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Grid Stability with High Renewable Penetration

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Outline

- Acknowledgements
- Power Grid Basics
- Renewable Integration Challenges
- Small Signal Stability – Why are we concerned?
- Distributed Control – Vector Lyapunov techniques
- Conclusions

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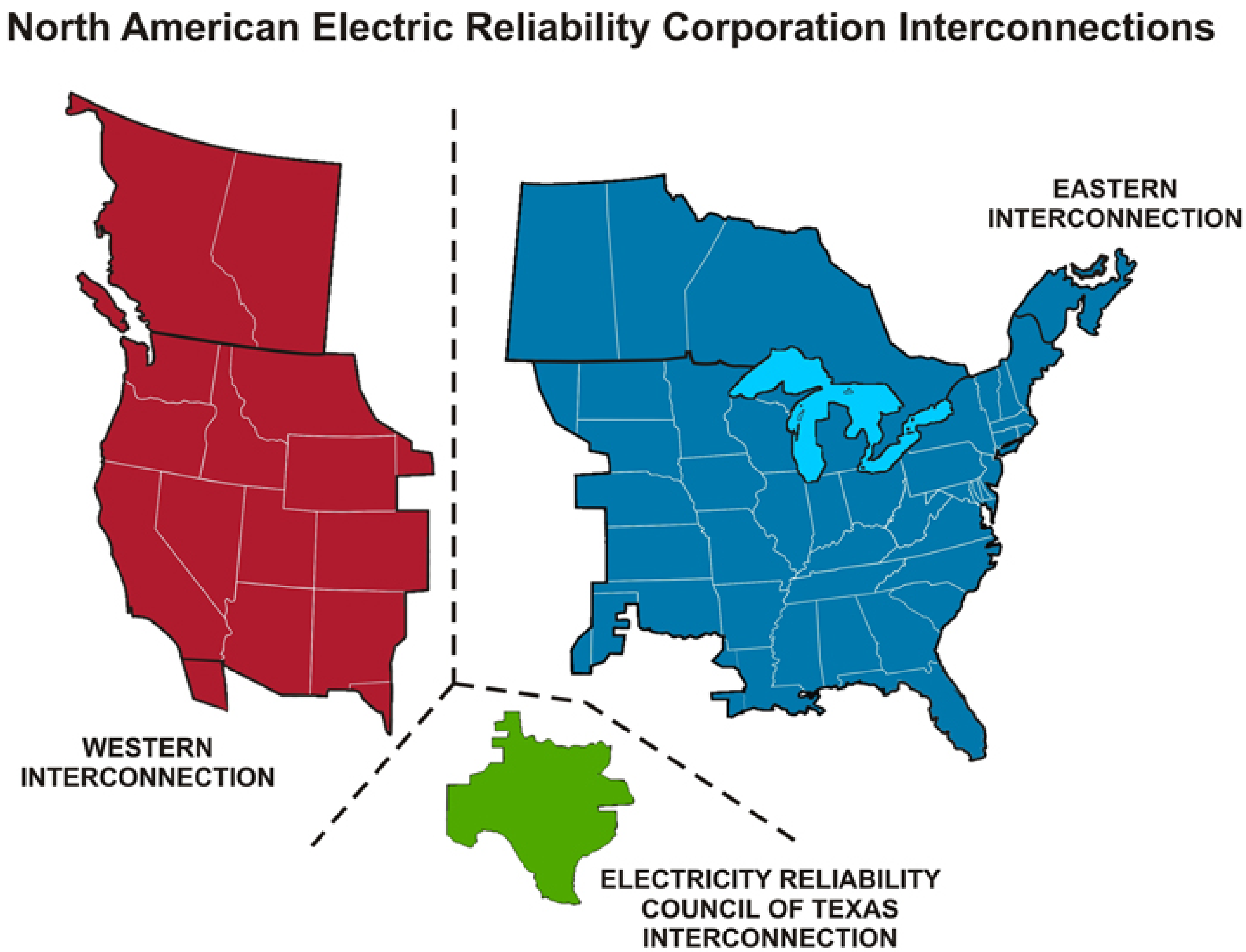
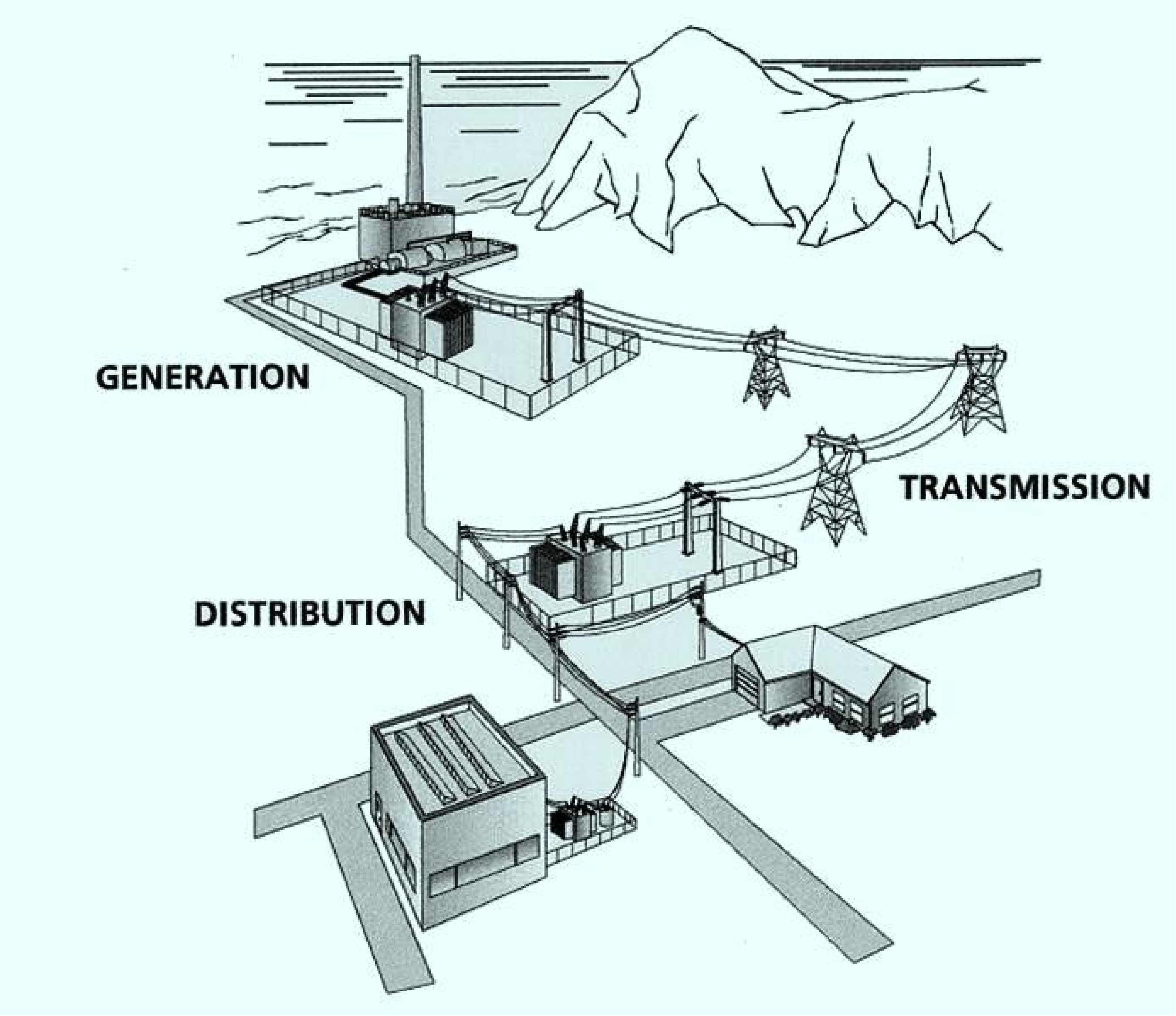
  - Ricky Concepcion
  - Felipe Wilches Bernal
  - David Wilson
  - Dave Schoenwald
  - Dr. Dan Trudnowski, Montana Tech University

U.S. Power Grid

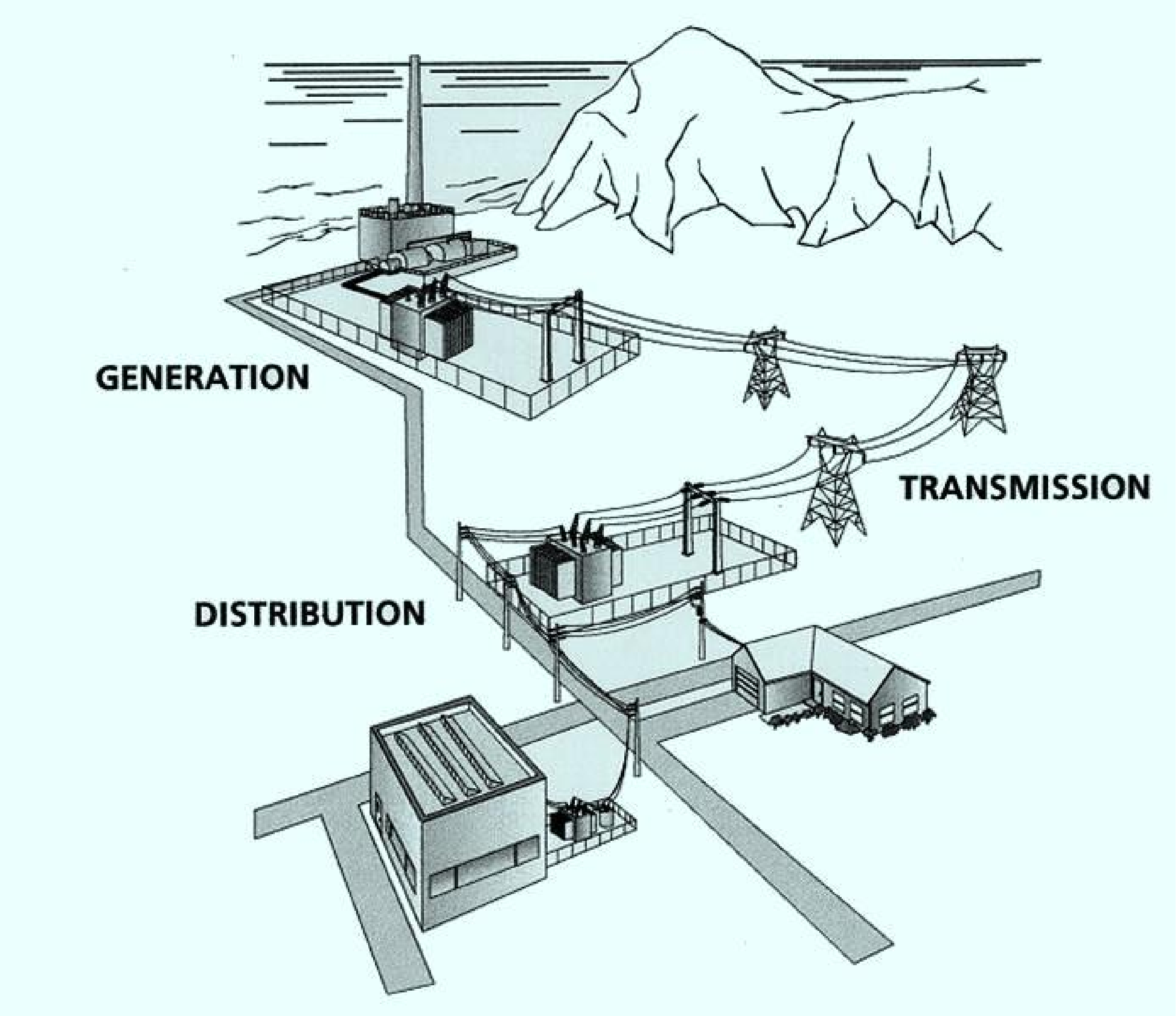


Power Grid Components



This presentation focuses on Transmission-level integration

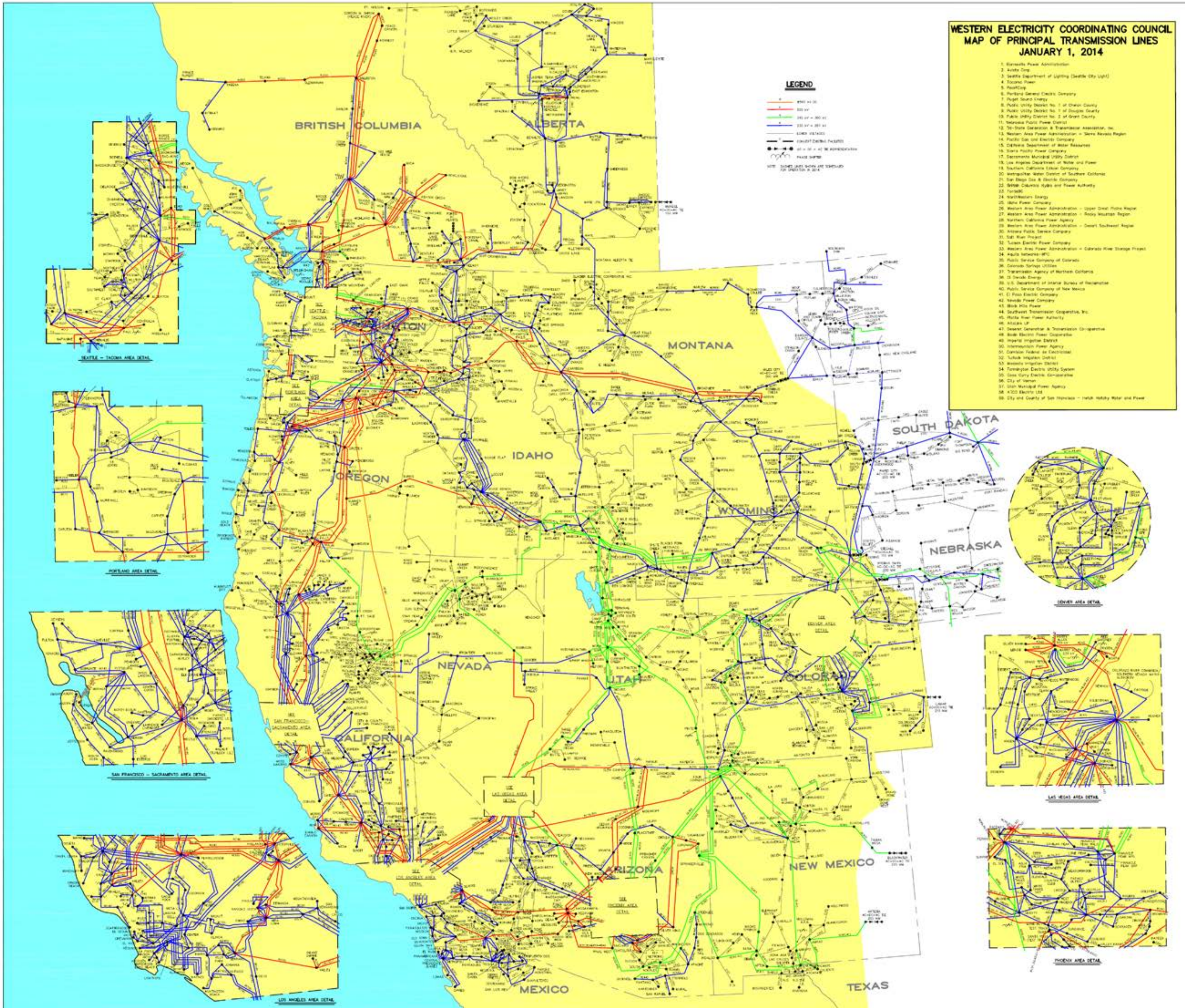
Renewable Integration Challenges



<u>Generation</u>
- Ramp rates to match variability
- Economic dispatch

<u>Transmission</u>
- Small signal stability
- Transient stability
- Low Voltage/ Frequency ride-through
- Voltage stability

<u>Distribution</u>
- Voltage control
- Power flows
- Protection



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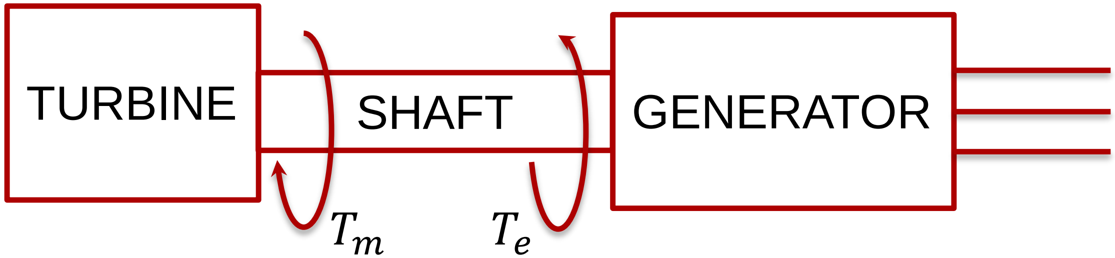
Frequency Regulation

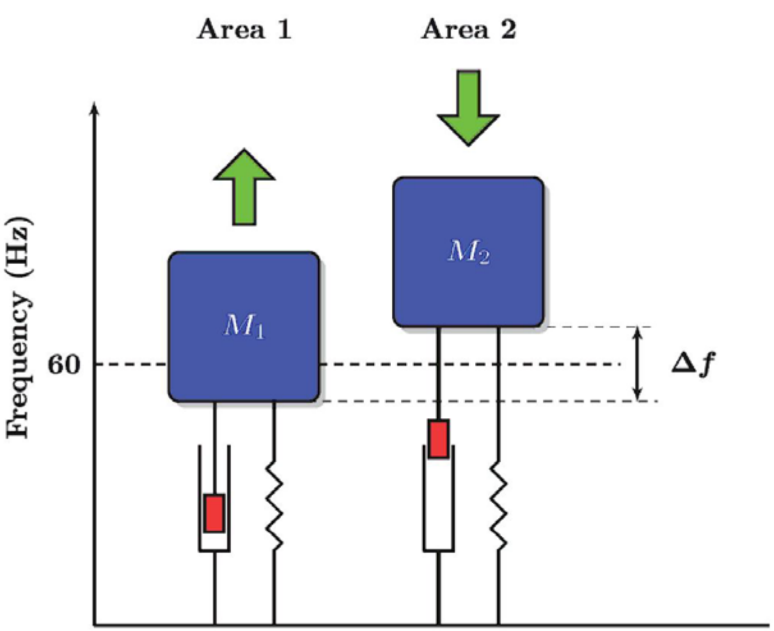
- For a motor-generator, the equations of motion are

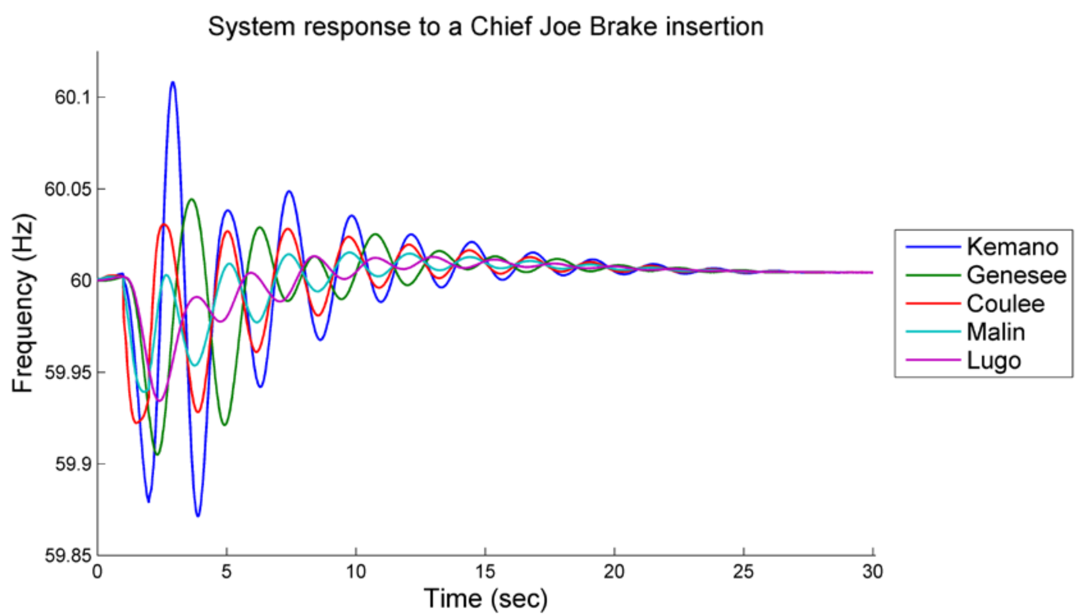


$$J\frac{d\omega}{dt} = T_m - T_e - K_D\omega$$

- For constant T_m (mechanical power),

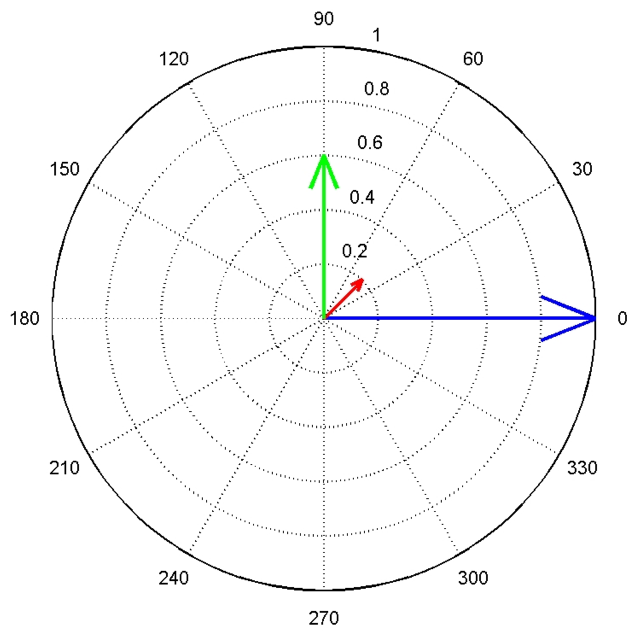
load ↑, frequency ↓ load ↓, frequency ↑

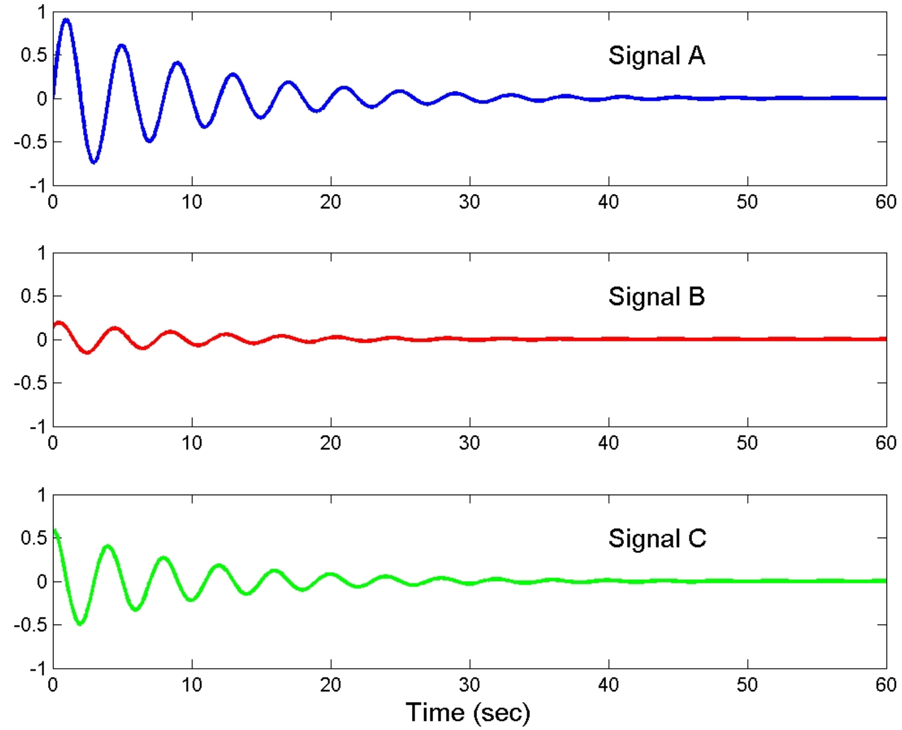




What is Mode Shape?

- Mode shape is defined by
  - Amplitude at each location
  - Phase at each location
- Typically look at
  - Generator speed (frequency)
  - Frequency measurements

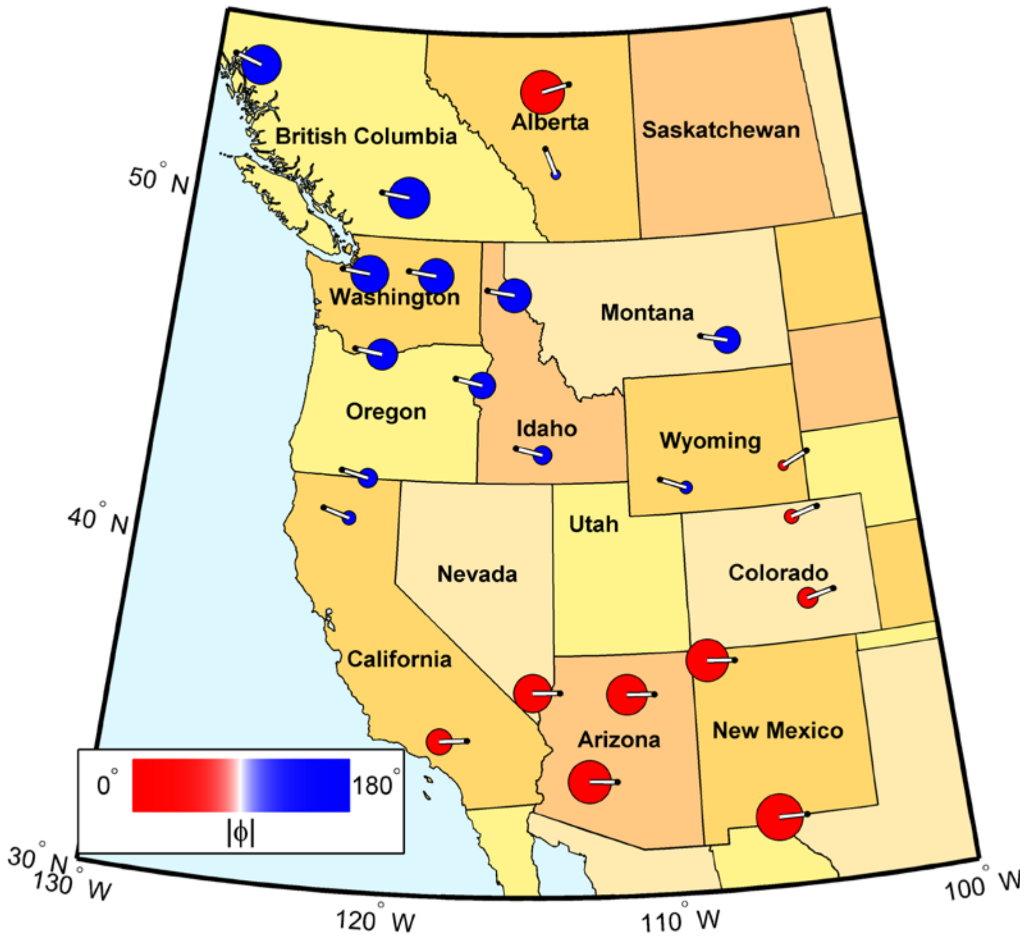




$$y_A(t) = 1.0\cos(2\pi f + 0)$$
$$y_B(t) = 0.2\cos(2\pi f + \pi/4)$$
$$y_C(t) = 0.6\cos(2\pi f + \pi/2)$$

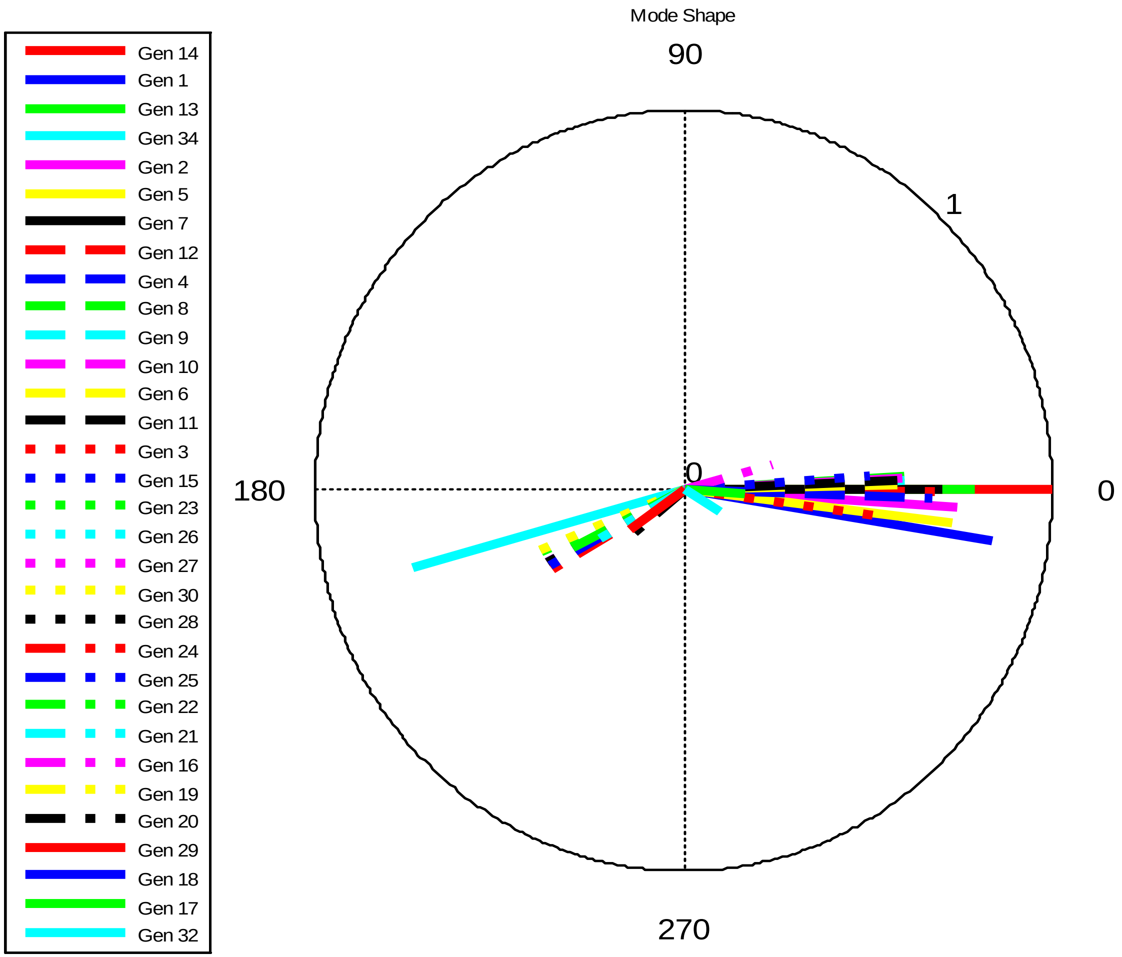
Visualizing Mode Shape

- 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"

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

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

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

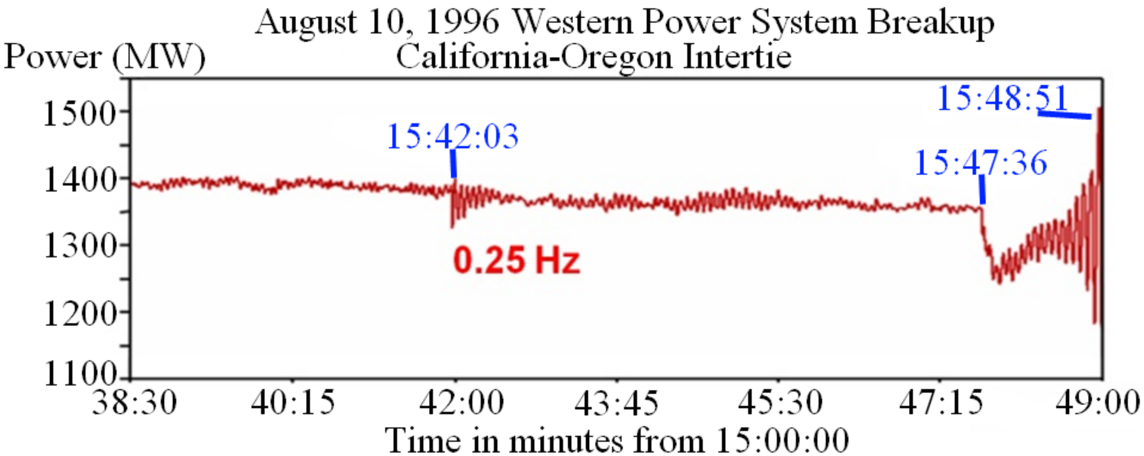
$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \quad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial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

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

Why are we concerned?

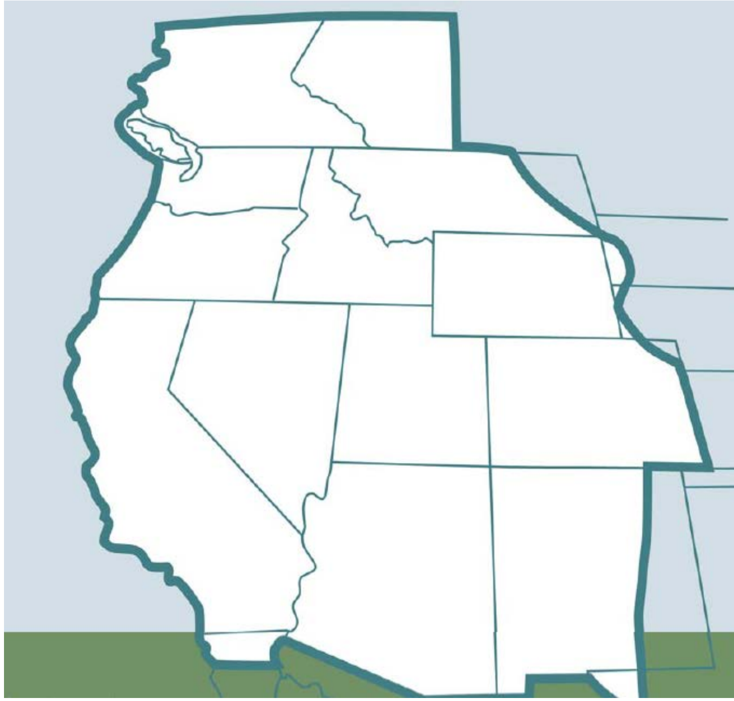
- Power systems are susceptible to low frequency oscillations caused by generators separated by long transmission lines that oscillate against each other
- These oscillations are not as well damped as higher frequency "local" oscillations
- High penetration of renewable generation can impact mode shape and damping – potential reduction in reliability

1996 breakup caused by low-frequency oscillations

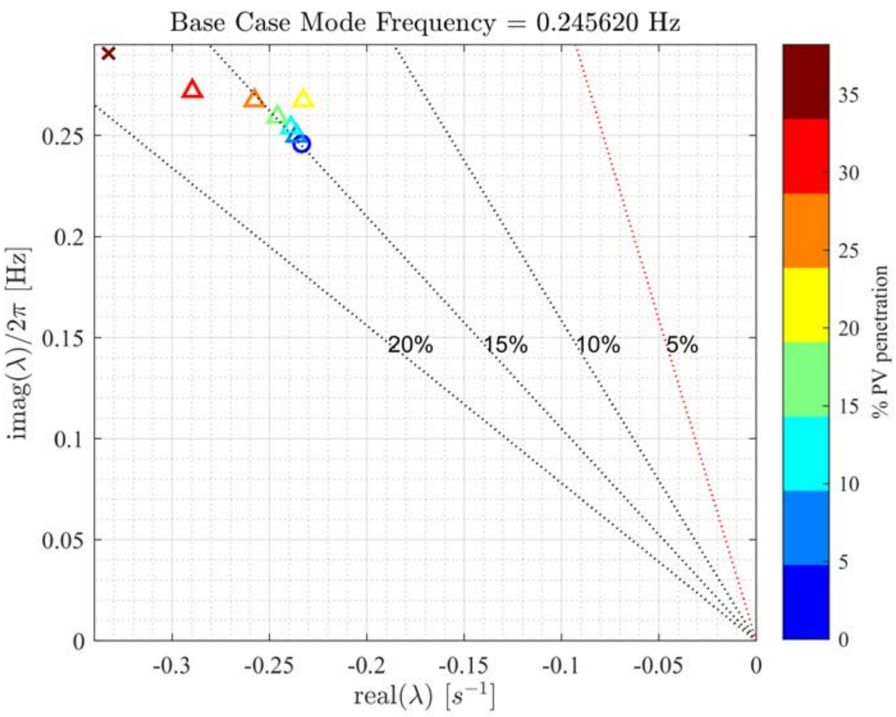


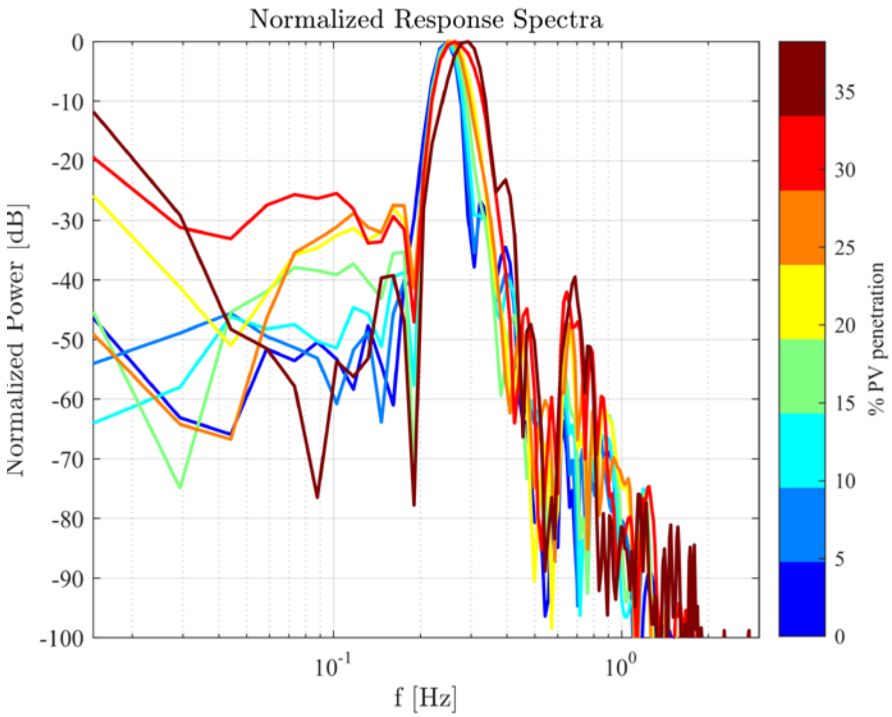
Why are we concerned?

- 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



What happens with Increased Renewables?

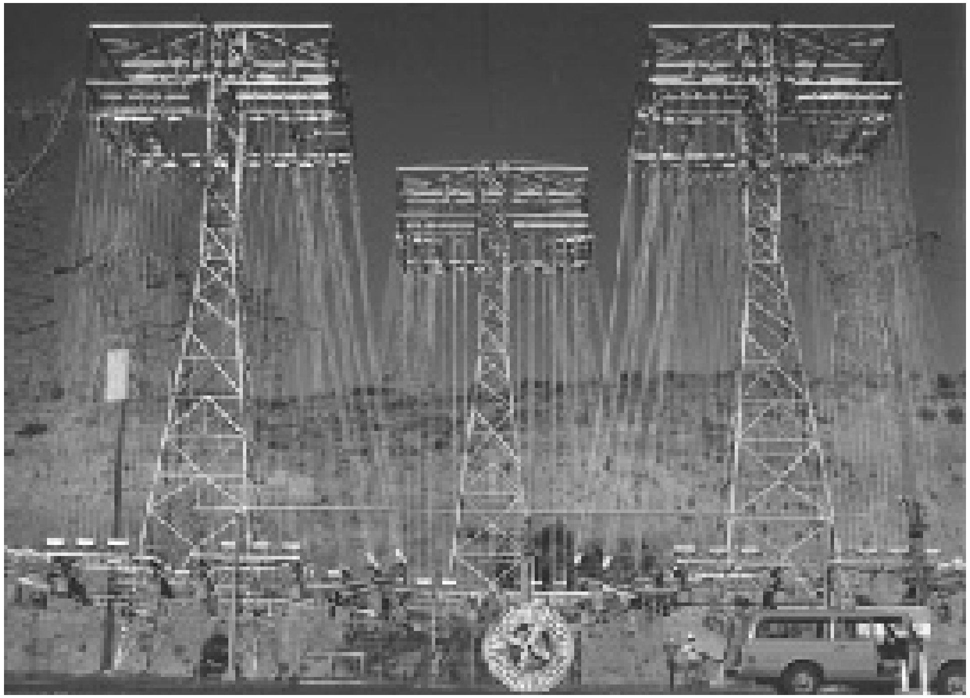


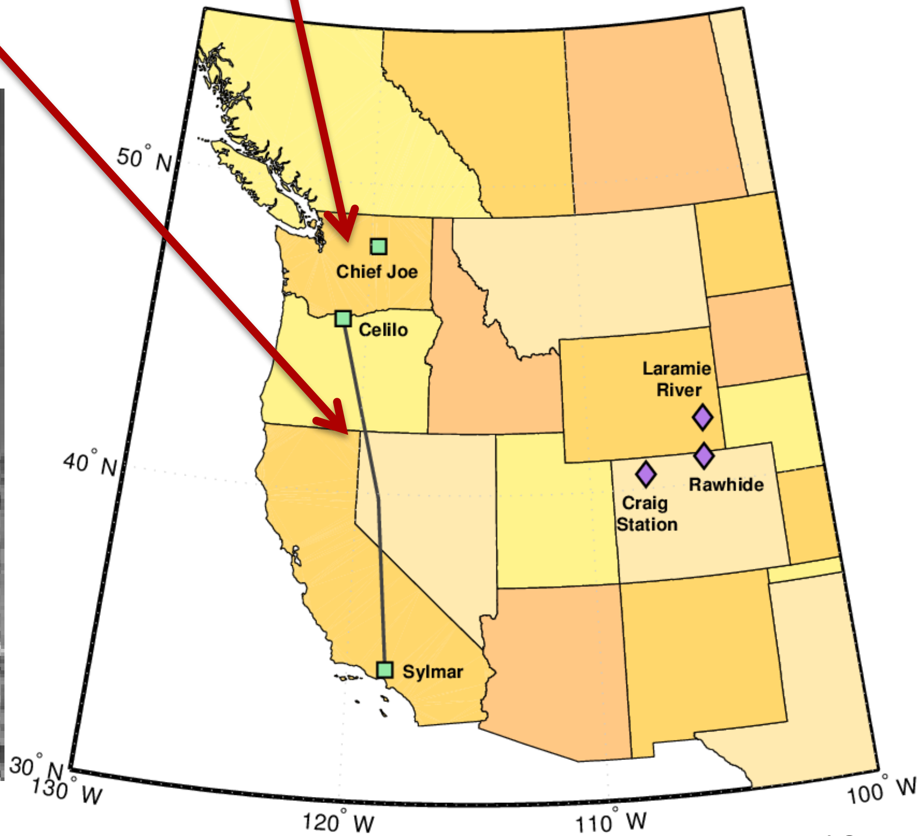


- Mode frequencies increase (less inertia)
- Damping stays roughly the same (for moderate penetrations)

Excitation Methods for System Id

- Natural disturbances
- Chief Joseph Brake (1.4GW, built in 1974)
- Pacific DC Intertie (PDCI) Modulation





Structured Perturbation Model

- Given a linear system (can also be applied to a nonlinear system):

$$\mathbf{S}: \begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx, \end{aligned}$$

- Partition the system into N-interconnected systems:

$$\mathbf{S}: \quad \dot{x}_i = A_i x_i + \sum_{j=1}^{N} e_{ij} A_{ij} x_j, \quad i \in N$$

- e_{ij} are the "structured perturbations", design control system so that system is stable as $e_{ij} \in [0,1]$
- Vector Lyapunov techniques provide a method for testing stability[1]

[1]D. D. Siljak, Decentralized Control of Complex Systems. Academic Press, 1991.

Power System 2-area Model

- Partition the system

$$
\begin{aligned}
S: \quad \dot{x} &= Ax + Bu, \\
y &= Cx,
\end{aligned}
$$

$$
A = \left[\begin{array}{cc:cc}
-\frac{D_1}{M_1} & -\frac{T}{M_1} & 0 & \frac{T}{M_1} \\
1 & 0 & 0 & 0 \\
\hdashline
0 & \frac{T}{M_2} & -\frac{D_2}{M_2} & -\frac{T}{M_2} \\
0 & 0 & 1 & 0
\end{array}\right]
$$

$$
B = \left[\begin{array}{c:c}
\frac{1}{M_1} & 0 \\
0 & 0 \\
\hdashline
0 & \frac{1}{M_2} \\
0 & 0
\end{array}\right]
$$

$$
x = \begin{bmatrix} \Delta\omega_1 \\ \Delta\delta_1 \\ \Delta\omega_2 \\ \Delta\delta_2 \end{bmatrix}, \quad u = \begin{bmatrix} \Delta P_{D1} \\ \Delta P_{D2} \end{bmatrix},
$$

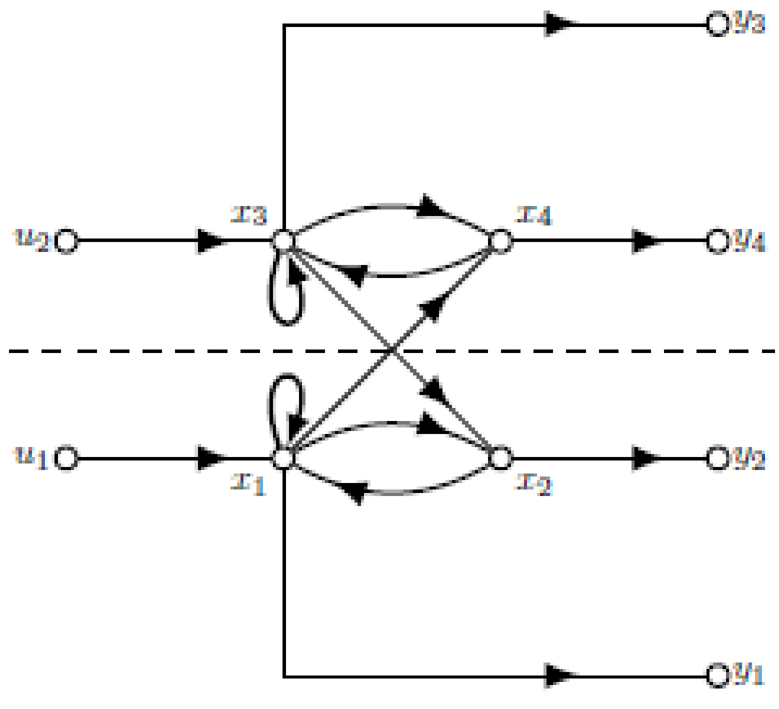


Fig. 2. Two-area system digraph.

Power System 2-area Model

- Structured perturbations - coupling uncertainty

$$\begin{bmatrix} \Delta\dot{\omega}_1 \\ \Delta\dot{\delta}_1 \end{bmatrix} = \begin{bmatrix} -\frac{D_1}{M_1} & -\frac{T}{M_1} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_1 \\ \Delta\delta_1 \end{bmatrix} + \begin{bmatrix} \frac{1}{M_1} \\ 0 \end{bmatrix} \Delta P_{D1} + e \begin{bmatrix} 0 & \frac{T}{M_1} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_2 \\ \Delta\delta_2 \end{bmatrix}$$

$$\begin{bmatrix} \Delta\dot{\omega}_2 \\ \Delta\dot{\delta}_2 \end{bmatrix} = \begin{bmatrix} -\frac{D_2}{M_2} & -\frac{T}{M_2} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_2 \\ \Delta\delta_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{M_2} \\ 0 \end{bmatrix} \Delta P_{D2} + e \begin{bmatrix} 0 & \frac{T}{M_2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_1 \\ \Delta\delta_1 \end{bmatrix}$$

- Can easily be rearranged to get the form:

$$\boldsymbol{S}: \quad \dot{x}_i = A_i x_i + \sum_{j=1}^{N} e_{ij} A_{ij} x_j, \quad i \in \boldsymbol{N}$$

- Local feedback – no uncertainty
- Global feedback – subject to the e coupling strength uncertainty

Power System n-area Model

- Local feedback – uncertainty in coupling

$$S_i: \quad \dot{x}_i = \begin{bmatrix} \lambda_i & \alpha_i \\ 1 & 0 \end{bmatrix} x_i + \sum_{\substack{j=1, \\ i \neq j}}^{n} e_{ij} \begin{bmatrix} 0 & \frac{T_{ij}}{M_i} \\ 0 & 0 \end{bmatrix} x_j + \begin{bmatrix} \frac{K_i}{M_i} & 0 \\ 0 & 0 \end{bmatrix} x_i$$

- Global feedback – uncertainty in coupling and communications

$$S_i: \quad \dot{x}_i = \begin{bmatrix} \lambda_i & \alpha_i \\ 1 & 0 \end{bmatrix} x_i + \sum_{\substack{j=1, \\ i \neq j}}^{n} e_{ij} \begin{bmatrix} \frac{K_{ij}}{M_i} & \frac{T_{ij}}{M_i} \\ 0 & 0 \end{bmatrix} x_j + \begin{bmatrix} \frac{K_{ii}}{M_i} & 0 \\ 0 & 0 \end{bmatrix} x_i$$

$$\lambda_i = -\frac{D_i}{M_i}, \quad \alpha_i = -\frac{T_i}{M_i}$$

Stability Test

- Construct an M-matrix,

$$w_{ij} = \begin{cases} \frac{1}{2\lambda_M(H_i)} - \bar{e}_{ii}\lambda_M^{1/2}(A_{ii}^T A_{ii}) \\ -\bar{e}_{ij}\lambda_M^{1/2}(A_{ij}^T A_{ij}) \end{cases}$$

$\lambda_M(\cdot)$ is the maximum eigenvalue

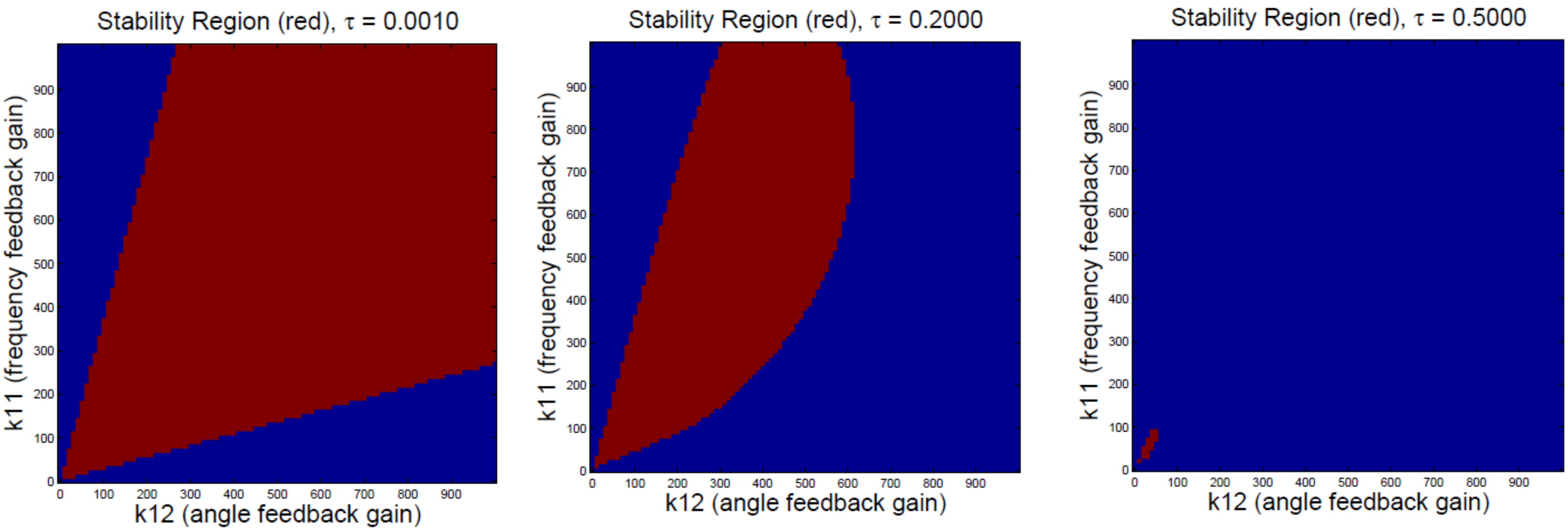
- where

the matrices H_i and G_i satisfy the Lyapunov matrix equation

$$A_i^T H_i + H_i A_i + G_i = 0 \qquad (12)$$

- Test eigenvalues of W (must be positive) for stability
- Vary control gains, identify stability regions for coupling/communications uncertainty

Example Stability Regions



- Two area system with bandlimited local feedback

Overlapping decomposition

- Uncertainty in tie line strength is overly conservative $e_{ij} \in [0,1]$
- Overlapping decomposition – share states with other subsystems

$$A = \left[\begin{array}{cc|c} A_{11} & A_{12} & A_{13} \\ \hline A_{21} & \multicolumn{1}{|c|}{A_{22}} & A_{23} \\ \hline A_{31} & \multicolumn{1}{|c}{A_{32}} & A_{33} \end{array}\right]$$

- Approach lends itself to power system model-based analysis (e.g., MATLAB PST)
- More difficult with commercial simulation software (e.g., PSLF, PST)
  - System linearization
  - Making sense of states

Conclusions – Future Research

- Moderate renewable penetrations (e.g., up to 50% of load) are not likely to cause any problems with inter-area oscillations
- Moderate renewable penetrations may excite an East-West mode in the U.S., additional analysis is underway
- Current/future research topics include:
  - Vector Lyapunov techniques for modelling communications uncertainty and model uncertainty
  - Impact of latency, availability, and scalability (e.g., communications range) on performance of distributed control systems for solar