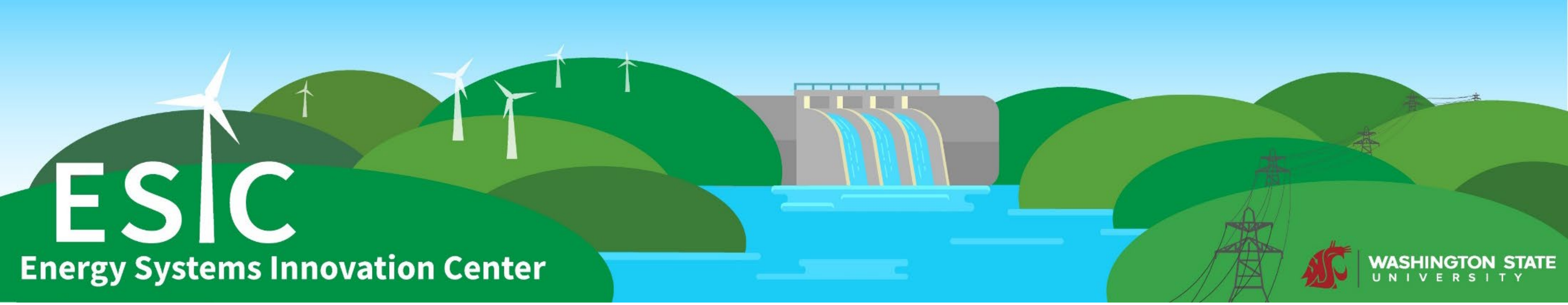


Introduction to Oscillations

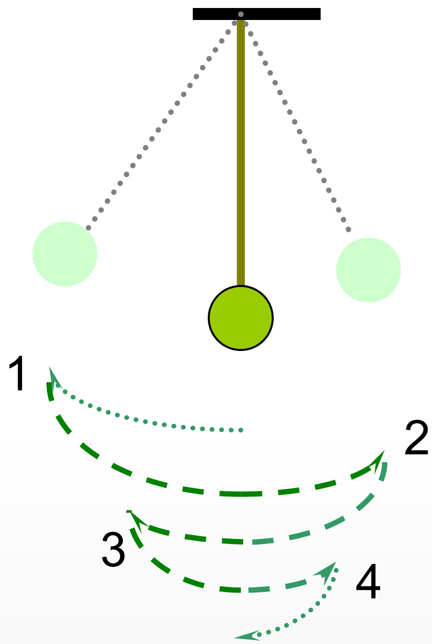
Mani V. Venkatasubramanian
Director, ESIC
Washington State University

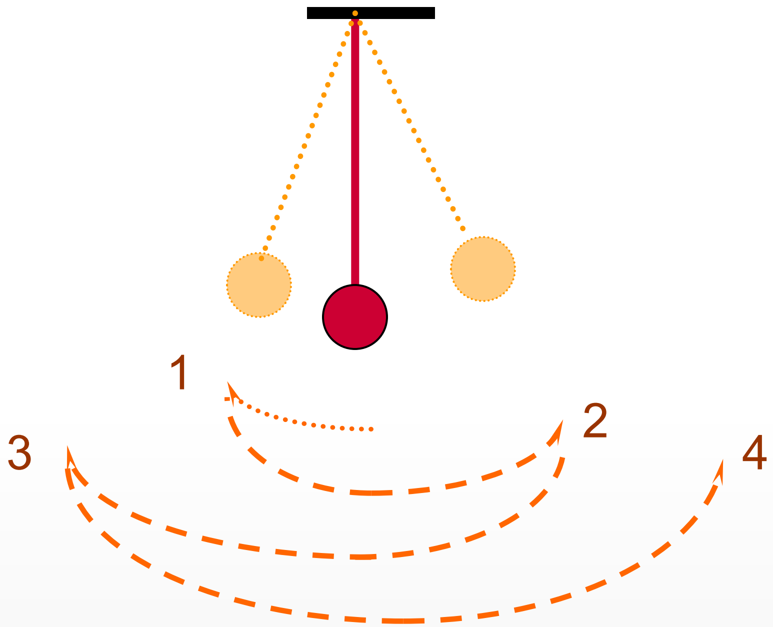
ESIC WASHINGTON STATE UNIVERSITY

Small Signal Stability

- Oscillations must remain well-damped for small-signal stability
- 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
- IBRs influencing grid dynamics and can cause subsynchronous oscillations

Pendulum Example





Positive damping

Oscillations damp out

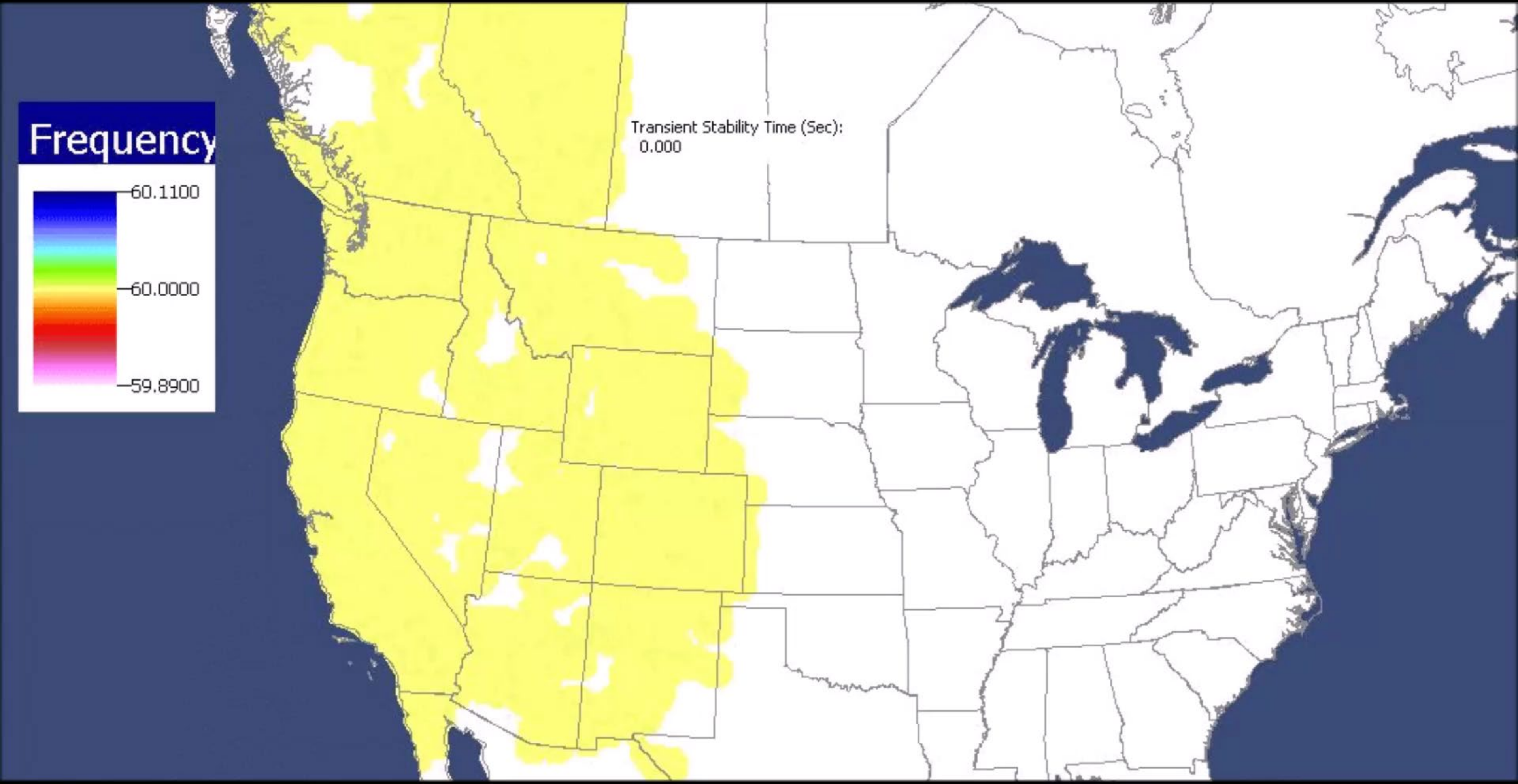
Negative damping

Growing oscillations

Oscillations Terminology

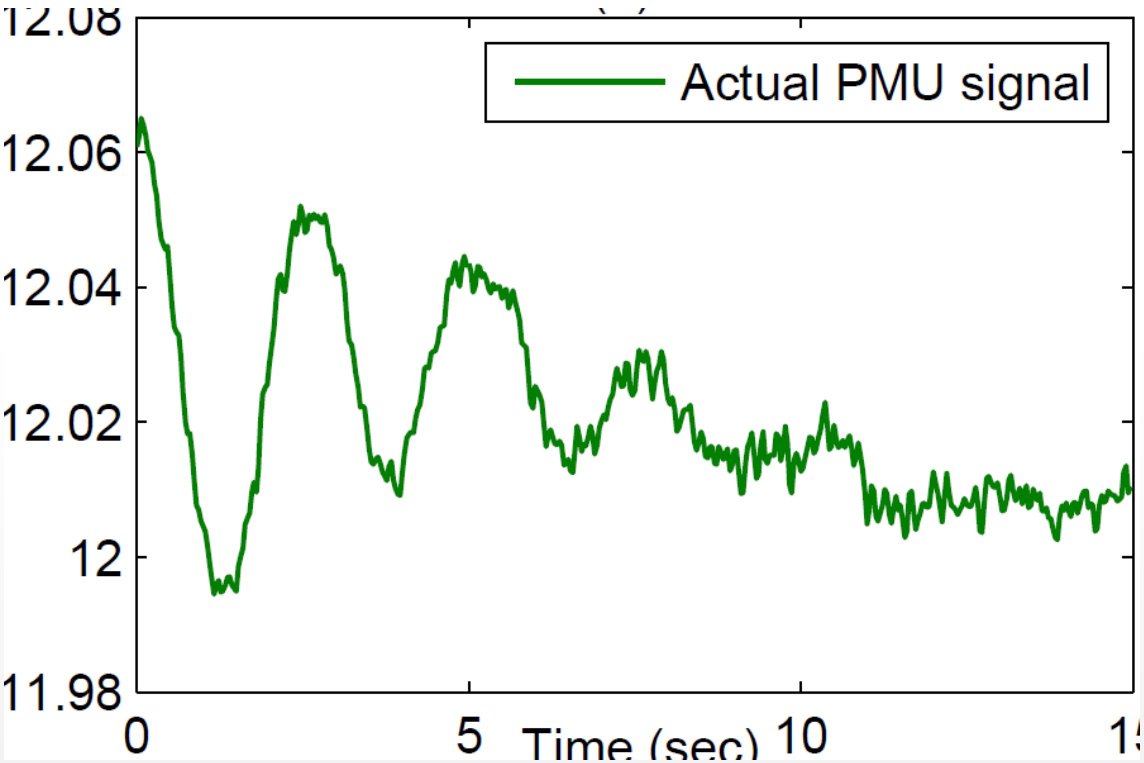
- Oscillations: Unintentional periodic exchange of energy across power system components
- Damped Oscillations
  - Well-damped or poorly damped?
- Undamped oscillations
  - Problematic, Causes rotor fatigue, Power quality issues, blackout
  - Forced Oscillations: Can interfere with system modes, interarea resonance

Well-damped oscillations



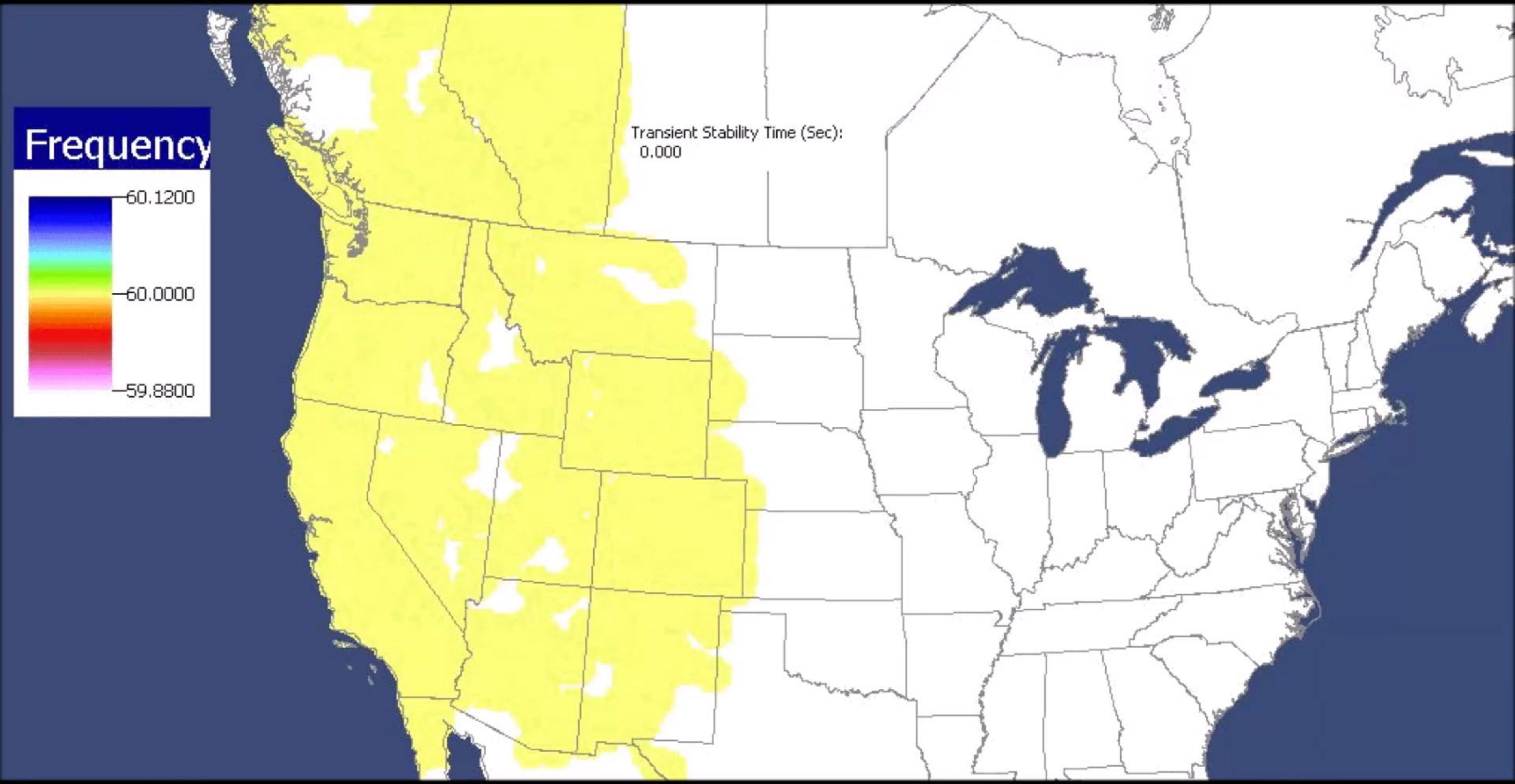
Powerworld Animation

Well-damped Response



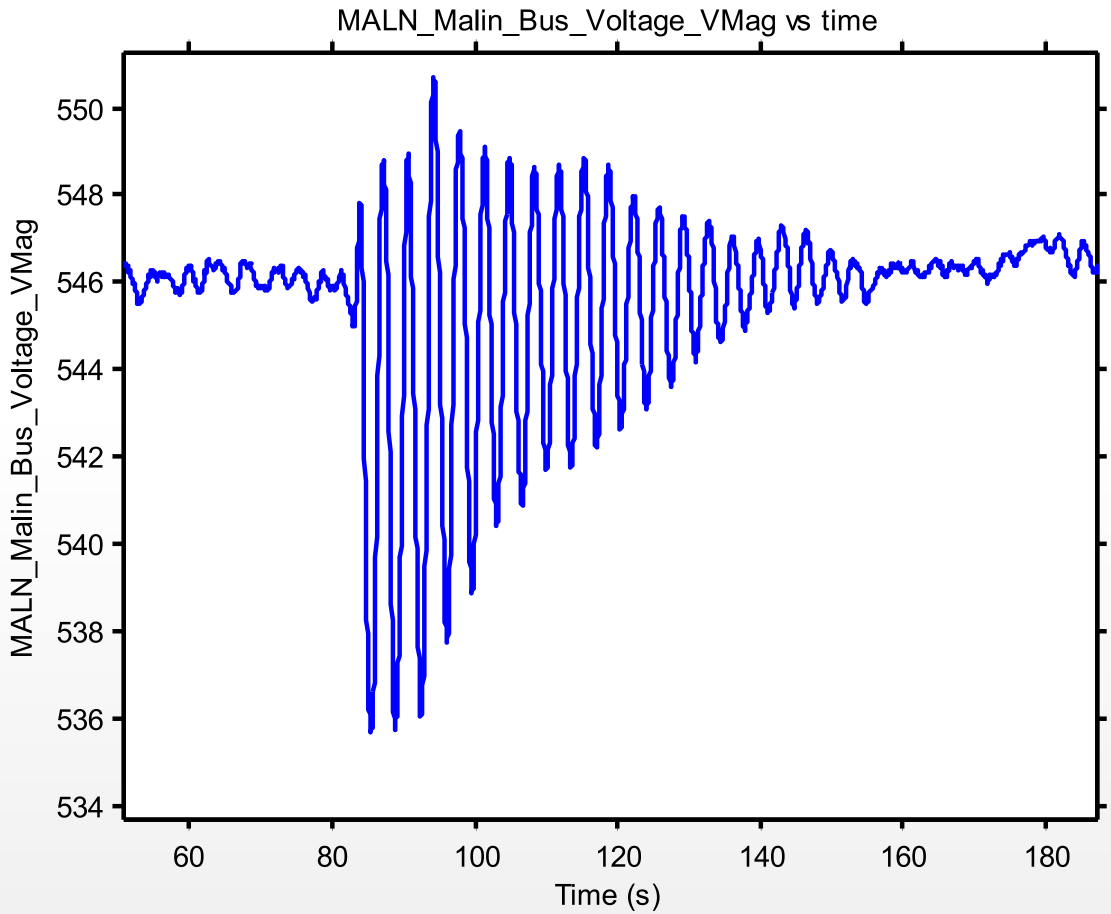
Recent WECC Event

Poorly Damped Oscillations



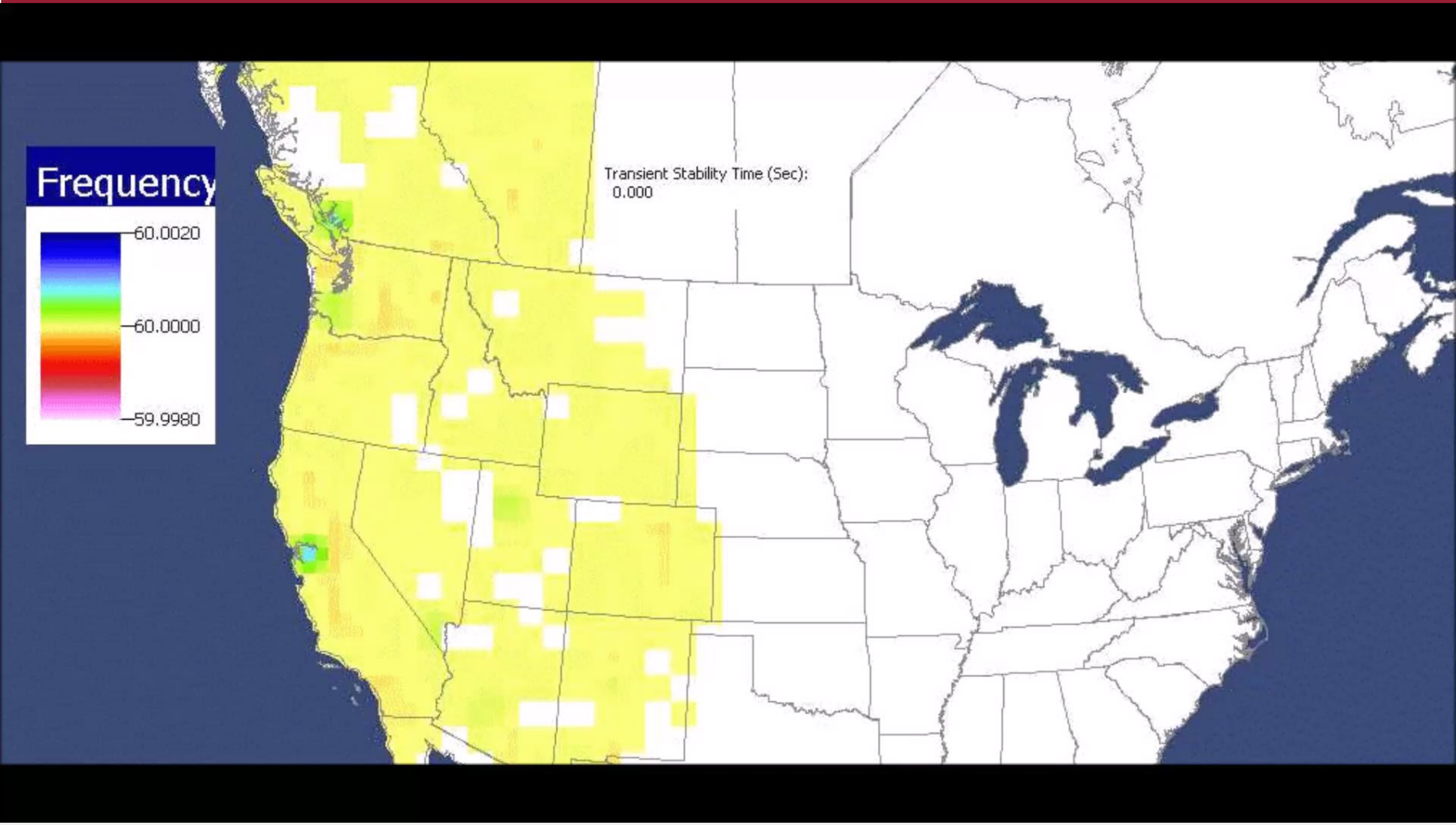
Powerworld Animation

Poorly Damped Oscillations

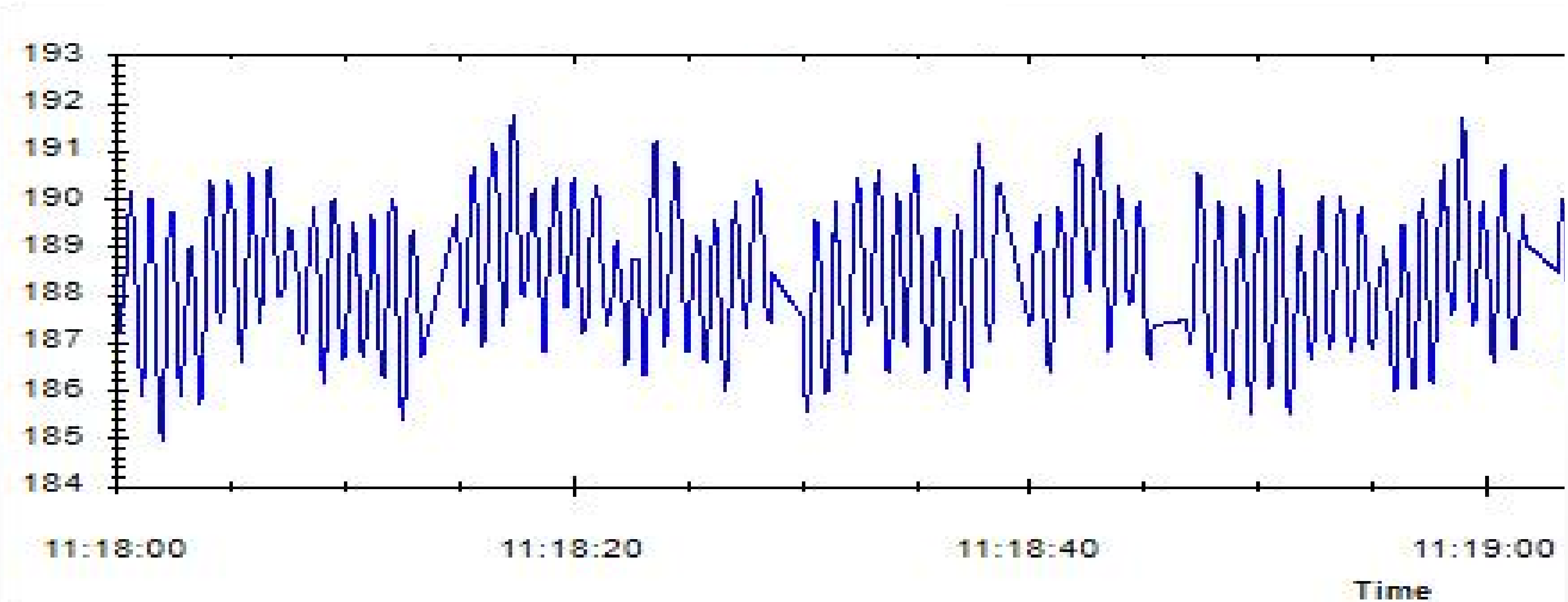


2000 Alberta Separation Event

Local oscillations

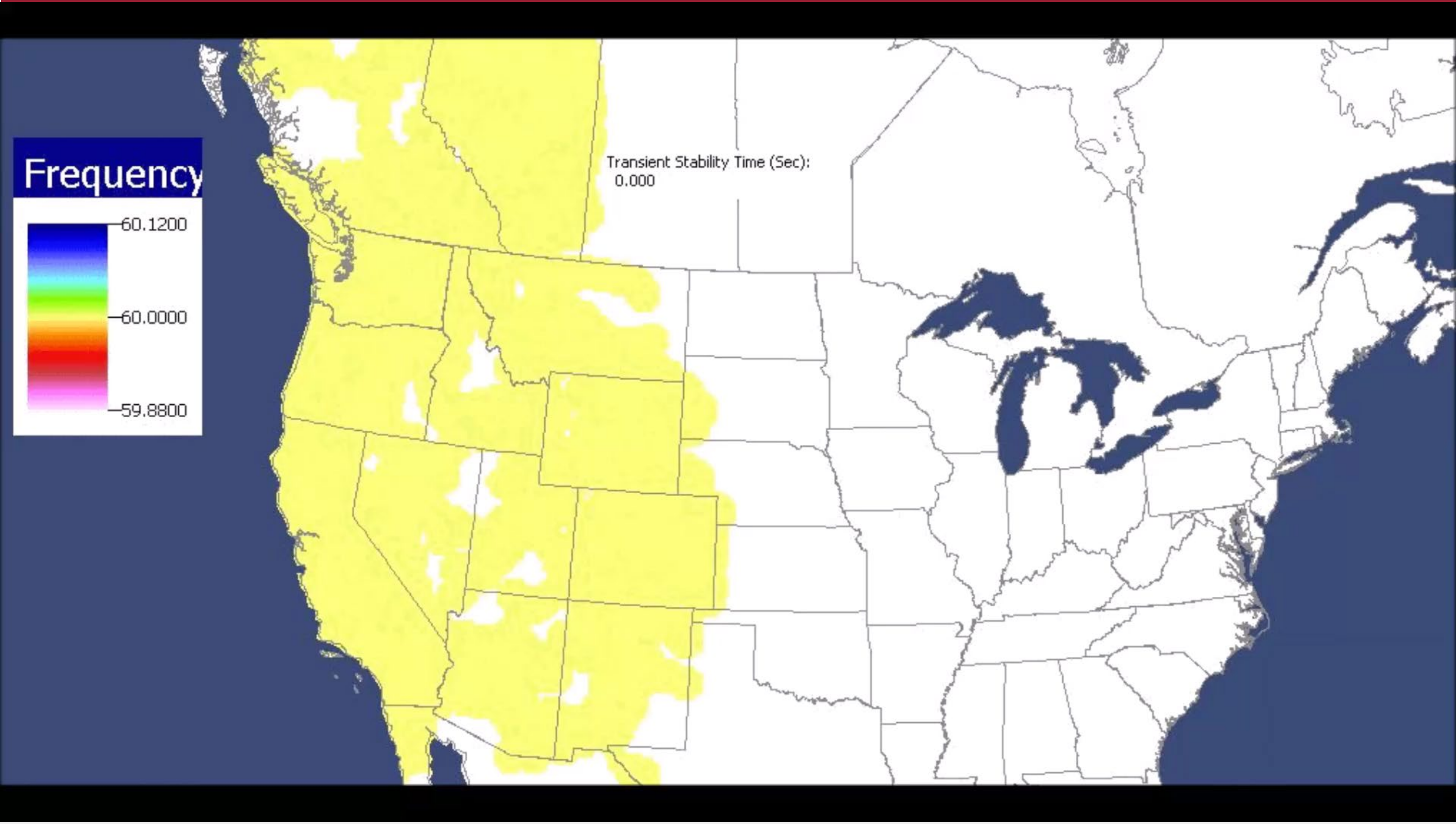


Sustained oscillations



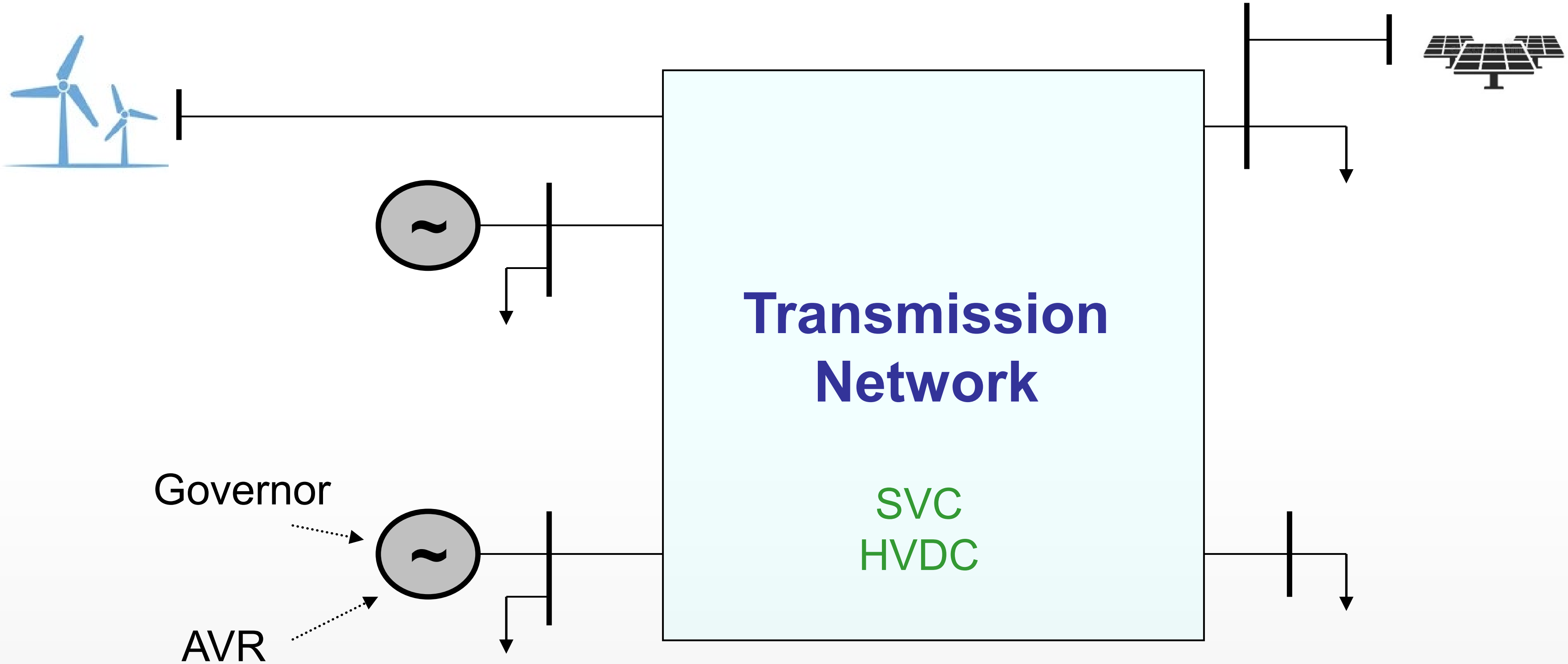
1 Hz Governor oscillations caused by a faulty valve

Inter-Area Oscillations



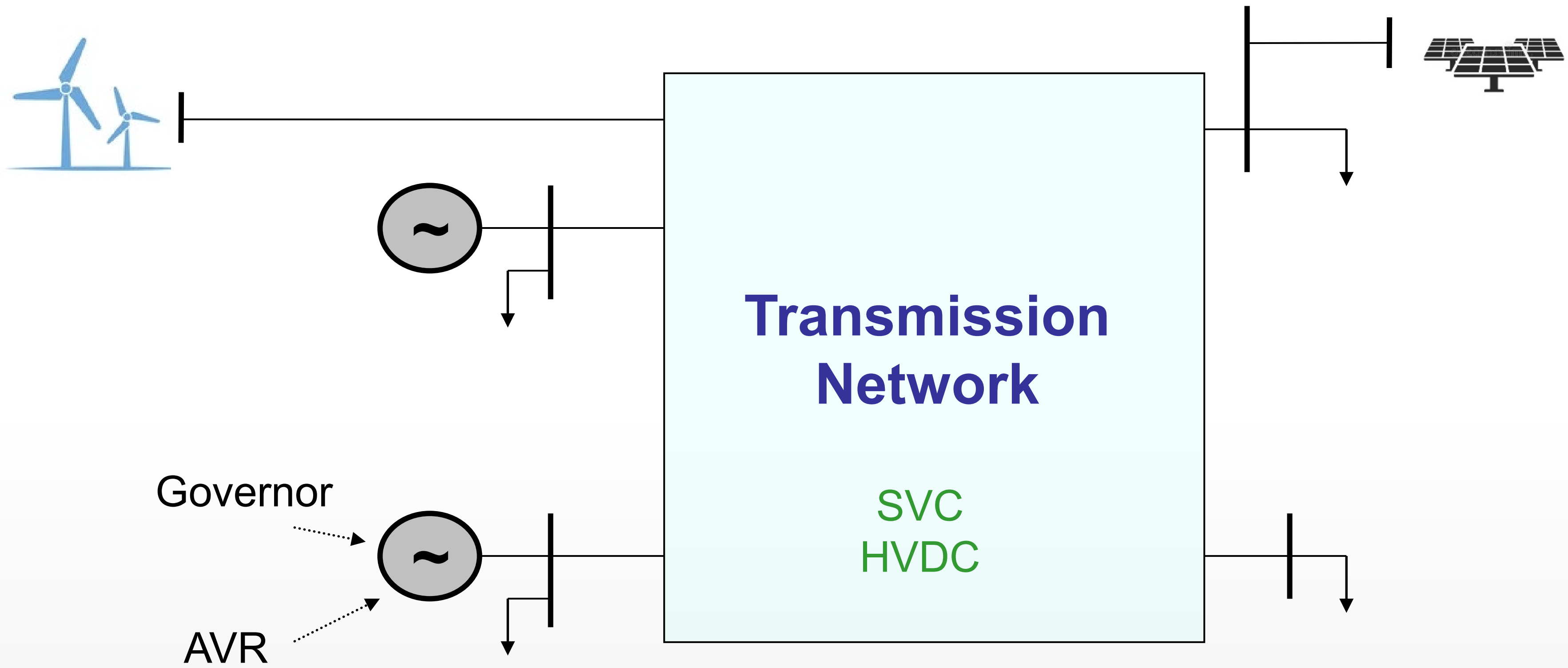
Powerworld Animation

Power System Dynamics



Generators, renewables, and controls interacting across the system

Subsynchronous Oscillations



Power electronic controls in renewables interacting with the power grid

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Linearization

System stability model

$$\frac{dx}{dt} = f(x, y)$$ Generator Dynamics

$$0 = g(x, y)$$ Power-flow Equations

Equilibrium point

$$0 = f(x, y)$$

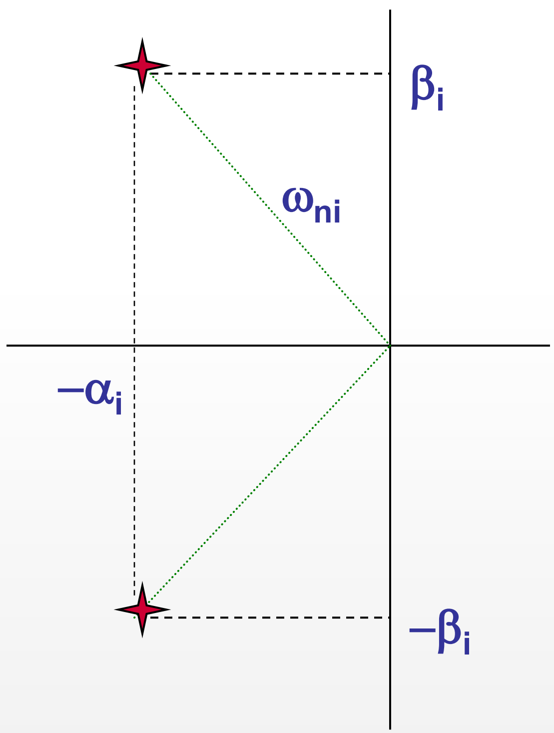
$$0 = g(x, y)$$

Small-signal model

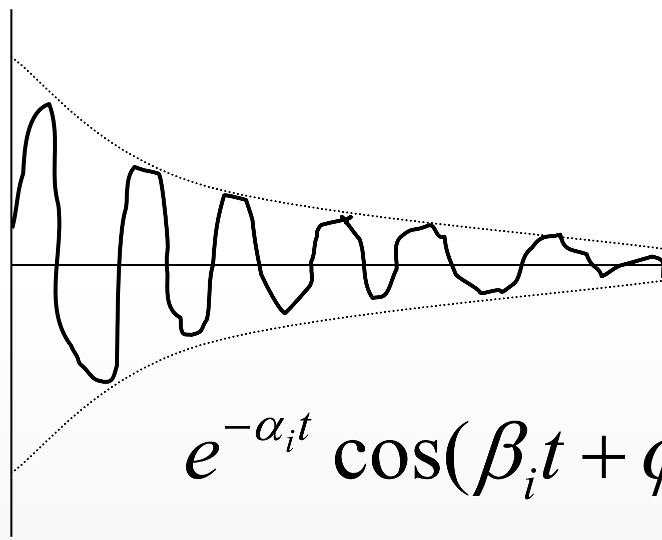
$$\frac{d(\Delta x)}{dt} = J \, \Delta x$$

Modal Response

Eigenvalue or Mode $\lambda_i = -\alpha_i \pm j\,\beta_i$



Modal time-response



$$e^{-\alpha_i t}\cos(\beta_i t + \varphi)$$

Mode frequency = $\beta_i / 2\pi$

Mode damping ratio = α_i / ω_{ni}

How fast does it damp out?

Modal Analysis

- *Thousands* of oscillatory modes in a power system
- Damping ratio of *every mode* should be above 5% or 0.05
- Well-damped mode responses "not seen"
- Damping from 0% to 5% gives poorly damped oscillatory responses
- Damping below 0% results in growing or undamped oscillations

Modal Properties

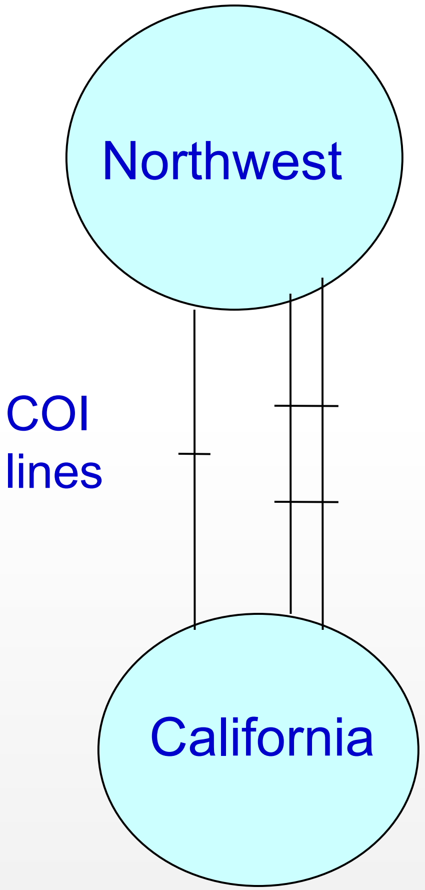
- Eigenvalue or Mode $\lambda_i = -\alpha_i + j\,\beta_i$
- Mode frequency
- Mode damping ratio

- Mode shape – which generators are swinging and how? (right eigenvector)
  - local mode (one generator/plant)
  - intra-area mode (several generators in one control area)
  - inter-area mode (generators across many control areas)

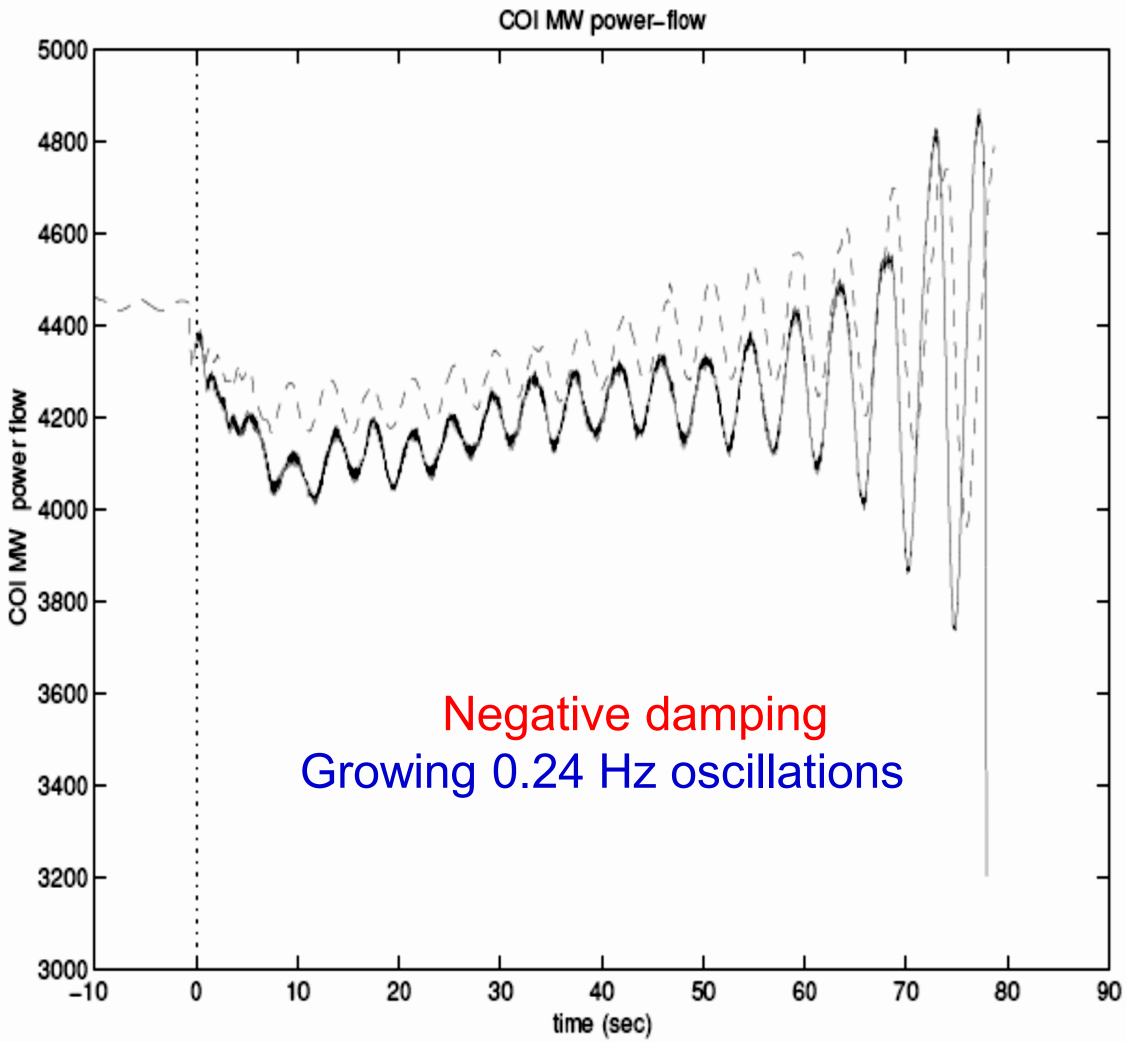
Well-known WECC modes

- 0.25 Hz North-South inter-area mode
- 0.37 Hz North-South inter-area mode
- Eastern interconnection, 0.25 Hz, 0.4 Hz, 0.5 Hz, 0.6 Hz, 0.7 Hz, …

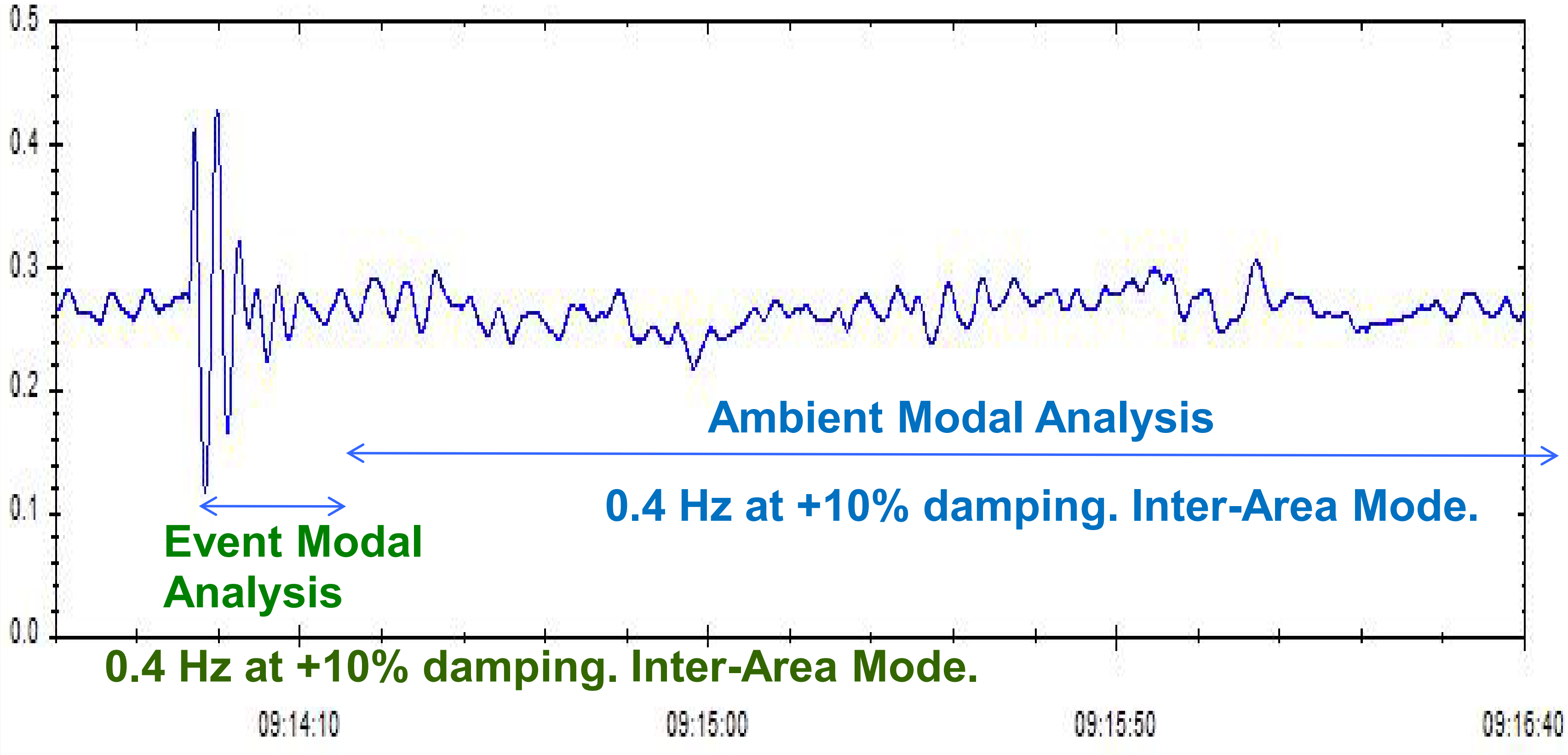
August 10, 1996 blackout



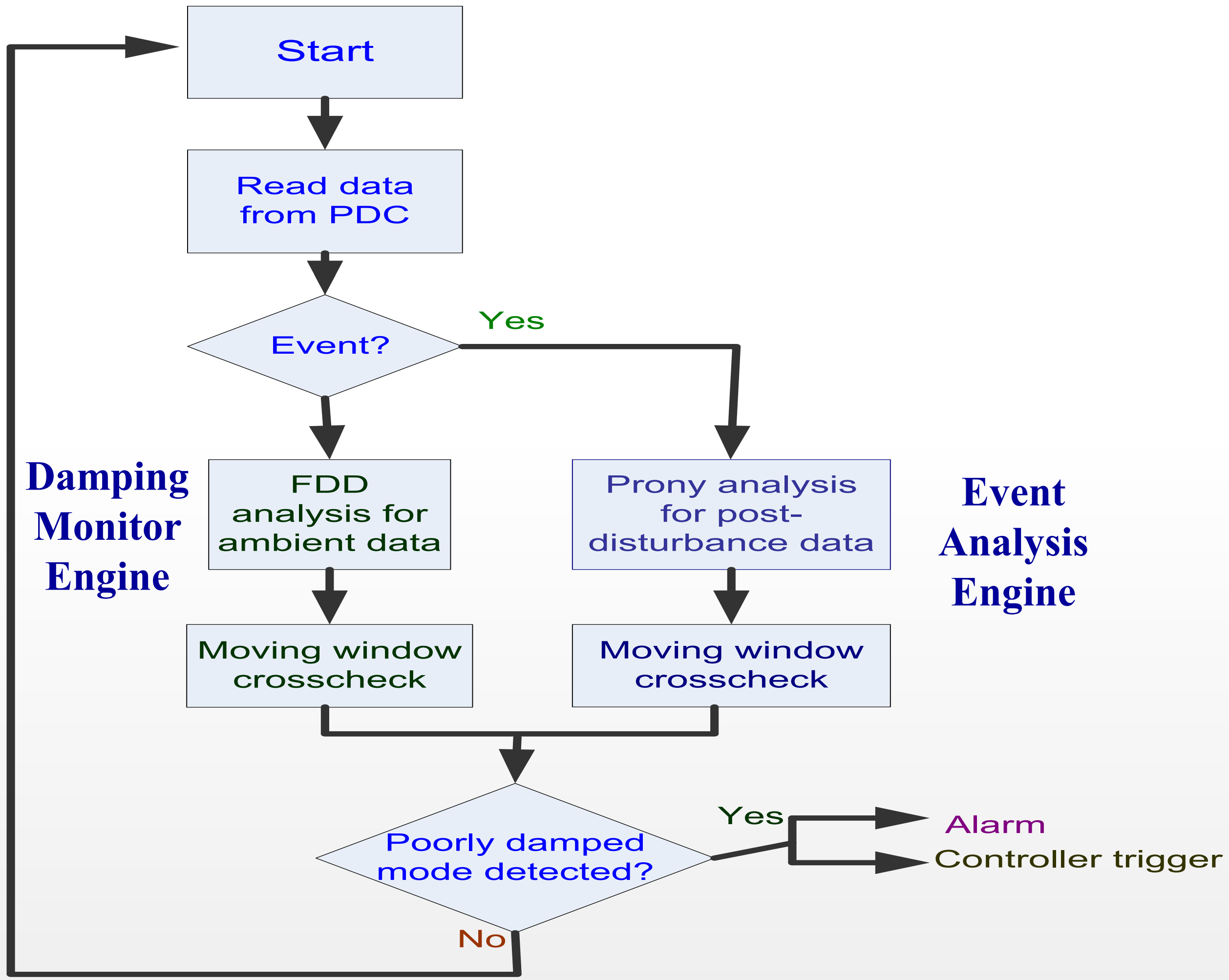
Inter-area mode



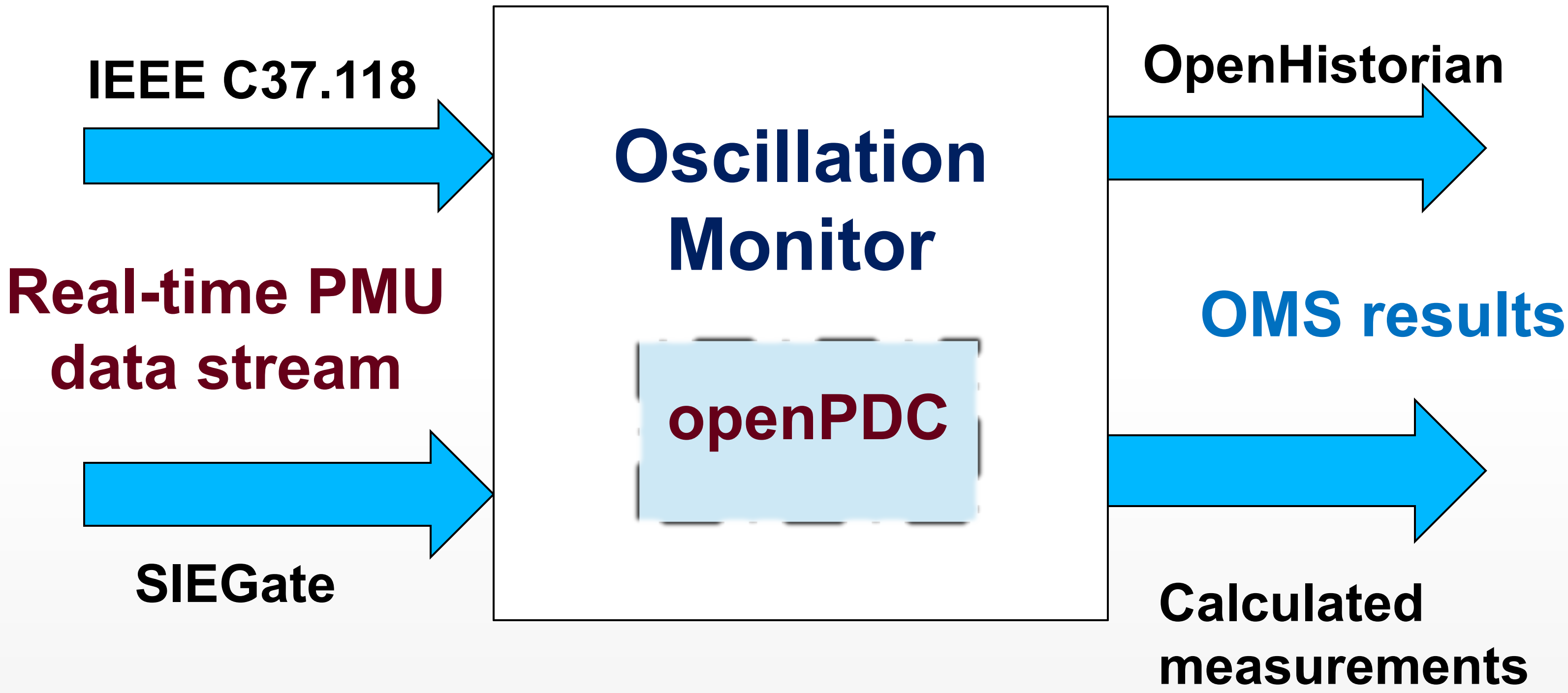
Measurement Based Analysis



Oscillation Monitoring



Oscillation Monitoring System



OMS action adapters built into OpenPDC platform.

Complementary Engines

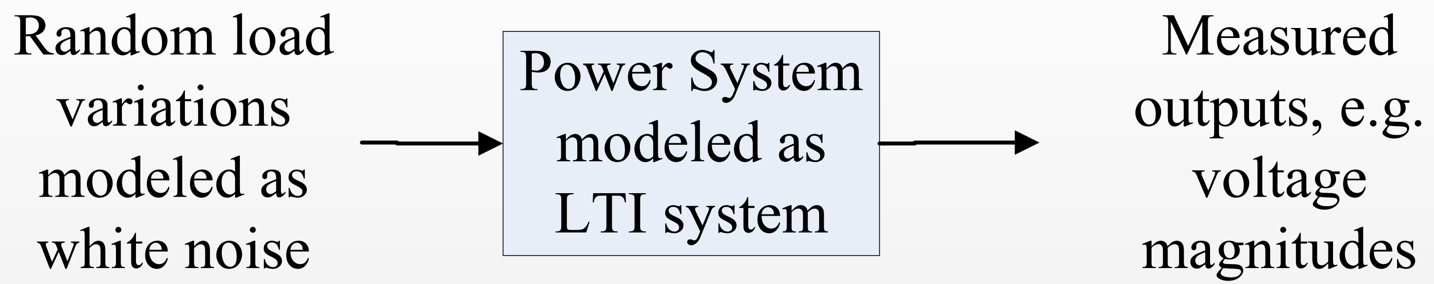
- Event Analysis Engine (EAE)
  - Multiple algorithms
  - Prony, Matrix Pencil, HTLS, ERA, MFRA, METRA.
  - Aimed at events resulting in sudden changes in damping
- Damping Monitor Engine (DME)
  - Ambient noise based. Continuous. Provides early warning on poorly damped modes.
  - Several algorithms
  - Fast Frequency Domain Decomposition (FFDD), Fast Stochastic Subspace Identification (FSSI), DFDO, Recursive Adaptive Stochastic Subspace Identification (RASSI), DFDD, RFDD, DRSSI, WSD

Ambient Modal Analysis

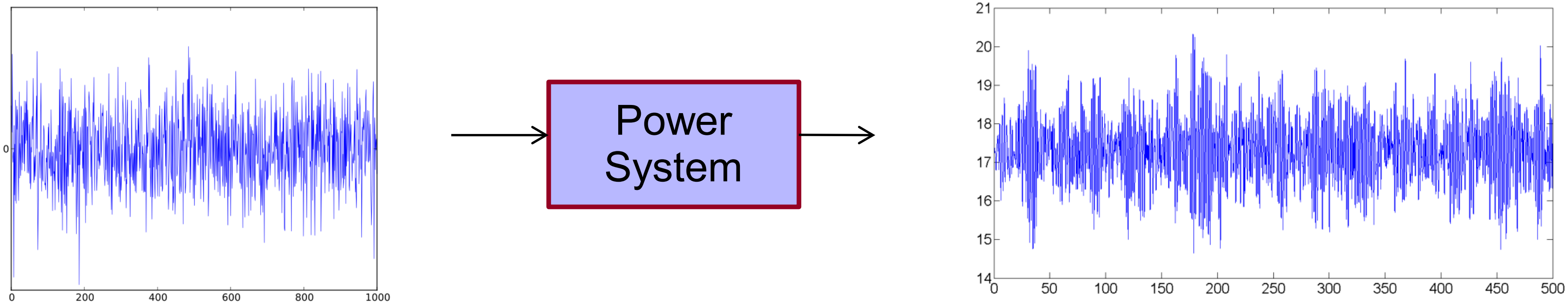
- Ambient noise based. Continuous. Tracks damping of modes online.
- Provides early warning on poorly damped modes.
- Time-domain algorithms:
  - ❑ Fast Stochastic Subspace Identification (FSSI-Covariance)
- Frequency-domain algorithms:
  - ❑ Fast Frequency Domain Decomposition (FFDD)

Mathematical Model

- **Power system is a high-order nonlinear time-invariant system**
- **However, for small perturbations, power system can be modeled as a Linear Time-Invariant (LTI) system for short periods of time**

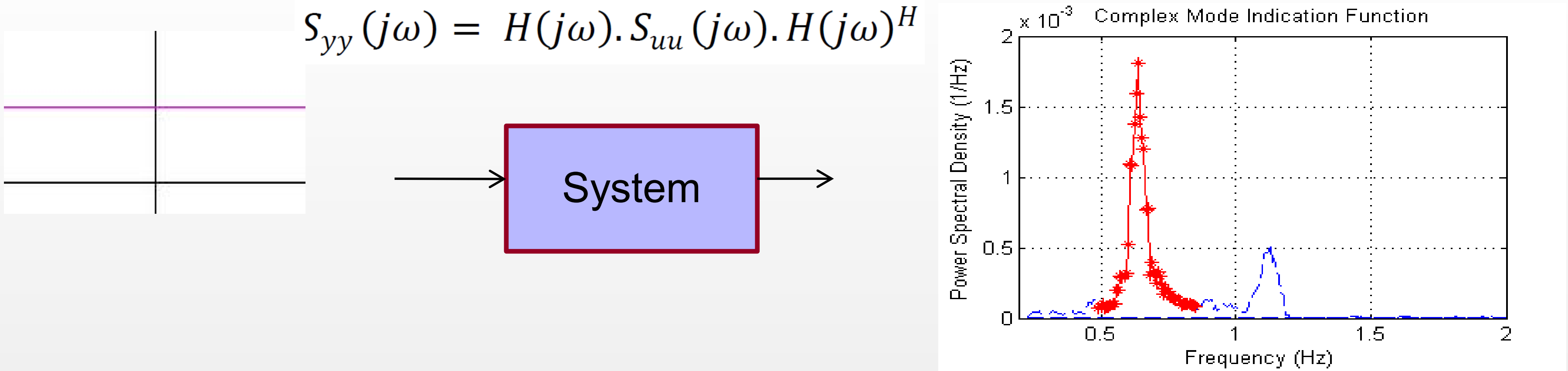


Frequency Domain Decomposition

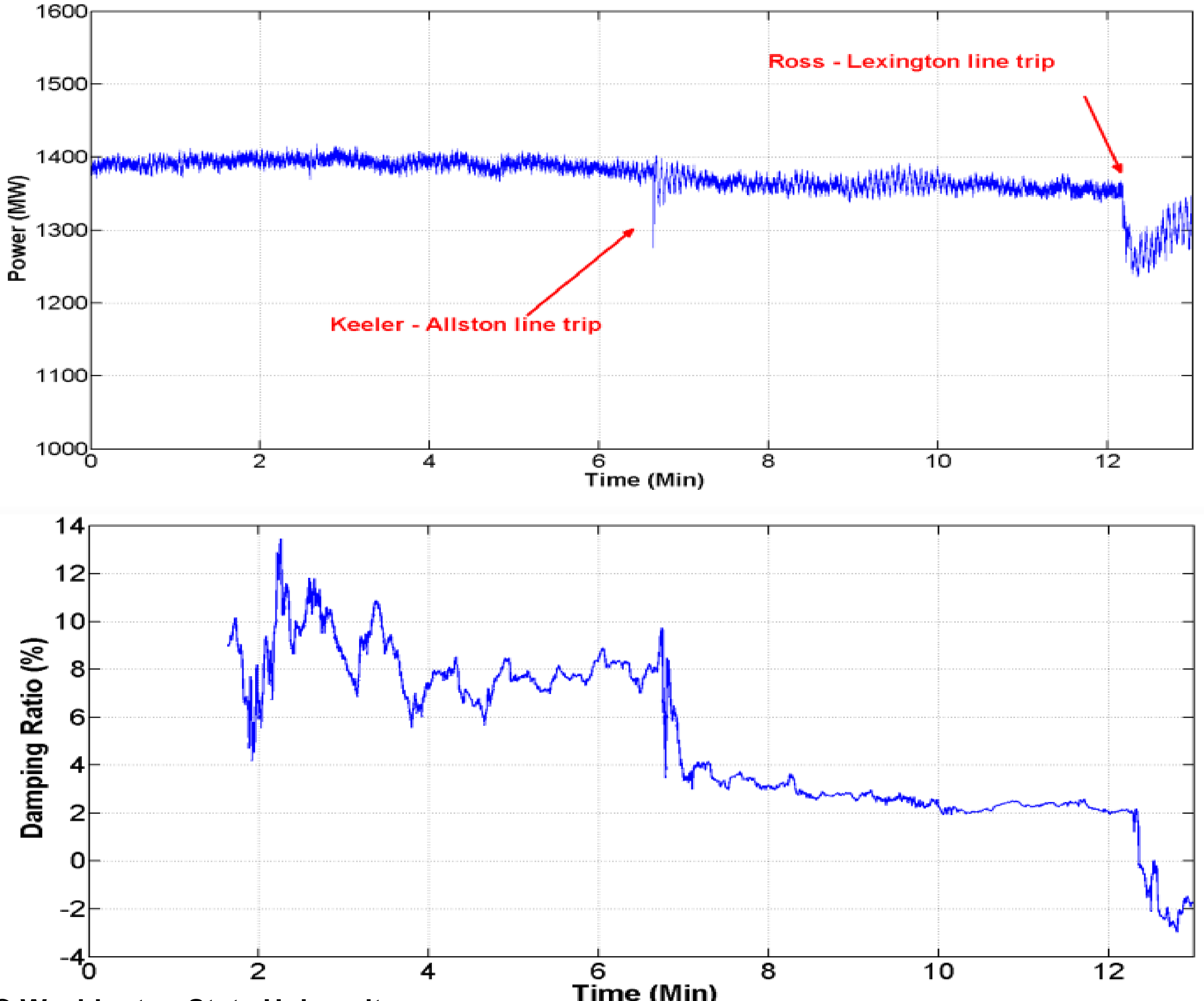


White noise

$$S_{yy}(j\omega) = H(j\omega).S_{uu}(j\omega).H(j\omega)^H$$

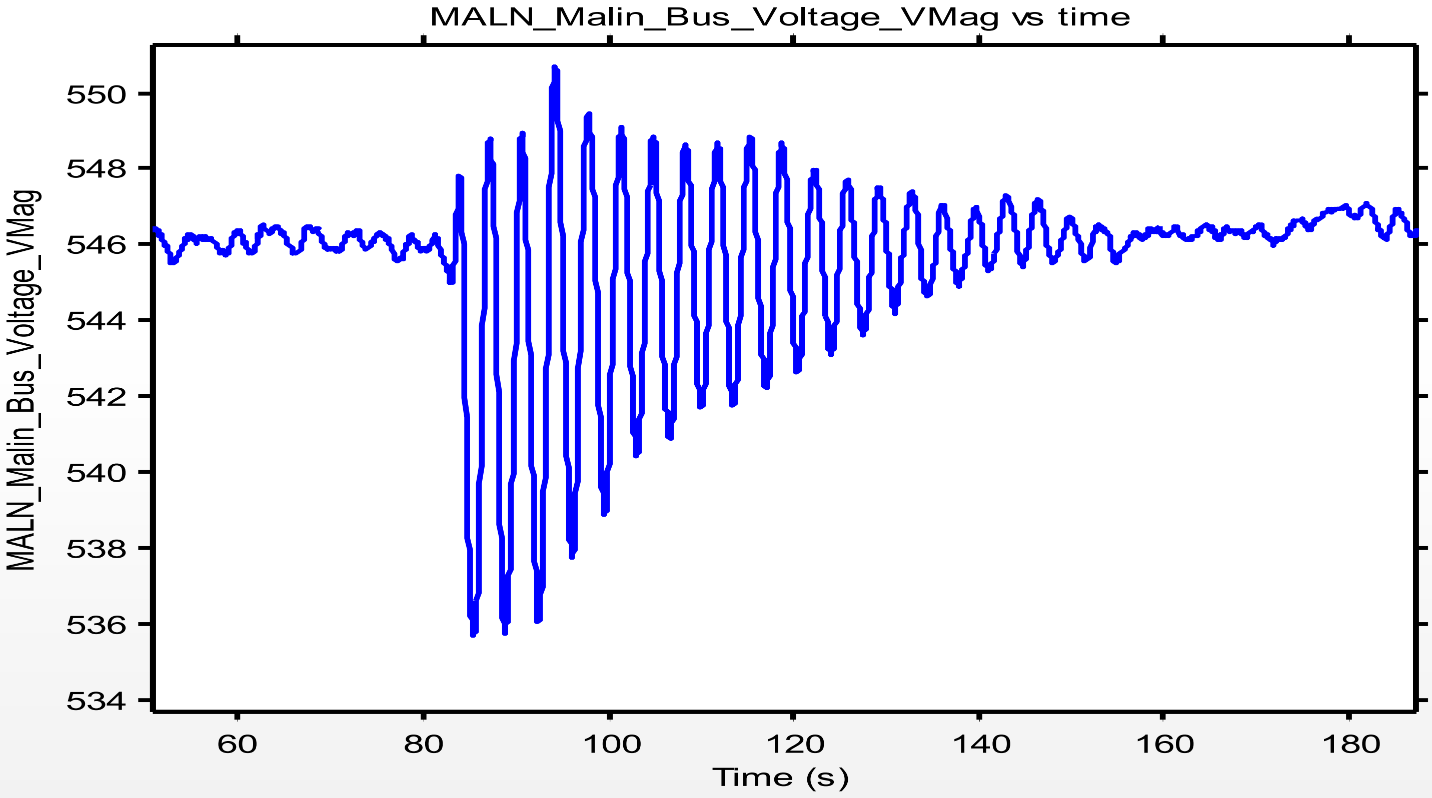


August 10, 1996 WECC Event Modal Estimates from PMUs



SSI analysis: **0.25 Hz COI mode damping moved from positive to negative as event progressed.**

Event (Ringdown) Analysis



Oscillation frequencies? Damping ratios? Mode shapes?

Mathematical Model

- **The response after small disturbances can be expressed as the sum of exponential terms**
  - **Transfer function** $$G_i(s) = \frac{\Delta y_i(s)}{\Delta u(s)} = \sum_{i=1}^{n} \frac{R_i}{s - \lambda_i}$$

    where $R_i = c_i \varphi_i \psi_i b$. ϕ_i **and** ψ_i **are the right and left eigenvectors.**
  - **Impulse response** $$y_j(t) = \sum_{i=1}^{n} R_i \exp(\lambda_i t)$$
  - **Sampling at constant period** $y(k) = \sum_{i=1}^{n} R_i z_i^k$ **where** $z_i = \exp(\lambda_i \Delta t)$

Ringdown Analysis

- Algorithms for ringdown event analysis
  - Prony's Method
  - Matrix Pencil Method
  - Hankel Total Least Square (HTLS)
  - Eigenvalue Realization Algorithm (ERA)
  - MFRA, METRA
- To verify linearity, crosscheck results from multiple engines and multiple time-windows.

June 17, 2016 Oscillation Event

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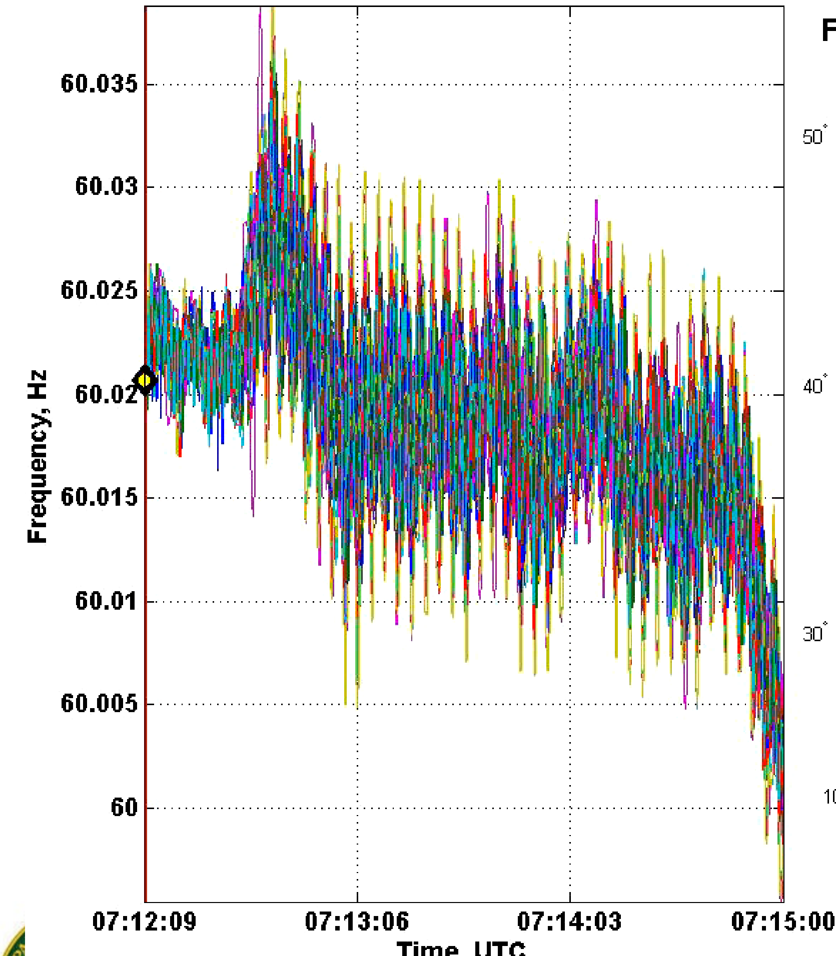

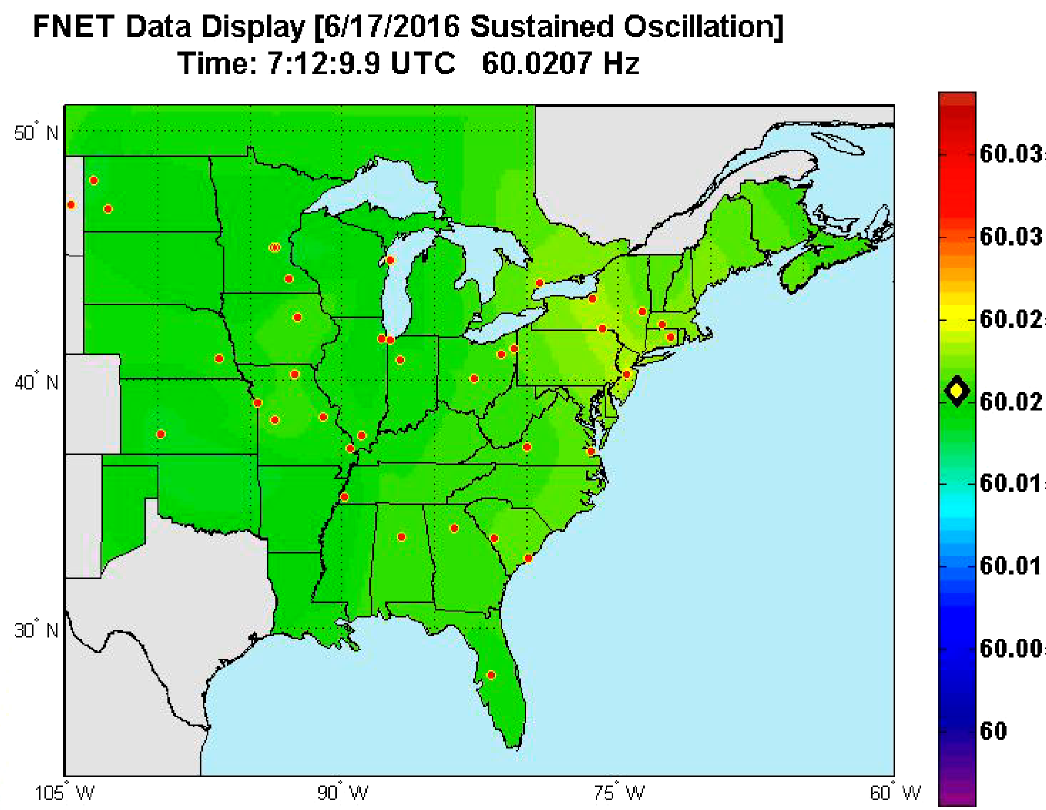

OAK RIDGE National Laboratory

FNET GridEye

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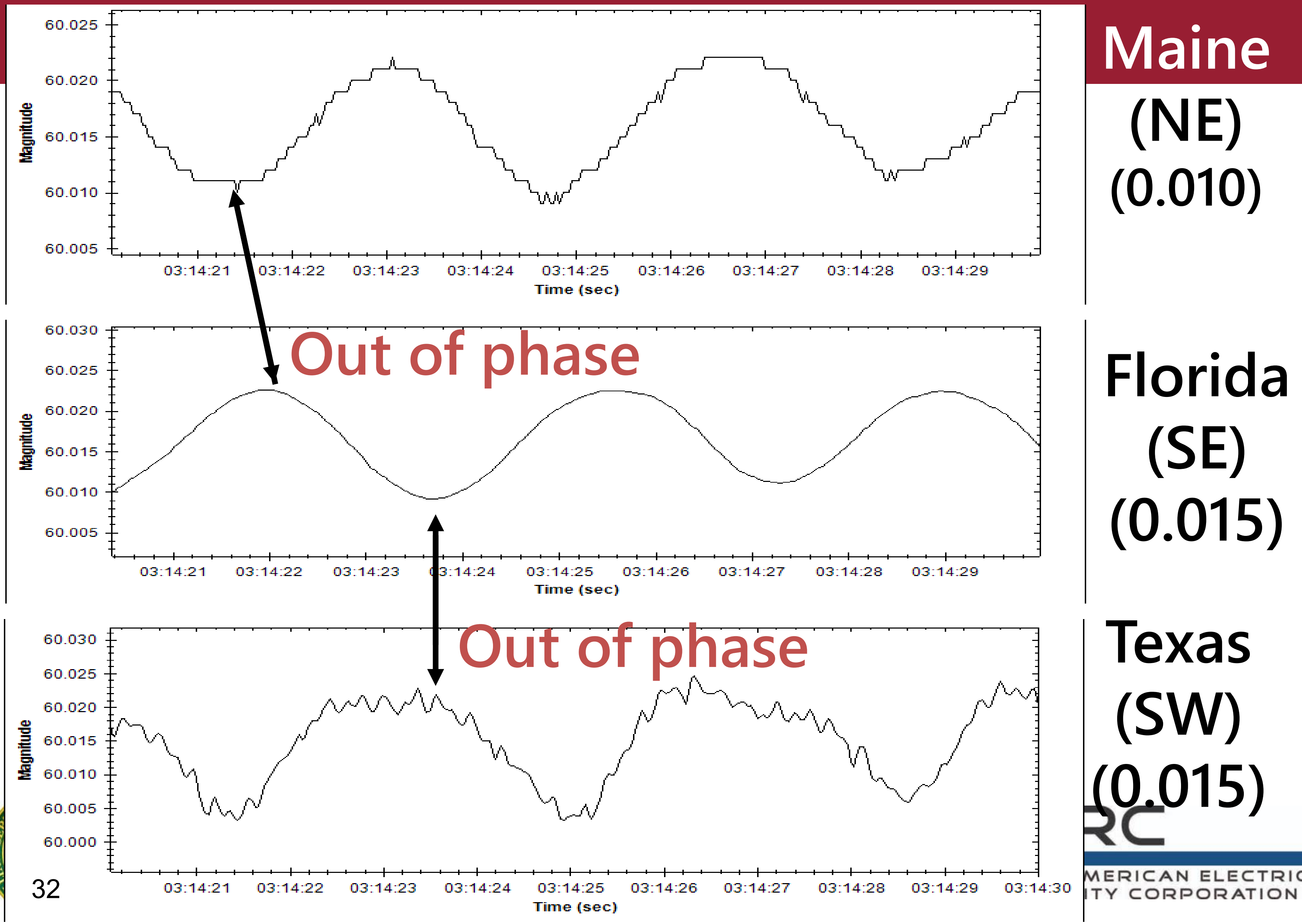
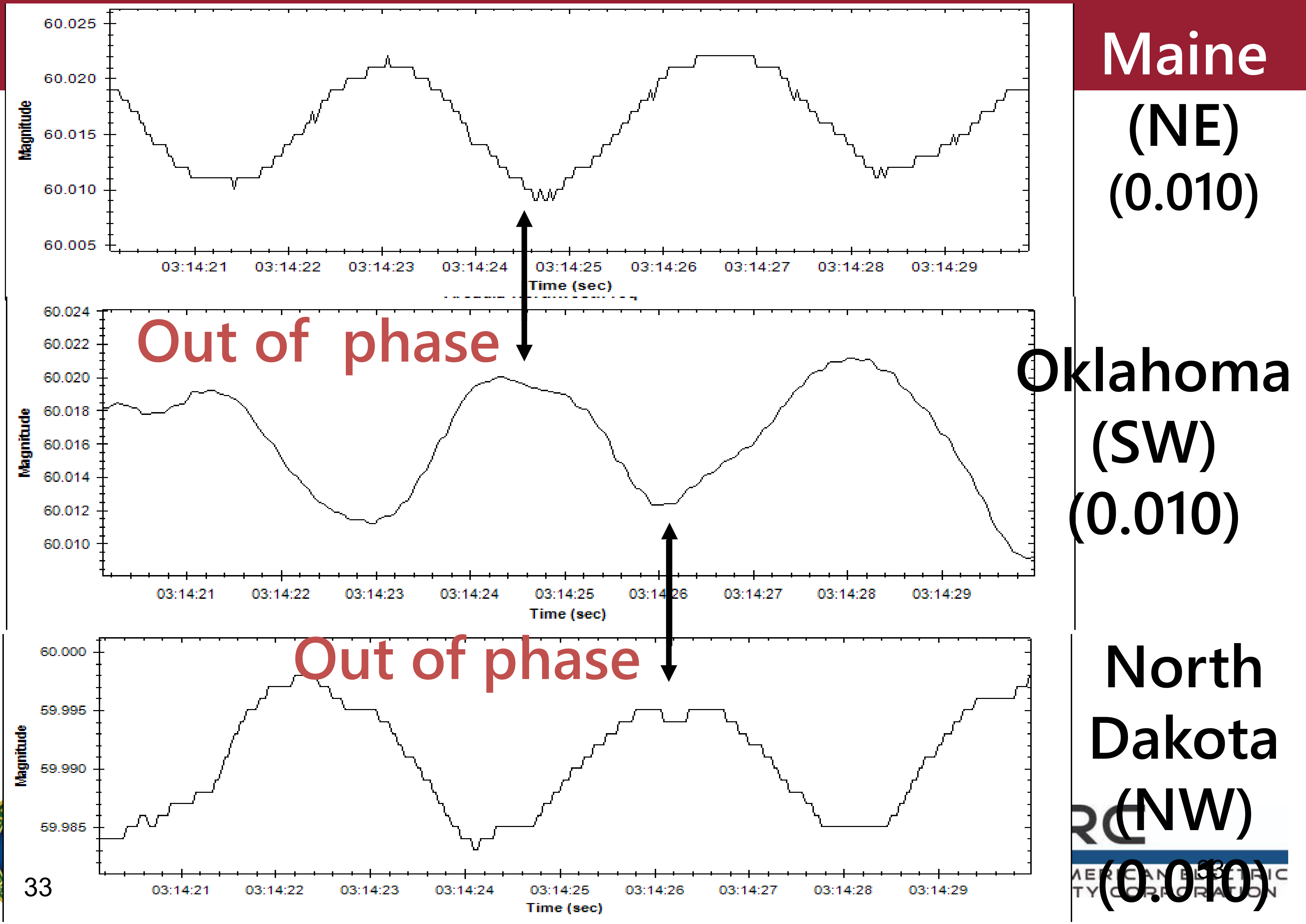
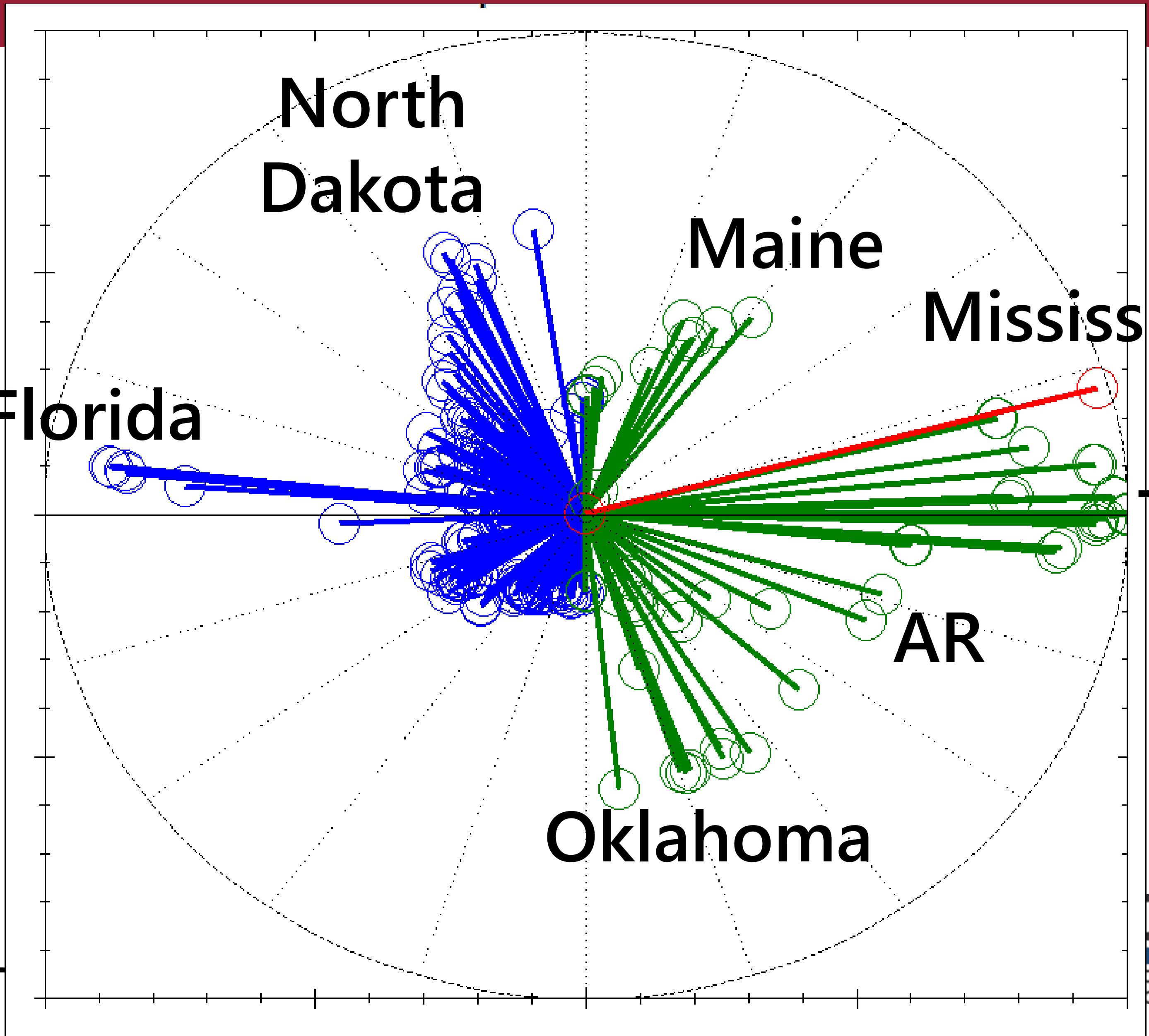
June 17, 2016 Oscillations



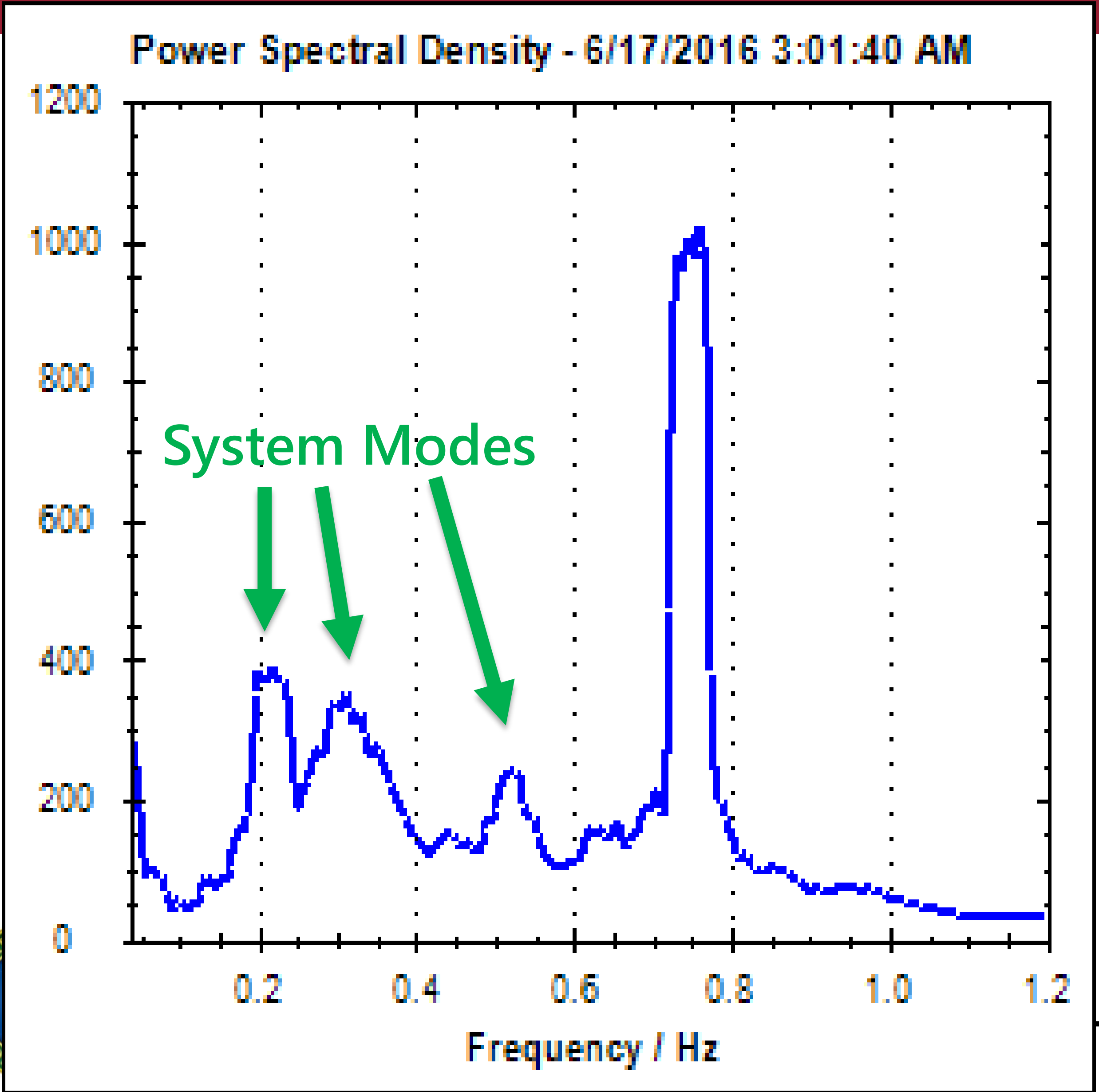
June 17, 2016 Oscillations



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

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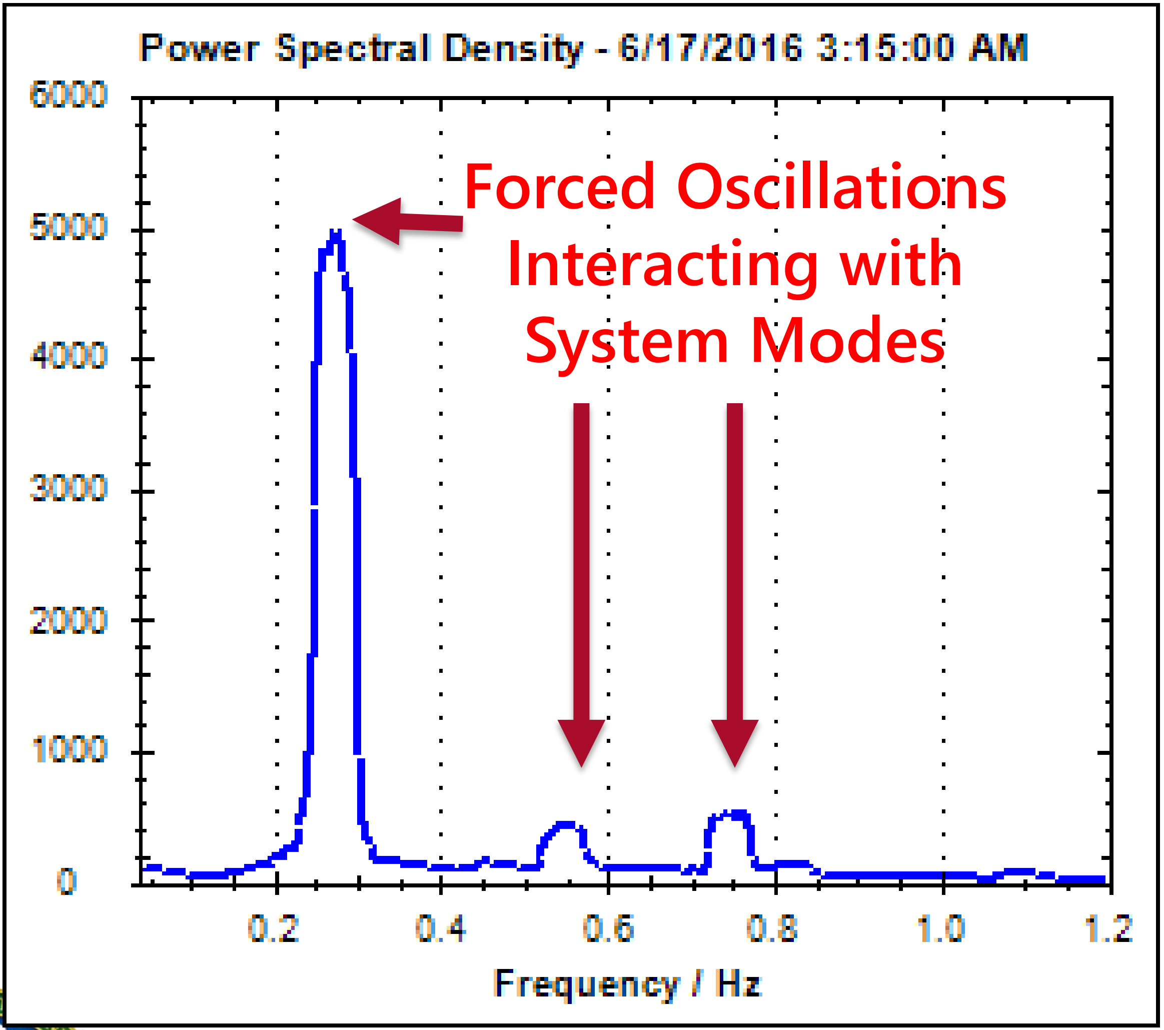
Power Spectrum @ 3:15 AM (During)



Main modes

0.28 Hz

0.56 Hz

0.75 Hz

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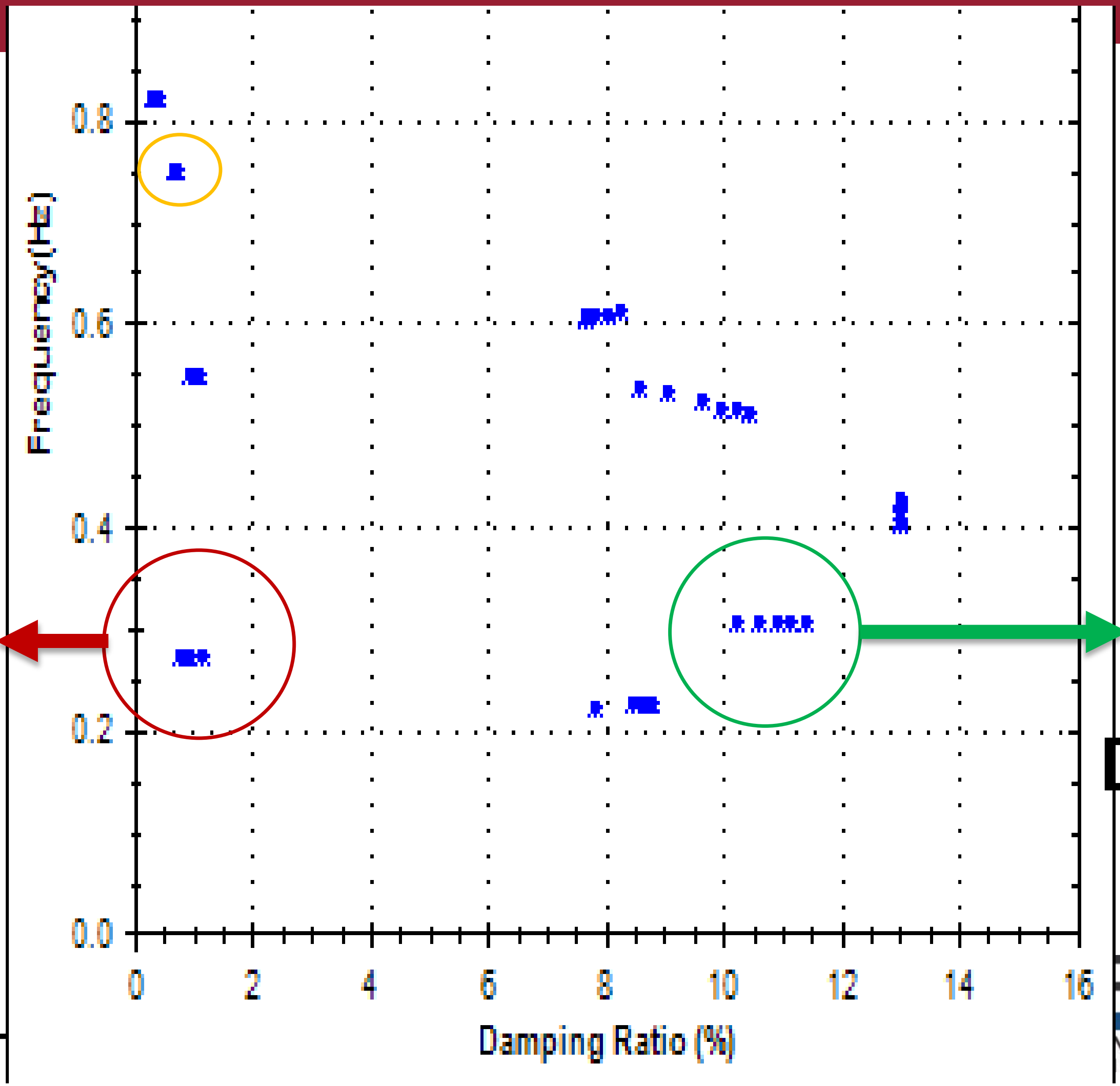
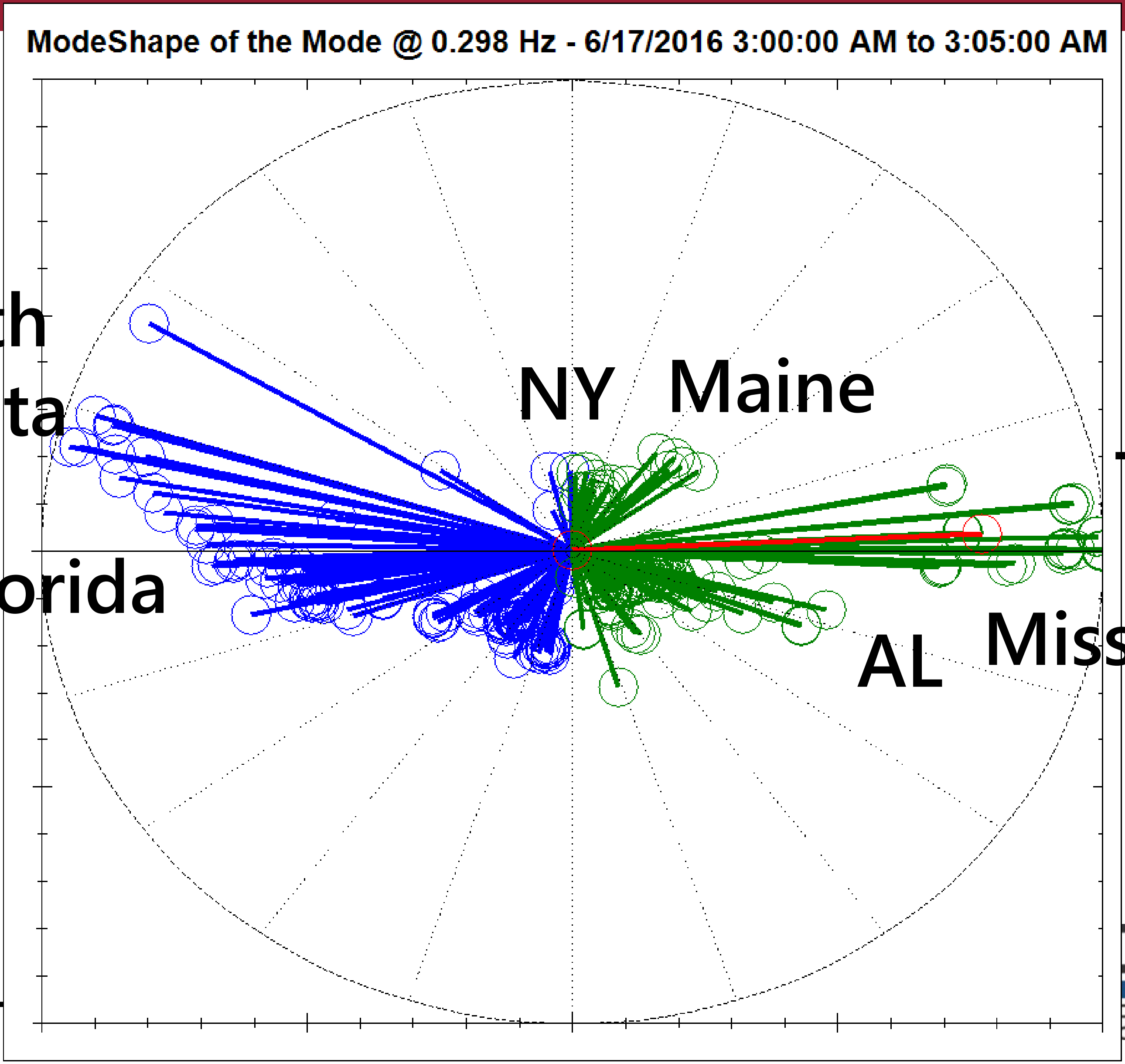
FSSI Estimates During Event (3:13 to 3:17)



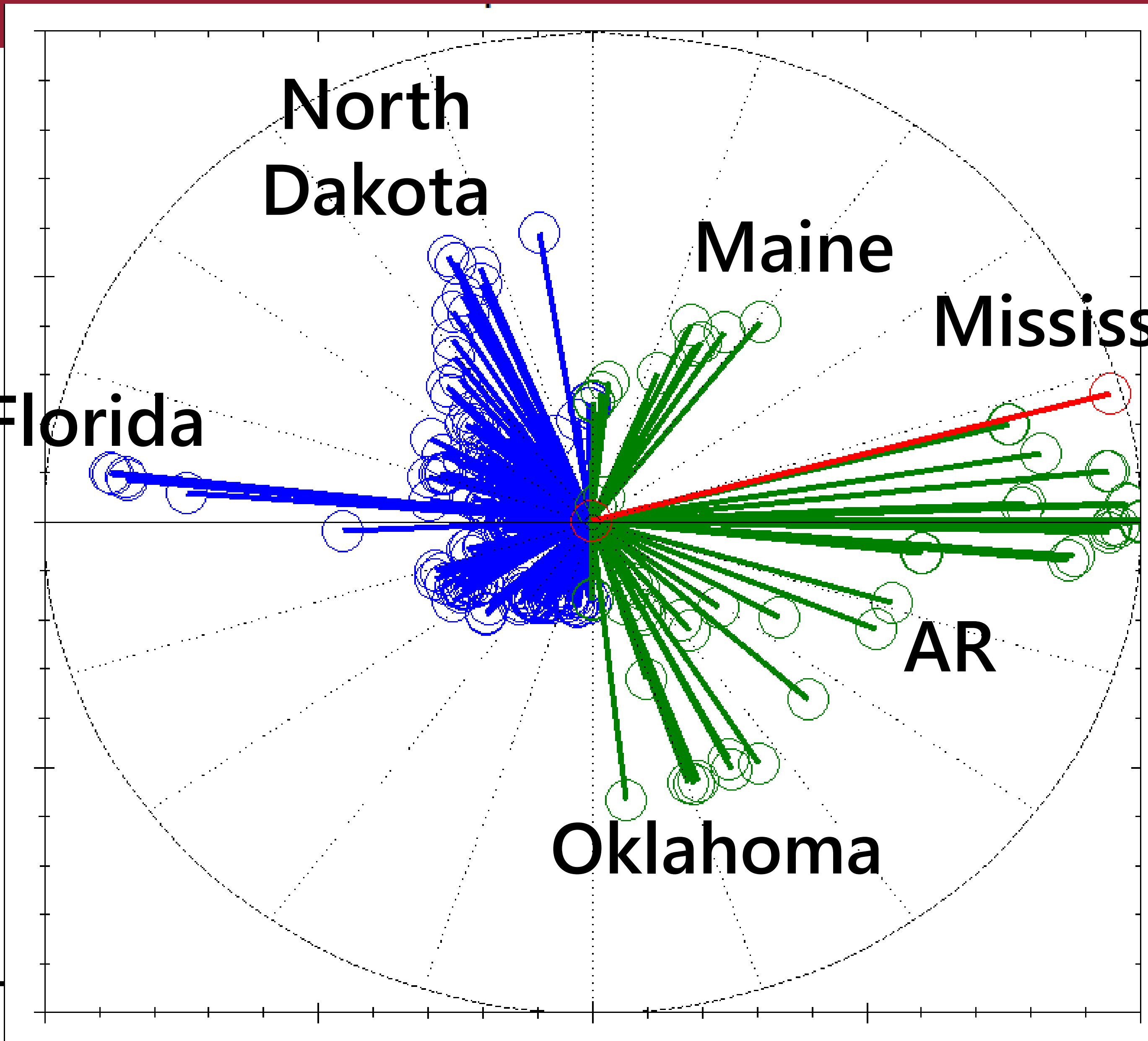
0.28 Hz Osc

0.3 Hz System Mode (10% Damping Ratio)

0.3 Hz North-South Mode from FFDD



0.28 Hz Oscillation Mode Shape



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

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

S. A. Nezam Sarmadi, V. Venkatasubramanian and A. Salazar, "Analysis of November 29, 2005 Western American Oscillation Event," in *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 5210-5211, Nov. 2016.

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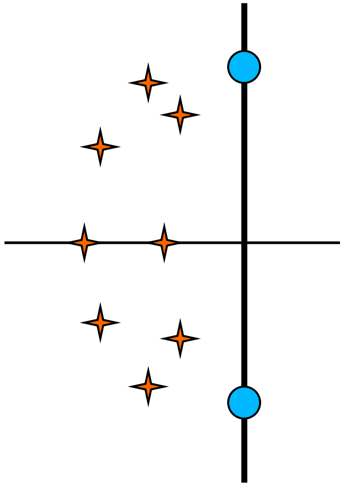
Modal Amplification Factors

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



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

Resonance Conditions

(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.

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

Research Questions

- How to distinguish between forced responses and natural responses?
- Source of forced oscillations?
- Subsynchronous oscillations (SSO) from power electronic controls? Resonance?
- Mitigatory operator/control actions for low damping conditions and forced oscillations?
- Impact of renewables on inter-area modes?
- Synchronized point-on-wave measurements