Forced Oscillations

Causes, Issues, and Mitigation

Sep. 2024

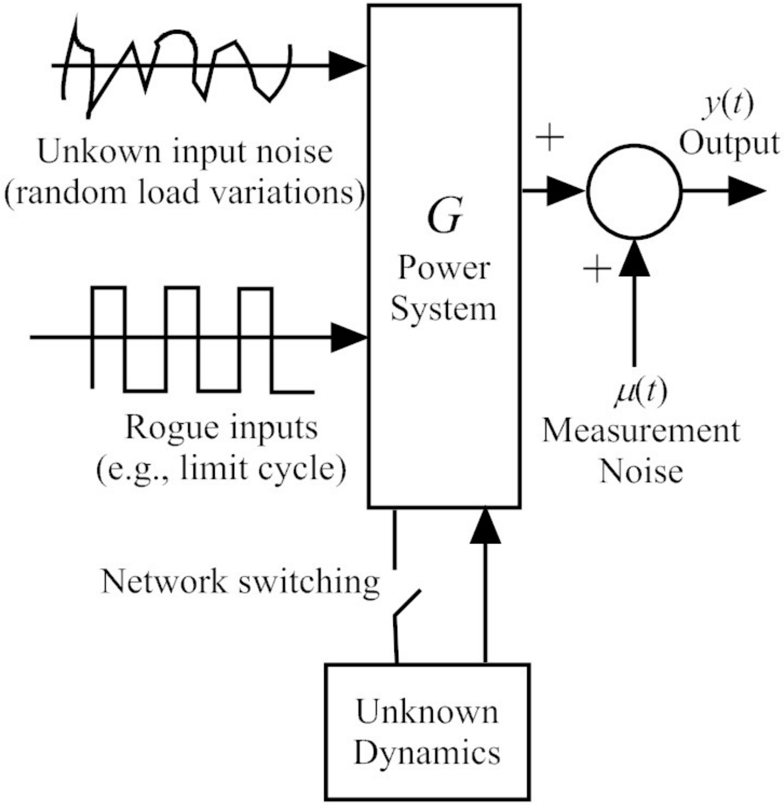
IEEE Forced Oscillation Task Force

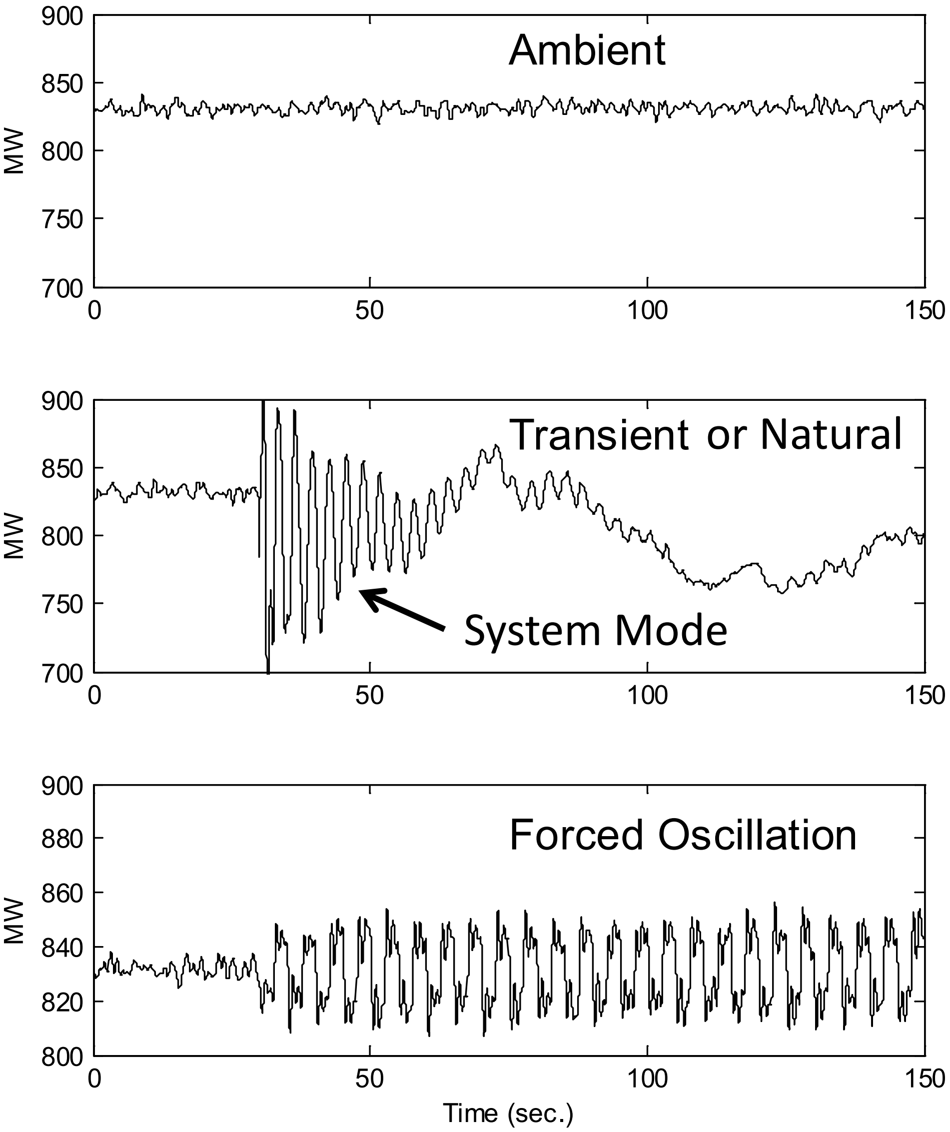
Dan Trudnowski

Primary reference:
IEEE/PES, “Forced Oscillations in Power Systems,” PES-TR110, 2023.

MONTANA
TECHNOLOGICAL UNIVERSITY

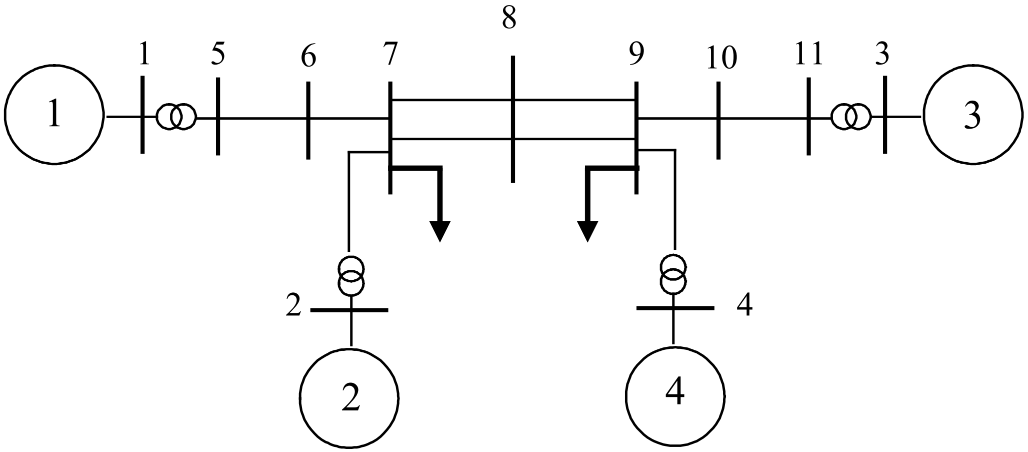
Dynamic Response Types





Background
Electromechanical Dynamics

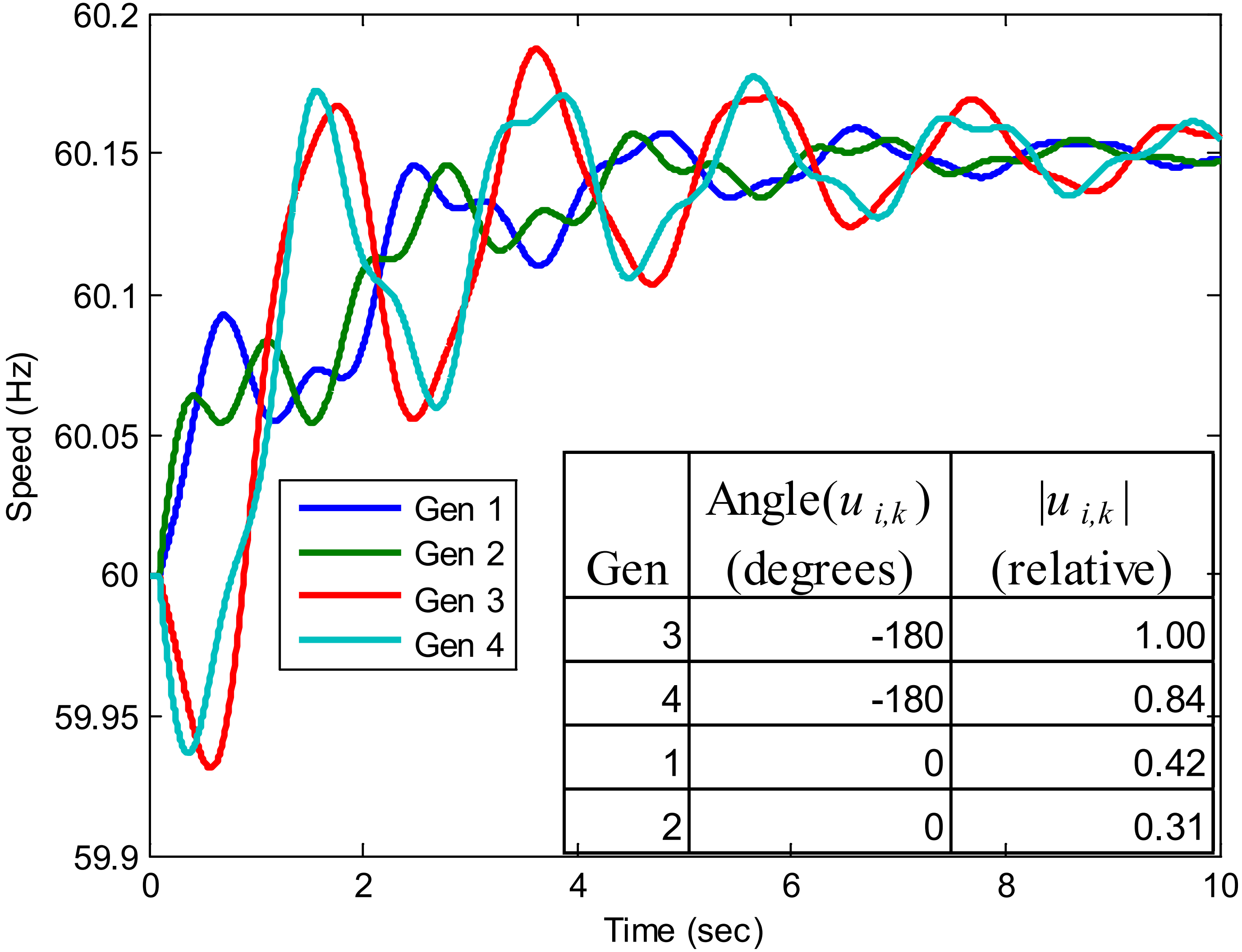
Mode Shape



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

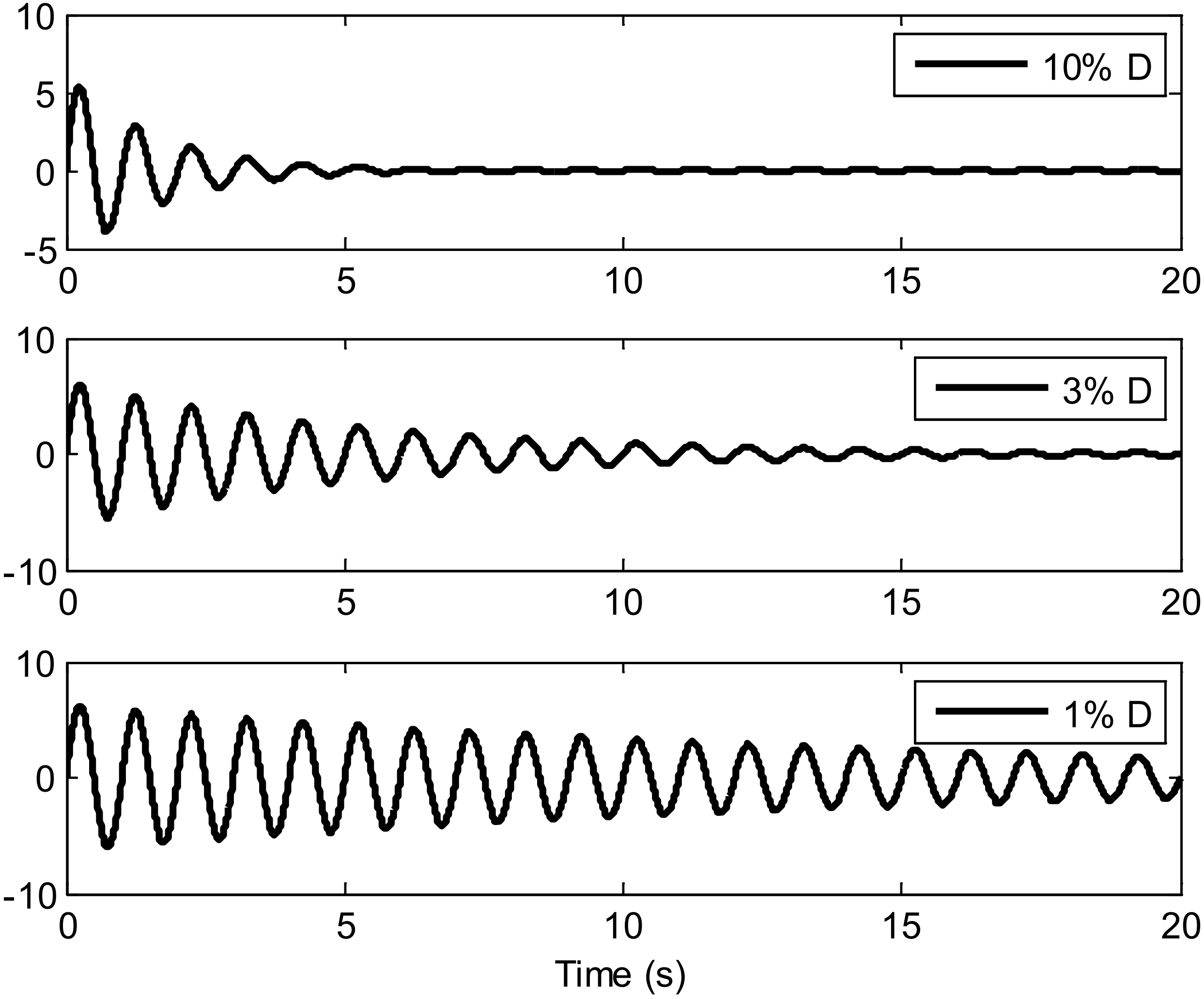
Gen	Angle($u_{i,k}$) (degrees)	Amplitude $\lvert u_{i,k} \rvert$
3	-180	1.00
4	-180	0.84
1	0	0.42
2	0	0.31

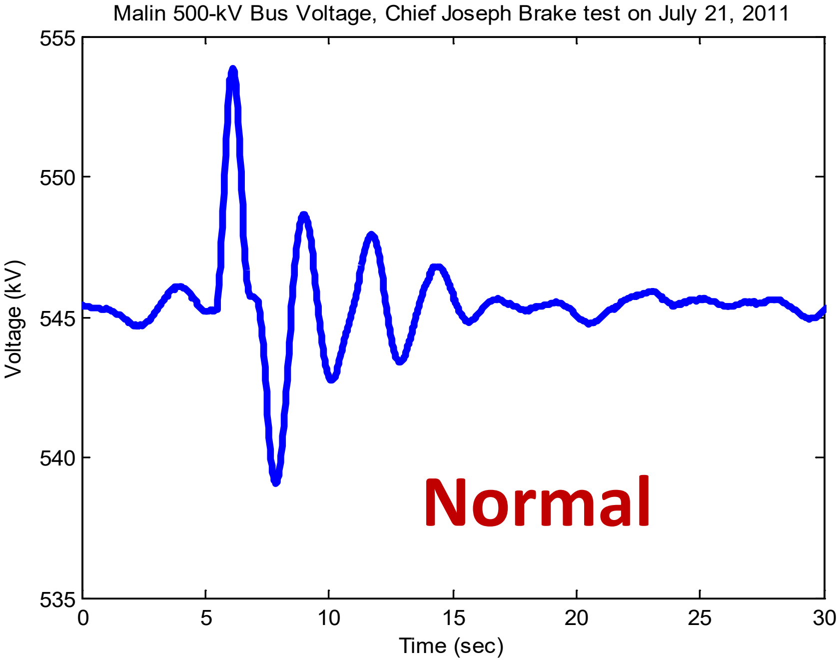
Mode Shape



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

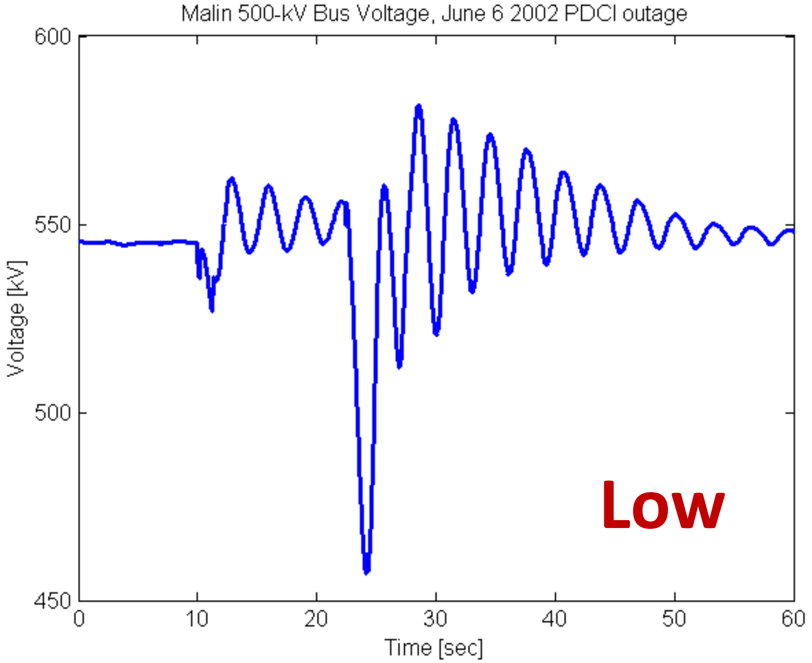
Damping


10
5
0
-5
10% D
0
5
10
15
20
10
0
-10
3% D
0
5
10
15
20
10
0
-10
1% D
0
5
10
15
20
Time (s)



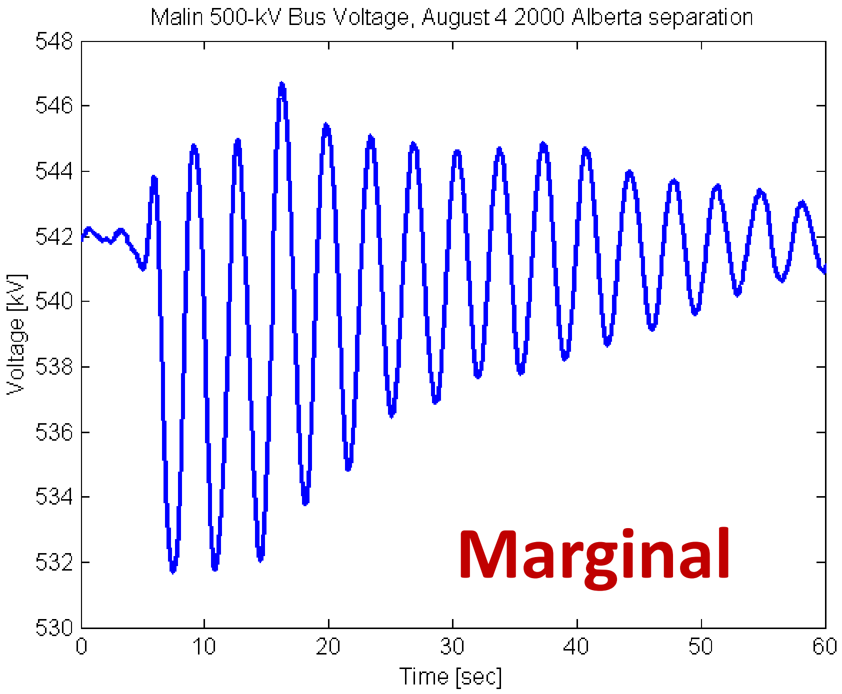
Malin 500-kV Bus Voltage, Chief Joseph Brake test on July 21, 2011

Normal



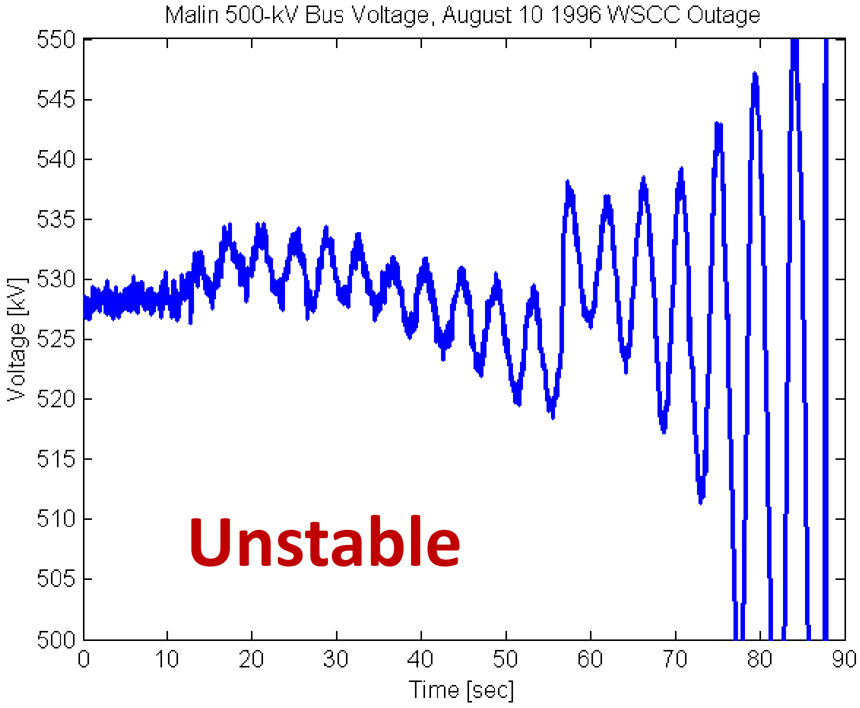
Malin 500-kV Bus Voltage, June 6 2002 PDCI outage

Low



Malin 500-kV Bus Voltage, August 4 2000 Alberta separation

Marginal

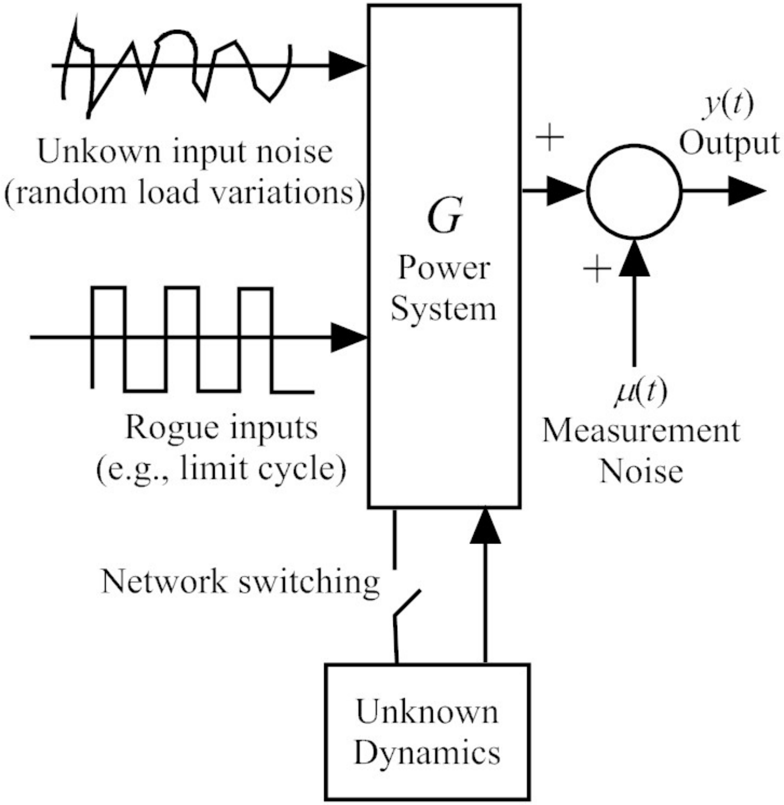


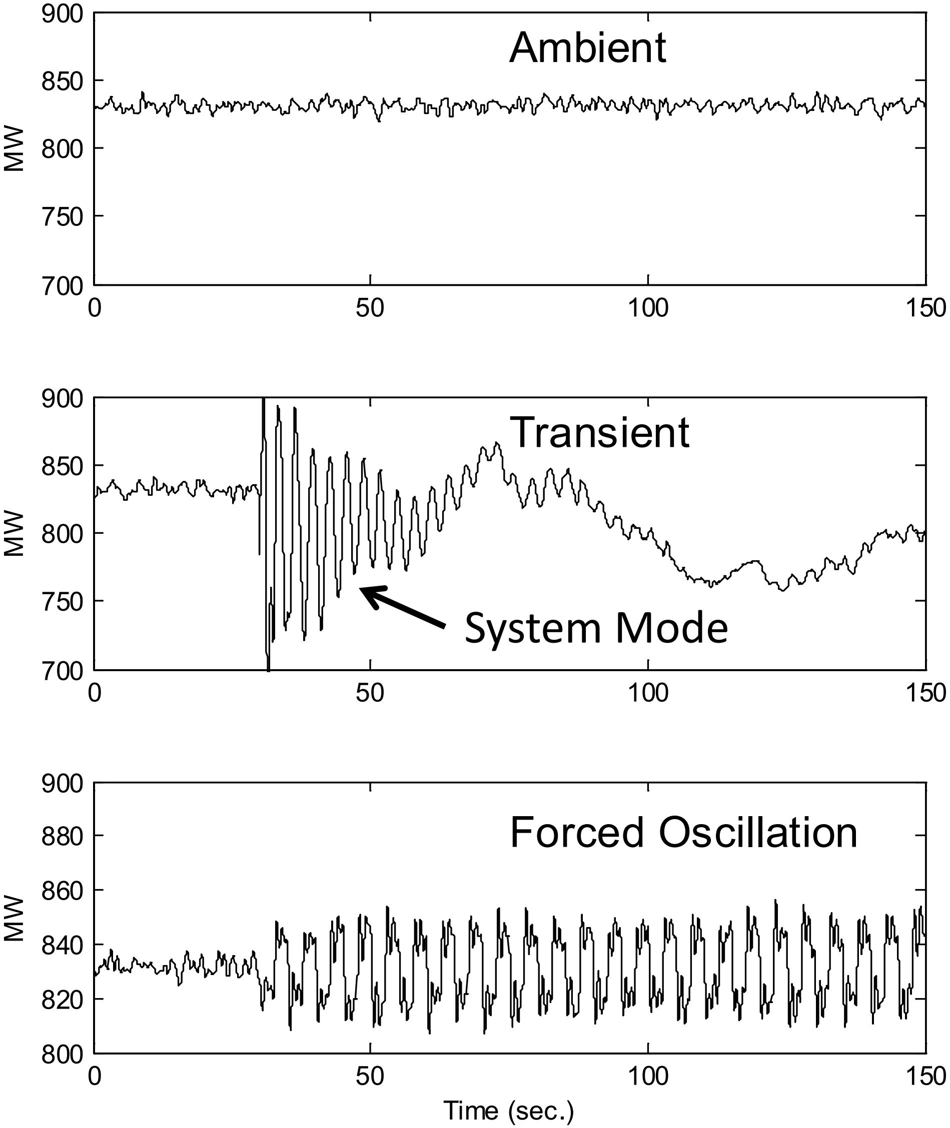
Malin 500-kV Bus Voltage, August 10 1996 WSCC Outage

Unstable

Forced Oscillation
An Overview

Dynamic Response Types





Forced Oscillations

- Response of system to an apparatus in a limit cycle
  - e.g. generator controller
- NOT A TRADITIONAL SYSTEM INSTABILITY
- 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.

Why Care about FOs?

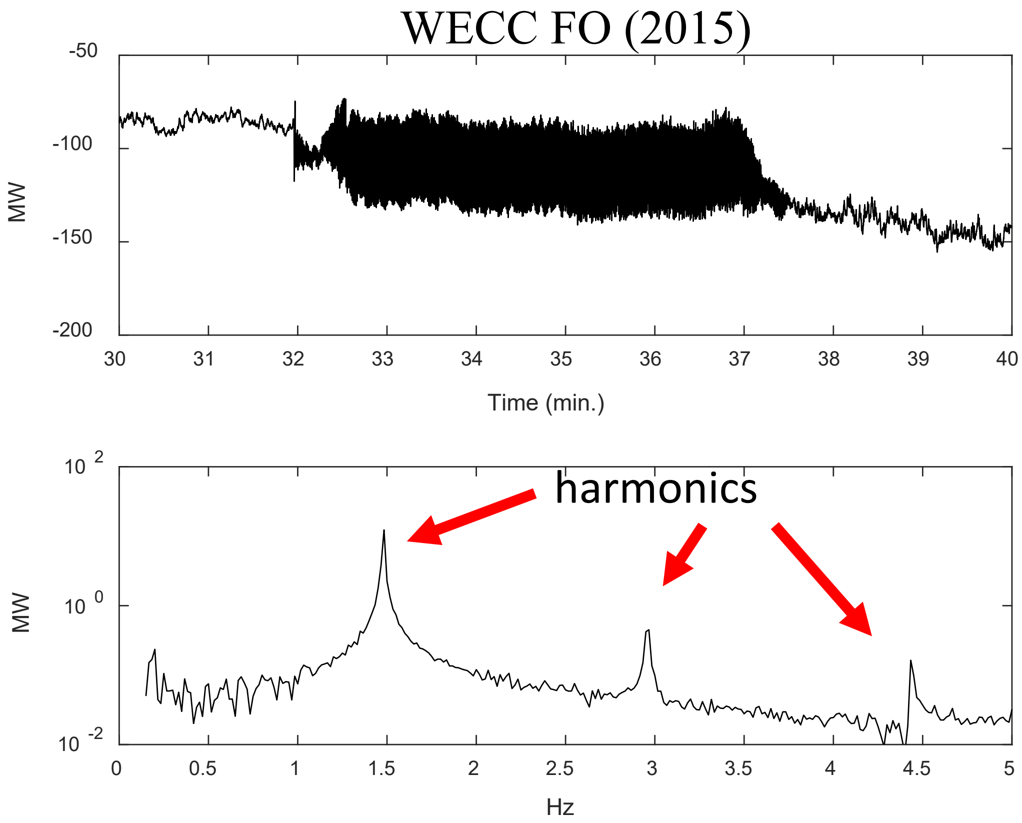
- Catastrophic event of rotor's vibration at Sayano–Shushenskaya hydro power station in 2009*

Before the accident

After the accident

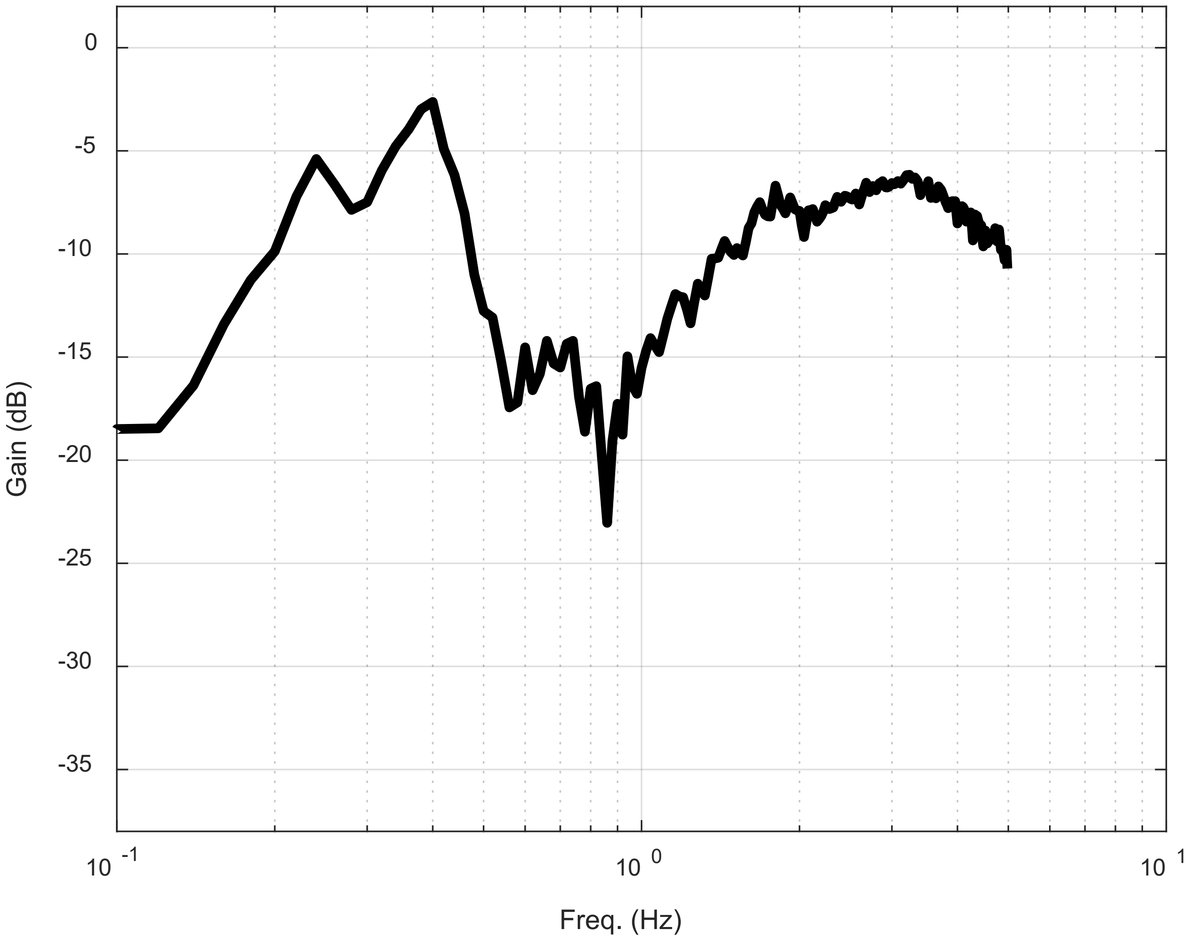
- https://en.wikipedia.org/wiki/2009_Sayano%E2%80%93Shushenskaya_power_station_accident
- S. Maslennikov, IEEE PES GM 2017, Panel session on "Industry Experiences in Dynamic-System Operational Monitoring and Control using PMUs"

FOs often contain harmonics



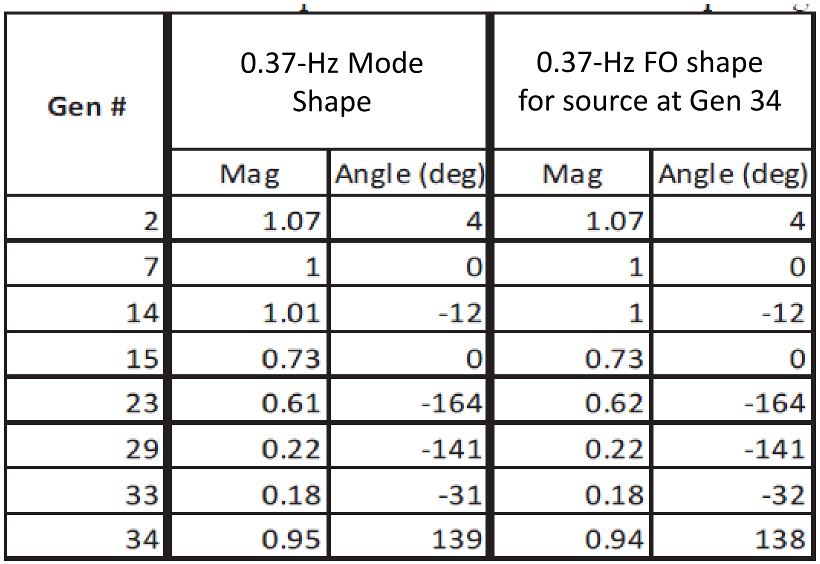
harmonics

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

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

Mode-Meter FO Biasing

- A MM is an automated real-time tool to track a given natural mode's frequency and damping
- Enables system safely to operate closer to stability edges
- LOTS of research over the past 20 years has provided successful algorithms
- But, an FO causes MM to bias
- This issue has prevented the full adoption of MMs by industry
- Potential solutions exist (e.g. [1, 2]). But, these are much more difficult to automate

[1] U. Agrawal, J. Follum, J. Pierre, and D. Duan, "Electromechanical Mode Estimation in the Presence of Periodic Forced Oscillations," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 1579-1588, Mar. 2019.
[2] L. Dosiek, "The Effects of Forced Oscillation Frequency Estimation Error on the LS-ARMA+S Mode Meter," *IEEE Trans. Power Syst.*, vol. 35, no. 2, pp. 1650-1652, Mar. 2020.

On-Line Oscillation Monitoring Goals

- Detect any sustained oscillations
  - Is it a FO or an un-damped transient?
  - General frequency band
  - Amplitude and locations of oscillations
  - Identify FO source
- 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.)

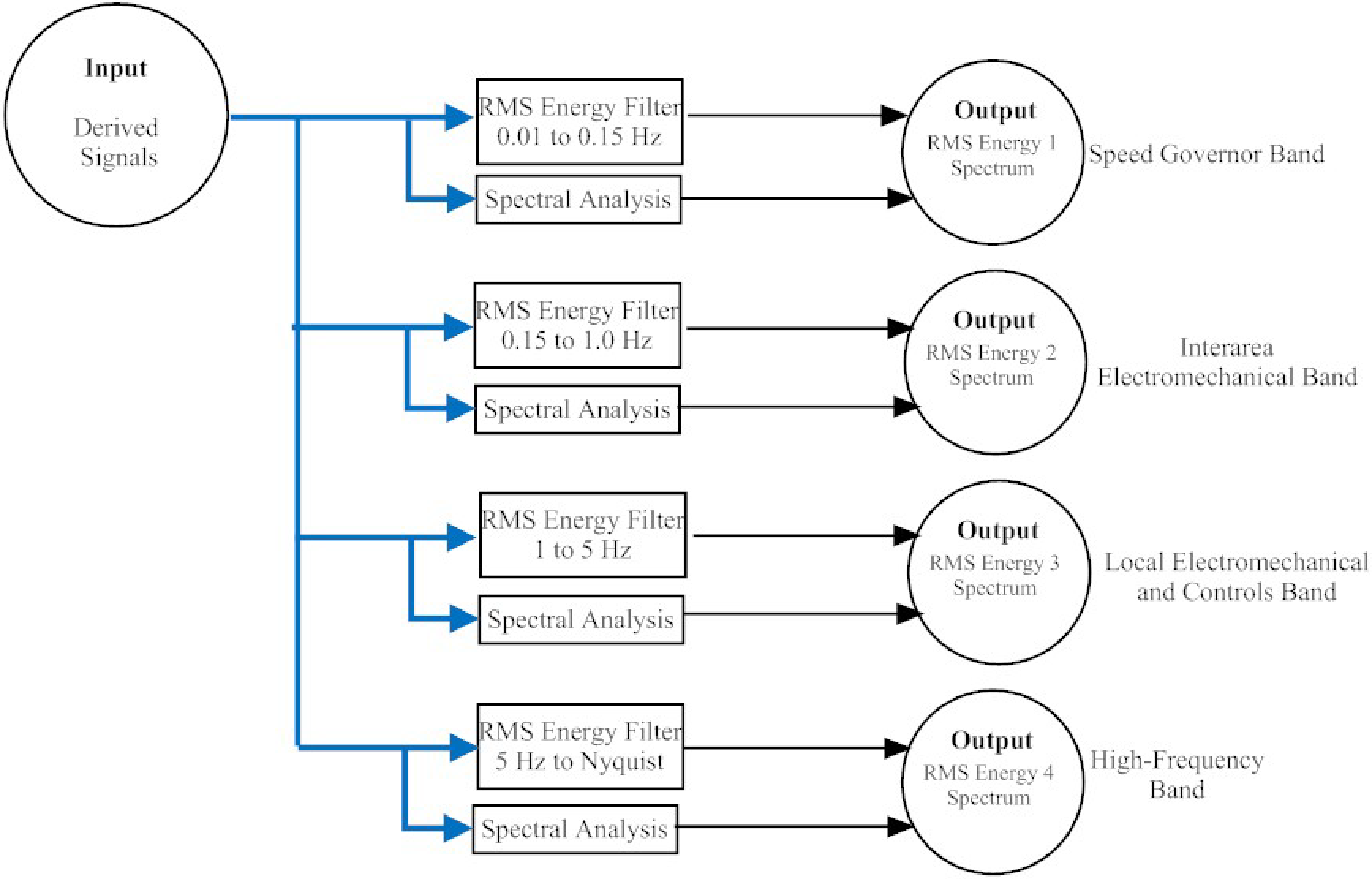
Detecting Oscillations

Automated Detection Approaches

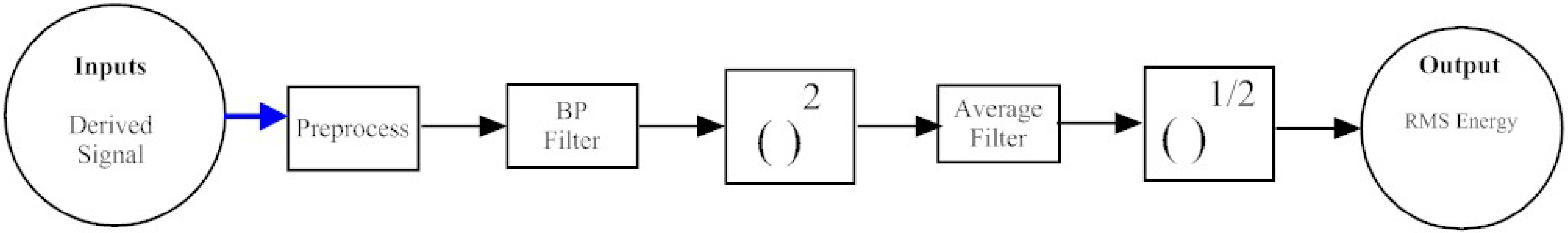
- Spectral (FFT) based
  - Quantifies FO amplitude at each location
  - Easy to implement
  - Struggles with stationarity
  - May be to de detailed for online operator applications
- Wide-band RMS energy detection
  - Quantifies FO amplitude at each location
  - Easy to implement
  - Compatible with 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

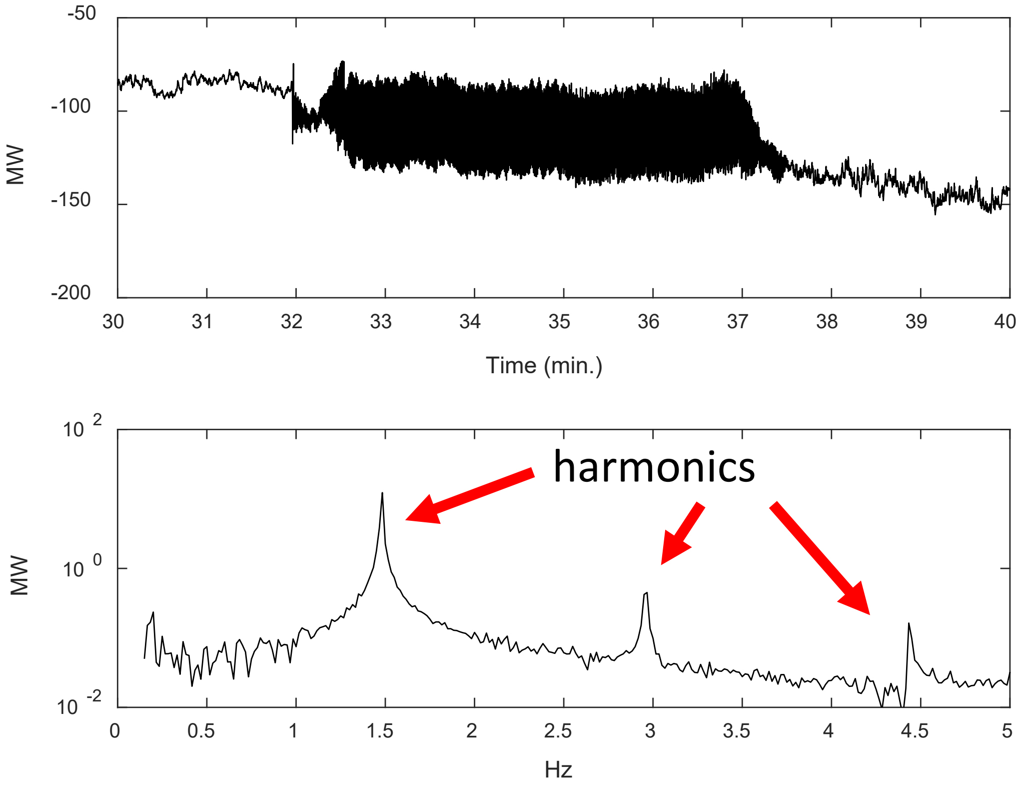


RMS Energy Filter



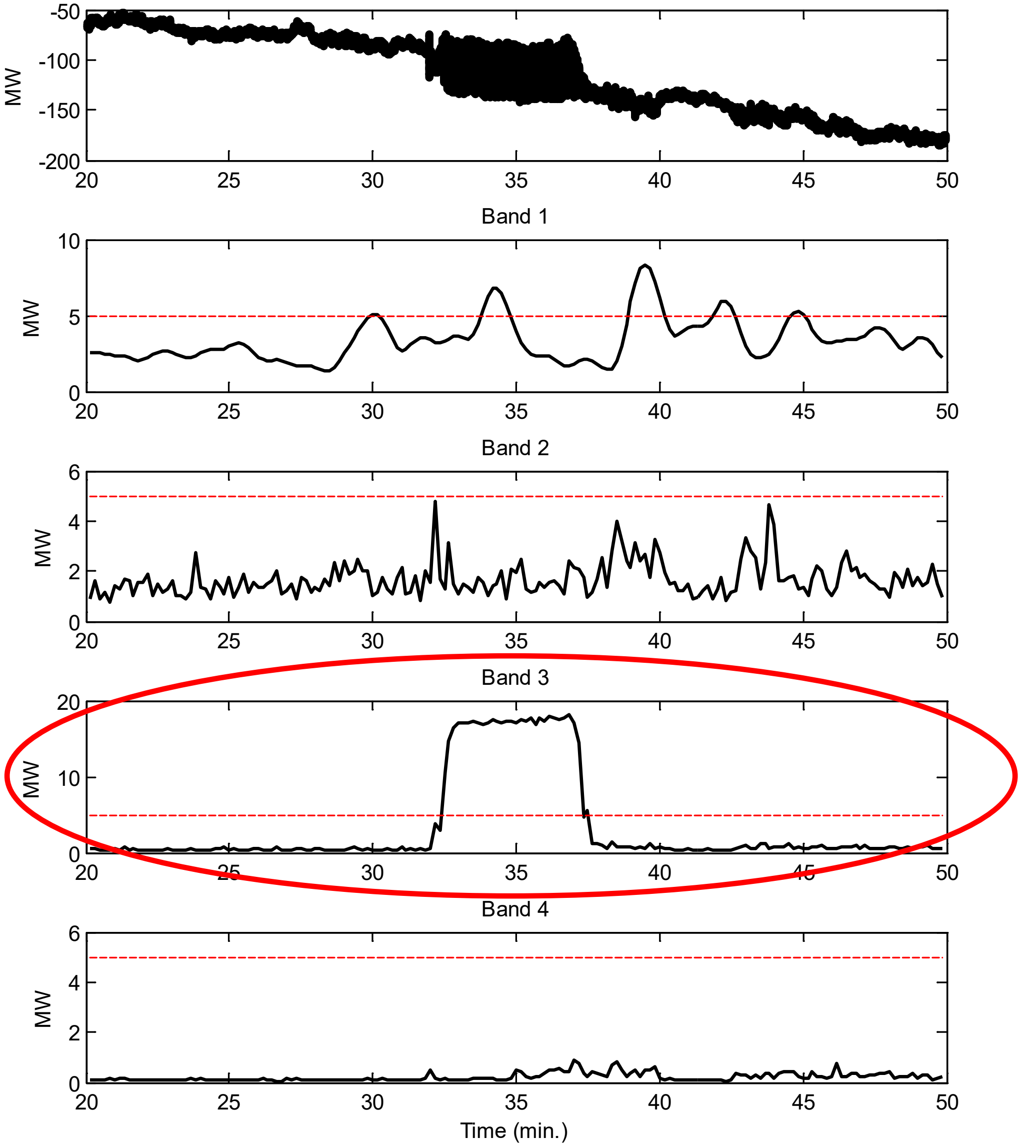
M. Donnelly, D. Trudnowski, J. Colwell, J. Pierre, and L. Dosiek, “RMS-energy filter design for real-time oscillation detection,” 2015 PESGM.

WECC FO



harmonics

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
10
Band 4
Time (min.)

Distinguishing Between FOs and Natural Oscillations

Distinguishing FOs from Natural Modes Approaches

- [1] Provides details on distinguishing approaches
  - Initial oscillation start-up characteristics
  - Phase of power oscillations
  - Harmonic detection
  - Cross-spectrum index
  - Statistics and periodogram methods
- Still a research topic
- Priority?

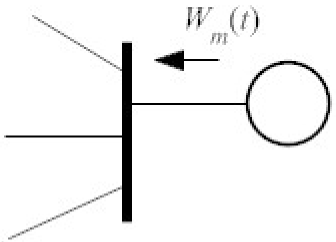
[1] IEEE/PES, “Forced Oscillations in Power Systems,” PES-TR110, 2023.

Locating the FO Source

Distinguishing FOs from Natural Modes Approaches

- Non-resonance FO typically sources from the location with the largest FO amplitude
    - E.g., BPA has successfully used RMS energy as the locating indicator
- For resonance FOs
    - Many approaches researched
    - Emerging methods utilize the phase angle between the real-power and the frequency (e.g., Dissipating Energy Flow)
- Still a research topic, but DEF has been implemented in some control centers.
- High priority

Energy Flow - Time Domain



$$W_m = \int \left[P_{em}(t)\mathrm{d}\big(\theta_m(t)\big) + Q_{em}(t)\mathrm{d}\big(V_m(t)\big)\right] =$$ Energy Flow

$P_{em}(t) =$ Real power flow

$Q_{em}(t) =$ Reactive power flow

$\omega_m(t) =$ Generator speed (frequency)

$V_m(t) = \ln\{U_m(t)\} =$ log of voltage

$$W_m = \int \left[\Delta P_{em}(t)\Delta\omega_m(t)\mathrm{d}t + \Delta Q_{em}(t)\dot{V}_m(t)\mathrm{d}t\right]$$

If W_m is increasing in time, the FO is sourced from the device.

Comments:

- Measure of phasing between P_{em} & ω_m, and Q_{em} & $\dot{V}_m$
- Requires single-frequency oscillation which necessitates significant preprocessing.
- Difficult to automate (detection of increasing W_m)

- L. Chen, Y. Min, and W. Hu, "An energy-based method for location of power system oscillation source," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 828-836, May 2013.
- S. Maslennikov, Bin Wang, Eugene Litvinov "Dissipating Energy Flow Method for Locating the Source of Sustained Oscillations"*, International Journal of Electrical Power and Energy Systems*, Issue 88, 2017, pp.55-62.

Energy Flow - Freq Domain

Parceval's theorem

$$\int x_1(t)x_2(t)\mathrm{d}t = \int X_1(f)X_2^*(f)\mathrm{d}f = 2\int \mathrm{Re}\{S_{x_1(t)x_2(t)}(f)\}\mathrm{d}f$$

$S_{x_1(t)x_2(t)}(f)$ = Cross spectrum between x_1 and x_2.

Now apply Parceval's theorem to Energy Flow

$$W_m = \int [\Delta P_{em}(t)\Delta\omega_m(t)\mathrm{d}t + \Delta Q_{em}(t)\dot{V}_m(t)\mathrm{d}t] = 2\int \widehat{W}_m(f)\mathrm{d}f$$

$\widehat{W}_m(f) = \mathrm{Re}\{S_{\Delta P_{em}(t)\Delta\omega_m(t)}(f) + S_{\Delta Q_{em}(t)\dot{V}_m(t)}(f)\} =$ Energy-Flow Spectra

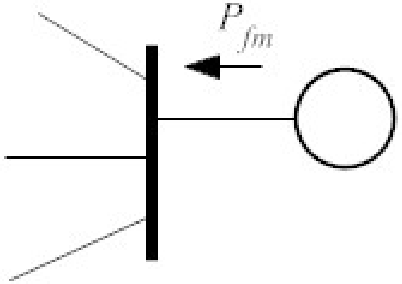
If $\widehat{W}_m(f)$ is positive, the FO is sourced from the device at frequency *f*.

Comments:

- Works with multi-frequency oscillation.
- Requires less data preprocessing and less data than time domain calculation.
- Easy to automate.
- EPG-MAS uses $S_{\Delta P_{em}(t)\Delta\omega_m(t)}(f)$ only

R. Xie and D. Trudnowski, "Tracking the Damping Contribution of a Power System Component Under Ambient Conditions," IEEE Trans. on Power Systems, vol. 33, no. 1, pp. 1116-1117, 2018.

Swing Equation Decomposition



$$\Delta\tilde{P}_f = \Delta\tilde{P}_e - R(f_o)\Delta\tilde{\omega} = \text{Estimated FO power}$$

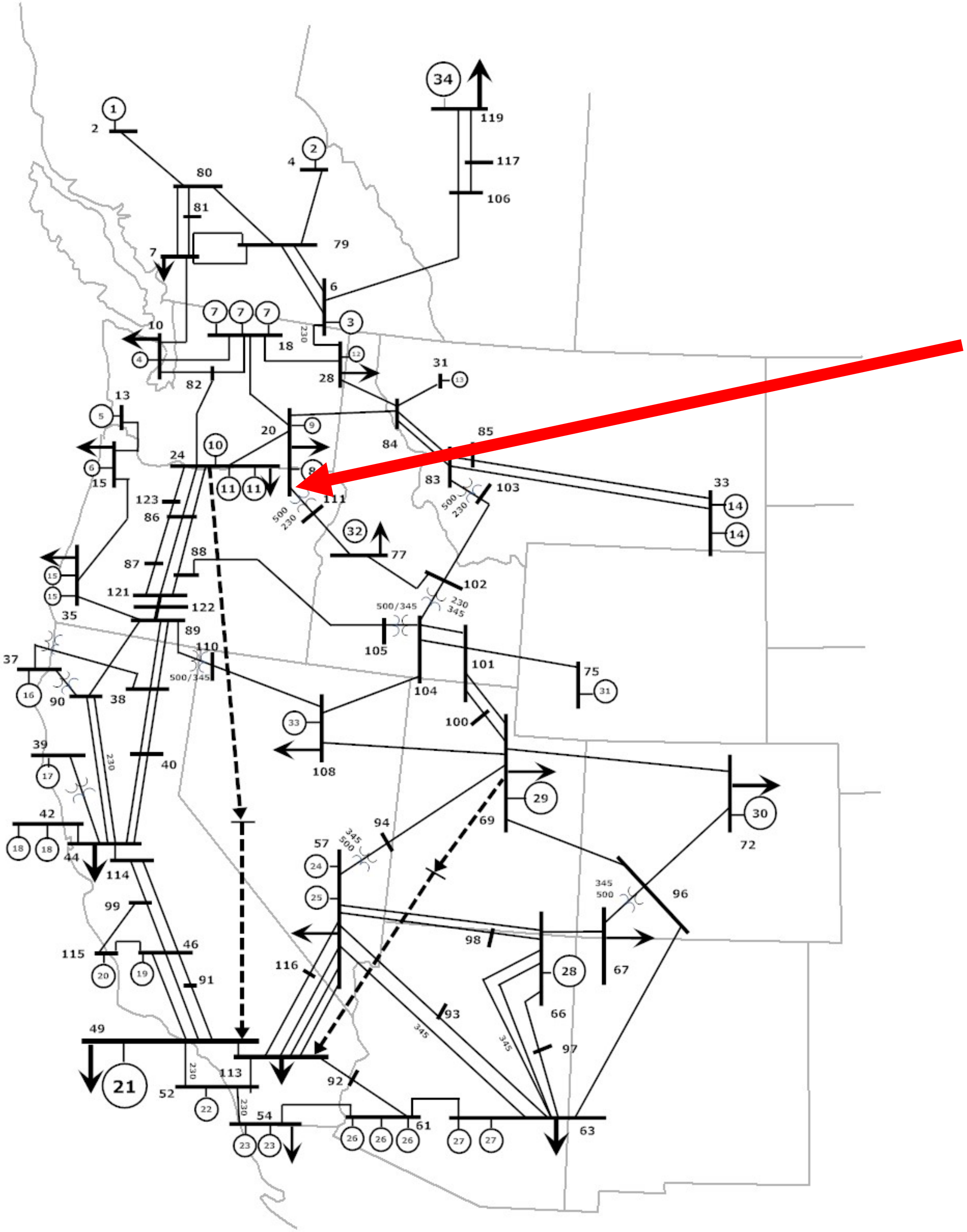
f_0 = frequency of FO

$\Delta\tilde{P}_e$ = Fourier component of $P_e(t)$ at frequency f_o

$\Delta\tilde{\omega}$ = Fourier component of $\omega(t)$ at frequency f_o

$R_m(f_o)$ = pre-calculated ambient ratio= $\frac{S_{\omega,P_e}(f_o)}{S_{\omega,\omega}(f_o)}$

R. Xie and D. Trudnowski, “Locating and Quantifying Turbine-Induced Forced-Oscillations for System Operations,” IEEE PESGM 2017.



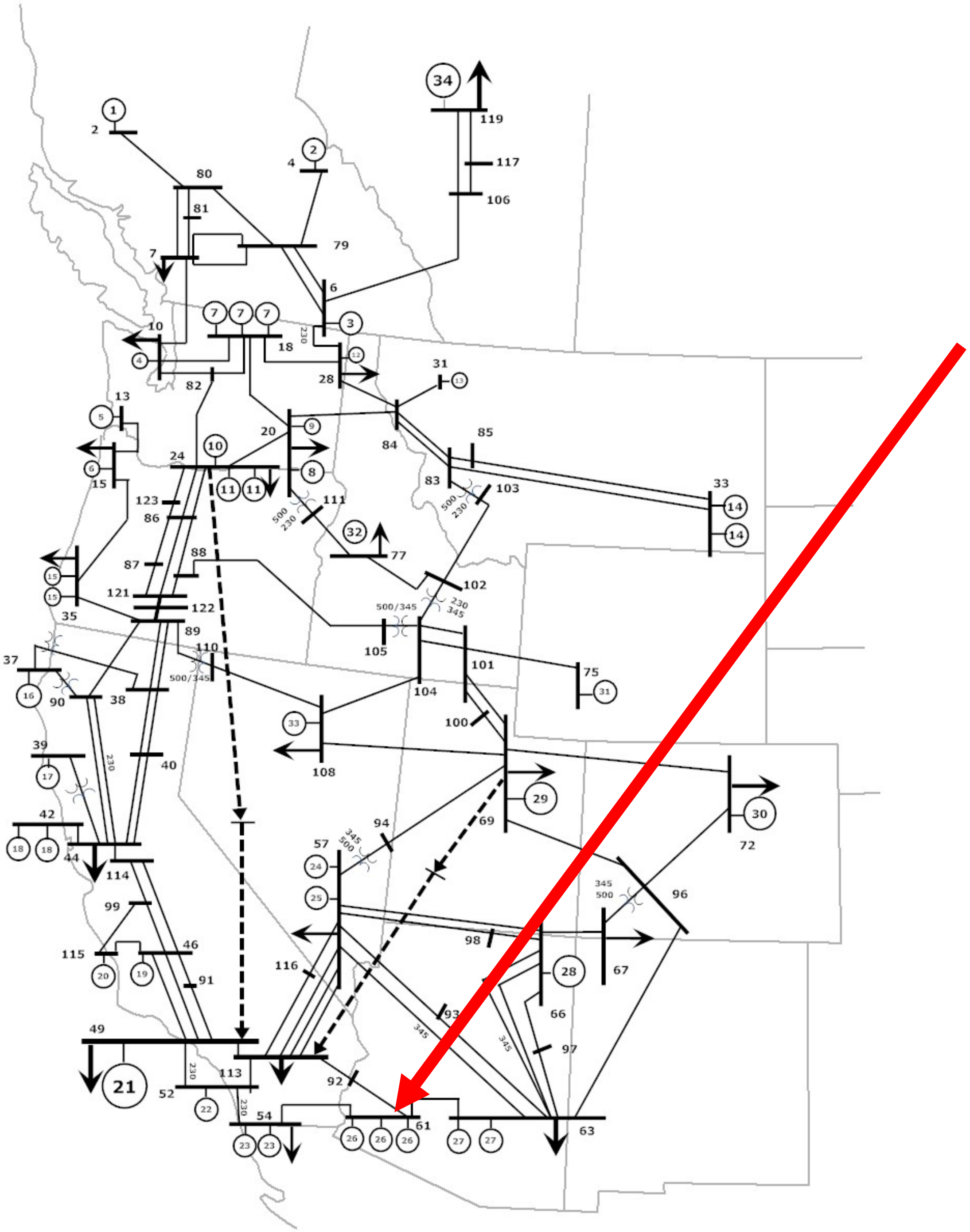
Example 1

- Forced Oscillation at Gen 11-1
- 1.6 Hz
- 25 MW
- Not near a mode

Example 1
FO at 1.6 Hz at Gen 11-1

Power Plant - Gen	RMS Energy (mHz)	RMS Energy (MW)	W (pu)	$\tilde{P}_f$ (MW)
1-1	0	1	0.00	0
2-1	0	2	0.00	0
3-1	0	1	0.01	0
4-1	1	5	0.00	0
5-1	0	3	0.00	0
6-1	1	5	0.00	0
7-1	0	2	0.00	0
7-2	0	2	0.00	0
7-3	0	2	0.00	0
8-1	1	8	0.00	0
9-1	1	9	0.00	0
10-1	1	20	0.00	0
11-1	10	78	0.55	25
11-2	1	16	0.00	0
12-1	0	1	0.00	0
13-1	0	0	0.00	0
14-1	0	0	0.00	0
14-2	0	0	0.00	0
15-1	1	1	0.00	0

Example 2



- Forced Oscillation at Gen 26-2
- 1.14 Hz
- 80 MW
- At a local mode

Example 2
FO at 1.14 Hz at Gen 26-2

Power Plant - Gen	RMS Energy (mHz)	RMS Energy (MW)	W (pu)	$\tilde{P}_f$ (MW)
26-1	33.5	123.3	-0.24	0.1
26-2	33.5	182.7	7.04	79.7
26-3	34.8	137.4	0.14	0.1
27-1	16.4	237.3	0.04	0.2
27-2	16.4	237.3	0.04	0.2
28-1	6.1	174.1	-0.06	0.2

Energy Flow Contouring

- Break system into closed-contour regions.
- If a FO is detected in an area at frequency f
  - Calculate $\widehat{W}_{mn}(f)$ for each branch into the region.
  - If all $\widehat{W}_{mn}(f)$ emit from the region, then the FO is sourced from within the region.
  - Drill into region to find source.

I. Singh, D. Trudnowski, M. Donnelly “A strategy for oscillation source location using closed-contour grouping and energy-flow spectra,” Proceedings of the 2020 T&D Conference & Exposition, Chicago, IL, April 2020.

Energy Flow Contouring

Parceval's theorem

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Now apply Parceval's theorem to Energy Flow

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$\widehat{W}_m(f) = \mathrm{Re}\{S_{\Delta P_{em}(t)\Delta\omega_m(t)}(f) + S_{\Delta Q_{em}(t)\dot{V}_m(t)}(f)\}$ = Energy-Flow Spectra

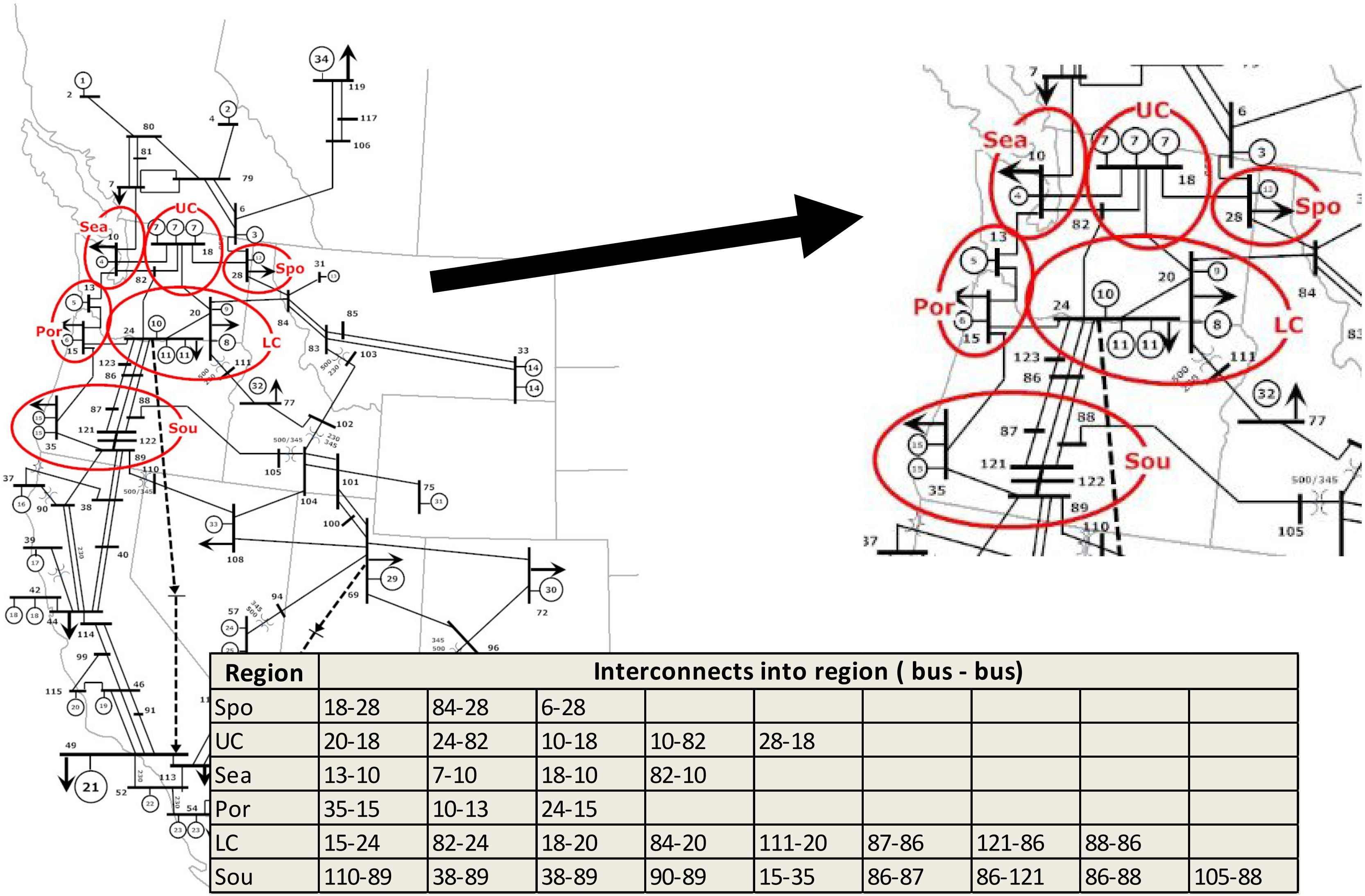
If $\widehat{W}_m(f)$ is positive, the FO is sourced from the device at frequency f.

Comments:

- Works with multi-frequency oscillation.
- Requires less data preprocessing and less data than time domain calculation.
- Easy to automate.
- MAS uses $S_{\Delta P_{em}(t)\Delta\omega_m(t)}(f)$ only

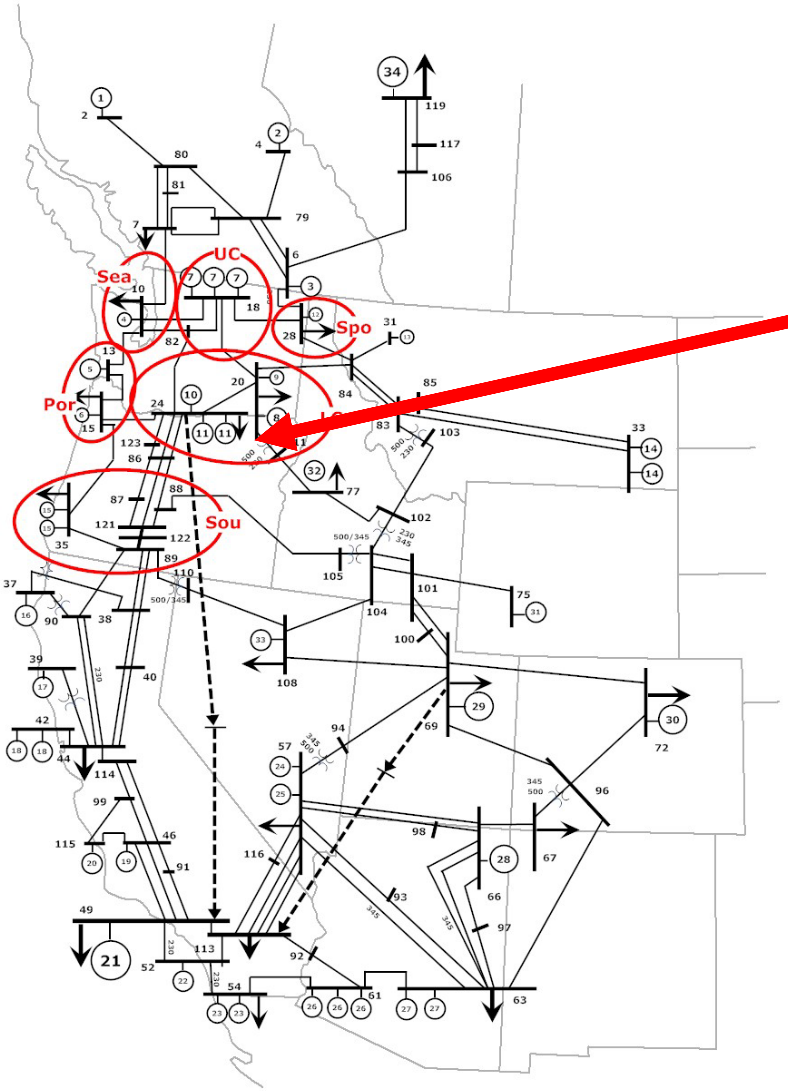
[1] R. Xie and D. Trudnowski, "Tracking the Damping Contribution of a Power System Component Under Ambient Conditions," IEEE Trans. on Power Systems, vol. 33, no. 1, pp. 1116-1117, 2018.

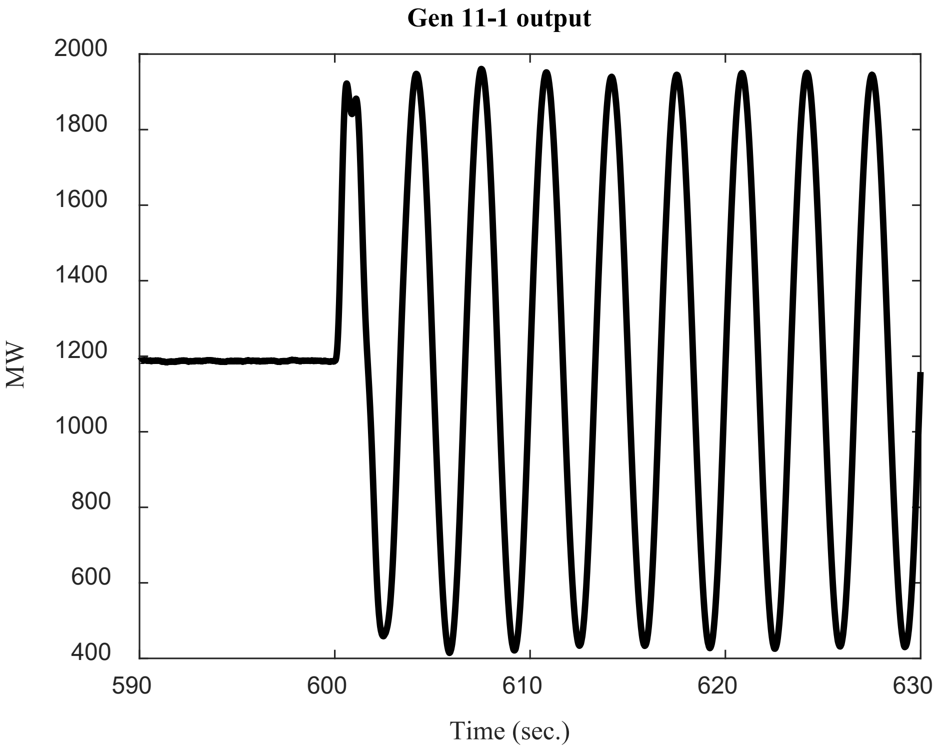
Example System



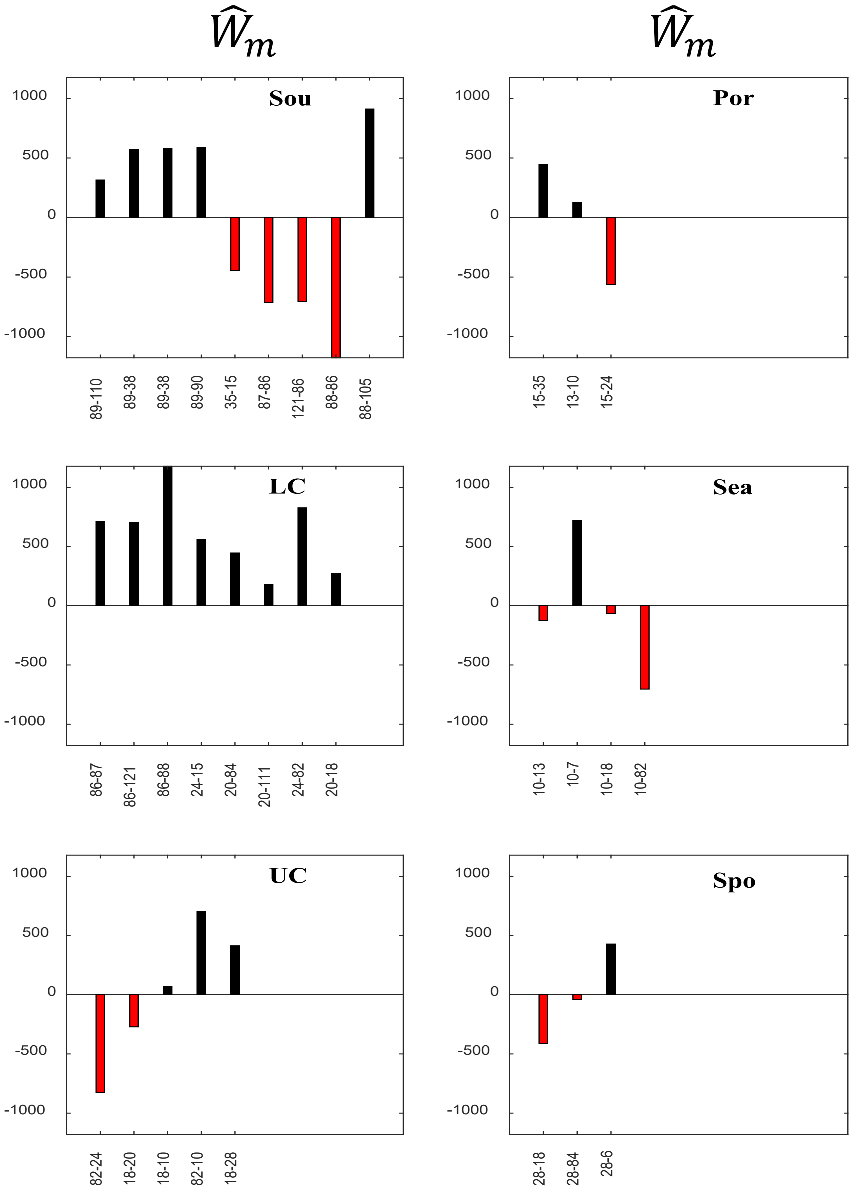
Region	Interconnects into region (bus - bus)								
Spo	18-28	84-28	6-28						
UC	20-18	24-82	10-18	10-82	28-18				
Sea	13-10	7-10	18-10	82-10					
Por	35-15	10-13	24-15						
LC	15-24	82-24	18-20	84-20	111-20	87-86	121-86	88-86	
Sou	110-89	38-89	38-89	90-89	15-35	86-87	86-121	86-88	105-88

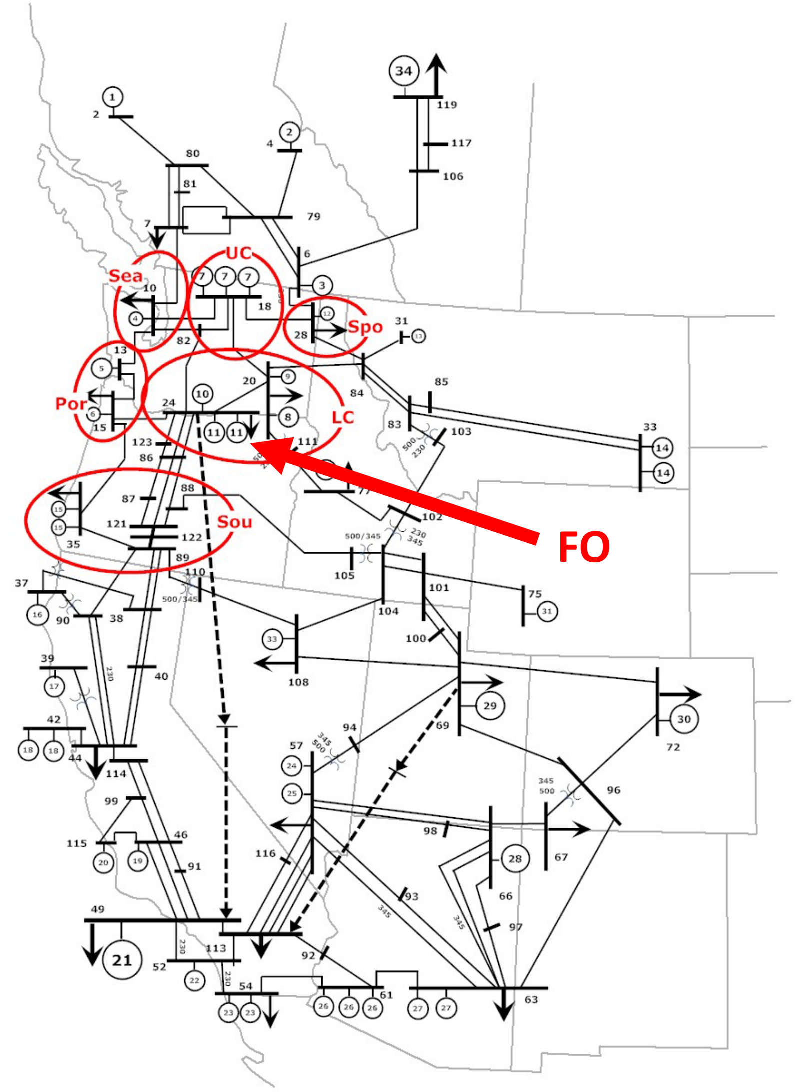
Example 1: FO at Gen 11-1, 0.3 Hz





Example 1: FO at Gen 11-1, 0.3 Hz





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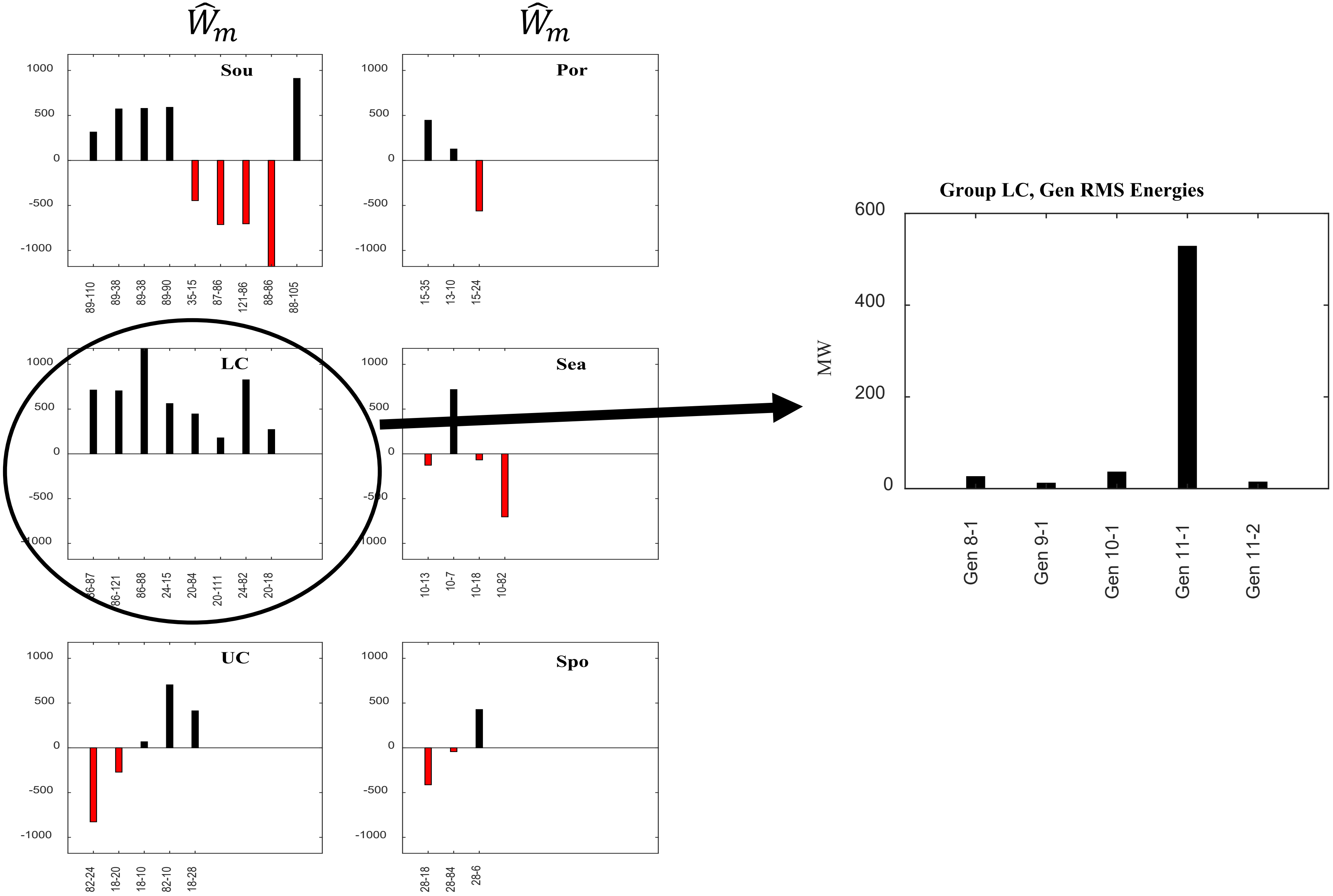


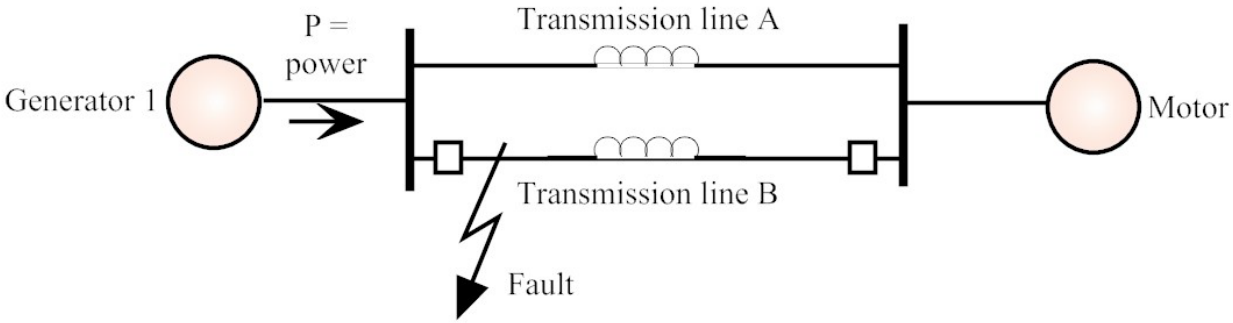
Conclusions and Next Steps

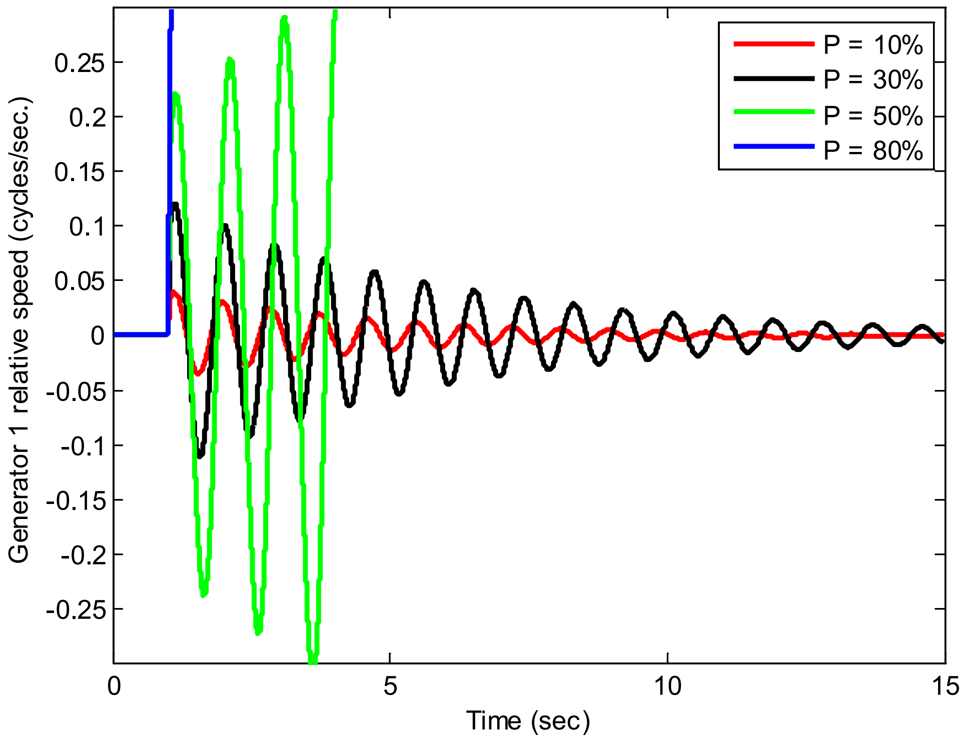
- [1] focused on defining an FOs and distinguishing them from natural oscillations.
- Distinguishing FOs and natural modes seems to be a lower priority for industry?
- There is some blur for IBR induced oscillations
  - Are they FOs or a new type of system mode?
- FO detection is a mature science
- FO source locating is a high priority for industry
  - Simple largest-amplitude-based methods effective for non-resonance Fos (e.g. RMS Energy)
  - Power vs. frequency phase angle approaches seem to work for resonance conditions and are the basis for emerging control center applications (e.g. EF)
  - Other approaches not as well tested
- Task Force directions?
  - Catalog and expand source locating
  - Better define IBR-induced oscillations
  - Only include results based on peer-reviewed publications

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

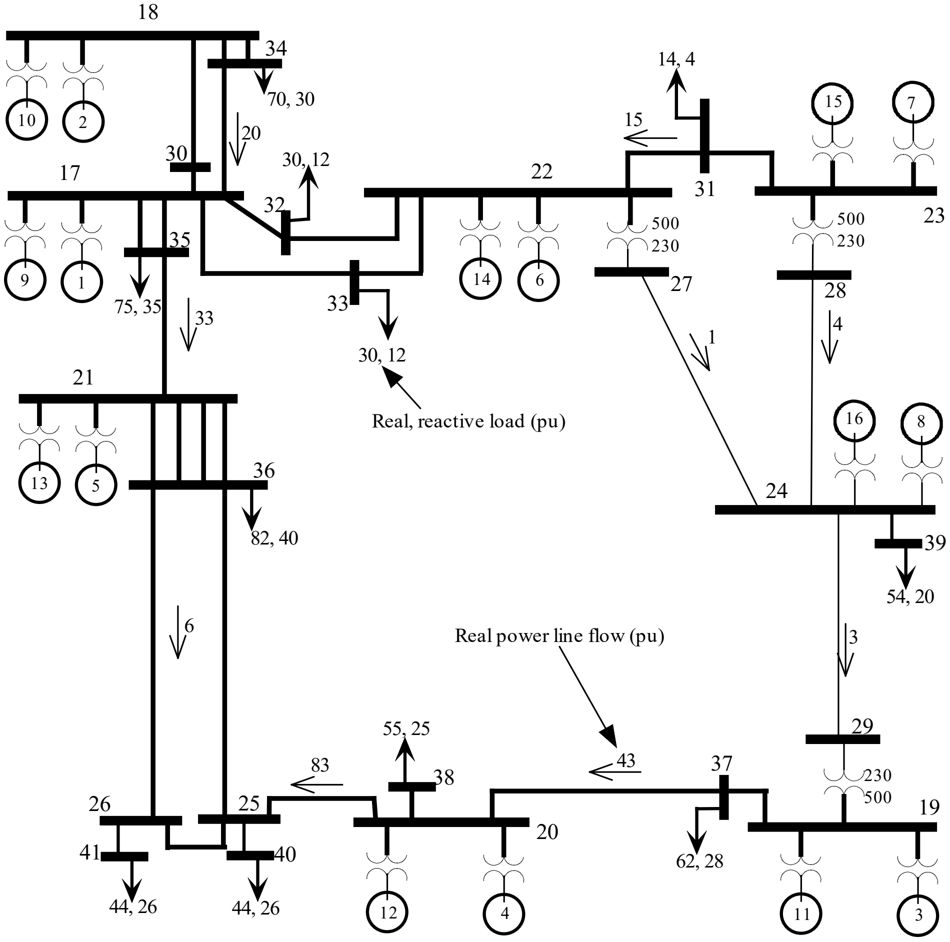
Extra Slides

Example


P =
power
Generator 1
Transmission line A
Motor
Transmission line B
Fault


Generator 1 relative speed (cycles/sec.)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0
5
10
15
Time (sec)
P = 10%
P = 30%
P = 50%
P = 80%

Damping vs Loading



Damping vs Loading