Tutorial

The characteristics of forced oscillations in power systems

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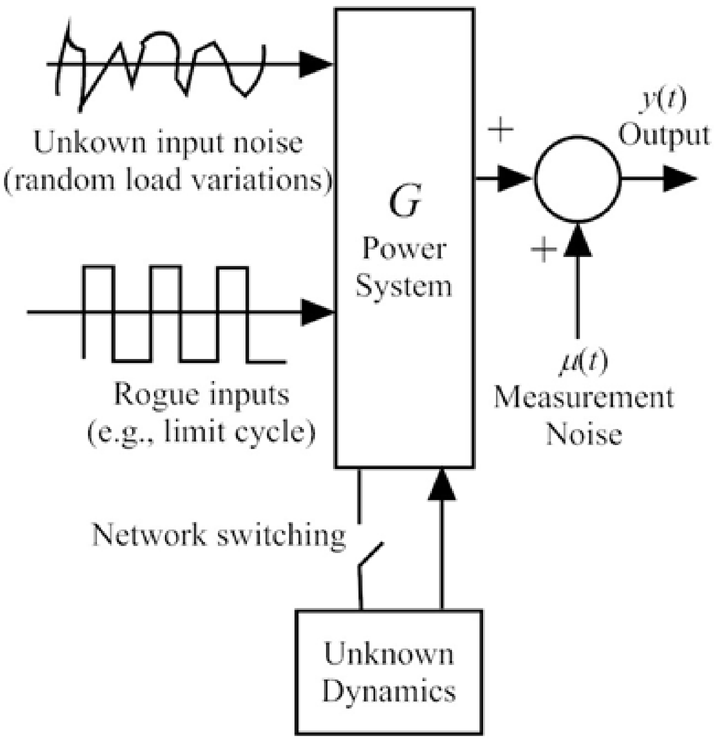
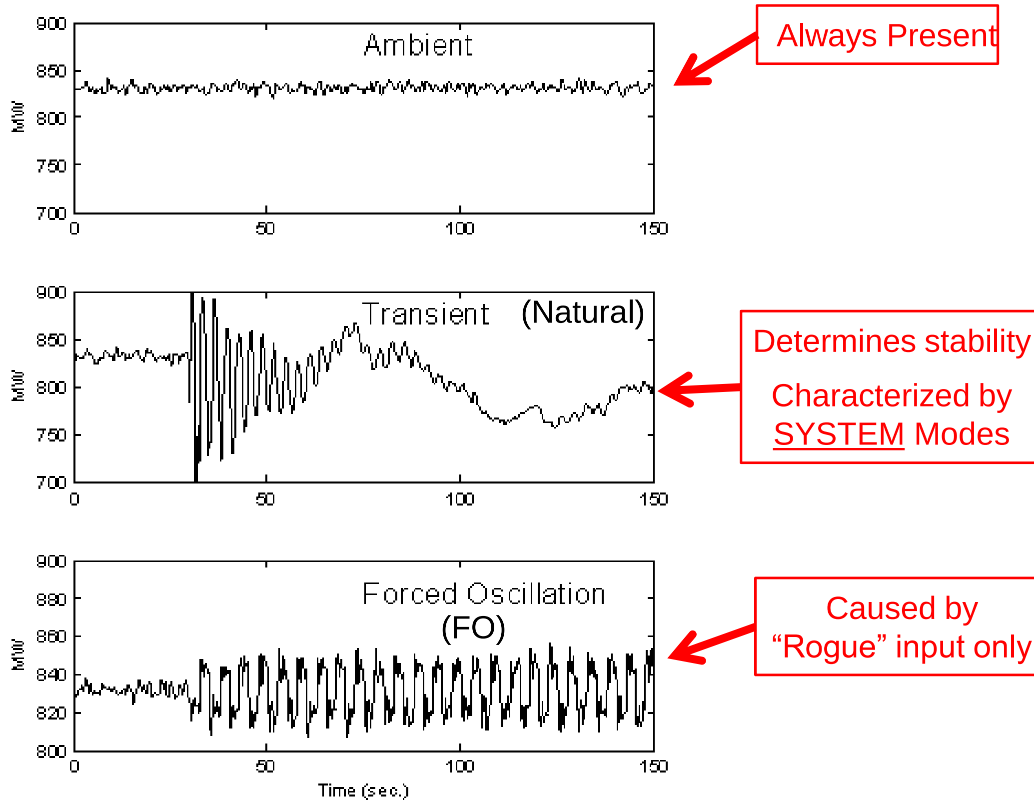
Overview

- Introduction to FO
- Characteristics of FO
- Distinguishing between FO and natural oscillations.
- Detecting FO
- Locating FO source

Introduction to FO

System Model

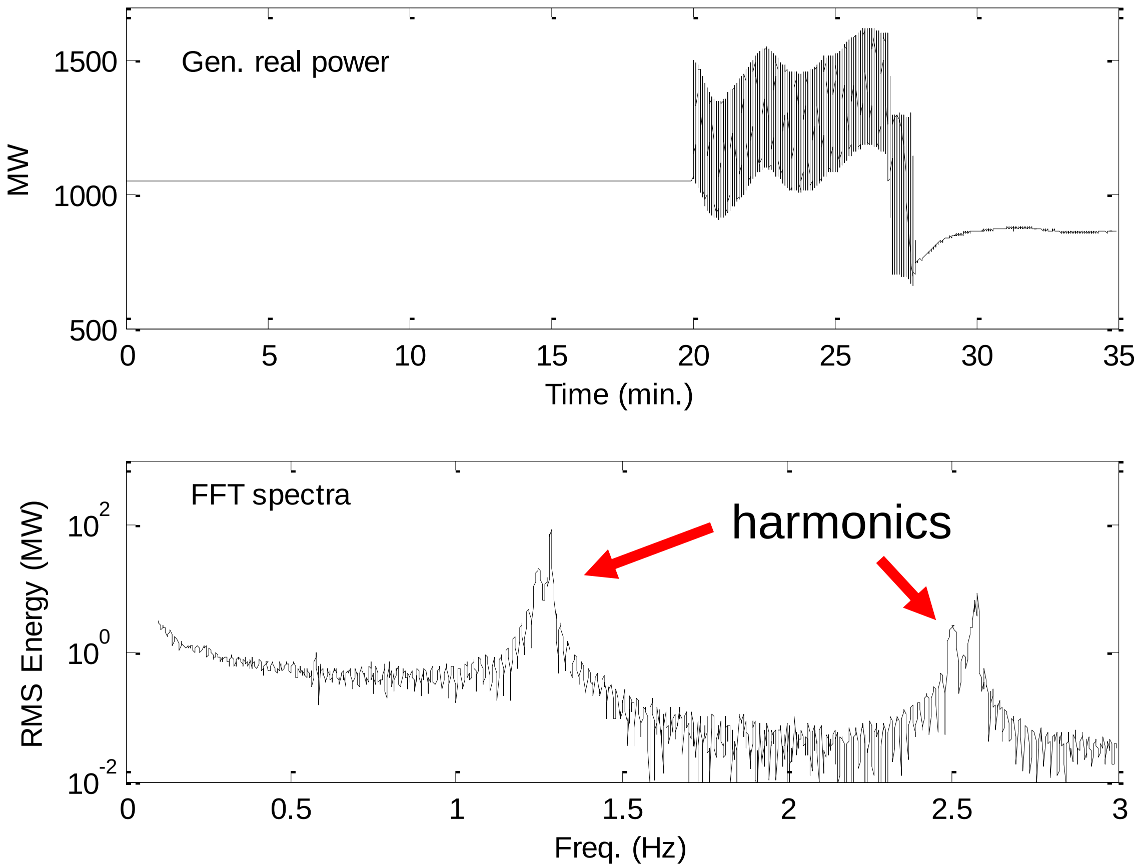




Forced Oscillations (FOs)

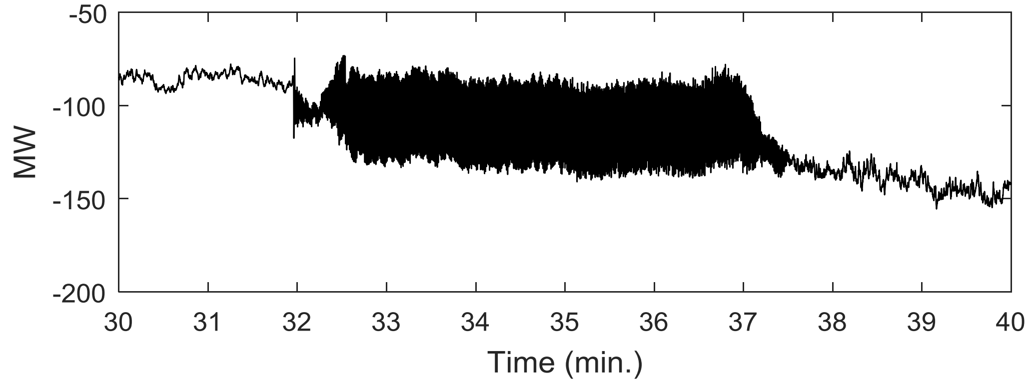
- Many causes, e.g.:
  - Generator rogue controller in limit cycle
  - Pulsing loads
  - NOT A SYSTEM INSTABILITY
- FOs very common
  - Periodically detected in the WECC system
- Can be very severe: Nov. 2005, Feb. 2010, Feb. 2014
- Easy to detect
- Can be difficult to locate
- Often bias Mode Meter algorithms

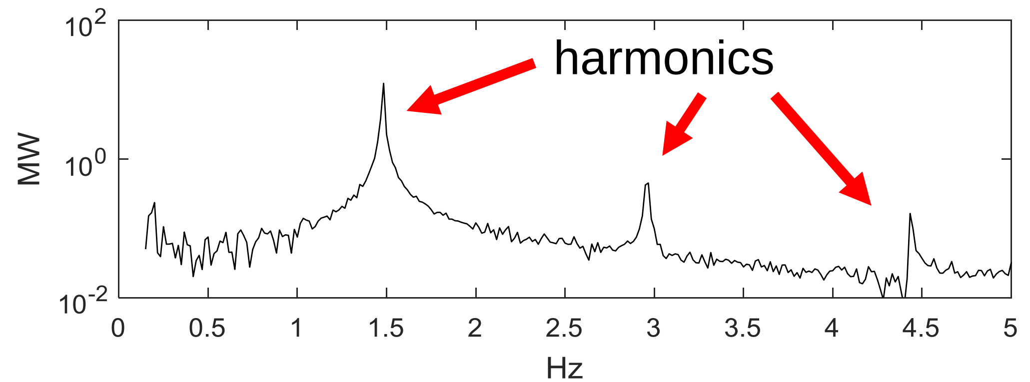
WECC FO, 2010

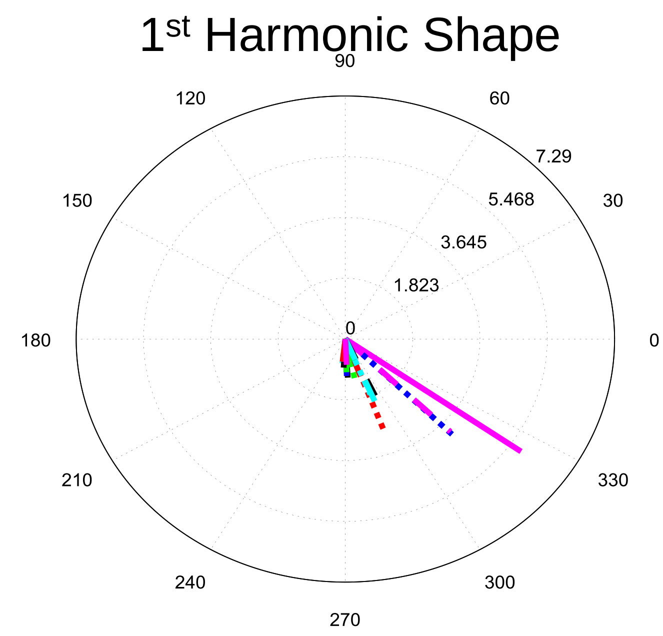


Gen. real power
MW
1500
1000
500
0
5
10
15
20
25
30
35
Time (min.)
FFT spectra
harmonics
RMS Energy (MW)
10^2
10^0
10^{-2}
0
0.5
1
1.5
2
2.5
3
Freq. (Hz)

WECC FO, 2015

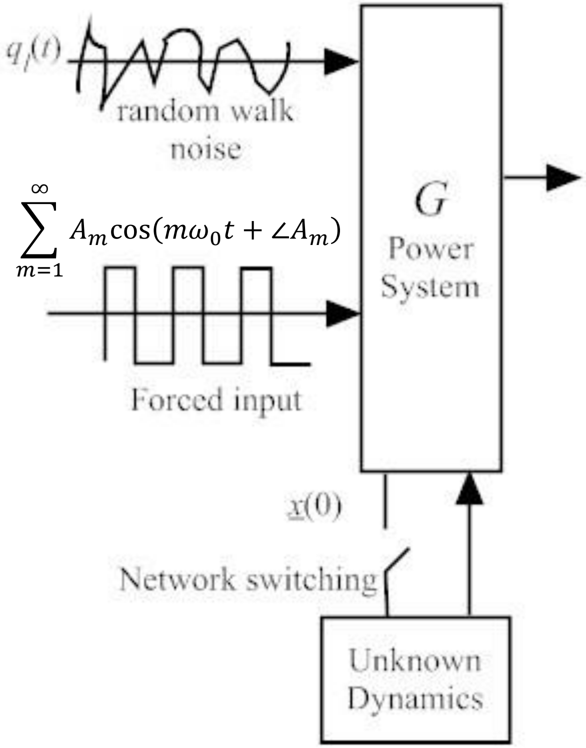

-50
-100
-150
-200
MW
30
31
32
33
34
35
36
37
38
39
40
Time (min.)


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


1st Harmonic Shape
90
120
60
150
30
180
0
210
330
240
300
270
7.29
5.468
3.645
1.823
0

FO characteristics

FO Characteristics



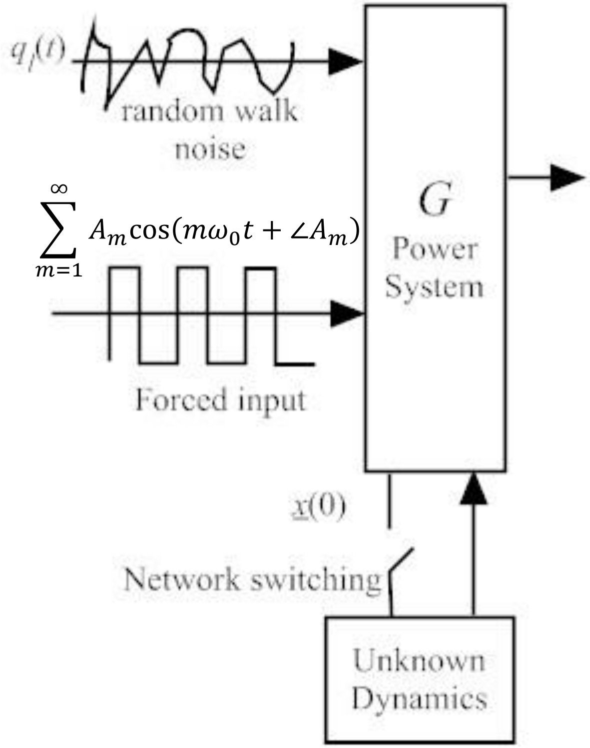
$$x_r(t) = \sum_{m=1}^{\infty}\left[\left|\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right||A_m|\cos\left(m\omega_0 t+\angle\left(A_m\sum_{i=1}^{N}\frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0-\lambda_i}\right)\right)\right] \Rightarrow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

$$+\left[\sum_{i=0}^{N}2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Rightarrow \textbf{Transient}$$

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

x_r = location r
$\lambda_i = \sigma_i + j\omega_i$ = ith system mode (eigenvalue)
v_i, u_i = ith left, right eigenvectors
b_1 = input vector for forced input
b_{2l} = input vector for lth random load

FO Characteristics



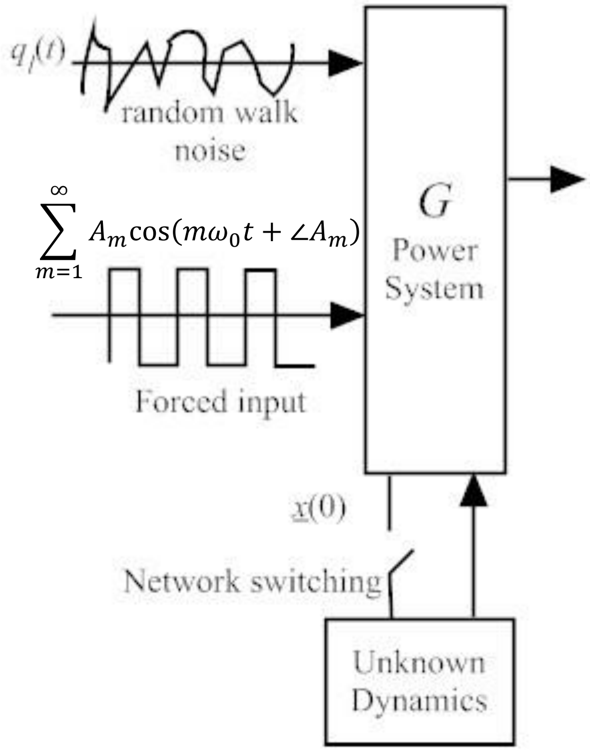
Harmonics

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

$$+ \left[\sum_{i=0}^{N} 2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right| e^{\sigma_i t} \cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Rightarrow \textbf{Transient}$$

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

FO Characteristics



FO Shape
(No Damping)

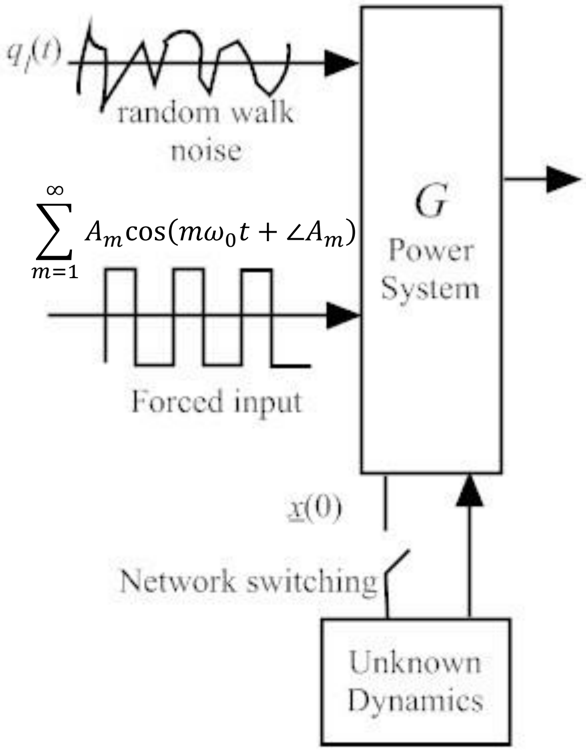
Harmonics

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

$$+\left[\sum_{i=0}^{N}2\left|\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right|e^{\sigma_i t}\cos\left(\omega_i t+\angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0)\right)\right)\right] \Rightarrow \textbf{Transient}$$

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

FO Characteristics



Harmonics

FO Shape (No Damping)

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

$$+ \left[\sum_{i=0}^{N} 2\left| \underline{u}_{ir}\underline{v}_i\underline{x}(0) \right| e^{\sigma_i t} \cos\left(\omega_i t + \angle\left(\underline{u}_{ir}\underline{v}_i\underline{x}(0) \right) \right) \right] \Rightarrow \textbf{Transient}$$

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

Colored by the **SYSTEM**

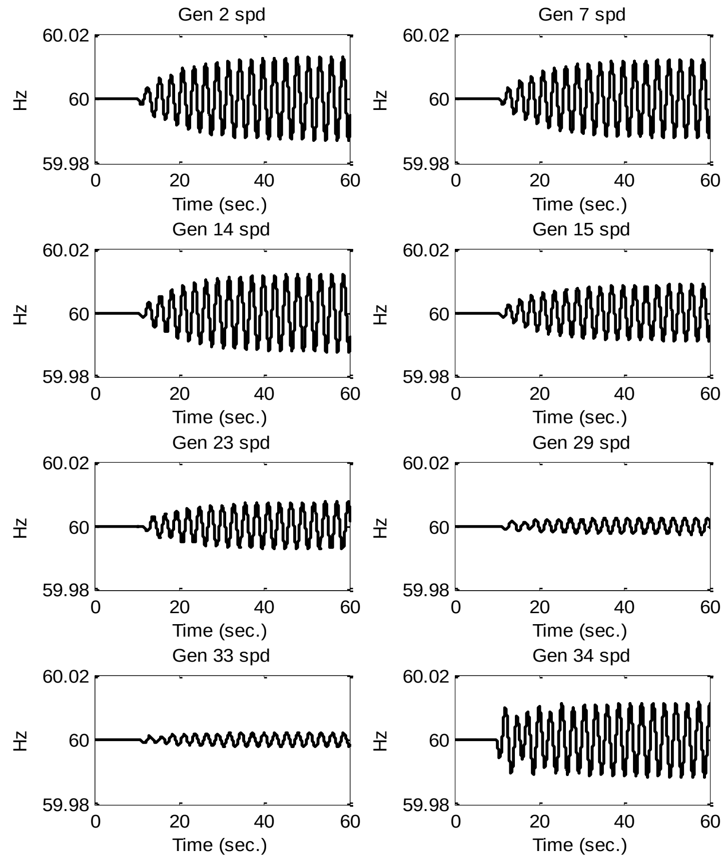
FO Characteristics – The "Shape"

$$\sum_{i=1}^{N} \frac{\underline{u}_{ir}\underline{v}_i\underline{b}_1}{jm\omega_0 - \lambda_i}$$

- FO shape is unique
- FO shape can be calculated from PMU measurements (amplitude and phase). – Spectral, filters, etc.
- If FO frequency is NOT at a system mode, FO shape typically points to the FO source (amplitude and phase).
  - Based upon simulations and real-world experiences.
  - Bases for current Oscillation Detection approaches.
  - System freq may be the best "locating" signal
- FO shape converges to SYSTEM MODE SHAPE if FO is at the mode freq. MOST DIFFICULT AND INTERESTING CASE.

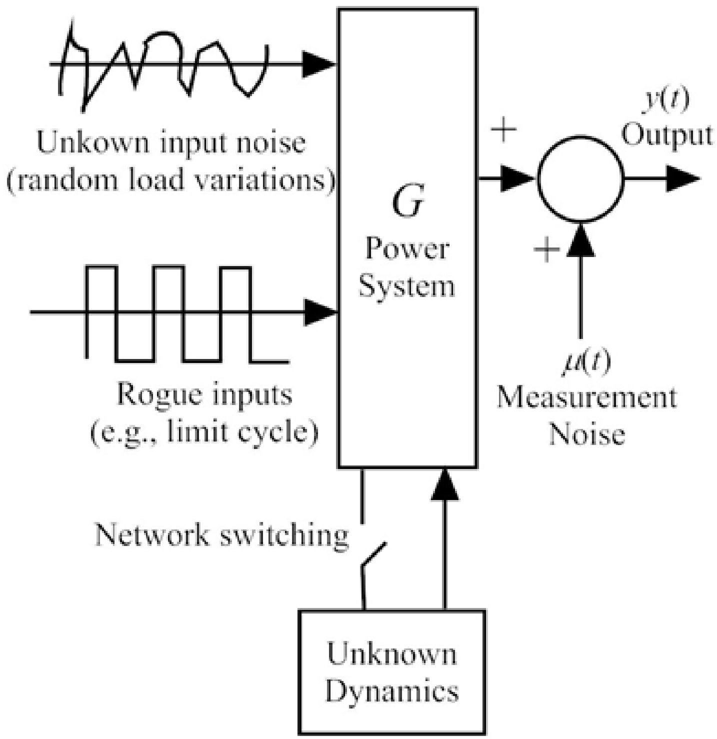
FO at a System Mode

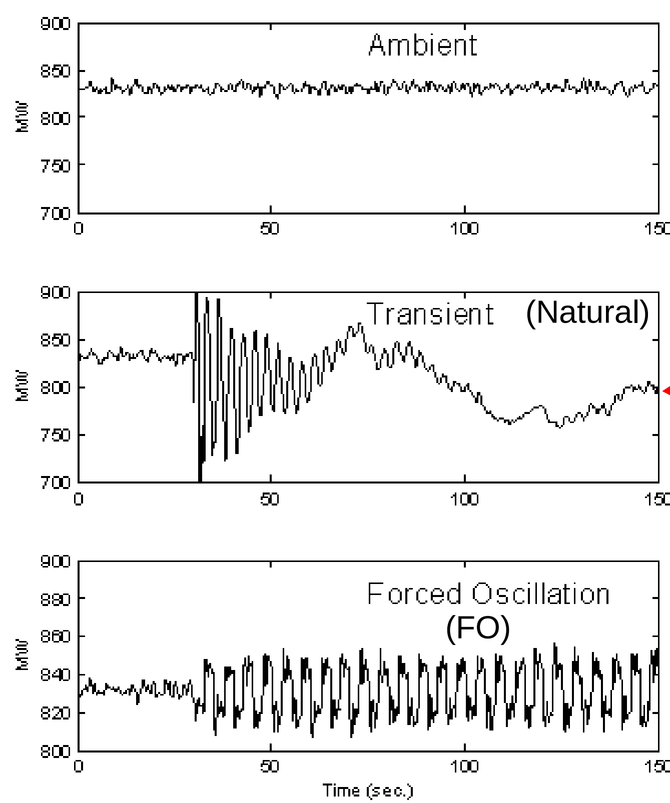
Gen #	Mode Shape		FO Shape	
	Mag	Angle (deg)	Mag	Angle (deg)
2	1.08	-1	1.07	4
7	1	0	1	0
14	1.04	-11	1.01	-12
15	0.73	1	0.73	0
23	0.64	-167	0.61	-164
29	0.21	-153	0.22	-141
33	0.15	-20	0.18	-31
34	0.85	-177	0.95	139



Distinguishing between FO and natural (transient) oscillations

System Model





Always Present

Determines stability

Characterized by SYSTEM Modes

Caused by "Rogue" input only

Transient vs Forced

Forced

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

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

Transient

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

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

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

Transient vs Forced

Forced

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

Harmonics

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

Transient

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

No Harmonics

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

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

Transient vs Forced

Forced

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

Harmonics

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

Transient

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

No Harmonics

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

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

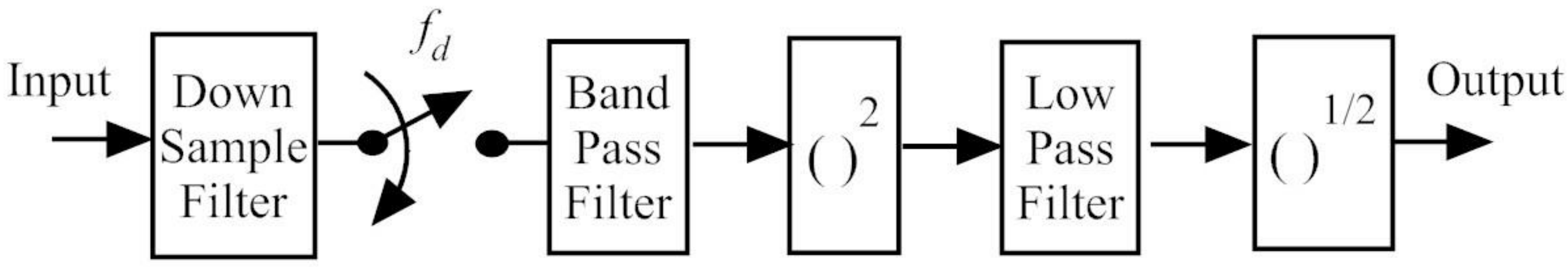
Unique to a Transient

Detecting Oscillations

Detecting Oscillations

- Signal Processing Methods for Detecting Oscillations (NOT NECESSARILY FO)
- RMS Energy
  - Fast, easy to automate
  - Don’t provide much resolution in freq.
  - May miss very small oscillations
- Spectral methods
  - Many varieties
  - Slow and more difficult to automate
  - Provide better resolution
  - Can detect very small oscillations

RMS Energy Filtering

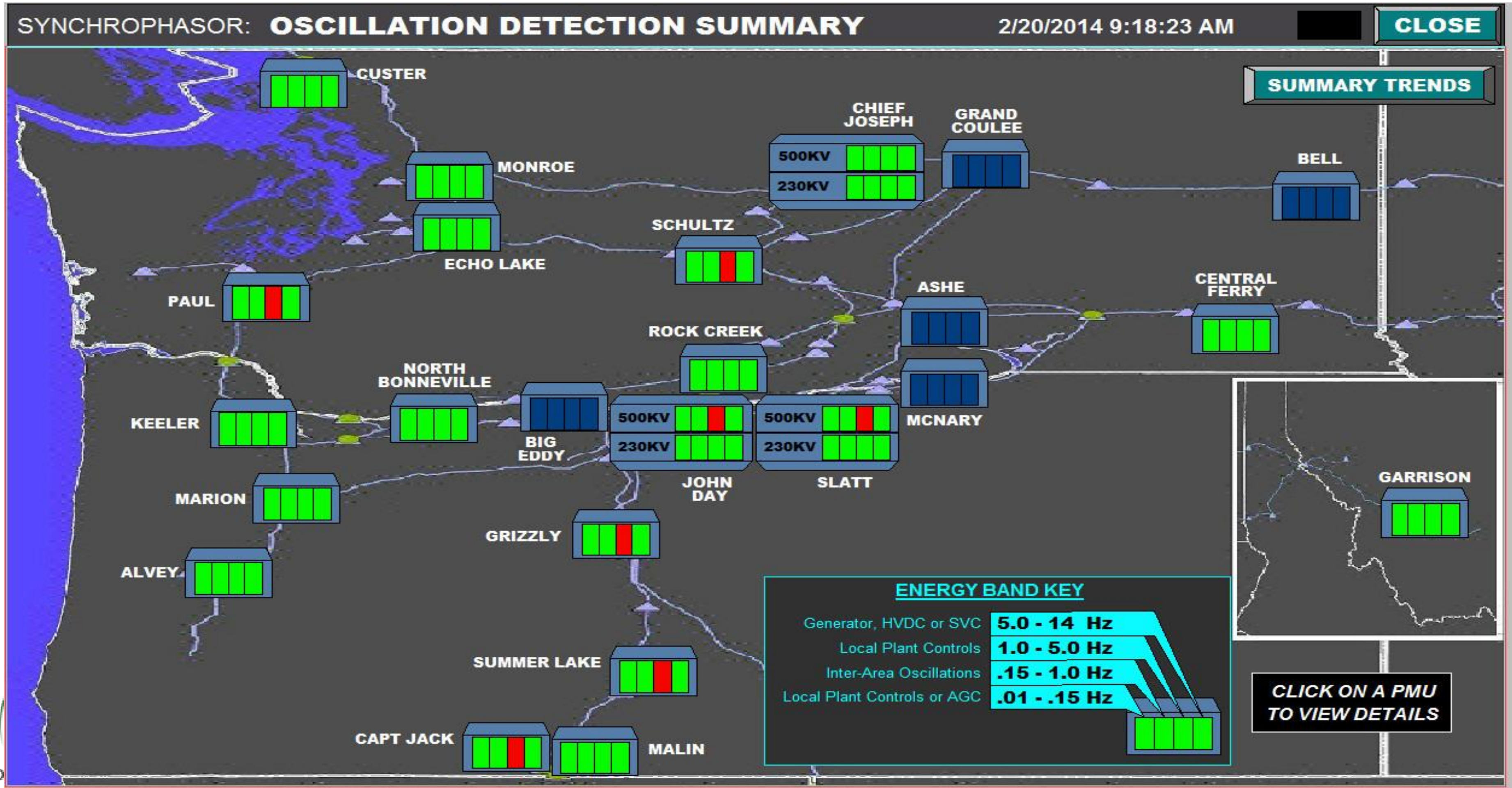


- Band 1 = 0.01 to 0.15 Hz = Speed governor band.
- Band 2 = 0.15 to 1 Hz = Inter-area electromechanical band.
- Band 3 = 1 to 5 Hz = Local electromechanical and controls band.
- Band 4 = 5.0 to 14 Hz = High frequency band (e.g., torsional dynamics).

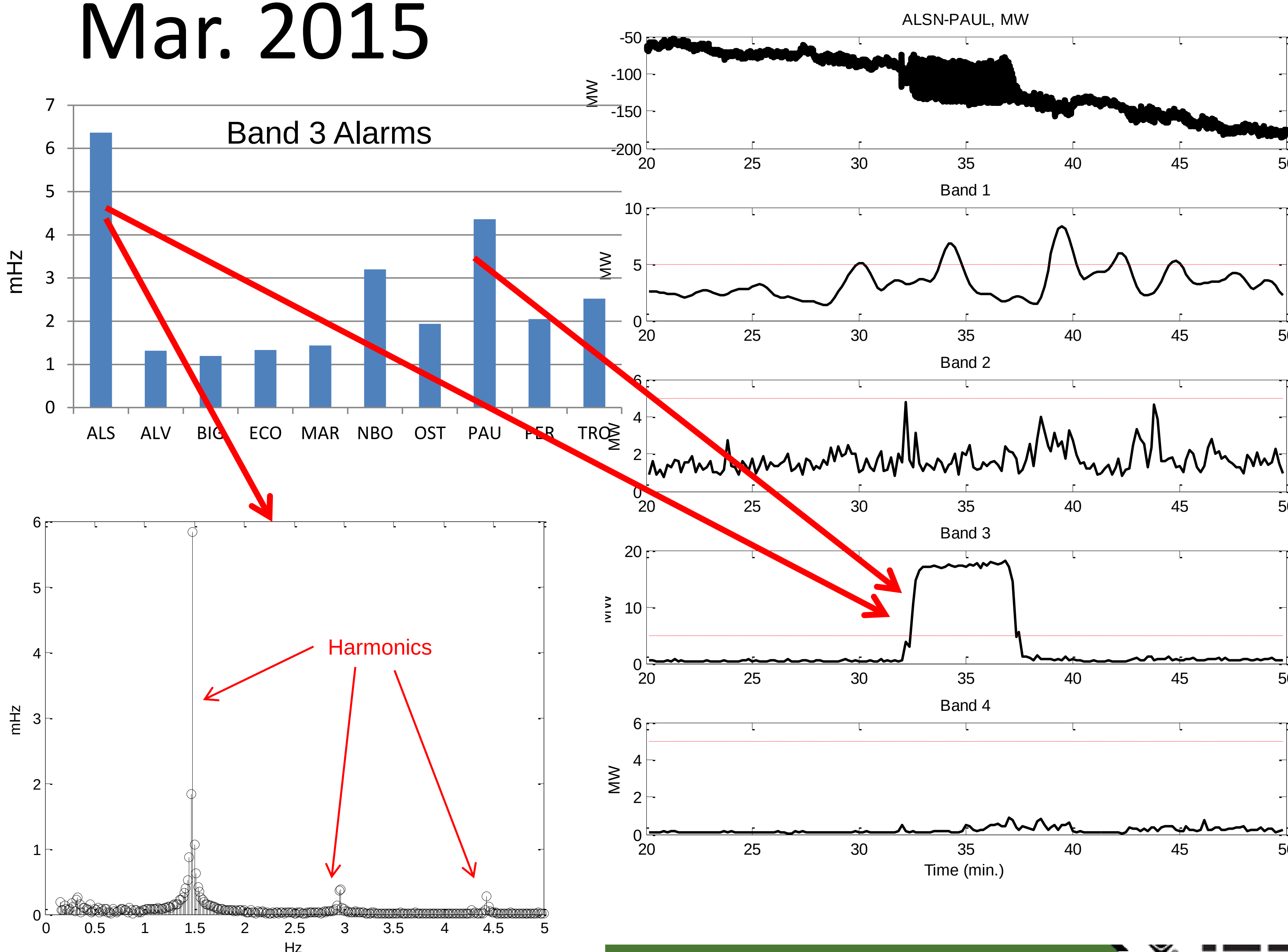
Screen Capture of BPA's Oscillation Detector

Alarms based upon oscillation energy

Cannot distinguish between a sustatined Transient and FO



Mar. 2015



ALSN-PAUL, MW
Band 1
Band 2
Band 3
Band 4
Time (min.)
MW
Band 3 Alarms
mHz
ALS
ALV
BIG
ECO
MAR
NBO
OST
PAU
TRO
Harmonics
Hz

Locating FO sources

Locating FO

- Most FO locating research based on signal processing approaches
- Many ASSUME that an observed oscillation is an FO
- Many ASSUME the source location (or shape) is where the largest amplitude oscillation is observed
  - Often true if FO is not near a system's natural mode
  - If FO is at system mode, FO shape converges to mode shape; therefore, amplitude misleading
- Current research is focusing on bringing power-system knowledge into the locating logic

Example
Locating Mechanical Torque FO

- Many FO originate from a faulty turbine control system (e.g., valve in a limit cycle).
- Consider the equation of motion for generator i:

$$2H_i\Delta\omega_i(s) = \underbrace{G_{gov,i}(s)\Delta\omega_i(s)}_{\text{Mechanical Torque from governor}} + \underbrace{\Delta T_{f,i}(s)}_{\text{Mechanical Torque FO}} - \Delta T_{e,i}(s)$$

- If H_i and $G_{gov,i}$ are known (or approximated), signal processing can be used to estimate the existence of $\Delta T_{f,i}(s)$
- Current research is looking at this approach.

Conclusions

- Many causes, e.g.:
  - Generator rogue controller in limit cycle
  - Pulsing loads
  - NOT A SYSTEM INSTABILITY!
- FOs very common
- Fairly easy to detect
- Can be difficult to locate if FO is near system mode
- Often bias Mode Meter algorithms
- Current research
  - Distinguishing between FO and natural oscillations
  - Locating FO sources
  - Non-biased mode meter algorithms

Questions?