ECEN 460 Power System Operation and Control Spring 2025

Lecture 22: Modal Analysis, Stabilizers Voltage Stability

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Announcements



- Please read Chapter 13
- By April 9 do Problem Set A
- Schedule for the rest of the semester is
 - Lab 10 week of April 7 consisting of time for the design groups to meet; all groups need to turn in a brief progress report in lieu of a lab report
 - Lab 3 week of April 14 (optional, ungraded machine lab, Wednesday times only; since Friday is a Reading Day the Friday lab folks can go to a Wednesday lab
 - Lab 11 (project presentations) by the individual teams to their TA before the end of classes (on or before April 29)
 - Exam 2 on Wednesday April 23 during class; similar format to other exam; comprehensive but more emphasis on material since the first exam
 - Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)

Running 2000 Bus Case with Composite Loads

- Show Texas2000_CMPLDW; this is the previous 2000 bus case with the CMPLDW model applied to all loads
 Run the generator drop
- To see and modify the parameters in the Model Explorer select Transient Stability, Load Characteristics

Explore		표 Load Characteristics X I	.oad Summary			
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Explore	Fields	Filter Advanced - Load C	haracteristic Generic	-		· Find Remo
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	tion Details	All (1)				
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	tingency Analysis	CIM5	Supported	icht type handet	kV	Load
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	Summary Generator Model Use Load Model Use Model Support Status Models in Use	CMLD				
		CMPLDW (1)				
		CMPLDWNF				
		CompLoad				
	Area AGC Models	DLIGHT				
	Bus Models	EXTL				
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III (Senerator Exciters	INDMOT 1P				
III (Senerator Governors	INDMOT 1P_PTR				
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	oad Characteristics	LDVFD_A				
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	oad Distributed Generation Models	# MOTORC				
	and Distribution Equivalent Tune	# MOTORW				

Load Characteristic Information

 Bement Type
 System
 Area
 Zone
 Owner
 Bus
 Load Model Group
 Load Model Group
 Load Characteristics Load Relays Distributed Gen Terminal and State Value

 Insert
 Delete
 Show Block Diagram
 Setu Cefaults
 Note: Multiple
 defaults availab

 Type
 Active - CMPLDW
 Sature
 (Only One Active procept by Buse Party Party

Run the generator drop scenario varying these parameters; with this model the grid is no longer well damped (prone to oscillations)

meters														
Bss	0.00000	Xcmp	0.00000	Q1e	1.00000	Ha_Vrsta	0.30000	Rsb_CompPFb	0.02000	Vrc2b_Vc2onb	9999.000 🔹	Ftr1c_TTr1c	0.00000	Tpod_Tstalld
Rfdr	0.00000	FmA	0.20000	Q1c	0.00000	Etrqa_Trsta	2.00000	Lsb_Vstallb	2.00000	Trc2b_Tthb	9999.000 🔹	Vrc1c_Vtr2c	9999.000 🜲	Tppod_Frstd
Xfdr	0.00000	FmB	0.10	Q2e	2.00000	Vtr 1a_Fuvra	0.00000	Lpb_Rstallb	0.20000	Th 1tb	0.70000	Trc1c_Ttr2c	9999.000	Hd_Vrstd
Fb	0.00000	FmC	0.0	Q2c	1.00000	Ttr1a_Vtr1a	9999.000 🔹	Lppb_Xstallb	0.20000	Th2tb	1.30000	Vtr2c_Vc1offc	0.00000	Etrqd_Trstd
Xxf	0.00000	FmD	0.00000	Qfrq	0.00000	Ftr1a_TTr1a	0.00000	Tpob_Tstallb	0.16000	Tvb	0.05000	Ttr2c_Vc2offc	9999.000	Vtr 1d_Fuvrd
Tfixhs	1.00000	Fel	0.00000	Mtypa	3.00000	Vrc1a_Vtr2a	9999.000 🔹	Tppob_Frstb	0.02000	LFmc	0.80000	Ftr2c_Vc1onc	0.00000	Ttr 1d_Vtr 1d
Tfixls	1.00000	PFel	1.00000	Mtypb	3.00000	Trc1a_Ttr2a	9999.000 🔹	Hb_Vrstb	0.30000	Rsc_CompPFc	0.02000	Vrc2c_Vc2onc	9999.000	Ftr1d_TTr1d
LTC	0.00000	Vd1	0.65000	Mtypc	3.00000	Vtr2a_Vc1offa	0.00000	Etrqb_Trstb	2.00000	Lsc_Vstallc	2.00000	Trc2c_Tthc	9999.000	Vrc1d_Vtr2d
Tmin	0.90000	Vd2	0.50000	Mtypd	1.00000	Ttr2a_Vc2offa	9999.000 🔹	Vtr 1b_Fuvrb	0.00000	Lpc_Rstallc	0.20000	Th1tc	0.70000	Trc1d_Ttr2d
Tmax	1.10000	frcel	0.00000	LFma	0.80000	Ftr2a_Vc1ona	0.00000	Ttr 1b_Vtr 1b	9999.000 🔹	Lppc_Xstallc	0.20000	Th2tc	1.30000	Vtr2d_Vc1offd
step	0.00625	PFs	0.80000	Rsa_CompPFa	0.02000	Vrc2a_Vc2ona	9999.000	Ftr 1b_TTr 1b	0.00000	Tpoc_Tstallc	0.16000	Tvc	0.05000	Ttr2d_Vc2offd
Vmin	1.02000	P1e	1.00000	Lsa_Vstalla	2.00000	Trc2a_Ttha	9999.000	Vrc1b_Vtr2b	9999.000 🔹	Tppoc_Frstc	0.02000	LFmd	1.00000	Ftr2d_Vc1ond
Vmax	1.04000	P1c	1.00000	Lpa_Rstalla	0.20000	Th1ta	0.70000	Trc1b_Ttr2b	9999.000 🔹	Hc_Vrstc	0.30000	Rsd_CompPFd	0.98000	Vrc2d_Vc2ond
Tdel	30.00000	P2e	2.00000	Lppa_Xstalla	0.20000	Th2ta	1.30000 🜲	Vtr2b_Vc1offb	0.00000	Etrqc_Trstc	2.00000	Lsd_Vstalld	0.45000	Trc2d_Tthd
Tdelstep	5.00000	P2c	0.00000	Tpoa_Tstalla	0.16000 📮	Tva	0.05000	Ttr2b_Vc2offb	9999.000 🔹	Vtr1c_Fuvrc	0.00000	Lpd_Rstalld	0.10000	Th 1td
Rcmp	0.00000	Pfrq	0.00000	Tppoa_Frsta	0.02000	LFmb	0.80000	Ftr2b_Vc1onb	0.00000	Ttr 1c_Vtr 1c	9999.000	Lppd_Xstalld	0.10000 🜲	Th2td
Show Torq	ue Speed Dialog													

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Modal Analysis in PowerWorld

- Goal is to make modal analysis easy to use, and easy to visualize the results
- Provided tool can be used with either transient stability results or actual system signals (e.g., from PMUs)
- Three ways to access in PowerWorld
 - From the Modal Analysis button (in Add-Ons)
 - On the Transient Stability Analysis form left menu, Modal Analysis (right below SMIB Eigenvalues)
 - By right-clicking on a transient stability or plot case information display, and selecting Modal Analysis Selected Columns or Modal Analysis All Columns

Modal Analysis: Three Generator Example

• A short fault at t=0 gets the below three generator case oscillating with multiple modes (mostly clearly visible for the red and the green curve)



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Modal Analysis: Three Generator Example



- Open the case **B3_CLS_UnDamped**
 - This system has three classical generators without damping; the default event is a self clearing fault at bus 1
- Run the transient stability for 5 seconds
- To do modal analysis, on the Transient Stability page select Results from RAM, view just the generator speed fields, right-click and select **Modal Analysis All Columns**
 - This display the Modal Analysis Form

Modal Analysis Form



First click on **Do Modal Analysis** to run the modal analysis

Modal Analysis Form										- 0	X
			Results								~
Modal Analysis Status Solved at 11/9/2021 10:02:26 AM			Number of	f Complex and Re	al Moder 2	In	dude Detrend in	Reproduced Sign	nals		
Data Source Type	Calculation Method		Number 0	Complex and Re	ai Modes 2	Su	btract Reproduc	ed from Actual			
O From Plot O File, Comtrade CFG O File, WECC CSV 2 O None, Existing Data	Matrix Pencil (Once)		Lowest Pe	rcent Damping	-0	011	Update Reprodu				
O File, JSIS Format O File, CSV (Data Starts Line 2)	Iterative Matrix Pencil										
O File, Comtrade CFF	O Dynamic Mode Decompo	sition				ange Initial Guesse					
Data Source Inputs from Plots or Files			Fr	equency (Hz) D		Largest Na Component in w	ame of Signal		atio Average to Largest	Largest Component in	Name of with Lar
	Do Modal Analy	sis					omponent in		omponent in		
From Plot Gen_Speed							ode,	Unscaled	Mode, UnScaled		Mode, S
From File Browse	Save in JSIS Format	Save to CSV	1	2.232	0.001		nscaled en Bus 1 #1 S	0.00314	0.4900	1.404	Gen Bus
			2	1.510	-0.011		en Bus 2 #1 S	0.00043	0.6838		Gen 3 #
Just Load Signals Group Disabled for Existing Data											
Data Sampling Time (Seconds) and Frequency (Hz)											
				•							
Start Time 0.050 🗭 End Time 5.000 🗢											
Maximum Hz 5.000 📮 Update Sampled Data	Store Results in PWB File										
	Always Reload Signals from	Source	<								>
Input Data, Actual Sampled Input Data Signals Options Reproc	uced Data Iterative Matrix F	Pencil Iteration [Details								
Type Name Latitude Longit	de Description Units	Include	Include	Exclude from	Alwa s inclu	de Detrend	Detrend	Post-Detrend	Post-Detreno	d Solved	Aver
			Reproduced	Iterative Matrix	in Itentive	Parameter A	Parameter B	Number Zeros	Standard		Ur
				Pencil (IMP)	Matrix Pencil (IMP)				Deviation		
1 Gen Bus 1 #1 Speed	Speed	YES	YES	NO	NO	1.0024	0.0004	4 (0.00457	YES	
2 Gen Gen Bus 2 #1 Speed		YES	YES	NO	NO	1.0024			0.00147	YES	
3 Gen Gen 3 #1 Speed	Speed	YES	YES	NO	NO	1.0025	0.0003	3 (0.00082	YES	
<		A									>
I Close 7 Help											
I Luose	- Fi										

Right-click on signal to view its dialog

Signals to include

Key results are shown in the upper-right of the form. There are two main modes, one at 2.23Hz and one at 1.51; both have very little damping.

Three Generator Example: Signal Dialog

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- The **Signal Dialog** provides details about each signal, including its modal components and a comparison between the original and reproduced signals (example for gen 3)

	Gen 3 #1 Speed	Data Detrend Parar	meters			Output Summary	
	Gen	Detrend Model = A	+ B*(t-t0) + C*(t-t0)^2	Used Detrend Model	Linear	Average Error. Scaled by SD	0.0000
s		Use Case Def	ault Detrend Model	Parameter A	1.0025	Average Error. Unscaled	0.0000
ription	Speed	Signal Specific I	_	Parameter B	0.0003	Cost Function Value, Scaled	0.0068
ndude ir	n Modal Analysis	None	○ Linear	Parameter C	0.0000	Include Detrend in Reprodu	uced Signal
lways E	xclude Signal During IMP	 Constant 	Quadratic	Standard Deviation (SD)	0.0008	Update Reproduced	1
lways I	nclude Signal During IMP						1
tual Inpu	ut Sampled Input Fast	1		ginal and Reproduced Sign	al Comparison		
	Time (Seconds)	Original Value	Reproduced Value	Difference			
1	0.050	1.002	1.002	0.000			
2	0.058	1.002	1.002	0.000			
4	0.067	1.002	1.002	0.000			
5	0.075	1.002	1.002	0.000			
6	0.085	1.002	1.002	0.000			
7	0.092	1.002	1.002	0.000			
8	0.108	1.002	1.002	0.000			
9	0.100	1.002	1.002	0.000			
10	0.125	1.002	1.003	0.000			
11	0.133	1.003	1.003	0.000			
12	0.142	1.003	1.003	0.000			
13	0.150	1.003	1.003	0.000			
14	0.158	1.003	1.003	0.000			
15	0.167	1.003	1.003	0.000			
16	0.175	1.003	1.003	0.000			
17	0.183	1.003	1.003	0.000			
	0.192	1.003	1.003	0.000			
18	0.200	1.003	1.003	0.000			
		4 000	1.007	0.000			
18	0.208	1.003	1.003	0.000			

Plotting the original and reproduced signals shows a near exact match



Caution: Setting Time Range Incorrectly Can Result in Unexpected Results!

- Assume the system is run with no disturbance for two seconds, and then the fault is applied and the system is run for a total of seven seconds (five seconds post-fault)
 - The incorrect approach would be to try to match the entire signal; rather just match from after the fault
 - Trying to match the full
 signal between 0 and 7 seconds
 required eleven modes!
 - By default the Modal Analysis Form sets thedefault start time to immediately after the last event



GENROU Example with Damping

- Open the case **B3_GENROU**, which changes the GENCLS to GENROU models, adding damping
 - Also each has an EXST1 exciter and a TGOV1 governor
 - The simulation runs for seven seconds, with the fault occurring at two seconds; modal analysis is done from the time the fault is cleared until the end of the simulation.



The image shows the generator speeds. The initial rise in the speed is caused by the load dropping during the fault, causing a power mismatch; this is corrected by the governors. Note the system now has damping; modal analysis tells us how much.

GENROU Example with Damping



sults mber of Complex and Real Modes west Percent Damping al and Complex Modes - Editable to Change Initial Guesses Frequency (Hz) Damping (%) Largest Component in Mode, Unscaled 1 2.053 11.353 0.00352 Gen 3 #1 Speec 2 1.649 19.638 0.00452 Gen Bus 2 #1 S 0.00084 0.
ude Exclude from Always include Detrend Detrend Post-Detrend Post-Detrend Post-Detrend Parameter A Parameter B Number Zeros Stani
Mode frequency, damping, and largest contribution of each mode in the signals. The slower mode is associated with the governors.

GENROU Example with Damping

Left image show how well the speed for generator 1 is • approximated by the modes More signal details





Actual Input Sampled Input Fast Fourier Transform Results Modal Results Original and Reproduced Signal Comparison

	Damping (%)	Frequency (Hz)	Magnitude Scaled by SD	Magnitude, Unscaled	Angle (Deg)	Lambda	Include in Reproduced Signal
1	11.353	2.053	2.300	0.003	13.82	-1.474	YES
2	19.638	1.649	2.038	0.003	10.46	-2.075	YES
3	65.427	0.236	4.757	0.006	-91.36	-1.283	YES
4	-34.022	0.098	0.689	0.001	135.64	0.222	YES



Just the 2.05 Hz mode

Dealing with Multiple Signals

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- When there are many signals, usually they are at least somewhat correlated, so we do not need to include all the signals in the calculation of α .
- Based on the previous quick calculation of b_k, we can determine how well the signals match the α.
- A natural algorithm for improving is to include the signals that do not match α well. That is, have high residuals.
- This gave rise to what is called the Iterative Matrix Pencil algorithm.

Iterative Matrix Pencil Method

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- When there are a large number of signals the iterative matrix pencil method works by
 - Selecting an initial signal to calculate the α vector
 - Quickly calculating the b vectors for all the signals, and getting a cost function for how closely the reconstructed signals match their sampled values
 - Selecting a signal that has a high cost function, and repeating the above adding this signal to the algorithm to get an updated α

An open access paper describing this is W. Trinh, K.S. Shetye, I. Idehen, T.J. Overbye, "Iterative Matrix Pencil Method for Power System Modal Analysis," *Proc. 52nd Hawaii International Conference on System Sciences*, Wailea, HI, January 2019; available at scholarspace.manoa.hawaii.edu/handle/10125/59803

Texas 2000 Bus Synthetic Grid Example

- For this example we'll again use the Texas 2000 bus grid, saved as **TSGC_2000_GenDrop**
- Use the Iterative Matrix Pencil Method to examine its modes
 - The contingency is the loss of two large generators (at bus 7098 and 7099)



The measurements will be the frequencies at all 2000 buses

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2000 Bus System Example, Initially Just One Signal

- Initially our goal is to understand the modal frequencies and their damping
- First we'll consider just one of the 2000 signals; arbitrarily I selected bus 8126 (Mount Pleasant)



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Some Initial Considerations

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- The input is a dynamics study running using a ¹/₂ cycle time step; data was saved every 3 steps, so at 40 Hz
- The contingency was applied at time = 2 seconds
- We need to pick the portion of the signal to consider and the sampling frequency
 - Because of the underlying SVD, the algorithm scales with the cube of the number of time points (in a single signal)
- I selected between 2 and 17 seconds
- I sampled at ten times per second (so a total of 150 samples)

2000 Bus System Example, One Signal

• The results from the Matrix Pencil Method are

Number of Complex and Lowest Percent Damping	g [1	0.137			-			Calculated mode
- Real and Complex Mode Frequency (Hz)	1		Name of Signal with Largest	Component in	Name of Signal with Largest Component in Mode, Scaled	Lambda	Include in Reproduced Signal	information
1 0.383	32.011	0.44275	Bus 1073 (ODE	12.224	Bus 7310 (WHA	-0.8136	YES	
2 0.670	24.191	0.38466	Bus 2120 (PARIS	11.549	Bus 8078 (MT. E	-1.0490	YES	
3 0.665	10.705	0.23093	Bus 2115 (PARIS	6.801	Bus 2115 (PARIS	-0.4501	YES	
4 0.312	14.397	0.16911	Bus 1073 (ODES	4.954	Bus 7310 (WHA	-0.2855	YES	
5 0.971	10.137	0.08179	Bus 1051 (MON	2.551	Bus 6147 (SAN /	-0.6215	YES	
6 0.052	41.828	0.04603	Bus 1074 (ODES	1.063	Bus 3035 (CHER	-0.1506	YES	
				PWD	/ectorGrid Variables			



Verification of results

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Some Observations

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- These results are based on the consideration of just one signal
- The start time **should** be at or after the event!

If it isn't then...



The results show the algorithm trying to match the first two flat seconds; this should not be done!!

Results											
Number	r of Complex and	Real Modes 8		Include Detrend	in Reproduced S	ignals					
- tomber	or complex and			Subtract Reprod	luced from Actua	I					
Lowest	Percent Damping	-10	00.000	Update Reproduced Signals							
Real an	d Complex Mode	s - Editable to Ch	nange Initial Gue	sses							
	Frequency (Hz)	Damping (%)	Largest ▼ Component Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Component in	Name of Signal with Largest Component in Mode, Scaled	Lambda	R			
1	0.000	100.000	0.93636	Bus 1073 (ODES	14.030	Bus 1077 (ODES	-1.6801	YE			
2	0.240	44.396	0.82180	Bus 1073 (ODES	12.073	Bus 1077 (ODES	-0.7473	YE!			
3	0.025	84.809	0.43068	Bus 4026 (CHRI	8.463	Bus 4026 (CHRI	-0.2476	YE!			
4	0.408	4.729	0.10932	Bus 1073 (ODES	1.587	Bus 1073 (ODES	-0.1213	YE!			
5	0.645	6.111	0.09142	Bus 2115 (PARIS	1.694	Bus 2115 (PARIS	-0.2482	YE!			
6	0.751	6.110	0.05556	Bus 4192 (BROV	1.042	Bus 4192 (BRO\	-0.2887	YE:			
7	0.954	3.484	0.02405	Bus 1051 (MON	0.397	Bus 6147 (SAN /	-0.2089	YE:			
8	0.000	-100.000	0.01406	Bus 4026 (CHRI	0.276	Bus 4026 (CHRI:	0.0565	VE			

2000 Bus System Example, Two Signals

W	ith	two s	ignal	S				
		of Complex and			Include Detrend Subtract Reprod		-	
	Lowest	Percent Damping		7.359	Update Repro	duced Signals		
	Real an	d Complex Mode	s - Editable to Ch	ange Initial Gue	sses			
		Frequency (Hz)	Damping (%)	Largest Component in Mode, Unscaled	Name of Signal with Largest Component in Mode, Unscaled	Largest Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambo
	1	2.266	17.168		Bus 7329 (NEW		Bus 7307 (WHA	-2
	2	1.413 0.958	21.844 7.359		Bus 4030 (FANN Bus 6147 (SAN)		Bus 4030 (FANN Bus 6147 (SAN /	-1 -0
	4	0.938	11.705		Bus 1051 (MON		Bus 8077 (MT. E	-0
	5	0.630	13.361		Bus 2120 (PARIS		Bus 4192 (BROV	-0
	6	0.352	36.405	0.44679	Bus 1051 (MON	13.024	Bus 7311 (WHA	-0
	7	0.322	14.403		Bus 1073 (ODES		Bus 7311 (WHA	-0
	8	0.000	100.000		Bus 1051 (MON		Bus 1051 (MON	-0
	9	0.064	36.756	0.02993	Bus 1073 (ODE:	1.182	Bus 7307 (WHA	-0

With one signal

Number of Complex and Real Modes 6

Lowest Percent Damping

✓ Include Detrend in Reproduced Signals Subtract Reproduced from Actual Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

10.137

	Frequency (Hz)	Damping (%)			Component in Mode, Scaled	Name of Signal with Largest Component in Mode, Scaled	Lambo
1	0.383	32.011	0.44275	Bus 1073 (ODES	12.224	Bus 7310 (WHA	-0
2	0.670	24.191	0.38466	Bus 2120 (PARIS	11.549	Bus 8078 (MT. E	-1
3	0.665	10.705	0.23093	Bus 2115 (PARIS	6.801	Bus 2115 (PARIS	-0
4	0.312	14.397	0.16911	Bus 1073 (ODES	4.954	Bus 7310 (WHA	-0
5	0.971	10.137	0.08179	Bus 1051 (MON	2.551	Bus 6147 (SAN /	-0
6	0.052	41.828	0.04603	Bus 1074 (ODES	1.063	Bus 3035 (CHER	-0

The new match on the bus that was previously worst (Bus 7061) is now quite good!





2000 Bus System Example, Iterative Matrix Pencil



- The Iterative Matrix Pencil intelligently adds signals until a specified number is met
 - Doing ten iterations takes about four seconds

Numb	er of Complex and	Real Modes 11		Include Detrend		-						
	Subtract Reproduced from Actual											
Lowe	Lowest Percent Damping 6.082 Update Reproduced Signals											
Real and Complex Modes - Editable to Change Initial Guesses												
	Frequency (Hz)	Damping (% 📥		Name of Signal with Largest Component in Mode, Unscaled	Component in	Name of Signal with Largest Component in Mode, Scaled	Lambda	Include in Reproduced Signal				
	1 0.631	6.082	0.10313	Bus BROWNSV	3.292	Bus BROWNSVI	-0.2415	YES				
	2 0.959	7.068	0.04897	Bus SAN ANTO	1.890	Bus SAN ANTOI	-0.4269	YES				
	3 1.364	7.246	0.03780	Bus ODESSA 1	1.420	Bus CHRISTINE	-0.6228	YES				
	4 0.593	7.897	0.07205	Bus BROWNSV	2.300	Bus BROWNSVI	-0.2949	YES				
	5 1.602	8.562	0.04887	Bus FANNIN 2 F	2.032	Bus FANNIN 2 F	-0.8650	YES				
	6 0.732	11.936	0.21348	Bus MONAHAN	4.054	Bus MONAHAN	-0.5529	YES				
	0.324	14.207	0.19906	Bus ODESSA 1	5.268	Bus WHARTON	-0.2917	YES				
	8 0.324	39.346	0.55936	Bus MONAHAN	12.994	Bus WHARTON	-0.8722	YES				
	9 0.060	39.972	0.03815	Bus ODESSA 1	1.196	Bus POINT CON	-0.1645	YES				
1	0 0.964	57.683	0.61264	Bus ODESSA 1	18.504	Bus POINT CON	-4.2760	YES				
1	1 0.000	100.000	0.59650	Bus ODESSA 10	14.434	Bus WHARTON	-2.5257	YES	_			

Takeaways So Far



- Modal analysis can be quickly done on a large number of signals
 - Computationally is an O(N³) process for one signal, where N is the number of sample points; it varies linearly with the number of included signals
 - The number of sample points can be automatically determined from the highest desired frequency (the Nyquist-Shannon sampling theory requires sampling at twice the highest desired frequency)
 - Determining how all the signals are manifested in the modes is quite fast!!

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Visualizing the Modes

• If the grid has embedded geographic coordinates, the contributions for the mode to each signal can be readily visualized utilizing geographic data views (GDVs)



Image shows the magnitudes of the components for the 0.63 Hz mode; the display was pruned to only show some of the values



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

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

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PSSs Regulations

- On ERCOT PSSs are required on all synchronous generators greater than 10 MW installed after January 2008
 - If a generator has a PSS then they need to be kept in-service; they also need to be tuned to help damp out oscillations between 0.2 to 2 Hz.
- WECC requires PSSs for synchronous generators connected to the bulk electric grid, and has a number specific requires associated with PSS values (see NERC VAR-501-WECC-3.1)

Classic Block Diagram of a System with a PSS





Image Source: Kundur, Power System Stability and Control

PSS Basics

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

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

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

$$\stackrel{jX'_d \quad R_s \quad R_e \quad jX_{ep}}{=} \frac{i}{z}$$

• Assume internal voltage has an additional component

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

- This can add additional damping if $sin(\delta)$ is positive
- In a real system there is delay, which requires compensation

Example PSS



- An example single input stabilizer is shown below (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



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



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2000 Bus System Results Without Stabilizers

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



Washout Filters and Lead-Lag Compensators

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Two common attributes of PSSs are washout filters and lead-lag compensators
 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 ulletand angle of the signal at low frequencies
 - Gain (dB) = 20 log Vout Vin Pass Band Stop Band 0dB -3dB (45°) Frequency Response Output Slope = +20dB/Decade Bandwidth -dB f_{c} (HP) Frequency (Hz) Phase (Logarithmic Scale) +90° Phase Shift +45° 0° Frequency (Hz)

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.electronicstutorials.ws/filter/filter 3.html





Lead-Lag Compensators

- For a lead-lag compensator of the below form with $\alpha \le 1$ (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



Stabilizer Design

- A M
- 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


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



Image Source: EEE Std 421.5-2016

Figure 31—Type PSS1A single-input power system stabilizer

Stabilizer Design Values

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

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- 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 $\frac{1}{2}$ of this value





Stabilizer Design Tuning

- A M
- 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

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- 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







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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PSS Example: Getting Initial Frequency, Damping

• The Modal Analysis button provides quick access





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PSS Tuning Example: Add PSS1As at Gens 2 and 3

- A M
- 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

 V_{SI}

We'll use
 simulation
 results



Δt

ALL OTHER CONTRIBUTIONS

Figure 31—Type PSS1A single-input power system stabilizer

PSS Example: Using Stabilizer Reference Signals

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- 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

🔵 Generat	or Information for Present	_		×
Bus Number	Z ✓			
Bus Name	Bus 2 V Find By Name Olosed			
ID	1 Find Energized NO (Offline)			
Area Name	1 (1)			
Labels	no labels Fuel Type Unknown			\sim
	Generator MVA Base 250.00 Unit Type UN (Unknown)			\sim
Power and V	oltage Control Costs OPF Faults Owners, Area, etc. Custom Stability			
Machine Mo	els Exciters Governors Stabilizers Other Models Step-up Transformer Ter	rminal	and State	
In	ert Delete Gen MVA Base 250.0 Show Block Diagram	Crea	ate VCurve]
Type SIGN	LSTAB V Active (only one may be active) Set to Defaults			
Parameter				
PU values	shown/entered using device base of 250.0 MVA $$			
DoRamp	0 🔹 dVolt4 0.00000 📼			
StartTime	0.00000			
dVolt1	0.05000 Duration4 0.00000			
Freq1	1.36000 dVolt5 0.00000			
Duration 1	0.00000 🛉 Freq5 0.00000 🗭			
dVolt2	0.00000 - Duration5 0.00000 -			
Freq2	0.00000			
Duration2	0.00000			
dVolt3	0.00000			
Freq3	0.00000			
Duration3	0.00000			

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

Standard Deviation Unscaled Scaled by SD 1 Gen V pu \ Gen Bus 2 #1 0.011 69.015 0.015 1.364 0.015 2 Gen Vstab \ Gen Bus 2 #1 0.035 -160.952 0.048 1.377 0.004	equency (Hz) and D	amping (%) 1.359 Hz, D	amping = -0,1 ⁴	14% ~	T	Results from Sele Floating Point Fiel		Object Custom F	-
Standard Deviation Unscaled Scaled by SD 1 Gen V pu \ Gen Bus 2 #1 0.011 69.015 0.015 1.364 0.015 2 Gen Vstab \ Gen Bus 2 #1 0.035 -160.952 0.048 1.377 0.004	₩ 🖽 🖬	+.0 .00 A A A Reco	rds * Geo * S	et + Columns			f(x) ▼ Ⅲ 0	ptions 🝷	
2 Gen Vstab \ Gen Bus 2 #1 0.035 -160.952 0.048 1.377 0.004	Туре	Name	Units	Description	Standard	Angle (Deg)		-	Cost Function
2 Gen Vstab \ Gen Bus 2 #1 0.035 -160.952 0.048 1.377 0.004	1 Gen	V pu \ Gen Bus 2 #1			0.011	69.015	0.015	1.364	0.0158
3 Gen MW \ Gen Bus 2 #1 25.013 -171.078 34.460 1.378 0.007		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 0.013	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 $\phi = 50^{\circ}$ then

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

PSS Tuning Example: 1.36 Hz Lead-Lag Values



• 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%



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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

Frequency (Hz) and Damping (%) 1.359 Hz, Damping = -0.098% Transfer Results from Selected Column to Object Custom Floating Pont Field Custom Floating Point Field Custom Floating Point Field 1 Transfer Results									
🕎 🛅 🎬 兆 🚧 🛤 🌺 Records ▼ Geo ▼ Set ▼ Columns ▼ 🔤 ▼ 🏙 ▼ 👹 ▼ 競 f(x) ▼ 田 Options ▼									
Туре	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 Vs	stab \ Gen Bus 3 #1			0.035	-161.183	0.049	1.392	0.0021	
3 Gen M	IW \ Gen Bus 3 #1			3.925	-139.661	5.462	1.392	0.0038	
4 Gen Sp	peed \ Gen Bus 3 #1			0.001	-49.263	0.001	1.386	0.0022	

• The values are $\alpha = 0.283$, T₁=0.22, T₂=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.



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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%

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 A M

Power System Voltage Stability

- A M
- Voltage Stability: The ability to maintain system voltage so that both power and voltage are controllable. System voltage responds as expected (i.e., an increase in load causes proportional decrease in voltage).
- Voltage Instability: Inability to maintain system voltage. System voltage and/or power become uncontrollable. System voltage does not respond as expected.
- Voltage Collapse: Process by which voltage instability leads to unacceptably low voltages in a significant portion of the system. Typically results in loss of system load.

Power System Stability Terms



Fig. 4. Classification of power system stability

[a] IEEE/PES Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", PES-TR77, April 2020

Small Disturbance Voltage Stability

- Small disturbance voltage stability can be assessed using a power flow (maximum loadability)
- Depending on the assumed load model, the power flow can have multiple (or no solutions)
- PV curve is created by plotting power versus voltage

 $\begin{array}{c|c} \text{Bus 1} & x = 0.2 \\ \hline & \text{(Slack)} \\ \hline & \text{Slack)} \\ \hline & \text{Slack)} \\ \hline & \text{Slack} \\ \hline \\ \hline & \text{Slack} \\ \hline \\ & \text{Slack$

$$P_L - BV\sin\theta = 0$$
$$Q_L + BV\cos\theta - BV^2 = 0$$

Where B is the line susceptance =-10, $V \angle \theta$ is the load voltage

Small Disturbance Voltage Stability

- Question: how do the power flow solutions vary as the load is changed?
- A Solution: Calculate a series of power flow solutions for various load levels and see how they change
- Power flow Jacobian

$$\mathbf{J}(\theta, V) = \begin{bmatrix} -BV\cos\theta & -B\sin\theta \\ -BV\sin\theta & B\cos\theta - 2BV \end{bmatrix}$$

det $\mathbf{J}(\theta, V) = VB^2 \left(2V\cos\theta - \cos^2\theta - \sin^2\theta \right)$
Singular when $\left(2V\cos\theta - 1 \right) = 0$

Maximum Loadability: Singular Power Flow Jacobian

- An important paper considering this was by Sauer and Pai from *IEEE Trans. Power Systems* in Nov 1990, "Power system steady-state stability and the load-flow Jacobian"
- Other earlier papers were looking at the characteristics of multiple power flow solutions
- Work with the power flow optimal multiplier around the same time had shown that optimal multiplier goes to zero as the power flow Jacobian becomes singular
- The power flow Jacobian depends on the assumed load model (we'll see the impact in a few slides)

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Bifurcations

- A M
- In general, bifurcation is the division of something into two branches or parts
- For a dynamic system, a bifurcation occurs when small changes in a parameter cause a new quality of motion of the dynamic system
- Two types of bifurcation are considered for voltage stability
 - Saddle node bifurcation is the disappearance of an equilibrium point for parameter variation; for voltage stability it is two power flow solutions coalescing with parameter variation
 - Hopf bifurcation is cause by two eigenvalues crossing into the right-half plane

PV and QV Curves

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- PV curves can be traced by plotting the voltage as the real power is increased; QV curves as reactive power is increased
 - At least for the upper portion of the curve
- Two bus example PV and QV curves



Small Disturbance Voltage Collapse

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- At constant frequency (e.g., 60 Hz) the complex power transferred down a transmission line is S=VI*
 - V is phasor voltage, I is phasor current
 - This is the reason for using a high voltage grid
- Line real power losses are given by RI² and reactive power losses by XI²
 - R is the line's resistance, and X its reactance; for a high voltage line X >>
 R
- Increased reactive power tends to drive down the voltage, which increases the current, which further increases the reactive power losses

PowerWorld Two Bus Example



Disable Power Flow Optimal Multiplier Disable Treating Continuous SSs as PV Bu Initialize from Flat Start Values Disable Balancing of F Minimum Per Unit Voltage for Constant Power Loads 0.700 Disable Transformer Tap Control if Tap Sens. is the Wrong Sign (Normally Check This) Constant Current Loads 0.500 Min. Sensitivity for LTC Control 0.0500 Pre-Processing Post-Processing Disable Angle Smoothing Disable Angle Rotation Processing Sharing of generator vars across groups of buses during remote regulation Allocate across buses using the user-specified remote regulation percentages O Allocate so all generators are at same relative point in their [min .. max] var range O Allocate across buses using the SUM OF user-specified remote regulation percentages ZBR Threshold 0.000200 Options for Areas on Economic Dispatch

Commercial power flow software usually auto converts constant power loads at low voltages; set these fields to zero to disable this conversion

Case is **Bus2_PV**

Power Flow Region of Convergence



Convergence regions with P=100 MW, Q=0 Mvar



Load Parameter Space Representation

- With a constant power model there is a maximum loadability surface, Σ
 - Defined as point in which the power flow Jacobian is singular
 - For the lossless two bus system it can be determined as





Load Model Impact

- With a static load model regardless of the voltage dependency the same PV curve is traced
 - But whether a point of maximum loadability exists depends on the assumed load model
 - If voltage exponent is > 1 then multiple solutions do not exist (see B.C. Lesieutre, P.W. Sauer and M.A. Pai "Sufficient conditions on static load models for network solvability," NAPS 1992, pp. 262-271)



Change the load to constant impedance; hence it becomes a linear model



Application: Conservation Voltage Reduction (CVR)

- If the "steady-state" load has a true dependence on voltage, then a change (usually a reduction) in the voltage should result in a total decrease in energy consumption
- If an "optimal" voltage could be determined, then this could result in a net energy savings
- Some challenges are 1) the voltage profile across a feeder is not constant, 2) the load composition is constantly changing, 3) a decrease in power consumption might result in a decrease in useable output from the load, and 4) loads are dynamic and an initial decrease might be balanced by a later increase

CVR Issues

ENREL



Fig. 4. Comparison of active and reactive powers between old and new appliances.

Conservation Voltage Reduction with Distributed Energy Resource Management System, Grid-Edge, and Legacy Devices

Preprint

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National Renewable Energy Laboratory

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Figure 4 from A, Bokhari, et. al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," *IEEE Trans. Power Delivery*, June. 2014

The gist of the 2023 NREL paper is distributed generation (like PV) can help with CVR through better feeder voltage regulation

Dynamic Load Response

- As first reported in the below paper, following a change in voltage there will be a dynamic load response
 - Residential supply voltage should be between 114 and 126 V
- If there is a heating load the response might be on the order of ten minutes
- Longer term issues can also come into play
 - Useful paper and figure reference: D. Karlsson, D.J. Hill, "Modeling and Identification of Nonlinear Dynamic Loads in Power Systems," IEEE. Trans. on Power Systems, Feb 1994, pp. 157-166





Determining a Metric to Voltage Collapse

- The goal of much of the voltage stability work was to determine an easy way to calculate a metric (or metrics) of the current operating point to voltage collapse
 - PV and QV curves (or some combination) can determine such a metric along a particular path $\overline{\xi}^{300}$
 - Goal was to have a path independent metric. The closest boundary point was considered, but this could be quite misleading if the system was not going to move in that direction



 Any linearization about the current operating point (i.e., the Jacobian) does not consider important nonlinearities like generators hitting their reactive power limits

Assessing Voltage Margin Using PV and QV Curve Analysis

- A common method for assessing the distance in parameter space to voltage instability (or an undesirable voltage profile) is to trace how the voltage magnitudes vary as the system parameters (such as the loads) are changed in a specified direction
 - If the direction involves changing the real power (P) this is known as a PV curve; if the change is with the reactive power (Q) then this is a QV curve
- PV/QV curve analysis can be generalized to any parameter change, and can include the consideration of contingencies

PV and QV Analysis in PowerWorld

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- Requires setting up what is known in PowerWorld as an injection group
 - An injection group specifies a set of objects, such as generators and loads, that can inject or absorb power
 - Injection groups can be defined by selecting Case Information, Aggregation, Injection Groups
- The PV and/or QV analysis then varies the injections in the injection group, tracing out the PV curve
- This allows optional consideration of contingencies
- The PV tool can be displayed by selecting Add-Ons, PV

This has already been done in the **Bus2_PV** case

PV and QV Analysis in PowerWorld: Two Bus Example



• Setup page defines the source and sink and step size



PV and QV Analysis in PowerWorld: Two Bus Example



- The PV Results Page does the actual solution
 - Plots can be defined to show the results
 - This should be done beforehand
 - Other Actions, Restore initial state restores the pre-study state

> · Setup	PV Results	
> · Quantities to track Limit violations PV output	Run Stop Restore Initial State on Completion of Run Option to restore	initial state
···· QV setup	Base case could not be solved	
> · Plots	Present nominal shift 0.000 Gen MW Load SMW Load IMW Load ZMW Present step size 150.00 0.00 0.00 0.00 View detailed results Sink 0.00 150.00 0.00 0.00 Other actions >>	
	Found 1 limiting case.	C1: $1 + 1 + 1$ D rest $1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1$
	Overview Legacy Plots Track Limits □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □ □	Click the Run button to run the
	Scenario Critical? Critical Reason Max Shift Max Export Max Import # Viol Worst V Viol Worst V Bus	PV analysis;
	1 base case YES Reached Nose 297.00 297.00 0	i v unur jono,
		Check the Restore Initial State
		on Completion of Run to restore
		the pre-PV state (by default it is
	٢	not restored)
Save Auxiliary Load	d Auxiliary Launch QV curve tool ? Help	70

PV and QV Analysis in PowerWorld: Two Bus Example





To restore the starting case, on the **PV Results** page select **Other Actions**, **Restore Initial State**

PV and QV Analysis in PowerWorld: 37 Bus Example



Usually other limits also need to be considered in doing a realistic PV analysis; example case is **Bus37_PV**

Shorter Term Dynamics

- On a shorter time-scale (minutes down to seconds) voltage stability is impacted by controls hitting limits (such as the action of generator over excitation limiters), the movement of voltage control devices (such as LTC transformers) and load dynamics
 - Motor stalling can have a major impact
- The potential for voltage instability can be quantified by looking at the amount and duration of voltage dips following an event



Fault Induced Delayed Voltage Recovery (FIDVR)

- FIDVR is a situation in which the system voltage remains significantly reduced for at least several seconds following a fault (at either the transmission or distribution level)
 - It is most concerning in the high voltage grid, but found to be unexpectedly prevalent in the distribution system
- Stalled residential air conditioning units are a key cause of FIDVR – they can stall within the three cycles needed to clear a fault



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