Available Methods, Algorithms and Tools for Oscillation Detection and Source Location

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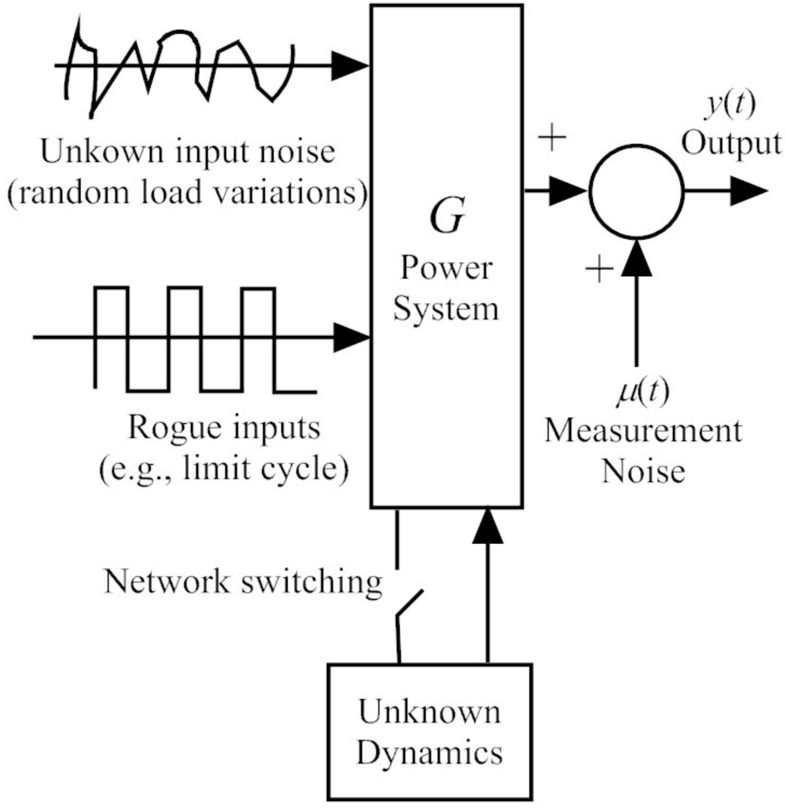
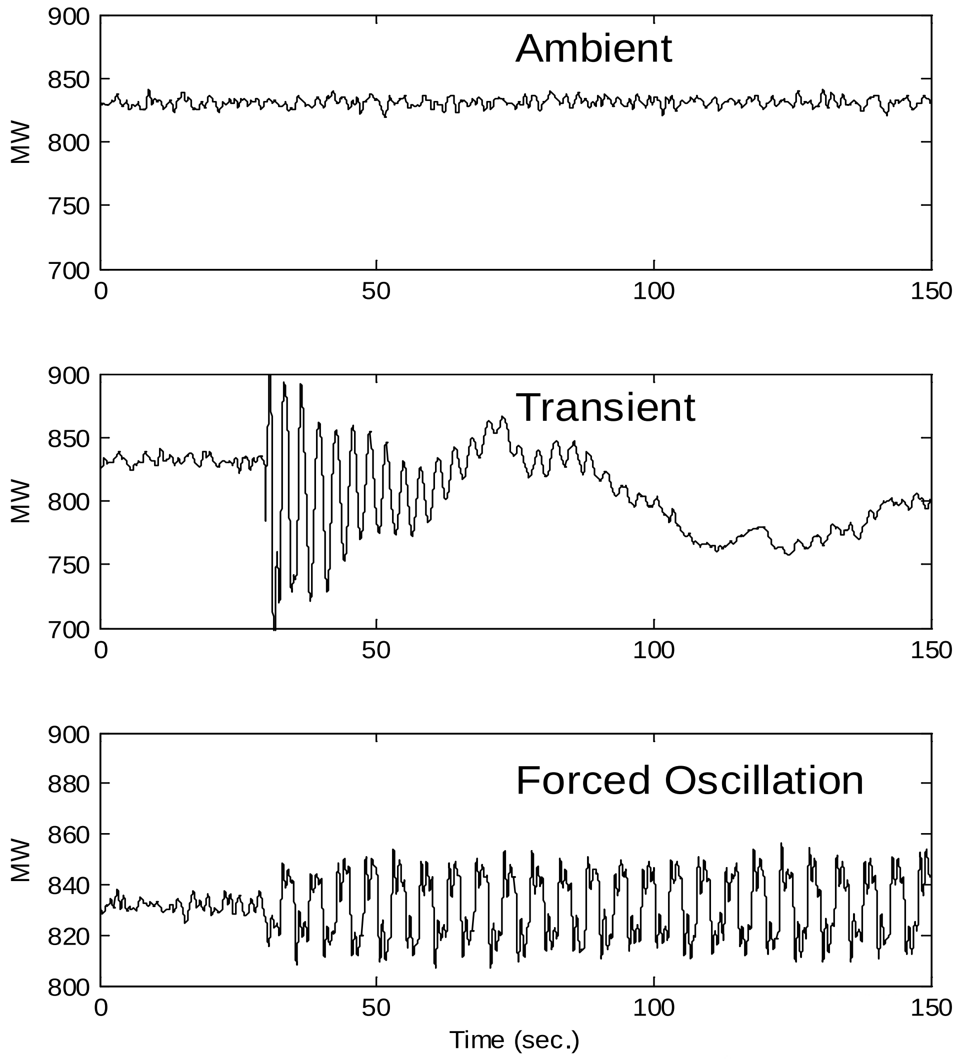
Power & Energy Society®

Dynamic Response Types

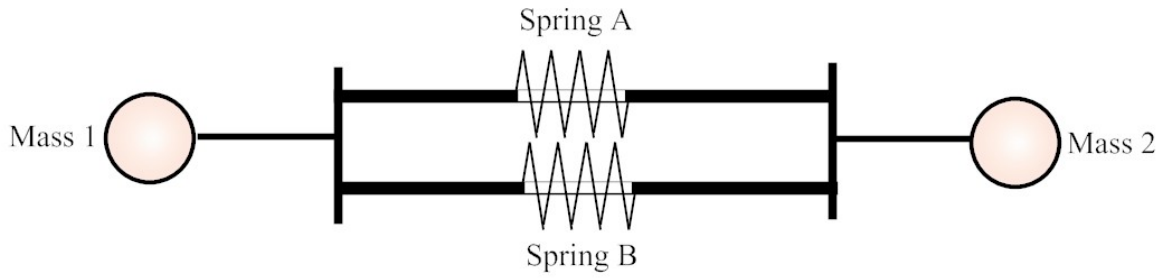




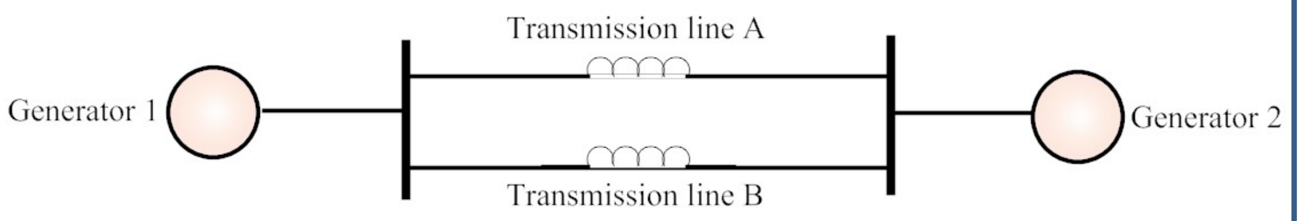
Electromechanical Dynamics

Synchronous Grids are Elastic

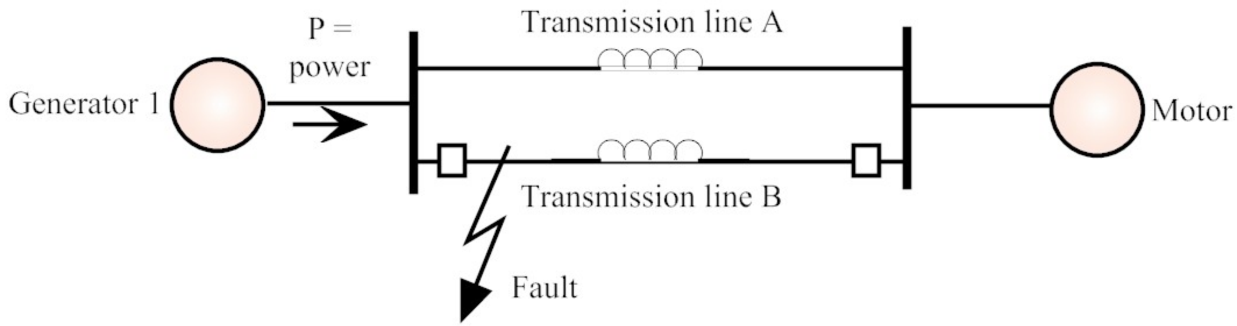
Mechanical



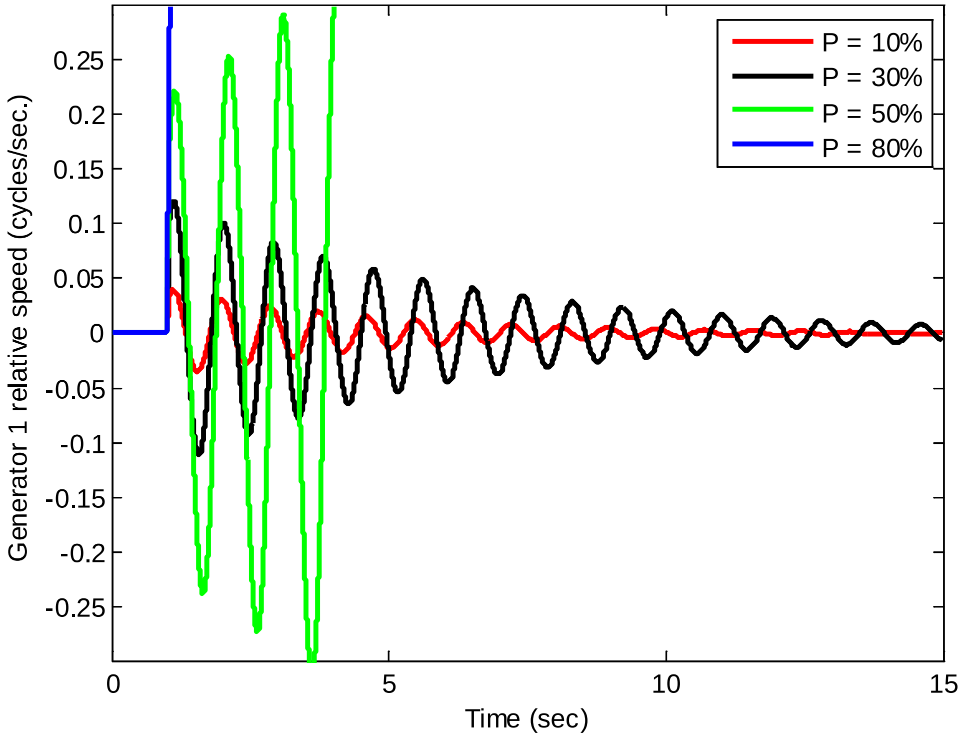
Electrical



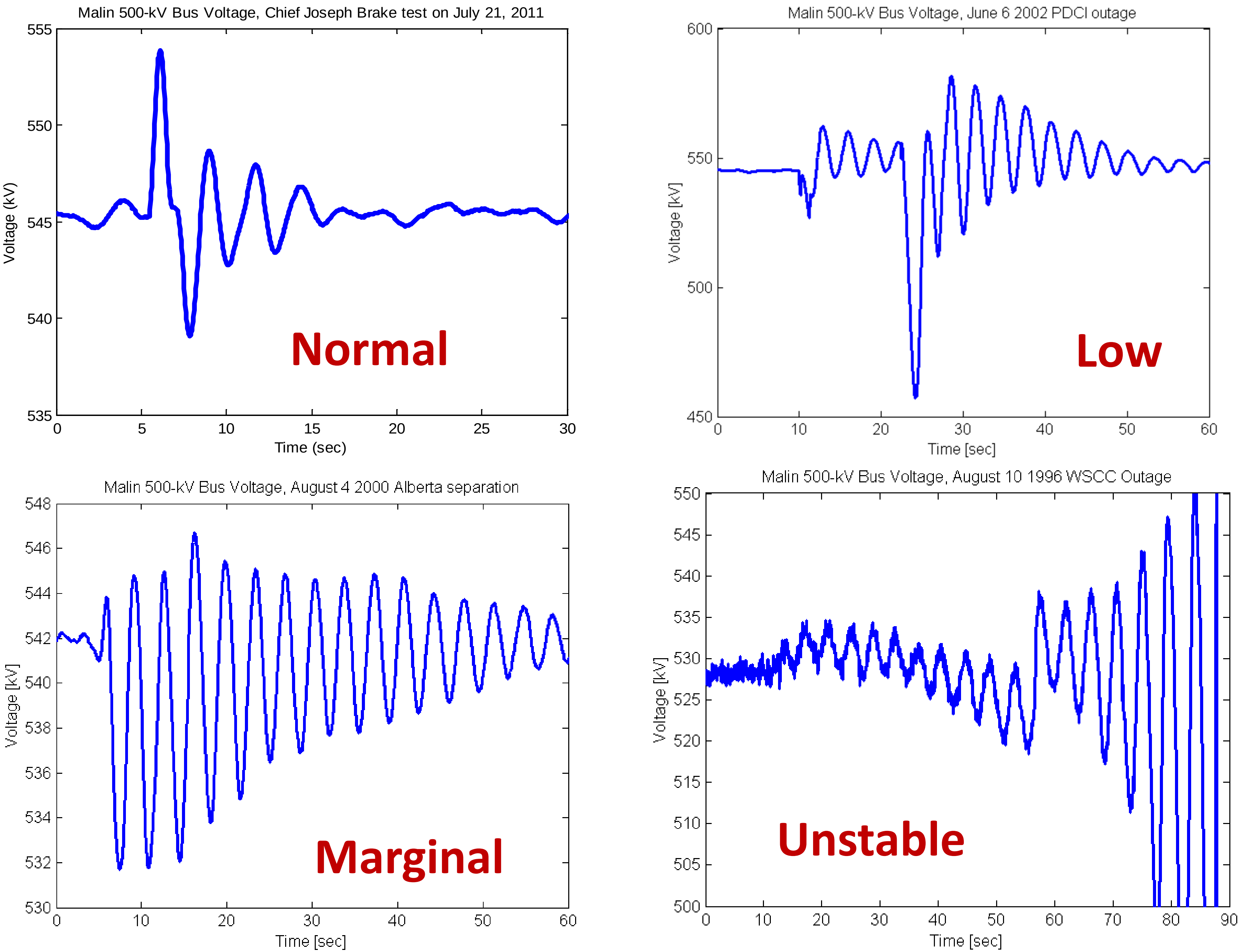
Example



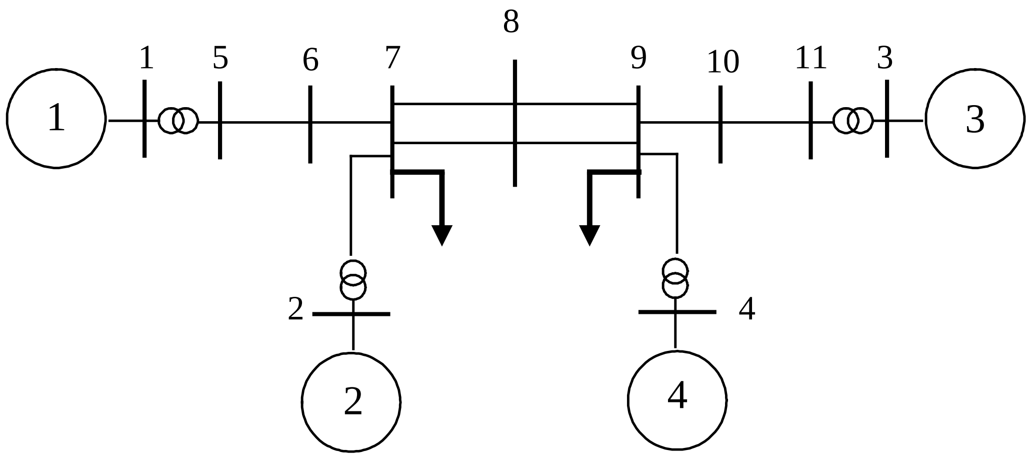
P =
power
Transmission line A
Generator 1
Motor
Transmission line B
Fault



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


Malin 500-kV Bus Voltage, Chief Joseph Brake test on July 21, 2011
Voltage (kV)
Time (sec)
Normal
Malin 500-kV Bus Voltage, June 6 2002 PDCI outage
Voltage [kV]
Time [sec]
Low
Malin 500-kV Bus Voltage, August 4 2000 Alberta separation
Voltage [kV]
Time [sec]
Marginal
Malin 500-kV Bus Voltage, August 10 1996 WSCC Outage
Voltage [kV]
Time [sec]
Unstable

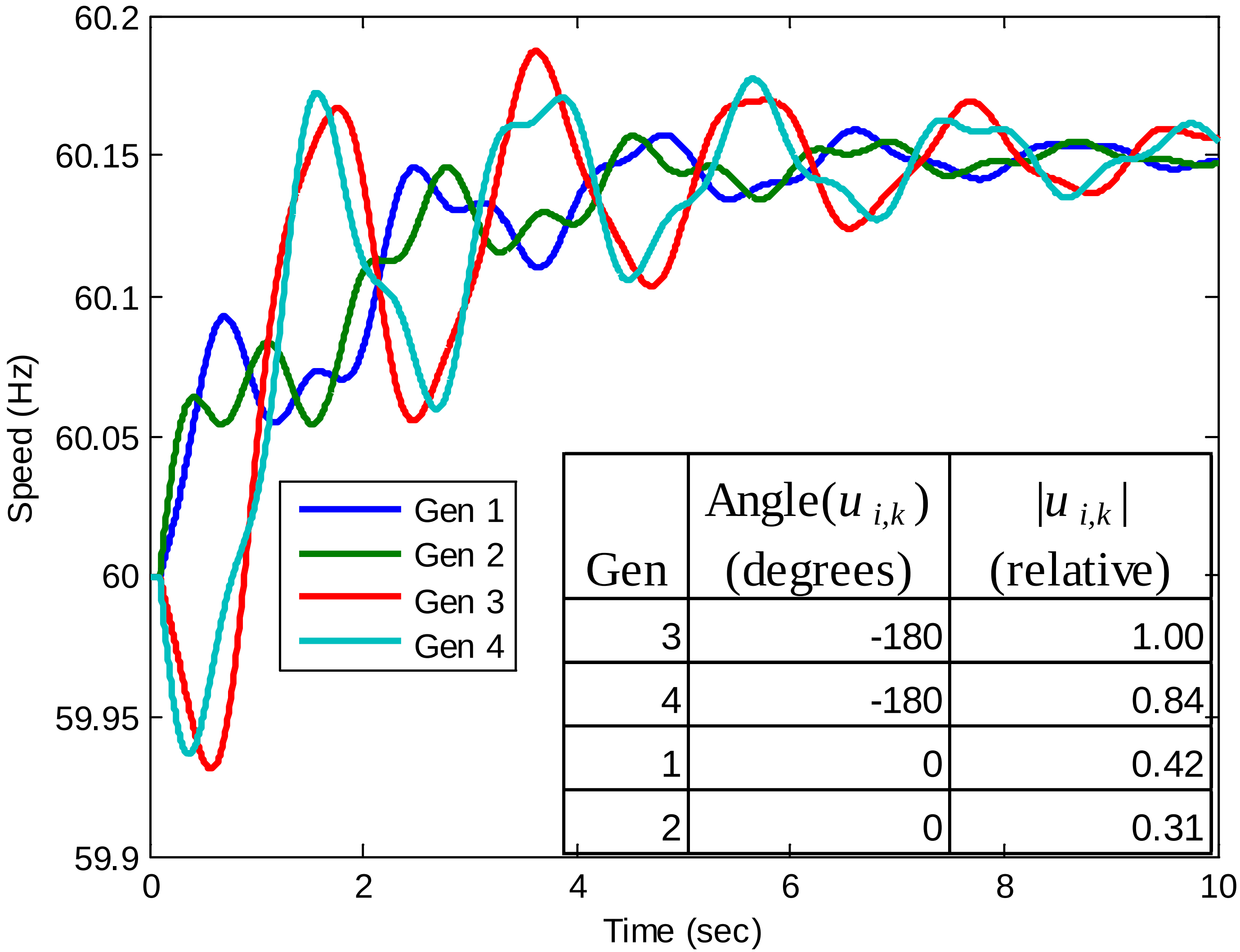
Mode Shape



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

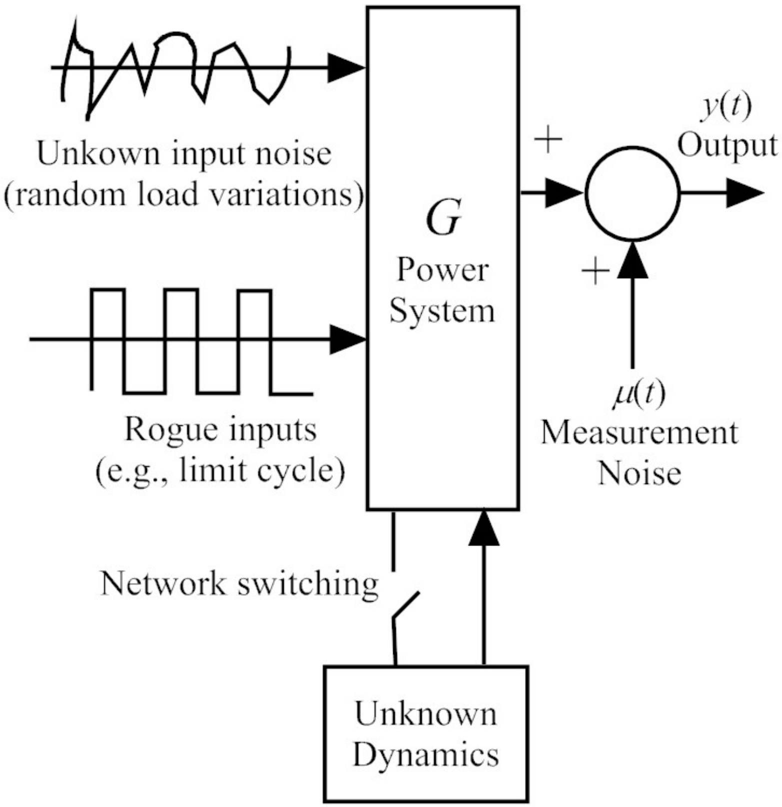
Mode Shape

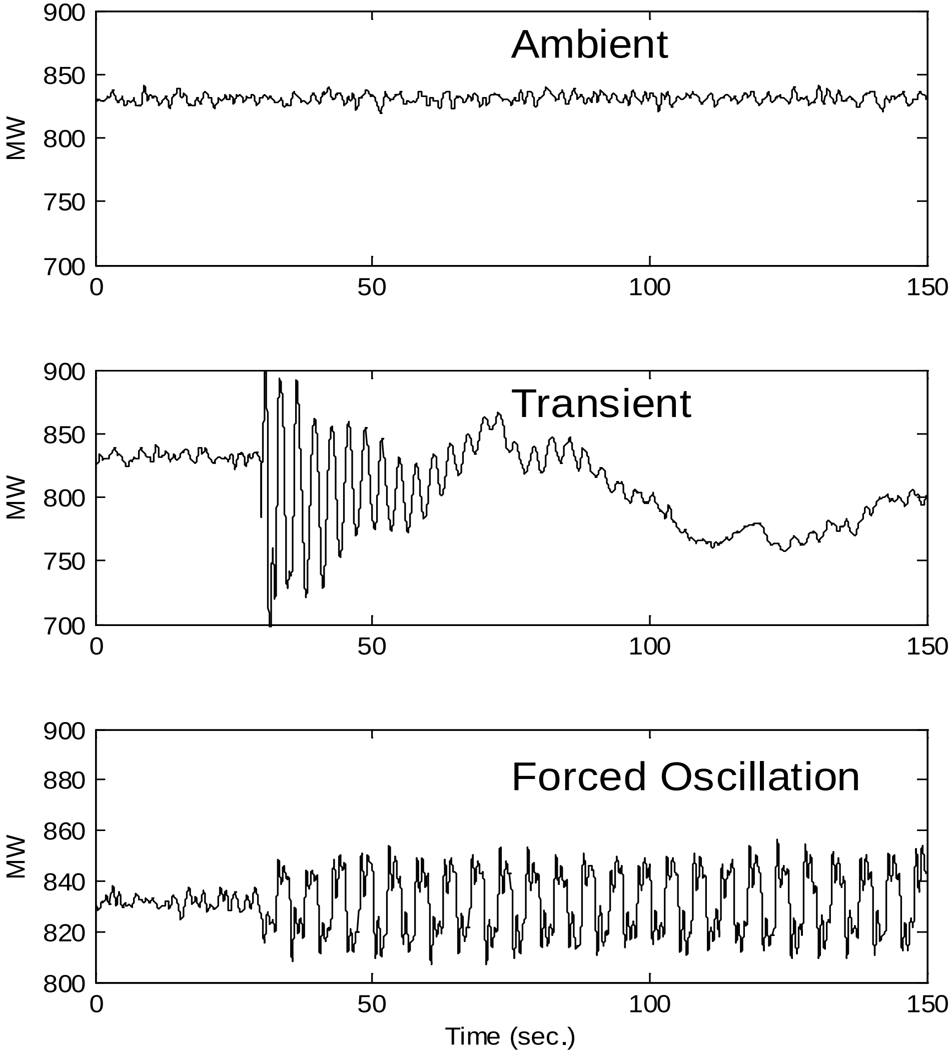


Gen	Angle($u_{i,k}$) (degrees)	$\|u_{i,k}\|$ (relative)
3	-180	1.00
4	-180	0.84
1	0	0.42
2	0	0.31

Forced Oscillations

Dynamic Response Types

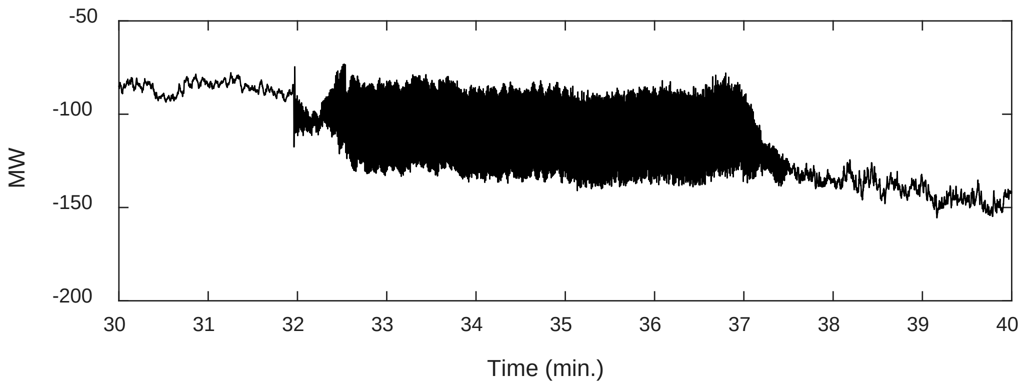


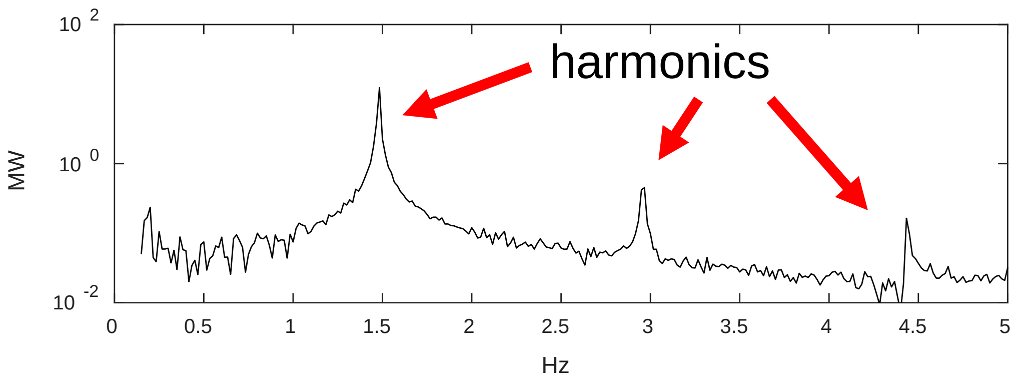


Forced Oscillations

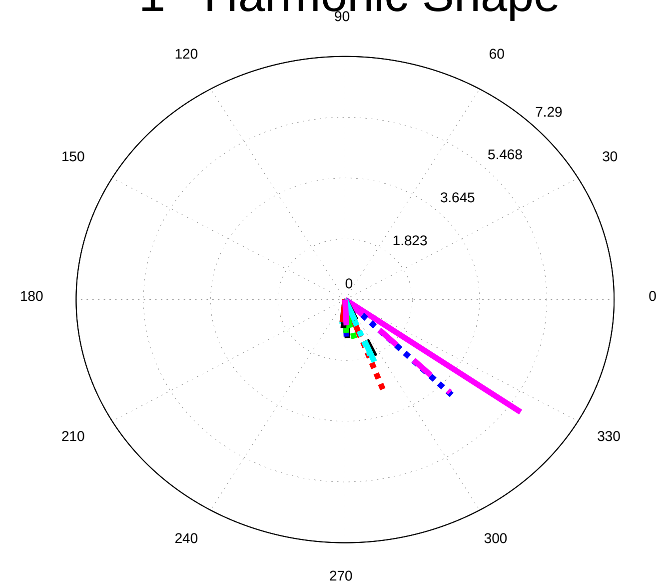
- Response of system to an apparatus in a limit cycle
  - e.g. generator controller
- NOT A SYSTEM INSTABILITY
- Very common
  - WECC = 16 events in 2008/9 operating season in WECC.
- Can be very severe if near a natural mode where the system gain is high (resonance):
  - WECC: November 30, 2005.

WECC FO, Mar. 2015

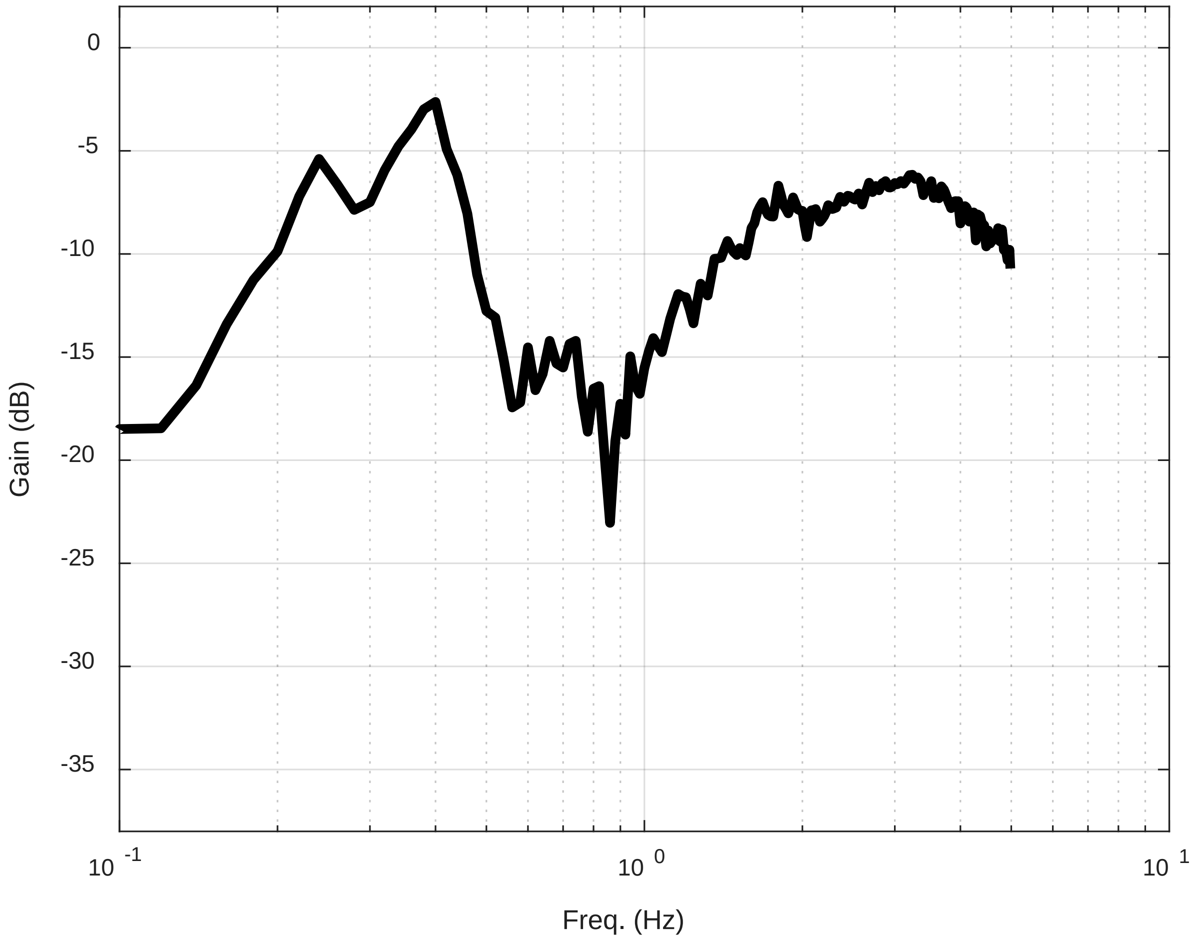




1st Harmonic Shape



Resonance



Do FOs Impose Any Threat?

- 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"

On-Line FO Monitoring Goals

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

Distinguishing between FO and Un-damped Transients

The Math

Forced

$$\hat{x}_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t + \angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Rightarrow \textbf{FO}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{i=1}^{N}|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}|e^{\sigma_i t}\cos\left(\omega_i t+\angle(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l})\right)\right]\right] \Rightarrow \textbf{Colored Noise}$$

Harmonics

Transient

$$\hat{x}_r(t) = 2|\underline{u}_{nr}\underline{v}_n\underline{x}(0)|\cos\left(\omega_n t+\angle\left(\underline{u}_{nr}\underline{v}_n\underline{x}(0)\right)\right) \Rightarrow \textbf{Transient}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[\sum_{\substack{i=1\\ i\neq n}}^{N}|\underline{u}_{ir}\underline{v}_i\underline{b}_{2l}|e^{\sigma_i t}\cos\left(\omega_i t+\angle(\underline{u}_{ir}\underline{v}_i\underline{b}_{2l})\right)\right]\right] \Rightarrow \textbf{Colored Noise}$$

$$+\sum_{l=1}^{M}\left[q_l(t)\circledast\left[|\underline{u}_{nr}\underline{v}_n\underline{b}_{2l}|\cos(\omega_n t+\angle\underline{u}_{nr}\underline{v}_n\underline{b}_{2l})\right]\right] \Rightarrow \textbf{Sinusoid Noise}$$

No Harmonics

Unique to a Transient

R. Xie and D. Trudnowski, "Distinguishing Between Natural and Forced Oscillations Using a Cross-Spectrum Index," Proceedings of the *IEEE Power & Energy Society General Meeting*, July 2017.

Distinguishing Between FO and Transient

- Consider oscillating signal y_r at location r broken into 3 windows. The "**cross-spectrum difference function**" is defined as:

$$S_r[\Omega] \triangleq \tilde{Y}^*_{rw_1}\tilde{Y}_{rw_2} - \tilde{Y}^*_{rw_2}\tilde{Y}_{rw_3}$$

- We now define a "**cross-spectrum index**" between channels r and g:

$$C_{rg}[\Omega] \triangleq \frac{\left|\mathrm{E}\left\{S_r^*[\Omega]S_g[\Omega]\right\}\right|^2}{\mathrm{E}\{S_r^*[\Omega]S_r[\Omega]\}\,\mathrm{E}\left\{S_g^*[\Omega]S_g[\Omega]\right\}}$$

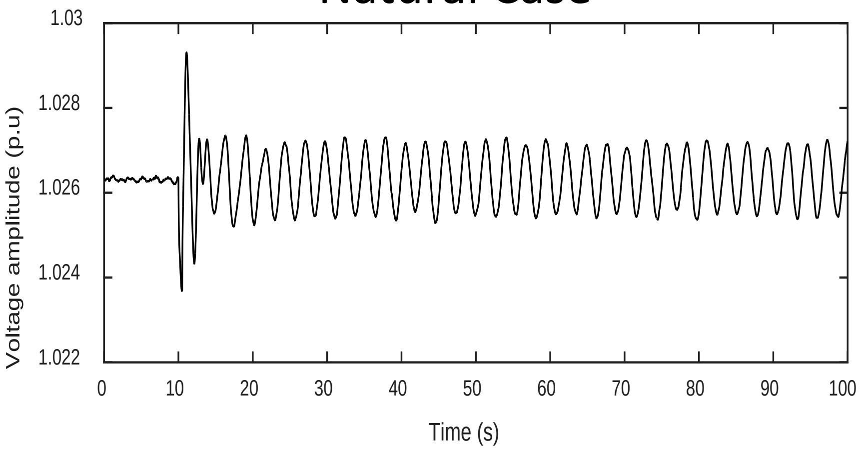
- LOTS of math shows:

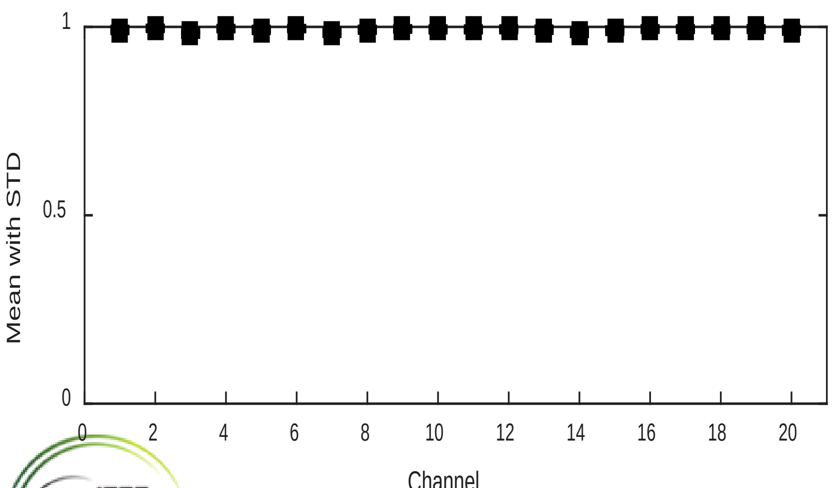
$C_{rg}[\Omega_n] \cong 1$ for a transient

$C_{rg}[\Omega_n] < 1$ for an FO

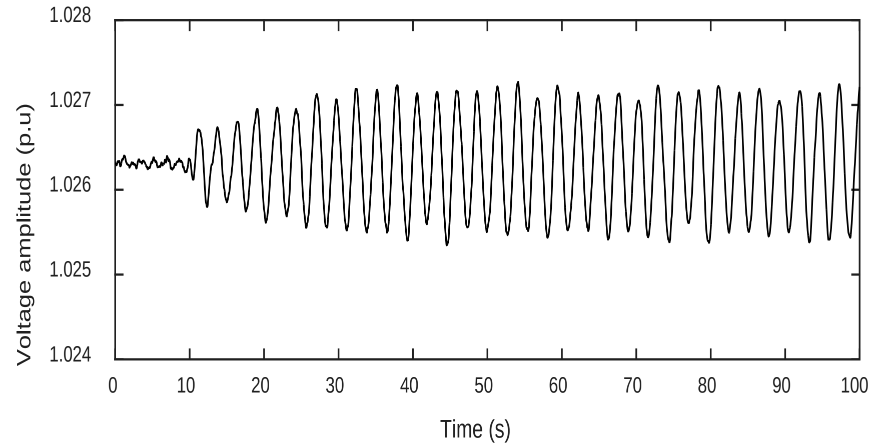
MiniWECC Simulation Example

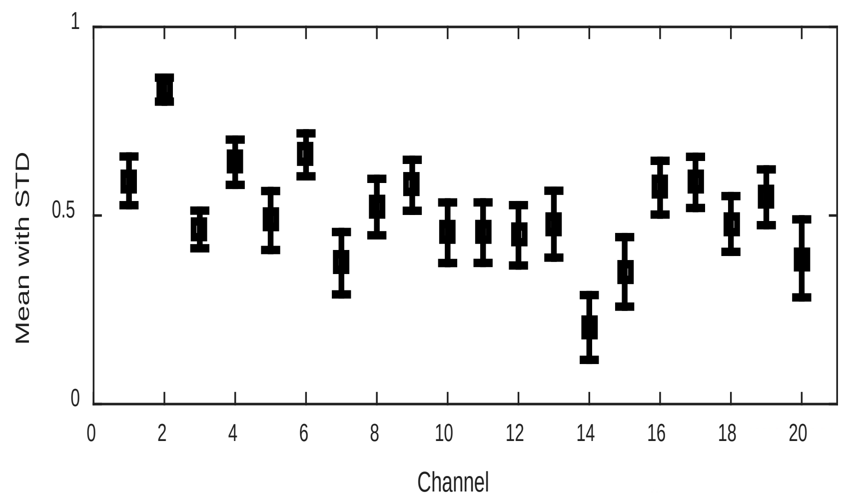
Natural Case





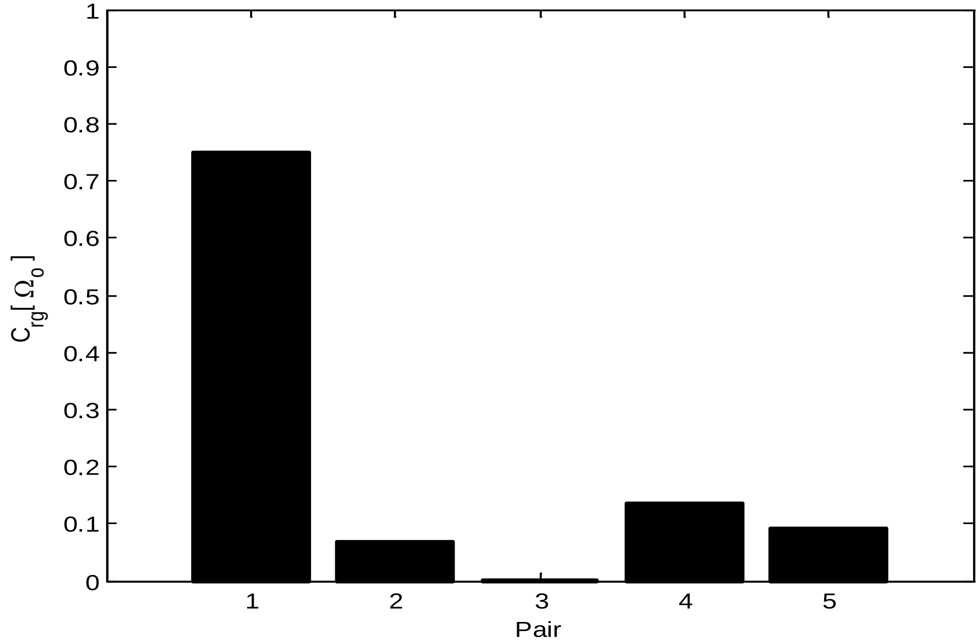
FO Case





Real-Life Example

WECC FO near system mode at 0.345 Hz for 15 min. (About 10 MW).



Research has shown:

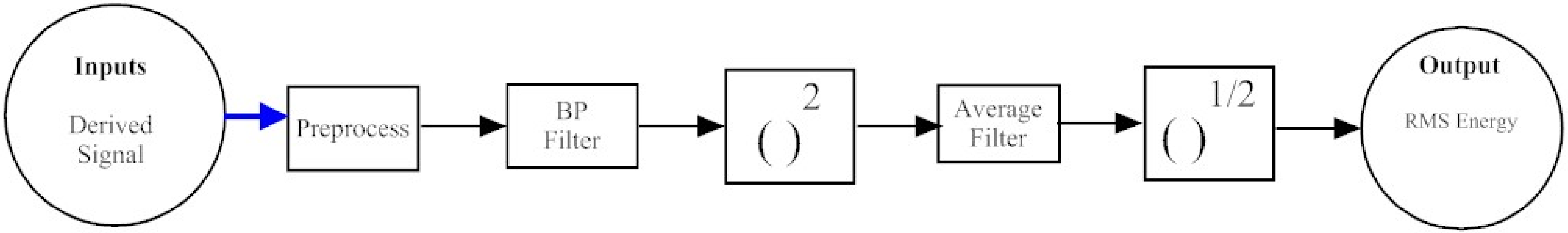
- Algorithm works great at inter-area modes.
- Works OK at local modes.
- Requires LOTS of data (minutes).

Locating FO sources

Approaches

- RMS Energy
  - Requires no system model or knowledge
  - Easy to implement for on-line use
  - Works the vast majority of time
    - Fails when FO is near system mode
  - Lots of experience; currently used at BPA control center
- Energy Flow
  - Requires some network information
  - Cannot quantify the FO
  - Seems to be reliable and robust for locating the FO source
  - Being prototyped at ISO New England (Maslennikov)
- Swing Equation Estimation
  - Only applicable to real-power turbine-induced FO
  - Requires no model information but does require baselining
  - Both quantifies and locates the FO
  - Initial tests indicate a need to measure generator speed

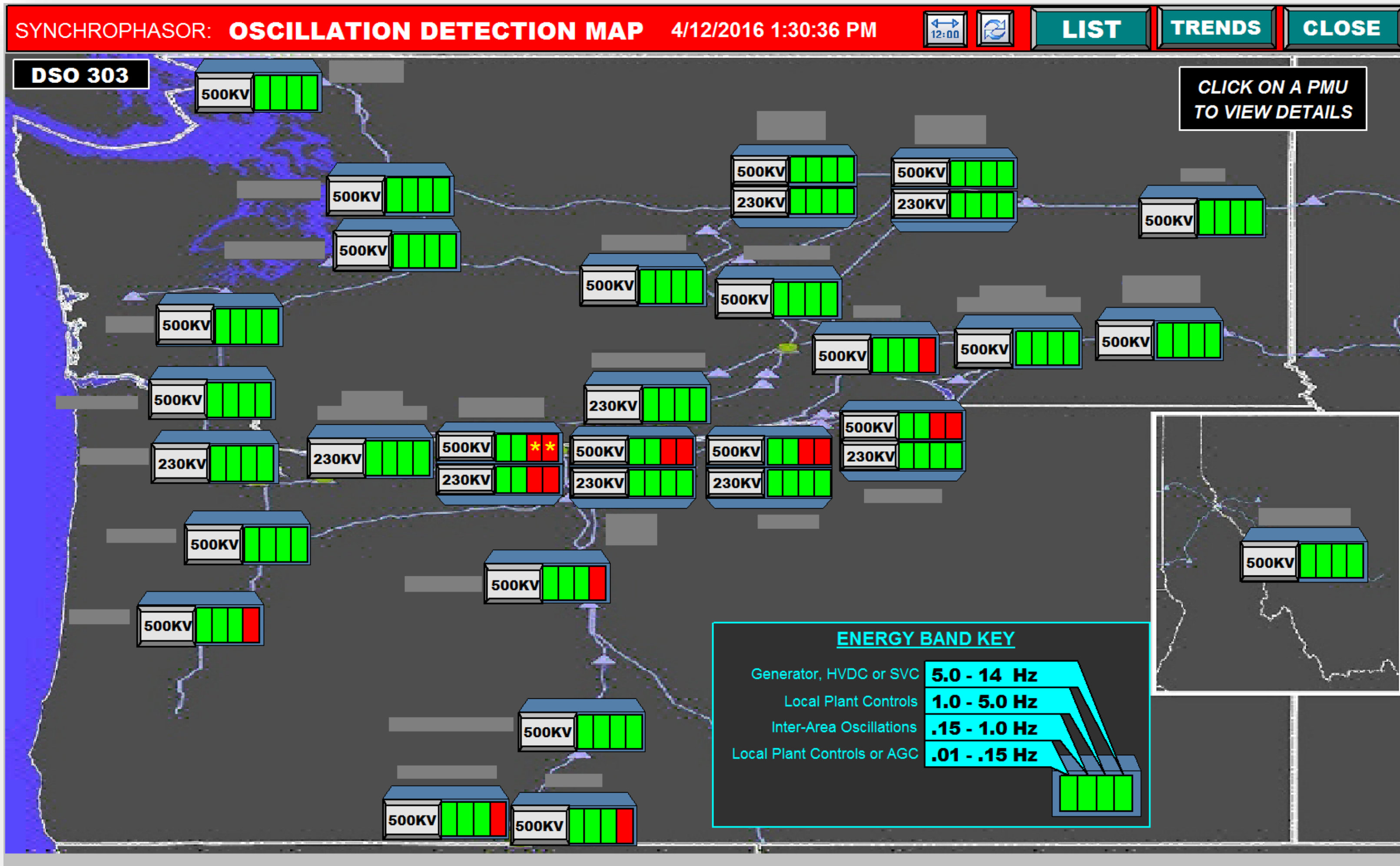
RMS Energy Filter



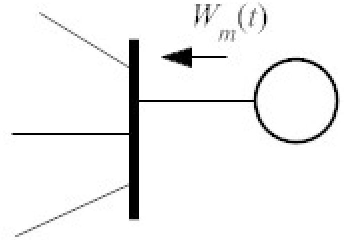
- Derived Signals = V, f, MW, MVAR.
- Bands:
  - 0.01 to 0.1 Hz = Speed governor band.
  - 0.15 to 1 Hz = Interarea mode band.
  - 1 to 5 Hz = Local mode and controls band.
  - 5 to Nyquist = High frequency band.

M. Donnelly, D. Trudnowski, J. Colwell, J. Pierre, and L. Dosiek, "RMS-energy filter design for real-time oscillation detection," Proceedings of the *IEEE Power & Energy Society General Meeting*, July 2015.

RMS Energy Display at BPA



Energy Flow



$$W_m(t) \triangleq \int_0^t \left[\Delta P_{em}(\hat{t})\Delta\omega_m(\hat{t})\mathrm{d}\hat{t} + \Delta Q_{em}(\hat{t})\mathrm{d}\left(\Delta \ln\left(V_m(\hat{t})\right)\right)\right]$$ = Energy Flow

$$\Delta P_{em}(t) = \mathrm{BP}\{\hat{P}_{em}(t)\}$$ = Filtered power flow

$$\Delta Q_{em}(t) = \mathrm{BP}\{\hat{Q}_{em}(t)\}$$ = Filtered reactive power flow

$$\Delta\omega_m(t) = \mathrm{BP}\{\hat{\omega}_m(t)\}$$ = Filtered generator speed (frequency)

$$V_m(t) = \mathrm{Mean}\{\hat{V}_m(t)\} + \mathrm{BP}\{\hat{V}_m(t)\}$$ = Filtered voltage

- Decreasing $W_m(t)$ implies oscillation dissipation
- Increasing $W_m(t)$ implies oscillation sourcing
- Requires a single frequency oscillation (or heavy filtering)
- Difficult to automate

- L. Chen, Y. Min, and W. Hu, "An energy-based method for location of power system oscillation source," IEEE Trans. on Power Systems, vol. 28, no. 2, pp. 828-836, May 2013.
- Slava 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 in the Freq Domain

Parceval's theorem applied to general signals $x_1(t)$ and $x_2(t)$ is

$$\int_0^{\infty} x_1(\hat{t})x_1(\hat{t})d\hat{t} = \int_{-\infty}^{\infty} X_1^*(f)X_2(f)df = 2\int_0^{\infty} \mathrm{Re}\{S_{x_1,x_2}(f)\}df$$

where $S_{x1,x2}$ is the cross-spectral density.
If we assume t is large, Parceval's applied to $W_m(t)$ is accurately estimated by

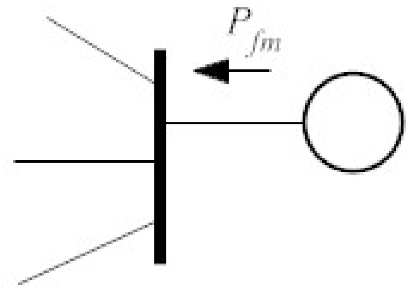
$$W_m(f) = 2\mathrm{Re}\int_0^{\infty} \left\{\hat{S}_{\Delta P_{em}(t)\Delta\omega_m(t)}(f) + \hat{S}_{\Delta Q_{em}(t)\mathrm{d}\left(\Delta\ln(V_m(t))\right)}(f)\right\} df$$

where $\hat{S}$ is the estimated cross-spectral density up-to time t. Therefore,

- If $\hat{S}_{\Delta P_{em}(t)\Delta\omega_m(t)}(f) > 0$ oscillation dissipation at frequency f
- If $\hat{S}_{\Delta P_{em}(t)\Delta\omega_m(t)}(f) < 0$ oscillation sourcing at frequency f
- Enables analysis of multiple frequencies.
- Easy to automate.

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, Jan. 2018

Swing Equation Decomposition



$$\Delta\tilde{P}_{fm} = \Delta\tilde{P}_{em} - R_m(f_0)\Delta\tilde{\omega}_m$$ = Estimated FO power

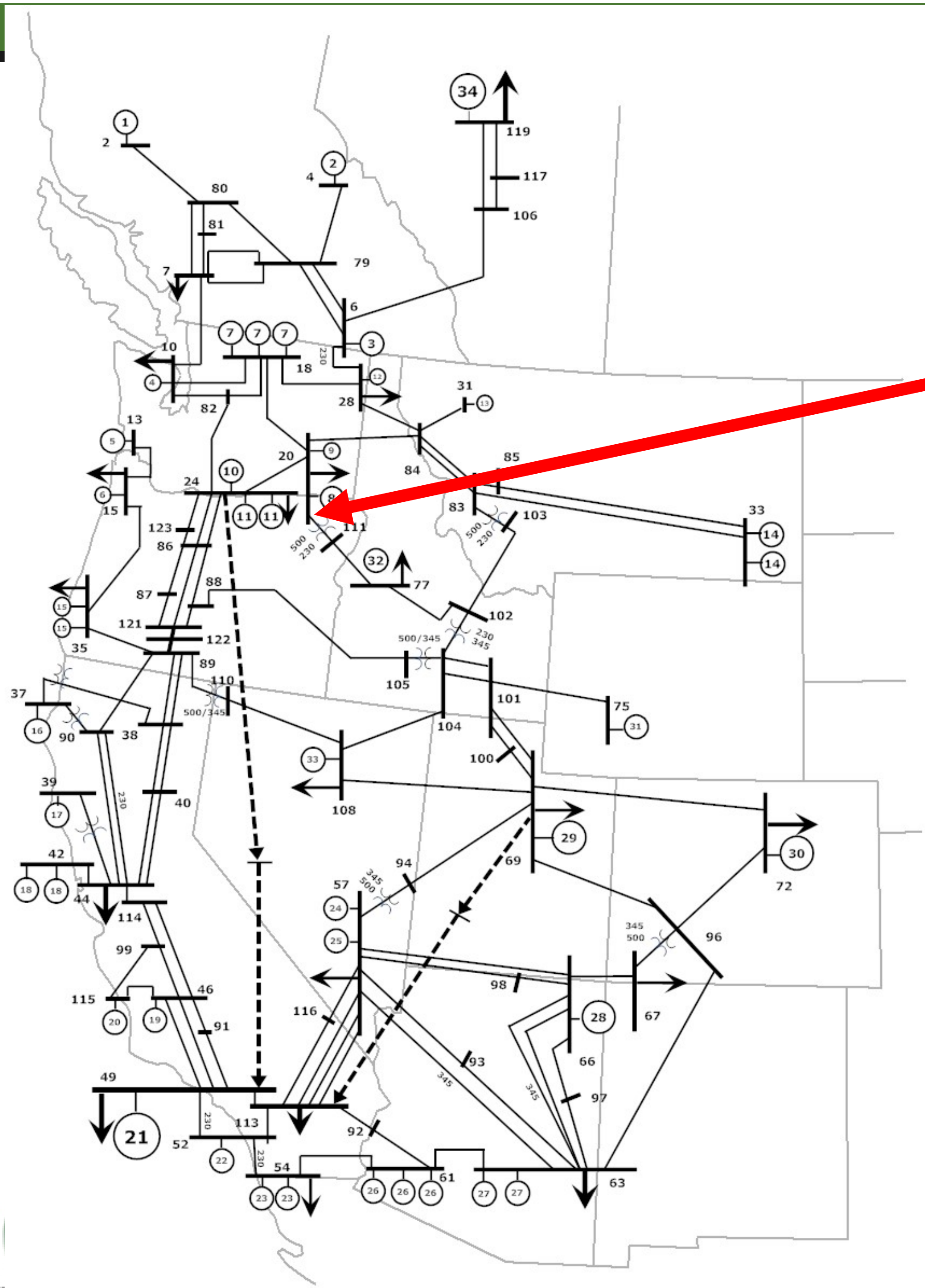
f_0 = frequency of FO

$\Delta\tilde{P}_{em} =$ Fourier Series component of $\Delta P_{em}(t)$

$\Delta\tilde{\omega}_m =$ Fourier Series component of $\Delta\omega_m(t)$

$R_m(f_0) =$ Pre-calculated ambient ratio $= \dfrac{S_{\omega P_e,m}(f)}{S_{\omega\omega,m}(f)}$

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

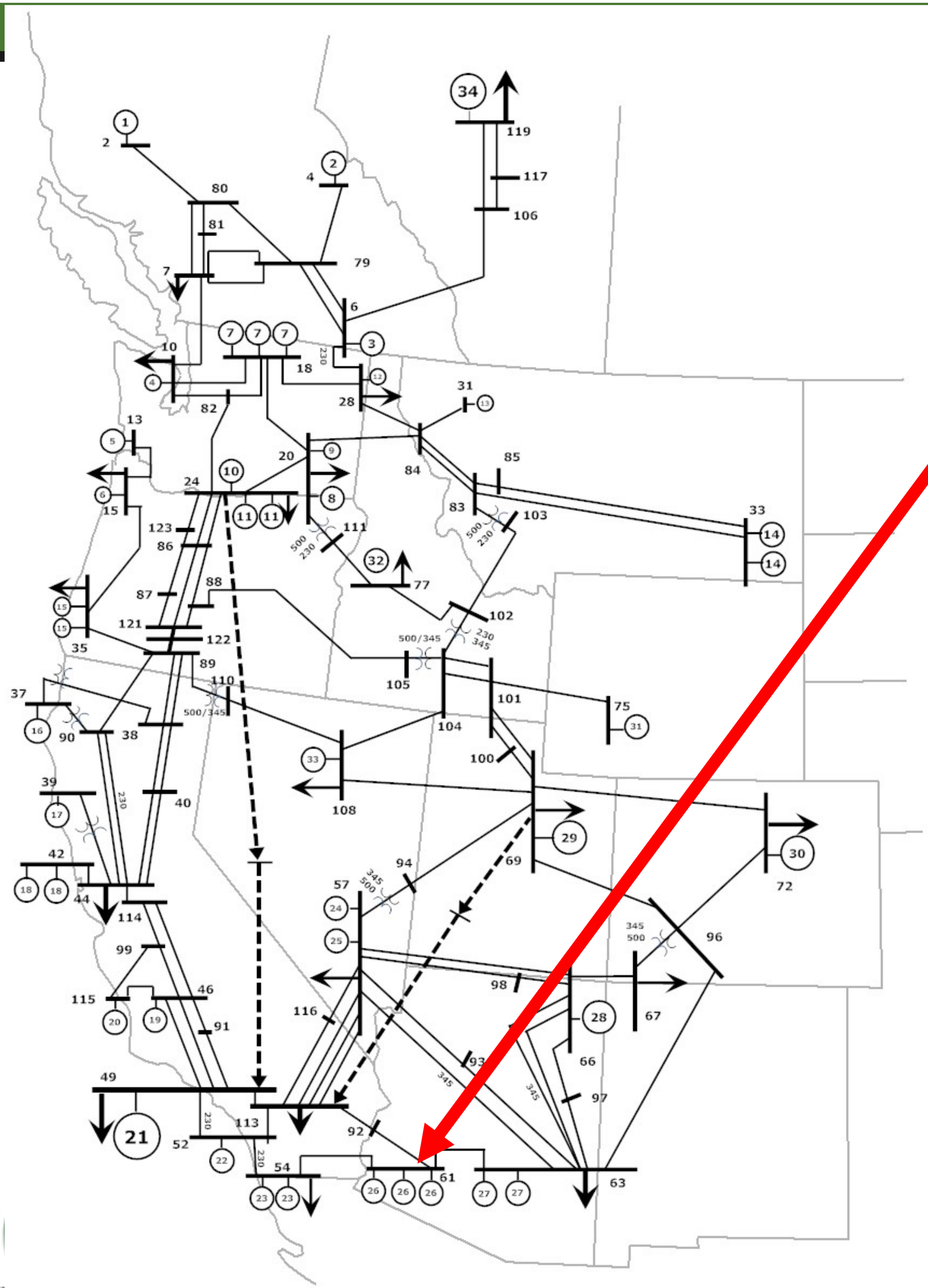


Example 1

- 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)	T_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

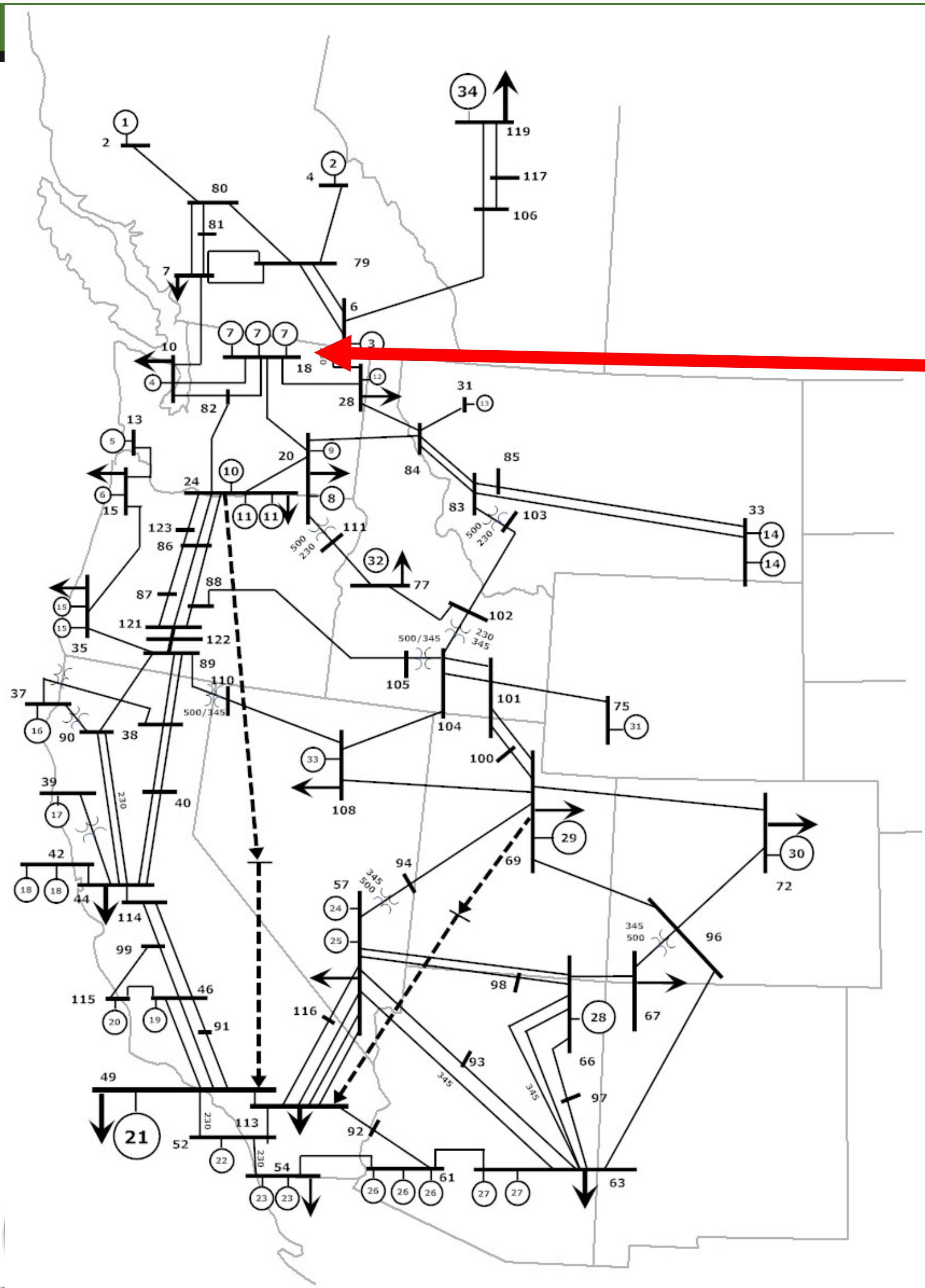


Example 2

- 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)	T_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



Example 3

- Forced Oscillation at Gen 7-1
- 0.37 Hz
- 100 MW
- At an inter-area

Example 3
FO at 0.37 Hz at Gen 7-1

Power Plant - Gen	RMS Energy (mHz)	RMS Energy (MW)	W (pu)	T_f (MW)
1-1	48	92	0.28	0
2-1	42	68	0.35	0
3-1	31	52	0.61	0
4-1	39	42	-0.01	0
5-1	40	86	0.00	0
7-1	39	129	6.34	100
7-2	39	47	0.18	0
7-3	39	46	0.01	0
8-1	35	53	0.23	0
10-1	34	72	0.31	0
13-1	40	31	0.27	0
21-1	14	130	-0.43	0
24-1	22	31	0.09	0
25-1	22	62	0.02	0
27-1	25	71	0.09	0
27-2	25	71	0.09	0
28-1	24	129	-0.17	0
29-1	10	55	0.07	0
30-1	24	127	-0.16	0
34-1	34	236	-0.54	1

Conclusions

- FOs are significant and can cause harm.
- Worst case is a resonance.
- RMS Energy monitoring is a proven simple approach for detection and locating. Does not work in the resonance case.
- Energy Flow is emerging as a better locating method.
- Distinguishing between FOs and Natural transients is very difficult. But, un-damped natural transients are extremely rare.