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.
- 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; 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

Example Washout Filter Values



Graph plots the equivalent of T₅ 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)



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° after 3.5 Hz
 - The compensated phase at the oscillatory frequency should be in the range of [-45°, 0°], preferably around -20°
 - 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 $f_c = 1/(2\pi\sqrt{T_1T_2})$
 - 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 T₁ and T₂ 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 1/4 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

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					- 8	0.151	43.593	23.0976	Speed \ Gen Ram345 (35) #1	-0.4582

• 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

$$\begin{aligned} f_c &= \frac{1}{\left(2\pi\sqrt{T_1T_2}\right)} = \frac{1}{\left(2\pi\sqrt{T_2T_210}\right)} = \frac{1}{\left(2\pi T_2\sqrt{10}\right)} \\ 0.6 &= \frac{1}{\left(2\pi T_2\sqrt{10}\right)} \to T_2 = \frac{1}{\left(2\pi\times0.6\times\sqrt{10}\right)} = 0.084 \\ T_1 &= 0.84 \end{aligned}$$

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 0.08 0.06 0.04 0.02 C -0.02 -0.04 -0.06 -0.08 -0.1 12 6 8 10 14 16 18 4 20 — Vstab. Gen Grafton 345 (1) #1 — Vstab, Gen Lake345 (2) #1 Vstab. Gen Lake345 (2) #2 Vstab, Gen Oak 345 (18) #1 Vstab, Gen Oak345 (18) #2 Vstab, Gen Oak 345 (18) #3 ✓ — Vstab, Gen Viking345 (19) #1 Vstab, Gen Viking 345 (19) #2 ✓ ____ Vstab, Gen Viking345 (19) #3 ☑. Vstab, Gen Prairie345 (22) #1 Vstab, Gen Dolphin 345 (23) #1 🗹 — Vstab, Gen Dolphin 345 (23) #2 Vstab, Gen Lion 345 (42) #1 Vstab. Gen Ram345 (35) #1

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





Images Source: IEEE Std 421.5-2016

TSGC 2000 Bus VPM Example



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Note: this grid is licitious and doesn't represent the real Texas grid

	Potential G	oal Plant R	etrements
1	Bus Number	Max MW	Status
	6078	563 MW	Cloved
	6079	563 MW	Closed
	6060	563 MW	Cloved
	8129	660 MW	Closed
	8130	GGD HW	Cloved
<u>.</u>	8131	660 MW	Closed



TSGC 2000 Bus Example



aquanciae ara

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

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	9 Bus	Freque	ency \ Bus 4195 (OILTON 0)			/ES	0.012			0.0002	0.0000	0.0015	NO		
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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

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Determining Modal Shape Example



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

Modal /	Analysis Signal	Dialog									x			
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	Damping (%)	Frequency	(Hz)	Magnitude Scaled by SD	Magnitude, Unscaled	Angle (Deg)	Lamb	da	Include in Reproduced Signal					
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2	4.639		1.598	2.404	0.000	-141.46		-0.466 Y	ES ES					
4	-14.864		0.236	0.027	0.000	-158.97		0.223 Y	ES					
	ОК				? Help	Print								

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



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)



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
 Below figure from
 - 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

