Forced Oscillation Resonance with Multiple System Modes

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Resonance with Inter-area Mode

Resonance effect high when:

(R1) Forced Osc freq near System Mode freq
(R2) System Mode poorly damped
(R3) Forced Oscillation location near distant ends (strong participation) of the System Mode

Resonance effect medium when:

Some conditions hold

Resonance effect small when:

None of the conditions hold

Jan 11, 2019 Eastern System Event

FNET Data Display [1/11/2019 Line Trip]
Time: 8:44:43.9 UTC  59.9807 Hz

Frequency, Hz

08:44:43 08:45:05 08:45:27 08:45:49

Time, UTC
0.25 Hz Oscillation Shape

Manitoba
MISO

New York

Florida

SoCo
0.24 Hz NE-NW-SE Mode Shape

ModeShape of the Mode @ 0.239 Hz - 1/11/2019 2:40:00 AM to 2:44:30 AM

0.24 Hz mode
10.1% Damping ratio
2686169.6 Energy

NERC
North American Electric Reliability Corporation
0.2 Hz N-S Mode Shape

ModeShape of the Mode @ 0.201 Hz - 1/11/2019 2:40:00 AM to 2:44:30 AM

- 0.2 Hz mode
- 10.9% Damping ratio
- 3443049.7 Energy
0.25 Hz Oscillation Shape

Manitoba
MISO

New York

Florida

SoCo
FSSI Pre-Event Analysis

FSSI Analysis
2:40:00 to 2:44:30.
442 signals.

10 mode clusters estimated.

0.2 Hz, 0.24 Hz and 0.3 Hz modes are of interest.
FSSI Analysis During Event

442 signals.

0.24 Hz mode excited by 0.25 Hz forced oscillation.

Effect of 0.2 Hz and 0.3 Hz modes?
Oscillation Shape Proposition

\[ \dot{x} = Ax + bu, \ u(t) = H \cos(\omega t + \gamma) \]

Sinusoidal steady state:

\[ x_i(t) = A_{FRi} \cos(\omega t + \Psi_{FRi}) \]

\[ A_{FR} \angle \Psi_{FR} = -(H \angle \gamma) \left( \sum_{i=1}^{2n_c} \tilde{v}_i \frac{|	ilde{w}_i^T b|}{\sqrt{\alpha_i^2 + (\omega - \beta_i)^2}} [\angle(\tilde{w}_i^T b) + \angle(\alpha_i + j(\omega - \beta_i))] \right. \]

\[ + \left. \sum_{i=2n_c+1}^{n} \tilde{v}_i \frac{|	ilde{w}_i^T b|}{\sqrt{\lambda_i^2 + \omega^2}} [\angle(\tilde{w}_i^T b) + \angle(\lambda_i + j\omega)] \right) \]

Oscillation shape is a weighted sum of mode shapes from all system modes.

Each mode $\alpha_i + j\beta_i$ contributes its mode shape $\tilde{v}_i$ multiplied by amplification factor $A_i$ and shifted by rotation factor $\psi_i$

\[
A_i = -\frac{|\tilde{w}_i^T b|}{\sqrt{\alpha_i^2 + (\omega - \beta_i)^2}}
\]
Modal Amplification Factors

\[ |A_i| = \frac{|\tilde{w}_i^T b|}{\sqrt{\alpha_i^2 + (\omega - \beta_i)^2}} \]

\[ \tilde{w}_i^T b \Rightarrow \text{Strong controllability (R3)} \]

\[ \omega \approx \beta_i \Rightarrow \text{Close frequencies (R1)} \]

\[ \alpha_i \text{ small} \Rightarrow \text{Poor damping (R2)} \]
**Kundur System Example**

![Diagram of the Kundur System Example with nodes G1, G2, G3, G4, L7, and L9, showing areas 1 and 2 with forced oscillation at 0.62 Hz.]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Type</th>
<th>Frequency</th>
<th>Damping Ratio</th>
<th>$A_i \angle \psi_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode IA</td>
<td>Inter-area</td>
<td>0.62 Hz</td>
<td>3.0%</td>
<td>4.70$\angle56.0^\circ$</td>
</tr>
<tr>
<td>Mode LA1</td>
<td>Local (Area1)</td>
<td>0.56 Hz</td>
<td>6.8%</td>
<td>0.91$\angle-151.7^\circ$</td>
</tr>
<tr>
<td>Mode LA2</td>
<td>Local (Area2)</td>
<td>0.67 Hz</td>
<td>1.4%</td>
<td>0.36$\angle174.7^\circ$</td>
</tr>
</tbody>
</table>
Mode shapes

Modal Contributions
Mode shapes

Oscillation shape
Resonance effects from modes

- Several modes may get excited. What we see is the net effect.

- Mode shapes of dominant modes known => We can estimate modal amplifications of system modes from analysis of PMU measurements.

- Resonance effect from each mode can be estimated by LSE formulation.

- Counteractions and controls.