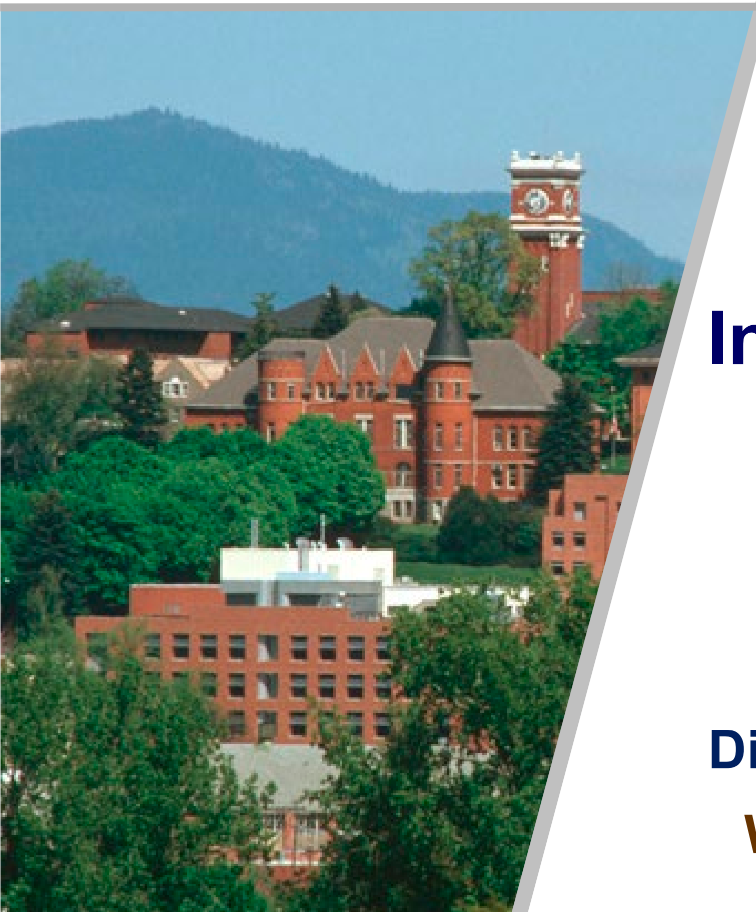

Interaction of Forced Oscillation with Multiple System Modes

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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.

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

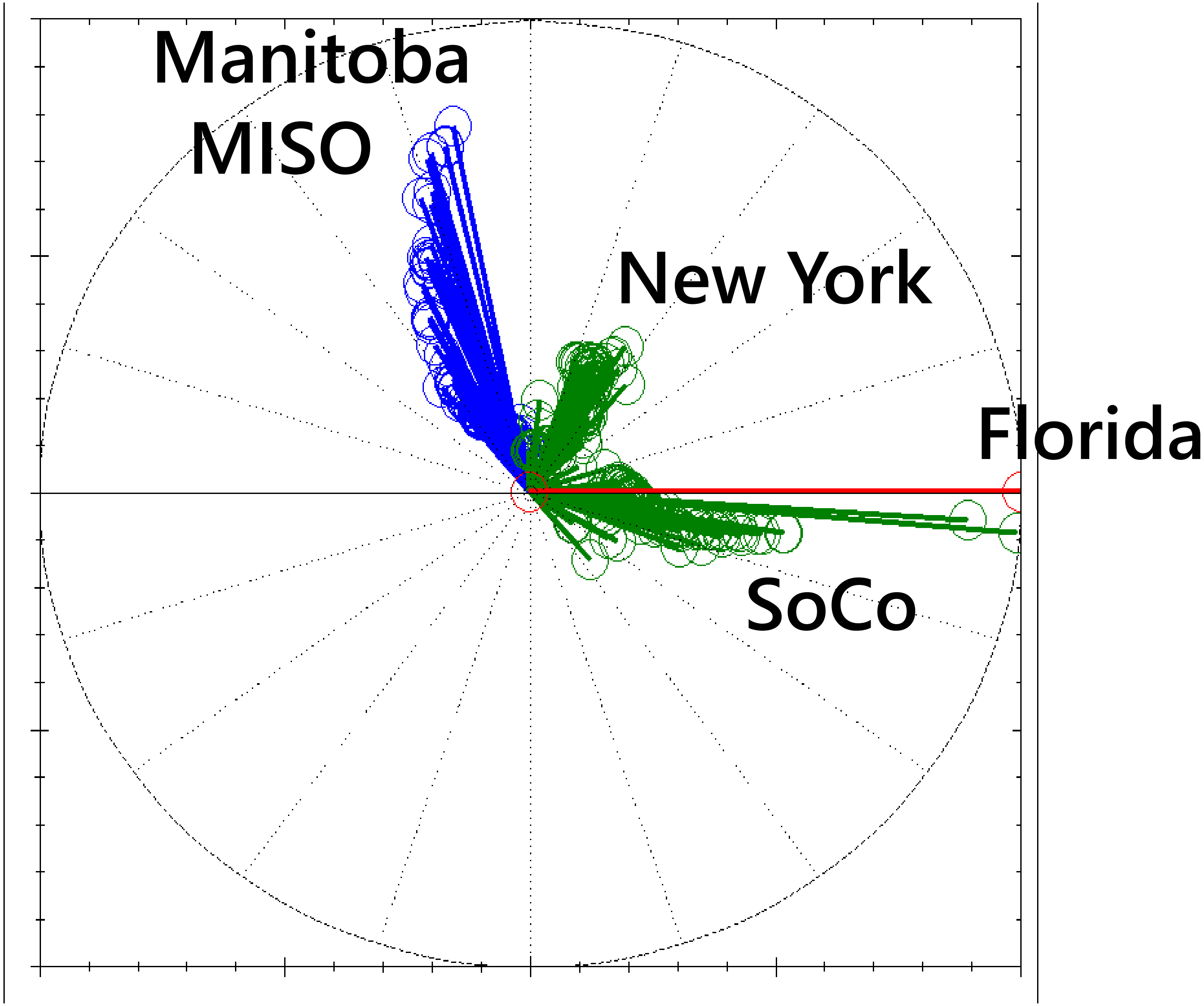
Resonance effect small when:

- None of the condition holds

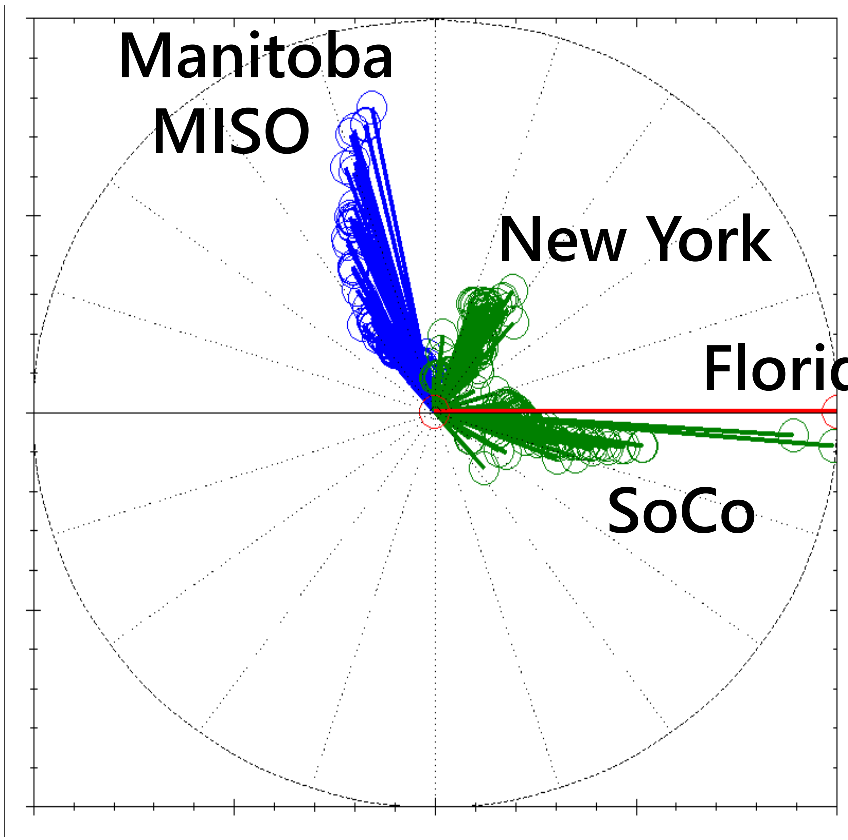
S.A.N. Sarmadi and V. Venkatasubramanian, "Inter-Area Resonance in Power Systems From Forced Oscillations," ***IEEE Trans. Power Systems*****, vol.31, no.1, pp.378-386, Jan. 2016.**

Jan 11, 2019 Eastern System Event

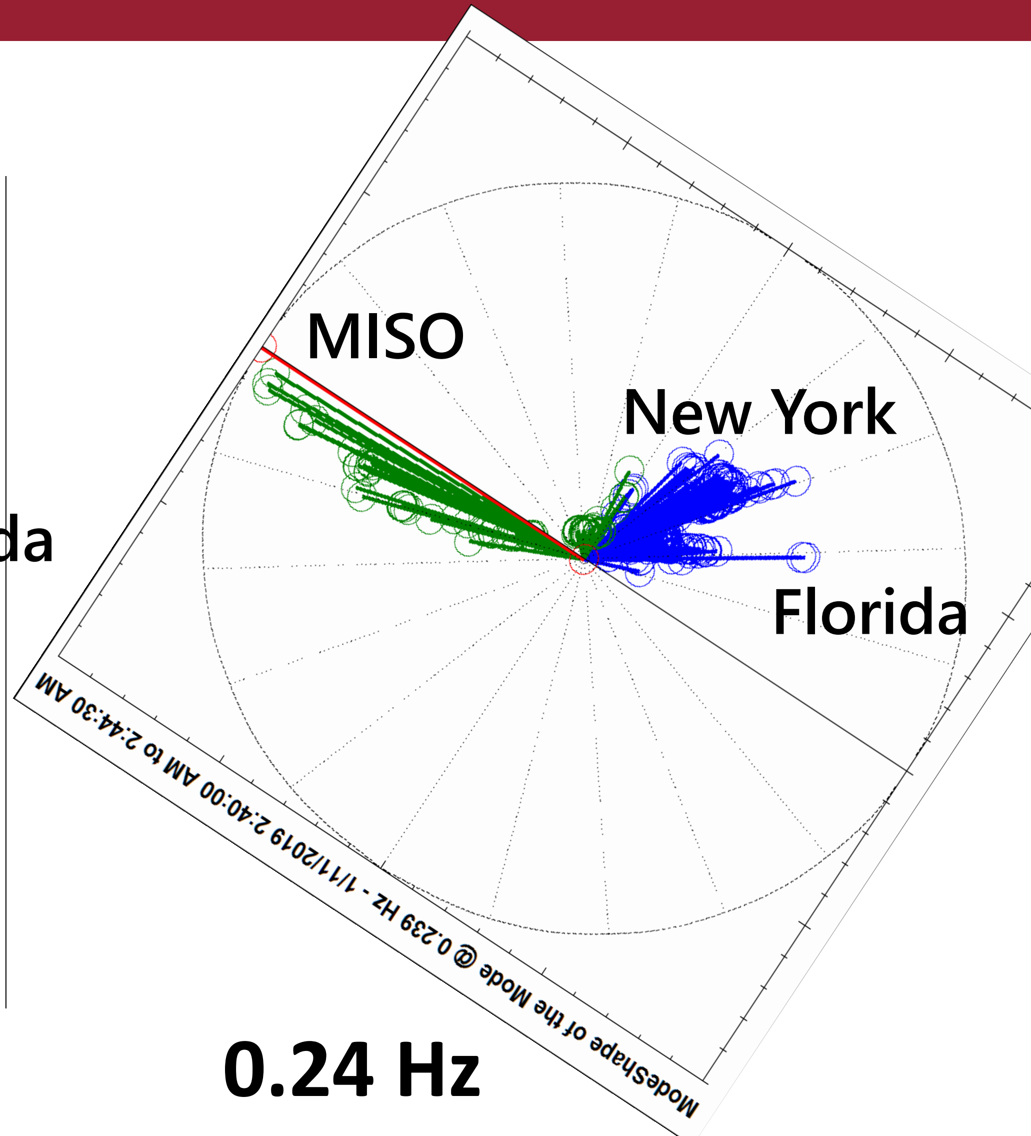
0.25 Hz Oscillation Shape



0.25 Hz Oscillation Shape Comparison



0.25 Hz
Oscillation Shape



0.24 Hz
Mode Shape

Oscillation Shape Proposition

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

Sinusoidal steady state:

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

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

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

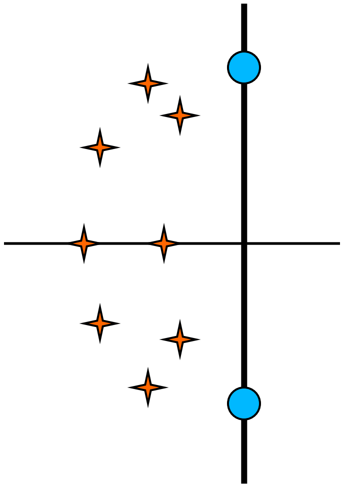
Y. Zhi and V. Venkatasubramanian, "Interaction of Forced Oscillation With Multiple System Modes," *IEEE Trans. Power Systems*, vol. 36, no. 1, pp. 518-520, Jan. 2021.

Oscillation Shape Proposition

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

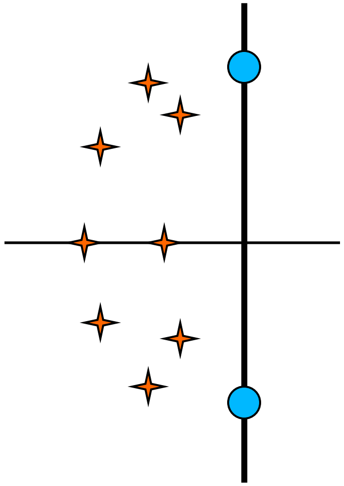
Each mode $\alpha_i + j\beta_i$ contributes its mode shape $\tilde{\mathbf{v}}_i$ multiplied by amplification factor A_i and shifted by rotation factor ψ_i

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



Modal Amplification Factors

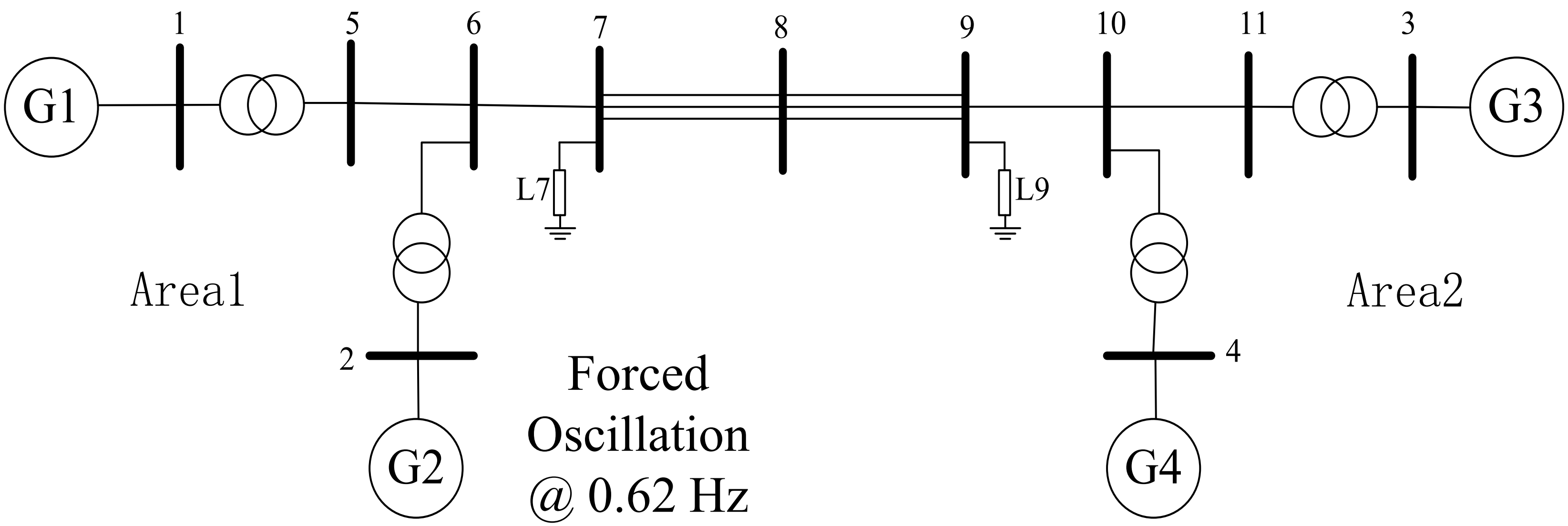
$$|A_i| = \frac{|\tilde{\mathbf{w}}_i^{\mathrm{T}}\mathbf{b}|}{\sqrt{\alpha_i^2 + (\omega - \beta_i)^2}}$$



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

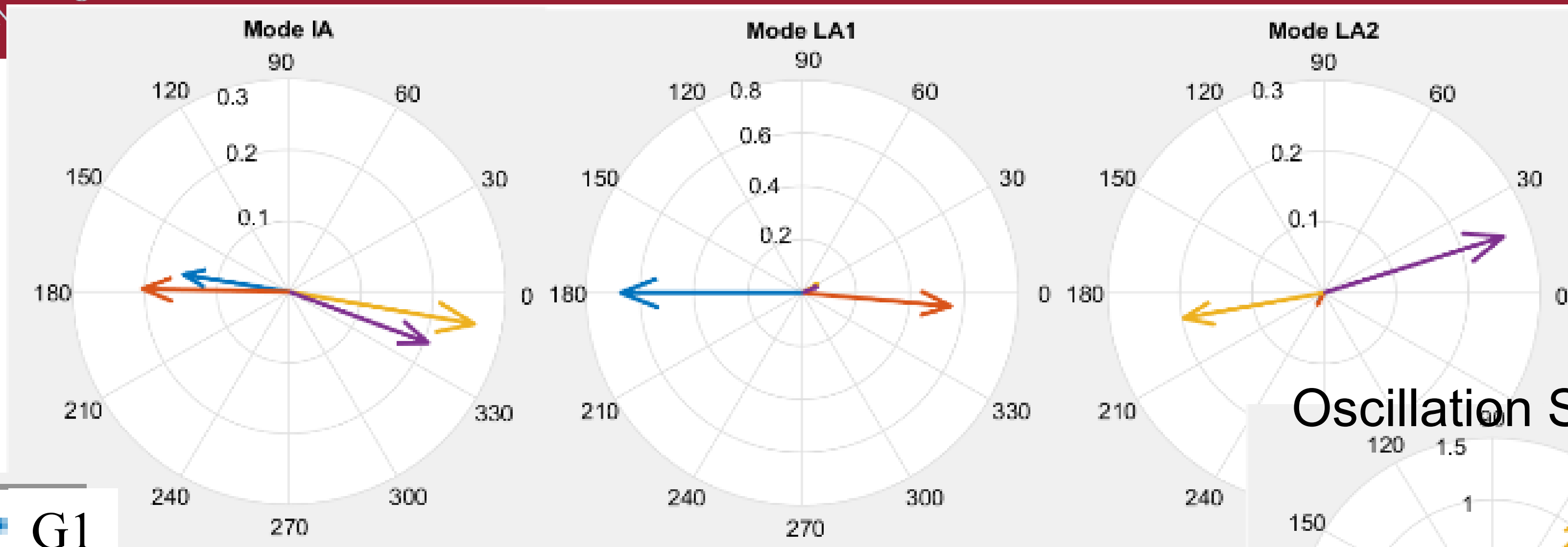
Y. Zhi and V. Venkatasubramanian, "Interaction of Forced Oscillation With Multiple System Modes," *IEEE Trans. Power Systems*, vol.36, no.1, pp.518-520, Jan. 2021.

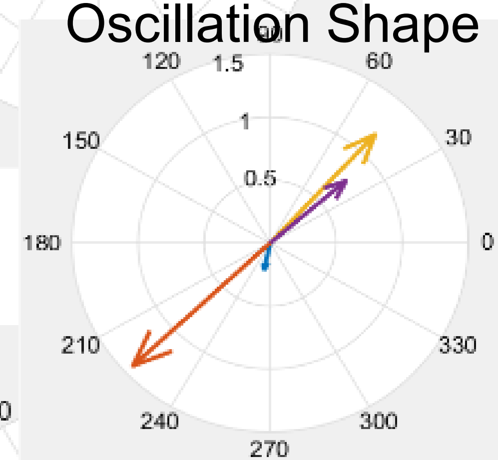
Kundur System Example



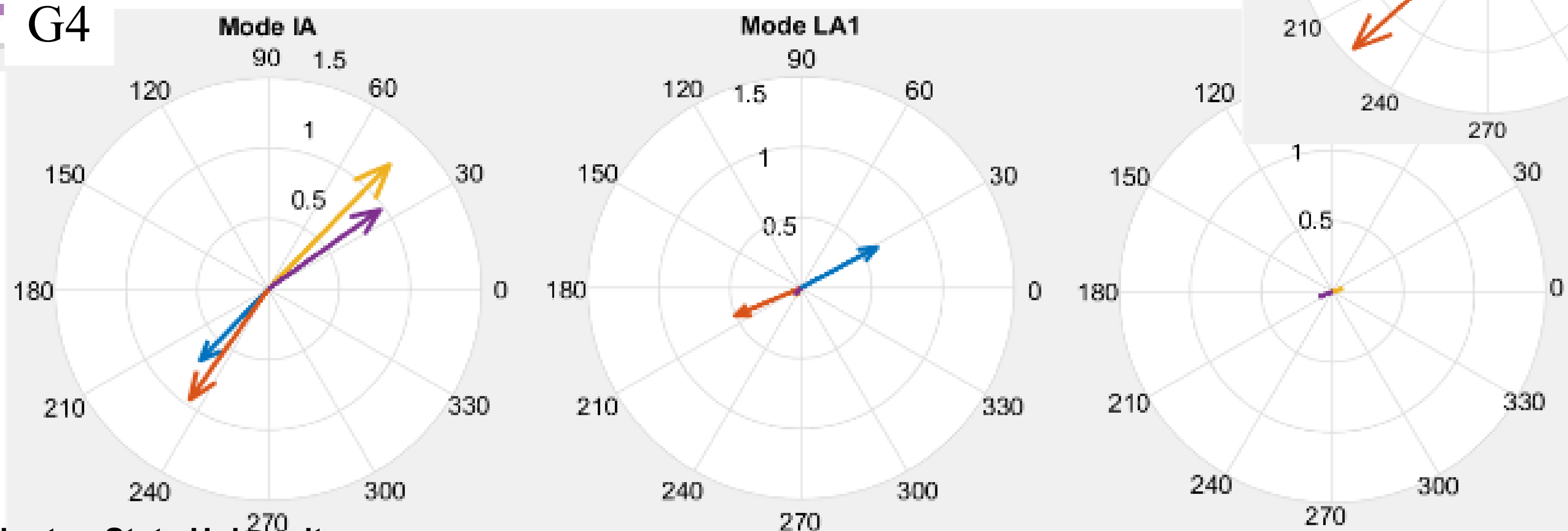
	Type	Frequency	Damping Ratio	$A_i\angle\psi_i$
Mode IA	Inter-area	0.62 Hz	3.0%	$4.70\angle 56.0°$
Mode LA1	Local (Area1)	0.56 Hz	6.8%	$0.91\angle -151.7°$
Mode LA2	Local (Area2)	0.67 Hz	1.4%	$0.36\angle 174.7°$

Mode shapes

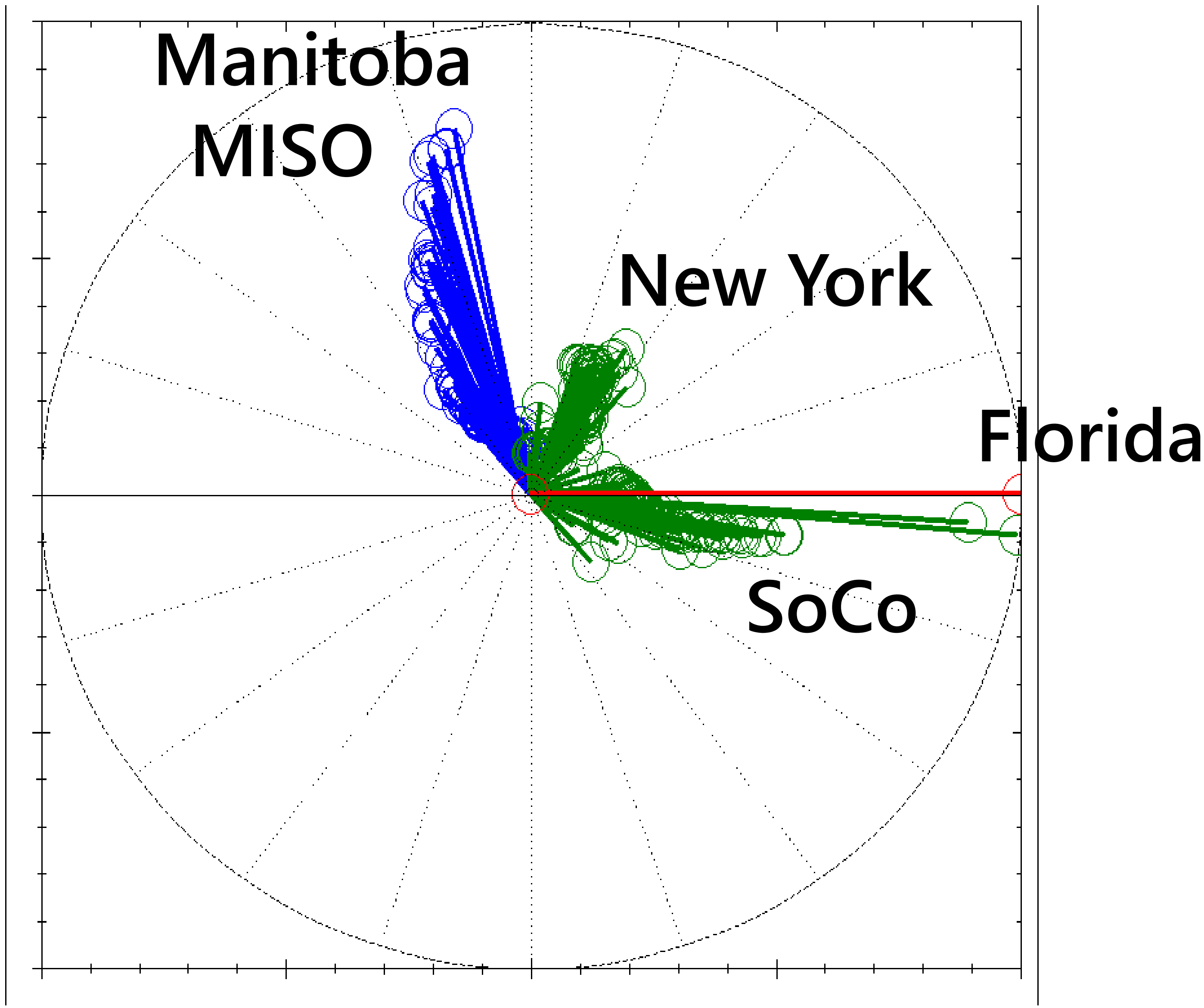




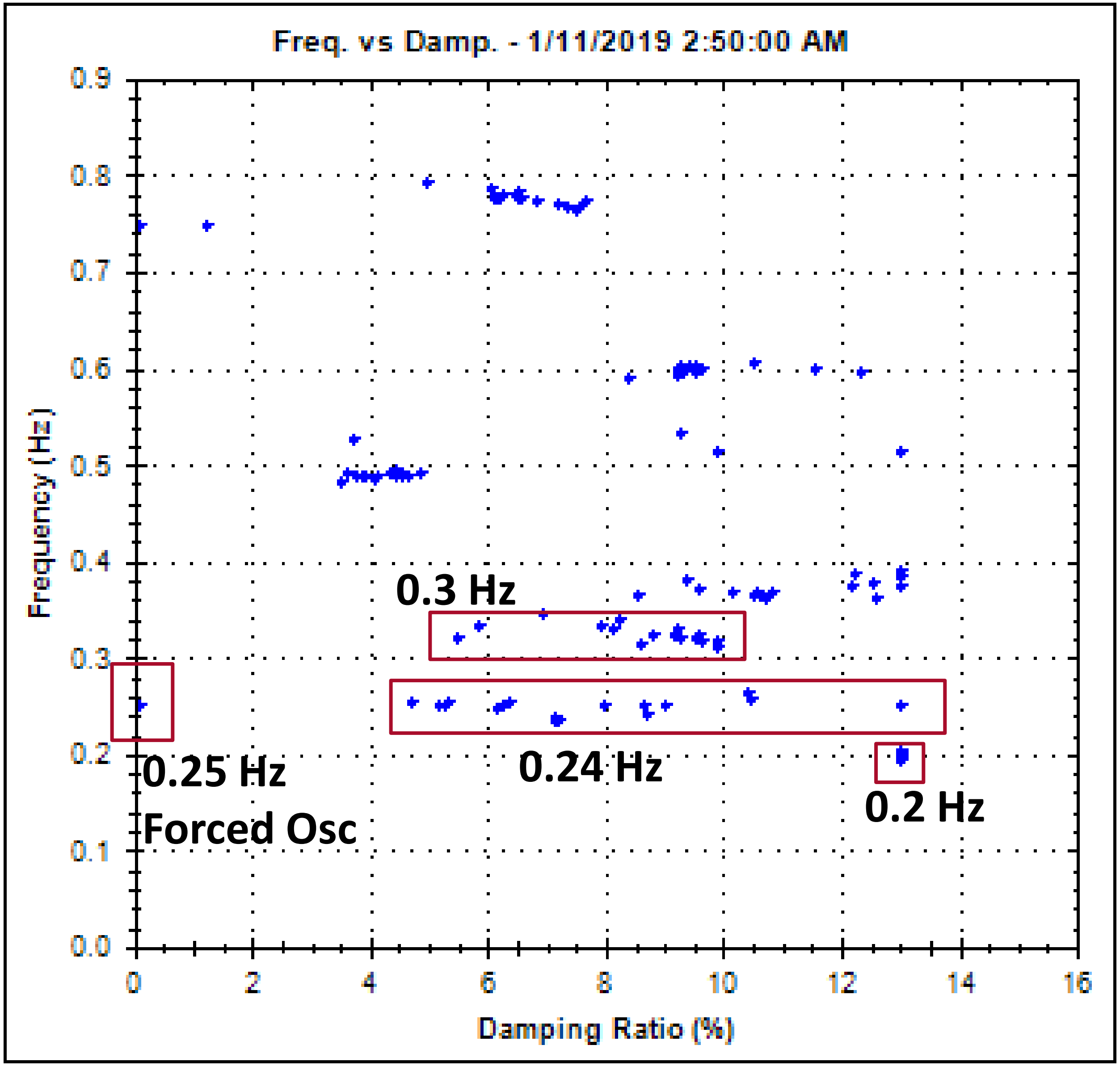
Modal Contributions



0.25 Hz Oscillation Shape



FSSI Analysis During Event



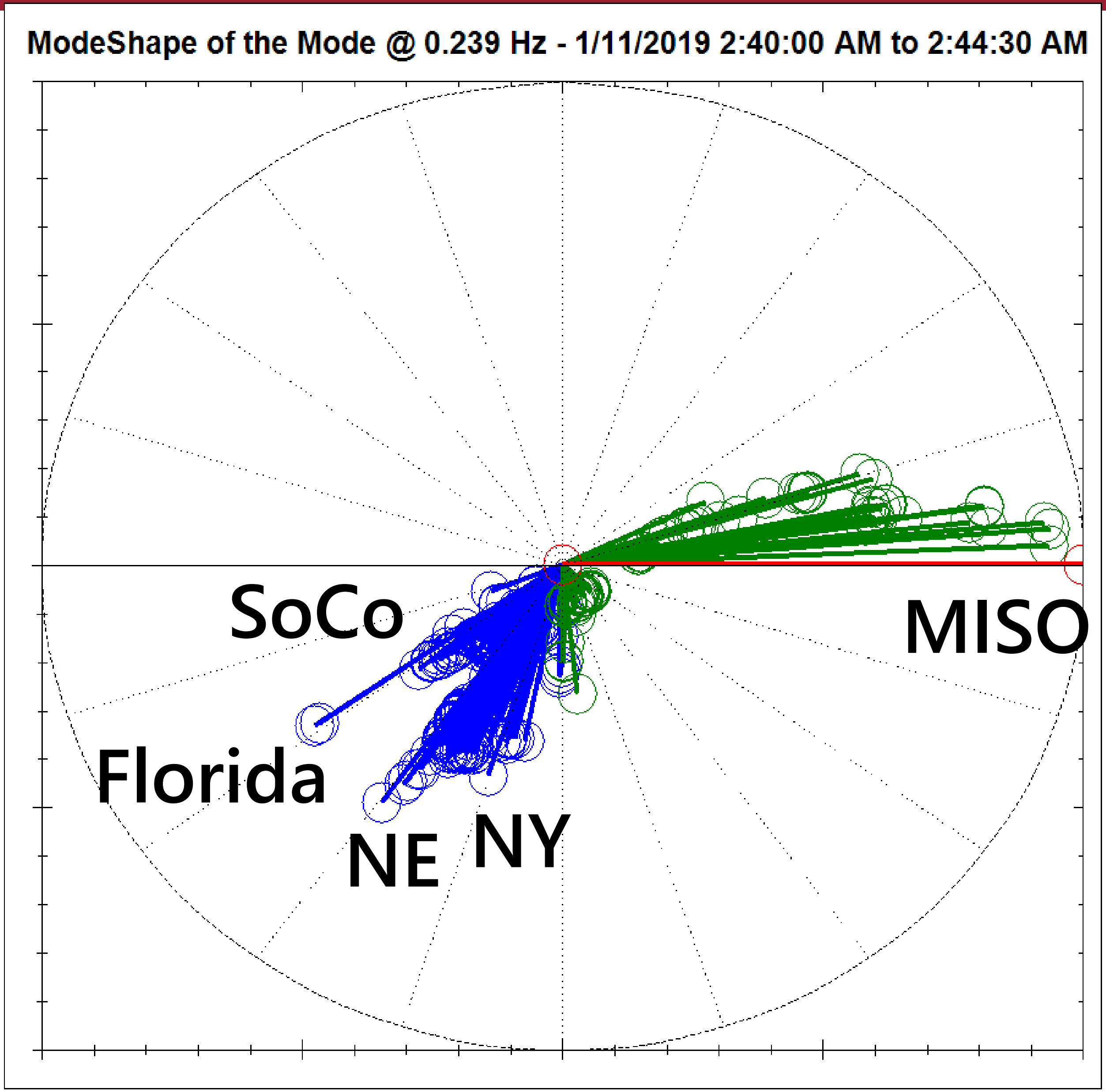
FSSI Analysis. 442 signals.

0.24 Hz mode excited by 0.25 Hz forced oscillation.

0.24 Hz and 0.3 Hz active.

0.2 Hz inactive.

0.24 Hz NE-NW-SE Mode Shape

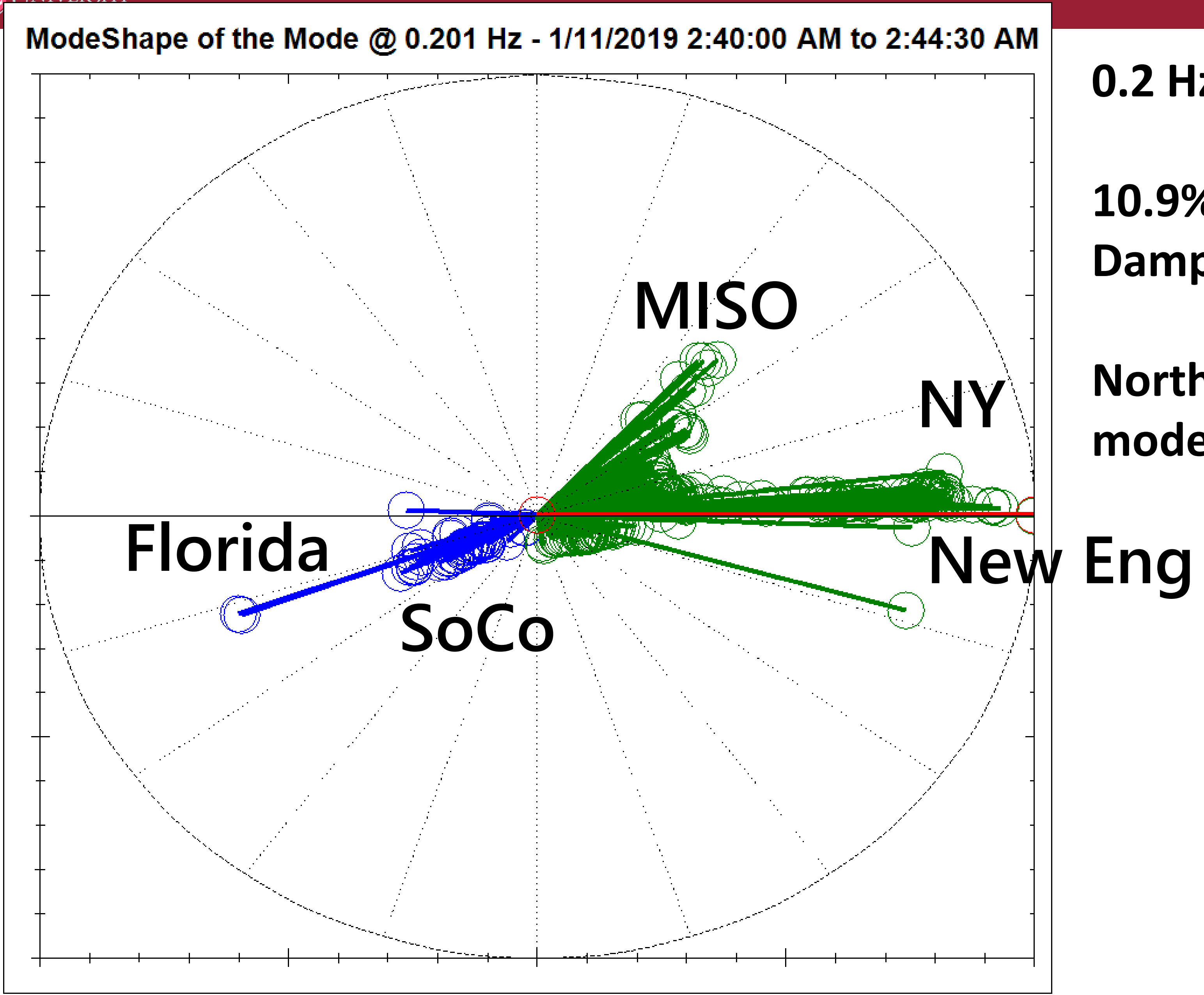


0.24 Hz mode

10.1% Damping ratio

NE-NW-SE mode

0.2 Hz N-S Mode Shape

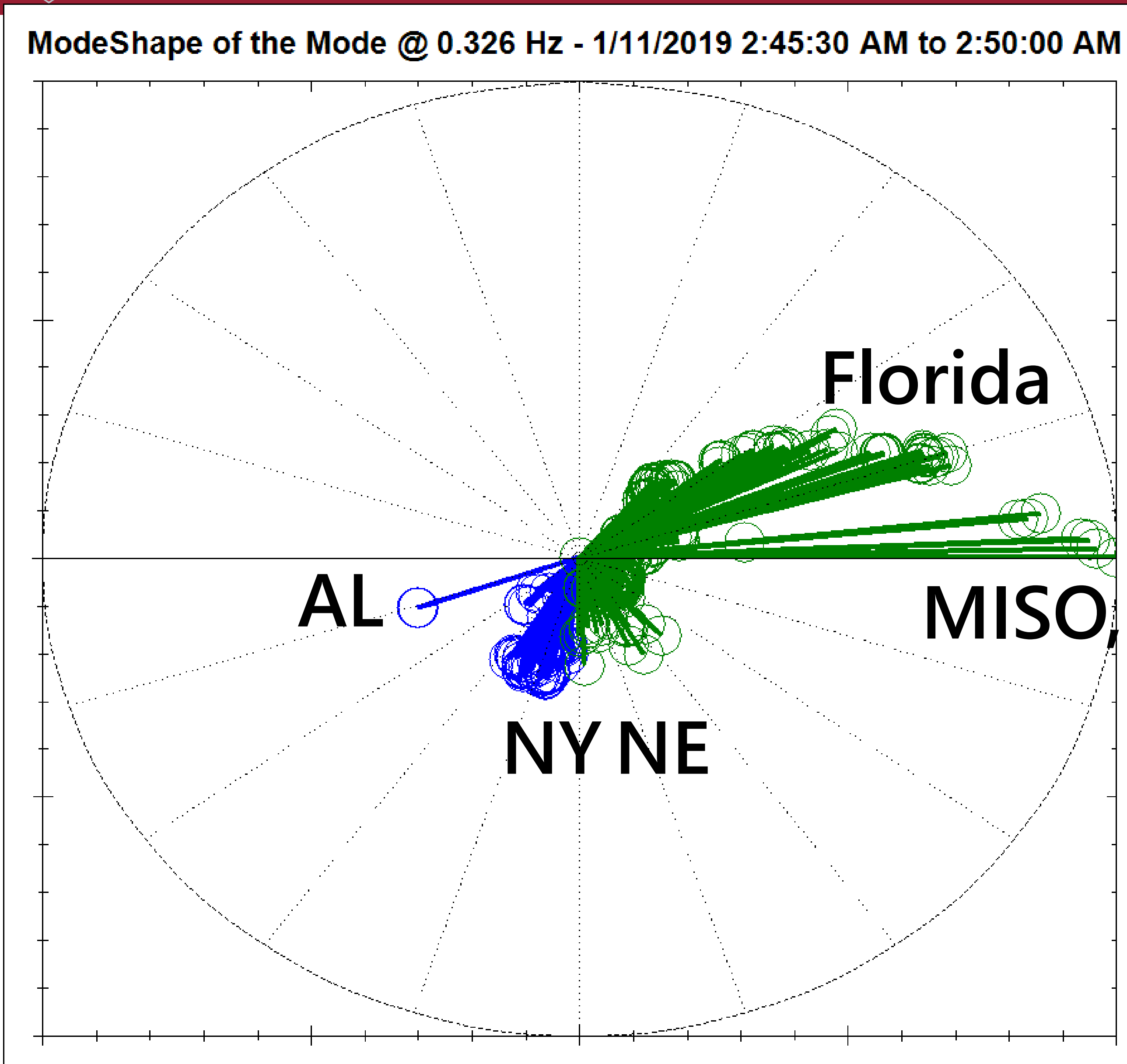


0.2 Hz mode

10.9% Damping ratio

North-South mode

0.3 Hz Mode Shape

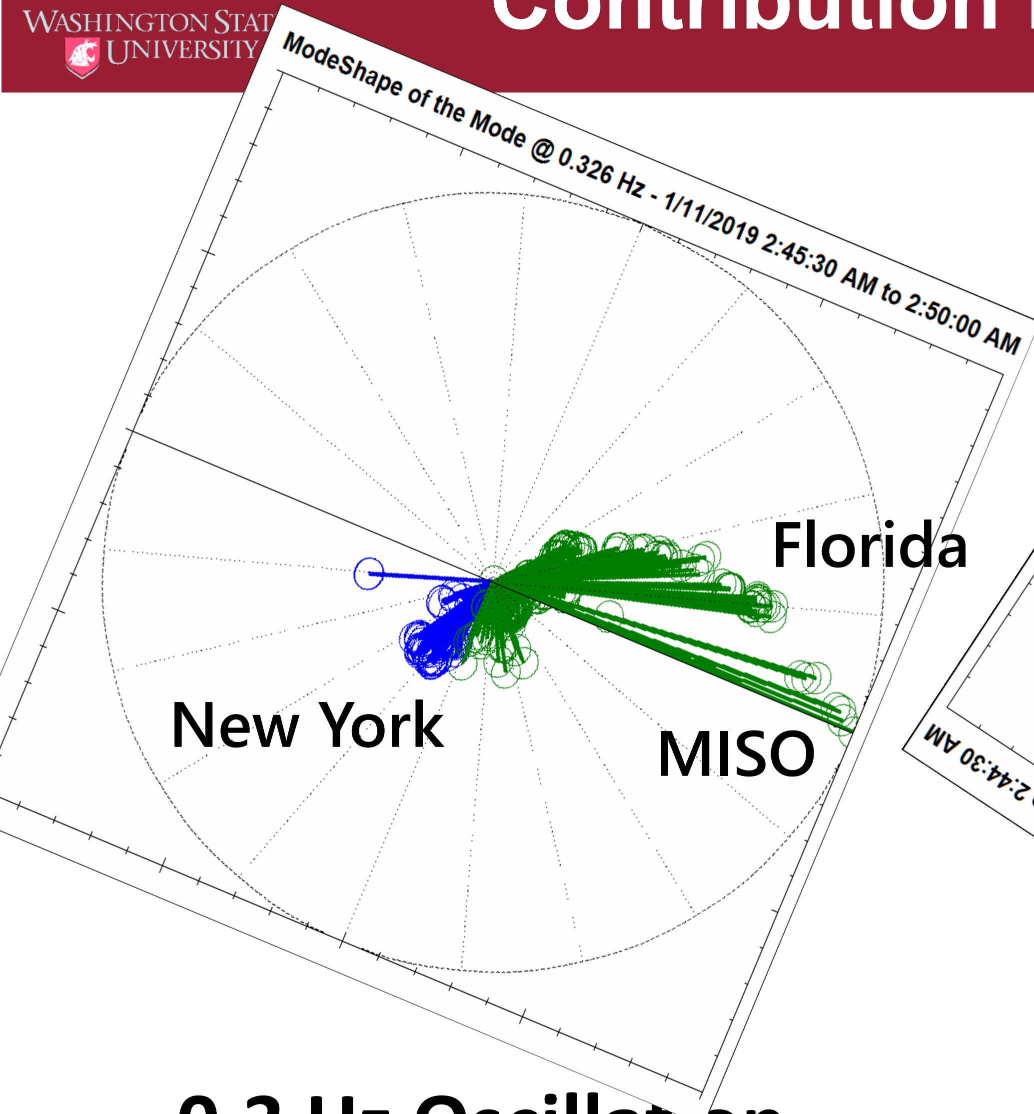


0.3 Hz mode

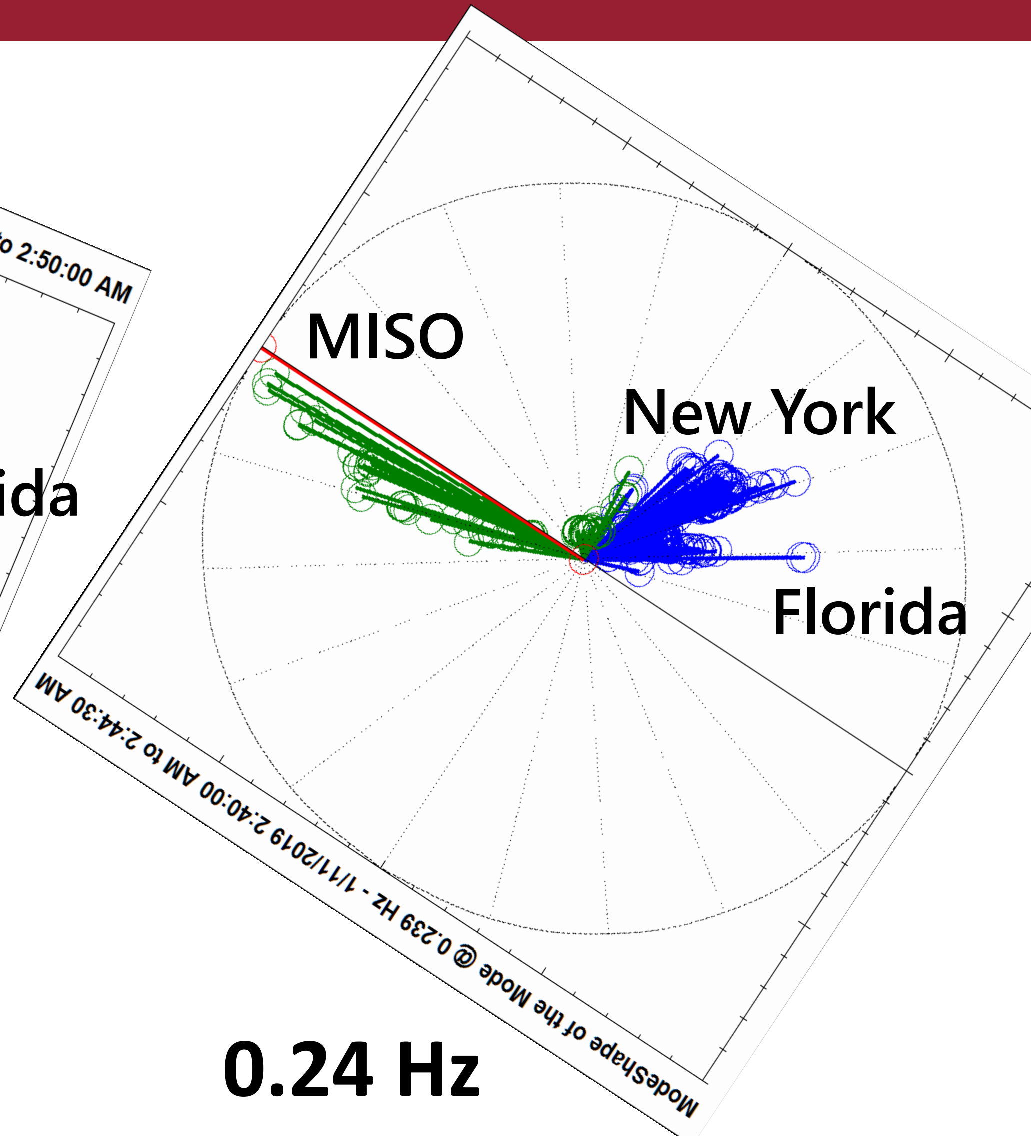
8.6% Damping ratio

North-South mode

Contribution from Two Modes

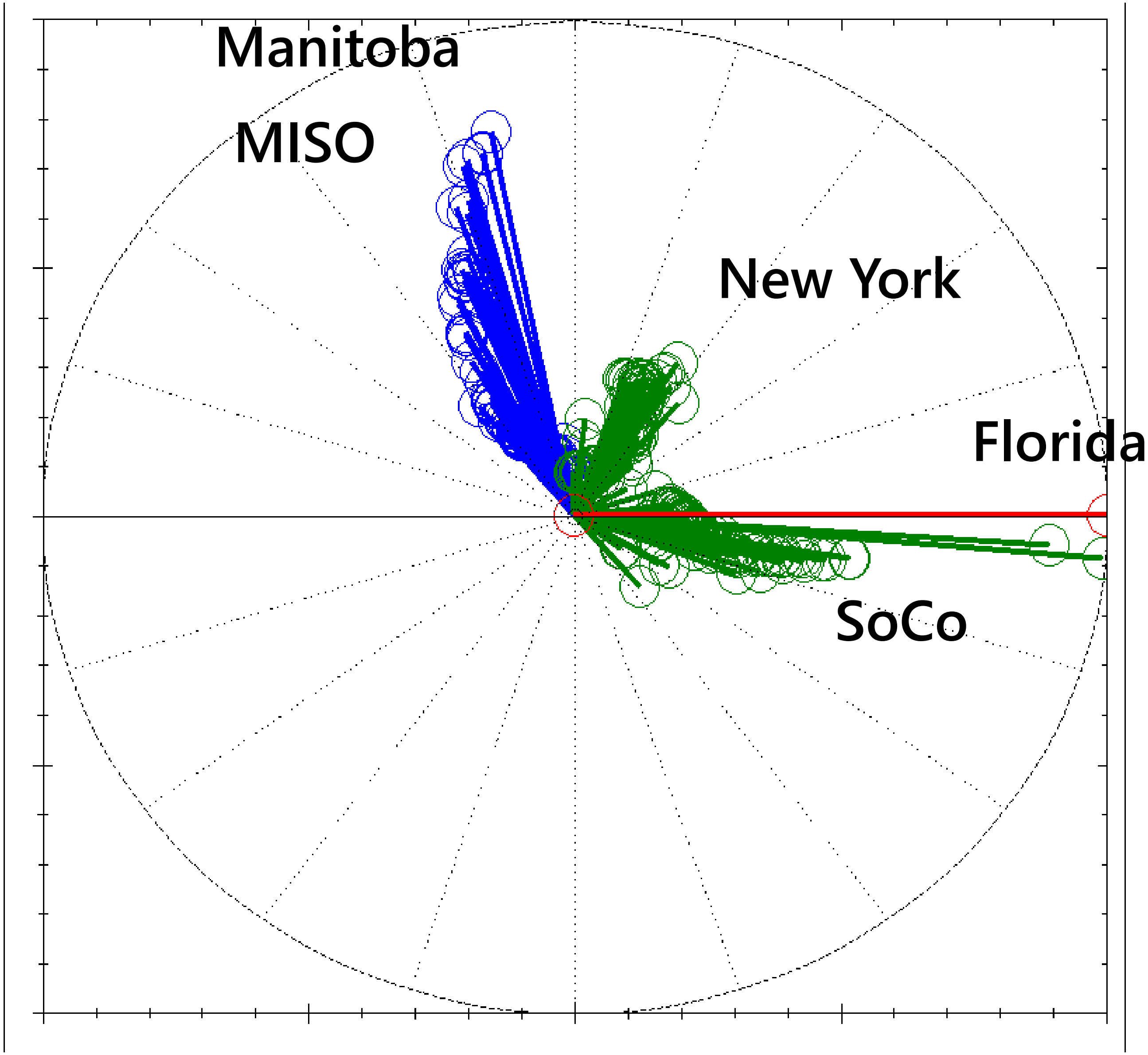


0.3 Hz Oscillation Shape



0.24 Hz Mode Shape

0.25 Hz Oscillation Shape



Oscillation Response is the net effect from 0.24 Hz and 0.3 Hz modes.

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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.