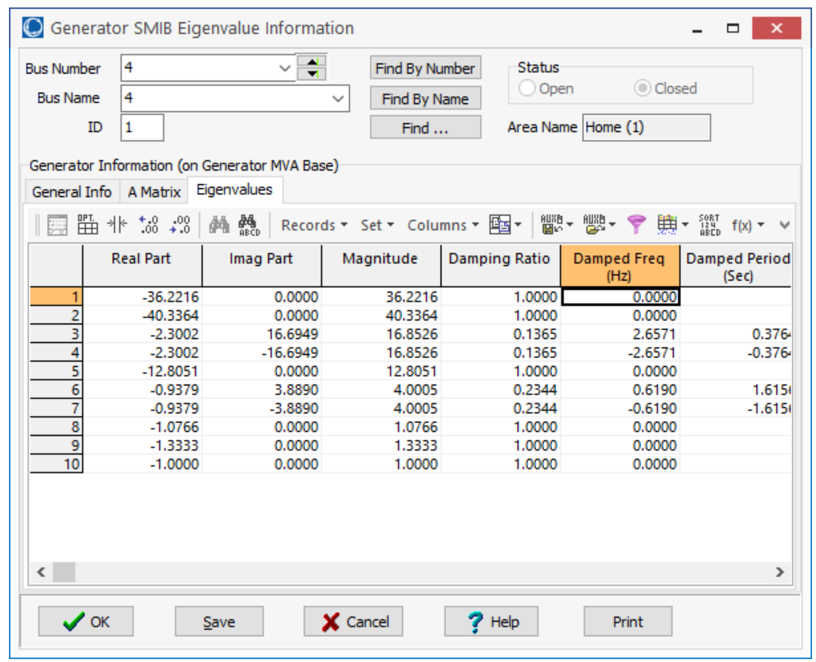


Image on the right shows the Gen 4 2.76 Hz mode; note it is highly damped

Modes Depend on the Signals!

- The below image shows the bus voltages for the previous system, with some (poorly tuned) exciters
  - Response includes a significant 0.664 Hz mode from the gen 4 exciter (which can be seen in its SMIB eigenvalues)



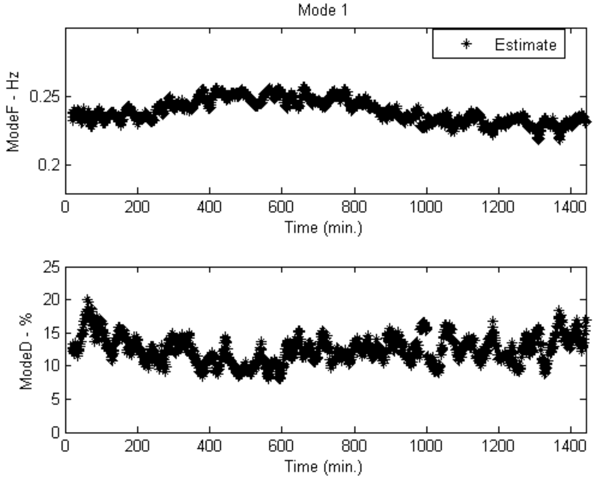


	Real Part	Imag Part	Magnitude	Damping Ratio	Damped Freq (Hz)	Damped Period (Sec)
1	-36.2216	0.0000	36.2216	1.0000	0.0000	
2	-40.3364	0.0000	40.3364	1.0000	0.0000	
3	-2.3002	16.6949	16.8526	0.1365	2.6571	0.376
4	-2.3002	-16.6949	16.8526	0.1365	-2.6571	-0.376
5	-12.8051	0.0000	12.8051	1.0000	0.0000	
6	-0.9379	3.8890	4.0005	0.2344	0.6190	1.615
7	-0.9379	-3.8890	4.0005	0.2344	-0.6190	-1.615
8	-1.0766	0.0000	1.0766	1.0000	0.0000	
9	-1.3333	0.0000	1.3333	1.0000	0.0000	
10	-1.0000	0.0000	1.0000	1.0000	0.0000	

Inter-Area Modes in the WECC

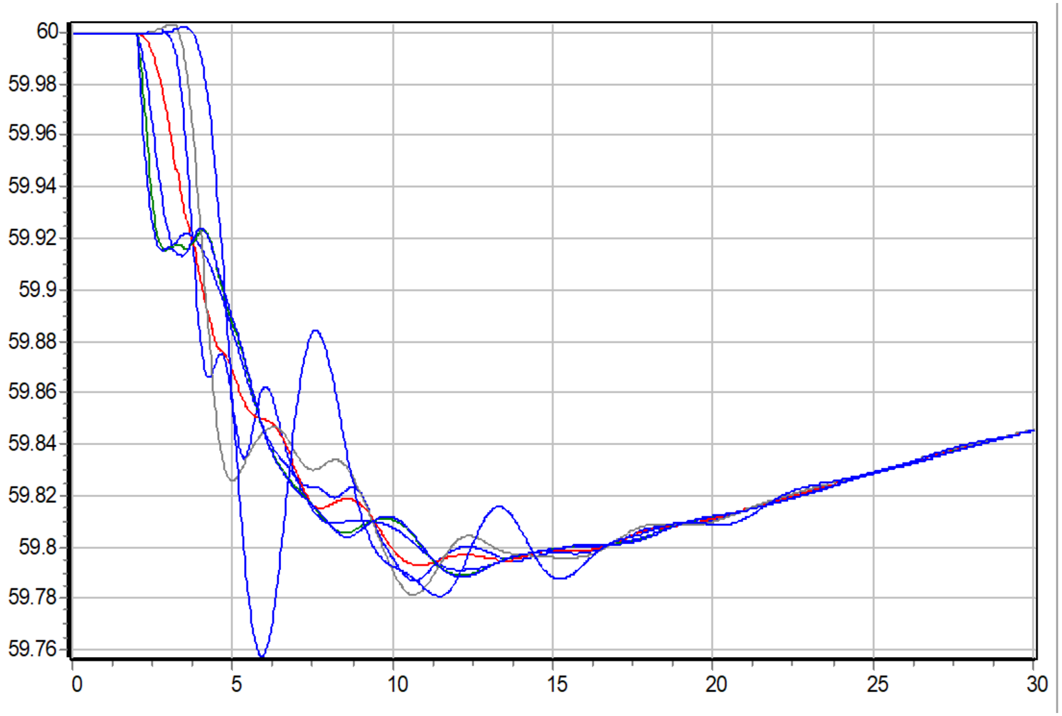
- The dominant inter-area modes in the WECC have been well studied
- A good reference paper is D. Trudnowski, “Properties of the Dominant Inter-Area Modes in the WECC Interconnect,” 2012
  - Four well known modes are NS Mode A (0.25 Hz), NS Mode B (or Alberta Mode), (0.4 Hz), BC Mode (0.6 Hz), Montana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

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



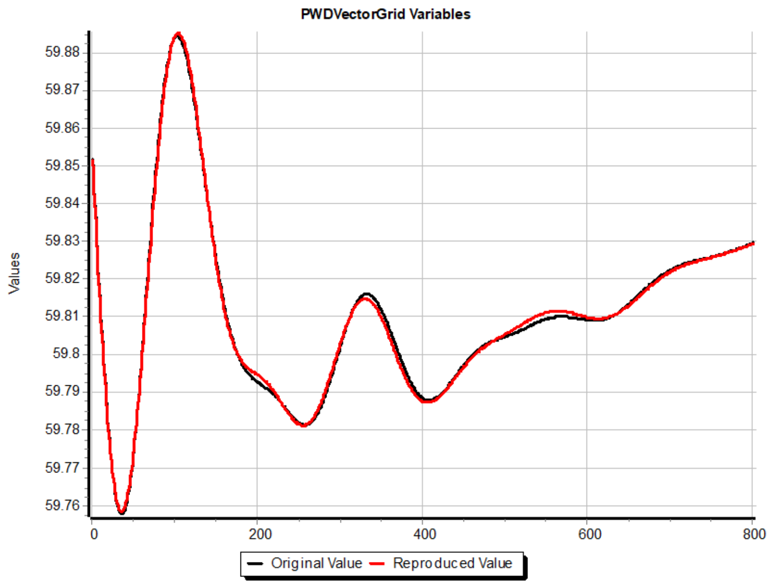
Example WECC Results

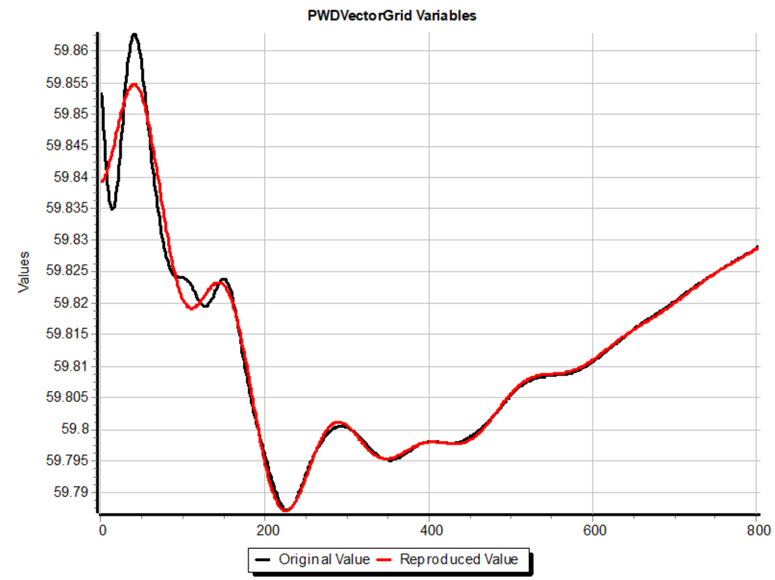
- Figure shows bus frequencies at several WECC buses following a large system disturbance



Example WECC Results

- The VPM was run simultaneously on all the signals
  - Frequencies of 0.20 Hz (16% damping and 0.34 Hz (11.8% damping)





Angle of 58.7° at 0.34 Hz and 132 ° at 0.20 Hz

Angle of -137.1° at 0.34 Hz and 142° at 0.20 Hz

Fast Fourier Transform (FFT) Applications: Motivational Example

- The below graph shows a slight frequency oscillation in a transient stability run
  - The question is to figure out the source of the oscillation (shown here in the bus frequency)
  - Plotting all the frequency values is one option, but sometimes small oscillations could get lost
  - A solution is to do an FFT