Inter-Area Resonance from Forced Oscillations in Power Systems

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Definitions

• System Mode – Inter-area Modes and Local Modes

• Natural/System oscillations – Oscillations from sources internal to the system

• Forced oscillations - Oscillations from sources external to the system
Resonance in Physics

High resonance effect when forced oscillation frequency close to system mode frequency and when system poorly damped.

\[
A = \frac{F_0/m}{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega \gamma)^2}}
\]

\[
\tan \delta = \frac{\omega \gamma}{\omega_0^2 - \omega^2}
\]
Forced Oscillations in WECC

• Many forced oscillations observed.
• **System modes keep getting excited by forced oscillations**
• Sources point to hydro units/controls...
• Oscillations at 0.4 Hz, 0.5 Hz, 0.6 Hz, 0.7 Hz, 0.8 Hz, 1.12 Hz... 2 Hz...
• Detection? Impact on nearby system modes?
• Resonance possible?
Resonance in Kundur Test System

- When does resonance occur?
- When is resonance severe versus mild?
- Sensitivity to forced oscillation frequency, location, system mode damping, and local versus inter-area mode.
- Recent paper in IEEE Trans. Power Systems
Poorly damped case

• Inter-area mode 0.56 Hz damping ratio at 2%.
• 35 MW forced oscillation in the middle of the system
• Tie-line oscillations of 74 MW (0.53 Hz), 200 MW (0.56 Hz) and 70 MW (0.59 Hz) show strong resonance effect.
Medium damped case

- Inter-area mode 0.56 Hz damping ratio at 5%.
- Tie-line oscillations of 65 MW (0.53 Hz), 90 MW (0.56 Hz) and 56 MW (0.59 Hz) show resonance effect.
Well damped case

- Inter-area mode 0.56 Hz damping ratio at 10%.
- Tie-line oscillations of 53 MW (0.53 Hz), 58 MW (0.56 Hz) and 50 MW (0.59 Hz) show low resonance effect.
Mode Shapes for Resonant Case

• SSI-Covariance can estimate system mode and forced oscillation simultaneously.
• Mode shape magnitude not dominant at source of forced oscillation for resonant case.
Inter-area mode 0.56 Hz damping ratio at 2%. Forced Oscillation (FO) at 0.56 Hz.

Largest Tie-line oscillations when FO at distant ends.
Resonance - Linear Phenomenon

<table>
<thead>
<tr>
<th>FO MW</th>
<th>Tie-line MW Osc</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>95</td>
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<tr>
<td>20</td>
<td>203</td>
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<tr>
<td>40</td>
<td>427</td>
</tr>
<tr>
<td>100</td>
<td>516</td>
</tr>
</tbody>
</table>

- Inter-area mode 0.56 Hz damping ratio at 2%. Forced Oscillation (FO) at 0.56 Hz at Bus 8.
- Tie-line Oscillation MW grows linearly with respect to Forced Oscillation MW up to a point.
35 MW Forced Oscillation can lead to **480 MW** Tie-line oscillations when FO freq close to system mode freq and system mode at 2% damping ratio.

Tie-line oscillations can be about **400 MW** if FO near the sending end; **480 MW** if FO near the receiving end;
Resonance with Inter-area Mode

**Resonance effect high** when:
• Forced Oscillation freq near System Mode freq
• System Mode poorly damped
• Forced Oscillation location near the two distant ends (strong participation) of the System Mode

**Resonance effect medium** when:
• Some conditions hold

**Resonance effect small** when:
• None of the conditions holds
FDD Mode Shapes on June 13, 2013

Case 1
0.38 Hz at 0.6% Damping Ratio

Case 2
0.38 Hz at 12% Damping Ratio
PMU Apparent Power Signals on PMU 1

**Case 1**
0.37 Hz at 0.6% Damping Ratio

**Case 2**
0.4 Hz at Near 8% Damping Ratio
No resonance on June 13, 2013

**Case 1**
- 0.37 Hz Forced Oscillation

**Case 1**
- 0.4 Hz at 15% Damping Ratio

**Case 2**
- 0.4 Hz at 14% Damping Ratio

Resonance effect **low** because system mode well-damped and FO location near the center of the mode.

No tie-line oscillations from 10 MW forced oscillation.
Medium Resonance on November 29, 2005

- 20 MW 0.27 Hz Forced Oscillation in Alberta Canada.
- System mode 0.26 Hz at around 7% damping.
- 200 MW Oscillations on California-Oregon Inter-tie.
- Resonance Amplification Factor = 10.
- Recent IEEE Trans. paper

Thanks to Greg Stults (BPA) and Jim Burns (BPA)
Medium resonance on November 29, 2005

Resonance effect medium because system mode well-damped (7%) and FO location near one end of the mode. 200 MW tie-line oscillations from 20 MW forced oscillation. (Recent IEEE Trans. Paper)
Medium Resonance on November 29, 2005

- System mode 0.26 Hz and Forced Oscillation at 0.27 Hz
- Forced Oscillation source near Sending End
- System Mode Well-damped at 7%
- Two out of three conditions were true.
- Resonance Amplification Factor = 10.
- Warning for the future.
Summary

• Forced Oscillations are problematic…
• Nov 29, 2005 Alberta event - documented instance of resonance between forced oscillation and inter-area mode.
• Resonance – risk for operational reliability of the grid
• Source location tricky in case of resonance
• MW output may not be the largest at the oscillation source due to nature of resonance.
• Mode shape angle may be a better indicator
• Further research needed