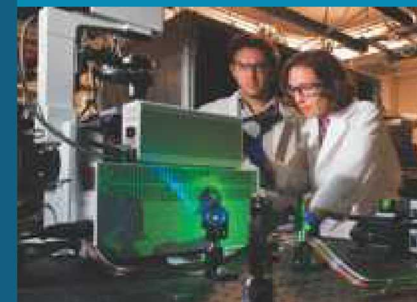
SAND2018-13611C

Small Signal Stability – Opportunities for Energy Storage



PRESENTED BY

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Outline

Acknowledgements

What is Small Signal Stability?

Small Signal Stability – Why are we concerned?

BPA Damping Controller Project

Opportunities for Energy Storage

Conclusions

Acknowledgements

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- Ryan Elliott
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- Bryan Pierre
- Ricky Concepcion
- Dr. Dan Trudnowski, Montana Tech University

Small Signal Stability

- Small signal stability – response to small disturbances (e.g. linear model is applicable)
- Given a nonlinear system model

$$\dot{x} = f(x, u) \qquad y = g(x, u)$$

- Assume a small perturbation about an operating point

$$x = x_0 + \Delta x$$

$$u = u_0 + \Delta u$$

- Use a Taylor series expansion of the nonlinear function

$$\Delta \dot{x} = A\Delta x + B\Delta u$$

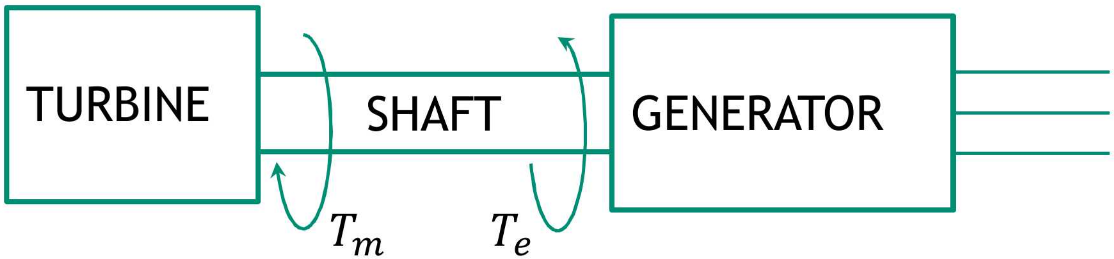
$$\Delta y = C\Delta x + D\Delta u$$

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \dots & \frac{\partial f_1}{\partial x_n} \\ \dots & \dots & \dots \\ \frac{\partial f_n}{\partial x_1} & \dots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \qquad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \dots & \frac{\partial f_1}{\partial u_r} \\ \dots & \dots & \dots \\ \frac{\partial f_n}{\partial u_1} & \dots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \dots & \frac{\partial g_1}{\partial x_n} \\ \dots & \dots & \dots \\ \frac{\partial g_m}{\partial x_1} & \dots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} \qquad D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \dots & \frac{\partial g_1}{\partial u_r} \\ \dots & \dots & \dots \\ \frac{\partial g_n}{\partial u_1} & \dots & \frac{\partial g_n}{\partial u_r} \end{bmatrix}$$

Electromechanical Stability

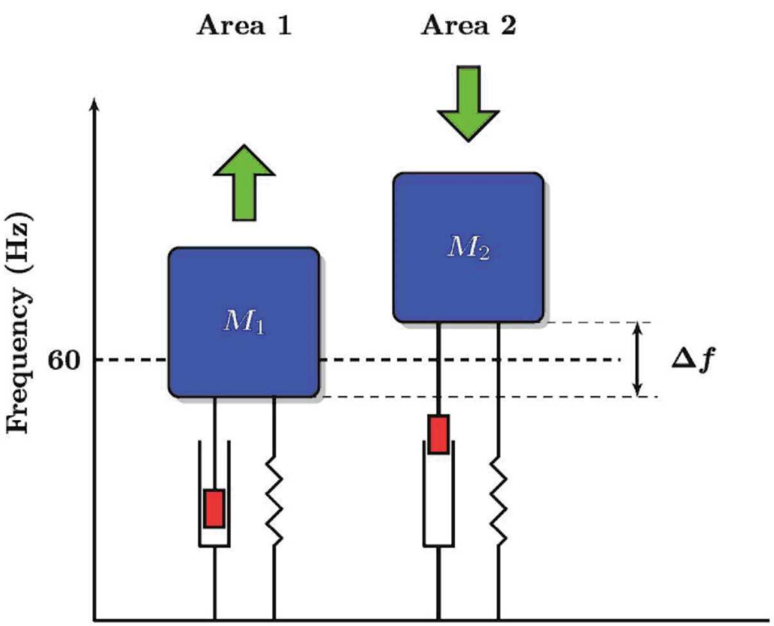
For a motor-generator, the equations of motion are

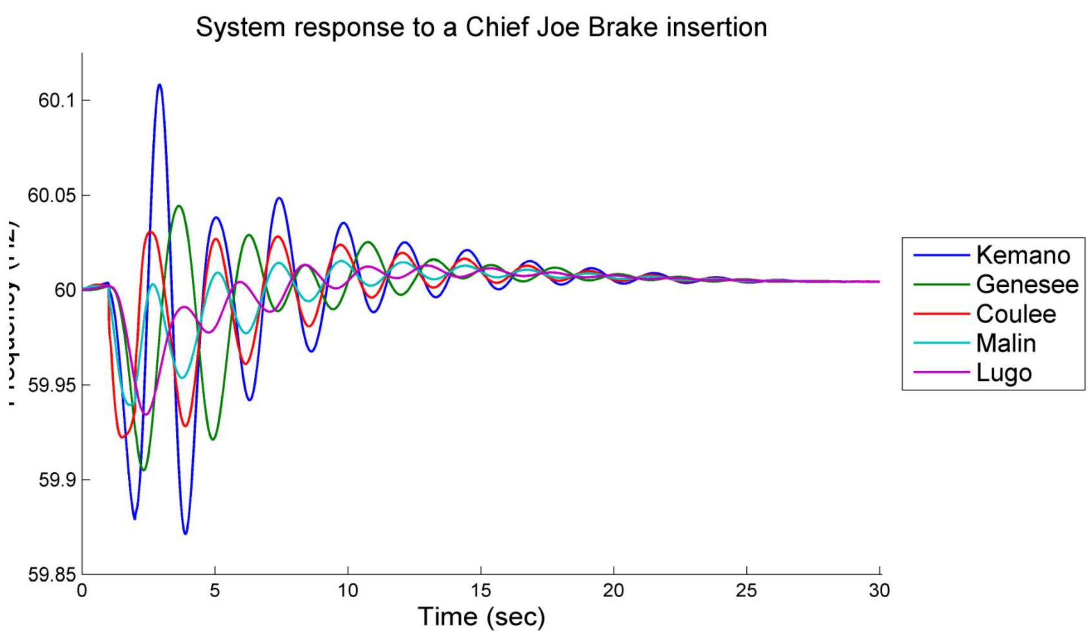


$$J\frac{d\omega}{dt} = T_m - T_e - K_D\omega$$

For constant T_m (mechanical power),

load ↑, frequency ↓ load ↓, frequency ↑





What is Damping?

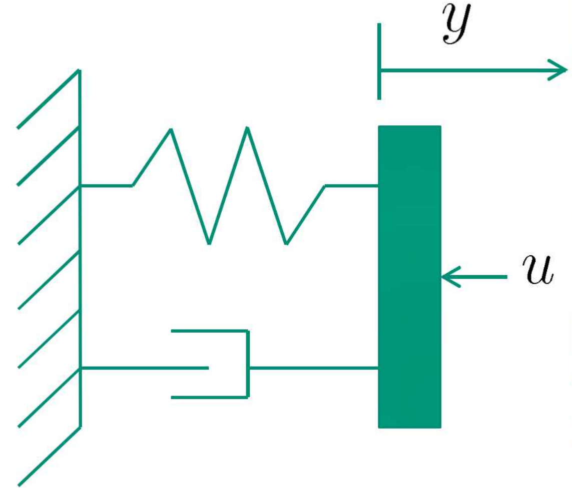
Consider a 2nd order system

$$\ddot{y} + 2\zeta\omega_0\dot{y} + \omega_0^2 = \omega_0^2 u$$

Taking the Laplace transform and rearranging yields

$$\frac{y(s)}{u(s)} = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2}$$

characteristic polynomial: $s^2 + 2\zeta\omega_0 s + \omega_0^2$



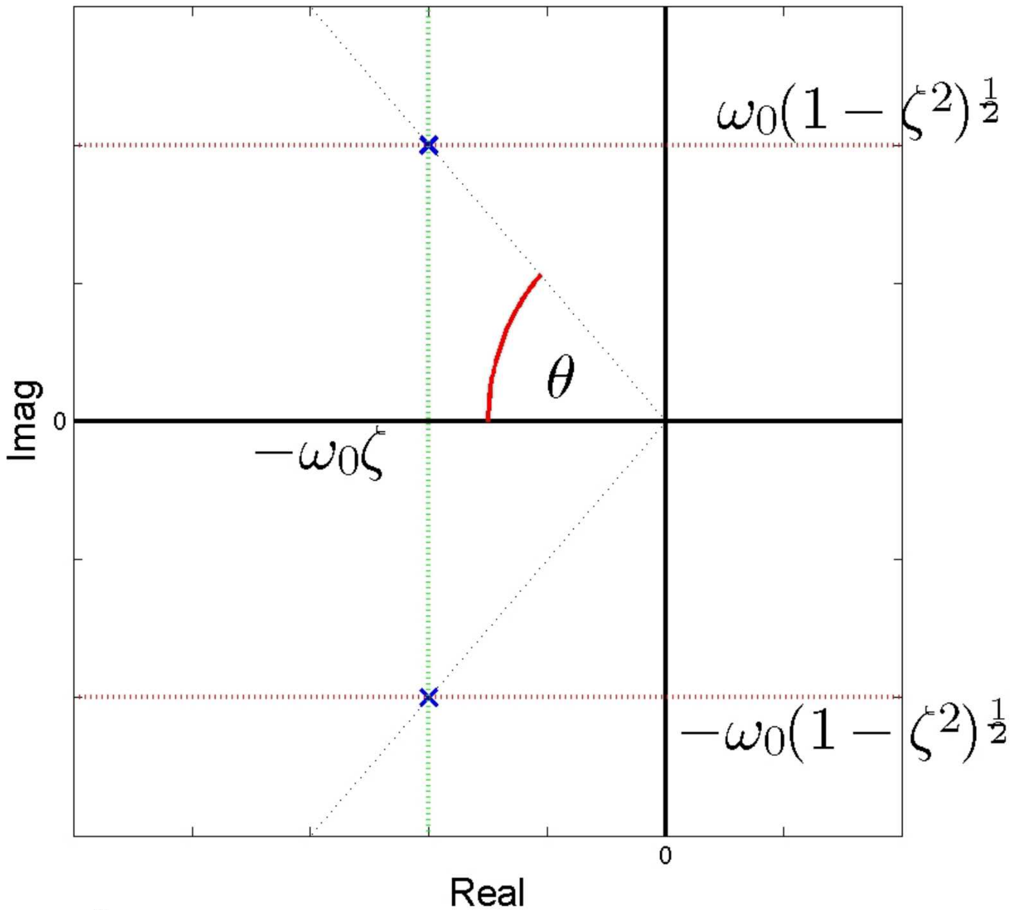
ζ damping ratio

ω_0 natural frequency (rad/s)

What is Damping?

$$CASE: \quad \zeta < 1$$

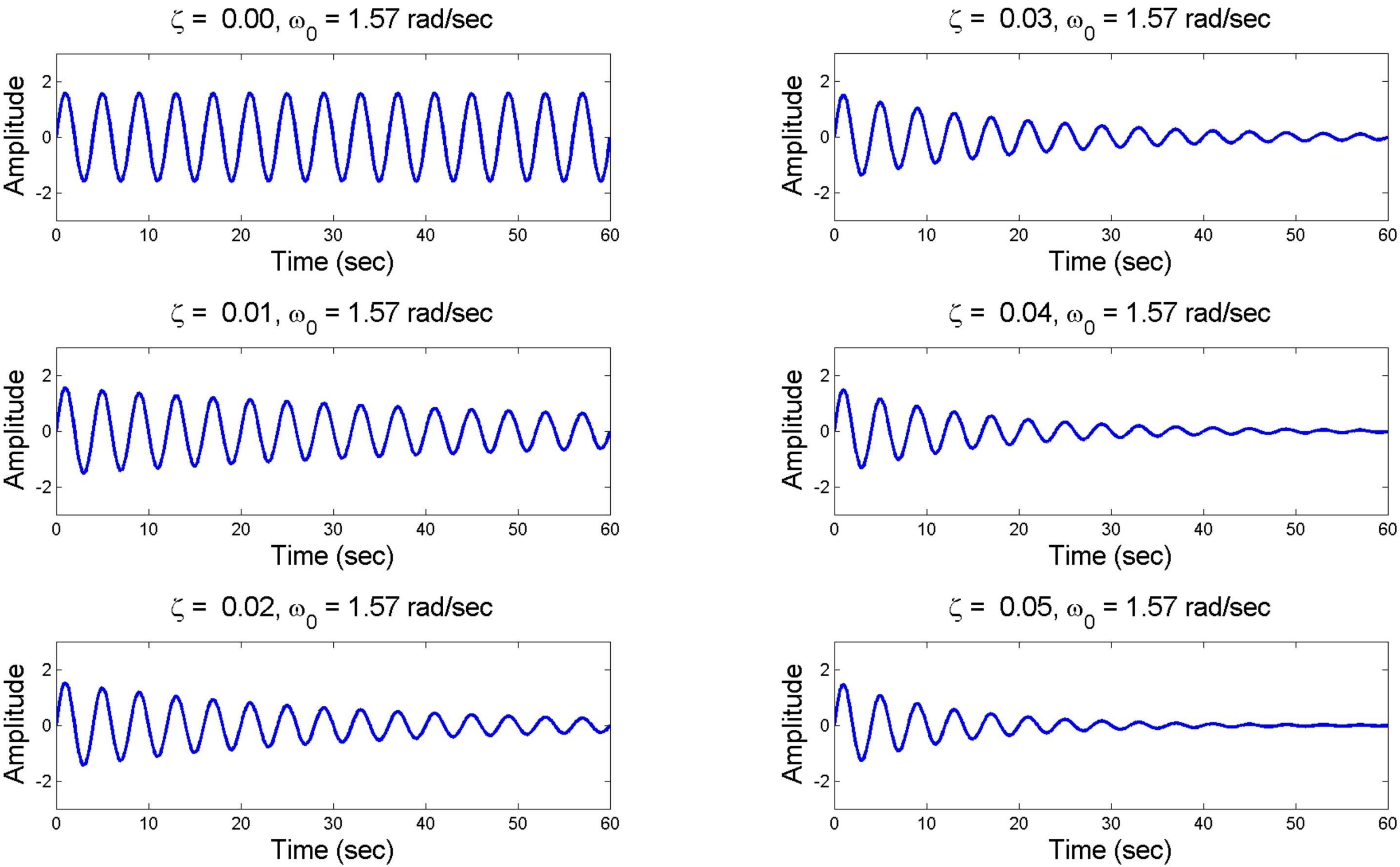
Under-damping: two complex conjugate eigenvalues



$$\text{damping ratio} = \zeta = \cos\theta$$

$$x(t) = e^{-\zeta\omega_0 t}\left(A\cos(w_d t) + B\sin(w_d t)\right), \quad w_d = \omega_0\sqrt{1-\zeta^2}$$

What is Damping?



What is Damping?

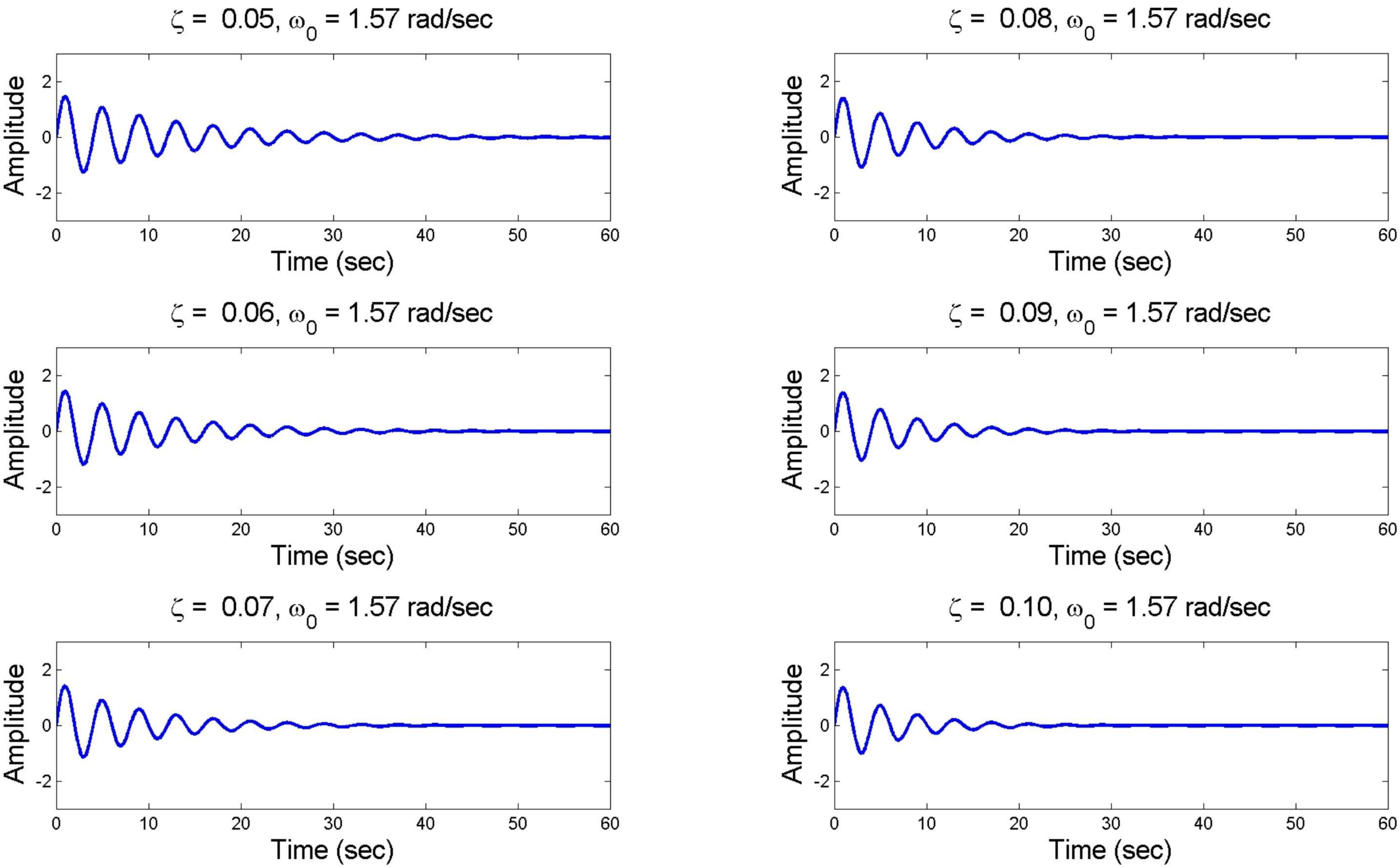
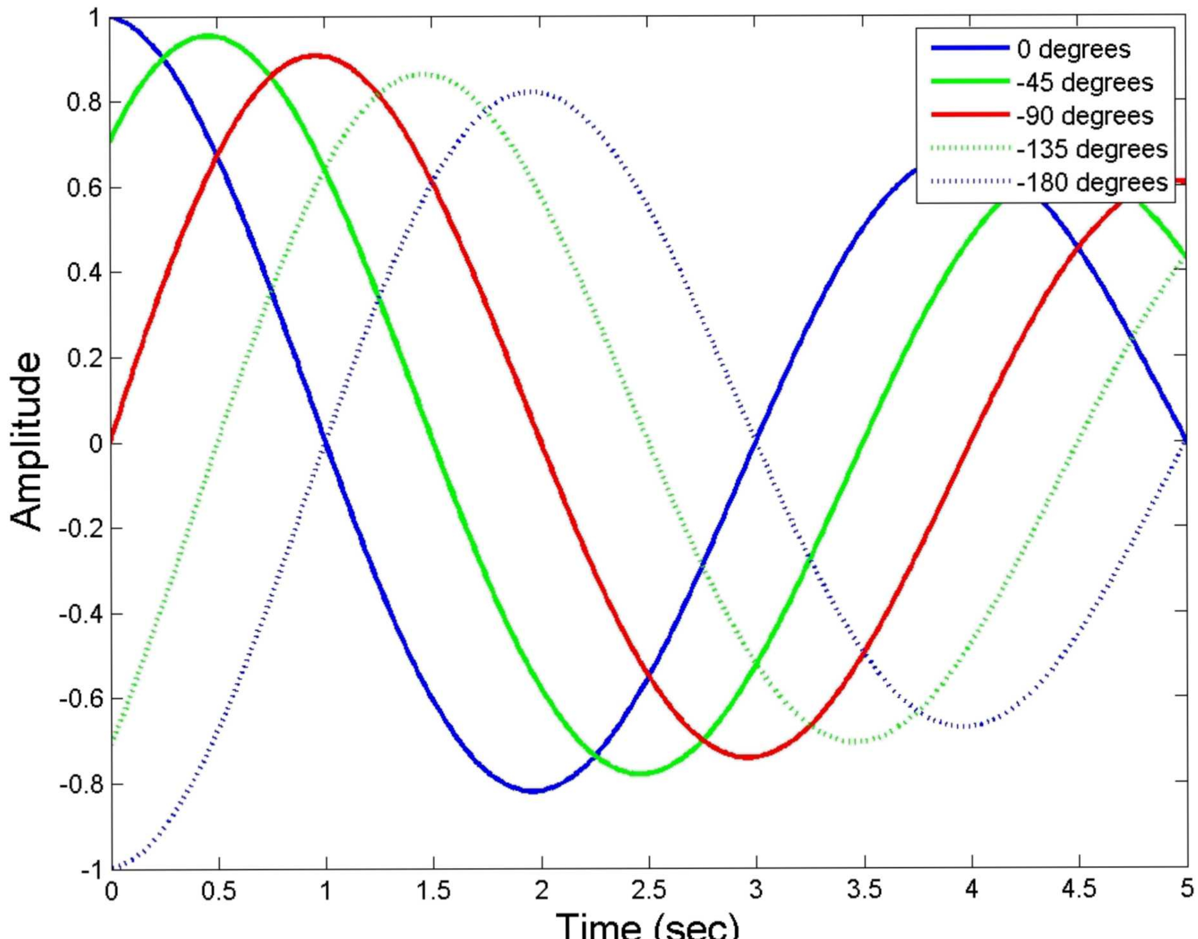


Illustration of Phase Relationship

Relationship between time and phase

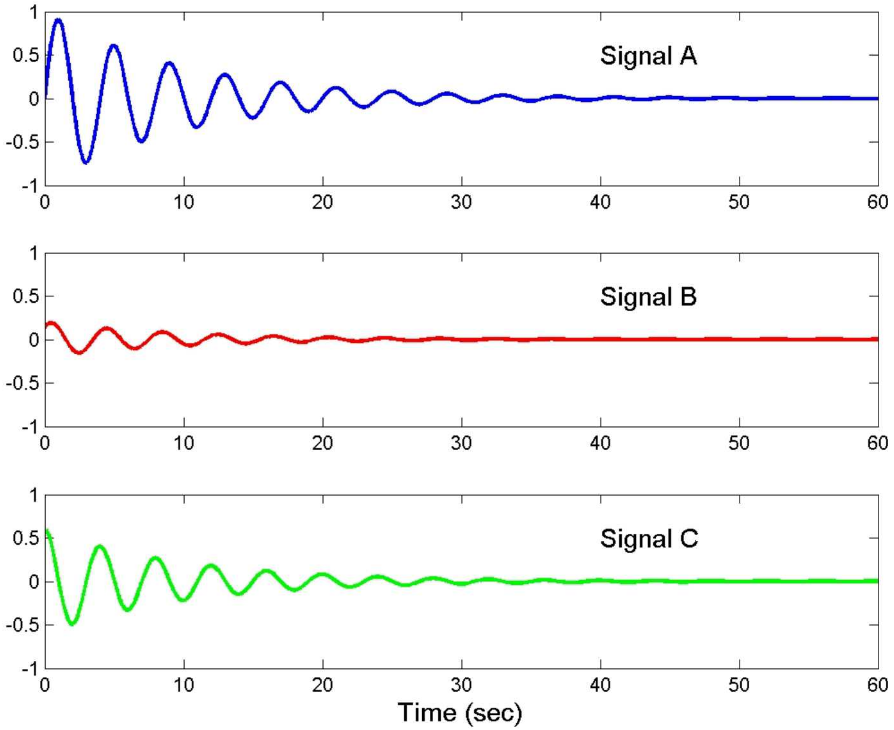
$$y(t) = e^{-0.1t}\cos(2\pi f t + \phi), \quad f = 0.25\ Hz$$

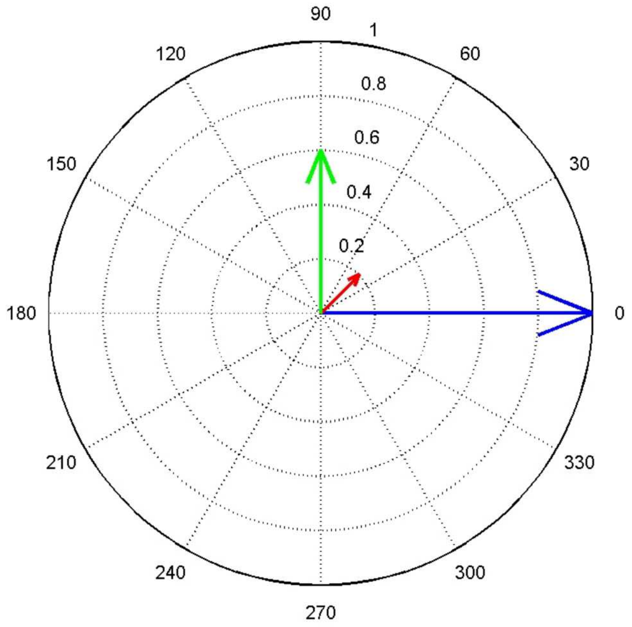


What is Mode Shape?

Mode shape is defined by
- Amplitude at each location
- Phase at each location

Typically look at
- Generator speed (frequency)
- Frequency measurements





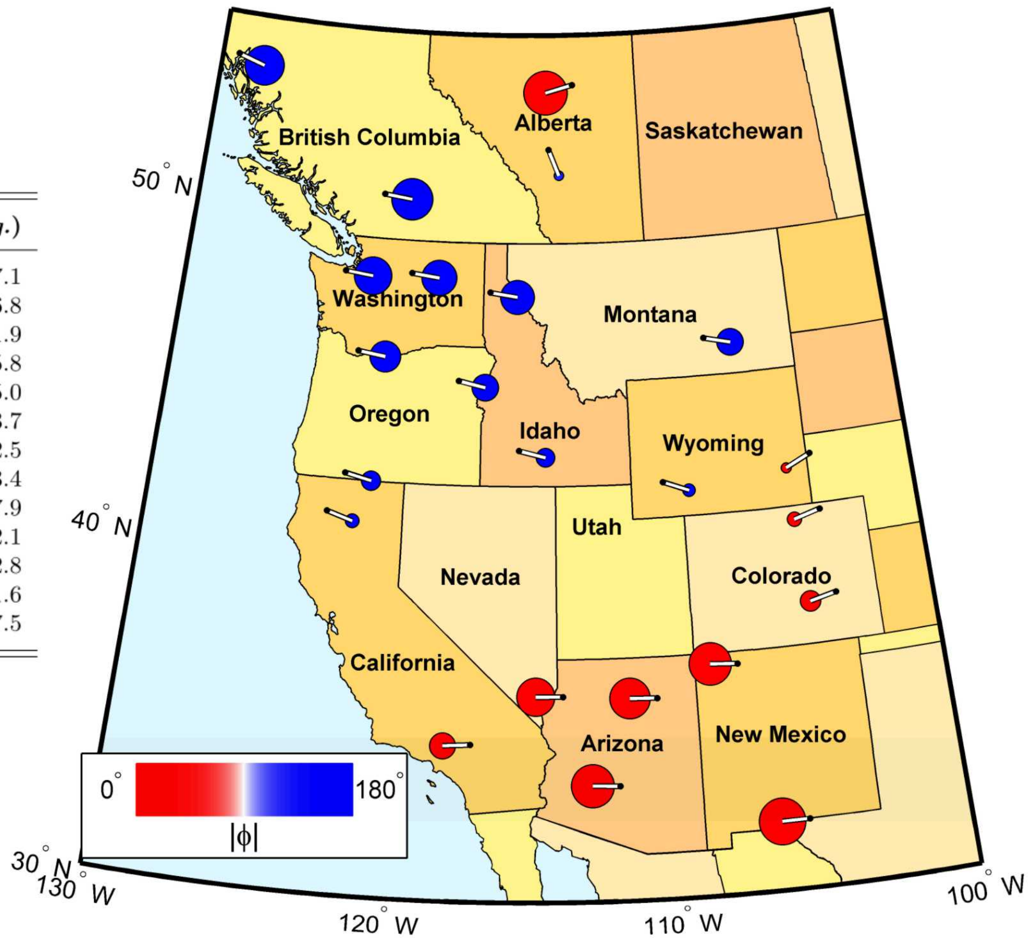
$$y_A(t) = 1.0\cos(2\pi f + 0)$$
$$y_B(t) = 0.2\cos(2\pi f + \pi/4)$$
$$y_C(t) = 0.6\cos(2\pi f + \pi/2)$$

Visualizing Mode Shape

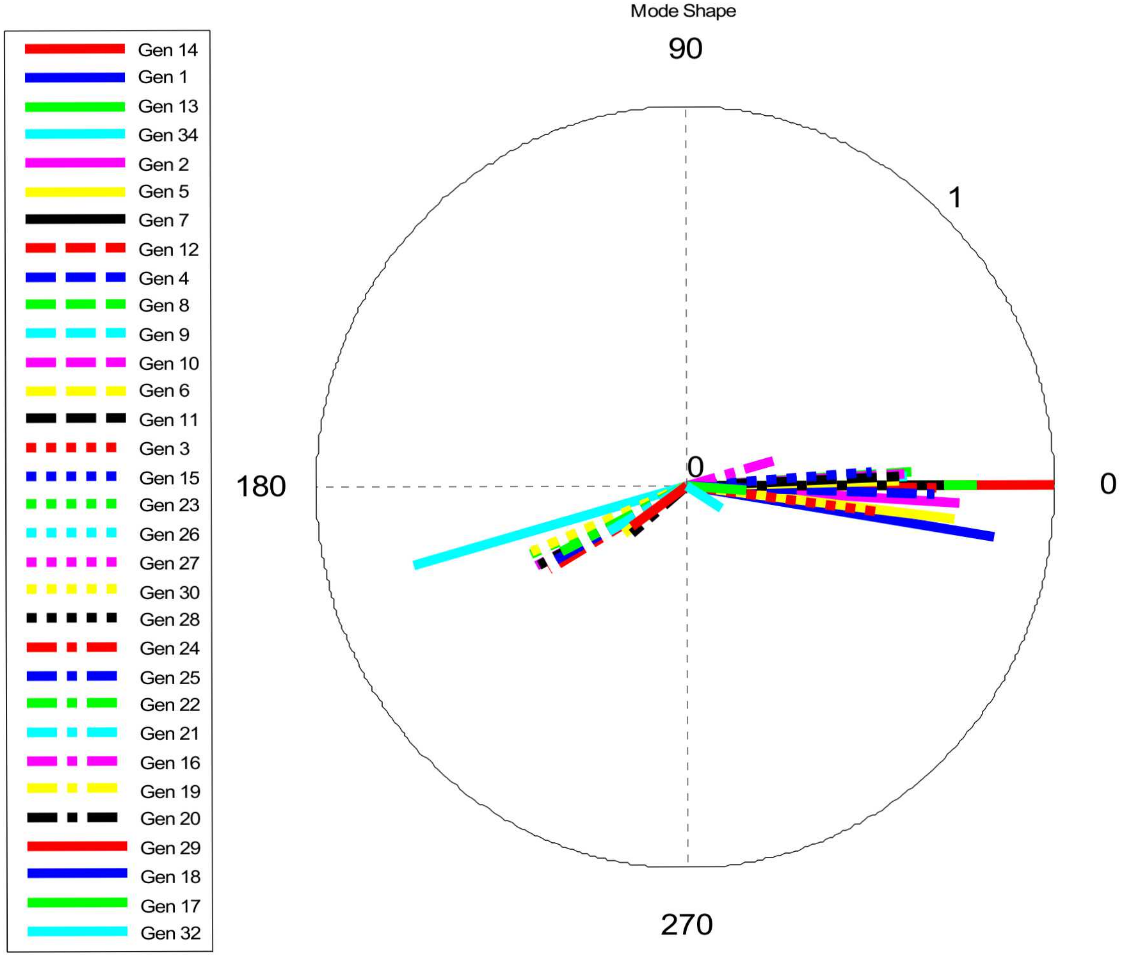
Mode shape defined by
- Amplitude
- Phase

Visualization approaches:
- Tables
- Graphically

Bus	Amp.	Shape(*Deg.*)	Bus	Amp.	Shape(*Deg.*)
Newman	1.00	0.0	Nicola	0.87	177.1
Hassayampa	0.93	0.4	Monroe	0.83	176.8
Genesee	0.91	11.6	Kemano	0.81	171.9
Four Corners	0.91	−2.0	Coulee	0.79	175.8
Moenkopi	0.86	1.3	Taft	0.75	175.0
Mead	0.80	3.2	Big Eddy	0.71	173.7
Vincent	0.52	9.5	Brownlee	0.61	172.5
Comanche	0.50	−8.5	Colstrip	0.57	173.4
Ault	0.34	−9.1	Malin	0.48	167.9
Laramie	0.21	−6.8	Midpoint	0.43	172.1
Valmy	0.05	56.3	Round Mt.	0.38	162.8
			Bridger	0.29	171.6
			Langdon	0.21	127.5



Visualizing Mode Shape – Compass Plot



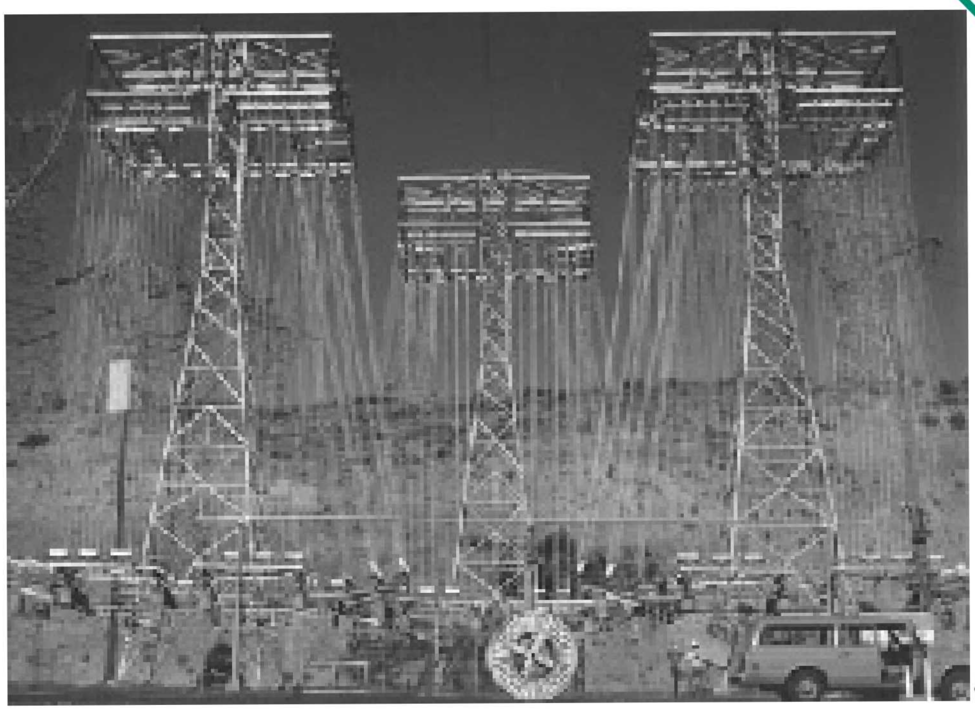
Classical approach presented in Graham Rogers' book, "Power System Oscillations"

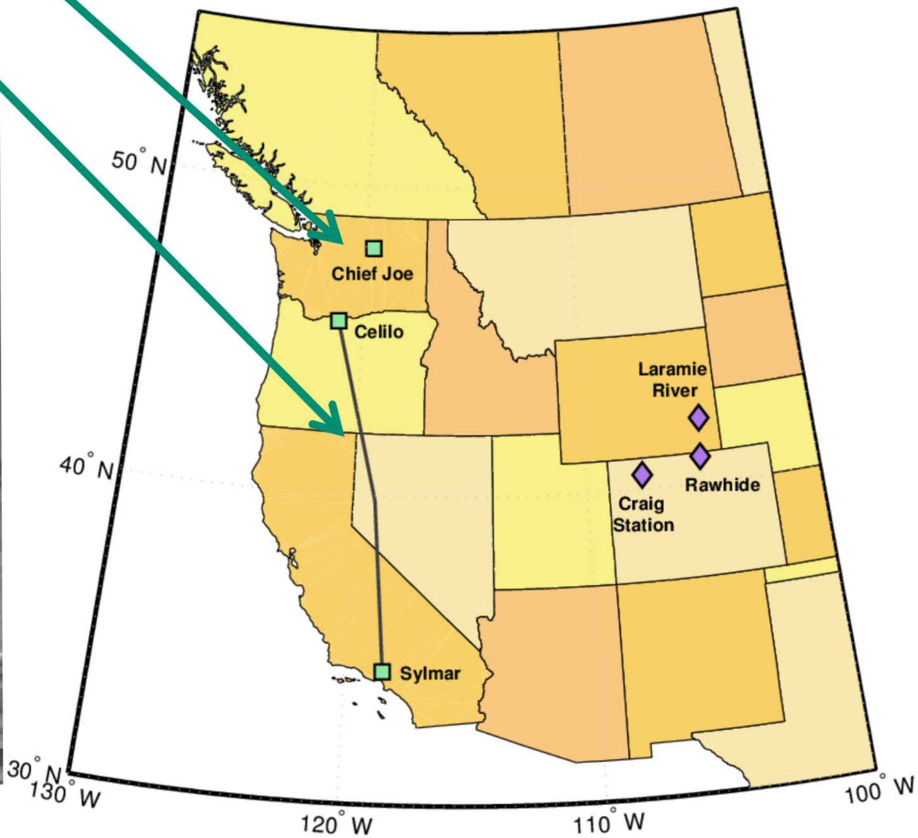
Excitation Methods for System Identification

Natural disturbances

Chief Joseph Brake (1.4GW, built in 1974)

Pacific DC Intertie (PDCI) Modulation





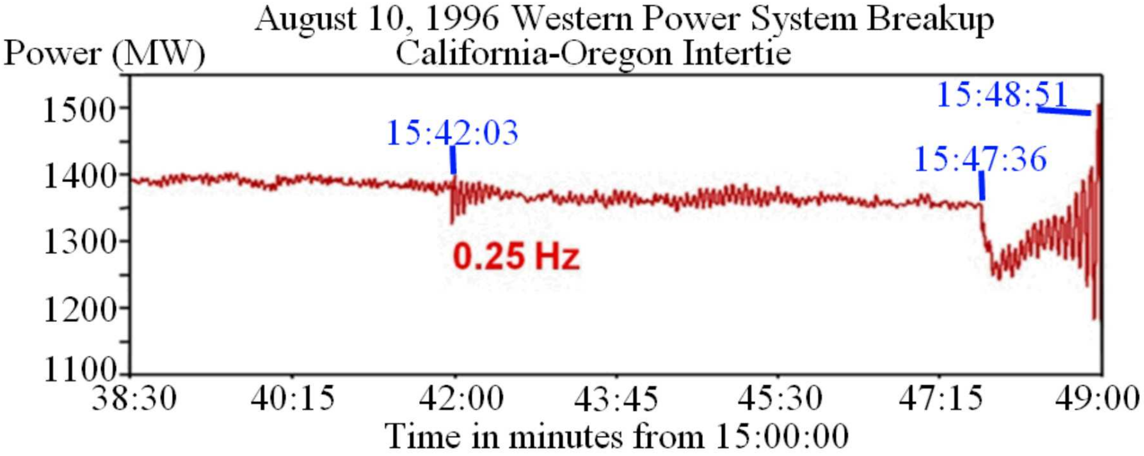
Why are we concerned?

Power systems are susceptible to low frequency oscillations caused by generators separated by long transmission lines that oscillate against each other

These oscillations are not as well damped as higher frequency "local" oscillations

High penetration of renewable generation can impact mode shape and damping – potential reduction in reliability

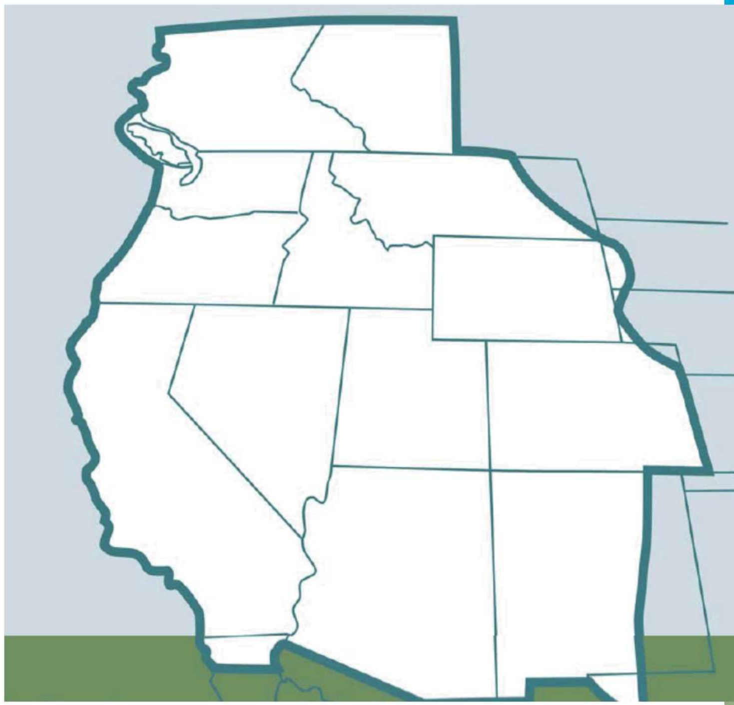
1996 breakup caused by low-frequency oscillations



Why are we concerned?

There are several low frequency oscillation modes in the Western Electricity Coordinating Council (WECC) region

- "North-South" mode nominally near 0.25 Hz (North-South mode A)
- "Alberta-BC" mode nominally near 0.4 Hz (North-South mode B)
- "BC" mode nominally near 0.6 Hz
- "Montana" mode nominally near 0.8 Hz
- "East-West" mode nominally near 0.4 Hz



Analysis Methods (Simulation)

Inject disturbances and analyze ringdowns (e.g. Prony, ERA)

PDCI modulation (ERA)

Linearize system equations (Q-R factorization, up to several thousand states)

Arnoldi's method (ARPack - Sandia contributed to development)

AESOPS algorithm

Transient simulation tools (plus data analysis in MATLAB)

- GE, PSLF
- Siemens, PSSE
- Power World
- Powertech Labs

Small signal analysis tools

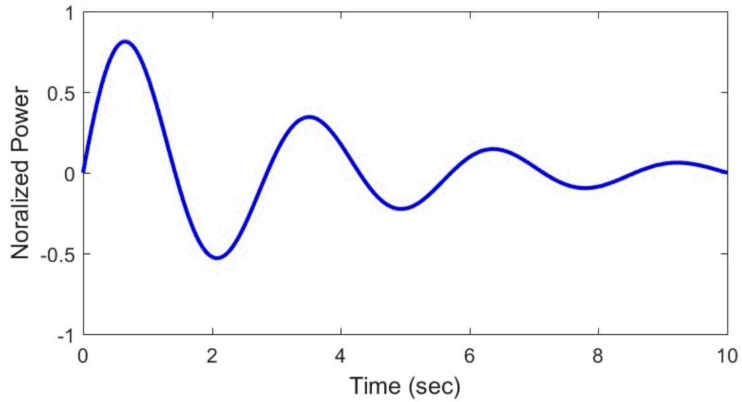
- Powertech Labs, SSAT

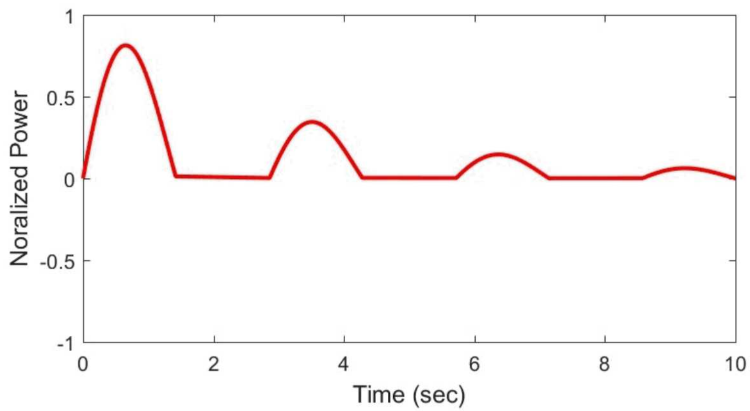
Typical System Model (WECC)

- 19,000 buses
- 4,000 generators
- 9,000 loads
- 8,000 transformers
- 16,000 transmission lines

Improving Small Signal Stability

Real power injections at the correct locations in the grid can be used to improve small signal stability





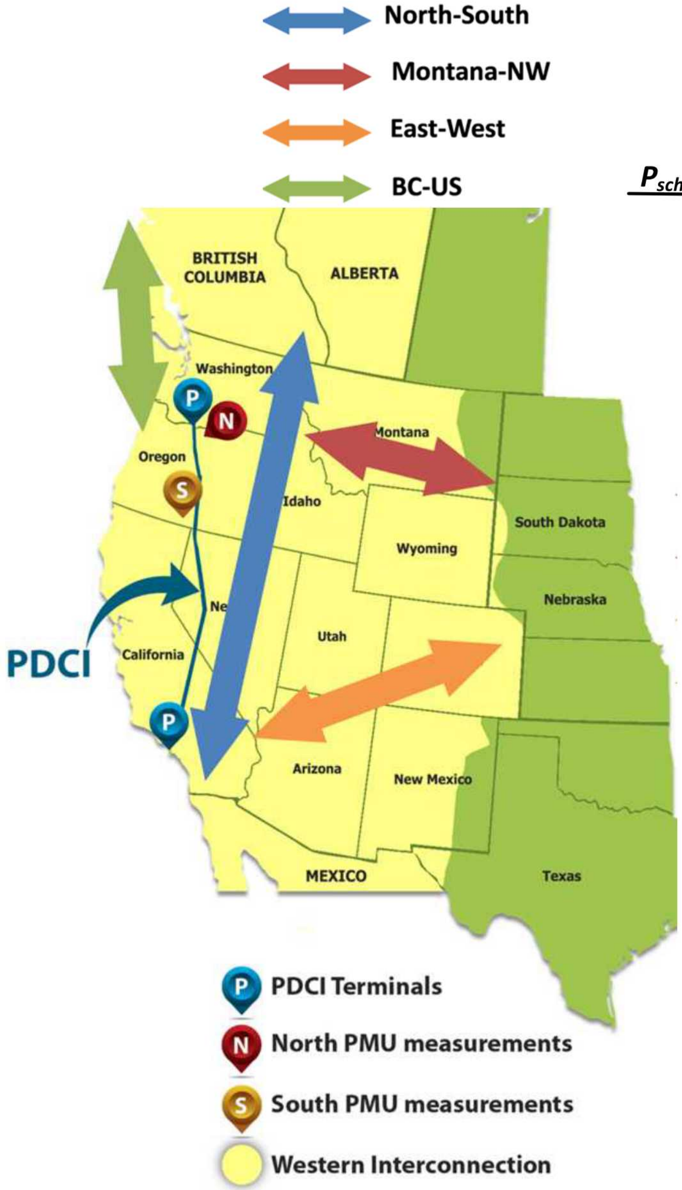
Proposed methods:

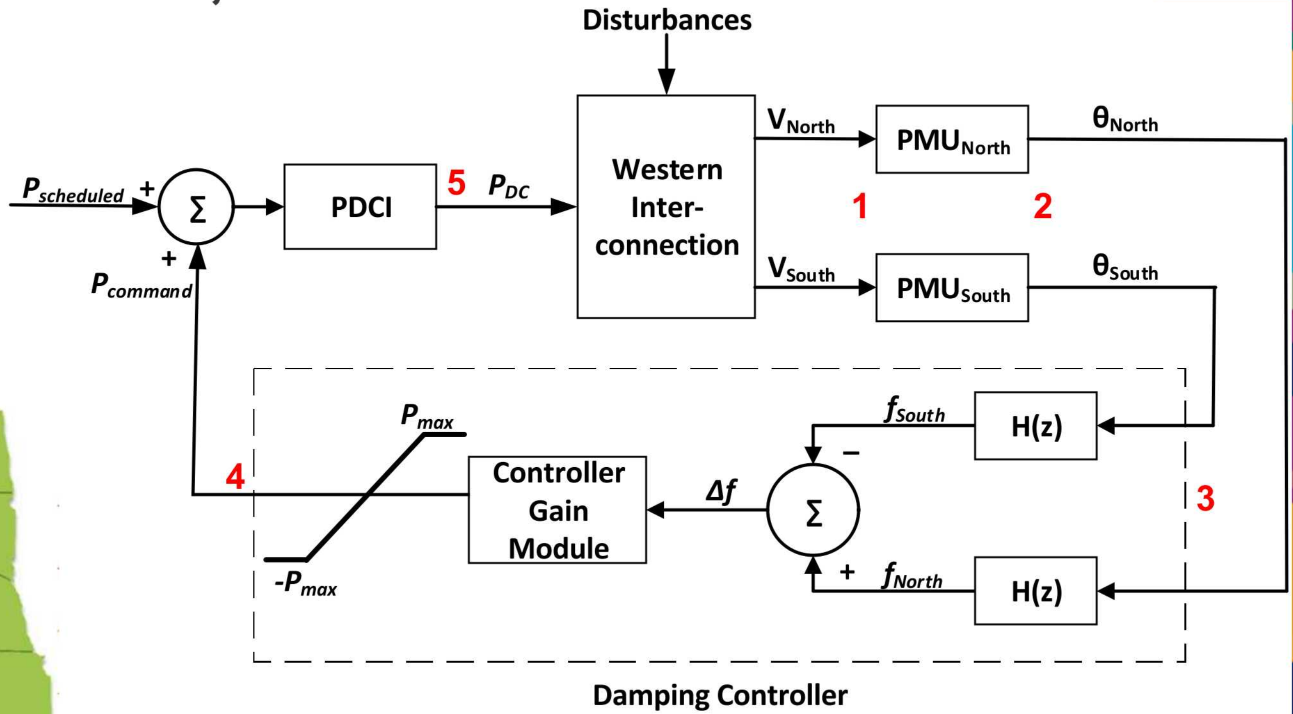
- High Voltage DC (HVDC) modulation
- Energy storage modulation
- Load modulation – demand response
- Load modulation – voltage control
- Transmission line impedance modulation
- Resistive braking
- Power system stabilizers (PSSs)

Basic requirements

- PMU signals for feedback
- "Actuators" in the correct locations
- Communications to distribute PMU data and/or control commands

BPA Damping Controller Project





1 PMUs take measurements

2 PMUs send data packets over network

3 Packets arrive at damping controller

4 Controller sends power command to PDCI

5 PDCI injects power command into grid

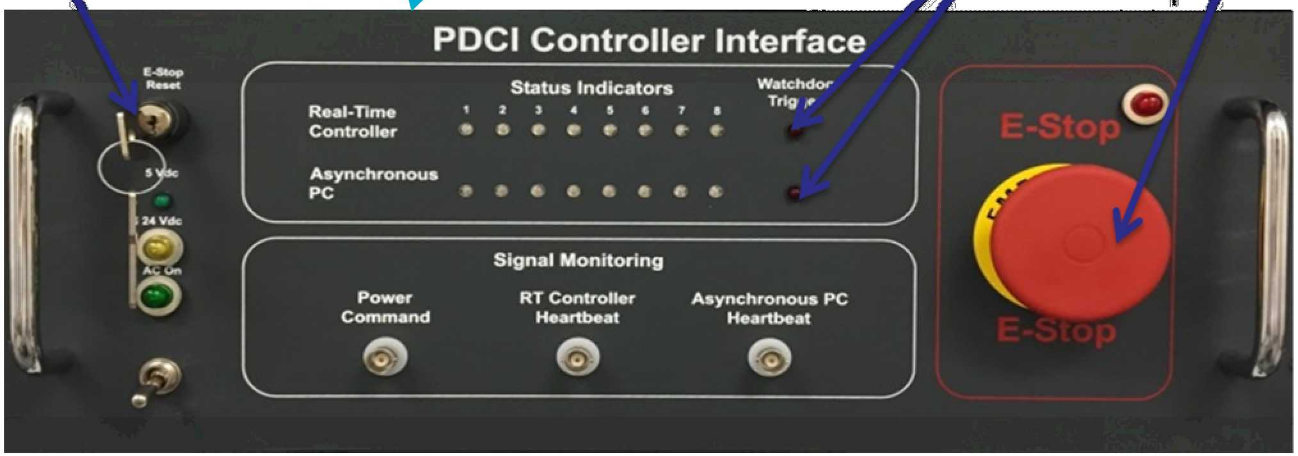
BPA Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

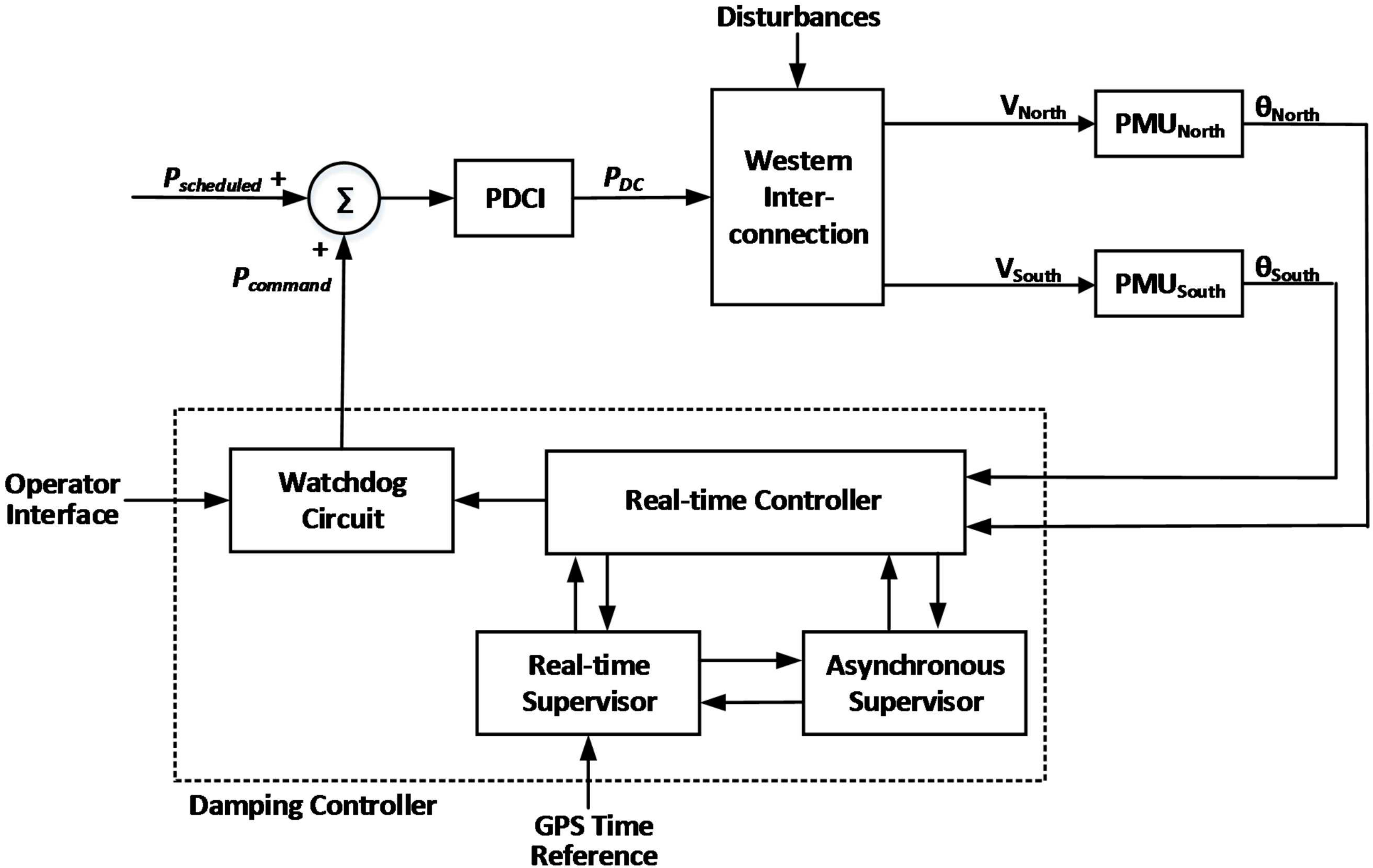
E-Stop button



Server for select supervisory functions

Real-time Control platform

Supervisory System Ensures "Do No Harm"



Watchdog Circuit: Detects hardware failures, ensures smooth state transitions, and handles E-stop functions.

Real-time Supervisor: Monitors latencies and data quality, switching to other PMU sites if needed.

Asynchronous Supervisor: Estimates gain/phase margin, PDCI health, and slower-than-real-time tasks.

Supervisory System Ensures "Do No Harm"

Redundancy and Diversity

- Utilizes 8 PMUs, 4 northern measurements, 4 southern. Allows for 16 control instances operating in parallel with the ability to seamlessly switch between them through a bumpless transfer.

Real-time supervisory

- Check latency of PMU measurements
- Assure PMU measurements are time aligned
- Check for data drop outs
- Check for data repeats
- Check PMU quality flags (flags in the PMU data)
- Check for GPS synchronization
- Check the E-Stop contacts
- Checks frequencies, voltage magnitudes, angles are with expected values
- Check PDCI power flow within limits

Watchdog Circuit

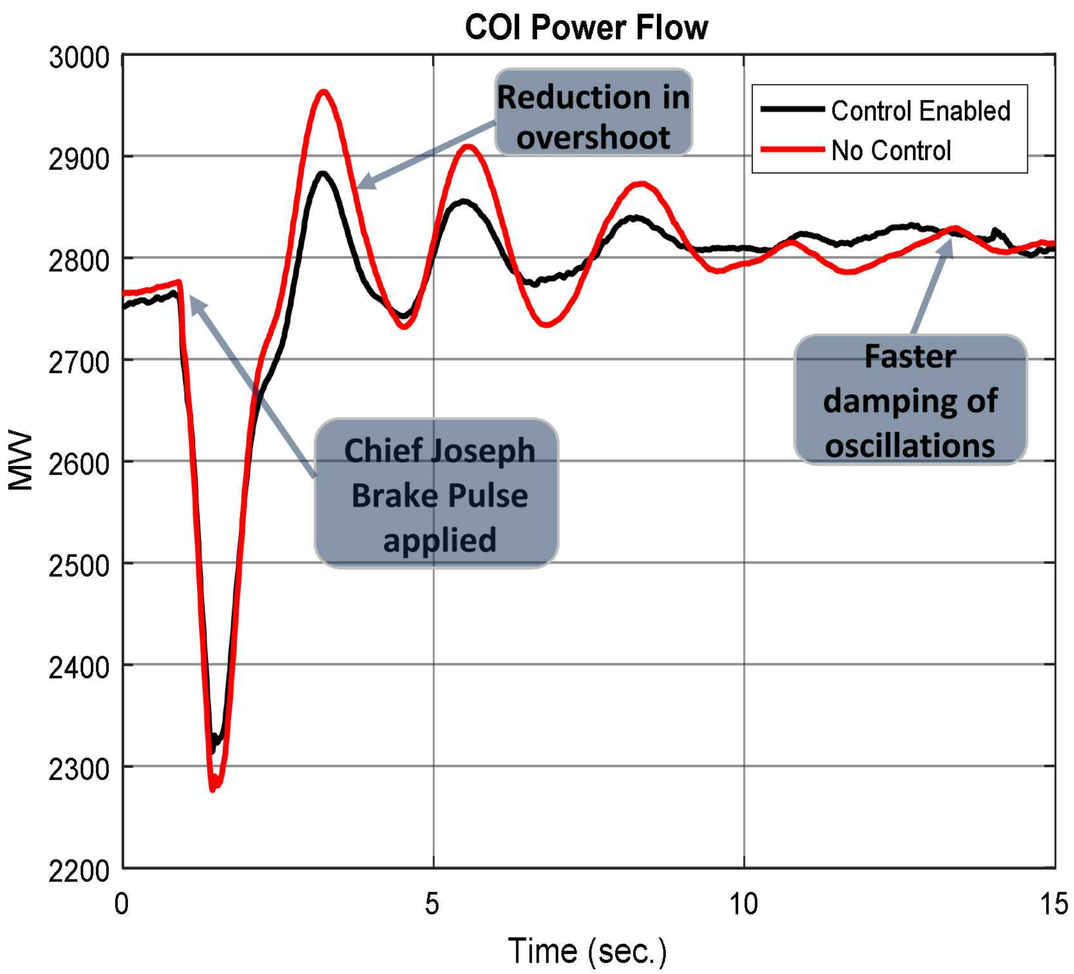
- Detects hardware failures
- Ensures smooth transitions
- Handles the E-Stop function

Asynchronous (still under development)

- Estimates gain and phase margin
- Verify the PDCI flow responded to command.
- Checks for forced oscillations.

Damping Controller Test Results - 2016

Tests conducted at Celilo Converter Station on September 28-29, 2016



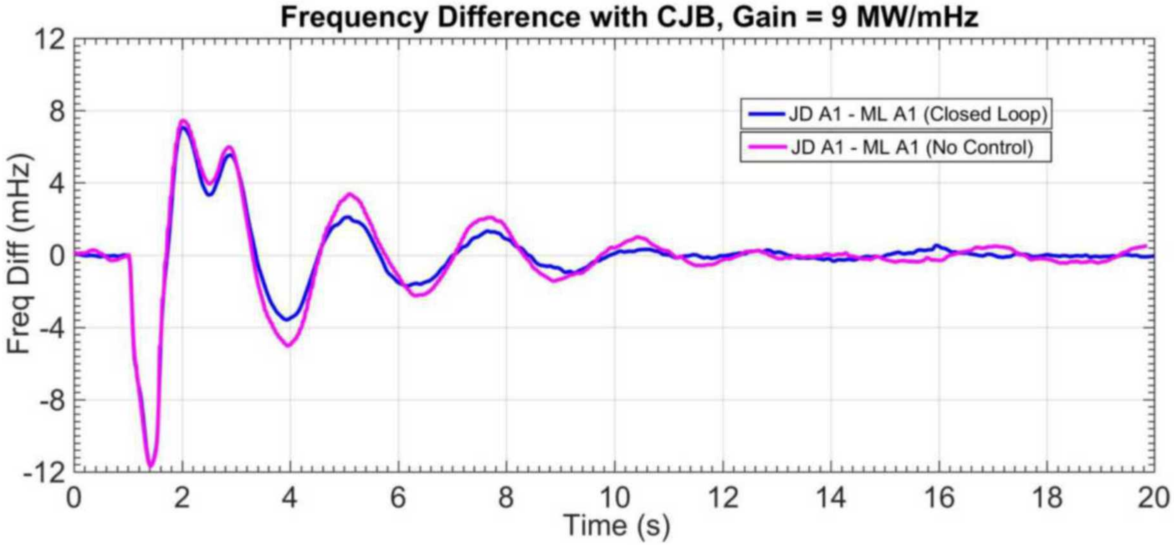
Chief Joseph brake test	Damping of North-South B Mode improved 4.5 percentage points (11.5% to 16.0%) in closed-loop vs. open-loop operation.
Square wave pulse test	Damping controller significantly reduces amplitude of North-South B mode oscillations in 15 seconds vs. 23 seconds in open-loop tests for the same reduction.
All tests	Controller consistently improves damping and does no harm to grid.

Damping Controller Test Results – May 23, 2018

Chief Joseph Brake Test

Gain = 9 MW/mHz

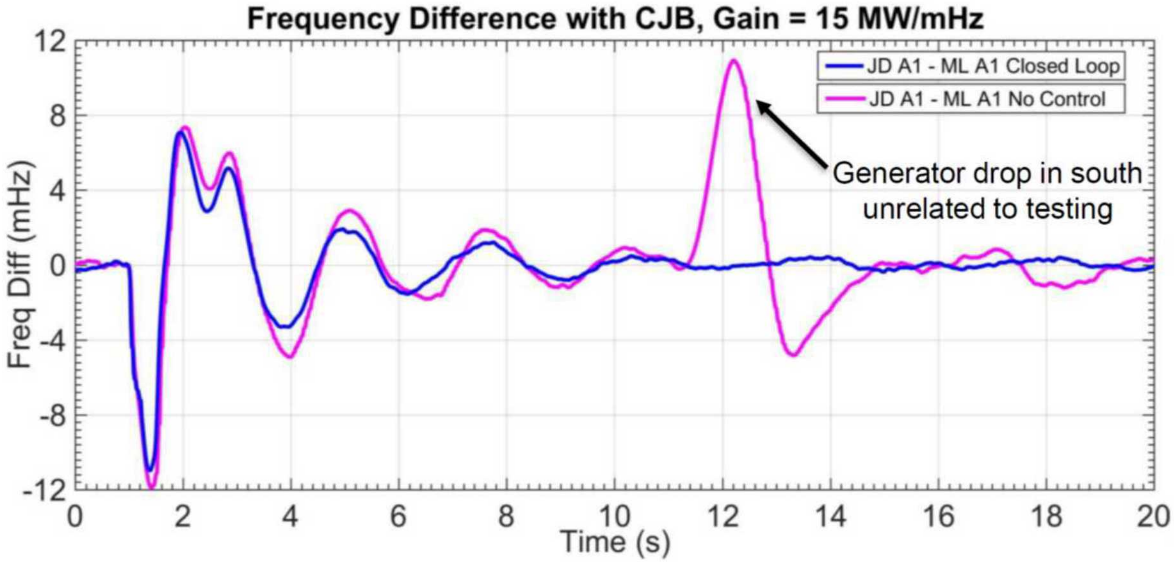
Damping improved by 4.5 percentage points (10.0% to 14.5%)



Chief Joseph Brake Test

Gain = 15 MW/mHz

Damping improved by 6 percentage points (10.0% to 16.0%)

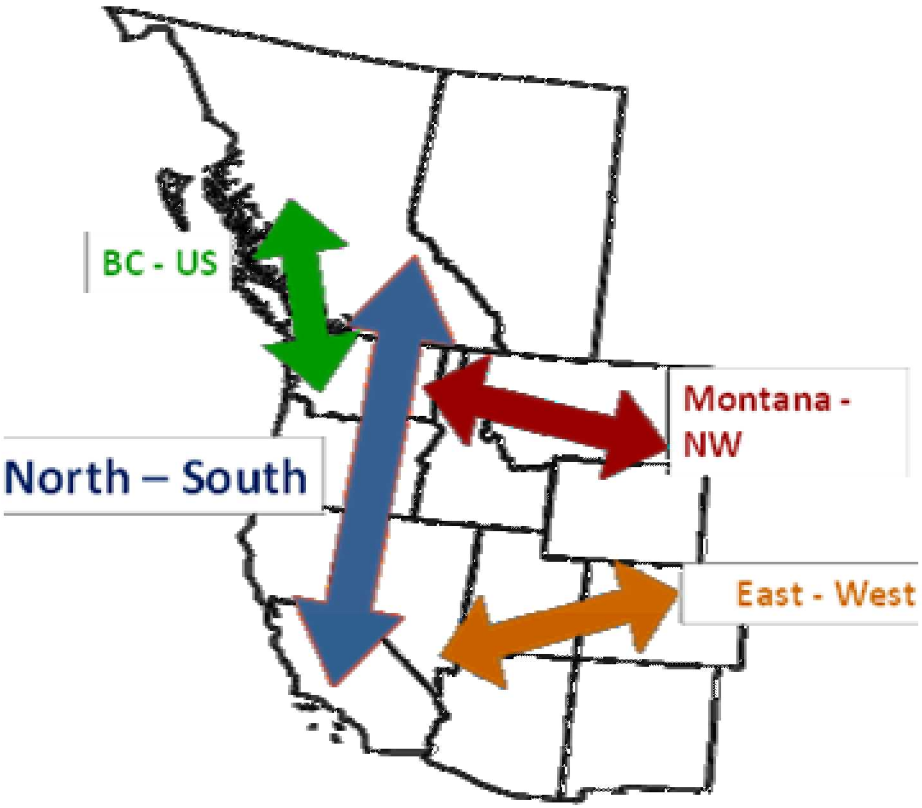


Opportunities for Energy Storage

PDCI Modulation has good controllability over N-S Mode

East-West mode becomes more visible with increased renewable penetrations

Eastern interconnection also has inter-area oscillations



Distributed Control of Energy Storage

Advantages:

Robust to single points of failure

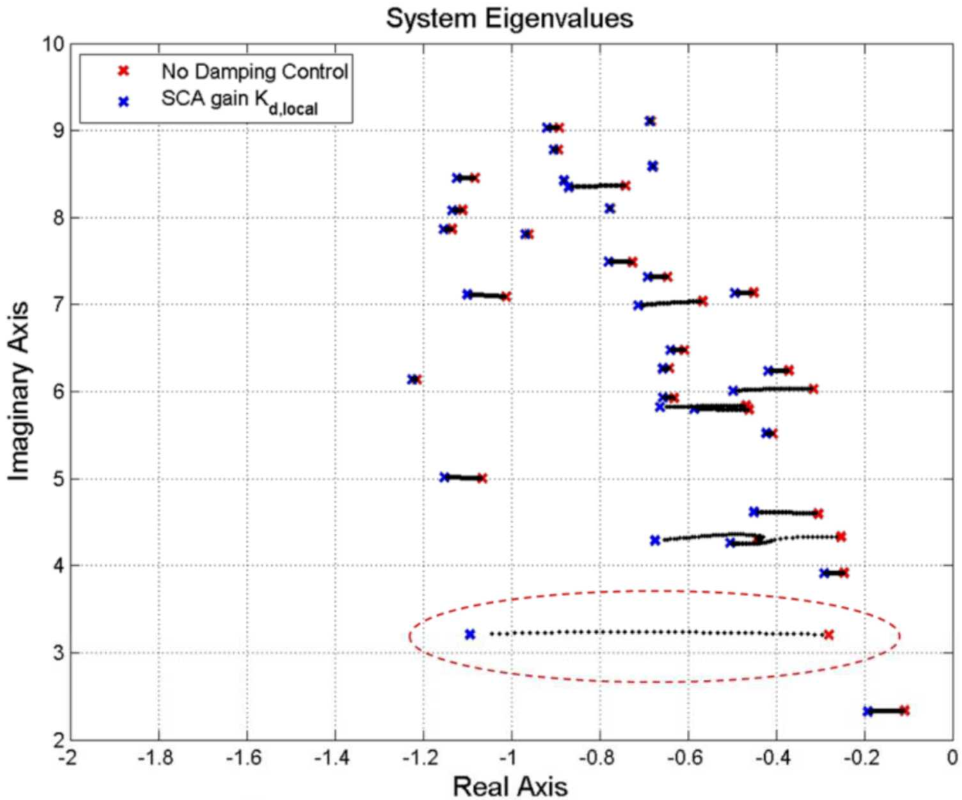
Controllability of multiple modes

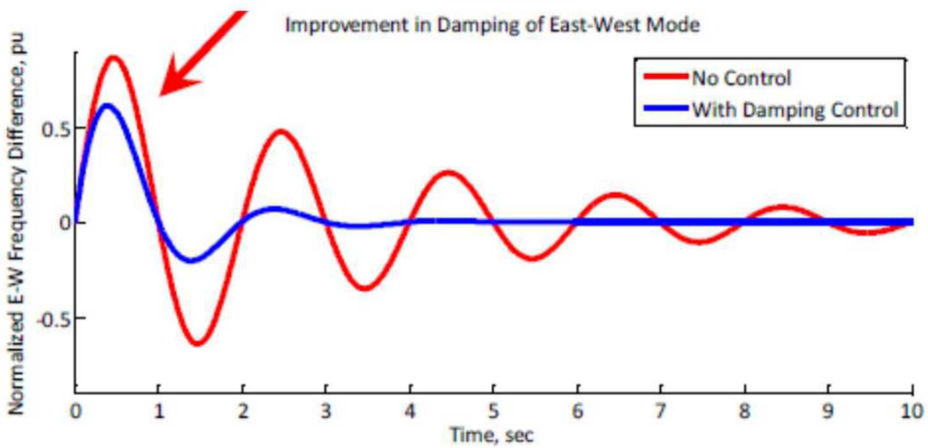
Size/location of a single site not as critical as more energy storage is deployed on grid

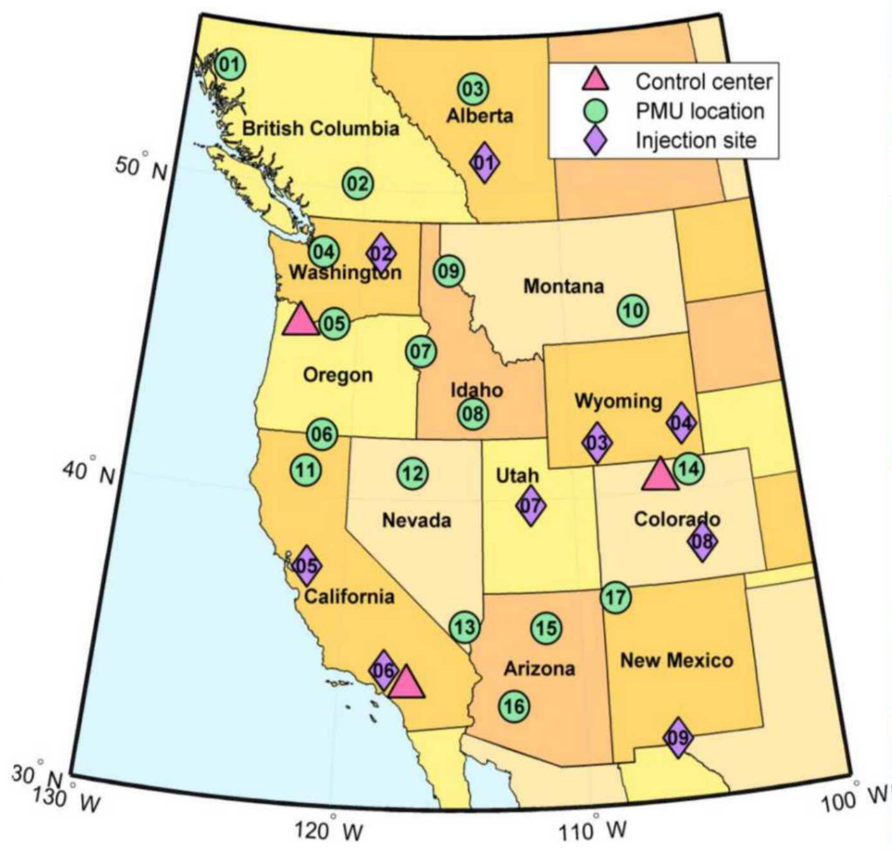
With 10s of sites engaged, single site power rating ≈ 1 MW can provide improved damping

Control signal is energy neutral and short in time duration - storage sites can perform other applications

Distributed Control of Energy Storage







Scenario: nine 10 MW energy storage systems located in the WECC

Summary

Small signal stability is a concern in all large power systems

HVDC modulation is an economical mitigation method – but it must be sited in the correct location to provide any benefit

Energy storage is capable of providing a small signal stability service

- ~100's of 1MW devices can provide a significant benefit
- ~10's of 1MW devices can provide some benefit
- Energy neutral response signal (ignoring conversion losses)
- High power, low energy application

Challenges:

- Compensation
- Communications
- Scheduling

Backup Slides

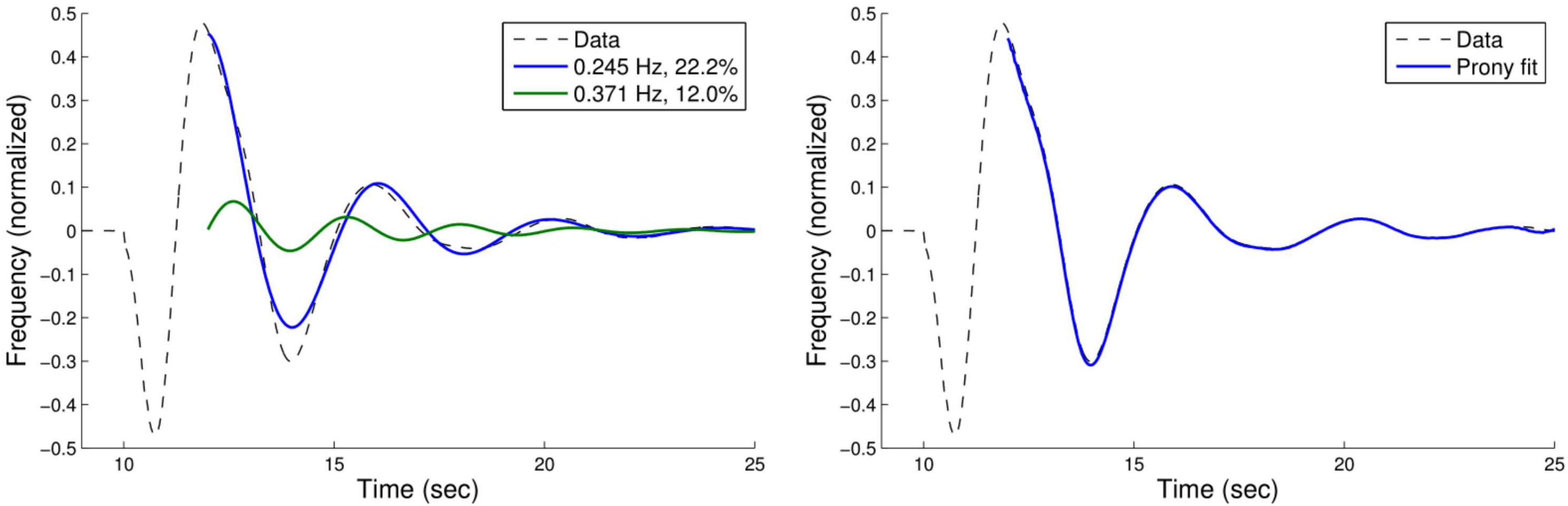
Prony's Method

Developed by Gaspard Riche de Prony in 1795

Similar to the Fourier transform

Expresses a function as a sum of sinusoids and damped exponentials

$$\hat{f}(t) = \sum_{i=1}^{N} A_i e^{\sigma_i t} \cos(2\pi f_i t + \phi_i)$$



(a) Prony decomposition. (b) Prony fit evaluation.

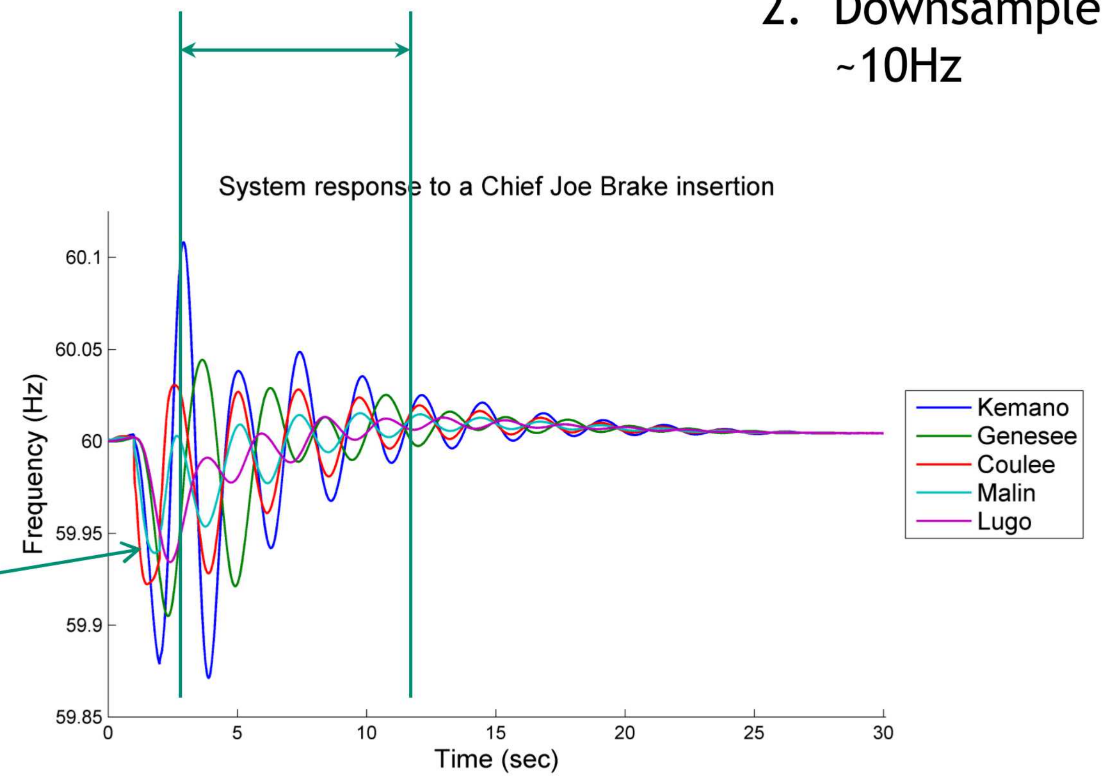
Prony's Method

Signal selection and pre-processing

- Assumes a linear model
- Modes of interest are 0.1-1 Hz

Steps:

1. Identify suitable time period
2. Downsample to ~10Hz



Prony's Method

Discrete-time system model

$$y(kT) = \sum_{i=1}^{n} B_i z_i^k, \quad k = 0, \ \ldots, \ N-1$$

The characteristic polynomial is given by

$$d(z) = 1 - a_1 z^{-1} + \ldots - a_n z^{-n}$$

The three steps are:

1. Assuming a model order n, solve for the coefficients of the characteristic polynomial by solving the auto-regressive sequence using measured data (linear prediction step)

$$y(kT) = a_1 y((K-1)T) + \ldots + a_n((K-n)T)$$

2. Calculate the roots of the characteristic equation -> poles of the discrete-time system.
3. Solve for the residues using the measured data and discrete-time poles (Vandermonde step)

Prony's Method

Two different approaches for estimating model order

- Use a reasonable order based on some criteria (e.g. known, Akaike information criteria – AIC, Bayesian information criteria – BIC, etc.)
- Extreme over-fit (e.g. ~200 poles)
  - Most "practitioners" use this approach
  - Dominant modes are selected based on the magnitude of the residue
  - Size the least-squares problem so that it is slightly over-determined

Handling multiple signals

- Multi-signal Prony (not very popular)
- Apply traditional Prony
  - Use frequency pairs to identify mode frequencies (need to know the mode shape in advance)
  - Use the frequencies to estimate the residues (step 3) which give you mode shape

Estimating the uncertainty of the mode frequency/damping is a difficult problem

Prony's Method

$$\begin{bmatrix} y(k) \\ y(k-1) \\ \vdots \\ y(k-N) \end{bmatrix} = \begin{bmatrix} y(k-1) & y(k-2) & \dots & y(k-n) \\ y(k-2) & y(k-3) & \dots & y(k-n-1) \\ \vdots & \vdots & \vdots & \vdots \\ y(k-N-1) & y(k-N-2) & \dots & y(k-N-n) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}$$

$$y = Ax \qquad x = (A^T A)^{-1} A^T y \qquad A \in \mathbf{R}^{N+1 \times n}$$

Two free parameters

- Number of poles, n
- Number of equations, N+1
- Number of data points, n+N+1
- Typically select

Solve the least squares probl $n = round\left(\frac{\text{number of samples}}{2}\right) - 11, \;\; n \approx N - 21$

Eigensystem Realization Algorithm (ERA)

ERA was developed by Ho and Kalman

Assumes a finite dimension, discrete-time, linear, time invariant system model:

The free impulse uence

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned}$$

The ERA system realization problem can be formulated as: given the output data y(k), construct the constant matrices [A;B;C] in terms of y(k) subject to (*)

$$y(k) = CA^{k-1}B \quad (*)$$

Eigensystem Realization Algorithm (ERA)

ERA algorithm steps:

1. Form the block-Hankel matrix

$$H_{rs}(k-1) = \begin{bmatrix} Y(k) & Y(k+1) & \cdots & Y(k+s-1) \\ Y(k+1) & Y(k+2) & \cdots & Y(k+s) \\ \vdots & \vdots & \cdots & \vdots \\ Y(k+r-1) & Y(k+r) & \cdots & Y(k+s+r-2) \end{bmatrix}$$

3. Select or estimate the model order

$$H_{rs}(0) = PDQ^T$$

$$\delta = \frac{d_i}{d_1} \qquad d_i = \begin{cases} d_i & \delta > \text{Threshold} \\ 0 & \delta \leq \text{Threshold} \end{cases}$$

Eigensystem Realization Algorithm (ERA)

ERA algorithm steps (continued)

4. Estimate the system model

$$\hat{A} = D^{-\frac{1}{2}} P^T H_{rs}(1) Q D^{-\frac{1}{2}}$$
$$\hat{B} = D^{\frac{1}{2}} Q^T E_m$$
$$\hat{C} = E_p^T P D^{\frac{1}{2}}$$

5. Estimate the mode shape and amplitude

$$E_p^T = [I_p,\ 0_p,\ \ldots,\ 0_p] \qquad E_m^T = [I_m,\ 0_m,\ \ldots,\ 0_m]$$

6. Can also estimate the modal amplitude coherence (degree to which a mode is excited by a specific input) and modal phase collinearity (strength of the linear relationship between the real and imaginary parts of the mode shape)

$$\text{mode shape} = \hat{C}\mu, \quad \text{mode amplitude} = \mu^{-1}\hat{B}, \quad \mu = \text{right e.v. of } \hat{A}$$

Eigensystem Realization Algorithm (ERA)

Applied to ringdown data

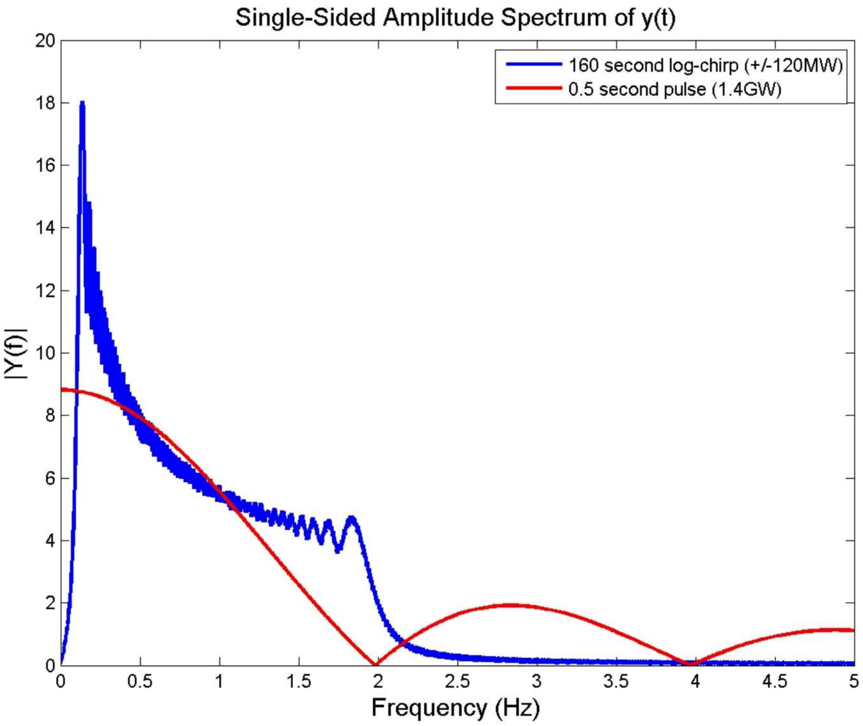
- Same process as for Prony (downsample, select linear response)
- More automated than Prony

Applied to other system stimulation (e.g. PDCI modulation)

- PDCI modulation provides a better excitation than Chief Joseph brake insertion (in simulation)

Steps:

1. Excite system and measure response
2. Calculate frequency domain transfer functions
3. Calculate impulse response from frequency domain transfer functions
4. Estimate system model using ERA



Eigensystem Realization Algorithm (ERA)

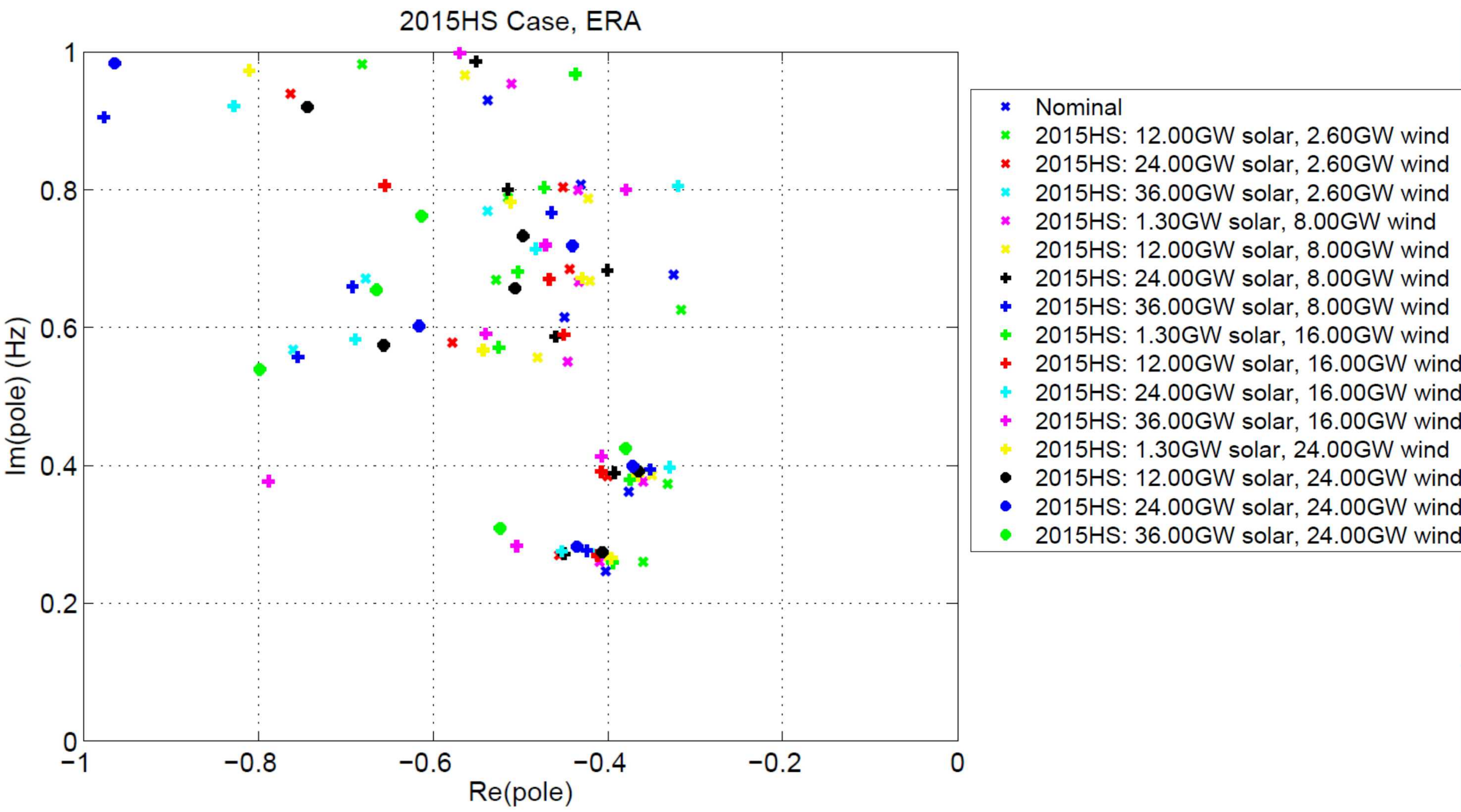
Advantages of ERA with a broad spectrum stimulus (e.g. log-chirp)

- Stimulate the system in the frequencies of interest
- Opportunities for additional filtering
  - Time domain response data
  - Frequency domain
  - Time domain impulse response
- Using a chirp signal (linear or logarithmic), relatively easy to eyeball frequency response
- More automated than Prony analysis
- You get the full system model (if you need it), Prony only gives you eigenvalues

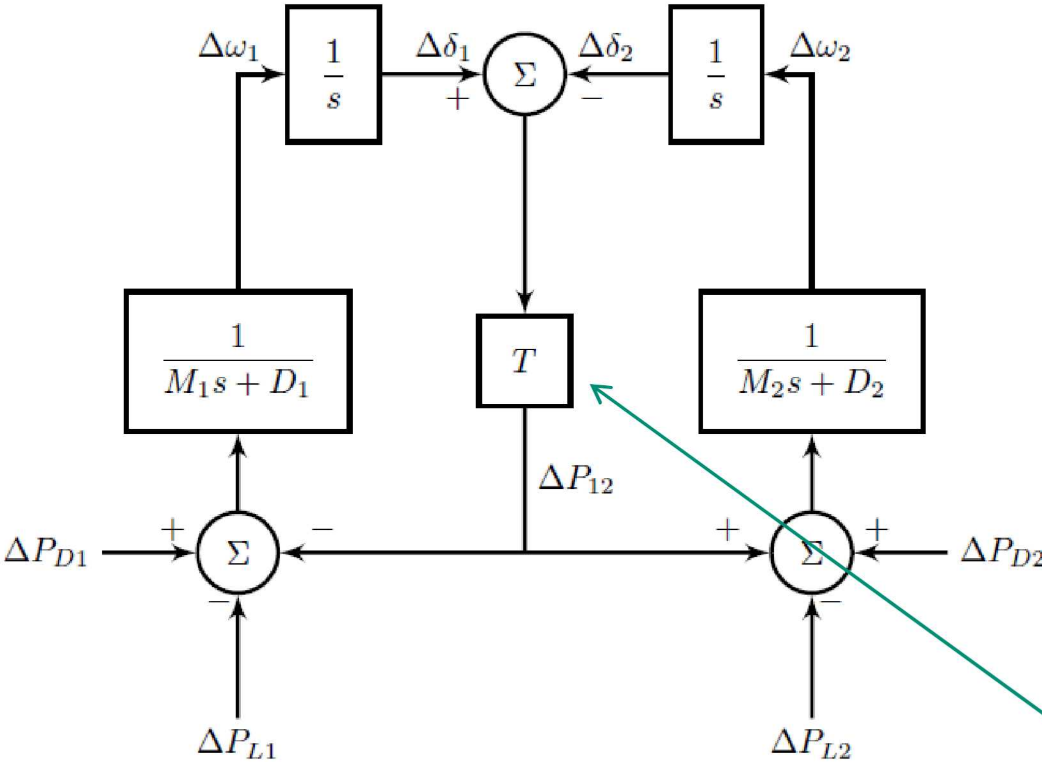
ERA does not totally automate the modal analysis

- Still need to look at mode shape to group results (see plot on next page)

Eigensystem Realization Algorithm (ERA)



Two Area System Model



Quantity	Description	Units
M_i	Area i inertia	sec
D_i	Area i damping	pu
T	Synchronizing torque coefficient	pu
ΔP_{Li}	Area i load variation	pu
ΔP_{Di}	Area i damping torque	pu
$\Delta\omega_i$	Area i speed deviation	pu
$\Delta\delta_i$	Area i angle deviation	pu
ΔP_{12}	Deviation in tie line flow	pu

As inertia decreases -> system responds faster

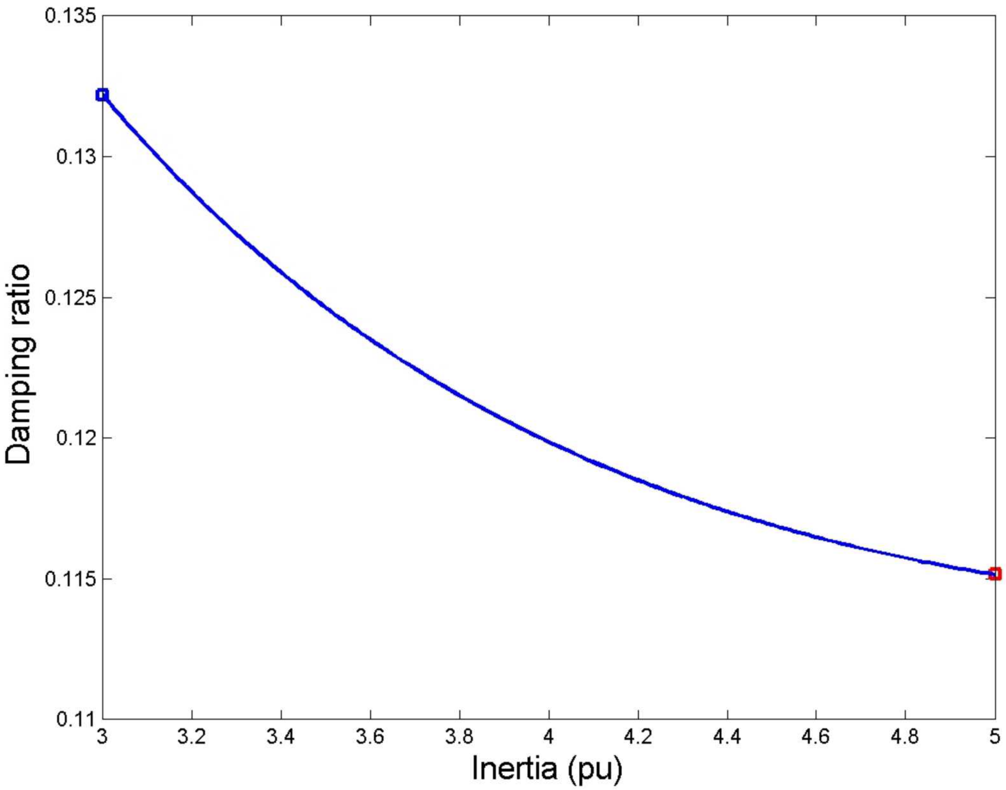
$$\zeta\omega_n \approx \frac{1}{2}\left(\frac{D_2}{M_2} + \frac{D_1}{M_1} - \frac{D_1 + D_2}{M_1 + M_2}\right)$$

Transmission line stiffness

$$T = \frac{V_1 V_2}{X_T}\cos(\delta) \approx \frac{V_1 V_2}{X_T}\delta$$

Two Area System Model - Damping

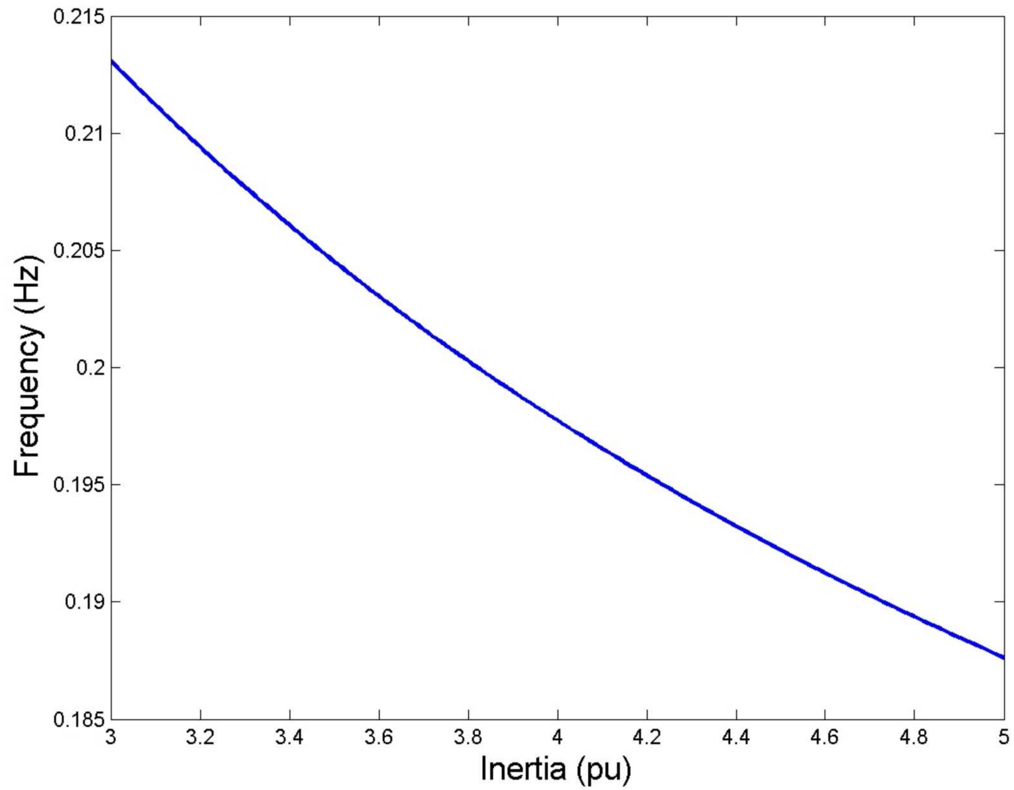
- As inertia is reduced, damping increases slightly (not changing damping)
- An equal reduction in inertia and damping (e.g. 25%) slightly reduces damping (0.1152 -> 0.1109)



Parameter	Value	Units
M_1	4	sec
M_2	$3-5$	sec
D_1	1.2	pu
D_2	1.2	pu
T	3.132	pu

Two Area System Model - Frequency

- As inertia is reduced, frequency increases (not changing damping)
- An equal reduction in inertia and damping (e.g. 25%) still results in an increased frequency (0.1977 Hz -> 0.2138 Hz)



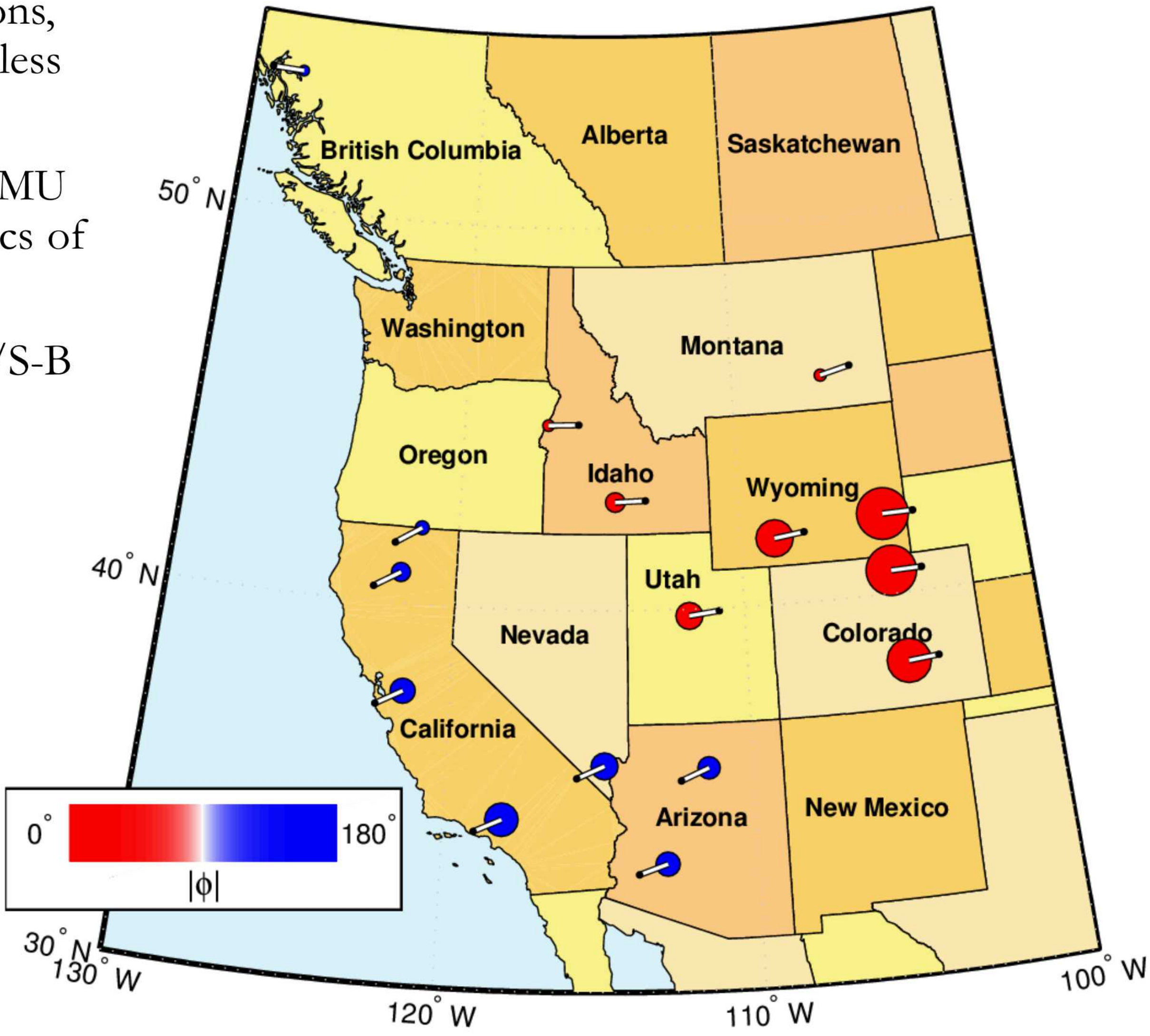
Parameter	Value	Units
M_1	4	sec
M_2	$3-5$	sec
D_1	1.2	pu
D_2	1.2	pu
T	3.132	pu

WECC – High Renewable Case

For high renewable penetrations, an East-West mode becomes less damped (8->6%)

In the process of analyzing PMU data to verify the characteristics of the mode

Very close in frequency to N/S-B mode (~0.4 Hz)



WECC – High Renewable Case

For all modes (except for the E/W mode)
- Mode frequency increased
- The change in mode frequency was greater for
- Mode damping stayed relatively constant
- Mode shape did not change significantly

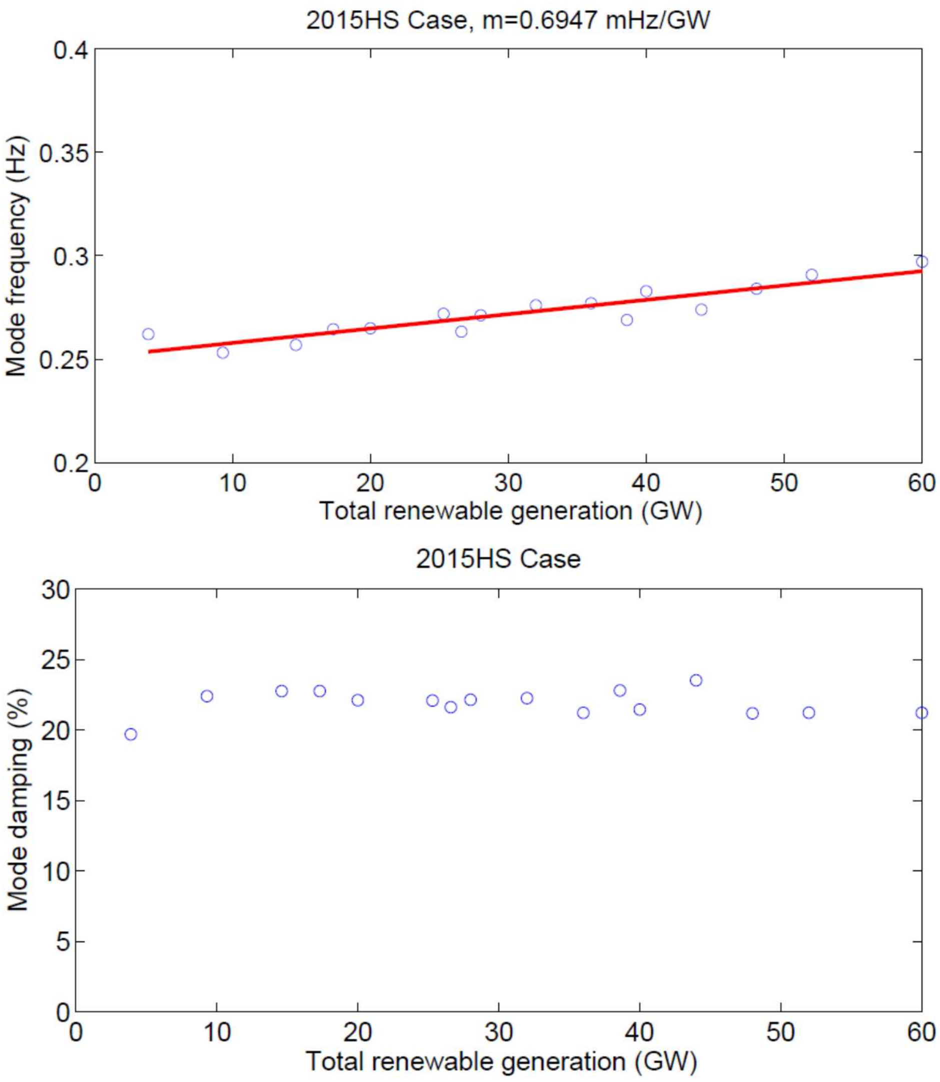


Figure 19: ERA results, 2015 heavy summer, NS mode A.

WECC – High Renewable Case

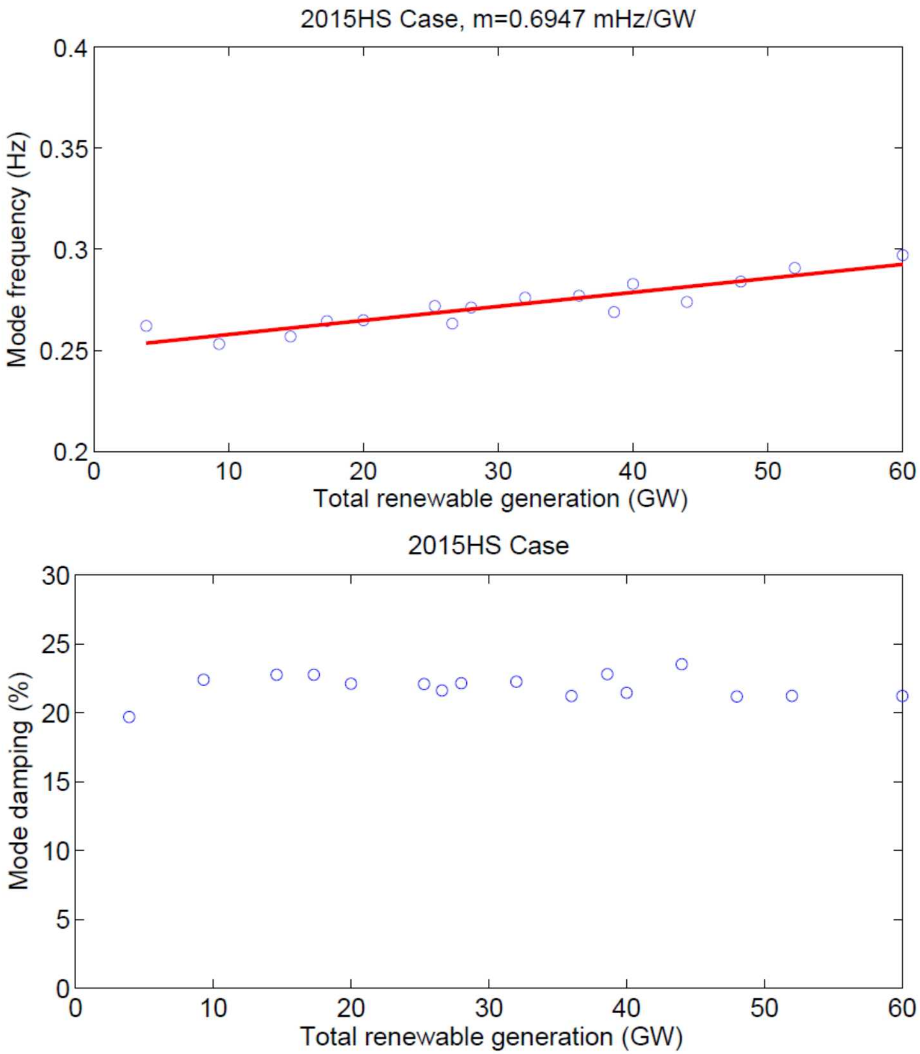


Figure 19: ERA results, 2015 heavy summer, NS mode A.

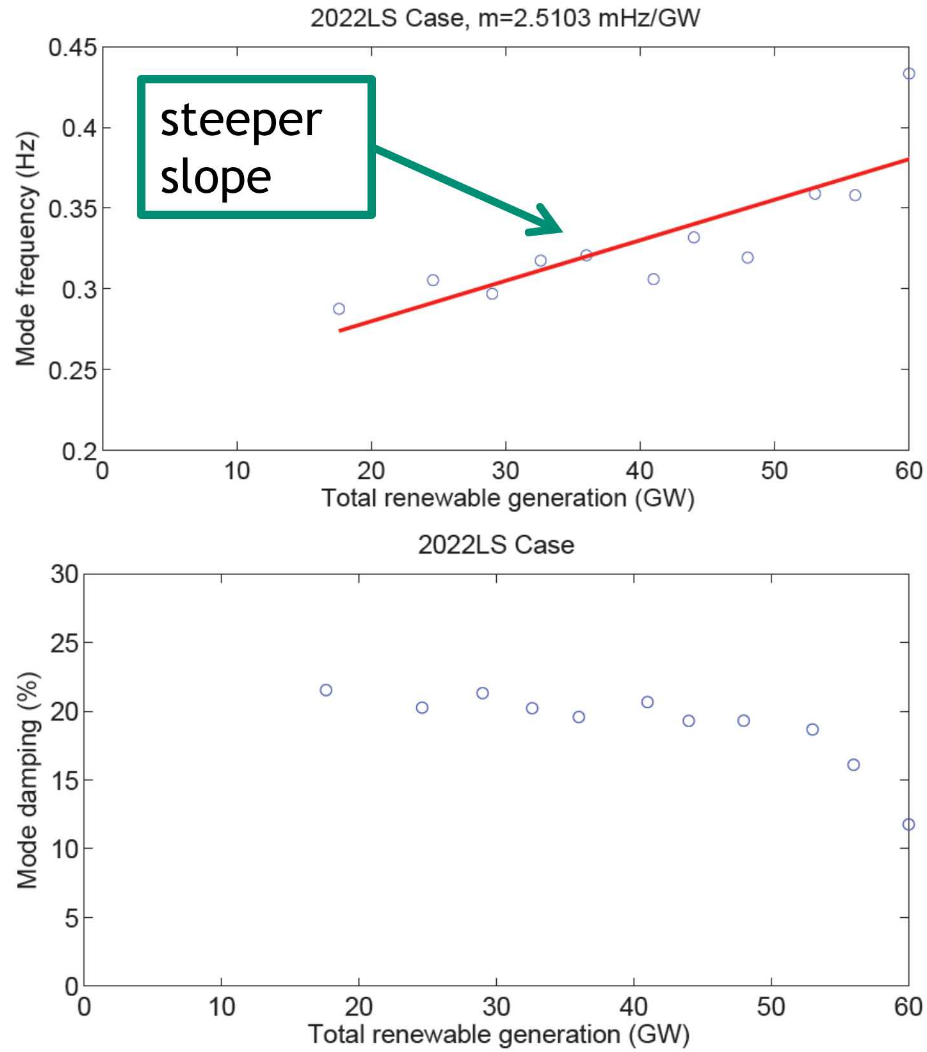


Figure 21: ERA results, 2022 light spring, NS mode A.