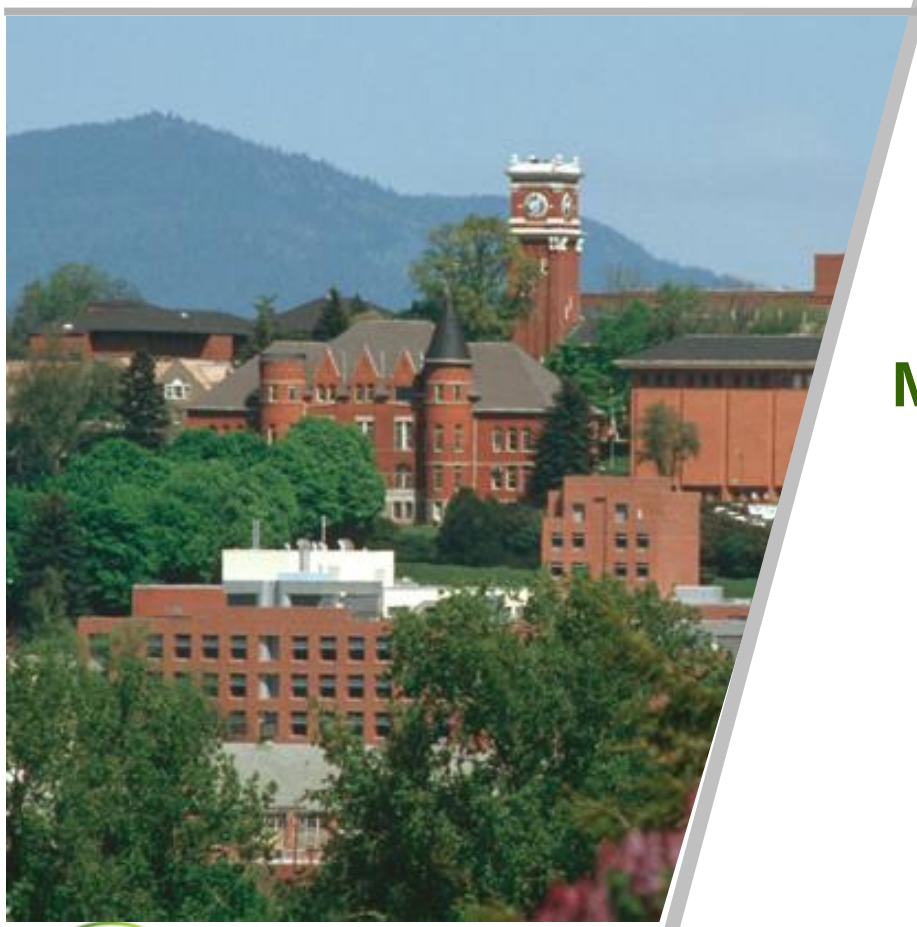

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Washington State University

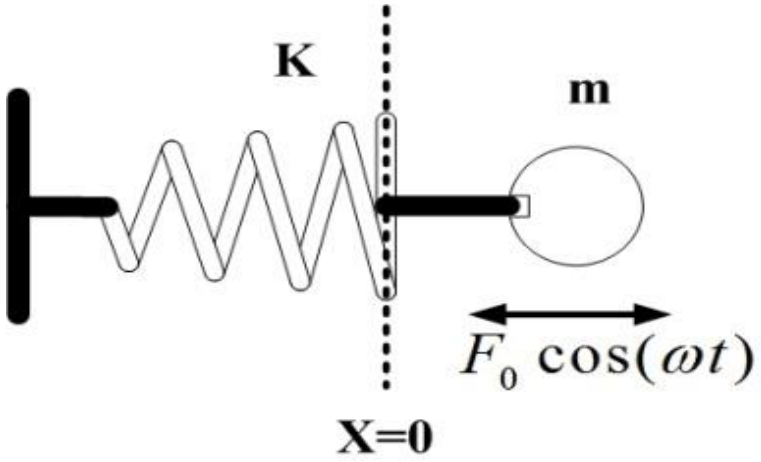
Seyed Arash Sarmadi

National Grid

Definitions

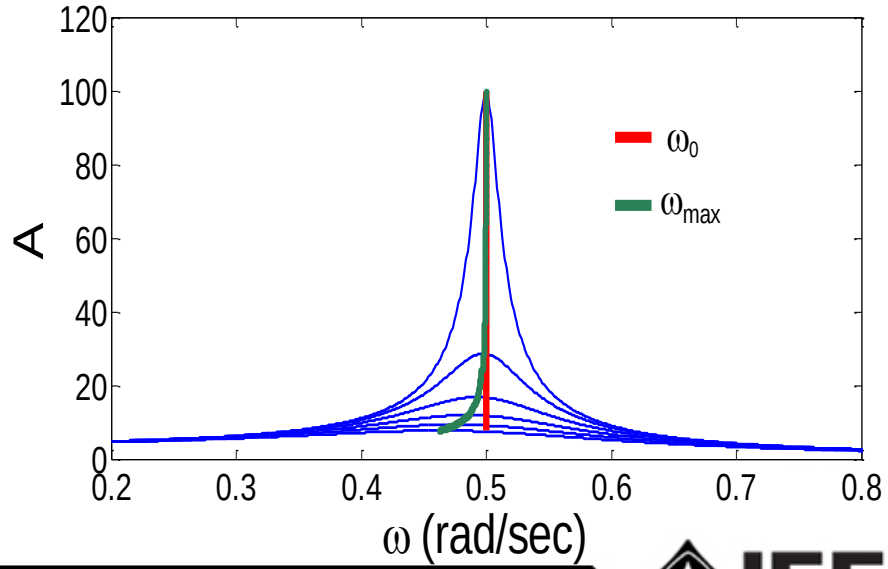
- System Mode – Inter-area Modes and Local Modes
- Natural/System oscillations – Oscillations from sources internal to the system
- Forced oscillations - Oscillations from sources external to the system

Resonance in Physics



$$\begin{cases} A = \dfrac{F_0/m}{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega\gamma)^2}} \\ \tan\delta = \dfrac{\omega\gamma}{\omega_0^2 - \omega^2} \end{cases}$$

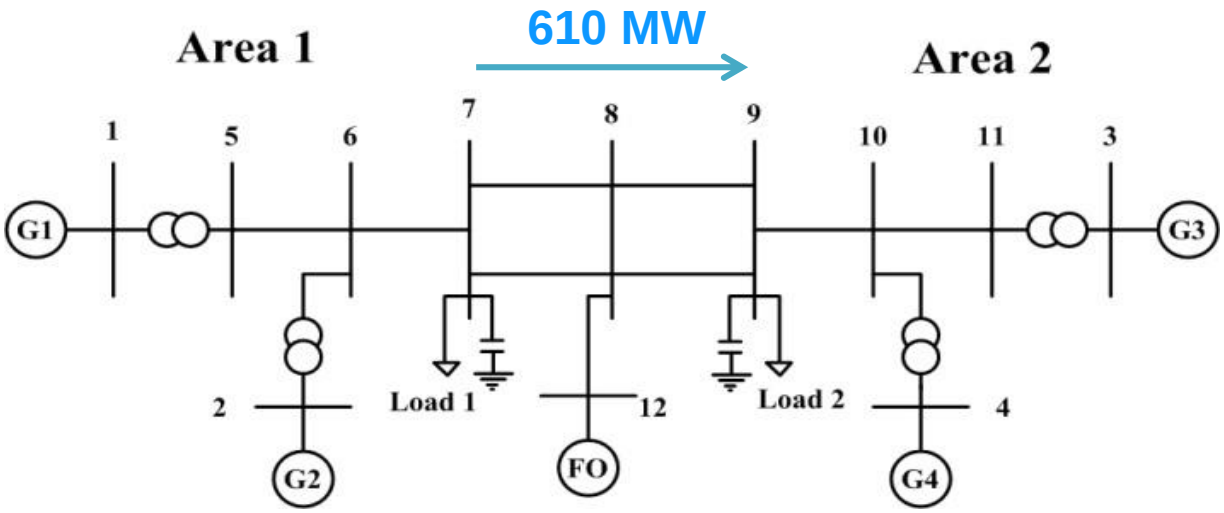
poorly damped



Forced Oscillations in WECC

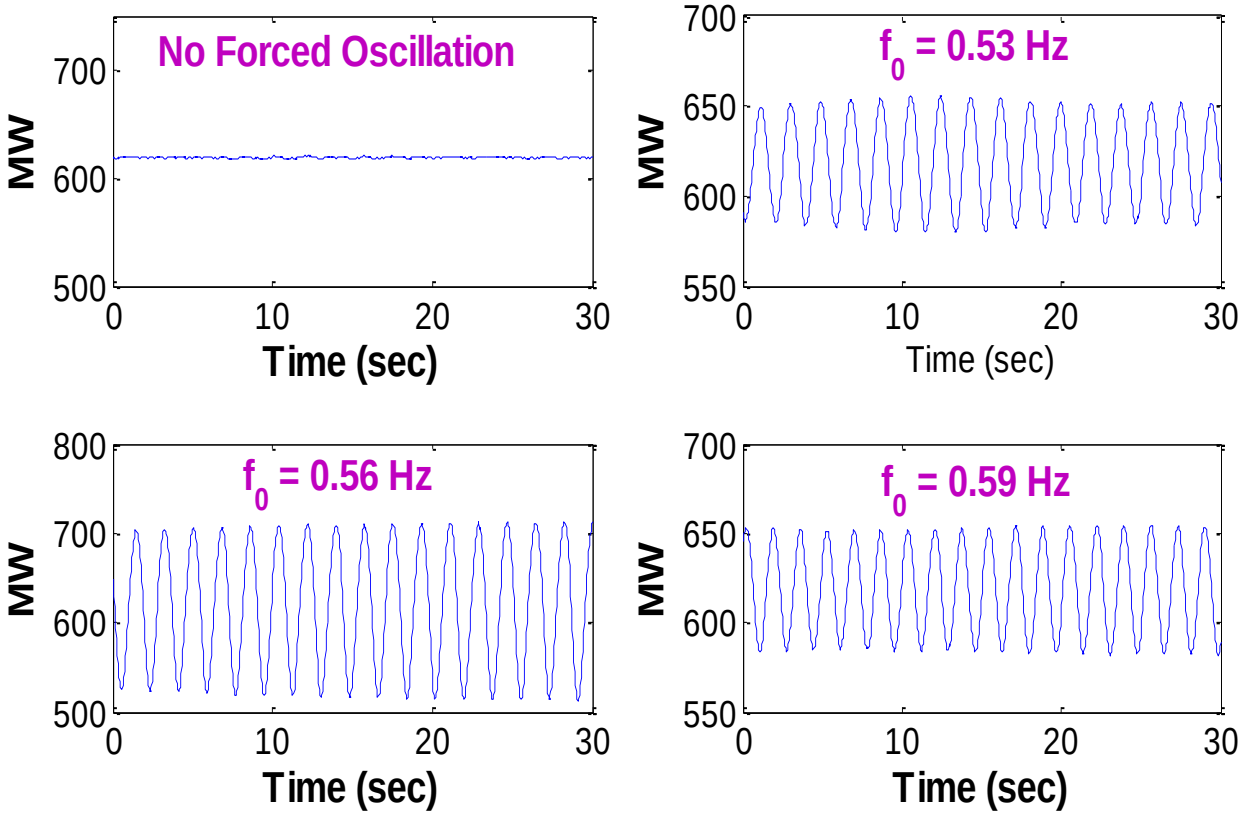
- Many forced oscillations observed.
- **System modes keep getting excited by forced oscillations**
- Sources point to hydro units/controls...
- Oscillations at 0.4 Hz, 0.5 Hz, 0.6 Hz, 0.7 Hz, 0.8 Hz,1.12 Hz… 2 Hz…
- Detection? Impact on nearby system modes?
- Resonance possible ?

Resonance in Kundur Test System



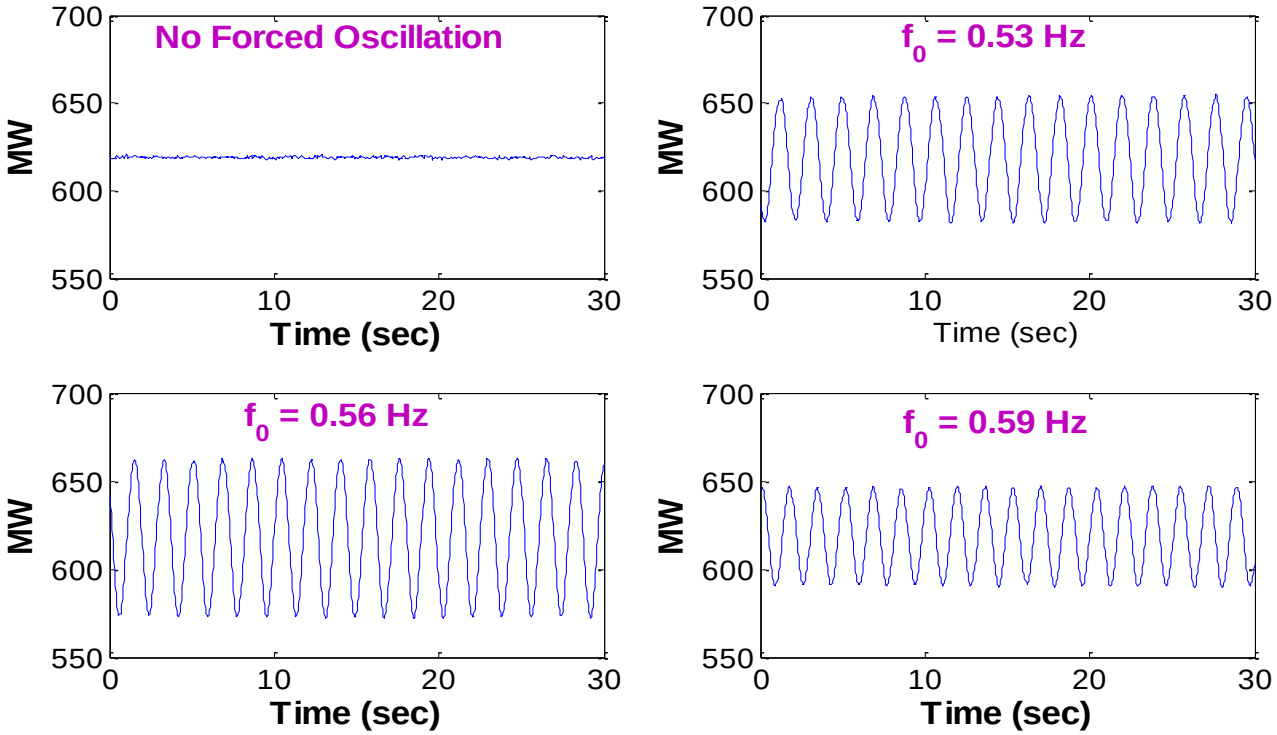
- When does resonance occur?
- When is resonance severe versus mild?
- Sensitivity to forced oscillation frequency, location, system mode damping, and local versus inter-area mode.
- Recent paper in IEEE Trans. Power Systems

Poorly damped case



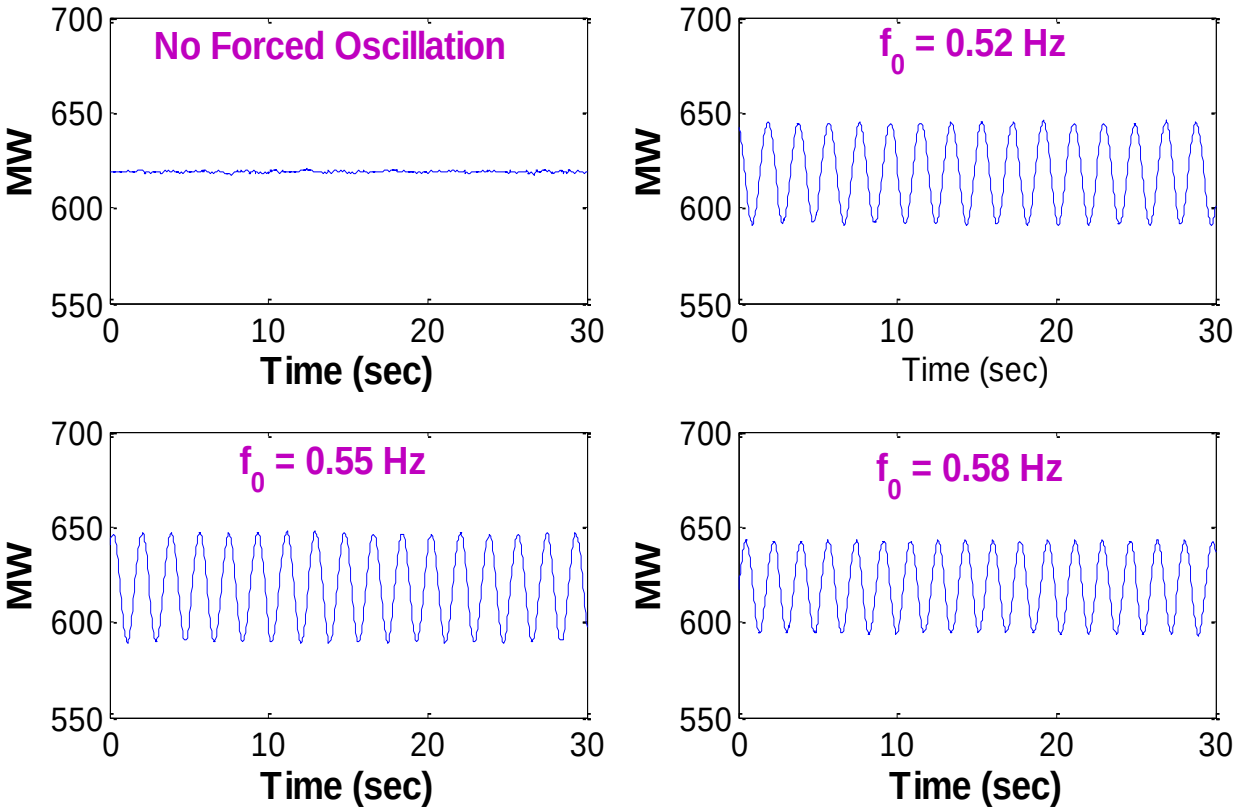
- **Inter-area mode 0.56 Hz damping ratio at 2%.**
- **35 MW forced oscillation in the middle of the system**
- **Tie-line oscillations of 74 MW (0.53 Hz), 200 MW (0.56 Hz) and 70 MW (0.59 Hz) show strong resonance effect.**

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.**

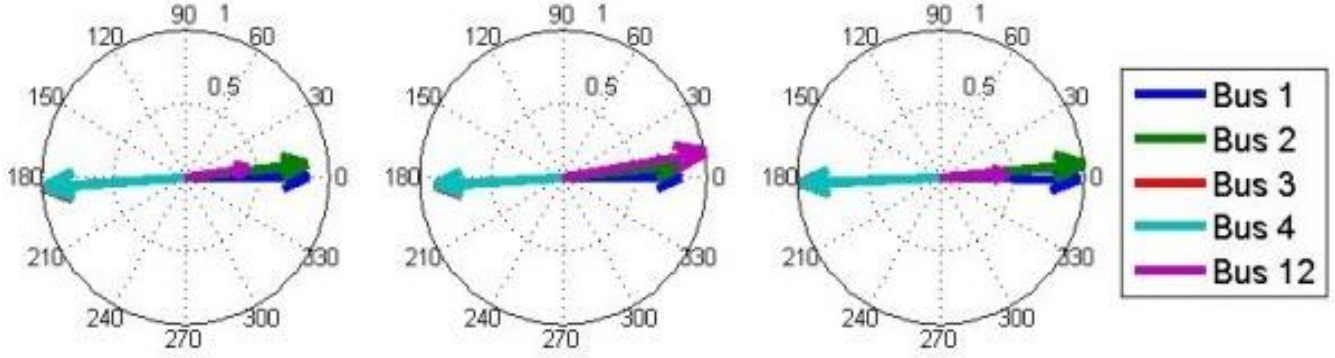
Well damped case



- **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.**

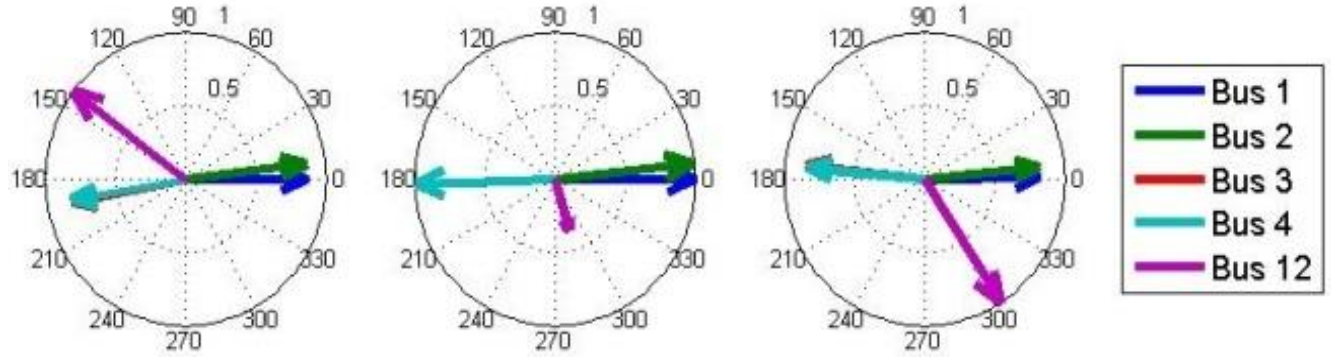
Mode Shapes for Resonant Case

System Mode



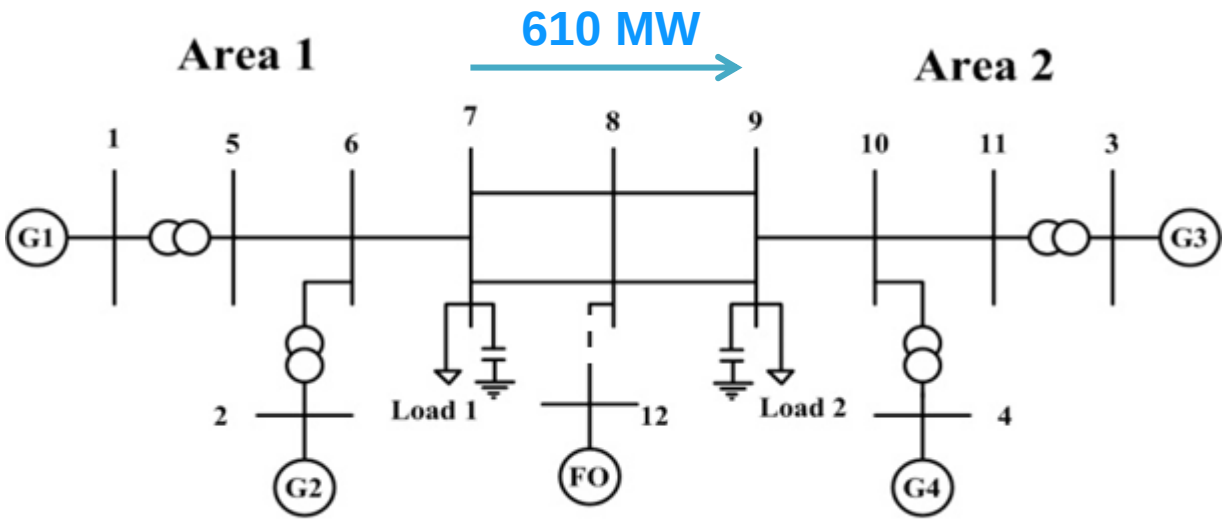
0.53 Hz | **0.56 Hz** | **0.59 Hz**

Forced Oscillation



- **SSI- Covariance can estimate system mode and forced oscillation *simultaneously*.**
- **Mode shape magnitude not dominant at source of forced oscillation for resonant case**

Sensitivity to location



FO Bus	Tie-line MW Osc
1	429
2	361
3	477
4	442
5	390
6	262
7	194
8	203
9	313
10	397
11	449

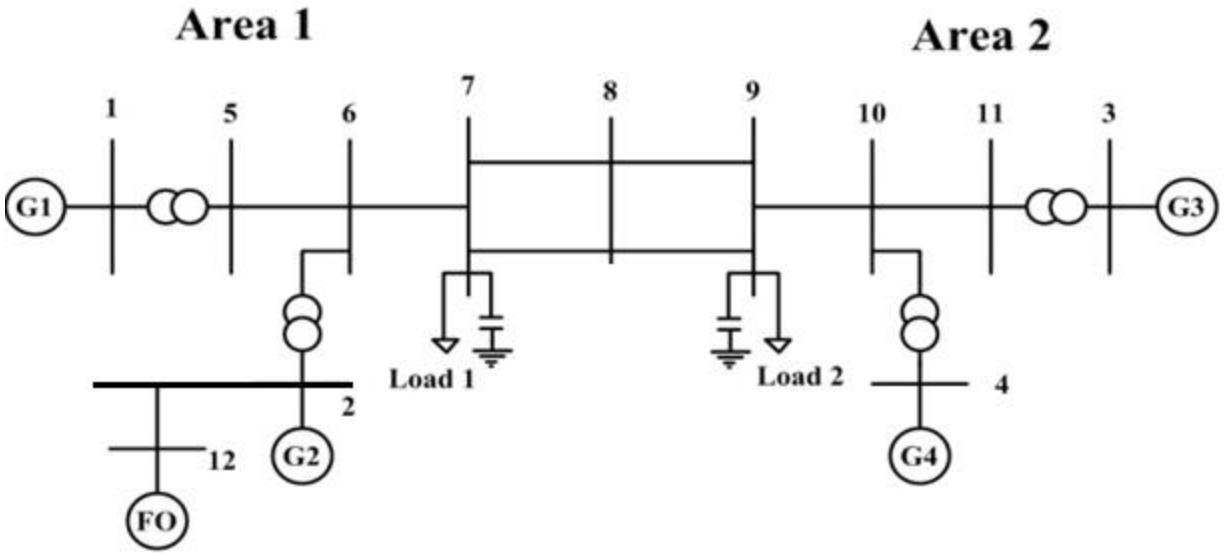
- **Inter-area mode 0.56 Hz damping ratio at 2%. Forced Oscillation (FO) at 0.56 Hz.**
- **Largest Tie-line oscillations when FO at distant ends.**

Resonance - Linear Phenomenon

FO MW	Tie-line MW Osc
2	20
10	95
20	203
40	427
100	516

- **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.**

High Resonance Case



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

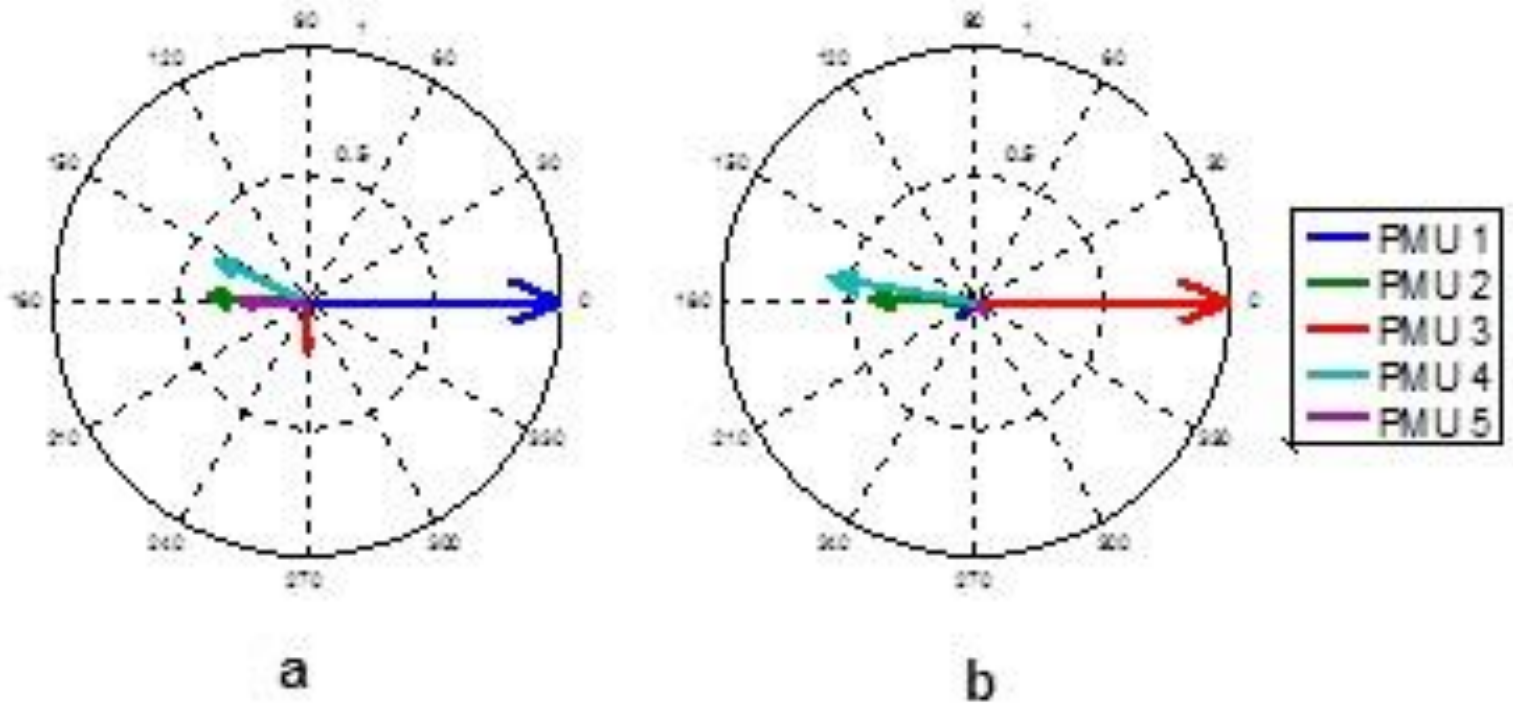
Resonance effect medium when:

- Some conditions hold

Resonance effect small when:

- None of the conditions holds

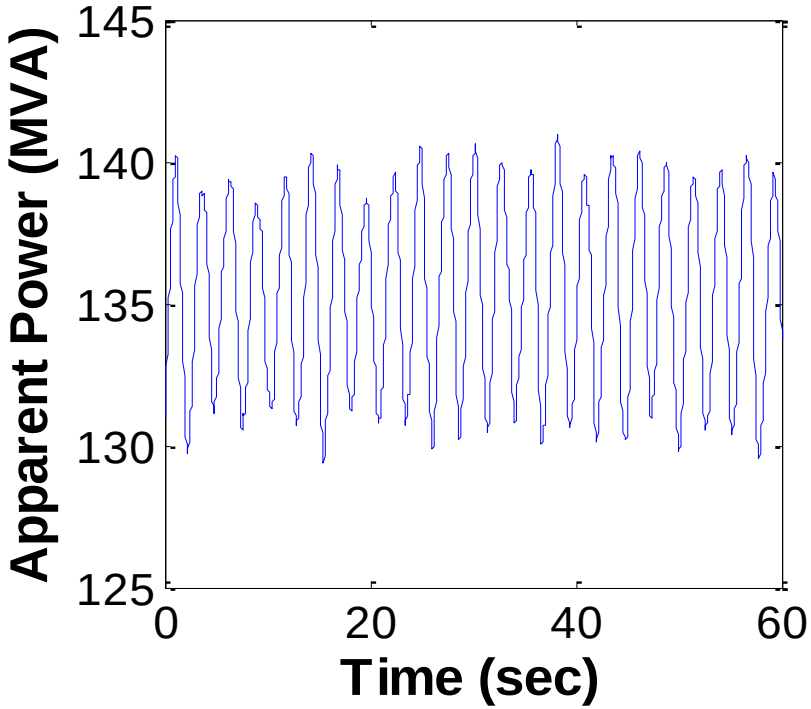
FDD Mode Shapes on June 13, 2013

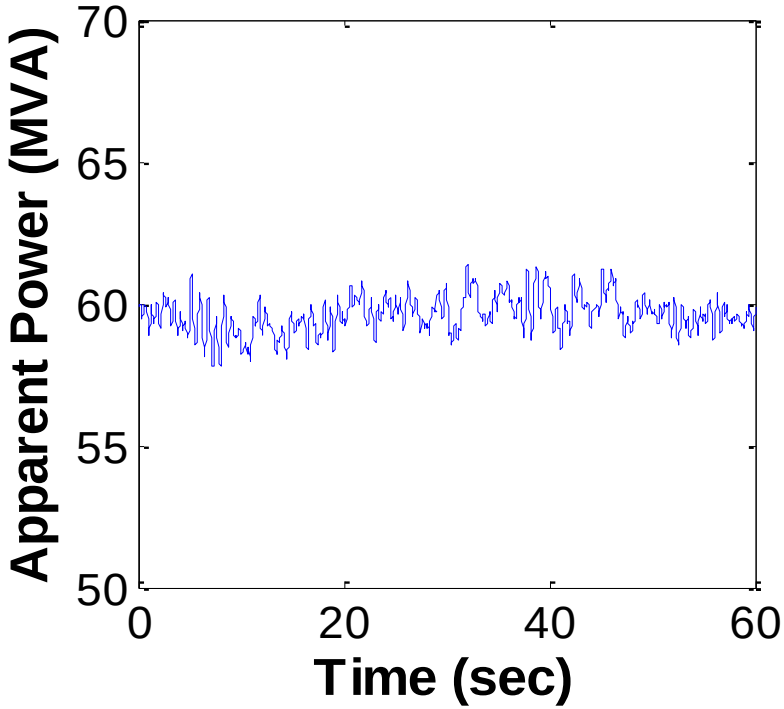


Case 1
0.38 Hz at
0.6% Damping Ratio

Case 2
0.38 Hz at
12% Damping Ratio

PMU Apparent Power Signals on PMU 1

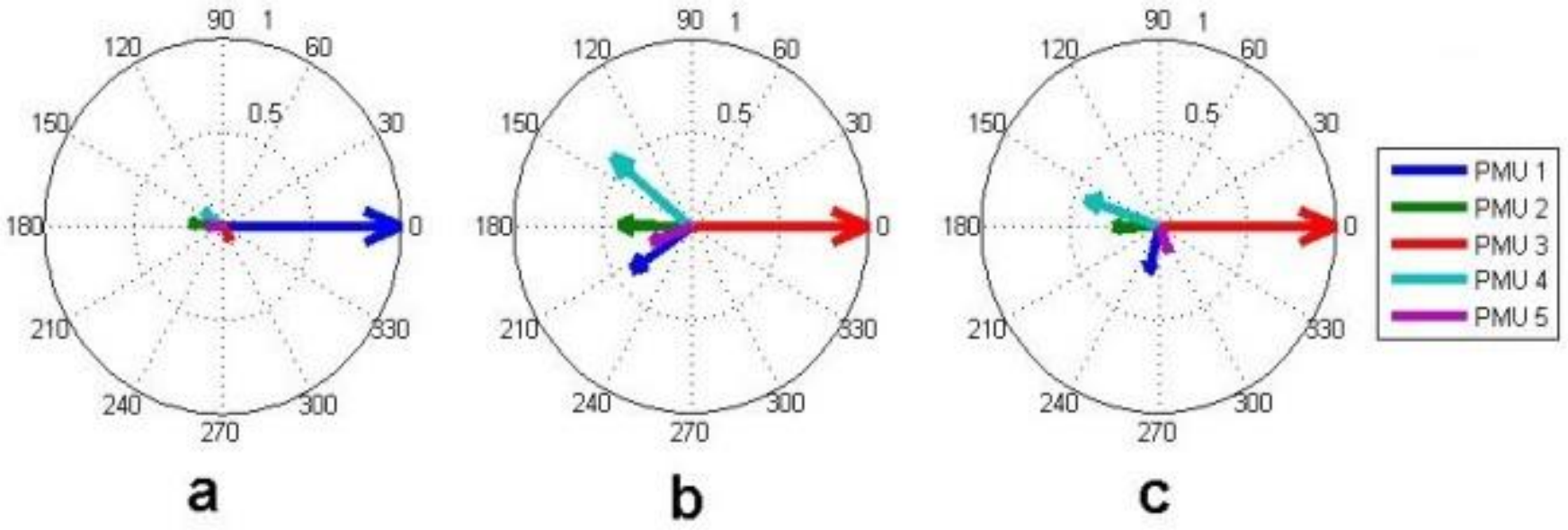




Case 1
0.37 Hz at
0.6% Damping Ratio

Case 2
0.4 Hz at
Near 8% Damping Ratio

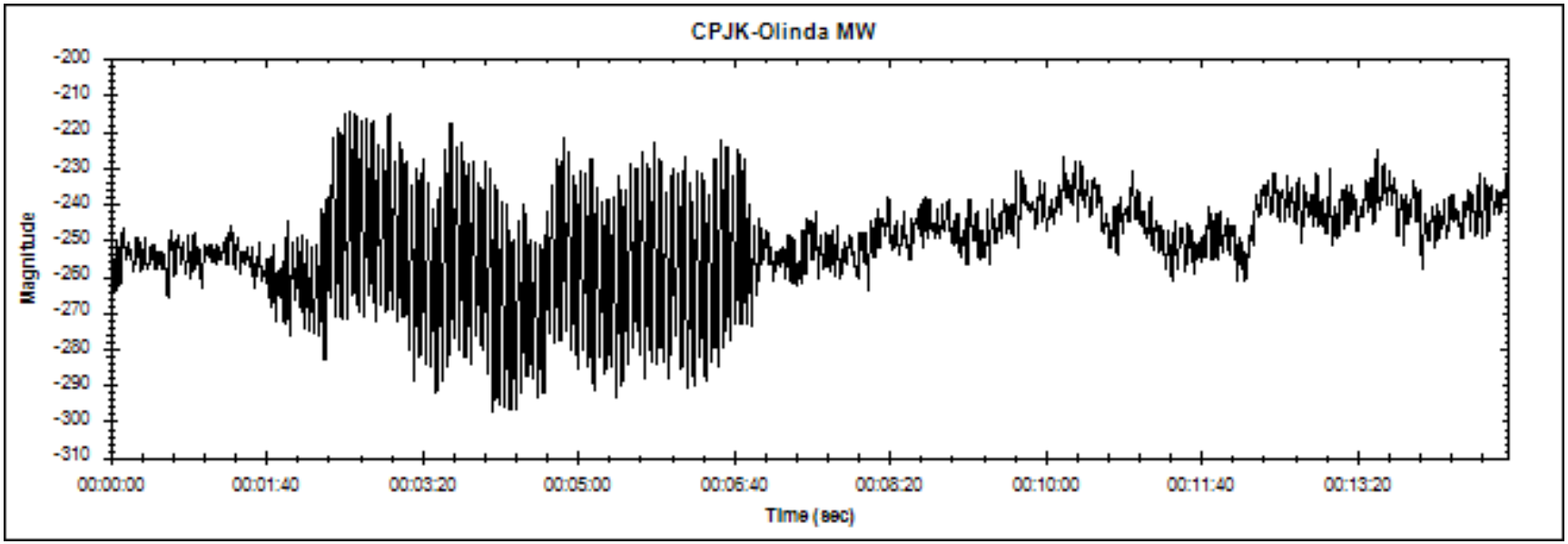
No resonance on June 13, 2013



Case 1	Case 1	Case 2
0.37 Hz	0.4 Hz at	0.4 Hz at
Forced Oscillation	15% Damping Ratio	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.

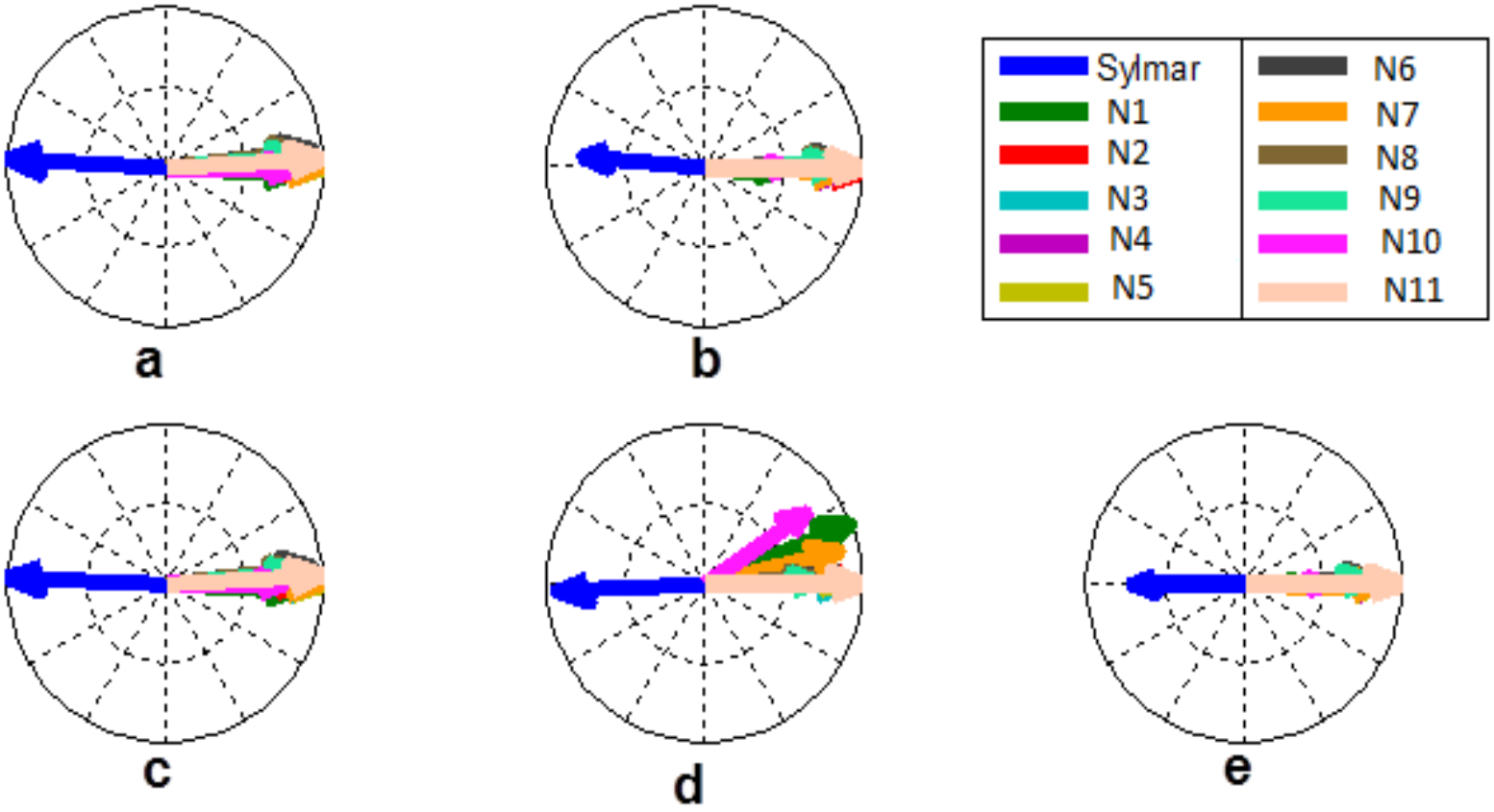
Medium Resonance on November 29, 2005



- **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**

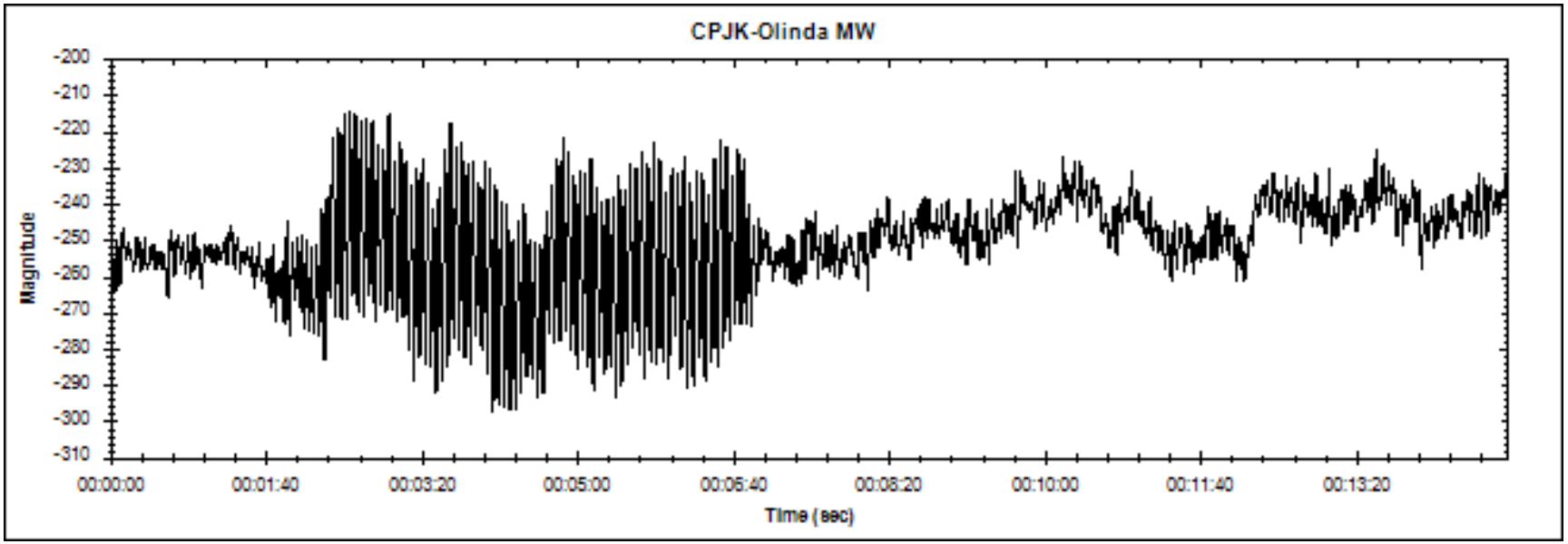
Thanks to Greg Stults (BPA) and Jim Burns (BPA)

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 Ocillation 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