Demystifying Power System Oscillations – Recent and Ongoing Efforts

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Power System Oscillations

- Power system oscillations
  - is a phenomenon of periodic energy exchange
  - represent dynamic risks
- PMU/FDR and AMI provide better observability
- Some historic events involving oscillations
  - 1996 Blackouts
  - 2003 Blackout
  - 2009 TX sub-synchronous oscillation (SSO)
- This talk only covers electromechanical, and up to electromagnetic oscillations
- Most relevant research aim to (i) **better understand** mechanisms and (ii) **mitigate properly**

Source: [1]

Source: [2]
Causes of Power System Oscillations

- Poorly-damped natural mode oscillation: bad control parameter, high loading

\[ \dot{x} = f(x) \approx Ax \]
\[ x = Py \]
\[ \dot{y} = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} y \]

if \( \exists i \in \{1, 2, \ldots, n\}, s.t. \text{Re}\{\lambda_i\} \approx 0 \)

Then, \( \omega_i = \text{Im}\{\lambda_i\}/2\pi \) is a poorly damped mode

- Forced oscillation: external periodic input, e.g. cyclic load

\[ \dot{x} = f(x) + Bu(t) \approx Ax + Bu(t) \]
\[ u(t) = A\cos(\omega t + \theta) \]

\[ x(t) = B\cos(\omega t + \varphi) \]

- New: Modulated oscillation – “nonlinear forced oscillation”

\[ \dot{x} = f(x) + Bu(t) \]
\[ u(t) = A\cos(\omega t + \theta) \]

\[ x(t) = B\cos(\omega t + \varphi) + C\cos(\omega't + \varphi) \]
Traditional Oscillation Analysis

- Traditional oscillation analysis aim at the detection, modal parameter estimation, and classification of oscillations.
  - Oscillation frequency, damping and mode shape
    \[ \hat{y}(t) = \sum_{i=1}^{n} A_i e^{\sigma_i t} \cos(\omega_i t + \theta_i) \]
- Model-based approach – small-signal analysis
  - Linearization → Eigen-analysis → modal parameters
- Measurement-based approaches [3]
  - Linear ring-down analysis: Prony, Matrix Pencil, ERA
  - Mode-meter analysis: R3LS, N4SID
  - Nonlinear methods: HHT, Energy tracker
- In current practice, oscillation analysis results are mostly used for monitoring purpose, while not much actionable info.

Recent Efforts on Nonlinear Oscillations

- Frequency-amplitude (F-A) curve [4-5]

  \[ OF = \frac{1}{2(t_{\text{max}} - t_{\text{min}})} \left[ \sqrt{\frac{\beta}{2}} \left( \frac{\sin(\delta_{\text{max}}/2) + \sin(-\delta_{\text{max}}/2)}{m(\delta_{\text{max}})} \right) \right] \]

  where \( m(x) = \sqrt{\cos \delta - \cos(\delta + x) - x \sin \delta} \)

Formulation of F-A curve

Properties of F-A curve

Quantification of the F-A characteristic indicates the margin to instability

Recent Efforts on Nonlinear Oscillations

- Test of F-A curve on the WECC 179-bus system

California-Oregon Intertie involved in August 1996 Blackout
Recent Efforts on Nonlinear Oscillations

• Modulated oscillation [6]

Forced oscillation with a frequency $\omega_{so}$ added to the magnitude of infinite bus

$$V_m = V_0 + \eta_{so} \sin(\omega_{so} t)$$

$\sim 0.03$Hz oscillations occurs in addition to the forcing frequency at $\sim 2$Hz.

A closer look using bifurcation analysis


Recent Efforts on Oscillation Source Location (OSL)

• Some existing methods (by 2015) for locating the oscillation source [7]

<table>
<thead>
<tr>
<th>Category</th>
<th>Key Idea</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping torque</td>
<td>The generator with a negative damping torque coefficient is the source</td>
<td>Possible unavailability of rotor angle and speed data. Possible failures under forced oscillation cases.</td>
</tr>
<tr>
<td>Mode shape</td>
<td>Largest magnitude, most leading phase of the mode shape or their combinations may indicate the source</td>
<td>Lack of a theoretical foundation. Possible failures for cases having weakly damped/undamped oscillation together with forced oscillation.</td>
</tr>
<tr>
<td>Energy</td>
<td>The device producing dissipation energy is the source</td>
<td>Strong assumption in modeling loads and network. Lack of theoretical proofs for multi-mode cases.</td>
</tr>
<tr>
<td>Equivalent circuit</td>
<td>The source of the equivalent circuit is the source of the oscillation</td>
<td>Possible failures when the phasor concept cannot be applied, e.g. non-sinusoidal oscillations. Lack of theoretical proofs for multi-mode oscillation cases.</td>
</tr>
<tr>
<td>Hybrid</td>
<td>A larger difference between simulations and measurements indicates the source</td>
<td>Possible unavailability of the accurate model of the entire system.</td>
</tr>
<tr>
<td>Traveling wave</td>
<td>The closer to the source, the earlier the location will exhibit oscillation</td>
<td>Inaccurate and unreliable detection of the oscillation arrival time. Unavailability of the wave speed map in real-time. Lack of investigations on multi-mode cases.</td>
</tr>
<tr>
<td>Machine learning</td>
<td>An offline trained decision tree from model-based simulations to locate the source using online measurements</td>
<td>Possible unavailability of the accurate model of the entire system. Can be only applied to forced oscillation cases.</td>
</tr>
</tbody>
</table>

• New methods, e.g. effective gen Z [8], UIO [9], RPCA [10], and harmonics [11].

Recent Efforts on OSL

- Energy method [12] \(\rightarrow\) Dissipating energy flow (DEF) [13] for locating the source

\[
U_i \angle \theta_i \quad P_{ij} + jQ_{ij} \quad \text{Bus } i \quad \text{Bus } j
\]

- How DEF works?
  - Given measured \(U, \theta\) (or freq), \(P\) and \(Q\) at one end of the line
  - Calculate \(\text{DEF}_{ij}\) by

\[
\text{DEF}_{ij}(t) = \int \left( \Delta P_{ij} d\theta_i + \frac{\Delta Q_{ij}}{V_i} dV_i \right) = \int \left( 2\pi \Delta P_{ij} \Delta f_i dt + \frac{\Delta Q_{ij}}{V_i} dV_i \right)
\]

- If \(\text{DE}\) is increasing, then oscillation source is behind Bus \(i\); otherwise, oscillation source is behind Bus \(j\).

- How to get DEF tool?
  - OSLp software by ISO-NE can be requested free of charge at [14]

[14] https://www.iso-ne.com/participate/support/request-software
Recent Efforts on OSL

- Test Cases Library [15-16] for evaluating OSL methods
- WECC 179-bus system
  - 179 buses, 29 machines (classical model)
  - Electromechanical modes: 0.26-1.88Hz
- 27 simulated cases
  - 9 poorly-damped natural oscillation cases
  - 18 forced oscillation cases
- Coverage
  - Linear/non-linear
  - Resonance/non-resonance
  - Sinusoidal/non-sinusoidal force
  - Force at excitation/governor
- 6 actual cases from ISO New England

[16] S Maslennikov, B Wang, Q Zhang, F Ma, X Luo, K Sun, E Litvinov, “A test cases library for methods locating the sources of sustained oscillations” accepted by IEEE PES General Meeting, 2016
Recent Efforts on OSL

- DEF’s effectiveness
  - Testing results on Test Cases Library [17] (right tables)
  - Performance at ISO-NE [18] (below)
    - Since 2017, online OSL has automatically processed 1200+ oscillatory. Alerts and Alarms generated by the PhasorPoint application
    - Correctly identified the source (generator and area) for all instances of oscillations with known sources inside and outside of ISO-NE
  - Testing results on recent simulated cases on a 240-bus WECC system [18]

Recent Efforts on OSL

- Cases leading to DEF’s failure [19]
- Incremental Energy in One Period (IEOP): net energy (negative when dissipated) in one period of the forced oscillation, calculated as follows.

\[
E_D^{D}_{Gi} = E_D^{D}_{Fd,i} + E_D^{D}_{Pm,i} + E_E^{D'}_{qi} + E_E^{D'}_{di}
\]

\[
E_D^{D}_{Fd,i} = \frac{\omega_F | \Delta E_{Fd,i} (\omega_F)| | \Delta E_{qi}^{'} (\omega_F)|}{2 (X_{di} - X_{di}')} \times \sin \left[ \angle \Delta E_{Fd,i} (\omega_F) - \angle \Delta E_{qi}^{'} (\omega_F) \right]
\]

\[
E_D^{D}_{Pm,i} = \frac{\omega_F | \Delta P_{mi} (\omega_F)| | \Delta \delta_i (\omega_F)|}{2} \times \sin \left[ \angle \Delta P_{mi} (\omega_F) - \angle \Delta \delta_i (\omega_F) \right]
\]

\[
E_E^{D'}_{qi} = -\frac{T_{di}^{'} \omega_F^2 | \Delta E_{qi}^{'} (\omega_F)|^2}{2 (X_{di} - X_{di}')} \]

\[
E_E^{D'}_{di} = -\frac{T_{qi}^{'} \omega_F^2 | \Delta E_{qi}^{'} (\omega_F)|^2}{2 (X_{qi} - X_{qi}')} \]

These control-related terms may change the sign of \( E_D^{D}_{Gi} \), leading to the DEF’s failure.

Ongoing Efforts on OSL

• The first OSL Contest co-hosted by NASPI and IEEE OSL Task Force [20].
  ➢ Goal: help develop & improve OSL tools, and help utilities identify & evaluate OSL tools for real-time use.
  ➢ Important dates:
    - Apr. 19, 2021: Test cases released [21], contest begins
    - May 28, 2021: Registration deadline
    - Jun. 11, 2021: Result submission deadline
    - Jul. 28, 2021: Awards announced

[20] https://www.naspi.org/node/890
Ongoing Efforts on OSL

- Test system used for OSL Contest
  - 240-bus reduced WECC system (109 machines with detail model + exc + gov)
  - High renewable penetration (~20%)
  - Power flow and dynamic data in PSS/E format now available (free of charge) at [22]
- Developed by NREL [23] under MIDAS-Solar project.

MIDAS-Solar: help operators understand the interaction of system scheduling and dynamics.

[22] https://www.nrel.gov/grid/test-case-repository.html
Ongoing Efforts on OSL

• Testing DEF by cases simulated on 240-bus WECC system [18]
  ➢ Resonance condition, interacting with local or inter-area modes
  ➢ Forced signal added to generator controls (one per each case), either at exciter or governor

Industry experience:
• “The vast majority of practically observed FO have the source in the governor of traditional generators
• The DEF method is the only method practically used today for online locating the source of oscillation in actual power system” [18]

> DEF identifies correct oscillation source(s) in governor for almost all cases
> DEF may potentially fail if the forced signal is in exciter

Potential Research on Power System Oscillations

- Additional efforts are still needed to explore other potential cause(s) of oscillations, including the nonlinearity-induced ones.
- A proper definition of oscillation source for poorly-damped natural oscillations is needed, or at least thoroughly discussed, if not exists.
- Investigation oscillations exist in a system with renewables, HVDC and other power electronics interfaced equipment.
- Oscillation management in distribution systems.
- More capable OSL methods with desired properties [7].

1. A rigorous theoretical foundation
2. The adaptability to different network topologies, different causes of oscillations and different models of dynamic elements that exist in reality
3. Reliability of locating the source of oscillation without any false alarm
4. Fully measurement-based, i.e. free of the system model
5. Free of additional equipment or only requiring the minimum equipment to be installed that are inevitably necessary
6. Useful even with partial observability, i.e. when only partial system states are monitored
7. Robustness against measurement noises and even missing data
8. Computationally efficient
9. Capable of working continuously in real time
