Measurement Based Stability Assessment

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Overview

• Develop, test, and refine algorithms to automatically estimate and quantify oscillations from PMUs in real time.
• Application
  – Real-Time Situational Awareness based upon actual system observations
• Participants:
  – Dan Trudnowski, Montana Tech
  – John Pierre, University of Wyoming
  – Lots of graduate students
• Collaborations (Past year)
  – PNNL (Jim Follum)
  – BPA (Nick Leitschuh, Dmitry Kosterev)
  – PEAK/WECC
System Model

Always Present

Determines stability
Characterized by SYSTEM Modes

Caused by “Rogue” input only

Unknown input noise (random load variations)
Rogue inputs (e.g., limit cycle)
Network switching
Unknown Dynamics

\( G \)

Power System

\( y(t) \)
Output

\( \mu(t) \)
Measurement Noise

Ambient

Transient (Natural)

Forced Oscillation (FO)
Screen Capture of BPA’s Mode Meter

Tracks SYSTEM Modes
Assumes Ambient and/or Transient condition
FO biases results
Screen Capture of BPA’s Oscillation Detector

Alarms based upon oscillation energy

Cannot distinguish between a Transient and FO
Project Objectives/Accomplishments

• Understand the fundamental nature and impact of FOs
  – FO harmonics, FO Shape, “Sinusoid” Noise in an undamped Transient
  – Most interesting (and difficult) case: FOs at system mode
• Develop Mode Meter algorithms that work in the presence of FOs
  – Several algorithms developed. Results presented at the 2014 review.
  – Methods require knowledge of the FO
  – WECC case: Sep 2014
• Develop Oscillation Detection Approaches
  – Goals:
    • Automated (no tuning, operations) – We’re pretty good at this with Energy Methods
    • Determine if an oscillation is natural or forced - Very difficult
    • Identify the root cause (location) of a FO – Energy and shape typically point to the source
• Modal Analysis Software Development (BPA, PEAK, EPG)
  – Oscillation Detector and Mode Meter used at the BPA control center for alarming
  – Working with BPA to refine and define alarming – Setting alarm thresholds
  – Support PEAK/WECC in the implementation of MAS
• BPA/WECC Probing Tests Support
  – Help design tests, analyze data
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 BPA OD System


- Often bias Mode Meter algorithms (Sep. 2014)
**FO Theory**

\[
x_r(t) = \sum_{m=1}^{\infty} \left[ \sum_{i=1}^{N} \frac{u_{ir} v_i b_1}{jm \omega_0 - \lambda_i} \right] A_m \cos \left( m \omega_0 t + \angle \left( A_m \sum_{i=1}^{N} \frac{u_{ir} v_i b_1}{jm \omega_0 - \lambda_i} \right) \right)
\Rightarrow \text{FO}
\]

\[
+ \sum_{i=0}^{N} 2 \left| u_{ir} v_j x(0) \right| e^{\sigma_i t} \cos \left( \omega_i t + \angle \left( u_{ir} v_j x(0) \right) \right) \Rightarrow \text{Transient}
\]

\[
+ \sum_{l=1}^{M} q_l(t) \oplus \left[ \sum_{i=1}^{N} \left| u_{ir} v_j b_{2i} \right| e^{\sigma_i t} \cos \left( \omega_i t + \angle \left( u_{ir} v_j b_{2i} \right) \right) \right] \Rightarrow \text{Colored Noise}
\]

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

\[ x_r(t) = \sum_{m=1}^{\infty} \left[ \sum_{i=1}^{N} \frac{u_{ir} v_j b_1}{j m \omega_0 - \lambda_i} \right] |A_m| \cos \left( m \omega_0 t + \angle \left( A_m \sum_{i=1}^{N} \frac{u_{ir} v_j b_1}{j m \omega_0 - \lambda_i} \right) \right) \Rightarrow \text{FO} \]

\[ + \sum_{i=0}^{N} 2 |u_{ir} v_j x(0)| e^{\sigma_i t} \cos(\omega_i t + \angle (u_{ir} v_j x(0))) \Rightarrow \text{Transient} \]

\[ + \sum_{l=1}^{M} q_l(t) \odot \left[ \sum_{i=1}^{N} |u_{ir} v_j b_{2l}| e^{\sigma_i t} \cos(\omega_i t + \angle (u_{ir} v_j b_{2l})) \right] \Rightarrow \text{Colored Noise} \]
FO Theory

\[
x_r(t) = \sum_{m=1}^{\infty} \left[ \sum_{i=1}^{N} \frac{u_{ir} v_j b_1}{jm \omega_0 - \lambda_i} \right] A_m \cos\left(\omega_0 t + \angle\left( \sum_{i=1}^{N} \frac{u_{ir} v_j b_1}{jm \omega_0 - \lambda_i} \right) \right) \Rightarrow \text{FO}
\]

\[
+ \sum_{i=0}^{N} 2 |u_{ir} v_j x(0)| e^{\alpha_i t} \cos(\omega_i t + \angle(u_{ir} v_j x(0))) \Rightarrow \text{Transient}
\]

\[
+ \sum_{i=1}^{M} q_i(t) \odot \left[ \sum_{i=1}^{N} |u_{ir} v_j b_{2i} b_{2i}| e^{\alpha_i t} \cos(\omega_i t + \angle(u_{ir} v_j b_{2i})) \right] \Rightarrow \text{Colored Noise}
\]
FO Theory

\[ x_r(t) = \sum_{m=1}^{\infty} \left[ \left| \sum_{i=1}^{N} \frac{u_{ir} v_j b_{1i}}{m \omega_0 - \lambda} \right| A_m \cos \left( m \omega_0 t + \angle \left( \sum_{i=1}^{N} \frac{u_{ir} v_j b_{1i}}{m \omega_0 - \lambda} \right) \right) \right] \]

\[ + \sum_{i=0}^{N} \left[ \frac{u_{ir} v_j x(0)}{m \omega_0 - \lambda} \right] e^{\sigma_i t} \cos \left( \omega_i t + \angle \left( u_{ir} v_j x(0) \right) \right) \]

\[ + \sum_{i=1}^{M} q_i(t) \otimes \sum_{i=1}^{N} \left[ u_{ir} v_j b_{2i1} \right] e^{\sigma_i t} \cos \left( \omega_i t + \angle \left( u_{ir} v_j b_{2i1} \right) \right) \]

\[ \Rightarrow \text{FO} \]

\( \Rightarrow \text{Transient} \)

\( \Rightarrow \text{Colored Noise} \)

Colored by the SYSTEM
FO Theory – The “Shape”

\[ \sum_{i=1}^{N} \frac{u_{ir}v_i b_1}{jm\omega_0 - \lambda_i} \]

- 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

<table>
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<tr>
<th>Gen #</th>
<th>Mode Shape</th>
<th>FO Shape</th>
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<tbody>
<tr>
<td></td>
<td>Mag</td>
<td>Angle (deg)</td>
</tr>
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<td>-1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>0</td>
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<tr>
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<tr>
<td>33</td>
<td>0.15</td>
<td>-20</td>
</tr>
<tr>
<td>34</td>
<td>0.85</td>
<td>-177</td>
</tr>
</tbody>
</table>

![Graphs of Gen 2, Gen 7, Gen 14, Gen 15, Gen 23, Gen 29, Gen 33, Gen 34 speed oscillations.](image)
Transient vs Forced

Forced
\[
\ddot{x}_r(t) = \sum_{m=1}^{\infty} \left[ \left| \sum_{i=1}^{N} \frac{u_{ir} v_i b_i}{jm\omega_0 - \lambda_i} \right| A_m |\cos (m\omega_0 t + \angle \left( A_m \sum_{i=1}^{N} \frac{u_{ir} v_i b_i}{jm\omega_0 - \lambda_i} \right) ) \right] \Rightarrow \text{FO}
\]
\[
\sum_{l=1}^{M} \left[ q_l(t) \otimes \left| \sum_{i=1}^{N} u_{ir} v_i b_{2l} |e^\sigma t \cos (\omega_l t + \angle (u_{ir} v_i b_{2l})) \right| \right] \Rightarrow \text{Colored Noise}
\]

Transient
\[
\ddot{x}_r(t) = 2|u_{nr} v_n x(0)| \cos (\omega_n t + \angle (u_{nr} v_n x(0))) \Rightarrow \text{Transient}
\]
\[
\sum_{l=1}^{M} \left[ q_l(t) \otimes \left| \sum_{i \neq n} u_{ir} v_i b_{2l} |e^\sigma t \cos (\omega_l t + \angle (u_{ir} v_i b_{2l})) \right| \right] \Rightarrow \text{Colored Noise}
\]
\[
\sum_{l=1}^{M} [q_l(t) \otimes |u_{nr} v_n b_{2l} | \cos (\omega_n t + \angle u_{nr} v_n b_{2l})] ] \Rightarrow \text{Sinusoid Noise}
\]
Transient vs Forced

Forced
\[ \ddot{x}_r(t) = \sum_{m=1}^{\infty} \left[ \sum_{l=1}^{N} \frac{u_{lr}v_l b_1}{j m_0 - \lambda_l} \right] |A_m| \cos \left( m \omega_0 t + \angle \left( A_m \sum_{l=1}^{N} \frac{u_{lr}v_l b_1}{j m_0 - \lambda_l} \right) \right) \Rightarrow \text{FO} \]
\[ \sum_{l=1}^{M} q_l(t) \odot \left[ \sum_{l=1}^{N} |u_{lr}v_l b_2| e^{\sigma_l t} \cos \left( \omega_l t + \angle \left( u_{lr}v_l b_2 \right) \right) \right] \Rightarrow \text{Colored Noise} \]

Transient
\[ \ddot{x}_r(t) = 2 |u_{nr}v_n x(0)| \cos \left( \omega_n t + \angle \left( u_{nr}v_n x(0) \right) \right) \Rightarrow \text{Transient} \]
\[ \sum_{l=1}^{M} q_l(t) \odot \left[ \sum_{l\neq n}^{N} |u_{lr}v_l b_2| e^{\sigma_l t} \cos \left( \omega_l t + \angle \left( u_{lr}v_l b_2 \right) \right) \right] \Rightarrow \text{Colored Noise} \]
\[ \sum_{l=1}^{M} \left[ q_l(t) \odot \left| u_{nr}v_n b_2 \right| \cos \left( \omega_n t + \angle u_{nr}v_n b_2 \right) \right] \Rightarrow \text{Sinusoid Noise} \]
Transient vs Forced

### Forced

\[
\tilde{x}_r(t) = \sum_{m=1}^{\infty} \left[ \left| \sum_{i=1}^{N} \frac{u_{ir} v_i b_1}{j m \omega_0 - \lambda_i} \right| A_m \cos \left( m \omega_0 t + \angle \left( A_m \sum_{i=1}^{N} \frac{u_{ir} v_i b_1}{j m \omega_0 - \lambda_i} \right) \right) \right] \Rightarrow \text{FO}
\]

\[
+ \sum_{l=1}^{M} \left[ q_l(t) \otimes \left[ \sum_{i=1}^{N} |u_{ir} v_i b_{2l}| e^{\sigma_l t} \cos (\omega_i t + \angle (u_{ir} v_i b_{2l})) \right] \right] \Rightarrow \text{Colored Noise}
\]

### Transient

\[
\tilde{x}_r(t) = 2 |u_{nr} v_n x(0)| \cos (\omega_n t + \angle (u_{nr} v_n x(0))) \Rightarrow \text{Transient}
\]

\[
+ \sum_{l=1}^{M} \left[ q_l(t) \otimes \left[ \sum_{i \neq n}^{N} |u_{ir} v_i b_{2l}| e^{\sigma_l t} \cos (\omega_i t + \angle (u_{ir} v_i b_{2l})) \right] \right] \Rightarrow \text{Colored Noise}
\]

\[
+ \sum_{l=1}^{M} \left[ q_l(t) \otimes \left[ |u_{nr} v_n b_{2l}| \cos (\omega_n t + \angle (u_{nr} v_n b_{2l})) \right] \right] \Rightarrow \text{Sinusoid Noise}
\]

Unique to a Transient
Source Locating using System Freq

An Oscillation Detection Example
BPA
Mar. 2015

Band 3 Alarms

Harmonics
Publications (Past year)

Conclusions, Future Work, and Risk Factors

• Conclusions
  – Developing a fundamental understanding of the nature of FOs
    • FO harmonics, FO Shape, “Sinusoid” Noise in an undamped Transient
    • Most interesting (and difficult) case: FOs at system mode.
  – Develop Mode Meter algorithms that work in the presence of FOs
    • Several algorithms developed. Require knowledge of the FO freq.
  – Oscillation Detection
    • Energy methods appear to work very well
    • Source locating is mostly heuristic (system frequency signals)
  – MAS Support (BPA, PEAK, EPG)

• Future
  – Oscillation Detection
    • Are Energy methods the best for power systems?
    • Distinguishing between FOs and Transients (“Sinusoid” noise, other physics?)
    • Locating the source (can we be more scientific?)
  – Conduct detailed comparison of Mode Meter algorithms
    • Include FO cases
    • Luke Dosiek (Union College)
    • Collaboration: Bernie Lesieutre (UWiscon)

• Risk Factor
  – Access to real-life data
Extra Slides
Mode Meter Confidence Bounds

- Mode Meter Confidence Bounds: Indicator of the statistical performance (mean and variance) of a mode meter
- Confidence Bound Methods Investigated and Developed
  - Monte Carlo Simulations for Error Bounds
  - Bootstrap Methods for Error Bounds
  - Computationally Efficient Bootstrap Methods
  - Recursive Maximum Likelihood (RML) Method for Mode Estimation with Closed Form Expressions for Error Bounds (no bootstrapping or monte carlo!)
Development of Mode Meter Algorithms that Work in Presence of Forced Oscillations

• Problem: Periodic Forced Oscillations (at frequencies close to modes) can fool traditional mode meters into thinking there is a lightly damped mode

• Solution: Incorporate possibility of FO into Mode Meter Algorithm

• Two New Algorithms
  – LS-ARMA+S (Least Squares Autoregressive Moving Average plus Sinusoid)
  – YW-ARMA+S (Yule Walker Autoregressive Moving Average plus Sinusoid)
Example: Small Forced Oscillation

Small FO starting at the 4 minute mark and extending to the 16 minute mark
Mode Meter Results: Traditional (LS-ARMA) & One that Incorporates Detecting Forced Oscillations (LS-ARMA+S)

Frequency Estimate
True Mode Frequency 0.372
FO frequency 0.392 Hz

Damping Ratio Estimate
True Damping Ratio
4.66%