Analysis and Mitigation of Resonant Forced Oscillations

Mani V. Venkatasubramanian

Habib Wajid

Yuan Zhi

Washington State University

(mani@wsu.edu)

PSERC Webinar
October 12, 2021

Presentation Outline

- Inter-Area Resonance - Oscillations
- Interactions of a forced oscillation with system modes
- Analysis of June 17, 2016 eastern event
- Theory base for the control
- Control for mitigation
- Future work

Small Signal Stability

- Oscillations must remain well-damped
- Either sustained oscillations or growing oscillations called small-signal instability
- Caused by unusual operating conditions or poor control designs
- Some eigenvalues become negatively damped resulting in small signal instability
- August 10, 1996 WECC blackout a classical example
- Forced Oscillations

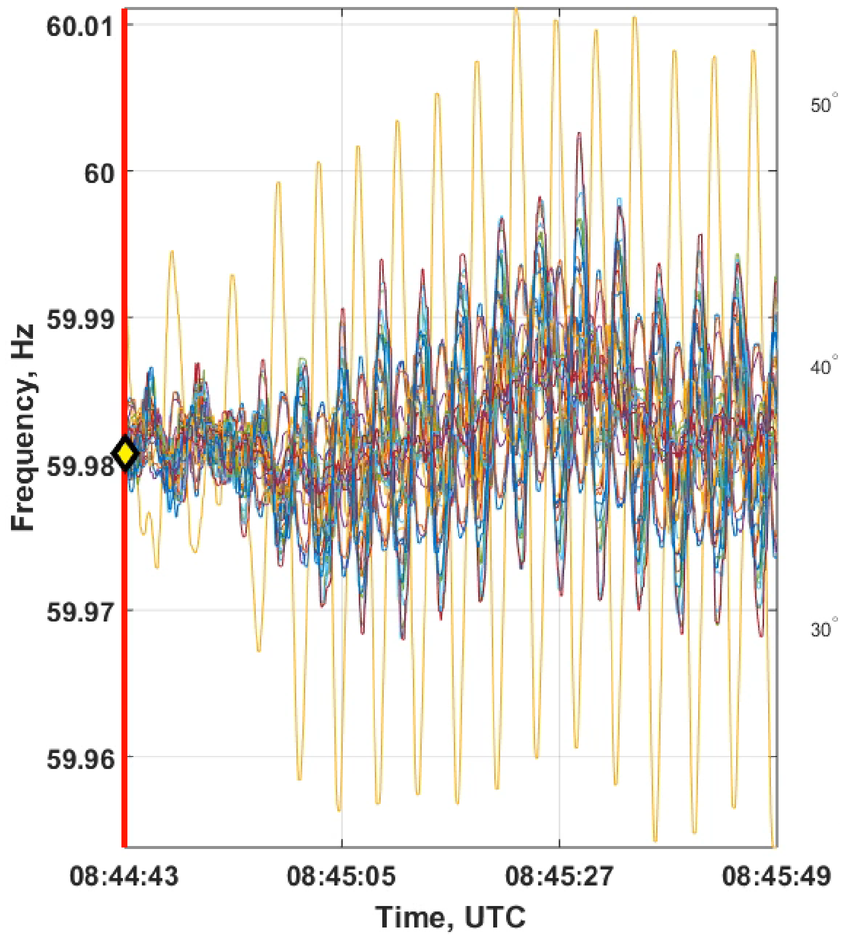
Forced Oscillation Sources

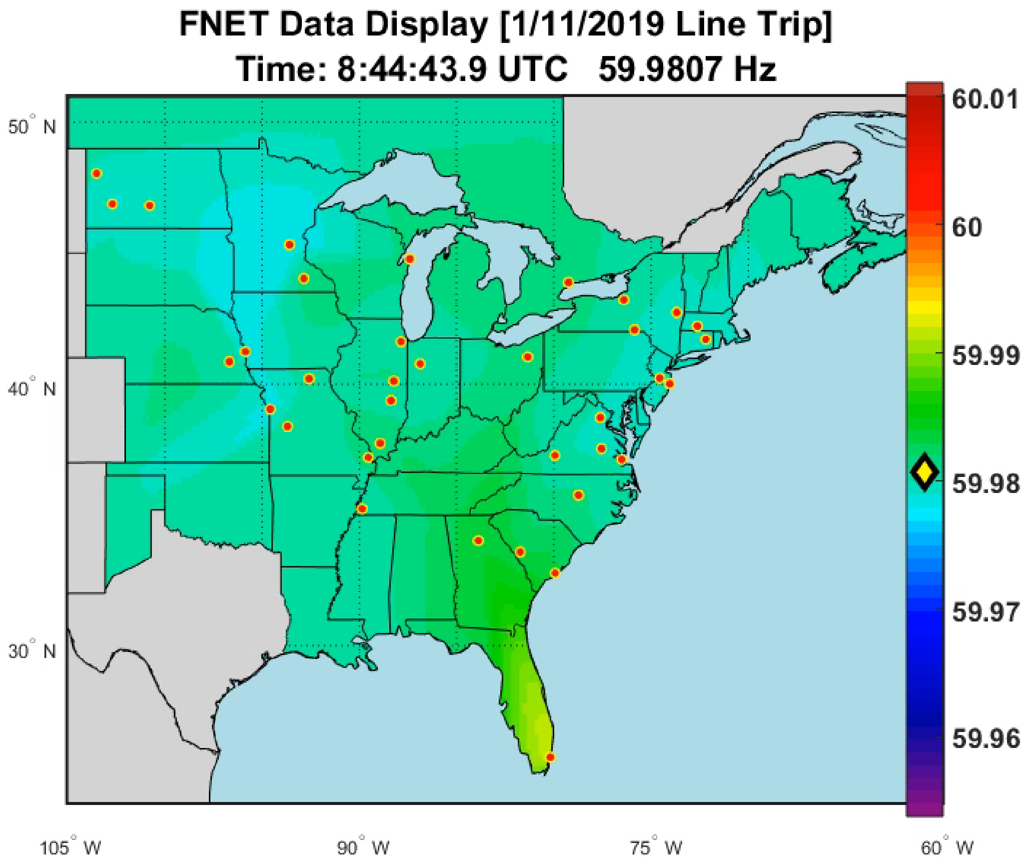
- Rough zone operation of certain hydro units (Francis turbines)
- Mechanical control failures (valves)
- Power electronics control issues (wind,solar,HVDC)
- Poor or incorrect designs (operation outside design range)
- Problematic loads: arc furnaces, oil refineries

Forced Oscillations

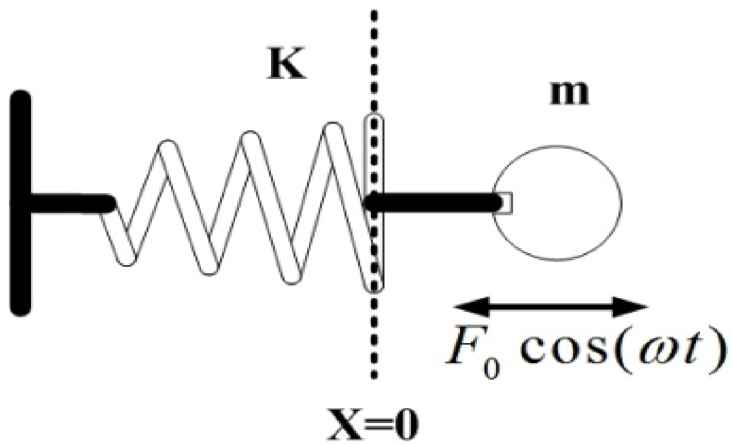
- Signature: Sudden appearance and end of oscillations (not related to grid events)
- Mechanism: Root cause external to power grid operations
- Warning signs: Not much. Problem tends to repeat itself until corrected.
- Challenge: Effects are local usually. Can lead to wide-area oscillations sometimes from inter-area resonance.

Jan 11, 2019 Eastern System Event



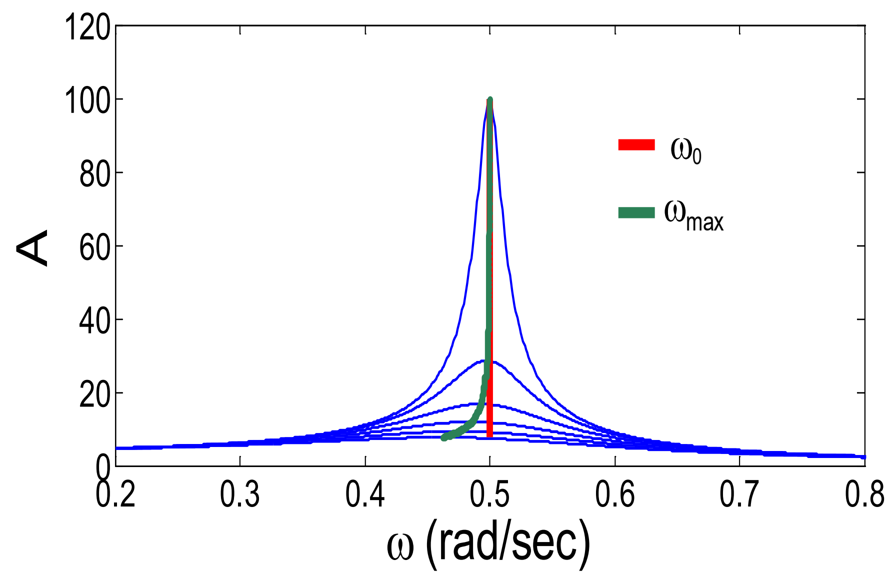


Resonance in Physics



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

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



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 of the conditions hold

Resonance effect small when:

- None of the condition holds

(Source: Our 2016 paper in IEEE Trans. Power Systems)

Oscillation Shape Proposition

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u, \quad u(t) = H\cos(\omega t + \gamma)$$

Sinusoidal steady state:

$$x_i(t) = A_{FR_i}\cos\left(\omega t + \Psi_{FR_i}\right)$$

$$\mathbf{A}_{FR}\angle\mathbf{\Psi}_{FR} = -(H\angle\gamma)\left(\sum_{i=1}^{2n_c}\tilde{\mathbf{v}}_i\frac{\left|\tilde{\mathbf{w}}_i^{\mathrm{T}}\mathbf{b}\right|}{\sqrt{\alpha_i^2+(\omega-\beta_i)^2}}\left[\angle\left(\tilde{\mathbf{w}}_i^{\mathrm{T}}\mathbf{b}\right)+\angle\left(\alpha_i+j(\omega-\beta_i)\right)\right]\right.$$
$$\left.+\sum_{i=2n_c+1}^{n}\tilde{\mathbf{v}}_i\frac{\left|\tilde{\mathbf{w}}_i^{\mathrm{T}}\mathbf{b}\right|}{\sqrt{\lambda_i^2+\omega^2}}\left[\angle\left(\tilde{\mathbf{w}}_i^{\mathrm{T}}\mathbf{b}\right)+\angle(\lambda_i+j\omega)\right]\right)$$

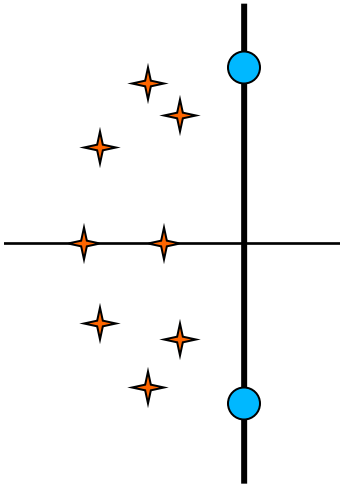
Y. Zhi and V. Venkatasubramanian, "Interaction of Forced Oscillation With Multiple System Modes," *IEEE Trans. Power Systems*, vol. 36, no. 1, pp. 518-520, Jan. 2021

Oscillation Shape Proposition

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

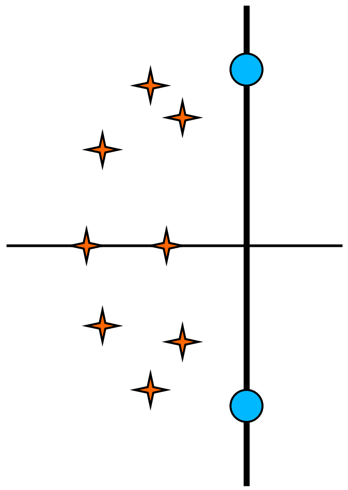
Each mode $\alpha_i + j\beta_i$ contributes its mode shape $\tilde{\mathbf{v}}_i$ multiplied by amplification factor A_i and shifted by rotation factor ψ_i

$$A_i = -\frac{\left|\tilde{\mathbf{w}}_i^{\mathbf{T}}\mathbf{b}\right|}{\sqrt{\alpha_i^2 + (\omega - \beta_i)^2}}$$



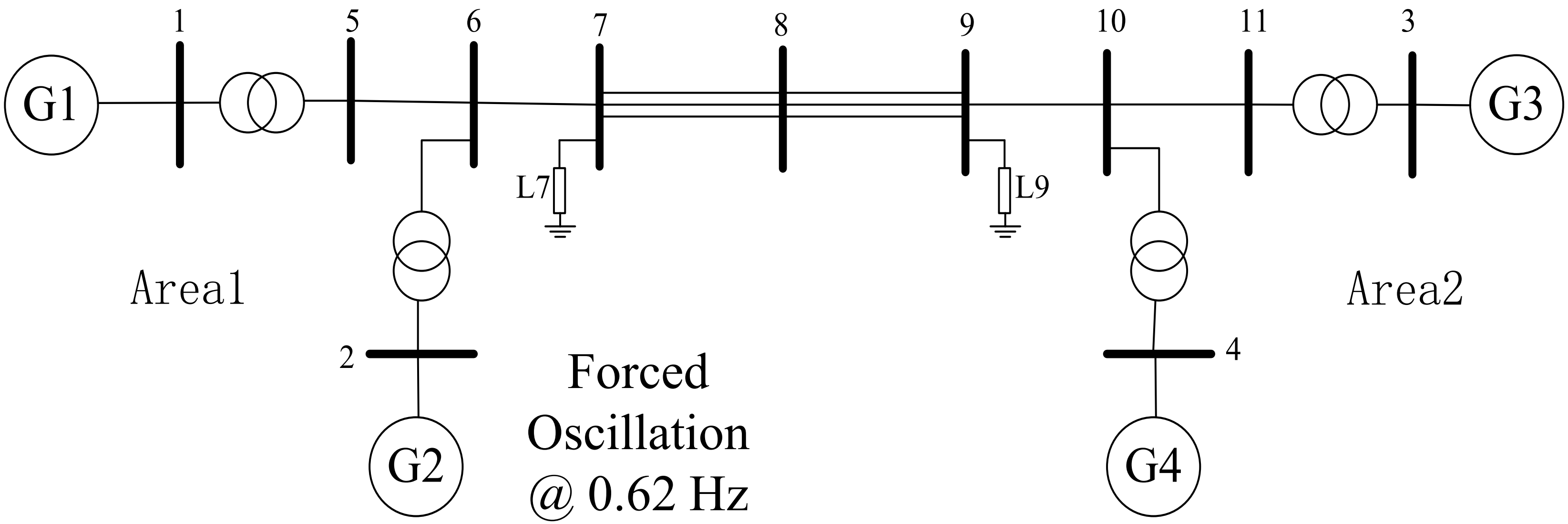
Modal Amplification Factors

$$|A_i| = \frac{\left|\tilde{\mathbf{w}}_{\boldsymbol{i}}^{\mathrm{T}}\mathbf{b}\right|}{\sqrt{\alpha_i^2 + (\omega - \beta_i)^2}}$$



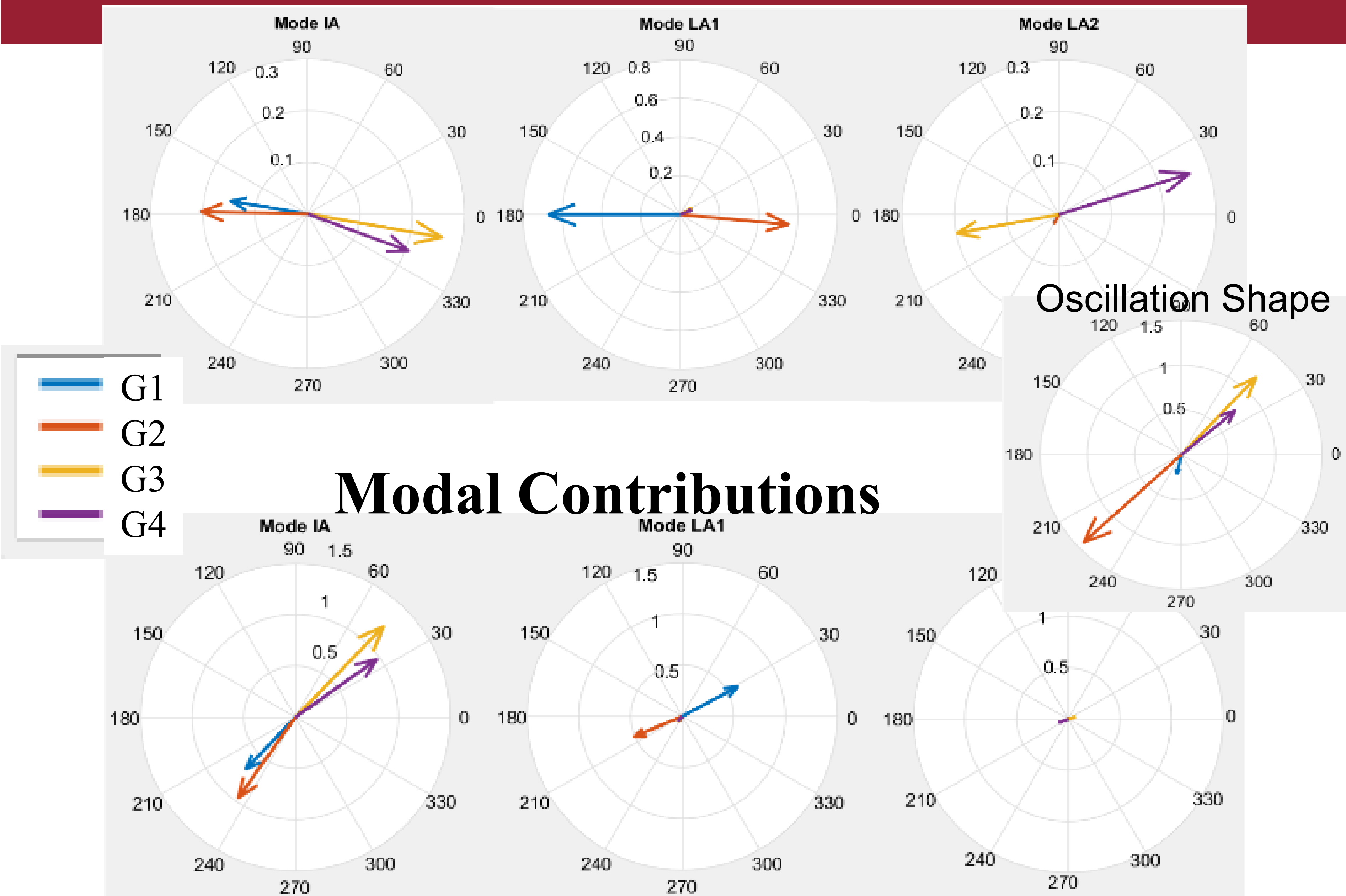
- $\tilde{\mathbf{w}}_{\boldsymbol{i}}^{\mathrm{T}}\mathbf{b}$ ⇒ Strong controllability (R3)
- $\omega \approx \beta_i$ ⇒ Close frequencies (R1)
- α_i small ⇒ Poor damping (R2)

Kundur System Example

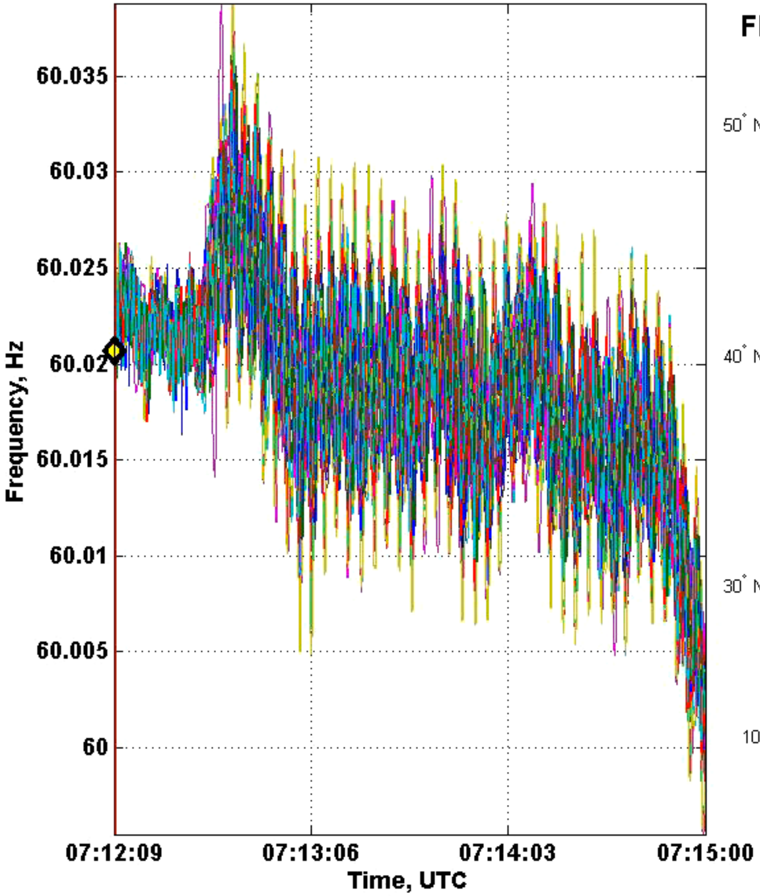


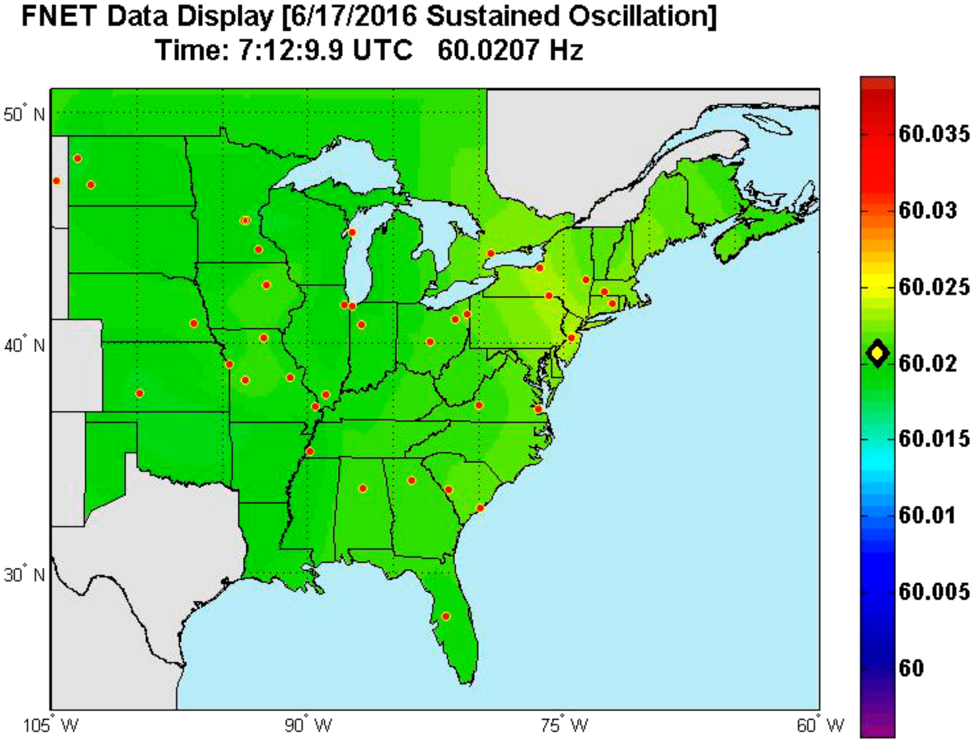
	Type	Frequency	Damping Ratio	$A_i\angle\psi_i$
Mode IA	Inter-area	0.62 Hz	3.0%	$4.70\angle 56.0°$
Mode LA1	Local (Area1)	0.56 Hz	6.8%	$0.91\angle -151.7°$
Mode LA2	Local (Area2)	0.67 Hz	1.4%	$0.36\angle 174.7°$

Mode shapes

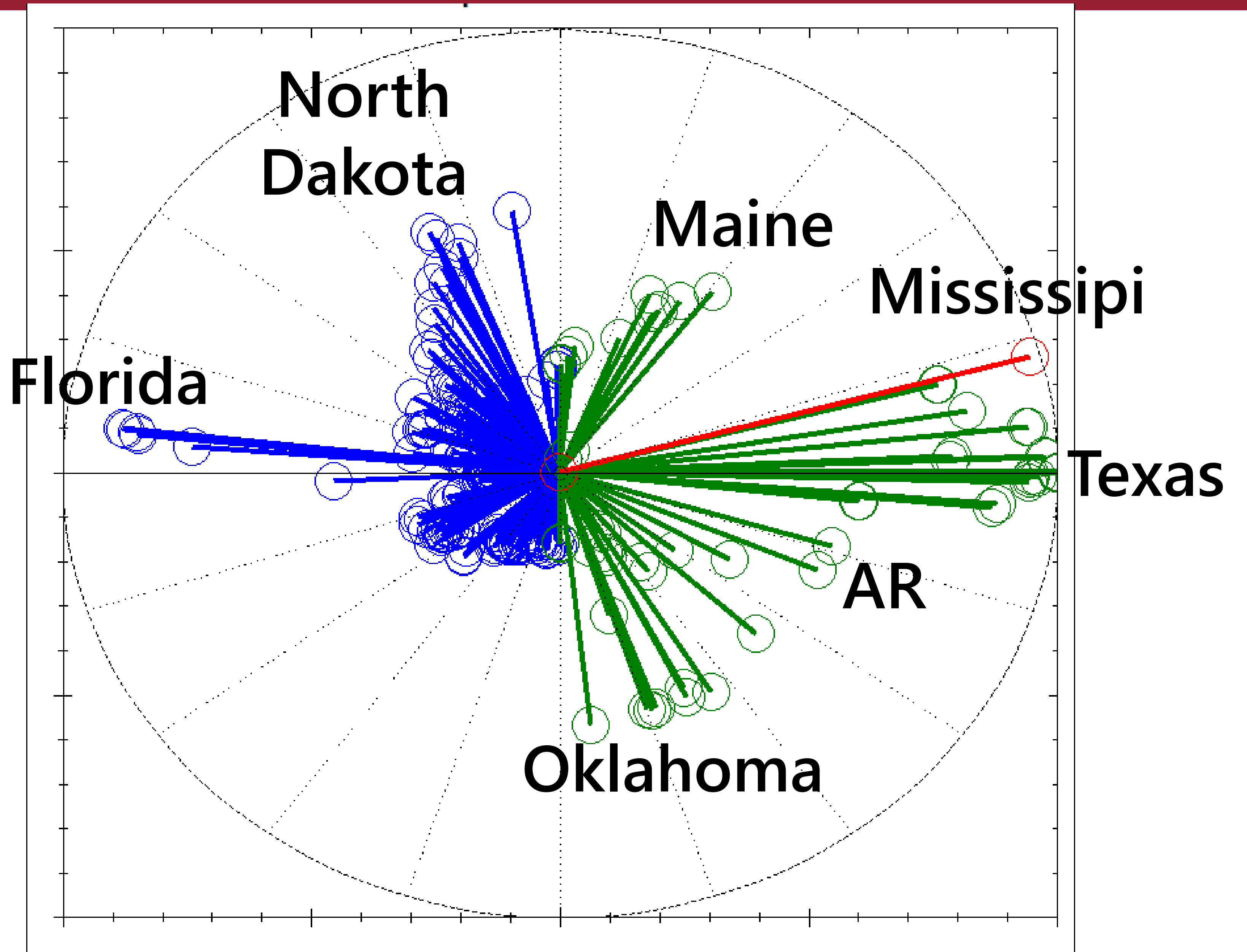

Mode IA
Mode LA1
Mode LA2
Oscillation Shape
G1
G2
G3
G4
Modal Contributions
Mode IA
Mode LA1

June 17, 2016 Eastern Event

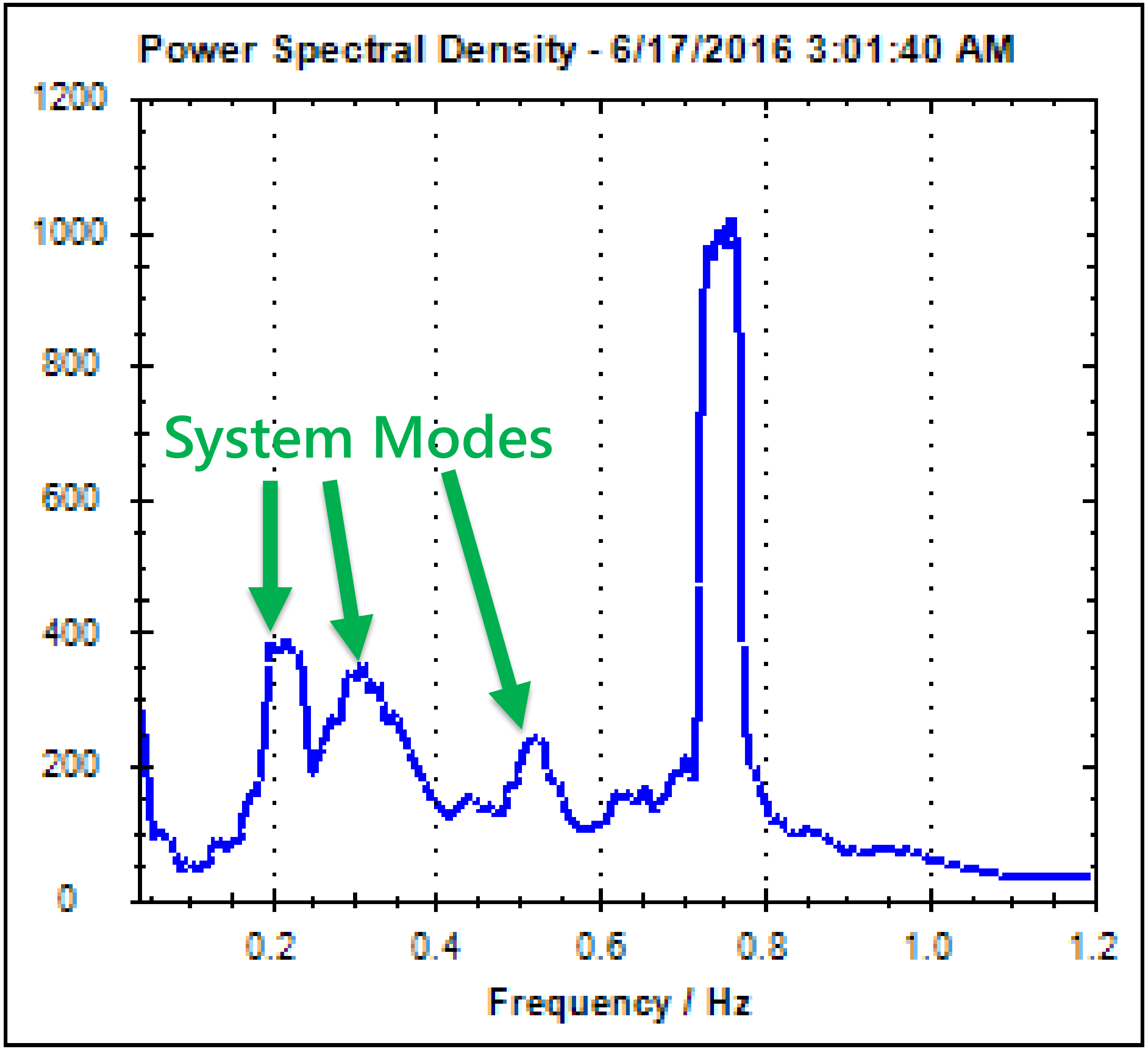




0.28 Hz Oscillation Shape



FFDD Power Spectrum @ 3:01 AM (Before)



Main modes

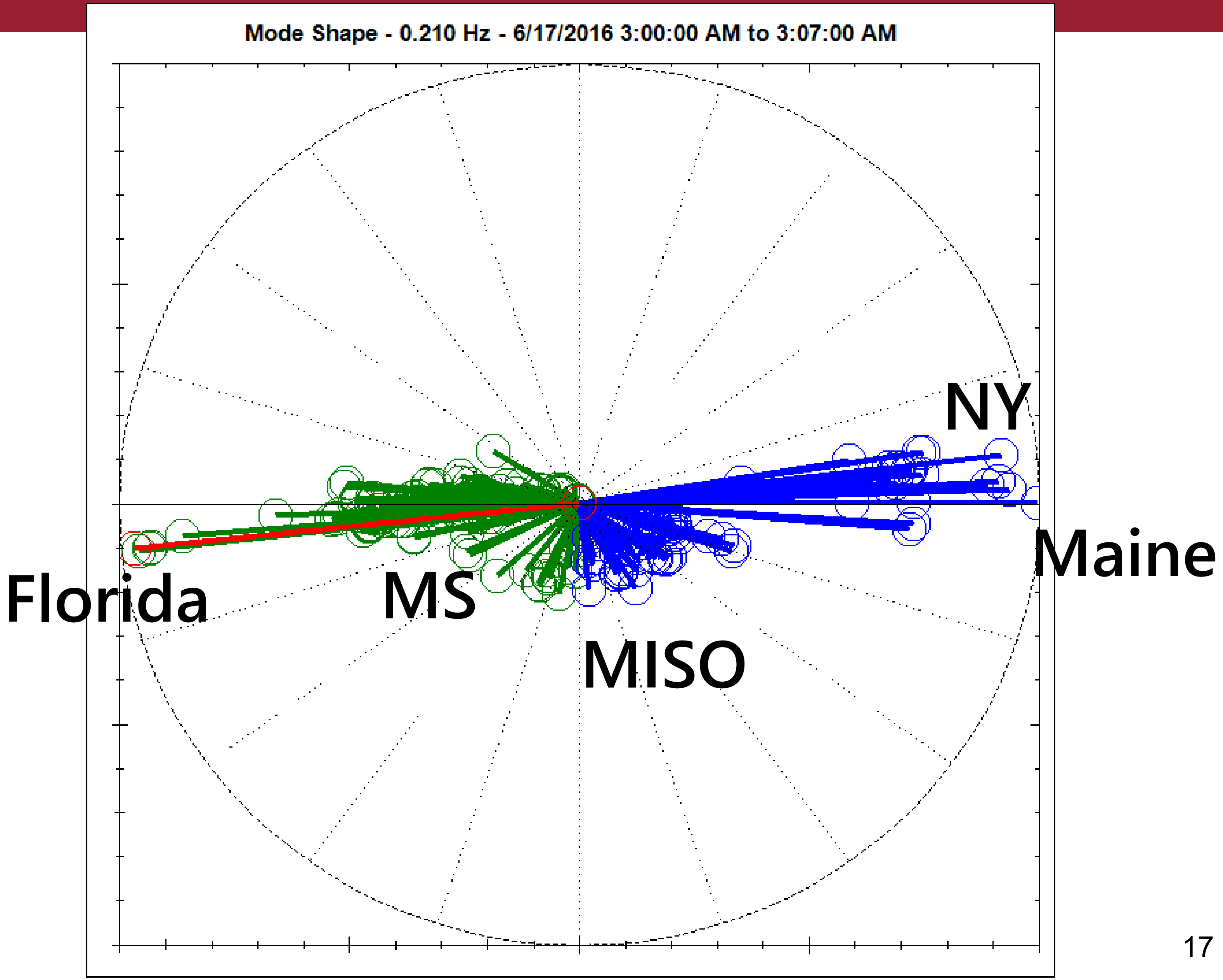
0.2 Hz

0.3 Hz

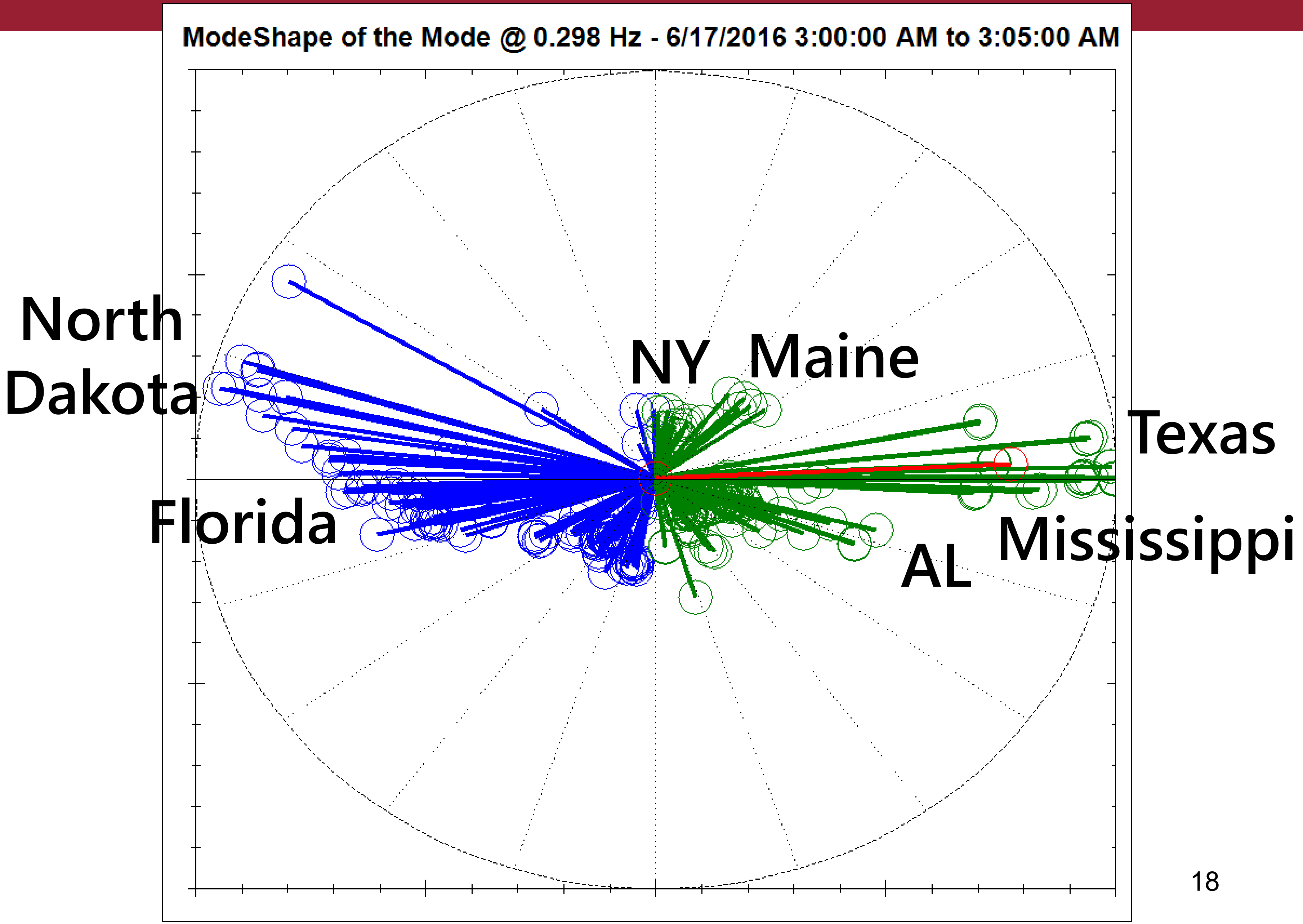
0.5 Hz

0.75 Hz

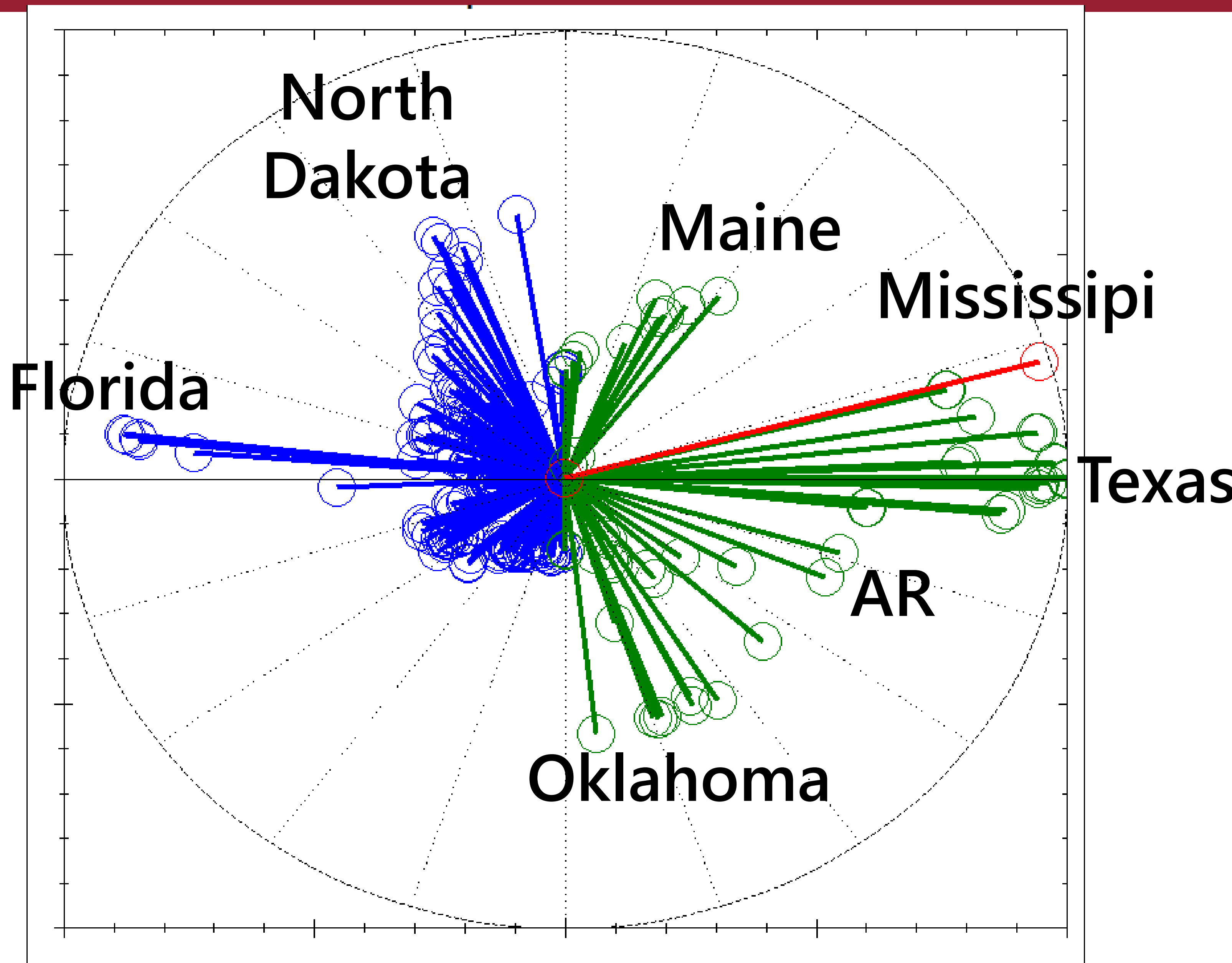
0.2 Hz North-South Mode from FSSI



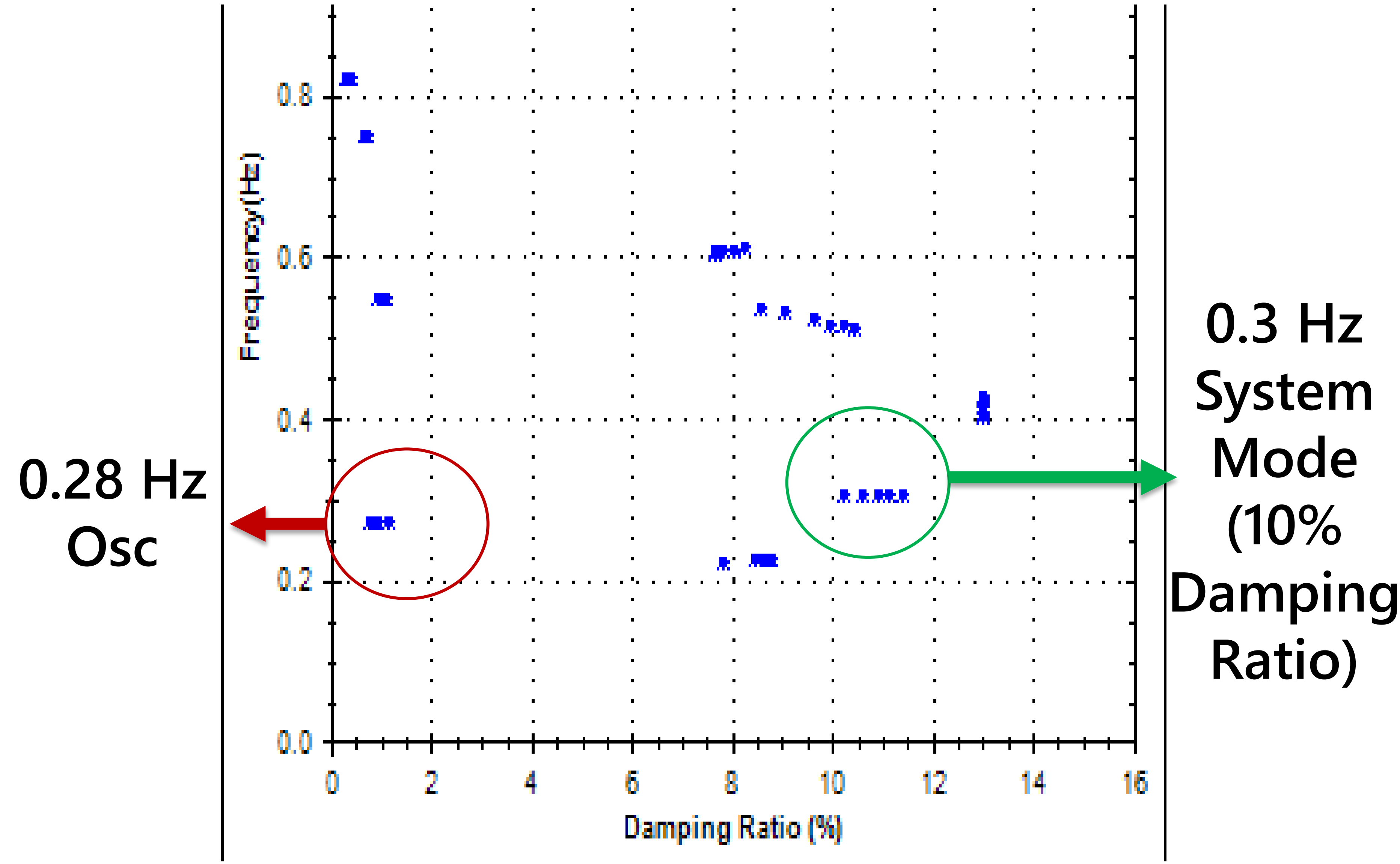
0.3 Hz North-South Mode from FFDD



0.28 Hz Oscillation Shape



FSSI Estimates During Event (3:13 to 3:17)



Resonance Conditions (June 17, 2016 event)

(R1) Forced Osc freq near System Mode freq **(close)**

- **0.28 Hz Oscillation versus 0.3 Hz Mode**

(R2) System Mode poorly damped **(invalid)**

- **0.3 Hz Well-damped (10% Damping Ratio)**

(R3) Forced Osc location near the two distant ends (strong participation) of the System Mode **(true)**

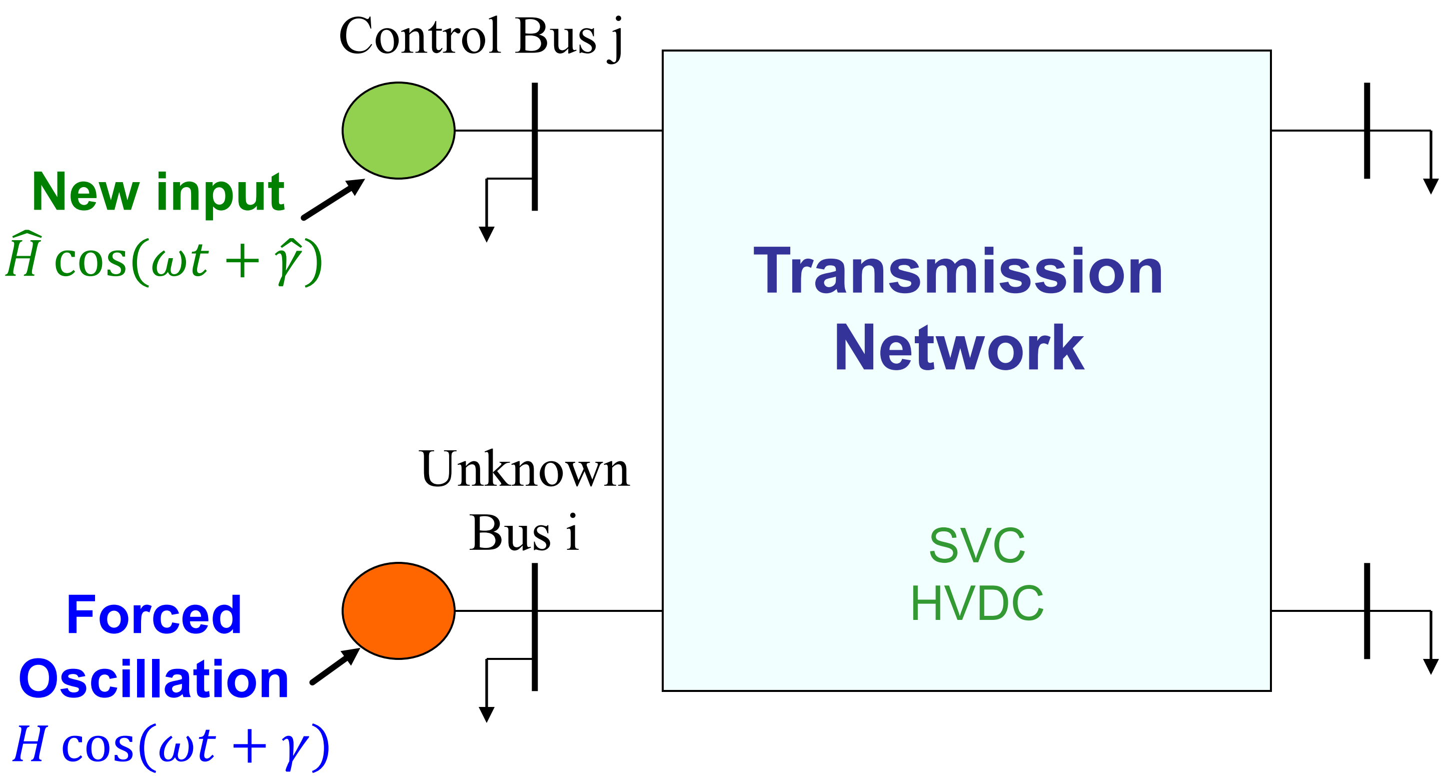
- **Mississippi Sensitive Location for the Mode**

Only 1+ conditions valid: Resonance effect small.

Mitigation of Resonant Oscillations

- How to stop the oscillations?
  - **Source location of forced oscillations**
  - **Many methods proposed**
  - **Problematic for resonant oscillations**
- How to reduce resonant oscillations?
  - **Increase the damping of inter-area mode**
  - **Closed-loop controls have been proposed**
  - **We propose an alternate open-loop control for interim reduction of oscillations**

Open-loop Control for Mitigation



Apply a strategically designed input at the same frequency with the correct phase and amplitude to "cancel out" the effects of unknown forced oscillation.

Superposition holds for small-signal analysis.

Theory Base

- Resonance mainly with one inter-area mode say $\alpha_r \pm j\beta_r$:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u,\ u(t) = H\cos(\omega t + \gamma)$$

Sinusoidal steady state:

$$x_i(t) = A_{FR_i}\cos\left(\omega t + \Psi_{FR_i}\right)$$

$$\mathbf{A}_{FR}\angle\mathbf{\Psi}_{FR}$$

$$= -(H\angle\gamma)\tilde{\mathbf{v}}_r \frac{\left|\tilde{\mathbf{w}}_r^{\mathrm{T}}\mathbf{b}\right|}{\sqrt{\alpha_r^2 + (\omega - \beta_r)^2}}\left[\angle\left(\tilde{\mathbf{w}}_r^{\mathrm{T}}\mathbf{b}\right) + \angle\left(\alpha_r + j(\omega - \beta_r)\right)\right]$$

Theory Base

$u(t) = H\cos(\omega t + \gamma)$ at bus i.

$\hat{u}(t) = \hat{H}\cos(\omega t + \hat{\gamma})$ applied at bus j.

Sinusoidal steady state:

$$x_i(t) = A_{FR_i}\cos\left(\omega t + \Psi_{FR_i}\right)$$

$$\text{Net Effect} = \tilde{w}_{ri} b_i \, H\angle\gamma + \tilde{w}_{rj} b_j \hat{H}\angle\hat{\gamma}$$

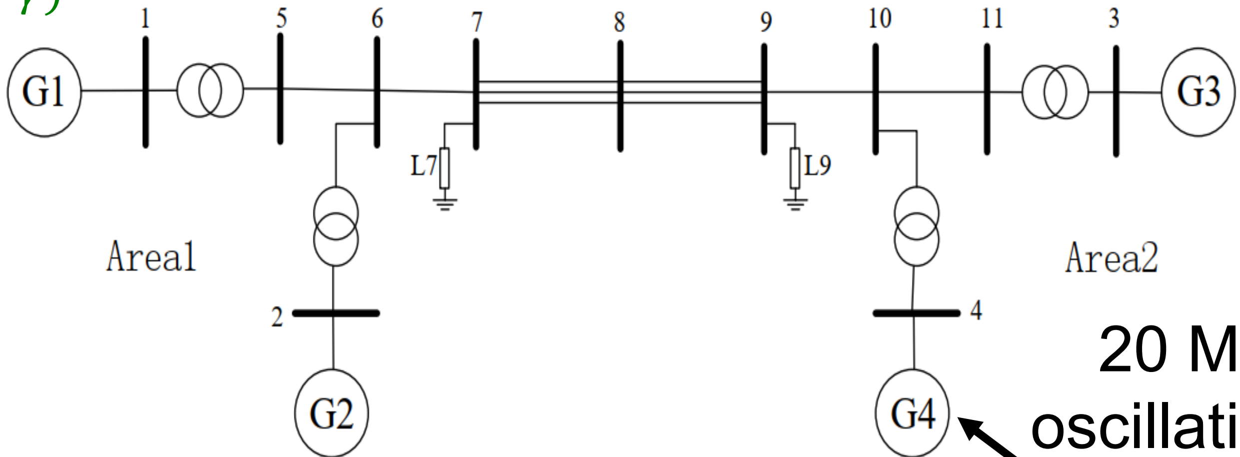
$$A_{FR_i} = 0 \text{ when } \hat{H}\angle\hat{\gamma} = -\frac{\tilde{w}_{ri} b_i \, H\angle\gamma}{\tilde{w}_{rj} b_j}$$

How to find the control signal amplitude $\hat{H}$ and the phase $\hat{\gamma}$ using local measurements?

Control Example

Control input
$\widehat{H}\cos(\omega t + \hat{\gamma})$

39 MW Tie-line oscillations



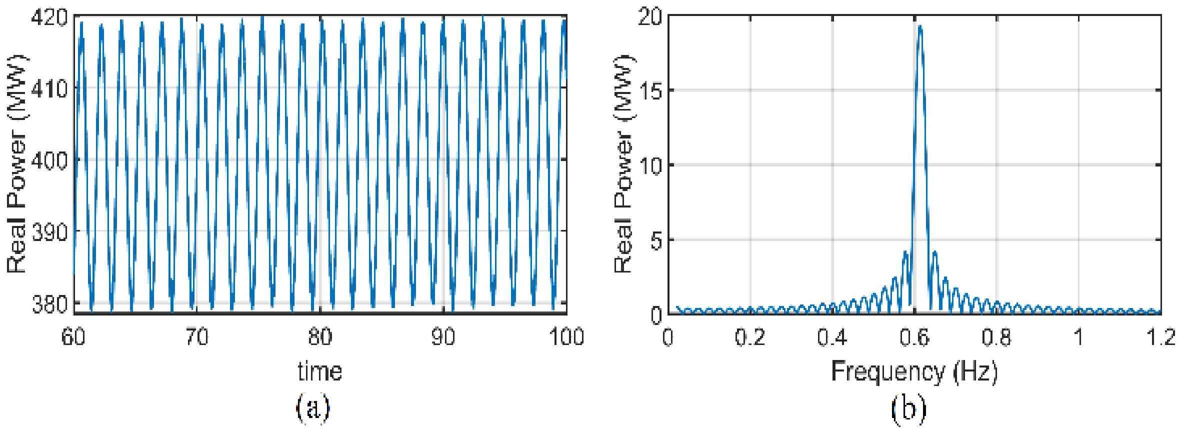
20 MW forced oscillation from the governor @ 0.61 Hz

Step 1) Estimate forced oscillation frequency

Step 2) Estimate $\hat{\gamma}$ by iteration starting from $\widehat{H}_0$ and $\hat{\gamma}_0$

Step 3) Adjust $\widehat{H}$ as relevant for effective mitigation

Step 1) Frequency Estimation

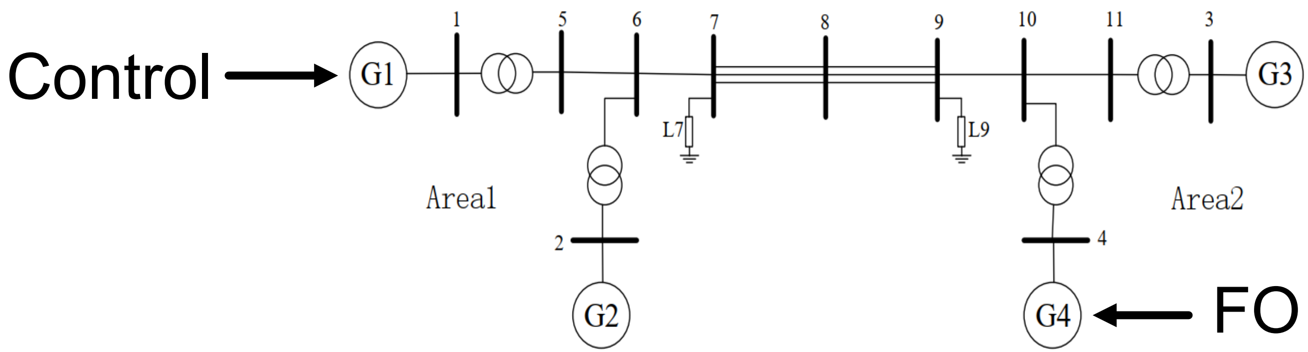


Estimate forced oscillation frequency @ 0.61 Hz

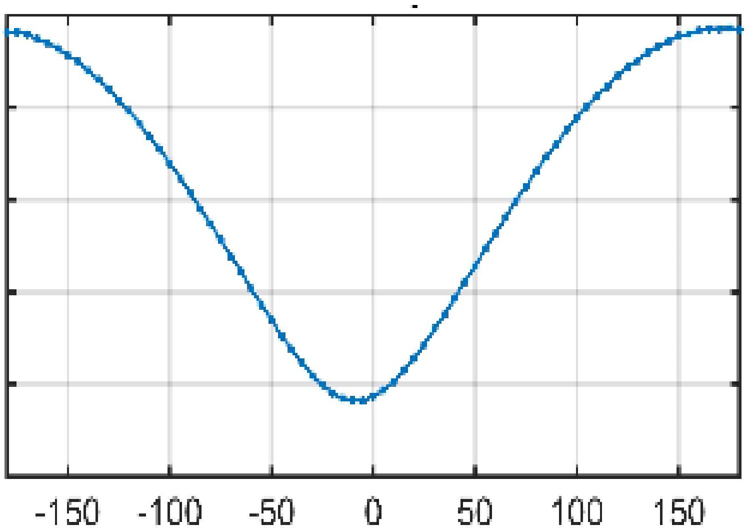
- We can use time-domain (Prony/HTLS/ERA) or frequency domain methods (FFT/PSD)
- Phase-Locked Loop

Method	Estimated Frequency (Hz)
FFT	0.61
Prony	0.61
Matrix Pencil	0.61
HTLS	0.61

Step 2) Phase Estimation



Use phase of P_{G1} to estimate $\hat{\gamma}_0$

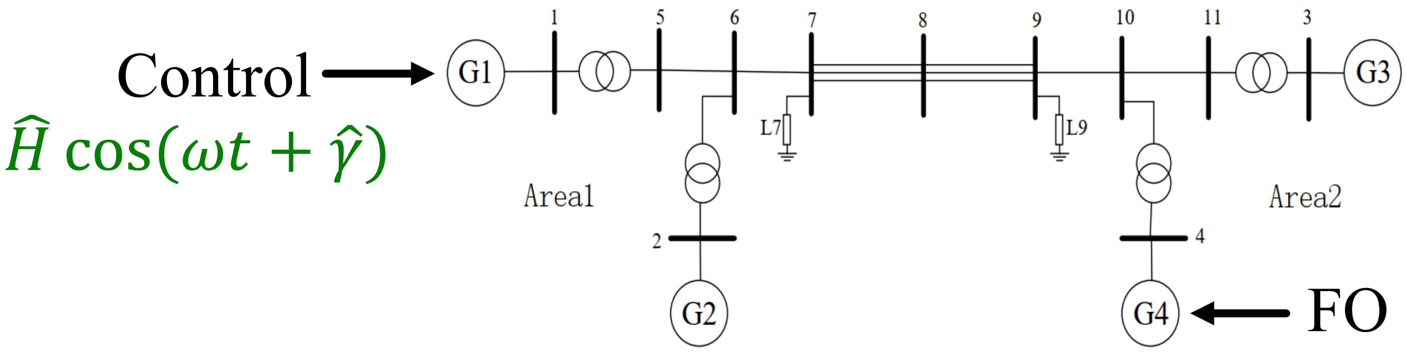


Control signal phase $\hat{\gamma}$

Minimum amplitude for $\hat{\gamma}$ = -9.9 deg

Control Angle (Degrees)	FO Magnitude P_{G1}(MW)	Gradient Search
10	20.26	Initialize
15	21.56	Flip
5	19.38	Continue
0	**18.70**	**Continue**
-5	**18.22**	**Continue**
-10	**18.28**	**Stop**

Step 3) Amplitude Estimation



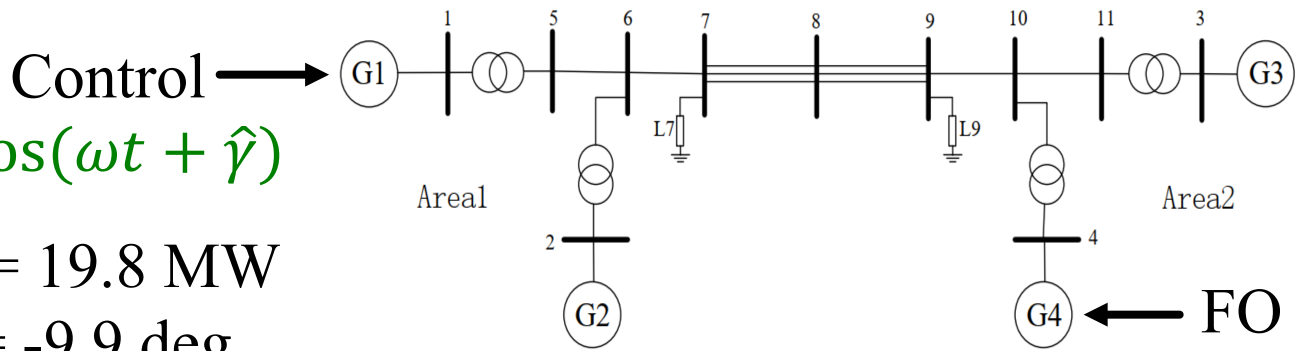
- Choose $\hat{\gamma}$ = -9.9 deg, and $\hat{H}_0$ = 10.4 MW.
- Increase $\hat{H}$ by $\widehat{\Delta H}$ and estimate the change in tie-line flow oscillation amplitude.
  - 16.2 MW oscillations @ $\hat{H}$ = 10.4 MW
  - 11.2 MW oscillations @ $\hat{H}$ = 15.6 MW
- Using linear extrapolation, estimate $\widehat{\Delta H}$ needed for desired mitigation. $\hat{H} \approx$ 19.8 MW for 0 MW oscillations
- Apply the control with $\hat{H}$ = 19.8 MW and $\hat{\gamma}$ = -9.9 deg
- Tie-line flow oscillations nearly zero.

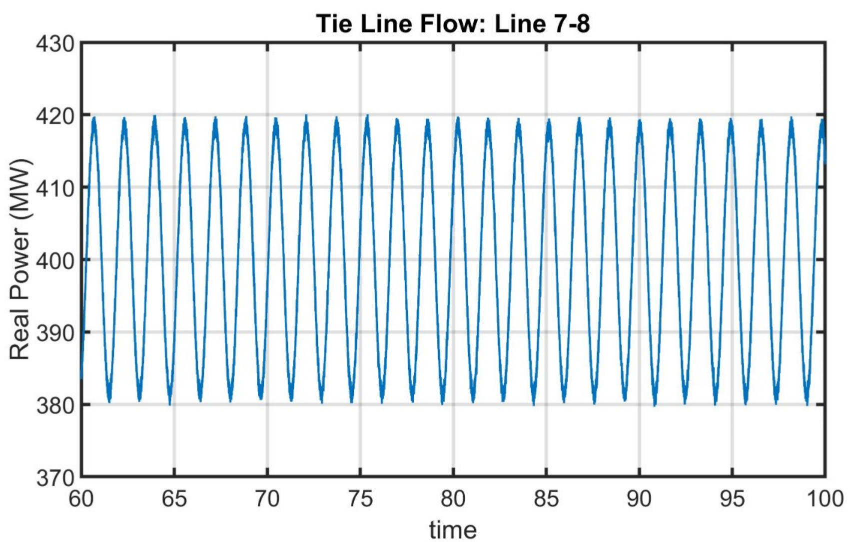
Control for Mitigation

$\hat{H}\cos(\omega t + \hat{\gamma})$

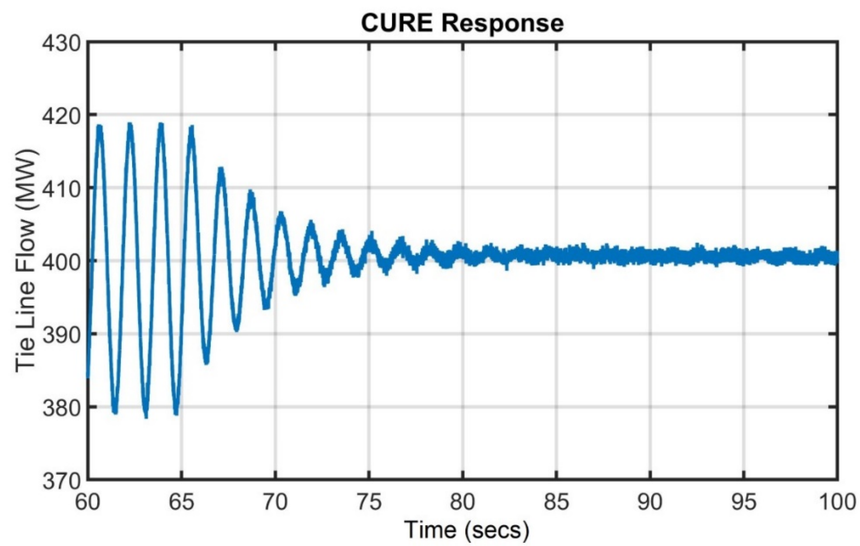
$\hat{H}$ = 19.8 MW

$\hat{\gamma}$ = -9.9 deg





Forced Oscillation response



Forced Oscillation and Control (applied @ 65 sec) response

Resonant Forced Oscillation Events

- Many resonant forced oscillations observed in different interconnections.
- Need to understand dominant inter-area modes and track the damping of system inter-area modes
- Inter-area resonance – potential risk for operational reliability
- Effective source location algorithms needed
- Controls for mitigation of resonant oscillations need to be developed and tested
- Novel open-loop control proposed

Questions?

Mani V. Venkatasubramanian

(mani@wsu.edu)