Power System Oscillations

Natural and Forced

Jan. 2025

NASPI EATT presentation

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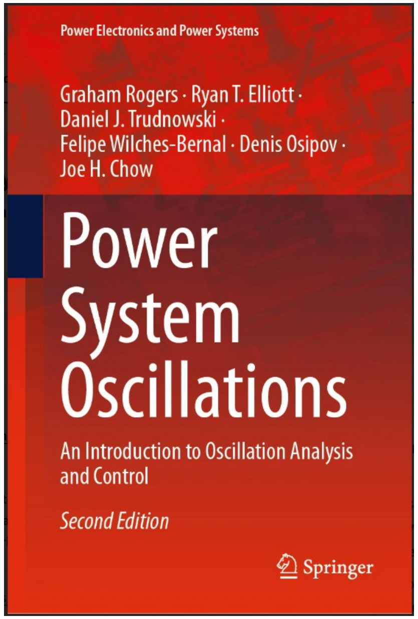
G. Rogers, R. Elliott, D. Trudnowski, F. Wilches-Bernal, D. Osipov, and J. Chow, Power System Oscillations, 2nd Ed., Springer 2025.



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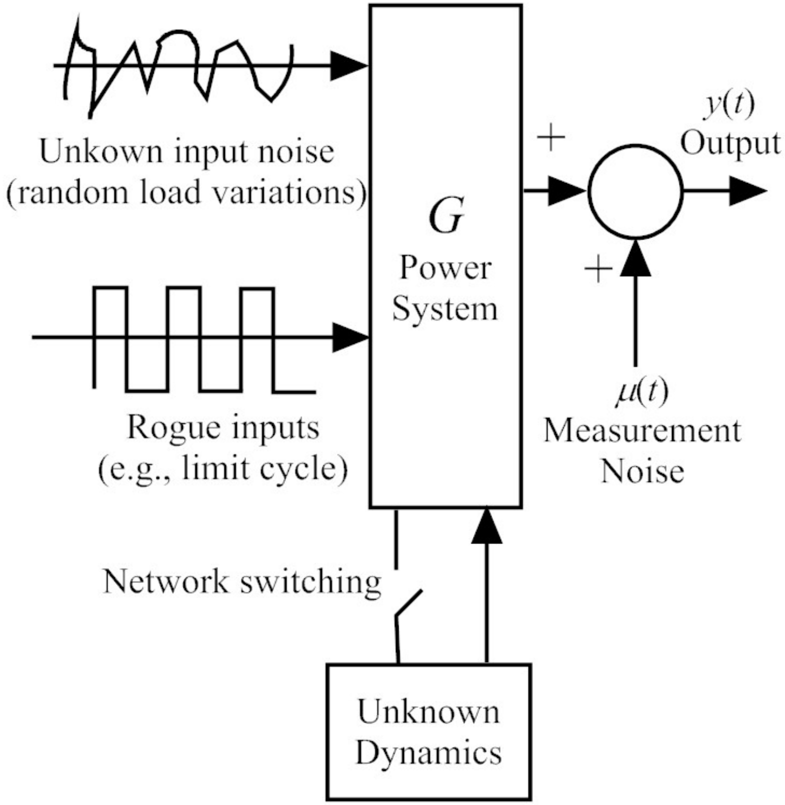
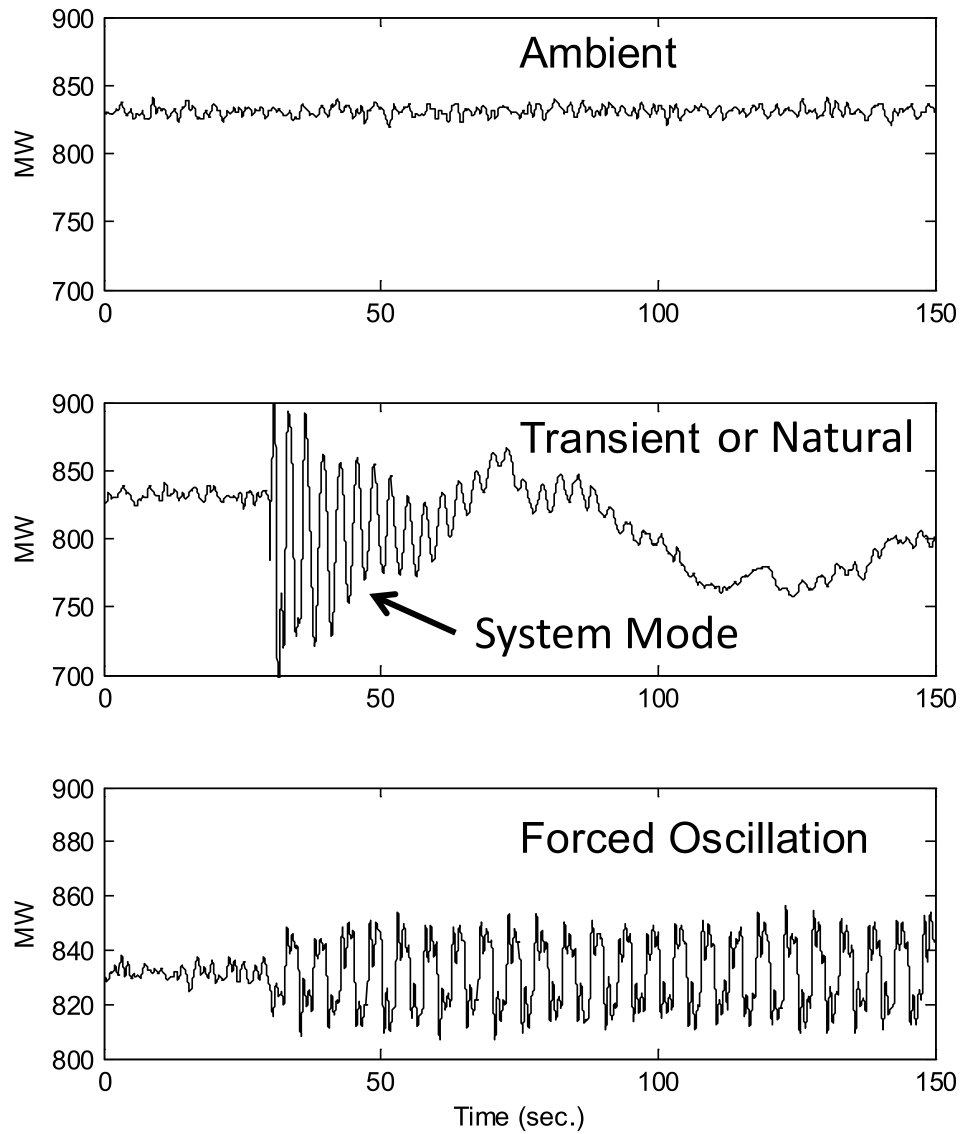
Dynamic Response Types



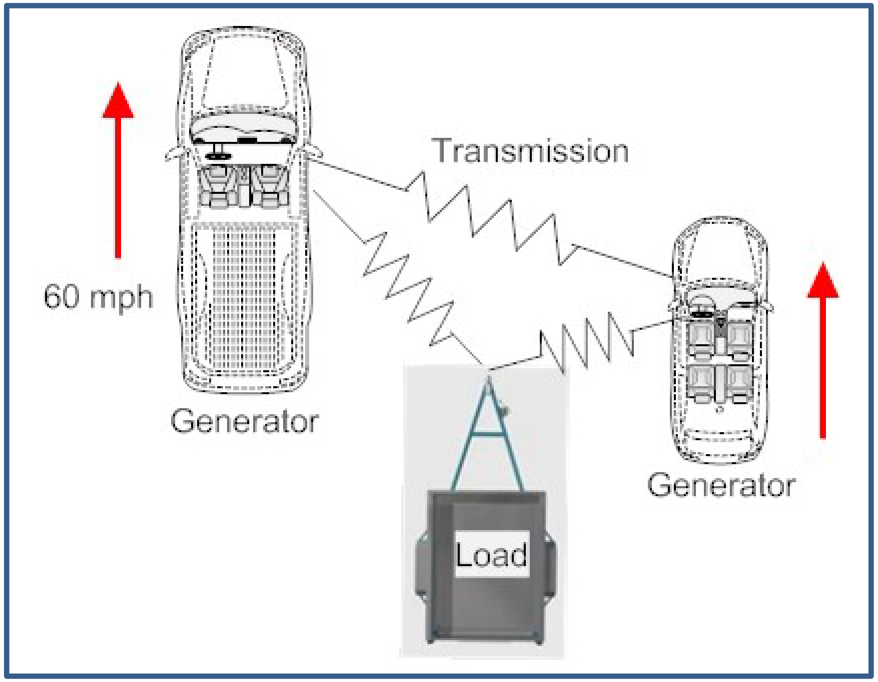


Natural Modes

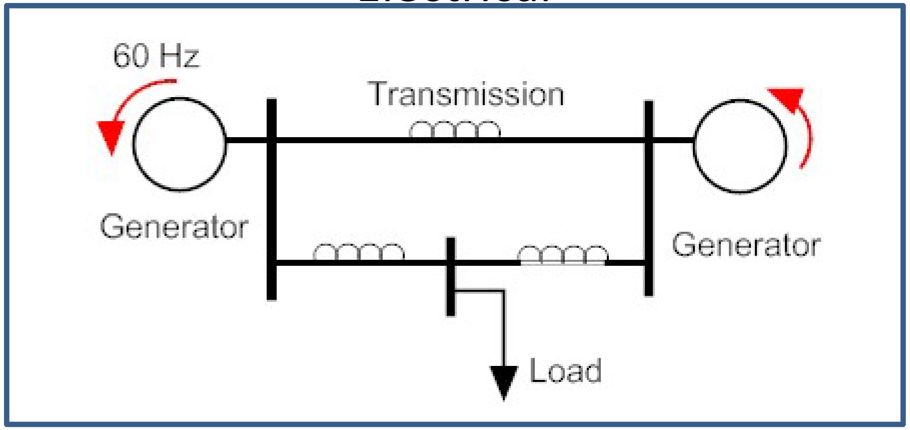
Electromechanical Dynamics

The Physics

Mechanical

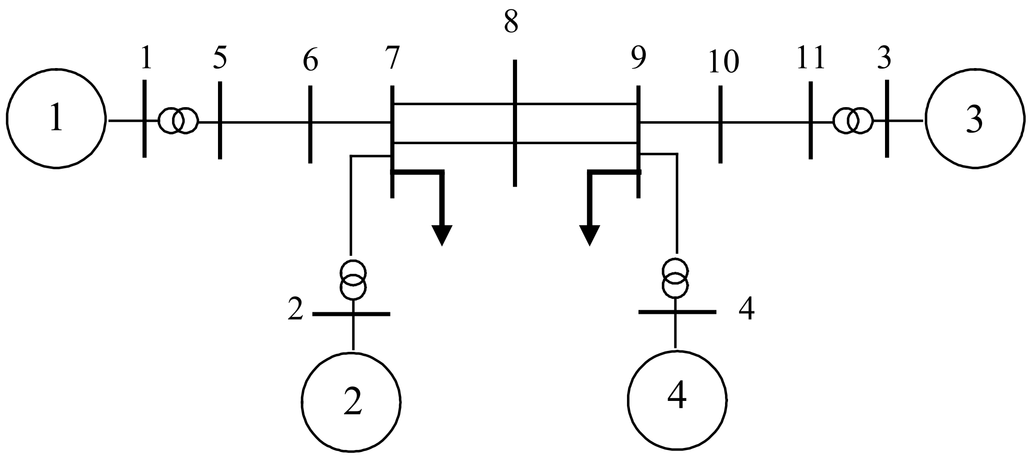


Electrical



Modes

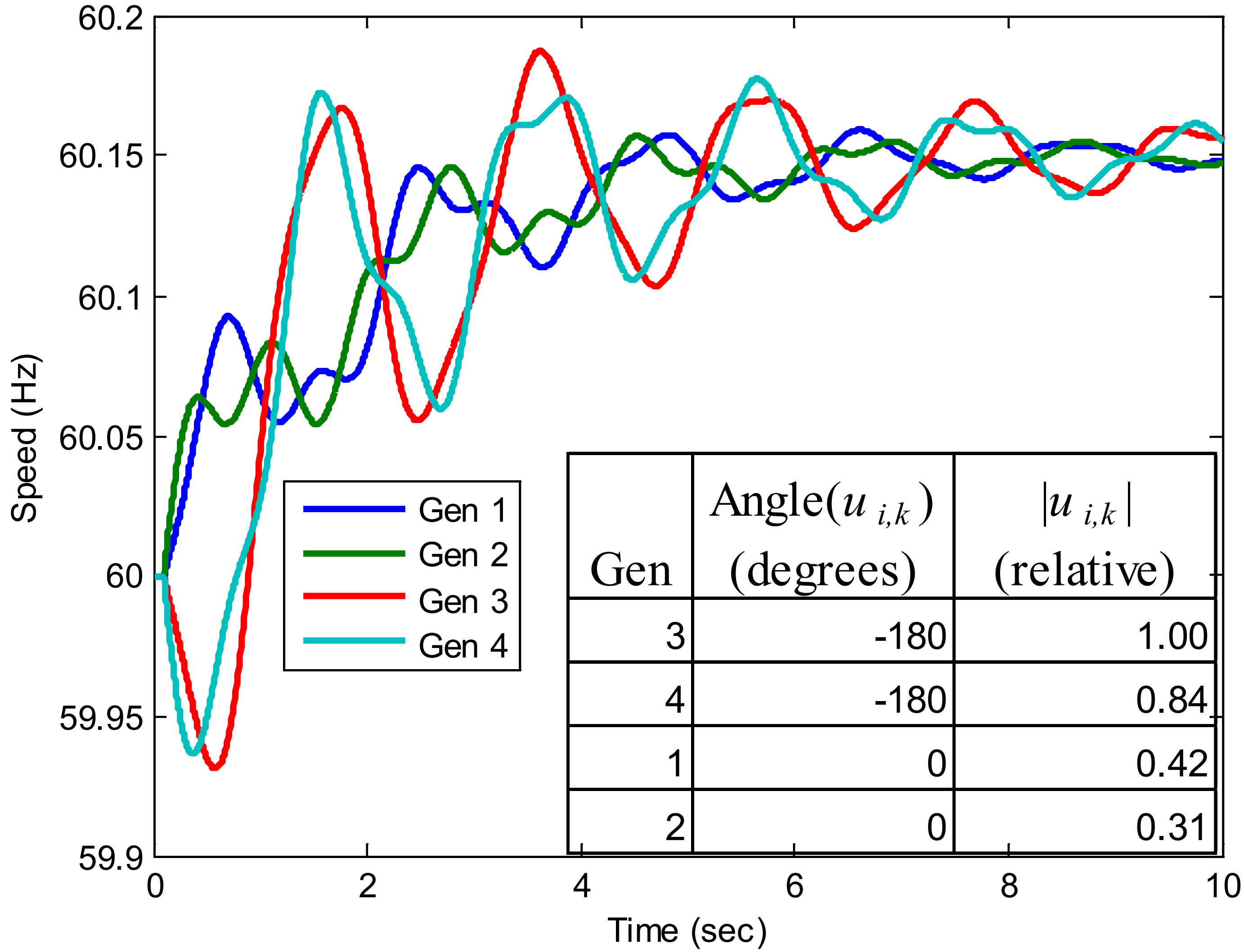
Frequency, Damping, Shape



Mode	Frequency (Hz)	Damping (%)
1	0.51	7.80
2	1.19	3.40
3	1.22	3.30

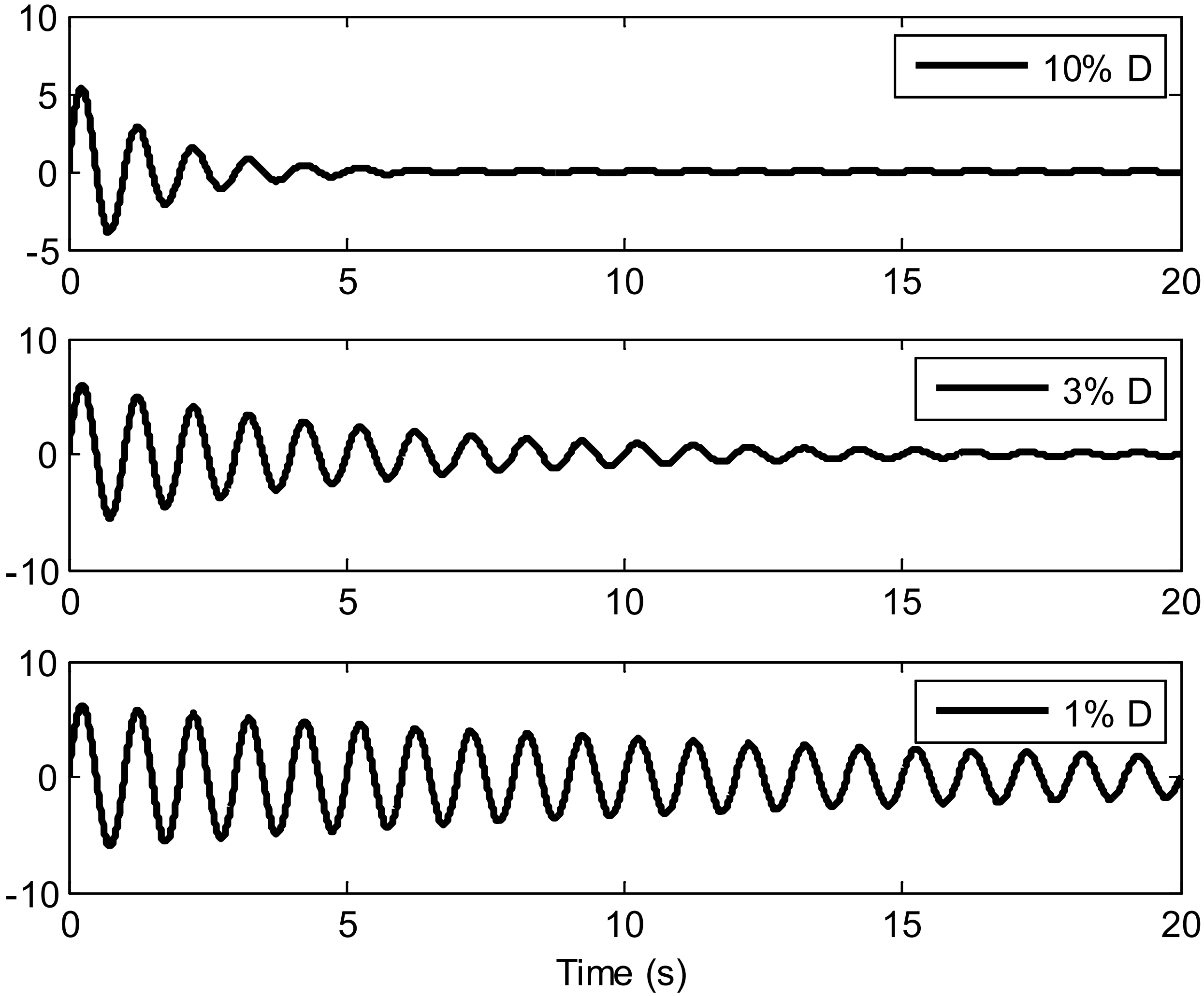
Gen	Angle($u_{i,k}$) (degrees)	Amplitude $\|u_{i,k}\|$
3	-180	1.00
4	-180	0.84
1	0	0.42
2	0	0.31

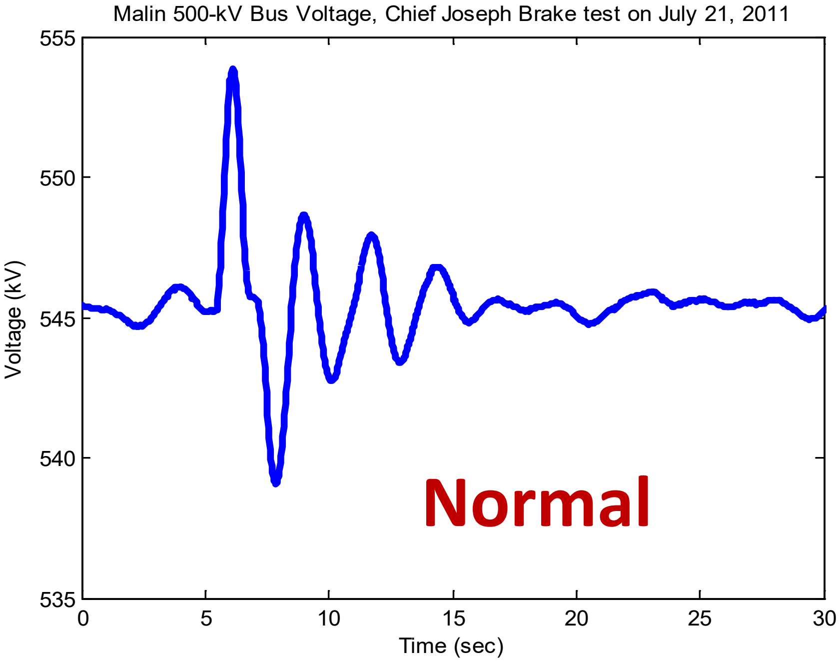
Mode Shape

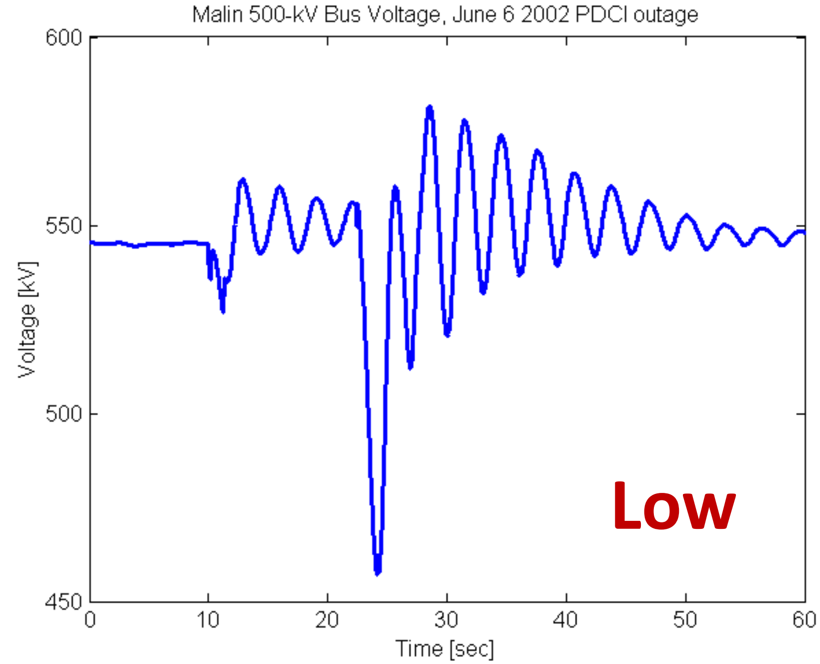


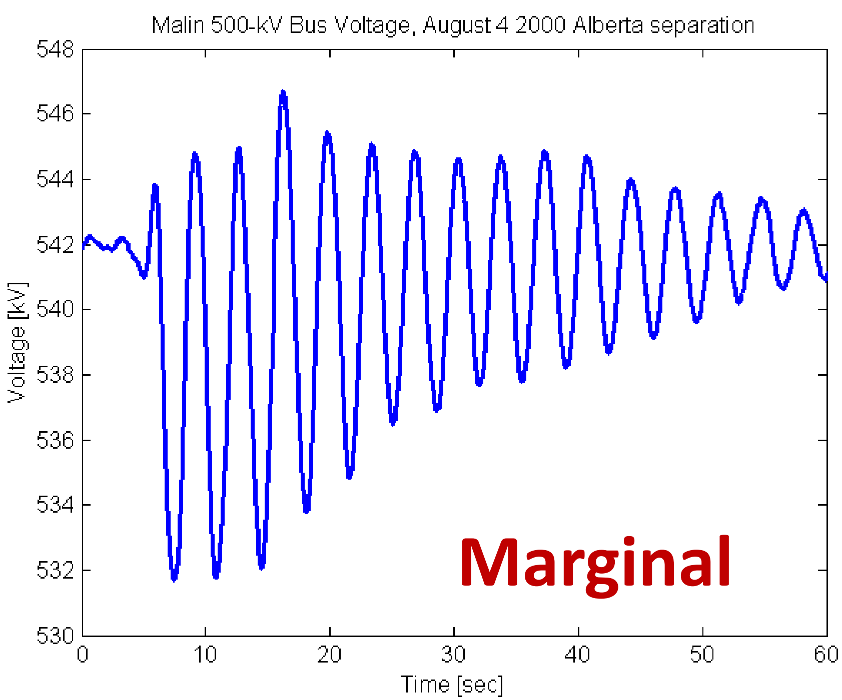
Gen	Angle($u_{i,k}$) (degrees)	$\lvert u_{i,k} \rvert$ (relative)
3	-180	1.00
4	-180	0.84
1	0	0.42
2	0	0.31

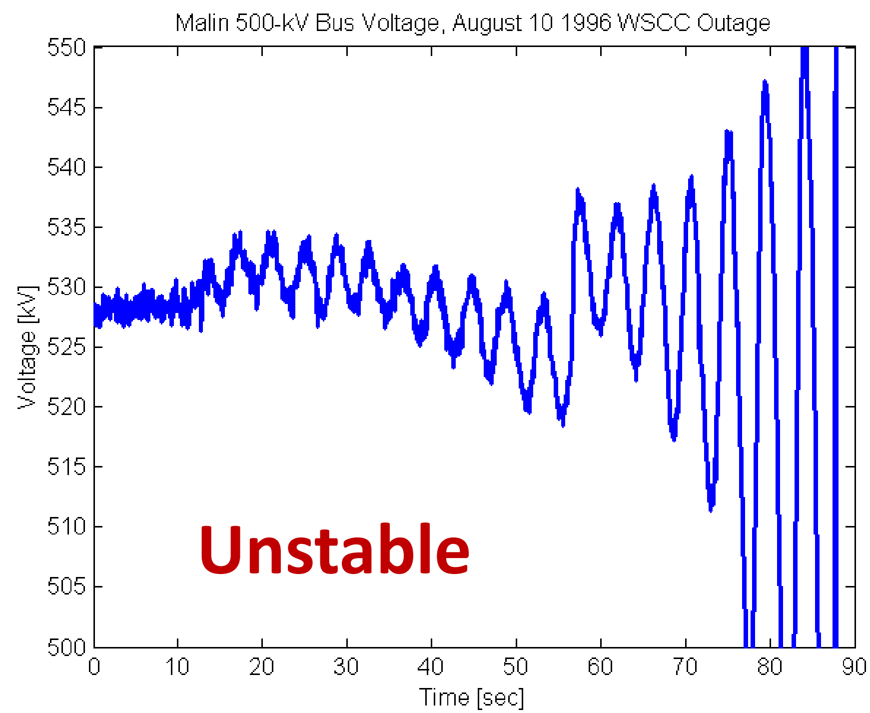
Damping




Malin 500-kV Bus Voltage, Chief Joseph Brake test on July 21, 2011
Voltage (kV)
555
550
545
540
535
0
5
10
15
20
25
30
Time (sec)
Normal

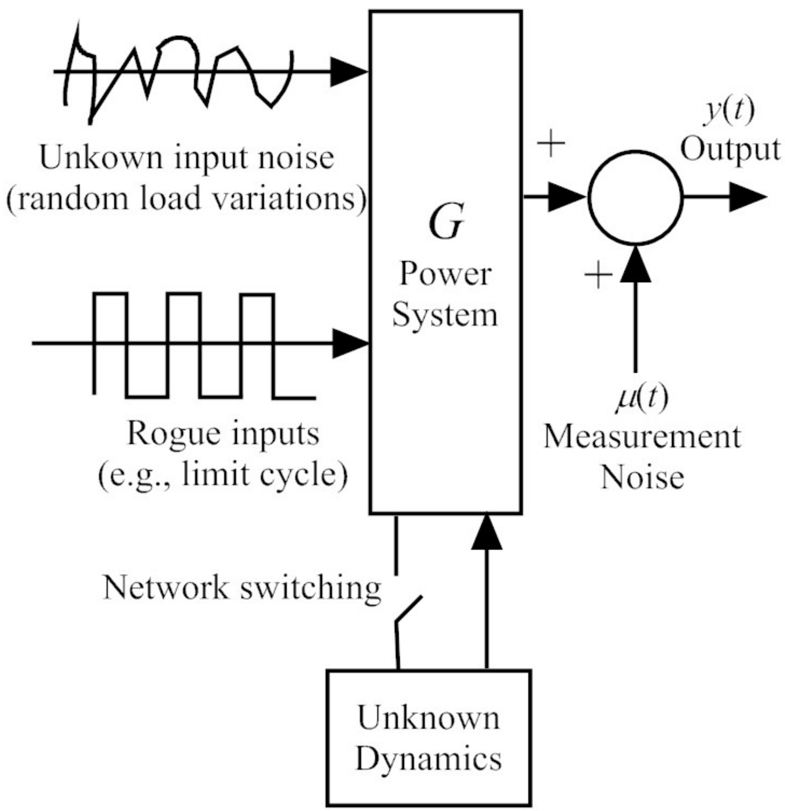

Malin 500-kV Bus Voltage, June 6 2002 PDCI outage
Voltage [kV]
600
550
500
450
0
10
20
30
40
50
60
Time [sec]
Low

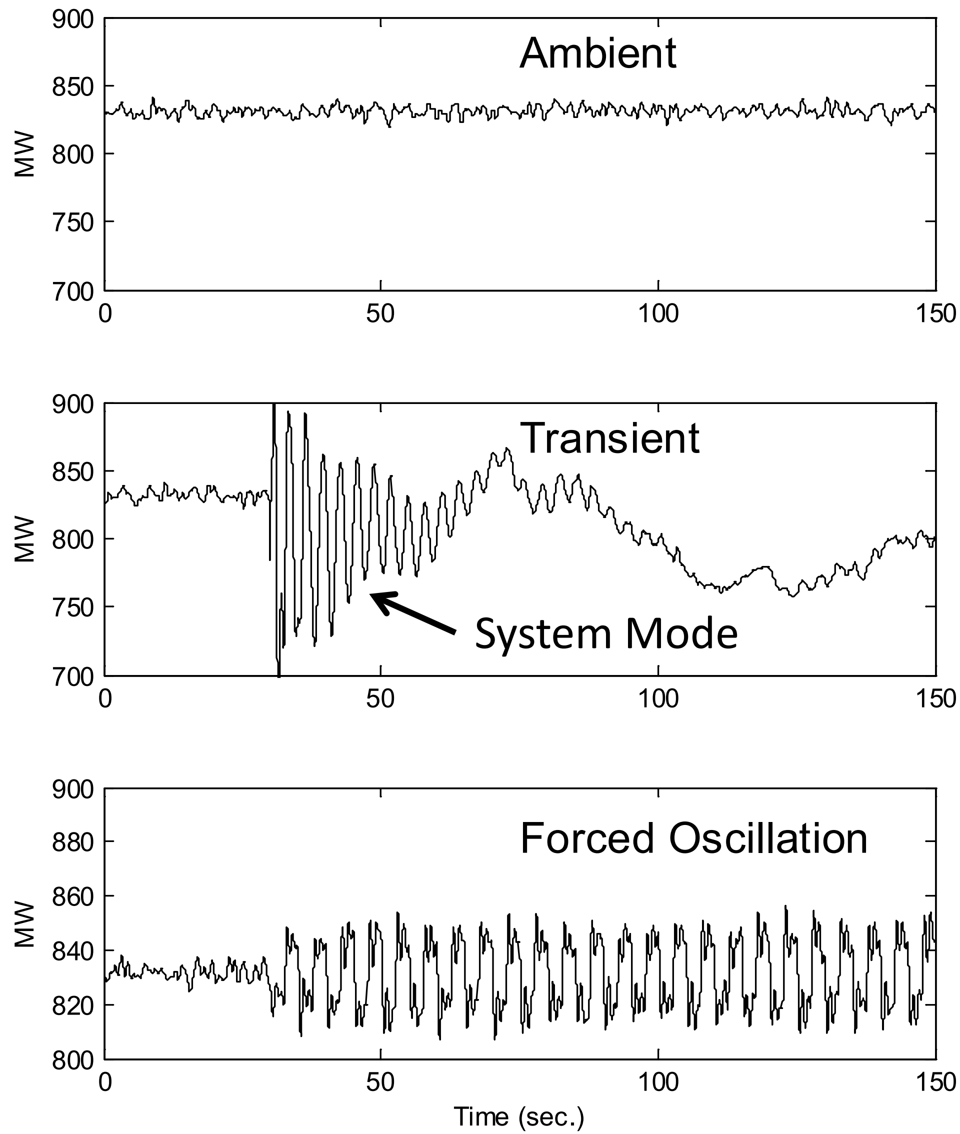

Malin 500-kV Bus Voltage, August 4 2000 Alberta separation
Voltage [kV]
548
546
544
542
540
538
536
534
532
530
0
10
20
30
40
50
60
Time [sec]
Marginal


Malin 500-kV Bus Voltage, August 10 1996 WSCC Outage
Voltage [kV]
550
545
540
535
530
525
520
515
510
505
500
0
10
20
30
40
50
60
70
80
90
Time [sec]
Unstable

Forced Oscillation

Dynamic Response Types



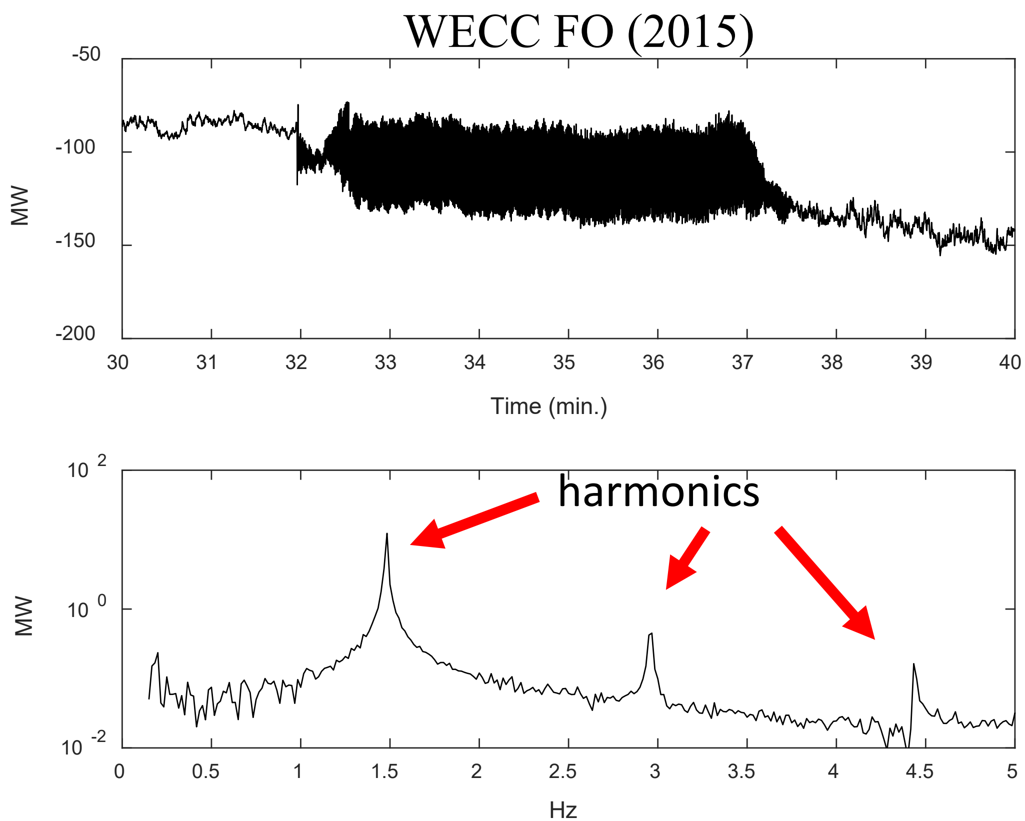


Forced Oscillations

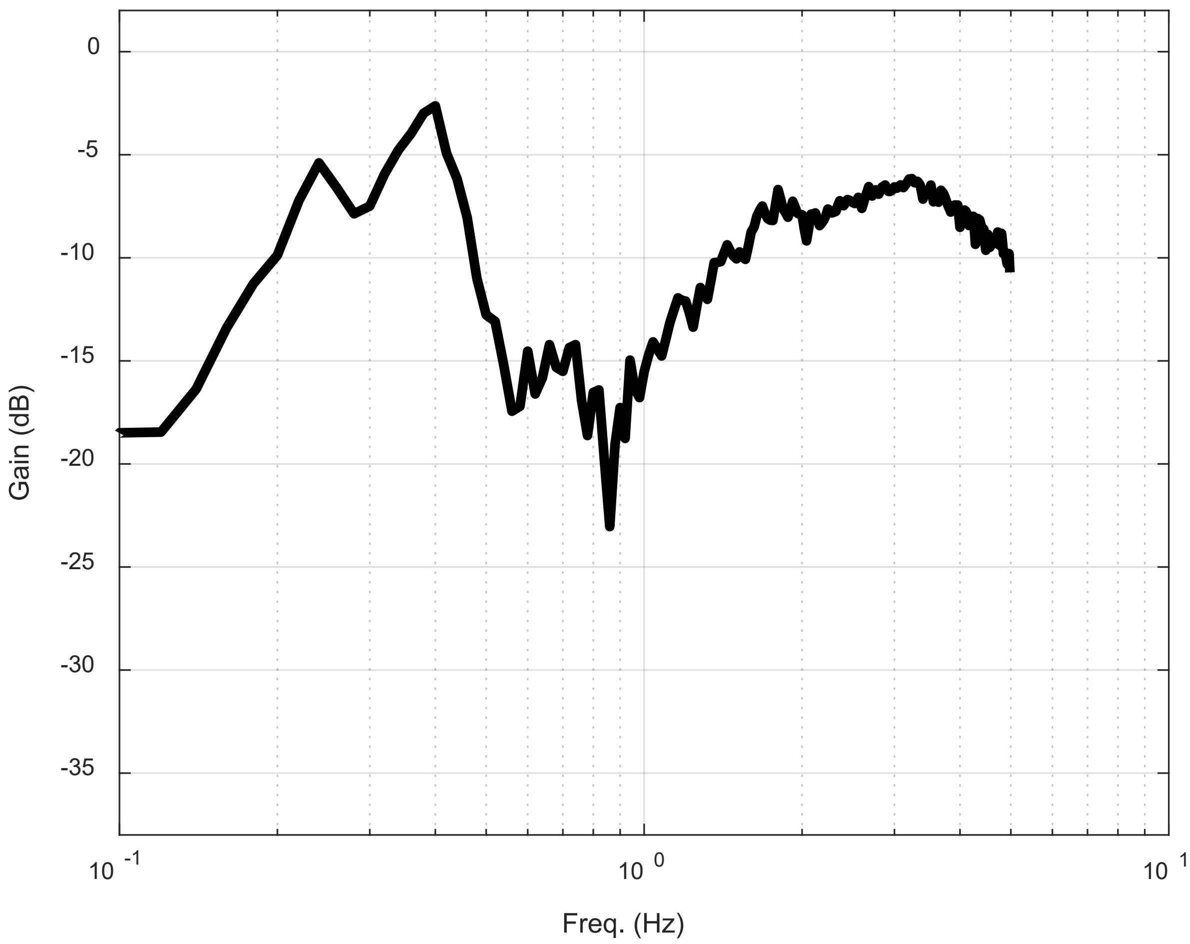
- Response of system to an apparatus in a limit cycle
  - e.g. generator controller
- NOT A TRADITIONAL SYSTEM INSTABILITY
- Can cause significant issues.
- Often contain multiple non-stationary frequencies.
- Some oscillations are difficult to categorize as a pure FO.
- Very common
  - WI = 16 events in 2008/9 operating season in WECC.
  - WI: 2005 [1], 2015 [2]
  - EI: 2016 [2], 2019 [3]
- Can be very severe if near a natural mode (resonance):
  - WI: 2005 [1].
- Inverter Based Resources (IBRs) can be significant
  - Often control based
  - Often higher frequency (well above 1 Hz)
- Real-power FOs tend to “propagate” more than reactive-power FOs.

[1] S. Sarmadi, et. al. “Analysis of November 29, 2005 western American oscillation event,” *IEEE Trans Power Syst.*, vol. 31, no. 1, pp. 5210-5211, 2016.
[2] NERC, “Interconnection oscillation analysis,” Tech. report, NERC, 2019.
[3] NERC, “Eastern interconnection oscillation disturbance,” Tech. report, NERC, 2019.

FOs often contain harmonics



Resonance – the FO is near a natural mode



Resonance – the FO shape follows the mode's shape

- At non-resonance, the largest observed oscillation amplitude is often indicative of its location.
- At resonance, the FOs shape follows the mode's shape [1].
- This makes locating an resonance FO source very difficult!

Gen #	0.37-Hz Mode Shape		0.37-Hz FO shape for source at Gen 34	
	Mag	Angle (deg)	Mag	Angle (deg)
2	1.07	4	1.07	4
7	1	0	1	0
14	1.01	-12	1	-12
15	0.73	0	0.73	0
23	0.61	-164	0.62	-164
29	0.22	-141	0.22	-141
33	0.18	-31	0.18	-32
34	0.95	139	0.94	138

[1] D. Trudnowski, R. Xie, I. West, "Shape properties of forced oscillations," North American Power Symposium (NAPS), Denver, CO, Sep. 2016.

Online Oscillation Monitoring

On-Line Oscillation Monitoring Goals

- Detect any sustained oscillations
  - General frequency band
  - Amplitude and locations of oscillations
  - Solved problem
- Is it a FO or an un-damped natural transient?
  - Research area
- Identify FO source
  - Max oscillation amplitude usually points to source
  - Resonance requires more sophisticated methods – energy flow (research area)
- Detect any low-damped natural modes
  - Termed a Mode Meter (MM)
  - FO biases a MM. Research area.
- Control Actions
  - Forced oscillations
    - remove the driving source
  - Low damped modes
    - Solutions require significant studies (e.g., reduced loading on key corridors, PSS unit adjustment, etc.)

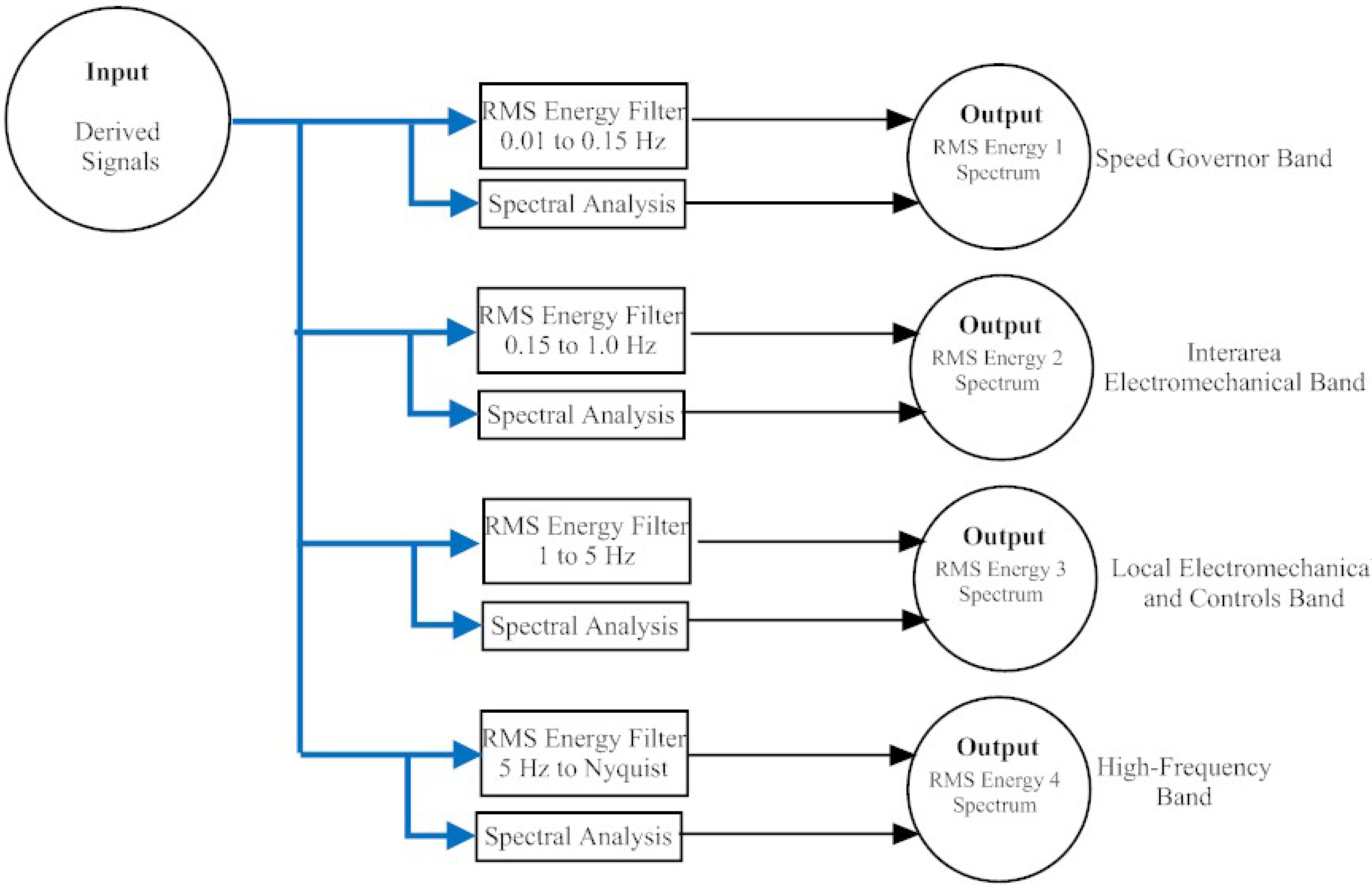
Detecting Oscillations

Automated Detection Approaches

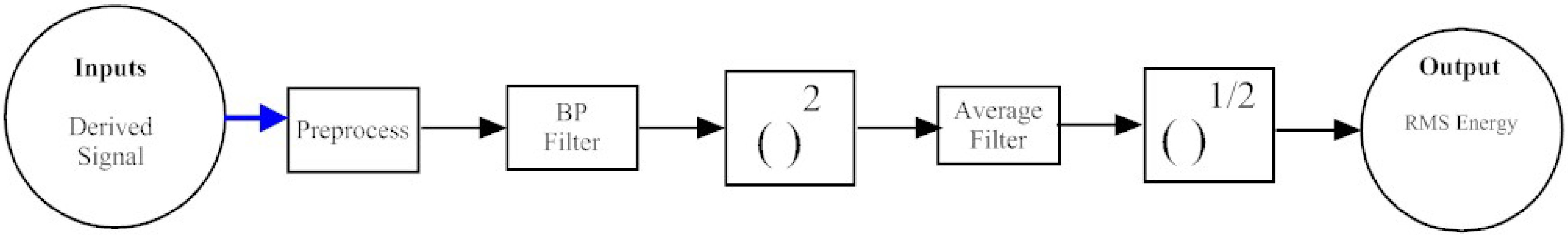
- Spectral (FFT) based
  - Quantifies FO amplitude at each location
  - Easy to implement
  - Struggles with stationarity
  - Too detailed for online operator applications
- Wide-band RMS energy detection
  - Quantifies FO amplitude at each location
  - Easy to implement
  - Compatible with operator goals (not too granule)
  - Has been (and is being) implemented in many control centers

[1] IEEE/PES, “Forced Oscillations in Power Systems,” PES-TR110, 2023.

Oscillation Detection (OD) Analytic

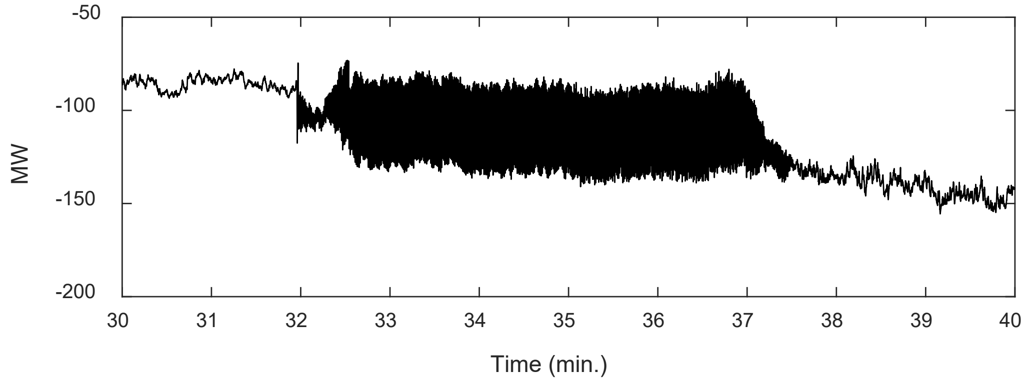


RMS Energy Filter

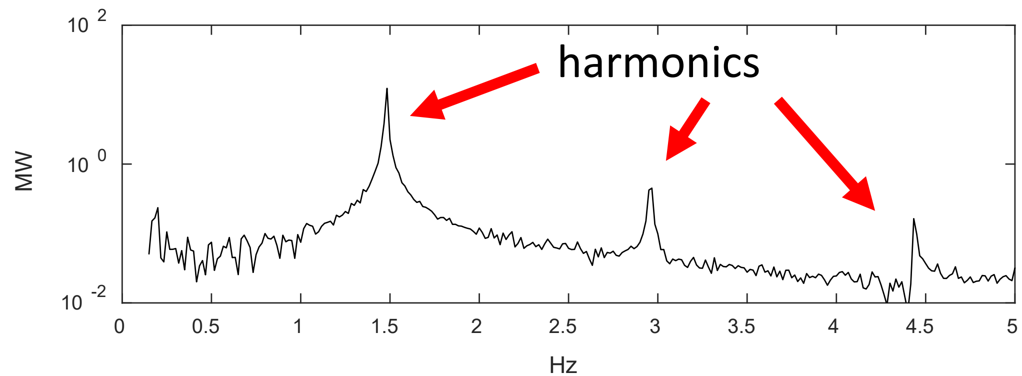


M. Donnelly, D. Trudnowski, J. Colwell, J. Pierre, and L. Dosiek, "RMS-energy filter design for real-time oscillation detection," 2015 PESGM.

WECC FO

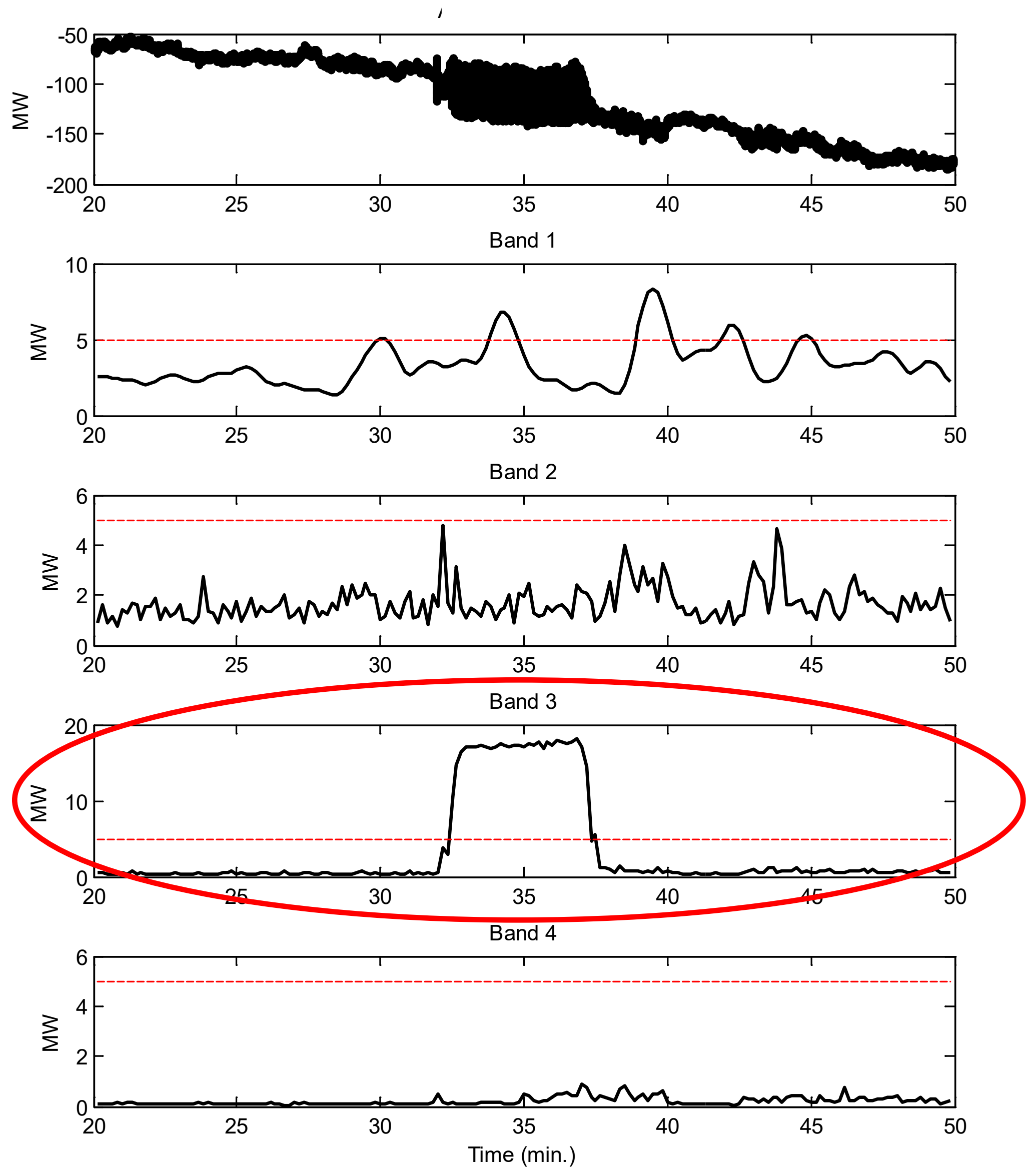


-50
-100
-150
-200
MW
30
31
32
33
34
35
36
37
38
39
40
Time (min.)



10^{2}
10^{0}
10^{-2}
MW
harmonics
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Hz

WECC FO



MW
-50
-100
-150
-200
20
25
30
35
40
45
50
Band 1
10
5
0
Band 2
6
4
2
Band 3
20
Band 4
Time (min.)

Closing Thoughts

- Power systems are
  - Naturally elastic and under damped
  - Have many natural modes of oscillation
  - A few of these modes are dominant
- Forced Oscillations
  - Very common
  - Are NOT an instability
  - Can cause significant issues
  - Resonance can cause FO to be wide spread
- Oscillation monitoring
  - Detection is a mature science
  - Distinguishing FOs and natural modes is a research area
  - Locating resonant FOs is a research area