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

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

$G$
Power System

+y(t)
Output

$\mu(t)$
Measurement Noise

Unknown Dynamics

Ambient

Transient (Natural)

Forced Oscillation (FO)
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


• Easy to detect

• Can be difficult to locate

• Often bias Mode Meter algorithms
WECC FO, 2010

- **Gen. real power**
  - Time (min.): 0, 0.5, 1, 1.5, 2, 2.5, 3
  - MW: 0, 5, 10, 15, 20, 25, 30, 35

- **FFT spectra**
  - Freq. (Hz): 0, 0.5, 1, 1.5, 2, 2.5, 3
  - RMS Energy (MW): 10^-2, 10^-1, 10^0, 10^-2

- **Harmonics**
WECC FO, 2015

Harmonics

1st Harmonic Shape
FO characteristics
FO Characteristics

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

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

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

\[ x_r = \text{location } r \]
\[ \lambda_i = \sigma_i + j\omega_i = \text{ith system mode (eigenvalue)} \]
\[ v_i, u_i = \text{ith left, right eigenvectors} \]
\[ b_1 = \text{input vector for forced input} \]
\[ b_{2l} = \text{input vector for lth random load} \]
\[ x_r(t) = \sum_{m=1}^{\infty} \left[ \sum_{i=1}^{N} \frac{u_{ir}v_{i1}}{jm\omega_0 - \lambda_i} \right] A_m \cos \left( m\omega_0 t + \angle \left( A_m \sum_{i=1}^{N} \frac{u_{ir}v_{i1}}{jm\omega_0 - \lambda_i} \right) \right) \Rightarrow FO \]

\[ \text{Harmonics} \quad + \sum_{i=0}^{N} 2 |u_{ir}v_{i1}x(0)| e^{\sigma_i t} \cos \left( \omega_i t + \angle (u_{ir}v_{i1}x(0)) \right) \Rightarrow \text{Transient} \]

\[ \text{Unforced input} \quad + \sum_{i=1}^{M} q_i(t) \otimes \left[ \sum_{i=1}^{N} |u_{ir}v_{i2}| e^{\sigma_i t} \cos \left( \omega_i t + \angle (u_{ir}v_{i2}) \right) \right] \Rightarrow \text{Colored Noise} \]
FO Characteristics

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

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

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

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

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

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

Harmonics

FO Shape (No Damping)

Colored by the SYSTEM

\[ \sum_{m=1}^{\infty} A_m \cos(m\omega_0 t + \angle A_m) \]

random walk noise

Forced input

\[ x(0) \]

Network switching

Unknown Dynamics

\[ q_i(t) \]
FO Characteristics – 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

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<th>Gen #</th>
<th>Mode Shape</th>
<th>FO Shape</th>
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<tr>
<td></td>
<td>Mag</td>
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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>
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Distinguishing between FO and natural (transient) oscillations
System Model

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

**Power System**

- **G**
- **y(t)** (Output)
- **μ(t)** (Measurement Noise)

**Always Present**
- Determines stability
- Characterized by SYSTEM Modes

**Caused by “Rogue” input only**
Transient vs Forced

**Forced**

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

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

**Transient**

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

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

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

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

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

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

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

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

**Forced**

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

\[ + \sum_{l=1}^{M} \left[ q_l(t) \oplus \left| \sum_{i=1}^{N} u_{ir}v_{jb}e^{\sigma_it} \cos \left( \omega_it + \angle (u_{ir}v_{jb}) \right) \right| \right] \Rightarrow \text{Colored Noise} \]

**Transient**

\[ \hat{x}_r(t) = 2 \left| u_{nr}v_{n}\bar{x}(0) \right| \cos \left( \omega_nt + \angle (u_{nr}v_{n}\bar{x}(0)) \right) \Rightarrow \text{Transient} \]

\[ + \sum_{l=1}^{M} \left[ q_l(t) \oplus \left| \sum_{i=1}^{N} u_{ir}v_{jb}e^{\sigma_it} \cos \left( \omega_it + \angle (u_{ir}v_{jb}) \right) \right| \right] \Rightarrow \text{Colored Noise} \]

\[ + \sum_{l=1}^{M} \left[ q_l(t) \oplus \left| u_{nr}v_{n}b_{2l} \cos(\omega_nt + \angle u_{nr}v_{n}b_{2l}) \right| \right] \Rightarrow \text{Sinusoid Noise} \]
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 sustained Transient and FO
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:

\[ 2H_i \Delta \omega_i(s) = G_{gov,i}(s) \Delta \omega_i(s) + \Delta T_{f,i}(s) - \Delta T_{e,i}(s) \]

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