# Analysis of Eastern Interconnection Forced Oscillation Events

## NERC Special Reliability Assessment

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IEEE PES Power & Energy Society®

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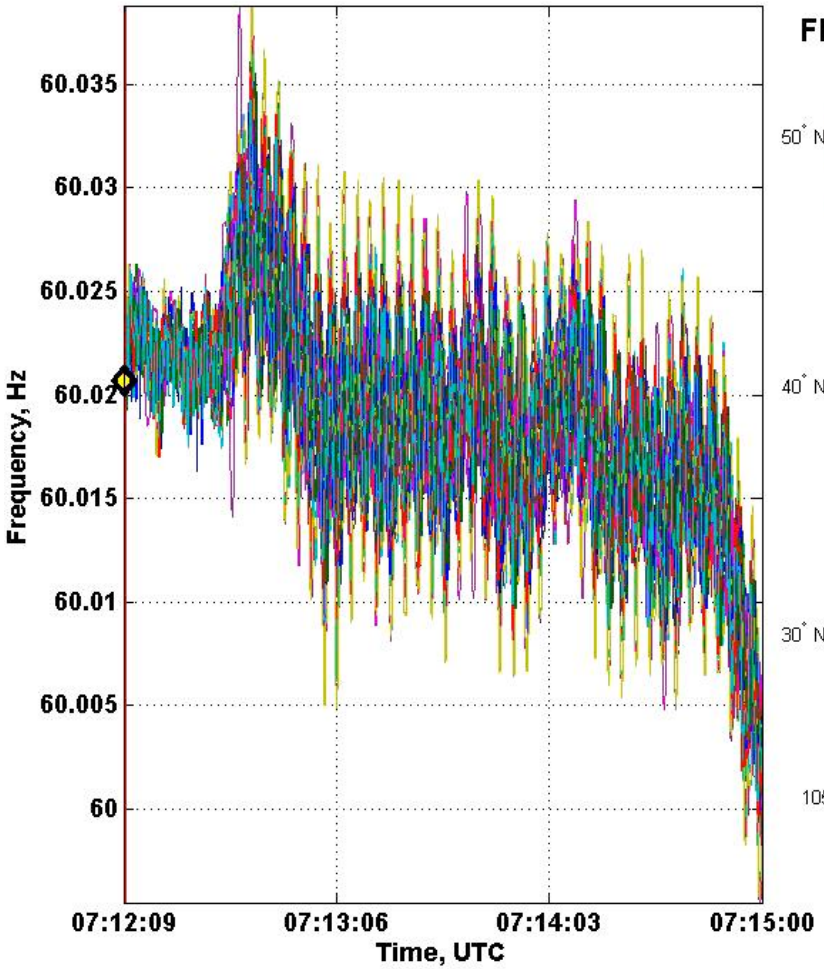
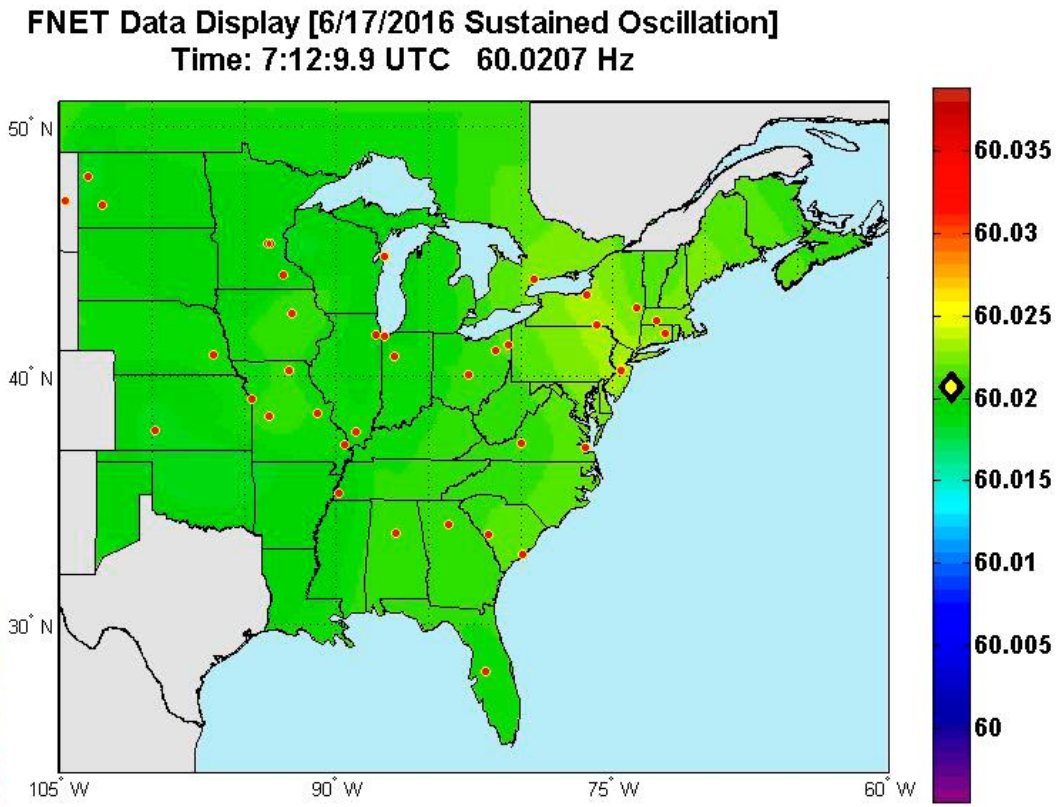
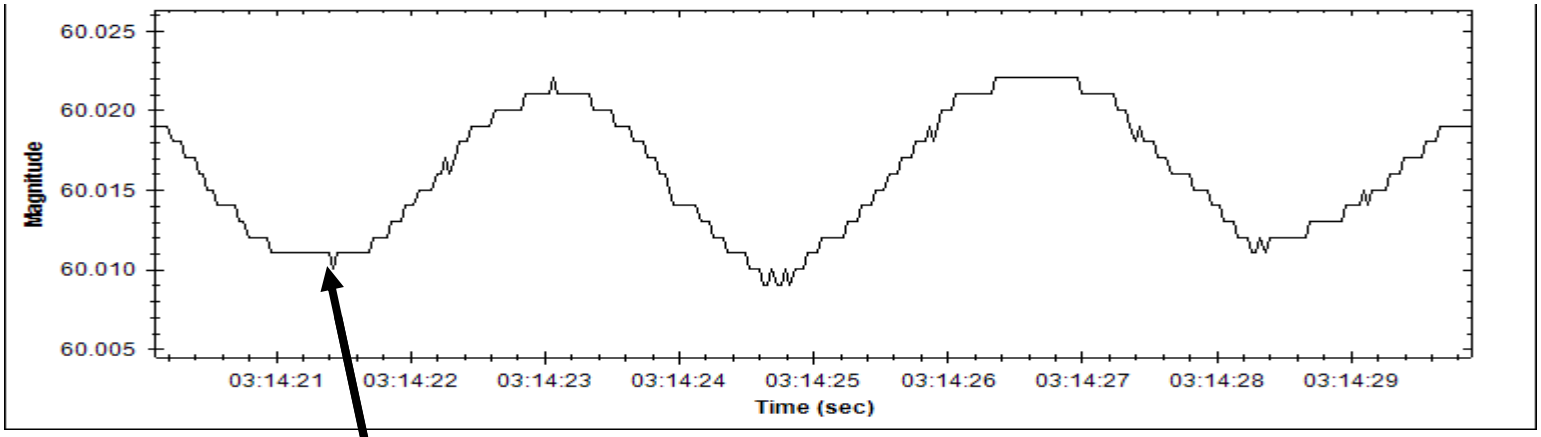
# June 17, 2016 and November 27, 2016 Oscillation Events

**We thank all the reliability coordinators for providing PMU data.**

# June 17 2016 Event

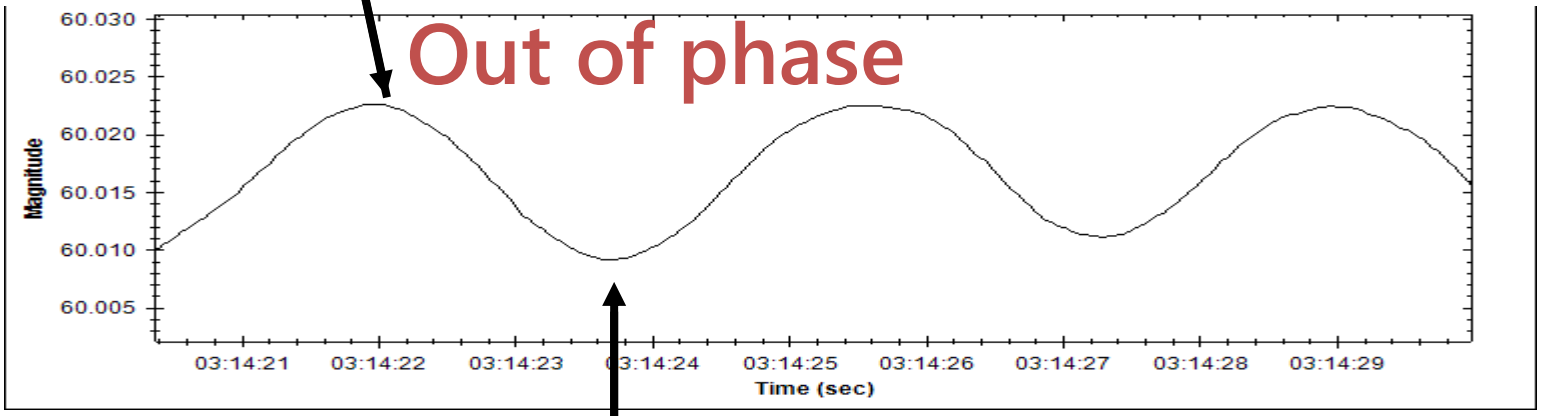




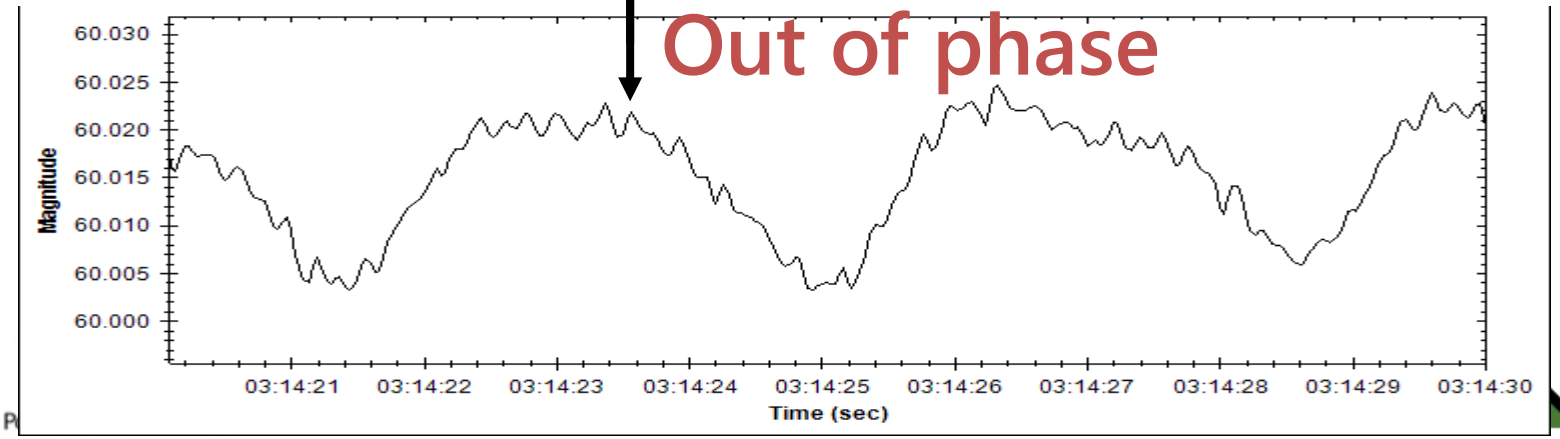

Maine (NE) (0.010)

Out of phase

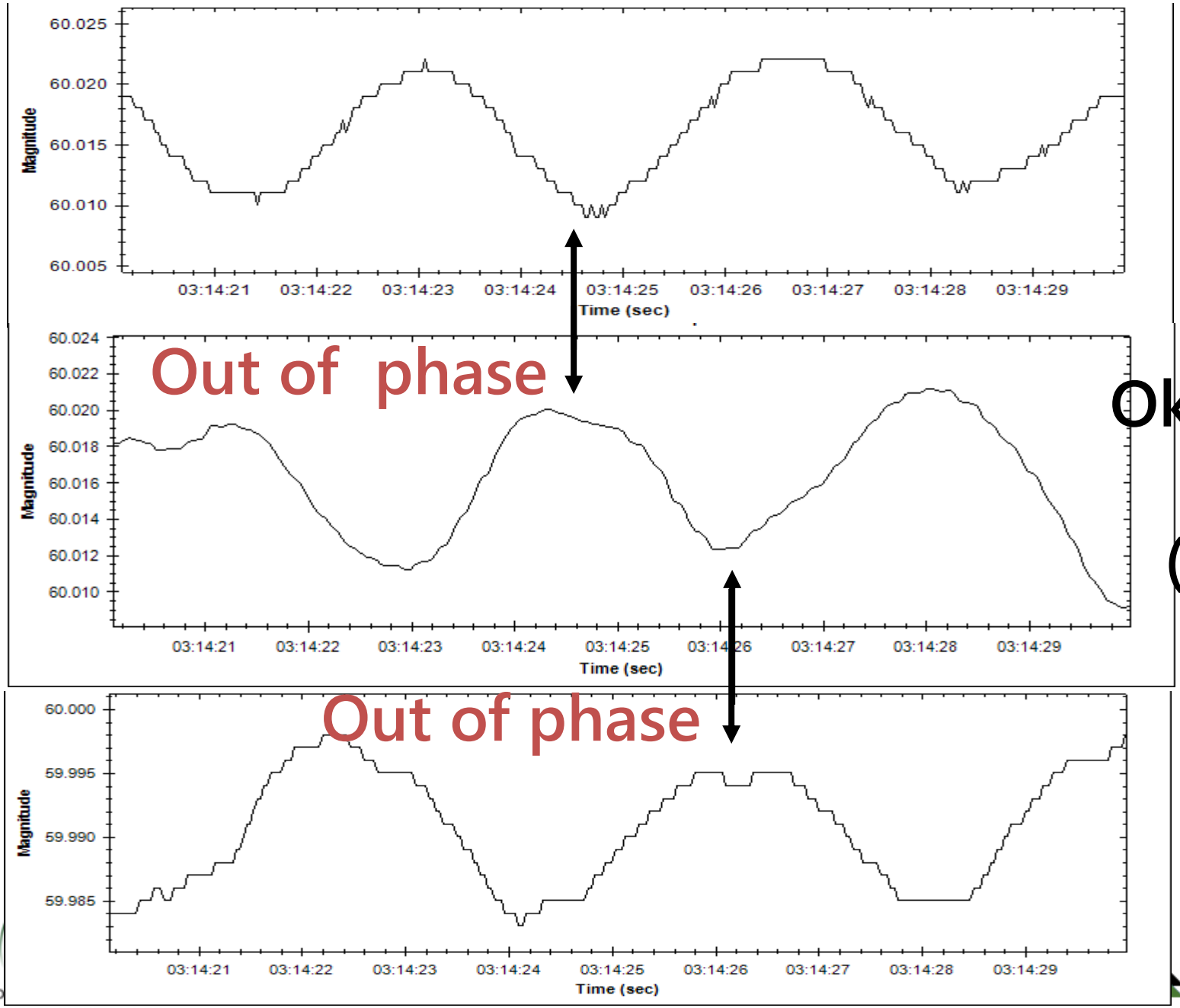



Florida (SE) (0.015)

Out of phase




Texas (SW) (0.015)

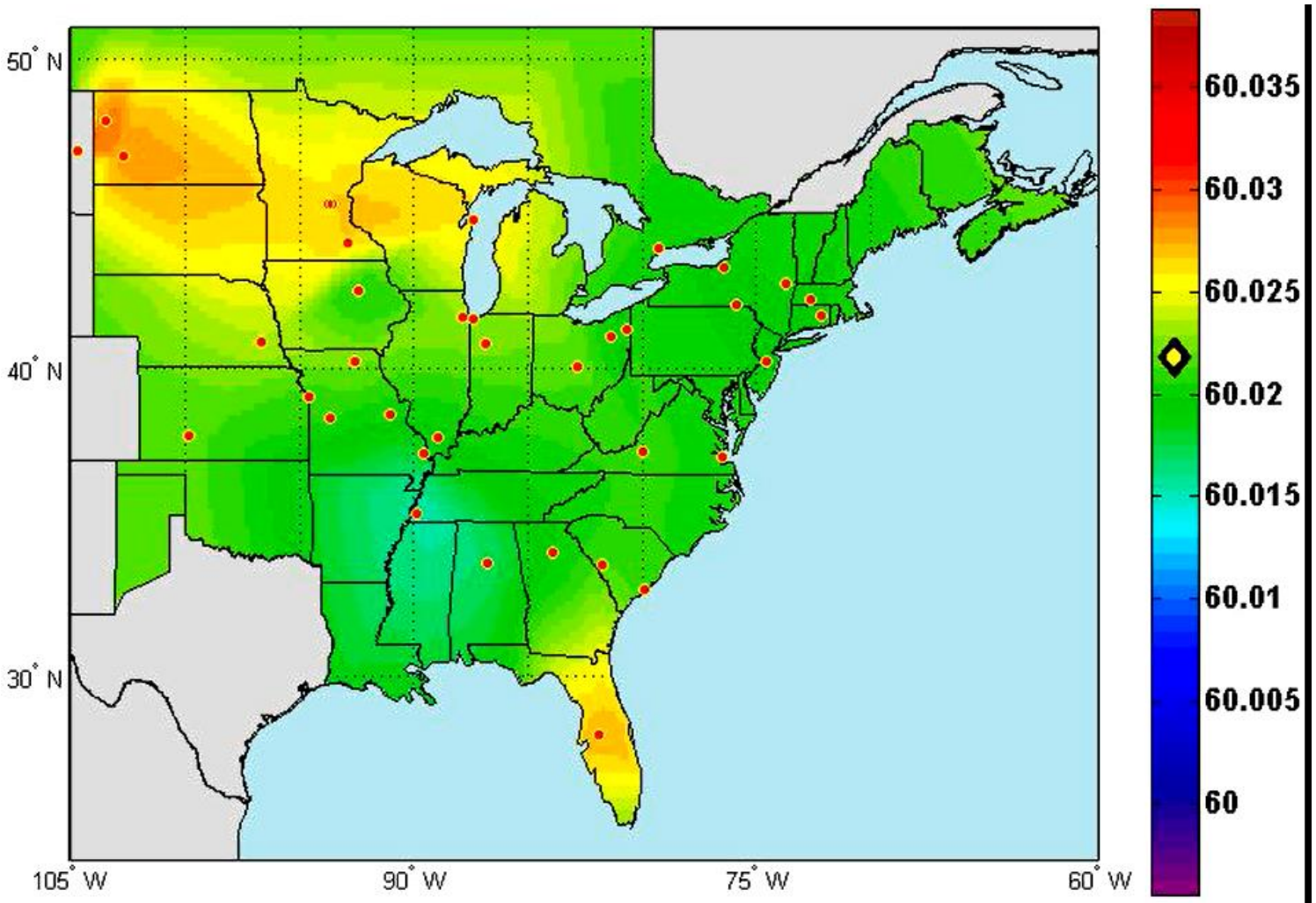



Maine (NE) (0.010)

Oklahoma (SW) (0.010)

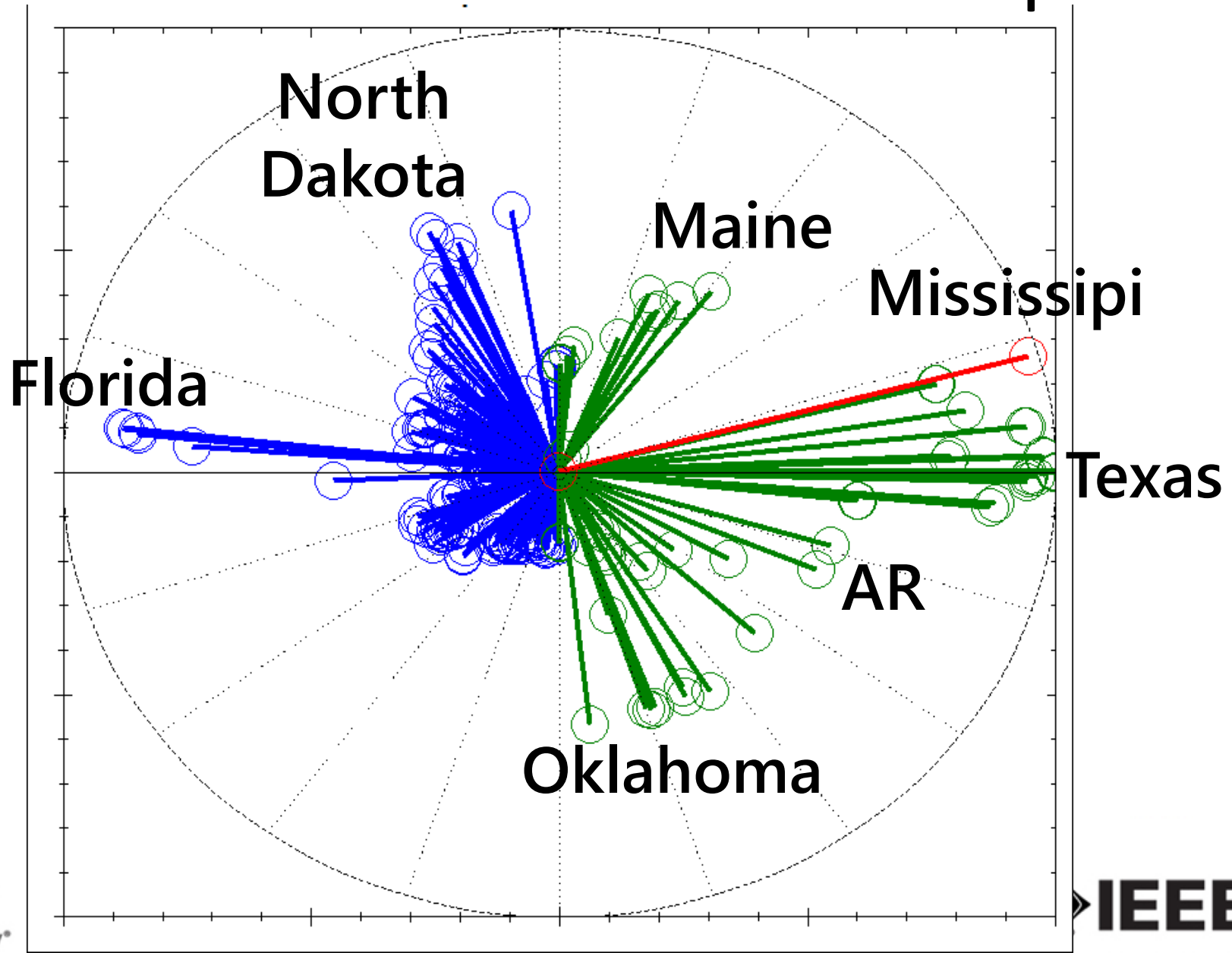
North Dakota (NW) (0.010)

# Fnet Video - In Phase Regions

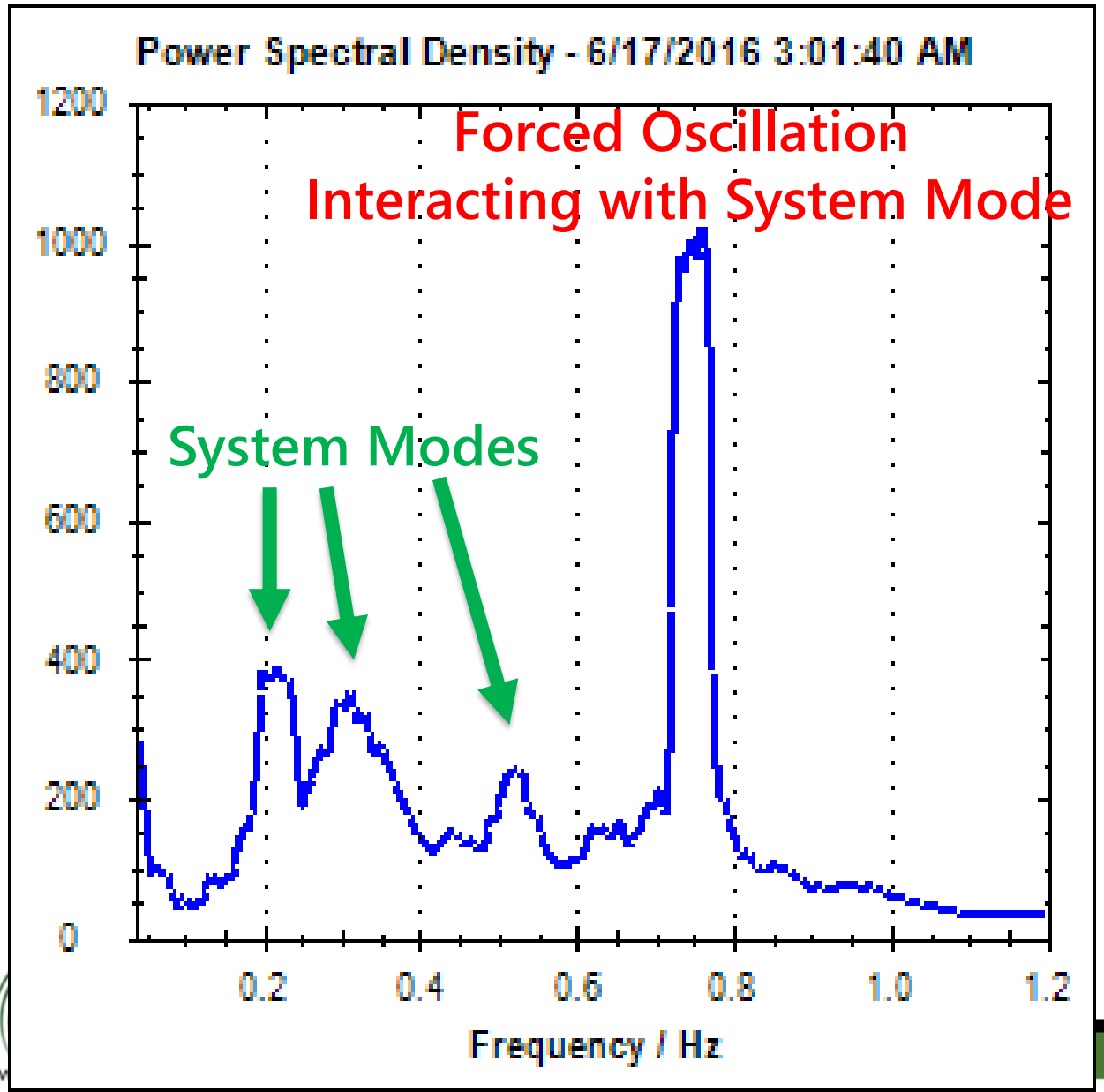



**North Dakota and Florida nearly in Phase**

# 0.28 Hz Oscillation Mode Shape



# FFDD Power Spectrum @3:01 AM (Before)




**Main modes**

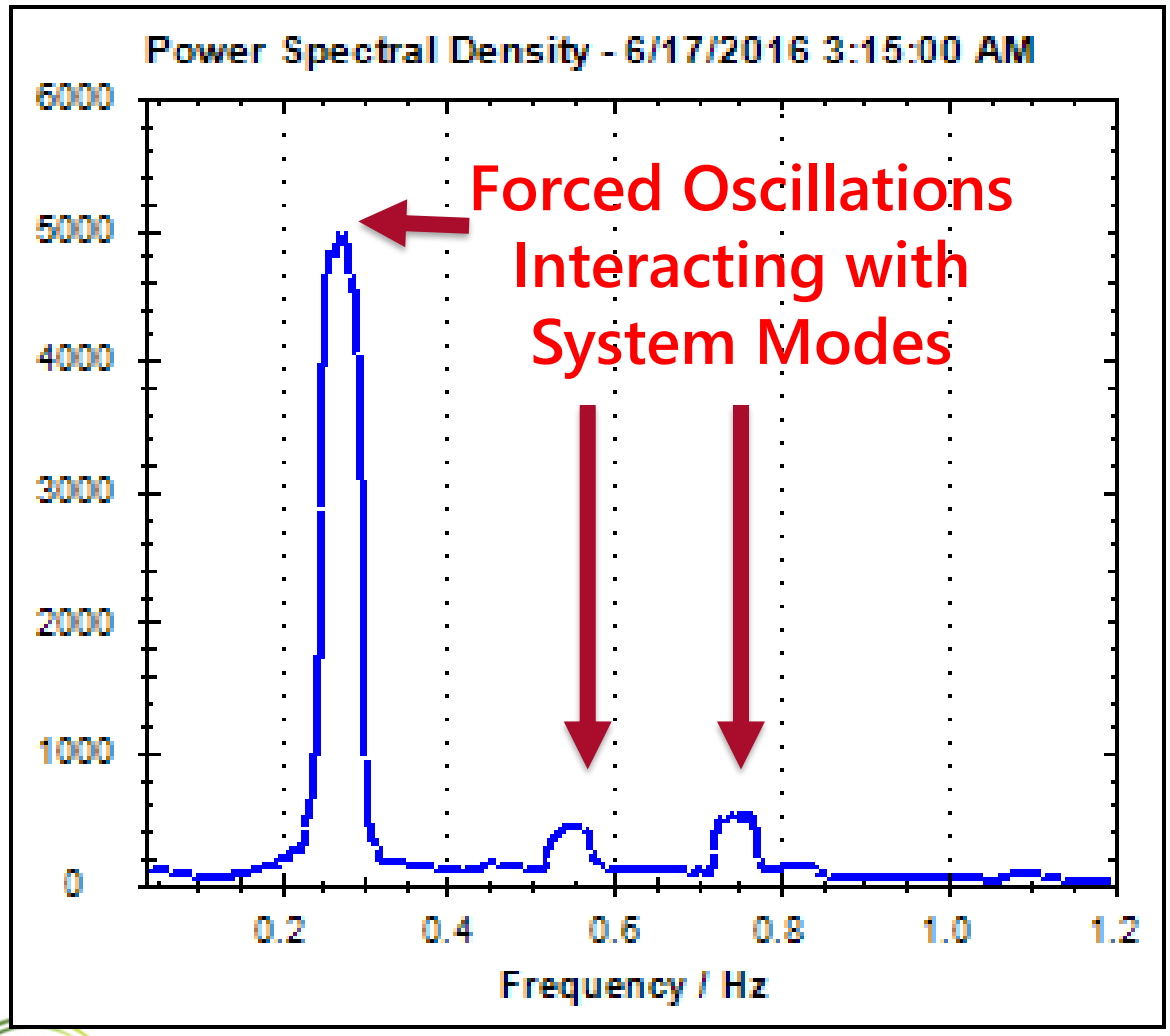
0.2 Hz

0.3 Hz

0.5 Hz

0.75 Hz

# Power Spectrum @ 3:15 AM (During)



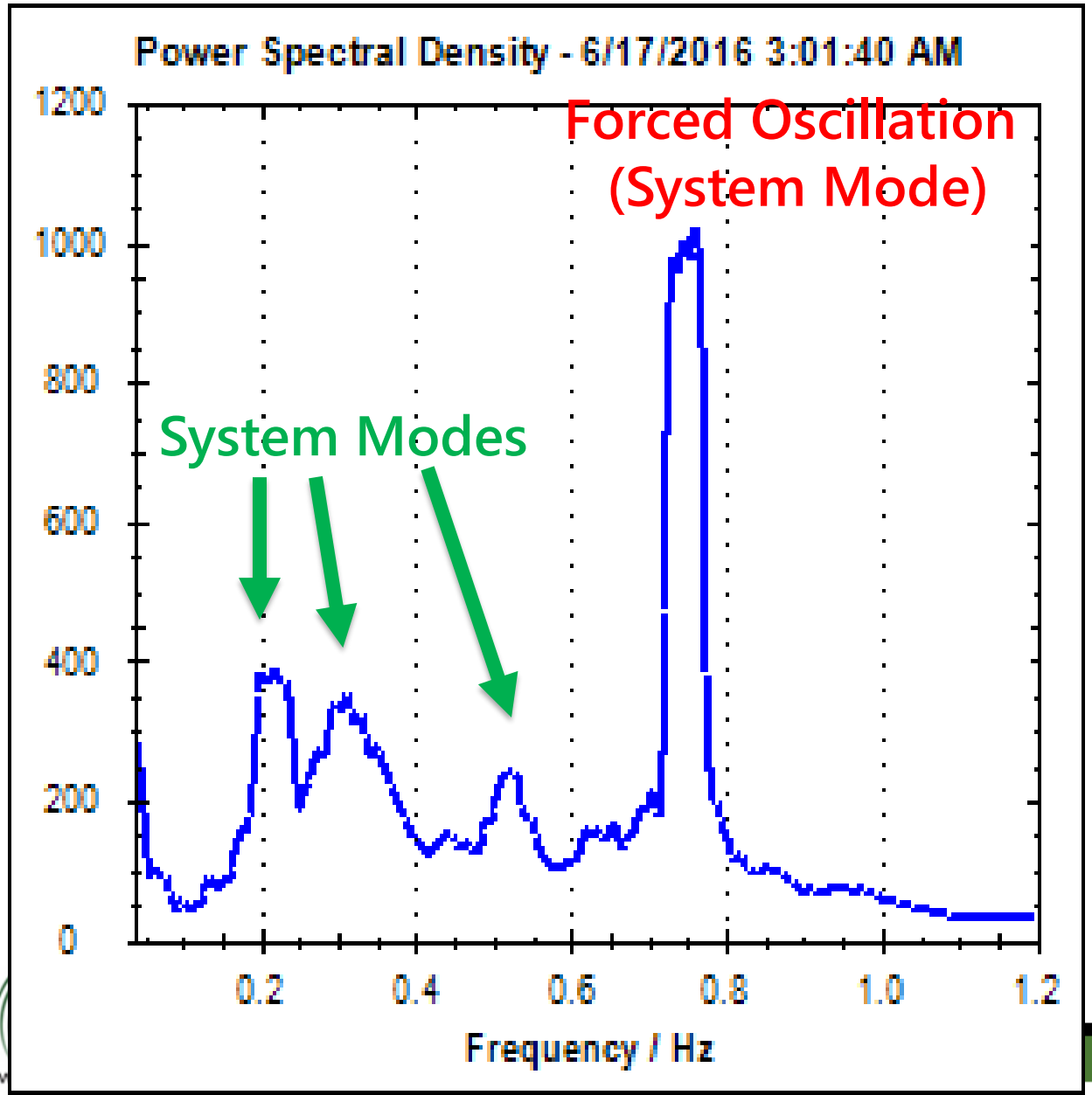

**Main modes**

0.28 Hz

*0.56 Hz*

0.75 Hz

# Power Spectrum @ 3:01 AM (Before)




## Main modes

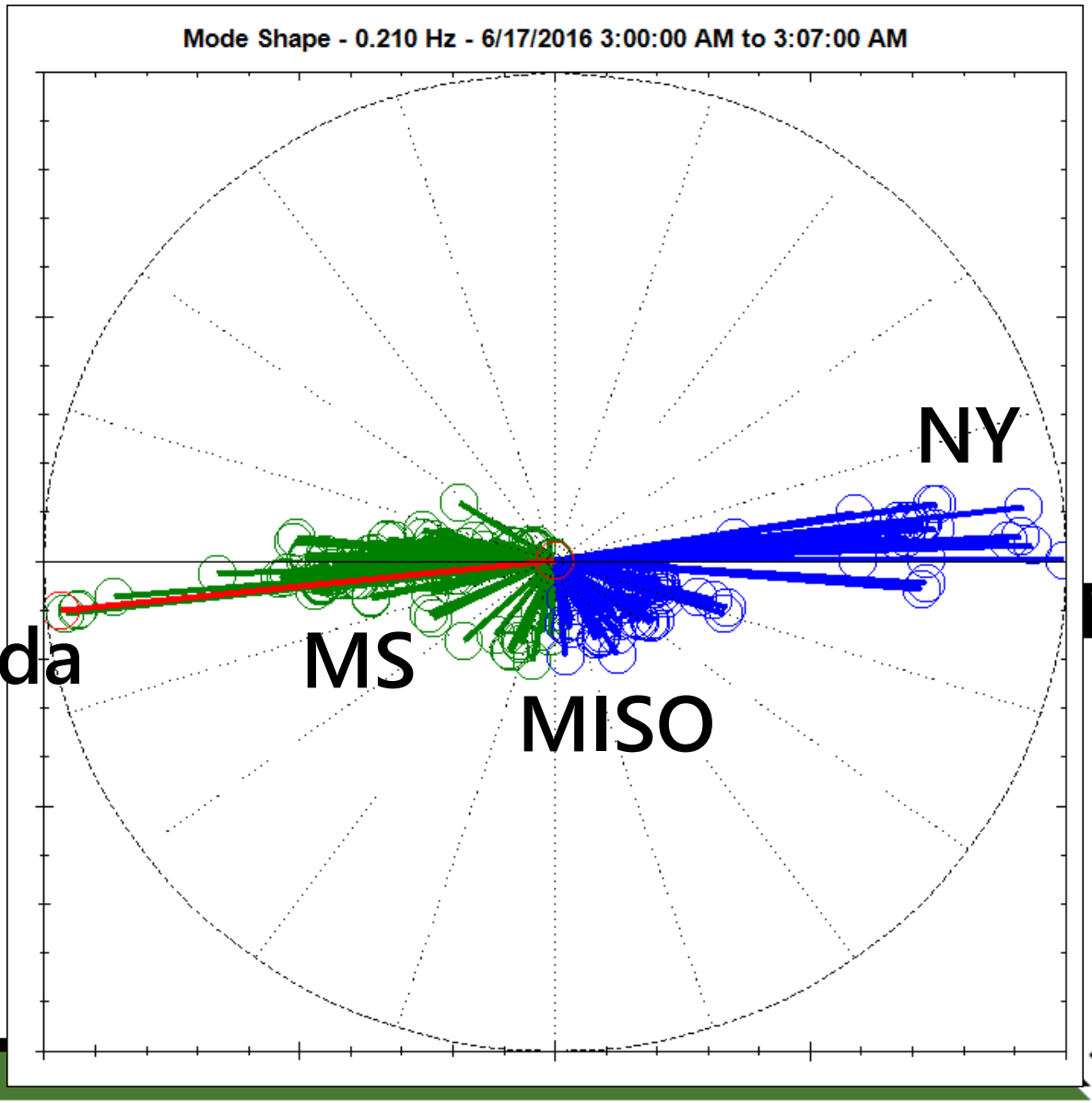
0.2 Hz

0.3 Hz

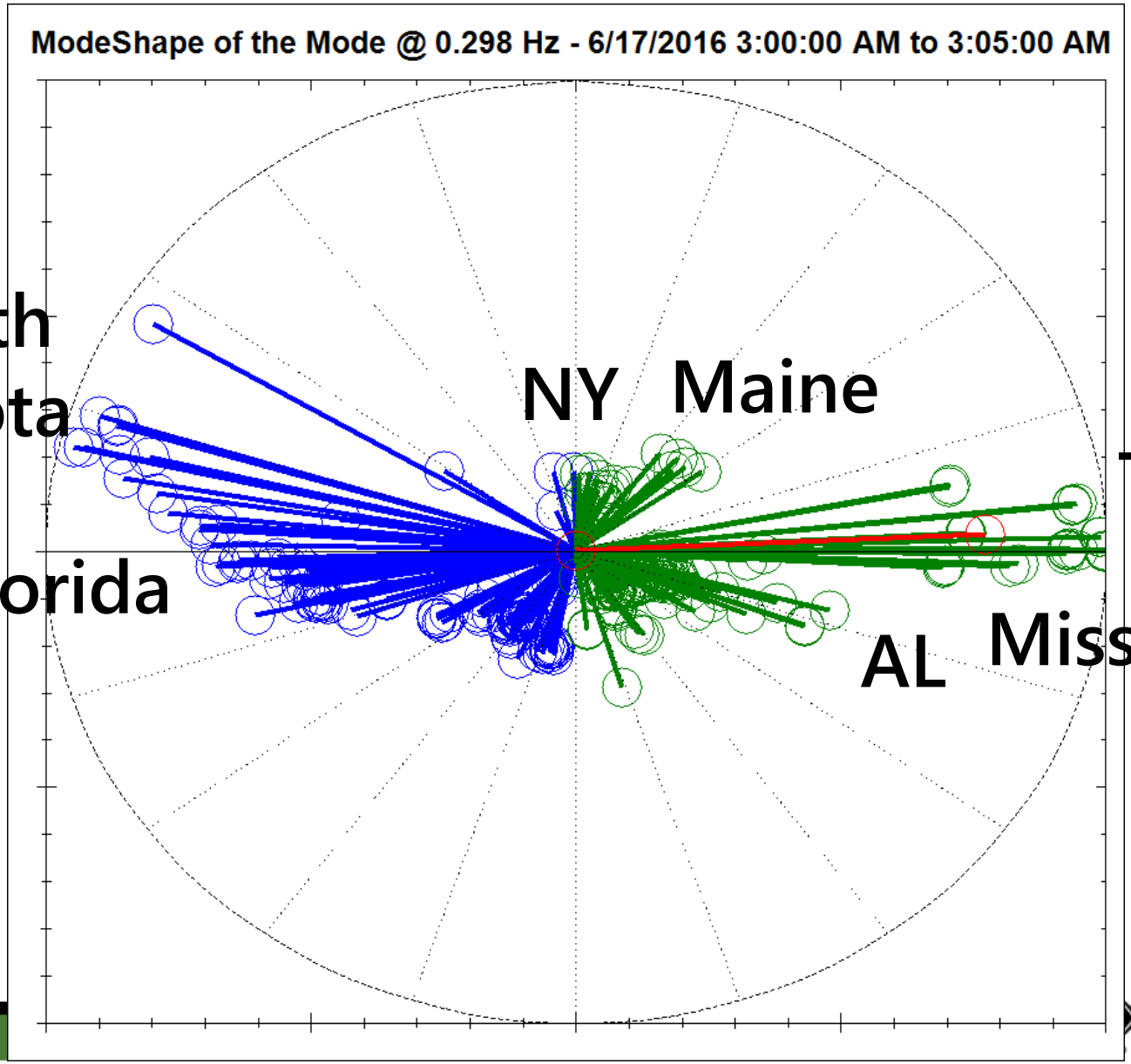
0.5 Hz

0.75 Hz

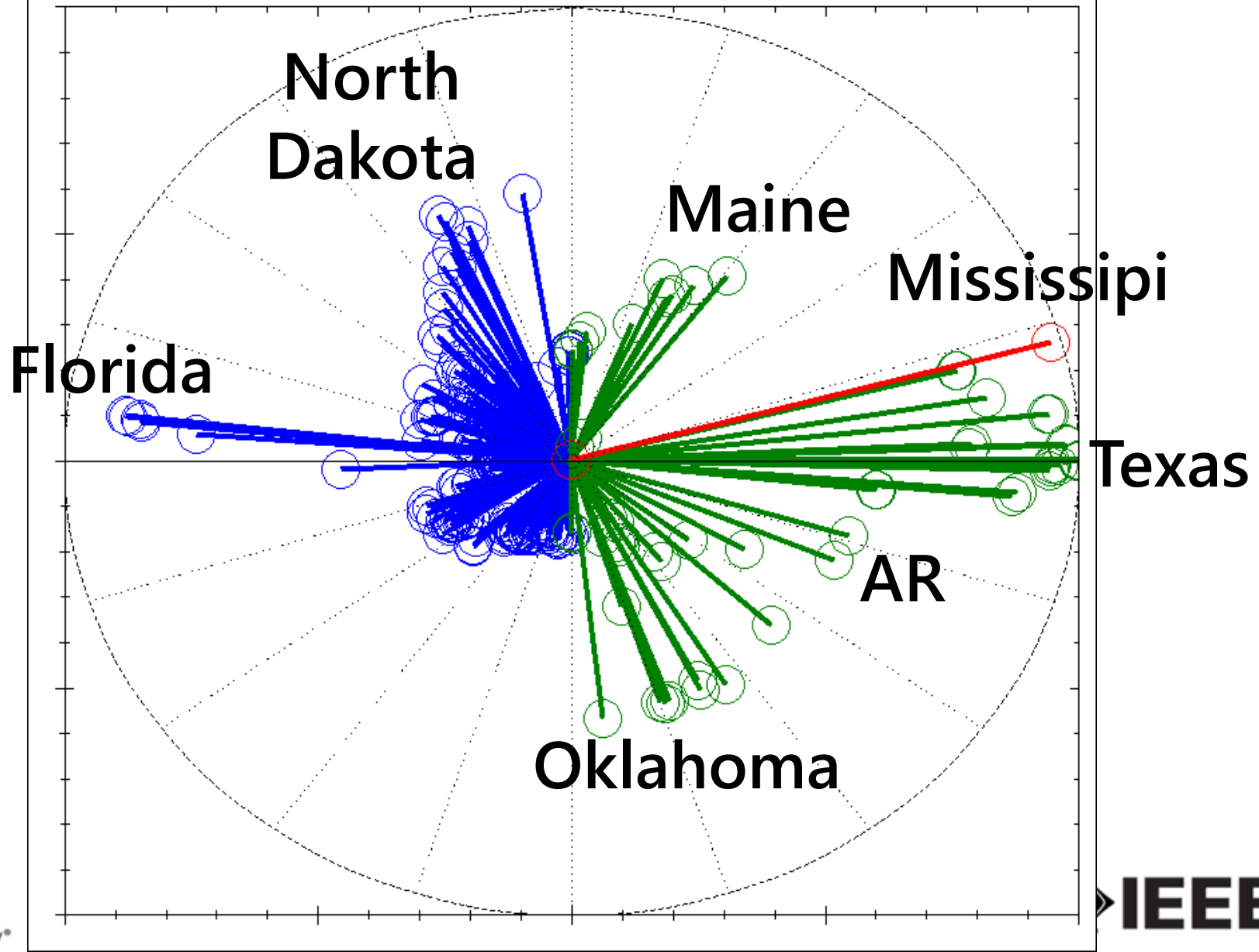
# 0.2 Hz North-South Mode from FSSI



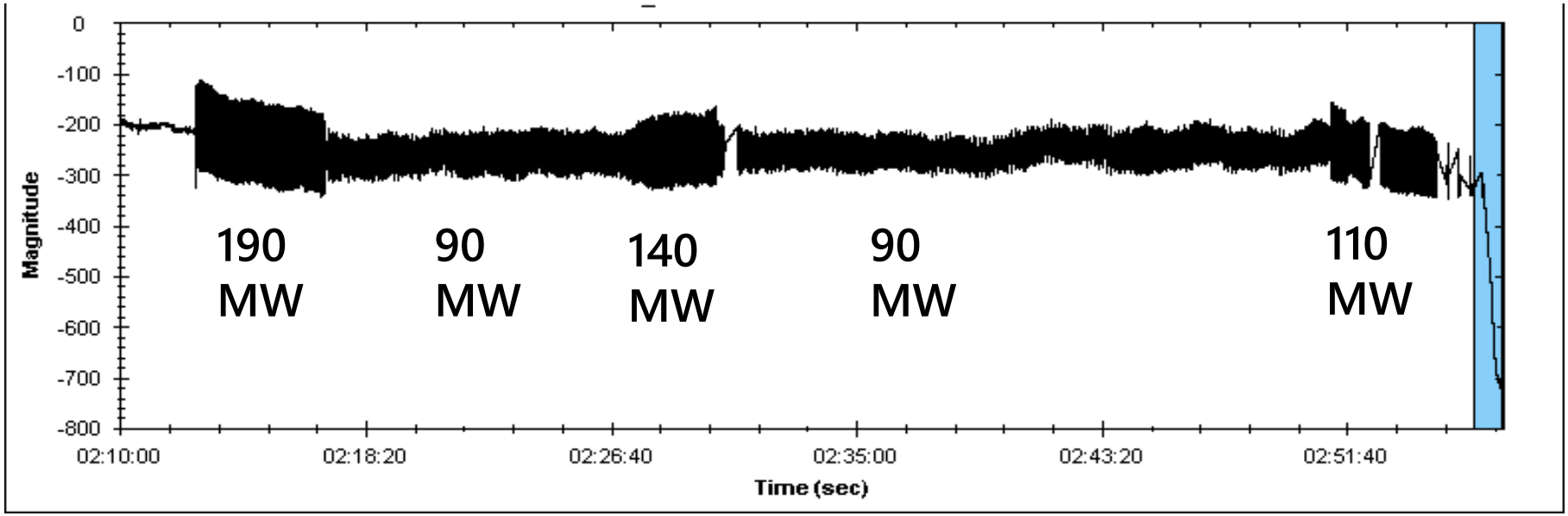
# 0.3 Hz North-South Mode from FFDD



# 0.28 Hz Oscillation Mode Shape



# Forced Oscillation Source




- 2:12:30 AM CDT: Oscillations started; Amplitude varied between 90 MW and 190 MW.
- Osc freq varied between 0.28 Hz and 0.23 Hz.
- 2:56:00 AM CDT: Oscillations stopped.
- Oscillation Source: Gen in Mississipi (FFDD & FSSI).

# 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:

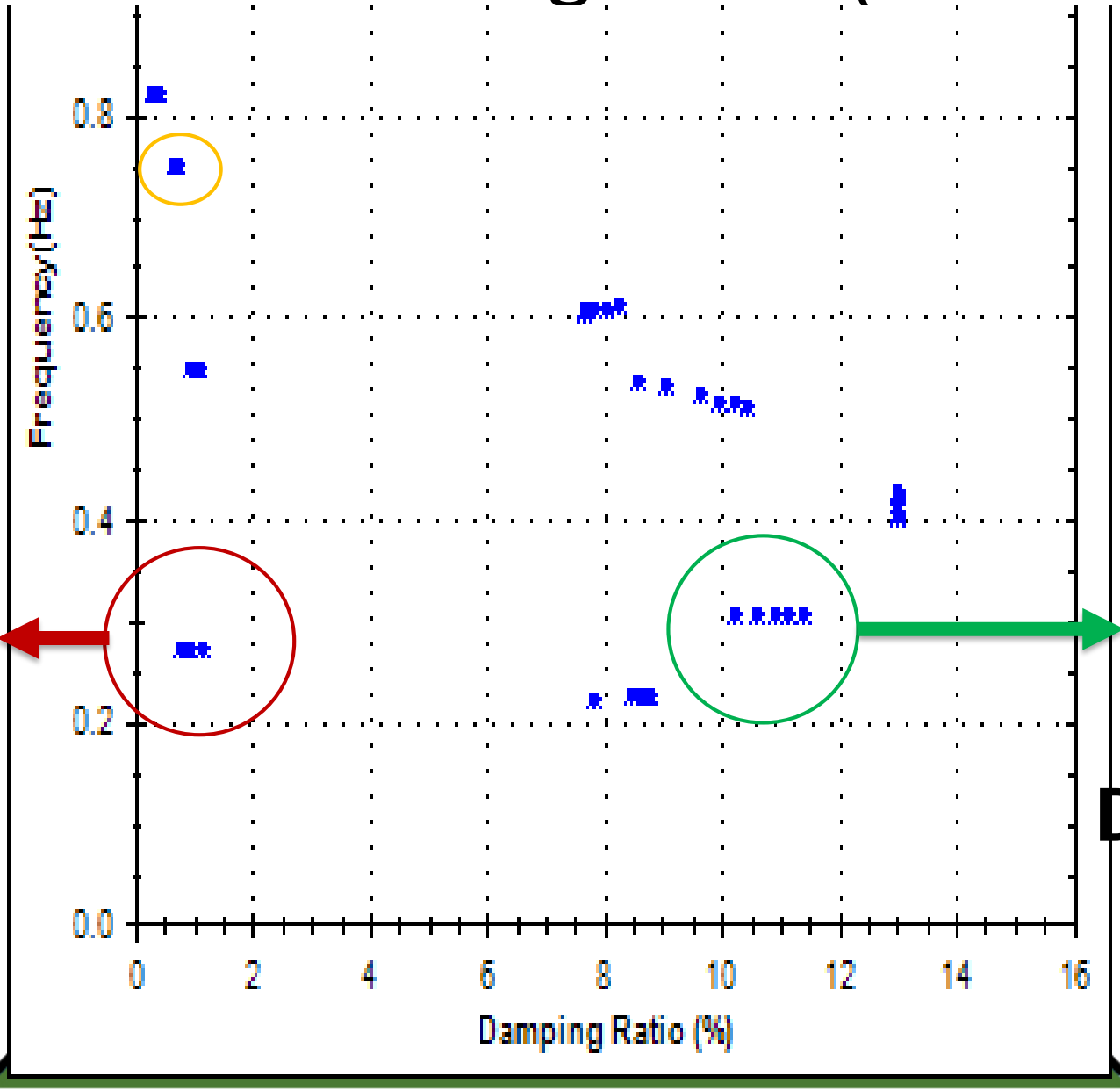
- Some conditions hold

**Resonance effect small** when:

- None of the conditions holds

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

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




0.28 Hz Osc

0.3 Hz System Mode (10% Damping Ratio)

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# Resonance Conditions (Event start)

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

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

(R2) System Mode poorly damped (invalid)

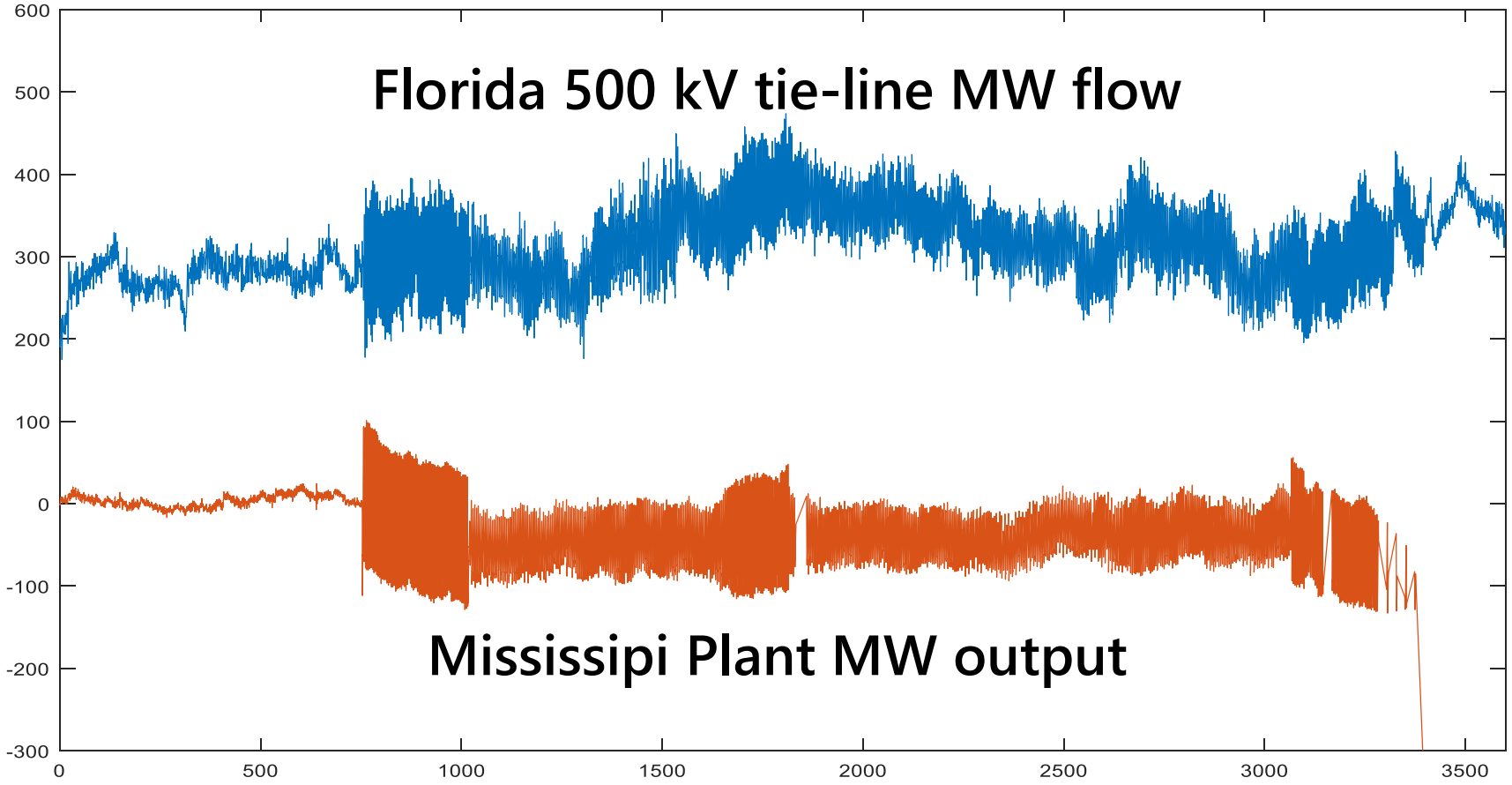
- **0.3 Hz Well-damped (10% Damping Ratio)**

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

- **Mississippi Sensitive Location for the Mode**

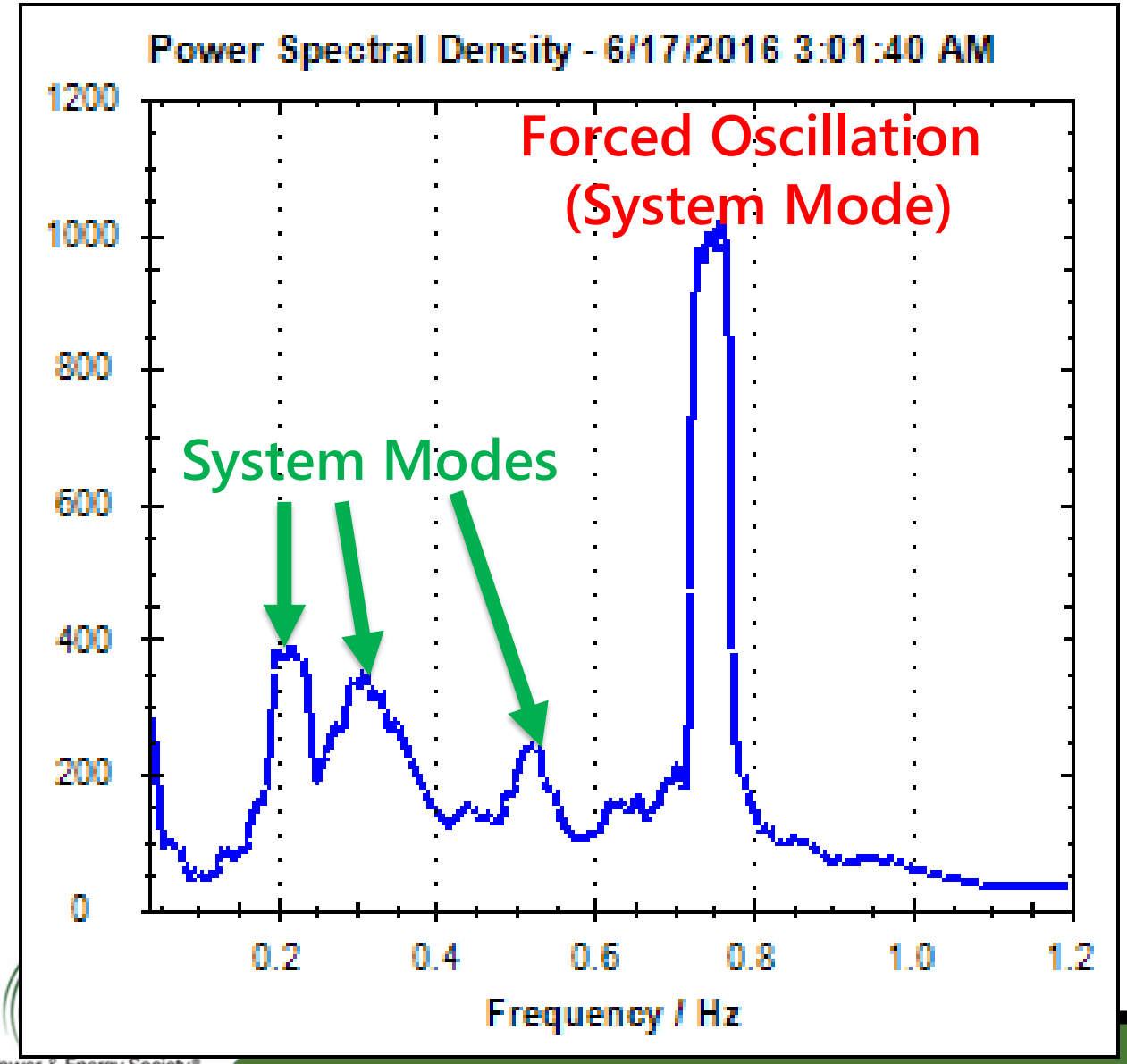
**Only 1+ conditions valid: Resonance effect small.**

# Florida key player for N-S modes




**Same Oscillation Amplitude 700 miles away.**
**Because of Resonance effect with the system mode.**

# Power Spectrum @ 3:01 AM (Before)




## Main modes

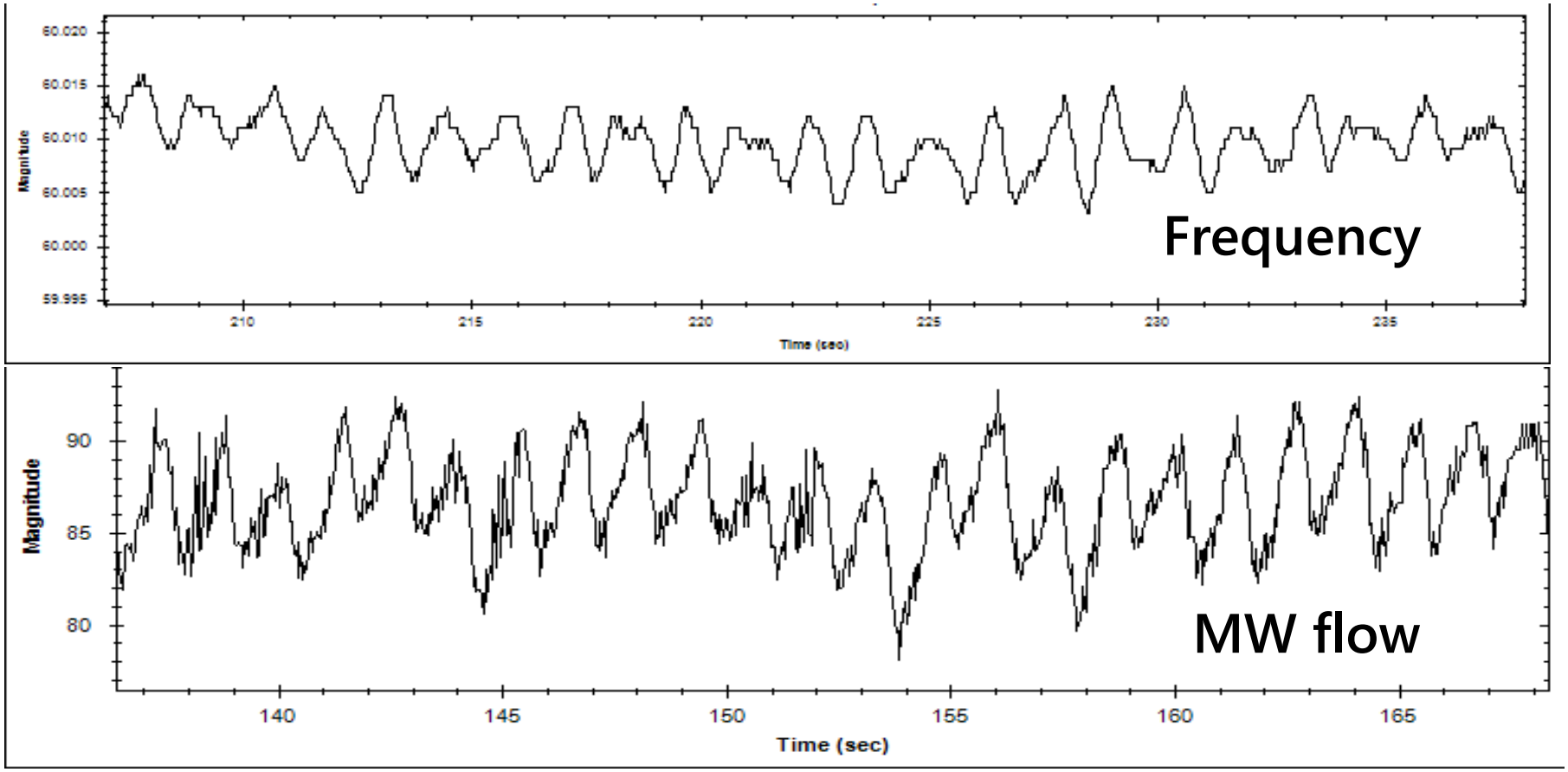
0.2 Hz

0.3 Hz

0.5 Hz

0.75 Hz

# 0.73 Hz Forced Oscillation

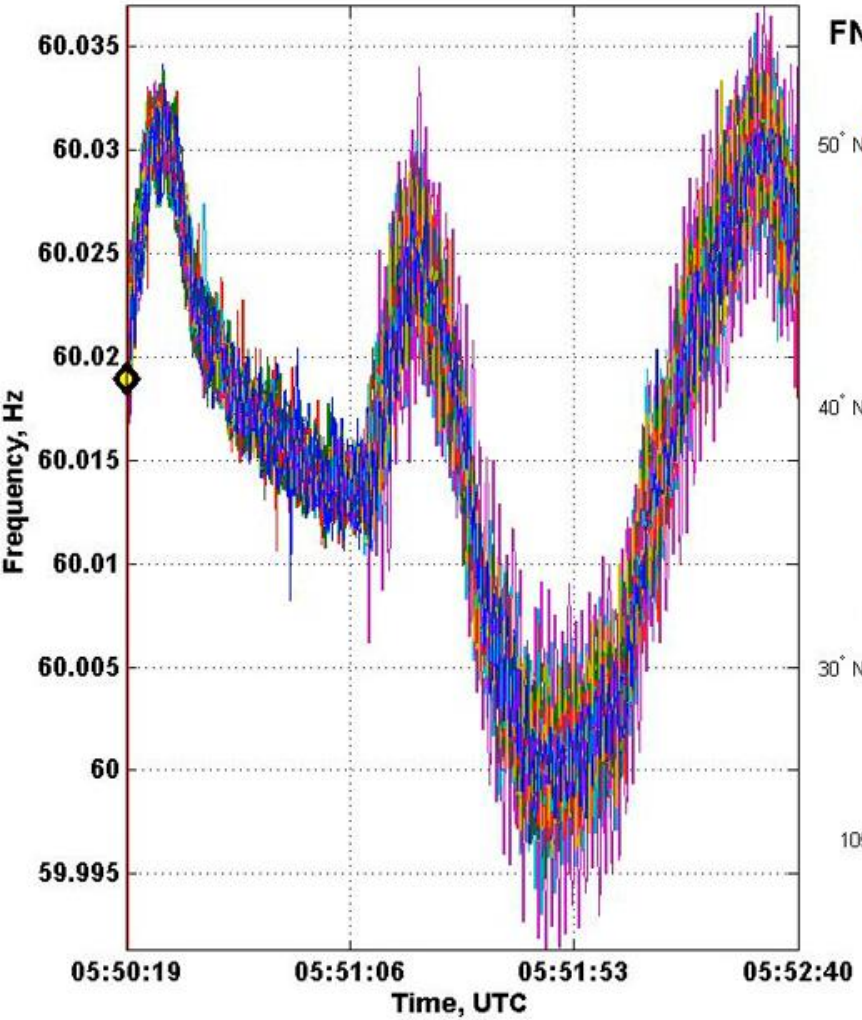


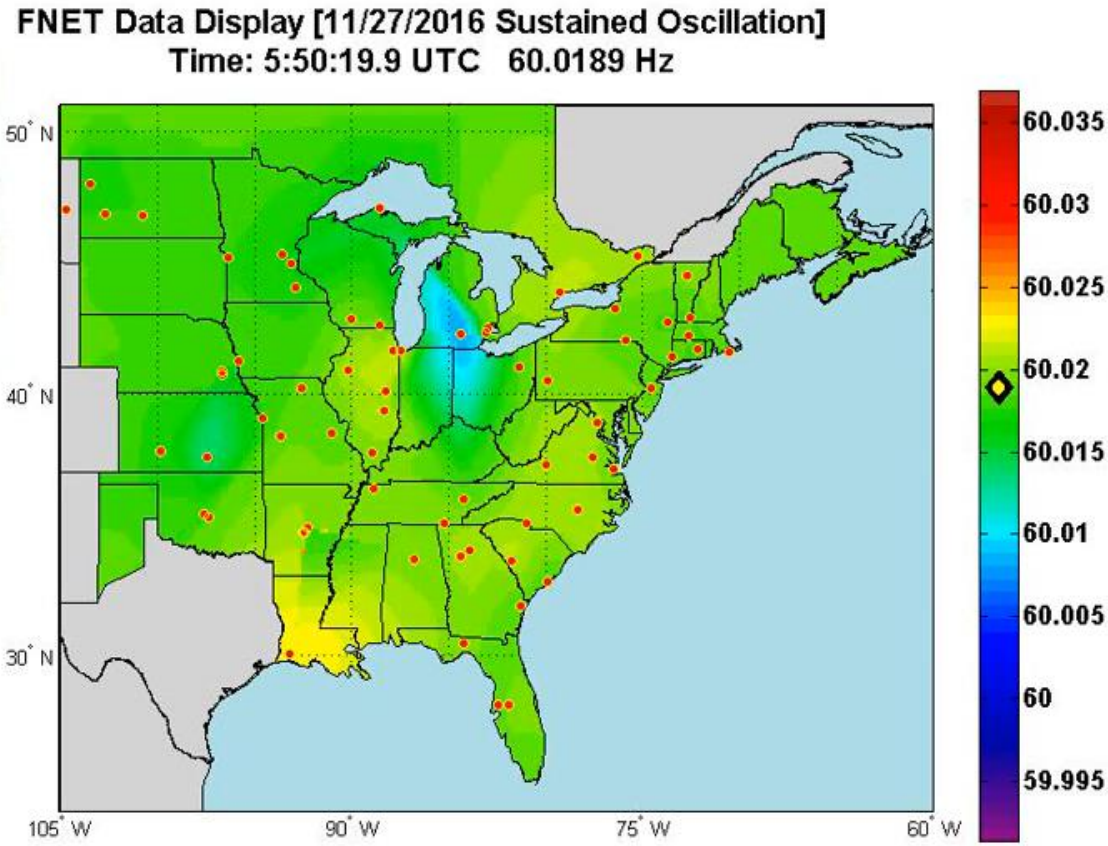

**10 MW oscillations visible in several MISO signals. Present throughout. Unrelated to the 0.28 Hz Mississippi Oscillations.**

# June 17 2016 Event Summary

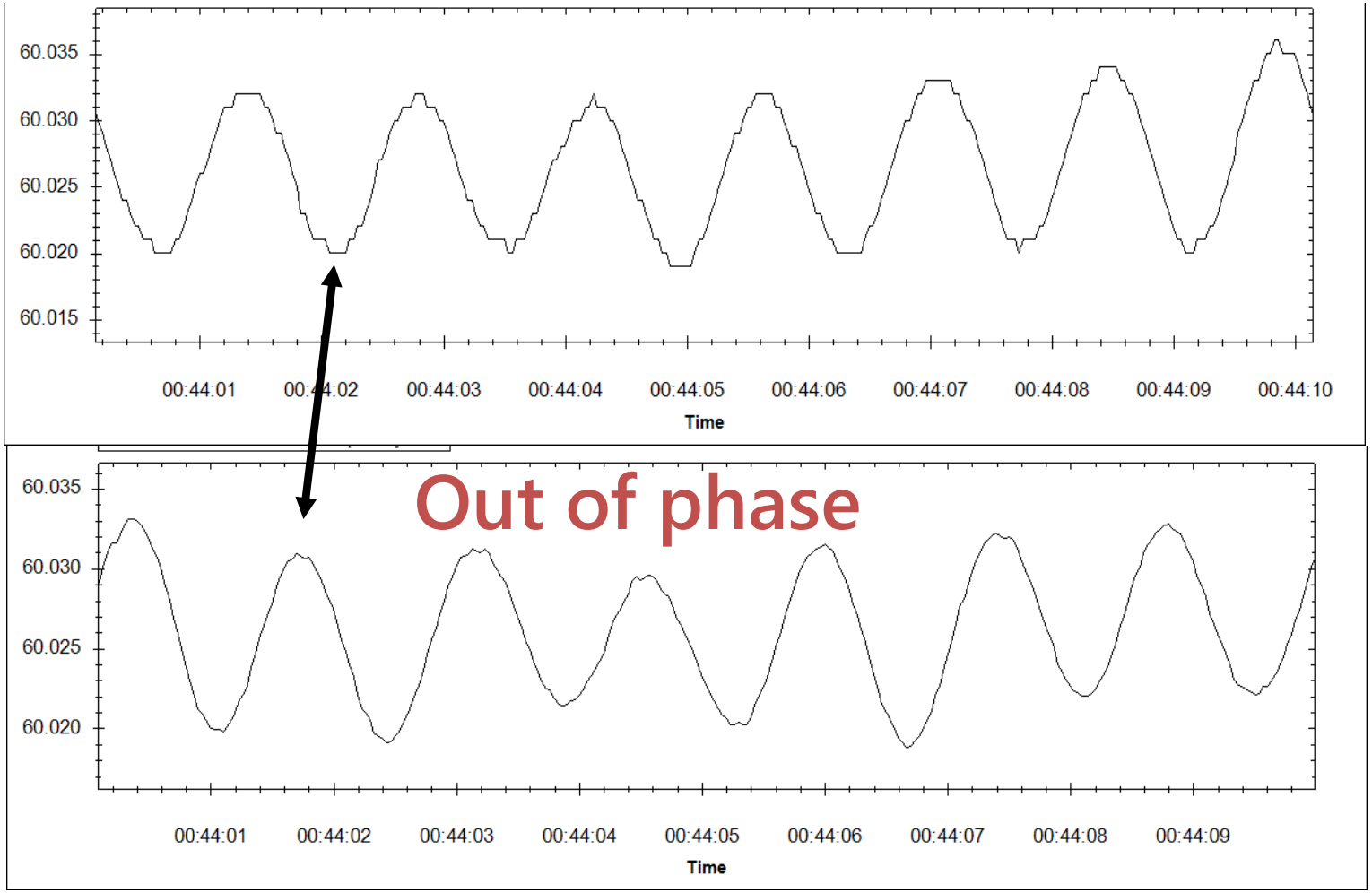
- **0.3 Hz Eastern Interconnection Mode has a complex mode shape: North-South-East-West**
- **Oscillation source in Mississippi was a sensitive location for the 0.3 Hz Mode**
- **Oscillation frequency 0.28 Hz slightly off**
- **0.3 Hz System mode well-damped (excellent)**
- **Resonance effect was mild**
- **Different 0.27 Hz oscillation in Midwest during event; 0.75 Hz oscillation present throughout.**

# November 27 2016 Event



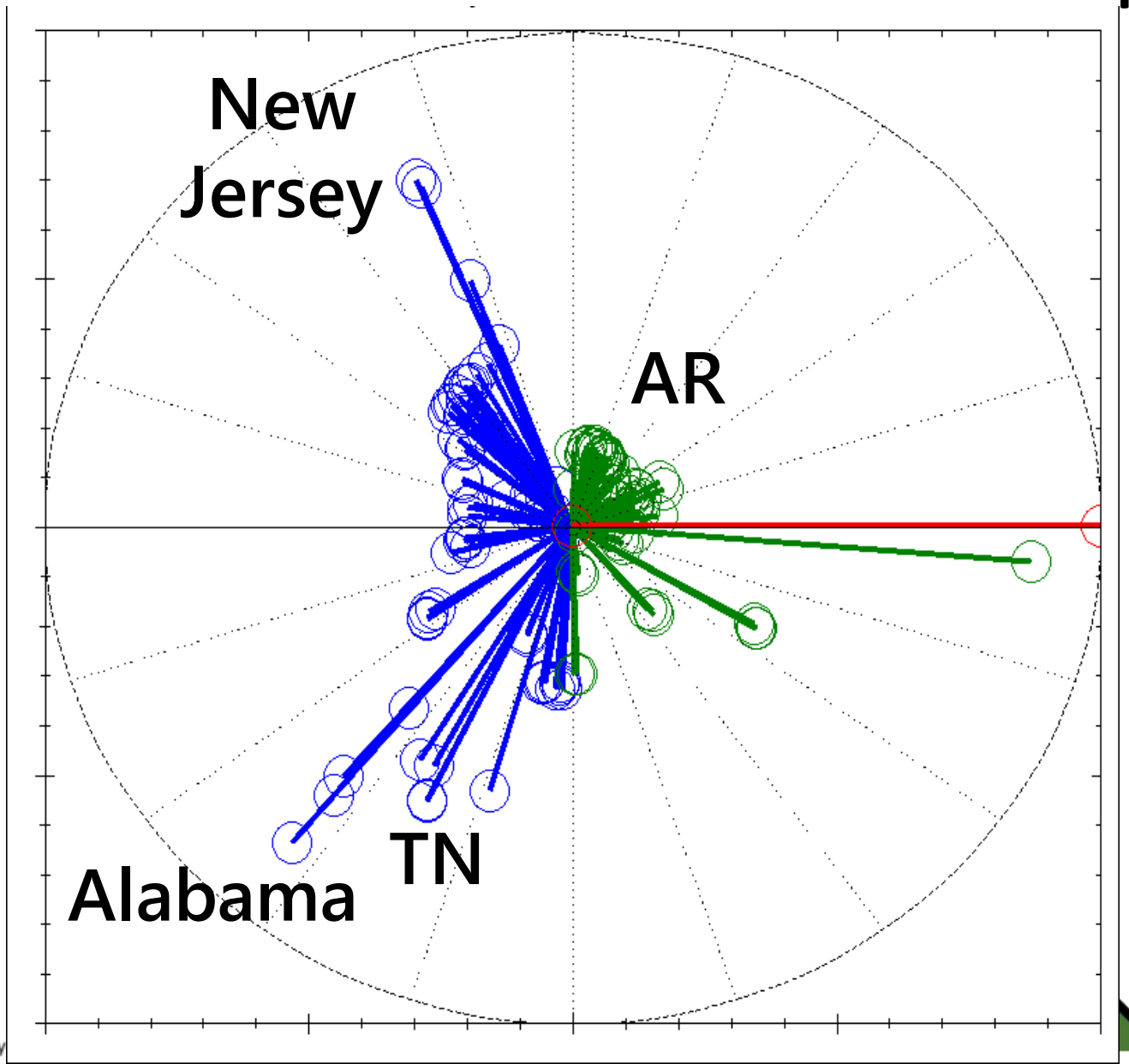
# Bus Frequency Time Plots



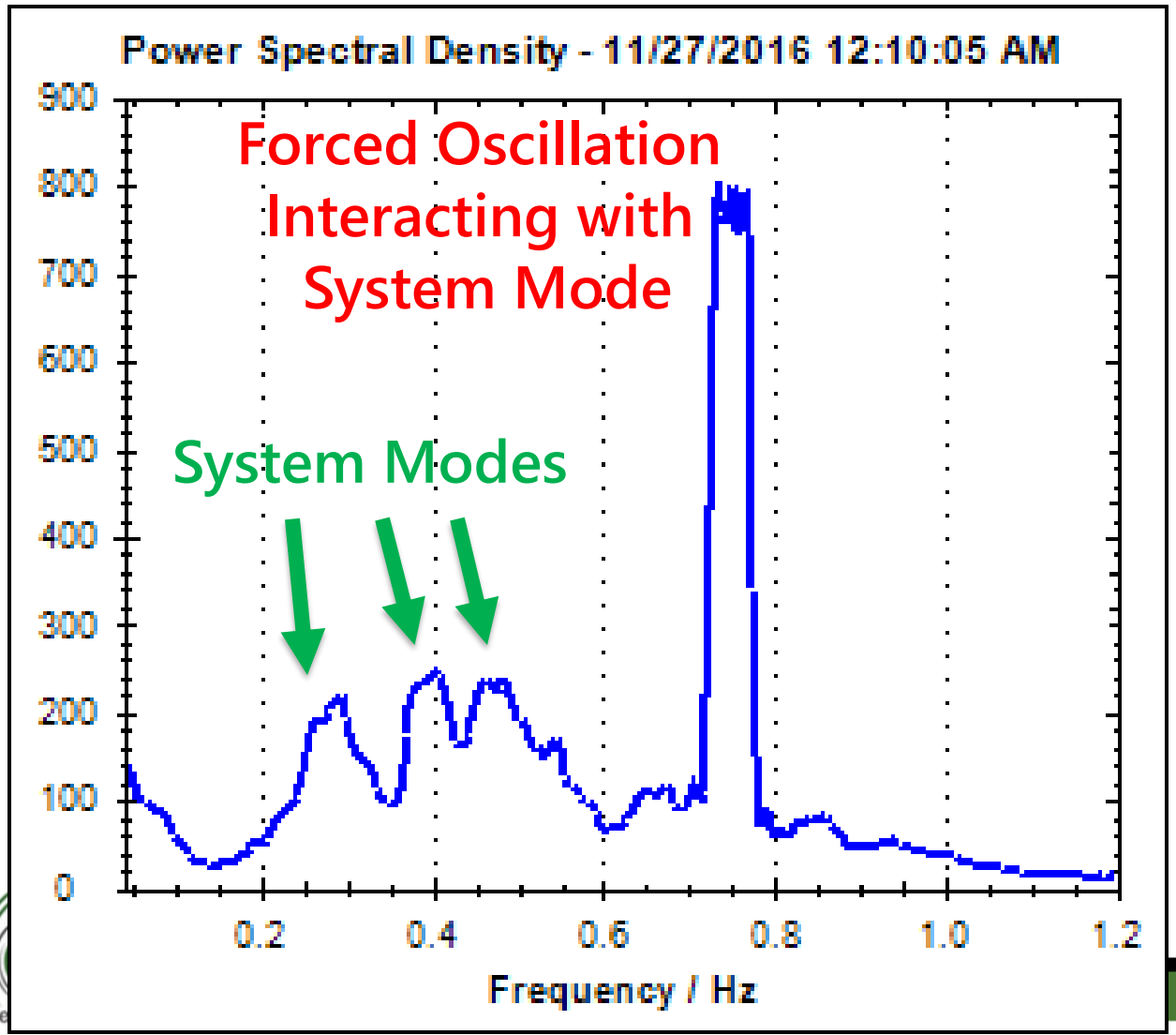

Alabama

New Jersey

# 0.7 Hz Oscillation Mode Shape



# FFDD Power Spectrum@12:10AM (Before)




**Main modes**

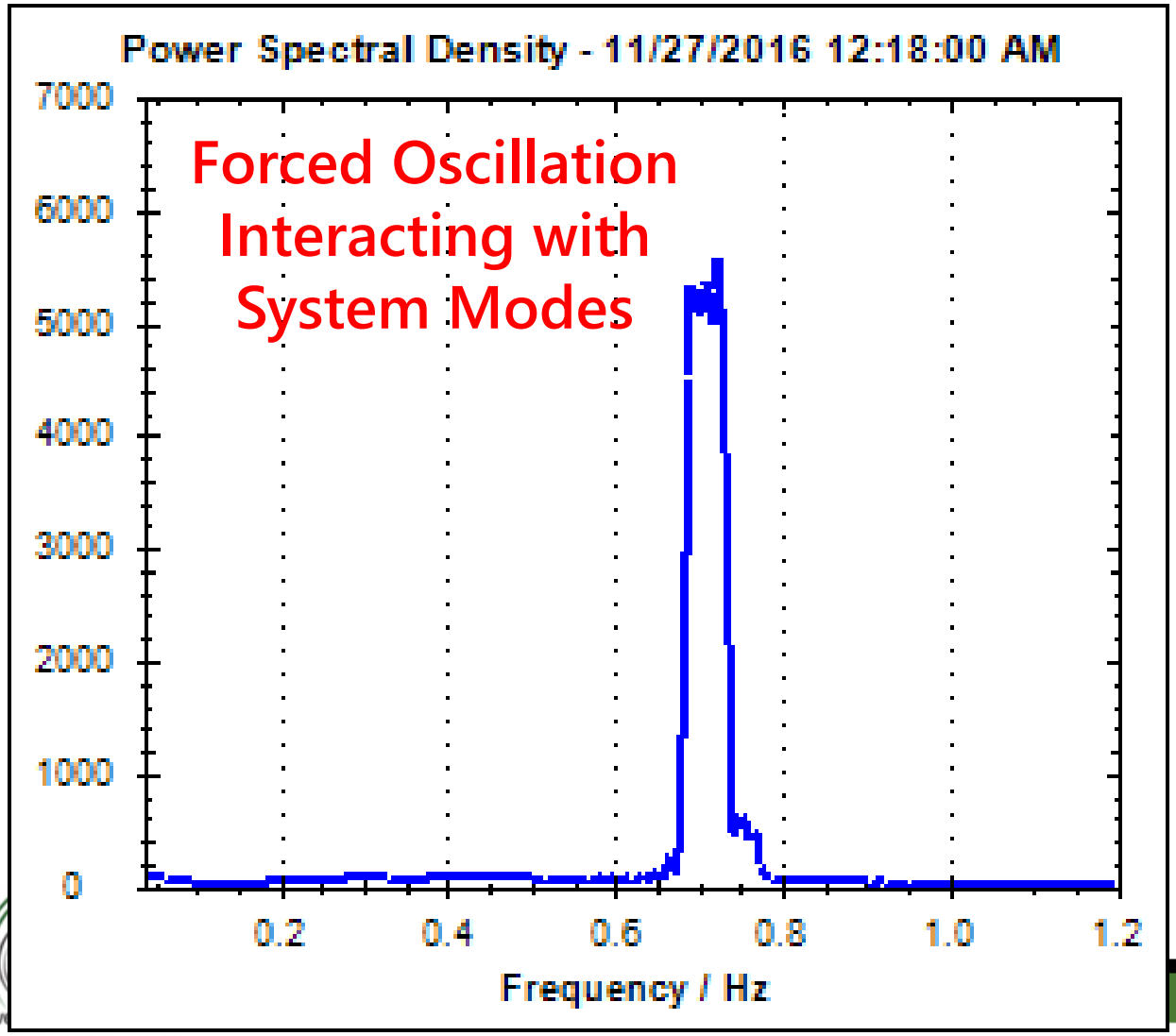
0.25 Hz

0.4 Hz

0.5 Hz

0.75 Hz

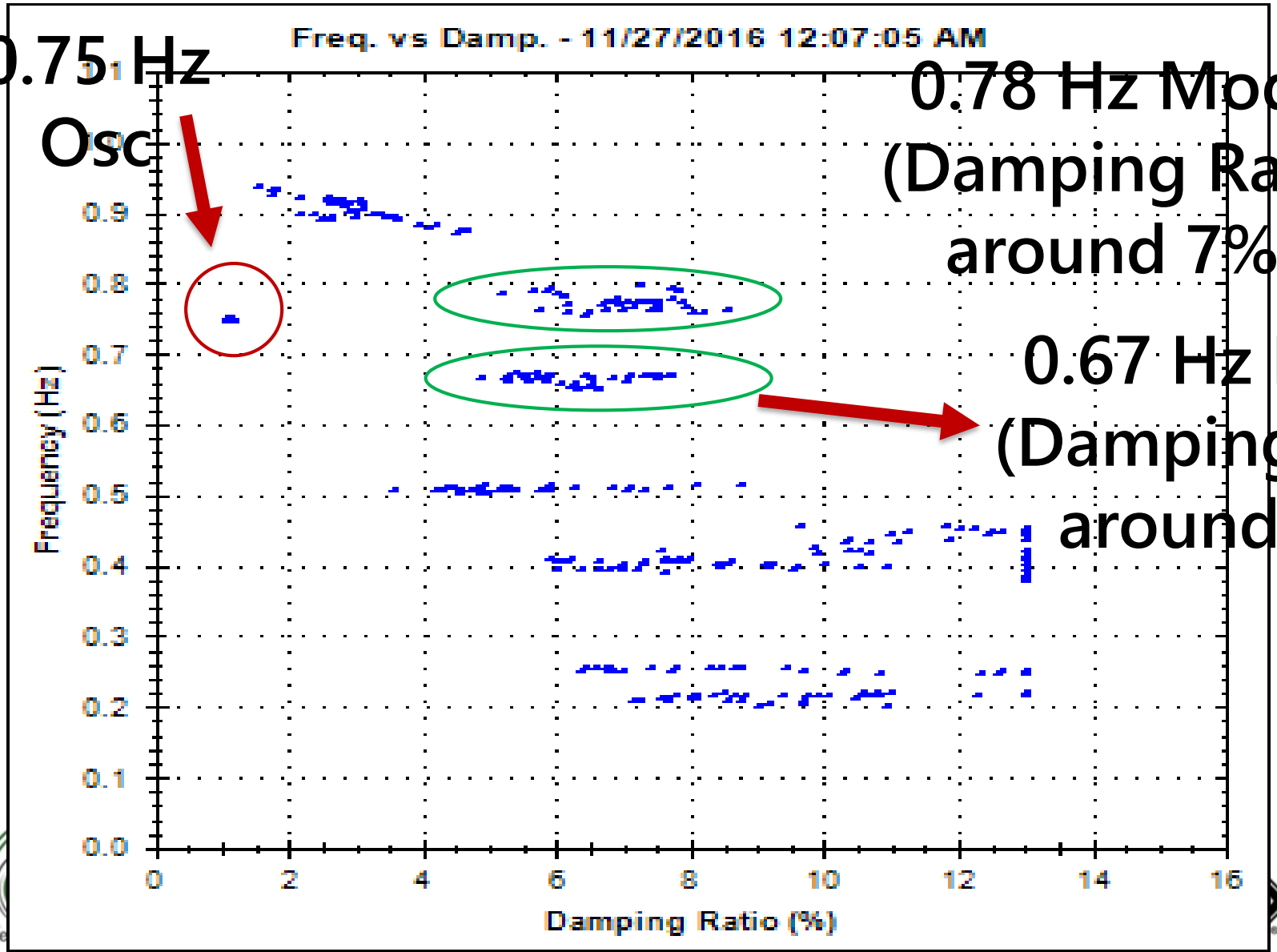
# Power Spectrum @ 3:15 AM (During)




**Main mode**

**0.75 Hz**

# FSSI Estimates Before GA Osc Event

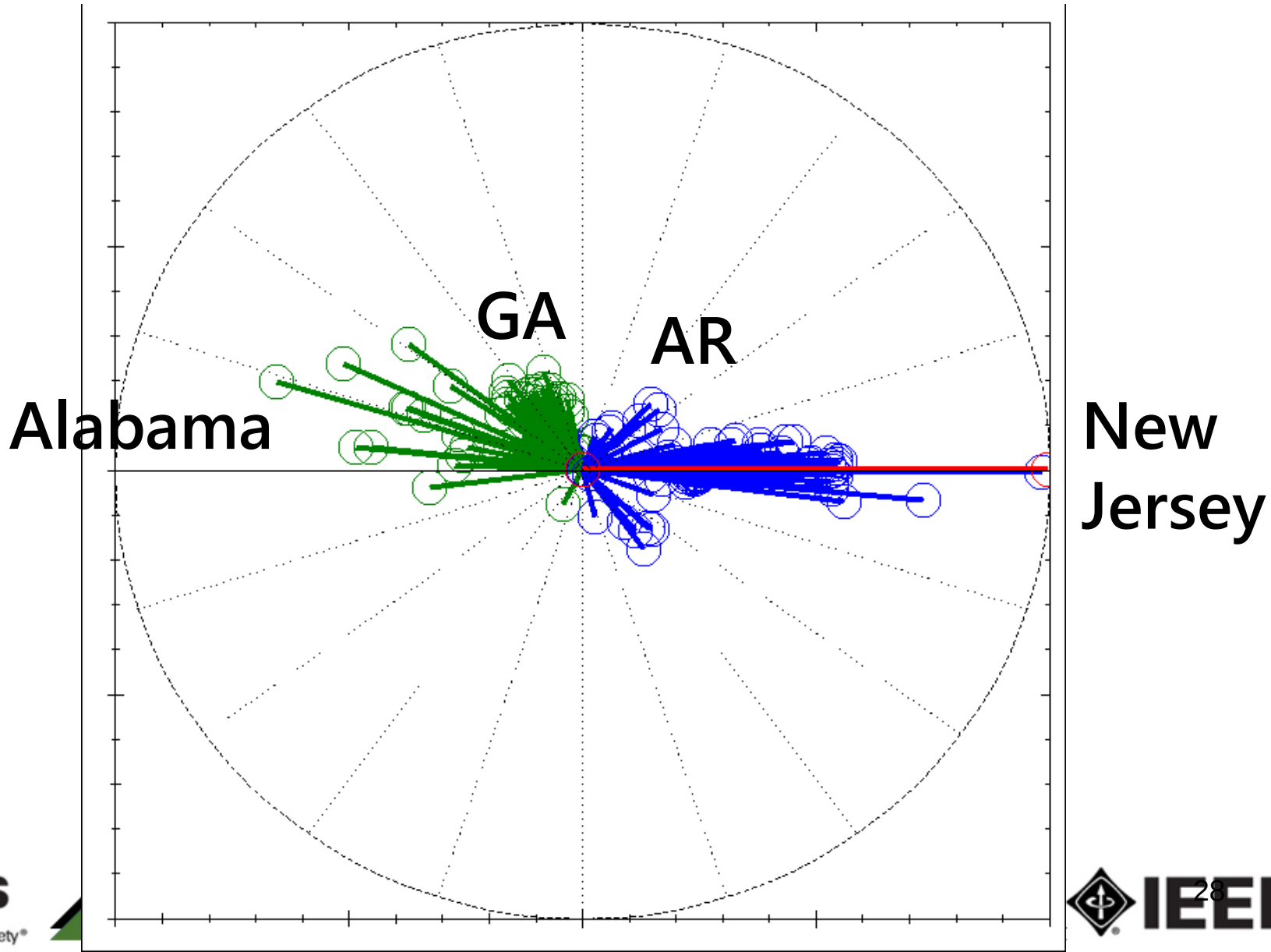



0.75 Hz Osc

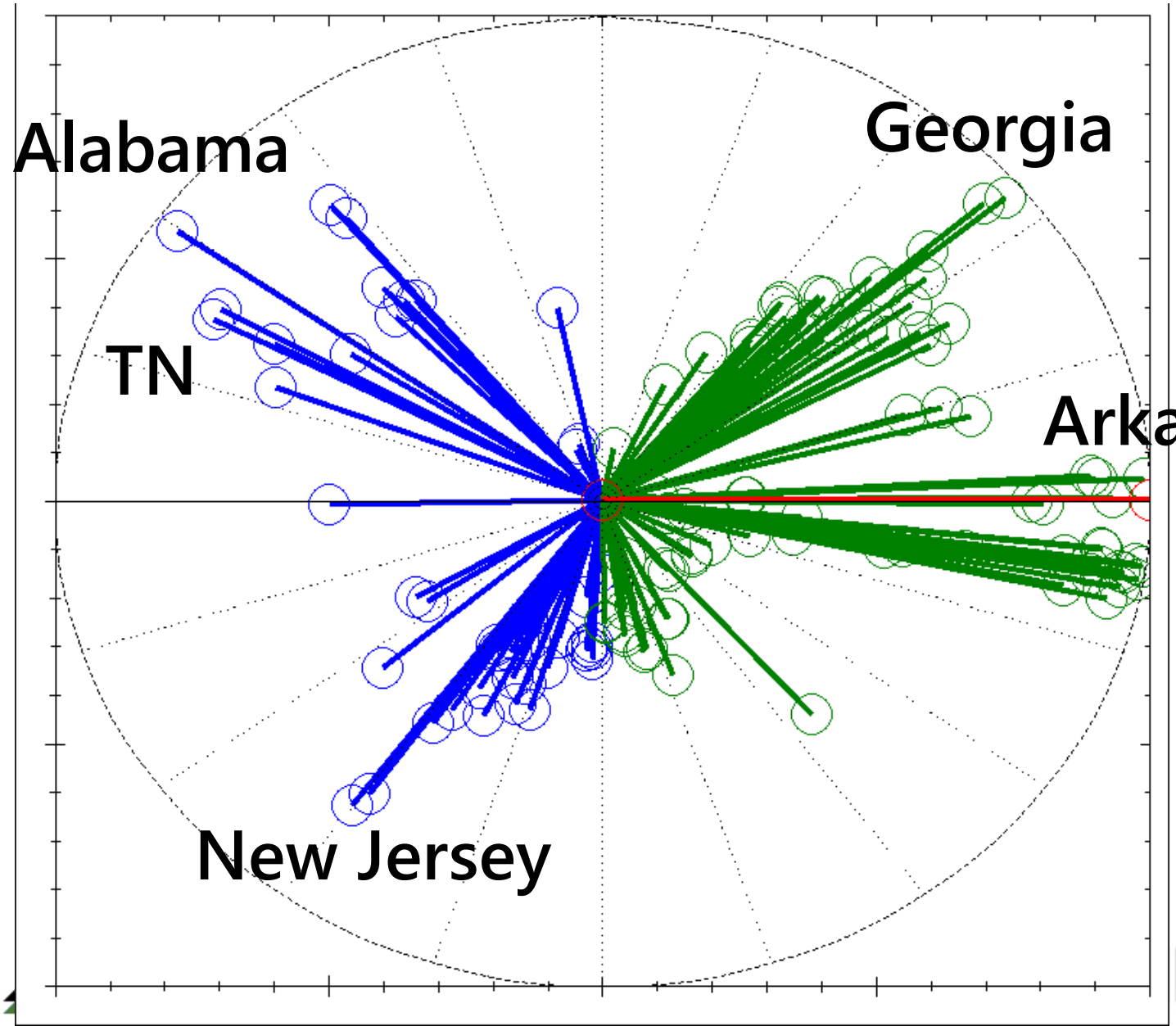
0.78 Hz Mode (Damping Ratio around 7%)

0.67 Hz Mode (Damping Ratio around 6%)

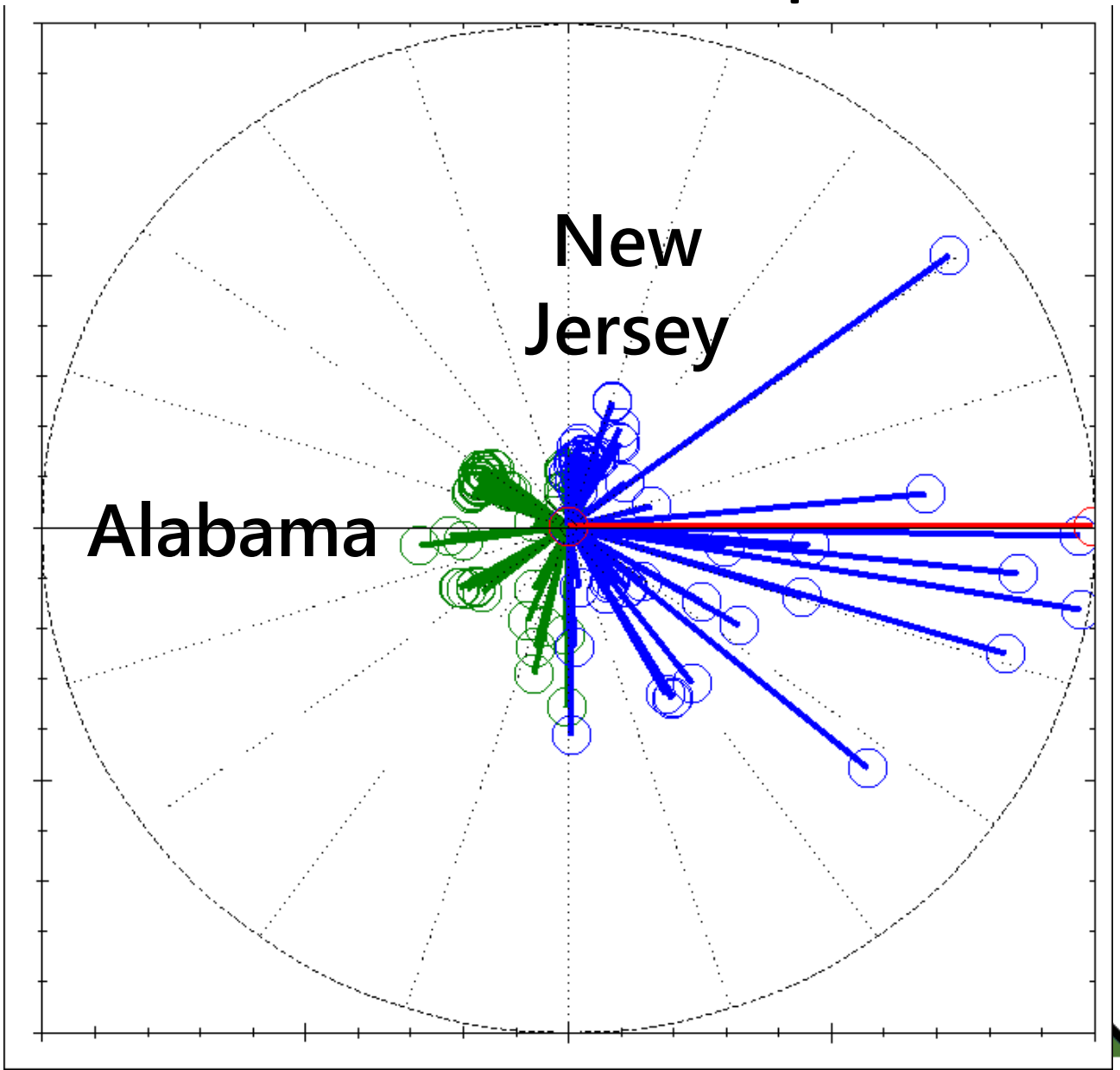
# 0.67 Hz System Mode Shape from FSSI



# 0.78 Hz System Mode Shape from FSSI

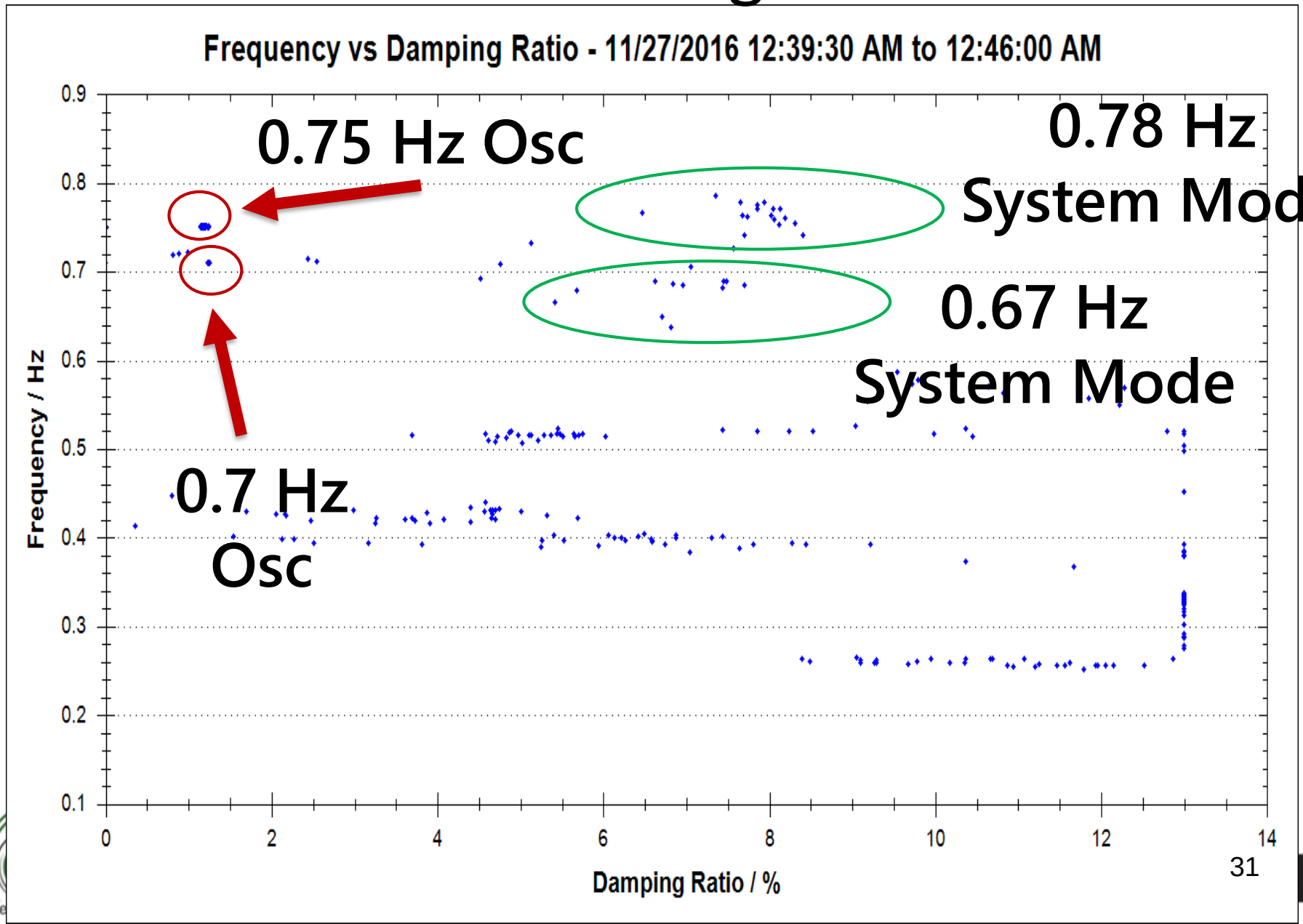


# 0.75 Hz Osc Mode Shape from FSSI

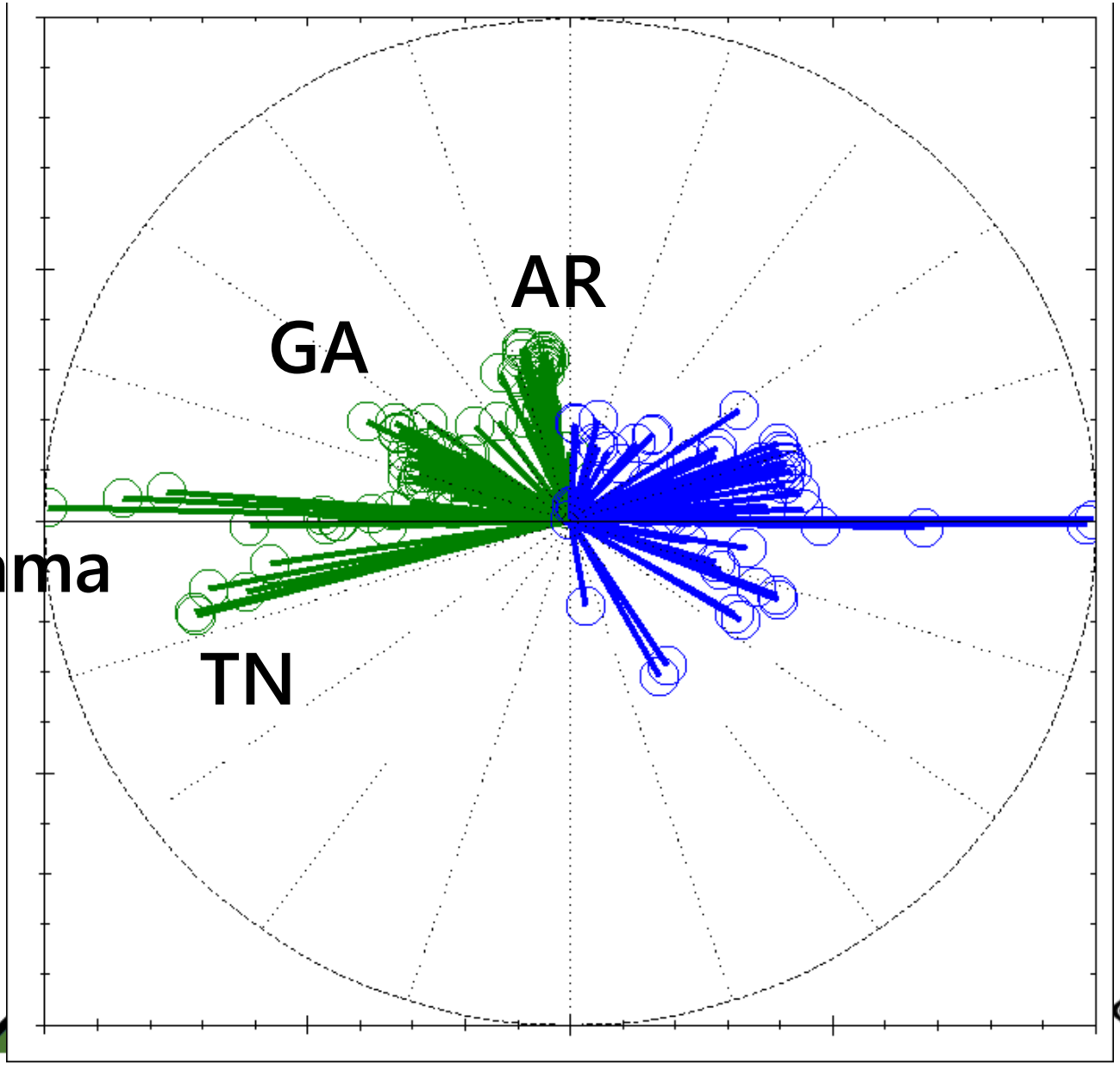



MISO signals

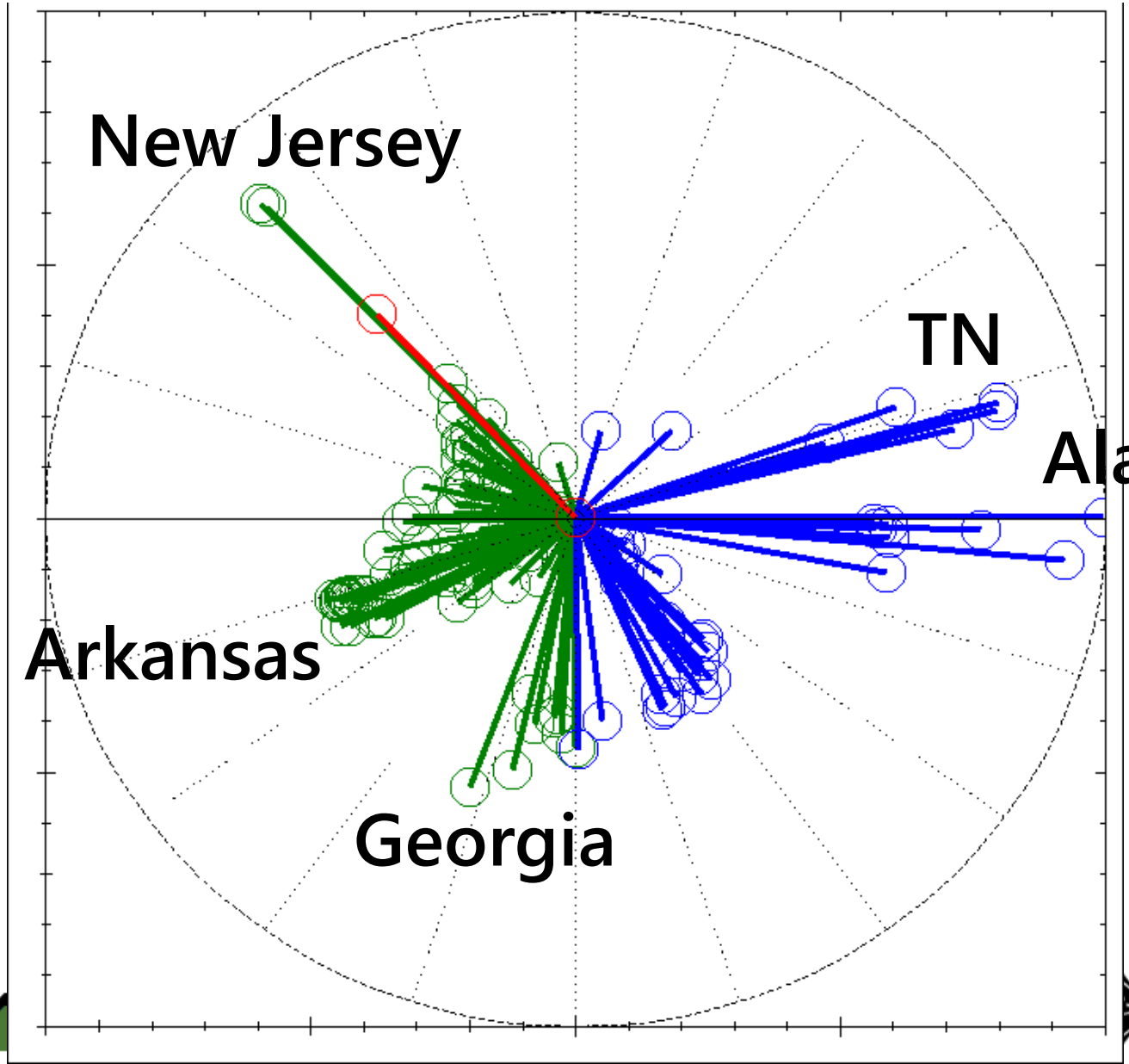
# FSSI Estimates During GA Osc Event



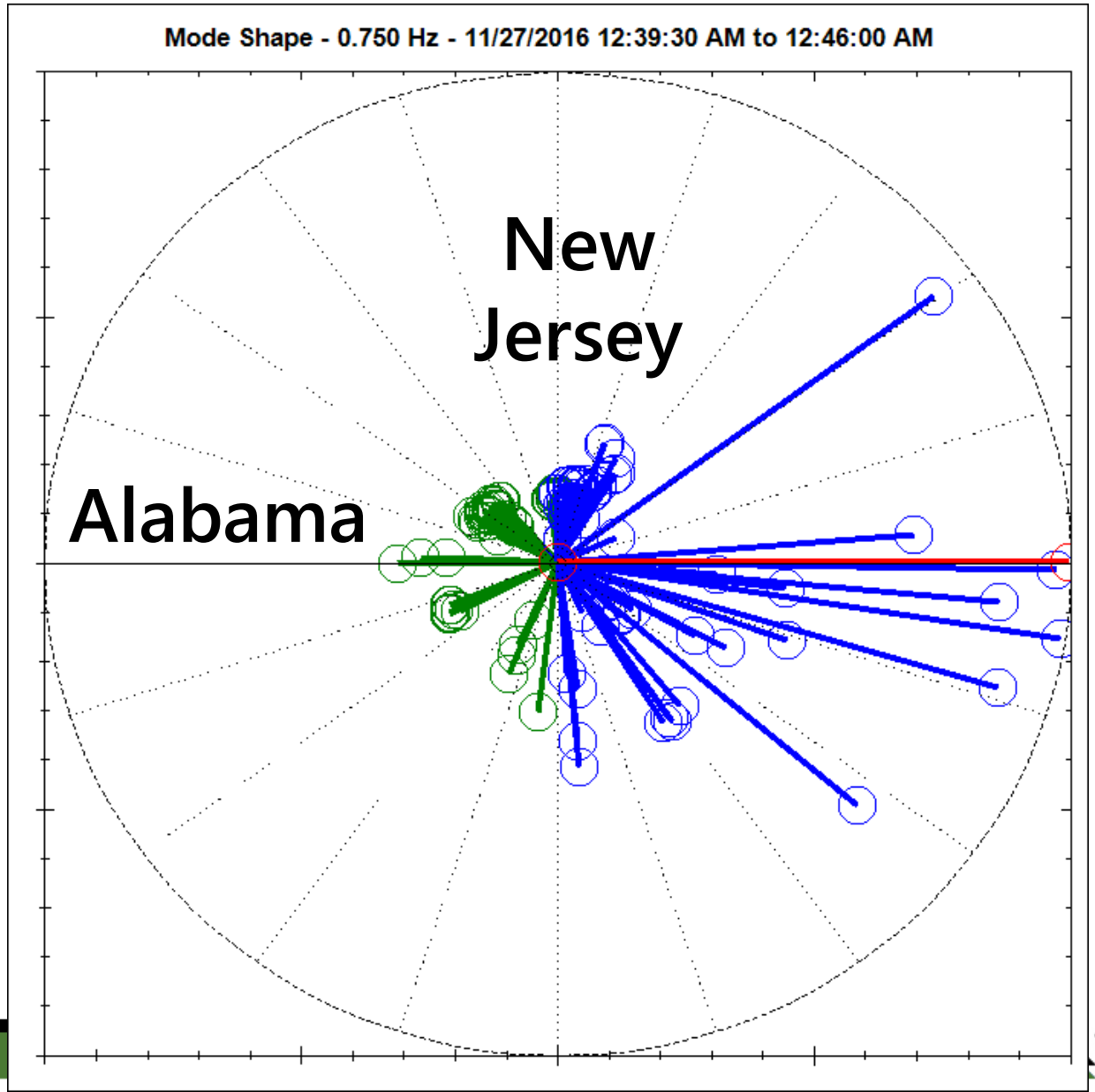
# 0.69 Hz System Mode Shape from FSSI



# 0.76 Hz System Mode Shape from FSSI

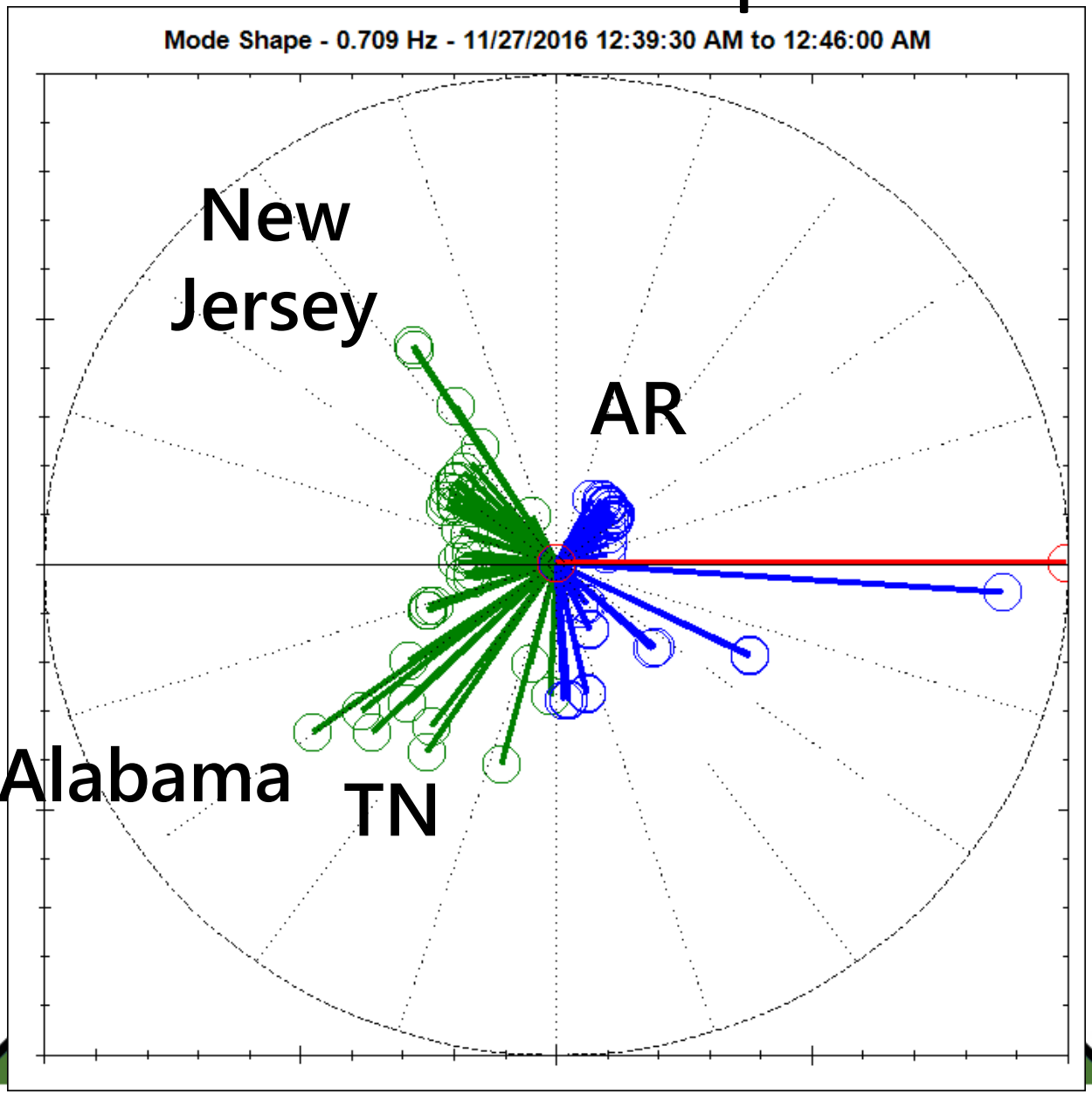


# 0.75 Hz Osc Mode Shape from FSSI




MISO signals

# 0.7 Hz Osc Mode Shape from FSSI



# Resonance with Inter-area Mode

**Resonance effect high** when:

(R1) Forced Osc freq near System Mode freq

(R2) System Mode poorly damped

(R3) Forced Osc 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 holds

(Source: Our recent papers in IEEE Trans. Power Systems)

# Resonance Conditions for the Ever Present 0.75 Hz Forced Oscillation

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

- **0.75 Hz Oscillation versus 0.78 Hz Mode**

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

- **0.78 Hz Well-damped (7% Damping Ratio)**

(R3) Forced Osc location near distant ends (strong participation) of the System Mode **(not true)**

- **MISO Location 33% Relative Energy for the Mode**

**Only ~1 condition valid: Resonance effect very small.**

# Resonance Conditions for the 0.7 Hz Georgia Forced Oscillation

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

- **0.7 Hz Oscillation versus 0.67 Hz System Mode**

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

- **0.67 Hz Well-damped (6% Damping Ratio)**

(R3) Forced Osc location near the two distant ends (strong participation) of the System Mode **(not true)**

- **GA Location 22% Relative Energy for the Mode**
- **Interaction with 0.78 Hz mode?**

**Only 1+ conditions valid: Resonance effect small.**

# Nov 27 2016 Event Summary

- **0.7 Hz Eastern Interconnection Mode Shape: VACAR versus TVA.**
- **Oscillation source in Georgia was not a sensitive location for the 0.67 Hz Mode**
- **Oscillation frequency 0.7 Hz close**
- **0.67 Hz System mode well-damped**
- **Resonance effect was mild**
- **0.75 Hz forced oscillation present throughout – weak resonance with 0.78 Hz system mode**

# EI Forced Oscillation Events

- **Forced oscillations are problematic.**
- **November 29, 2005 Alberta Event – Inter-Area oscillation resonance event in the west.**
- **Sept 5, 2015 – Resonance event in the west.**
- **June 17, 2016 and November 27, 2016 events – Oscillation resonance events in the east.**
- **Inter-Area Resonance – potential risk for operational reliability**
- **Source location and follow-ups.**