



# Grid Stability with High Renewable Penetration

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national  
interest*



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# Outline

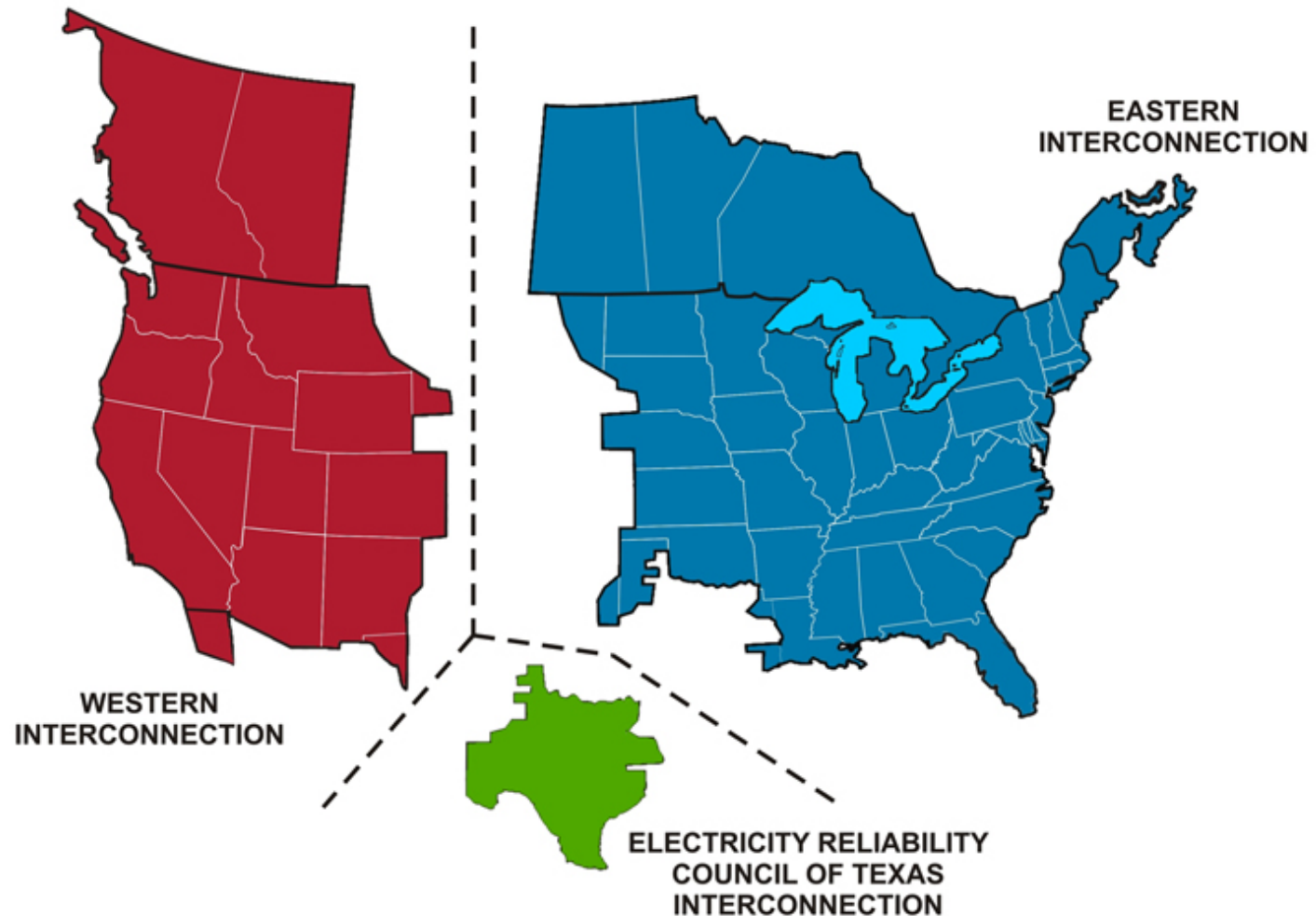
- Acknowledgements
- Power Grid Basics
- Renewable Integration Challenges
- Small Signal Stability – Why are we concerned?
- Distributed Control – Vector Lyapunov techniques
- Conclusions

# Acknowledgements

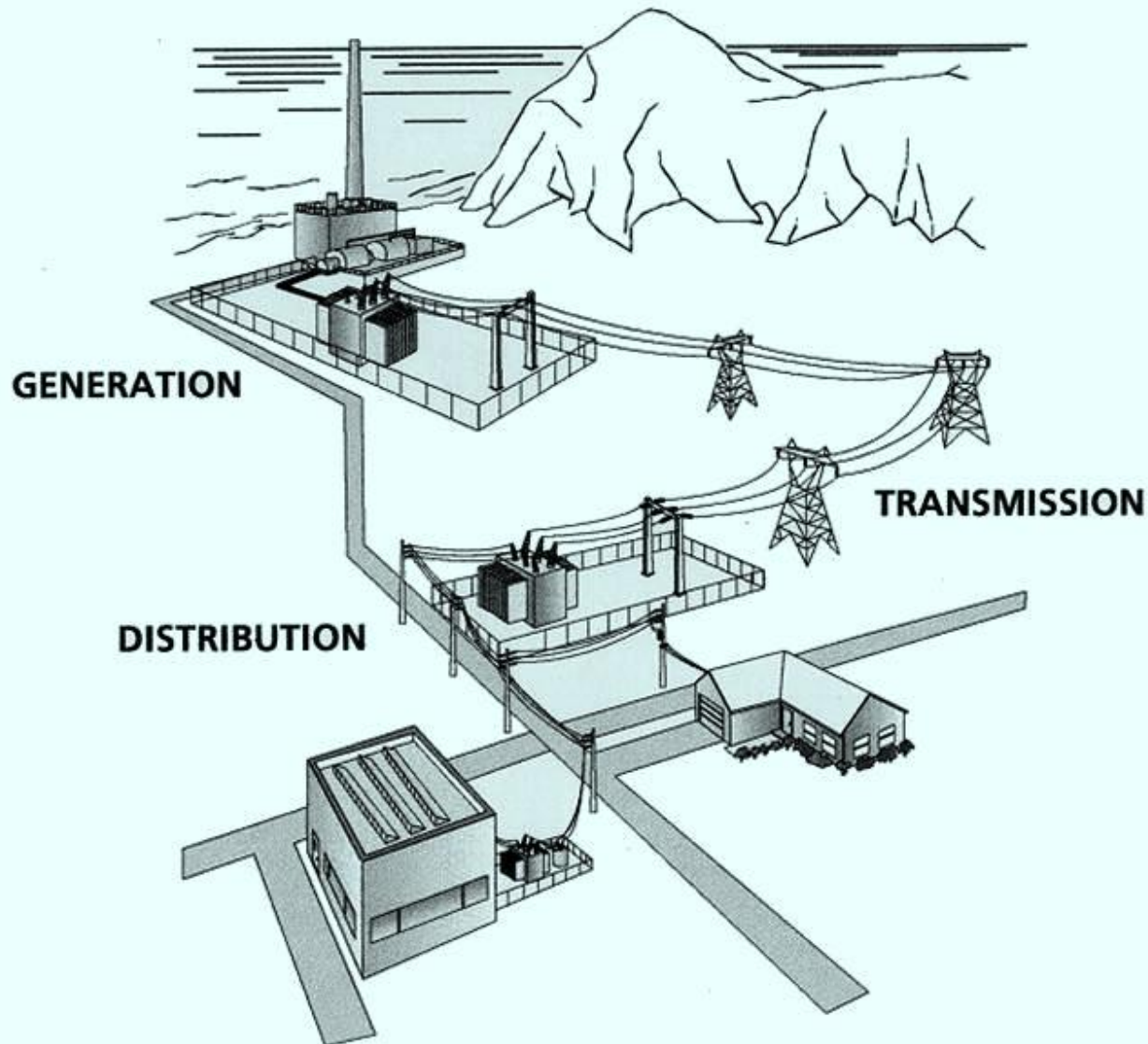
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  - David Wilson
  - Dave Schoenwald
  - Dr. Dan Trudnowski, Montana Tech University

# U.S. Power Grid

## North American Electric Reliability Corporation Interconnections

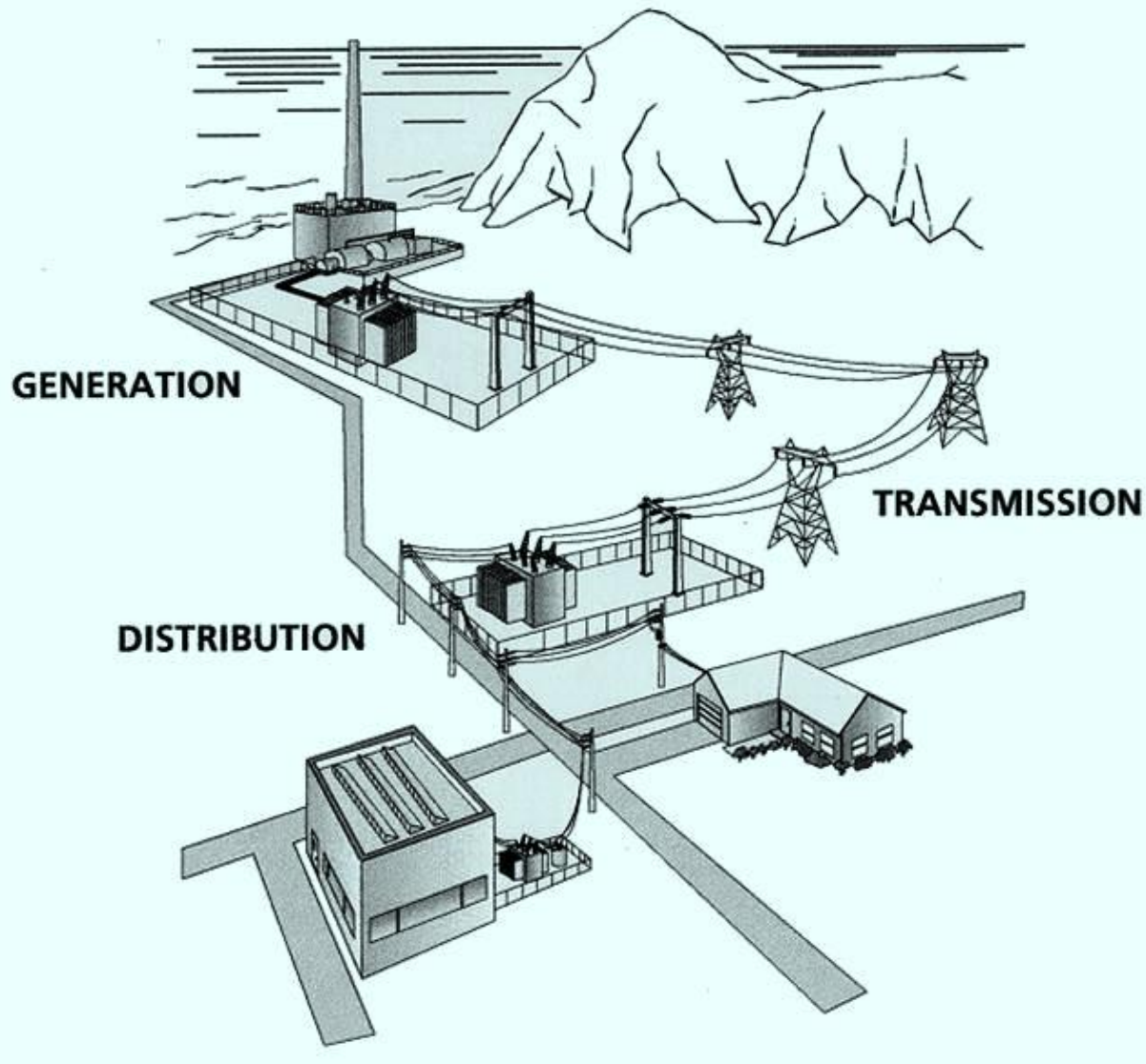


# Power Grid Components



This presentation  
focuses on  
Transmission-level  
integration

# Renewable Integration Challenges



## Generation

- Ramp rates to match variability
- Economic dispatch

## Transmission

- Small signal stability
- Transient stability
- Low Voltage/  
Frequency ride-through
- Voltage stability

## Distribution

- Voltage control
- Power flows
- Protection

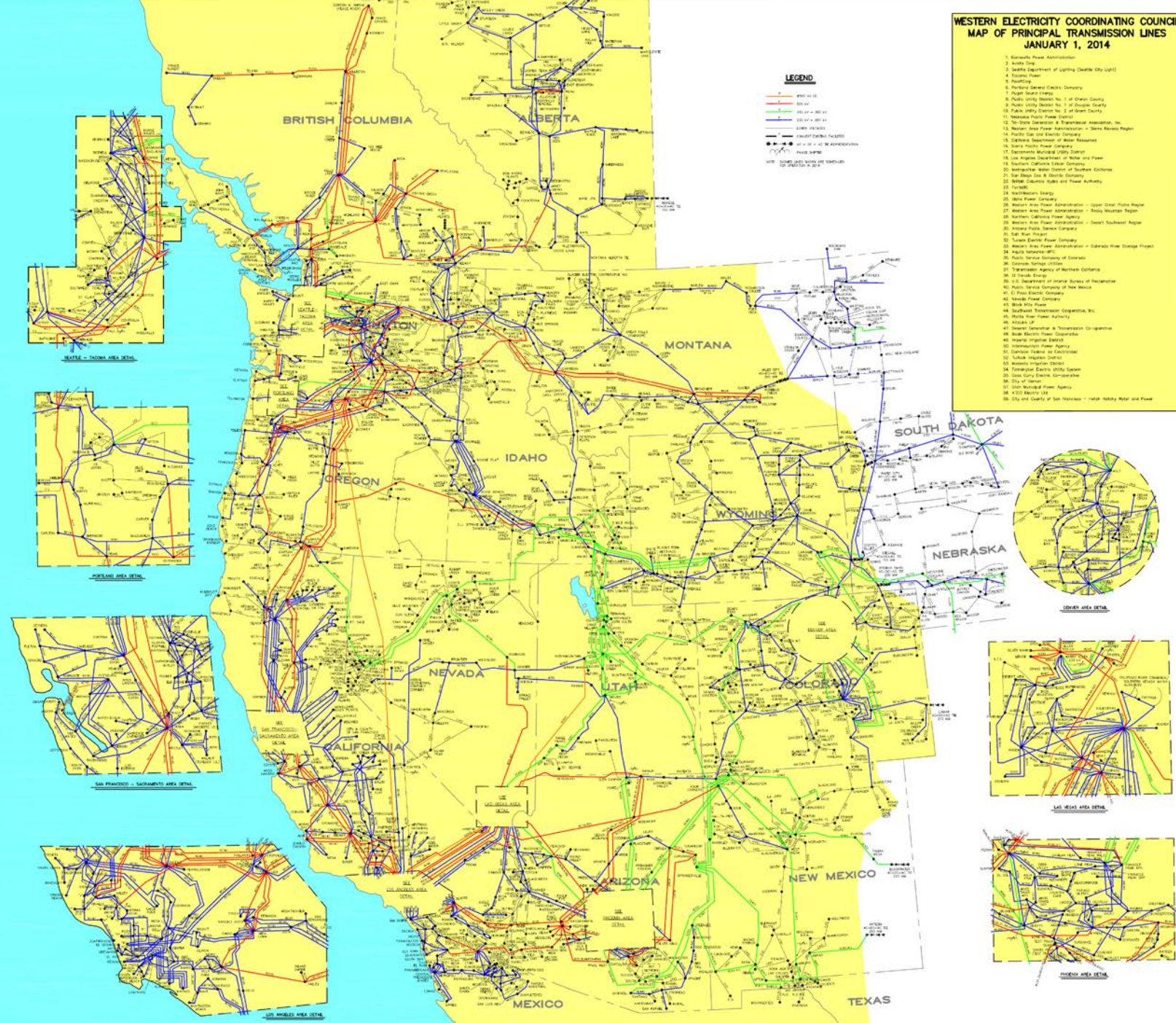


**WESTERN ELECTRICITY COORDINATING COUNCIL  
MAP OF PRINCIPAL TRANSMISSION LINES  
JANUARY 1, 2014**

**LEGEND**

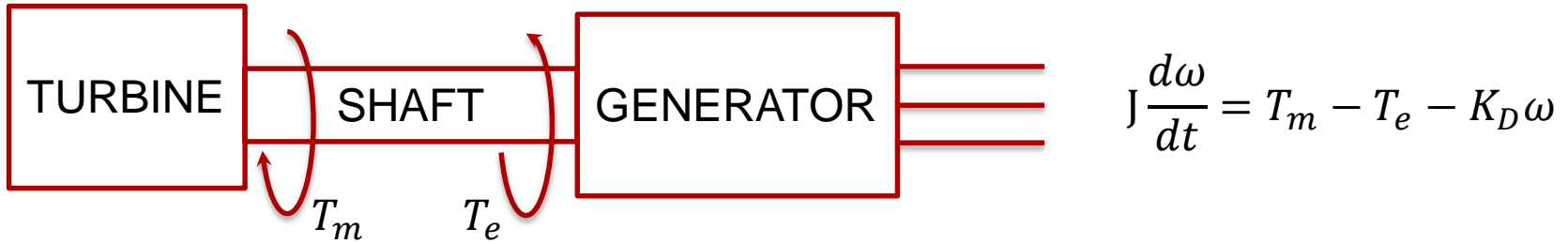
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1. Nevada Power Administration
2. Amity Corp.
3. Seattle Department of Lighting (Seattle City Light)
4. Tacoma Power
5. Puget Sound
6. Portland General Electric Company
7. Puget Sound Energy
8. Puget Sound Energy No. 1 of Oregon County
9. Puget Sound Energy No. 2 of Oregon County
10. Puget Sound Energy No. 3 of Oregon County
11. Nevada Public Power District
12. Toiyabe National Park & Transmission Association, Inc.
13. Western Area Power Administration - Nevada Region
14. Pacific Gas and Electric Company
15. California Department of Water Resources
16. Sierra Pacific Power Company
17. Sacramento Municipal Utility District
18. Los Angeles Department of Water and Power
19. Southern California Edison Company
20. Metropolitan Water District of Southern California
21. San Diego Gas & Electric Company
22. Western California Edison and Power Authority
23. TCEC
24. Northwestern Energy
25. West Power Company
26. Western Area Power Administration - Upper Great Plains Region
27. Western Area Power Administration - Rocky Mountain Region
28. Northern California Power Agency
29. Western Area Power Administration - Southwestern Region
30. Arizona Public Service Company
31. Salt River Project
32. Tucson Electric Power Company
33. Western Area Power Administration - Colorado River Storage Project
34. Aquila Interests, LLC
35. Pacific Service Company of Colorado
36. Colorado Springs Utilities
37. Transwestern Agency of Western Colorado
38. U.S. Energy Corp.
39. U.S. Department of Interior Bureau of Reclamation
40. Basin Electric Company of New Mexico
41. U.S. Energy Corp.
42. Nevada Power Company
43. Black Hills Power
44. Southwest Transmission Corporation, Inc.
45. White Pine Power Authority
46. Alaska LP
47. Inland Empire & Transmission Co-operative
48. Basin Electric Power Corporation
49. Inland Empire & Transmission Co-operative
50. Intermountain Power Agency
51. Colorado Public Electric Service
52. Utah Valley Electric
53. Western Interconnection
54. Transwestern Electric Utility System
55. Utah Valley Electric
56. City of Denver
57. Colorado Public Electric Service
58. AT&T Electric Ltd.
59. City and County of San Francisco - Public Utility Water and Power

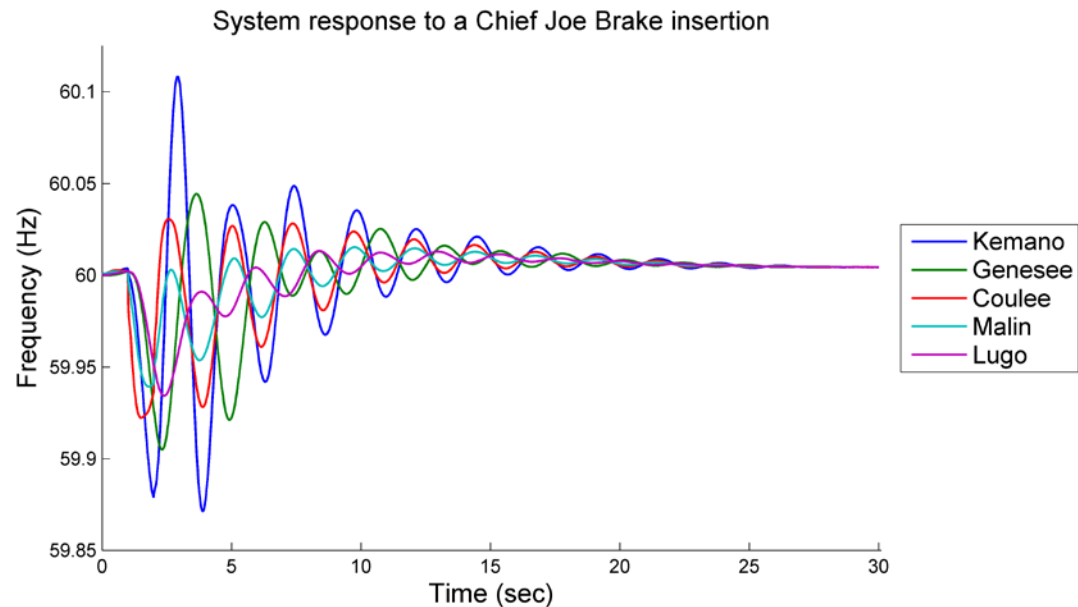
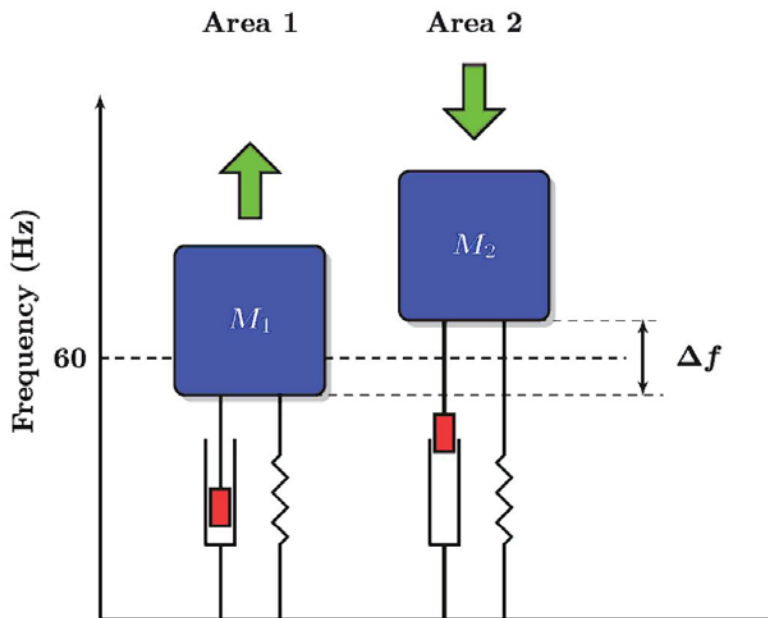


# Frequency Regulation

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



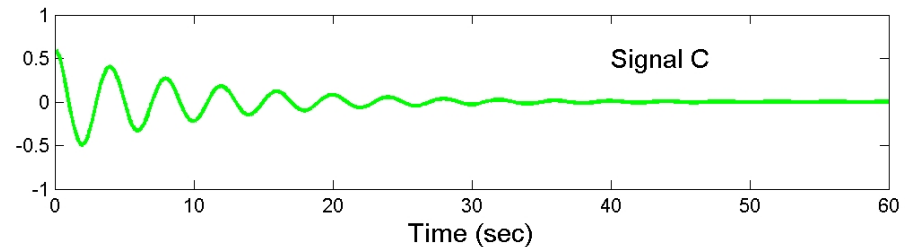
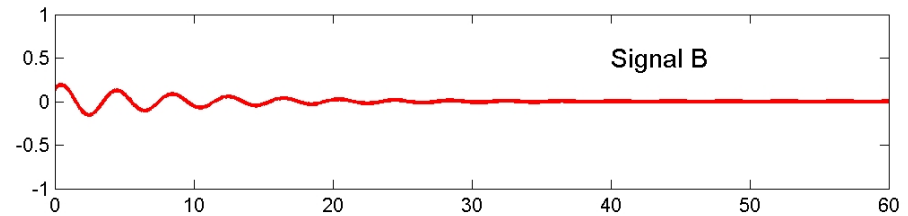
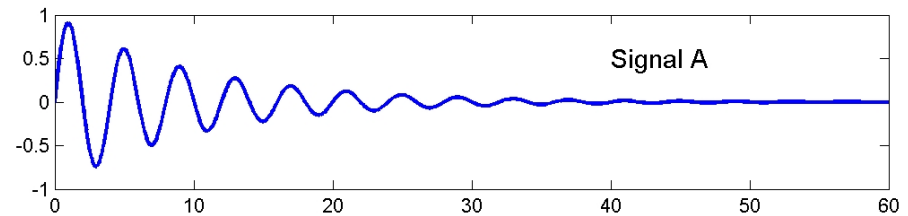
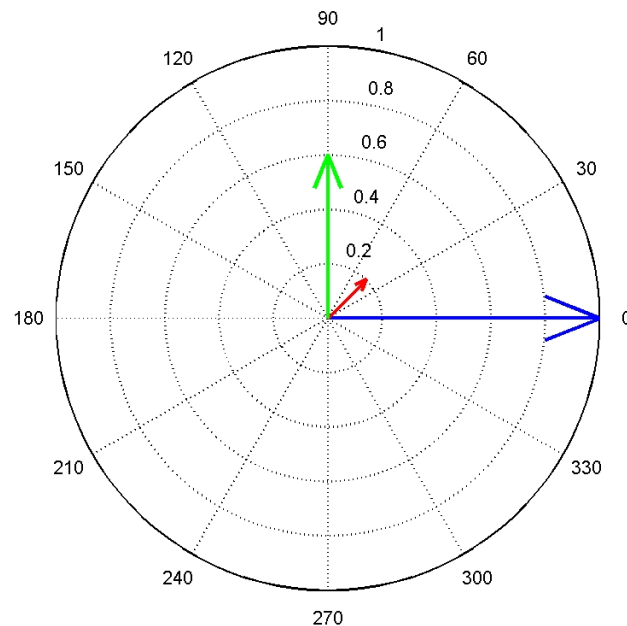
- For constant  $T_m$  (mechanical power),  
 load  $\uparrow$ , frequency  $\downarrow$       load  $\downarrow$ , frequency  $\uparrow$





# What is Mode Shape?

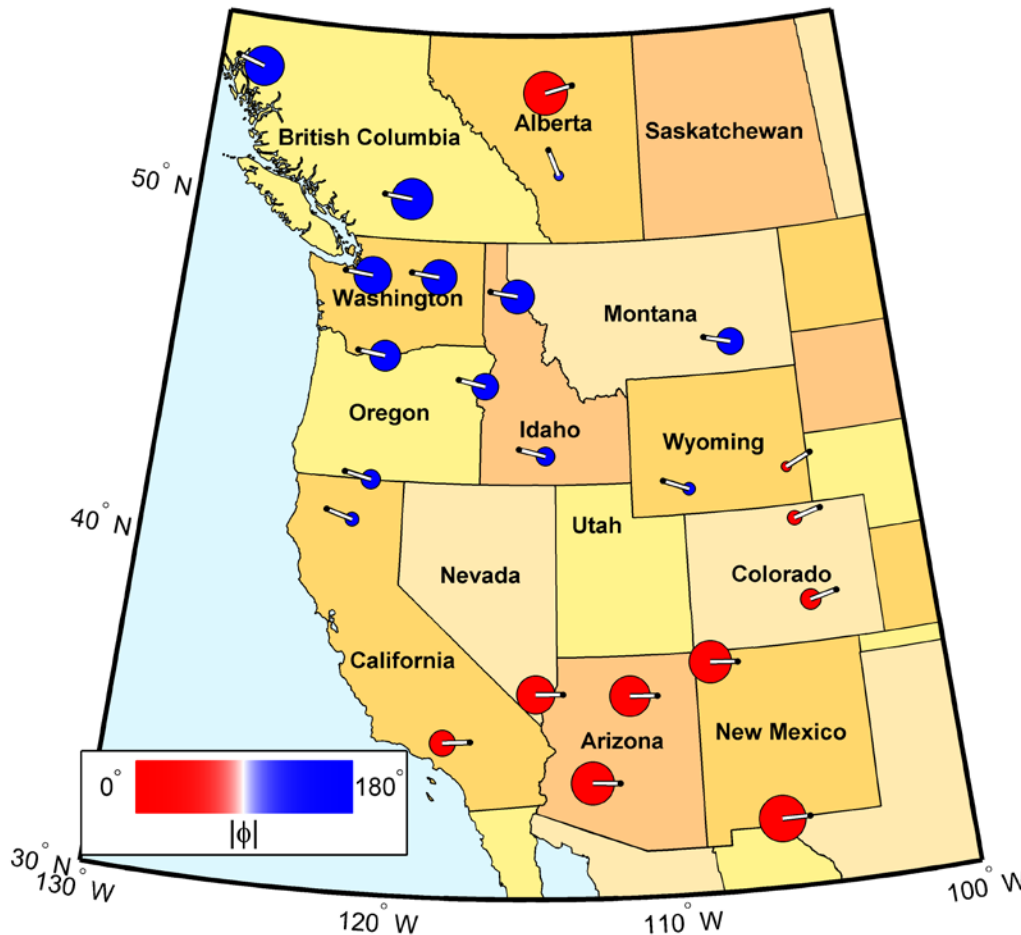
- Mode shape is defined by
  - Amplitude at each location
  - Phase at each location
- Typically look at
  - Generator speed (frequency)
  - Frequency measurements



$$\begin{aligned}y_A(t) &= 1.0 \cos(2\pi f + 0) \\y_B(t) &= 0.2 \cos(2\pi f + \pi/4) \\y_C(t) &= 0.6 \cos(2\pi f + \pi/2)\end{aligned}$$

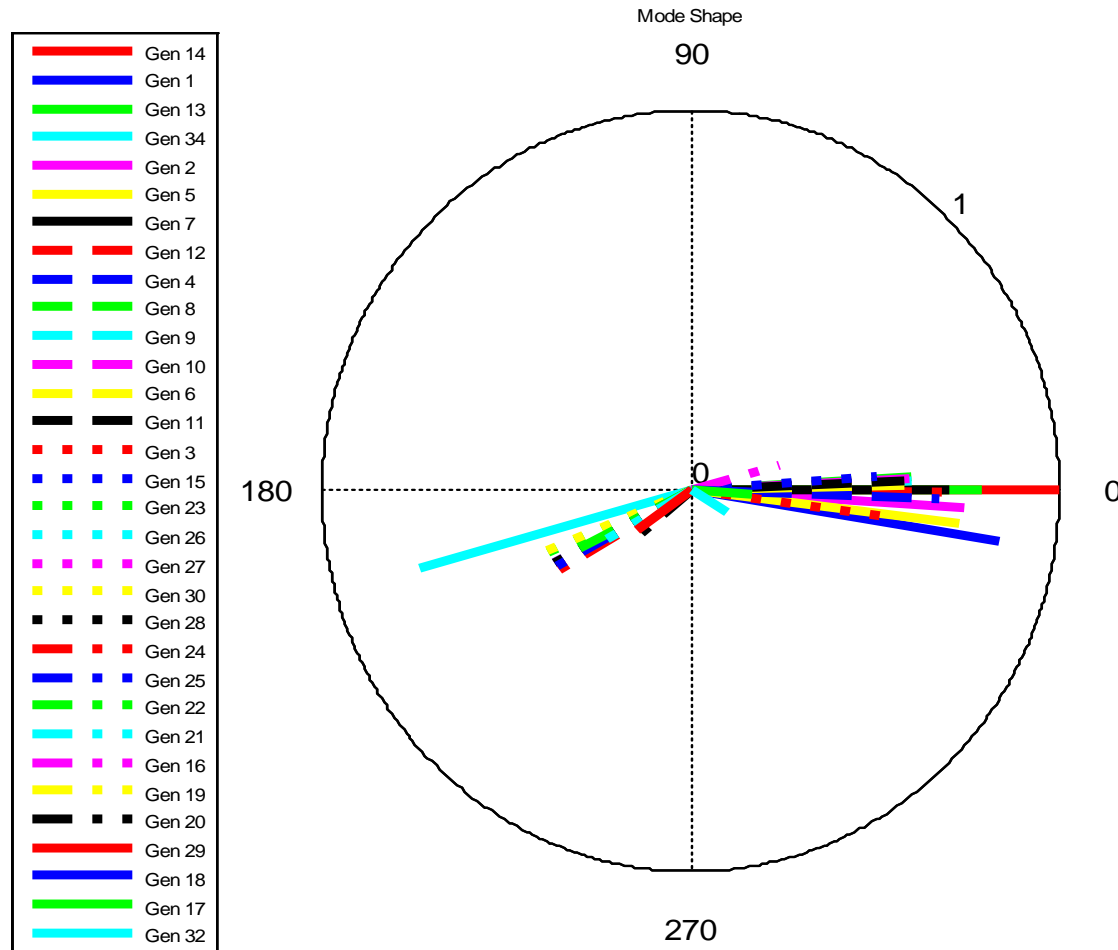
# Visualizing Mode Shape

- 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

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

- 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

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

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

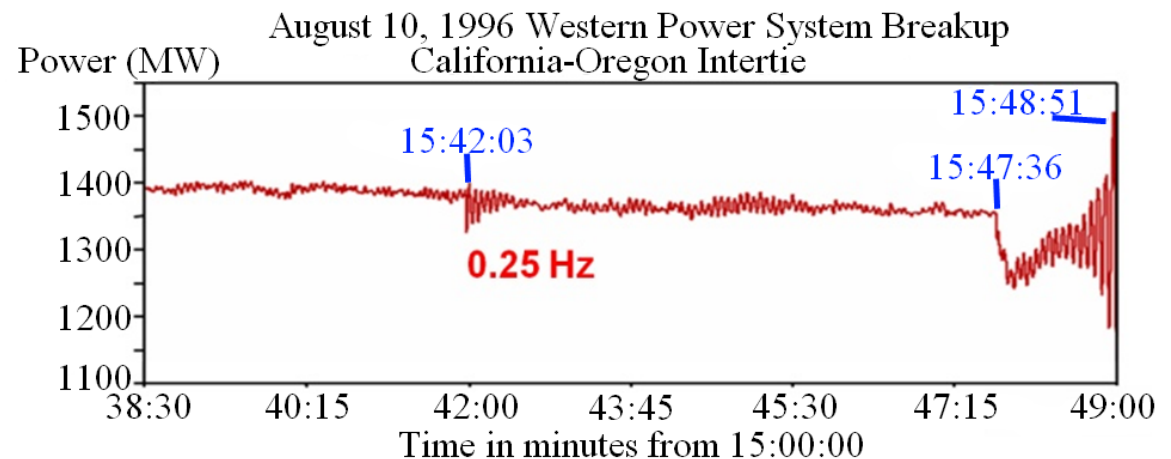
$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \quad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_r} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$
$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} \quad D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\ \vdots & \ddots & \vdots \\ \frac{\partial g_n}{\partial u_1} & \cdots & \frac{\partial g_n}{\partial u_r} \end{bmatrix}$$



# Why are we concerned?

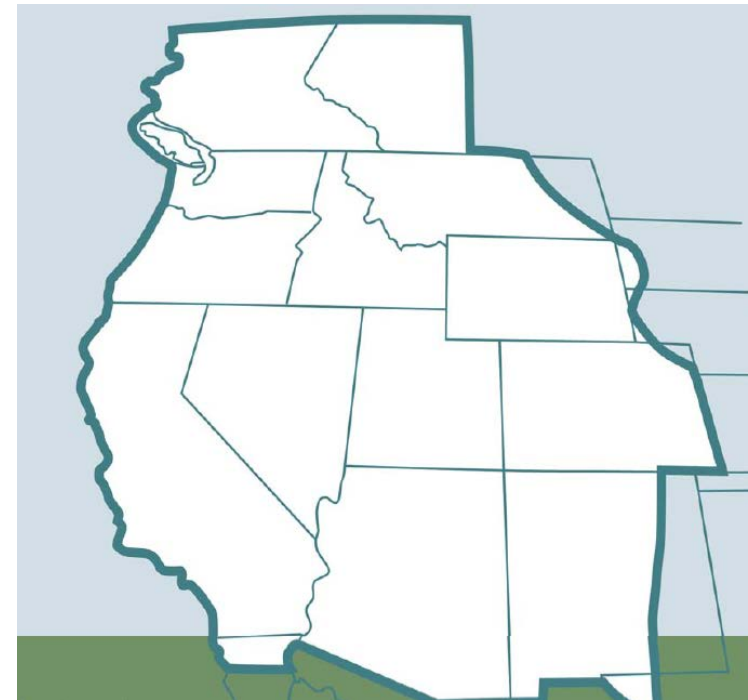
- Power systems are susceptible to low frequency oscillations caused by generators separated by long transmission lines that oscillate against each other
- These oscillations are not as well damped as higher frequency “local” oscillations
- High penetration of renewable generation can impact mode shape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

1996 breakup  
caused by low-  
frequency  
oscillations

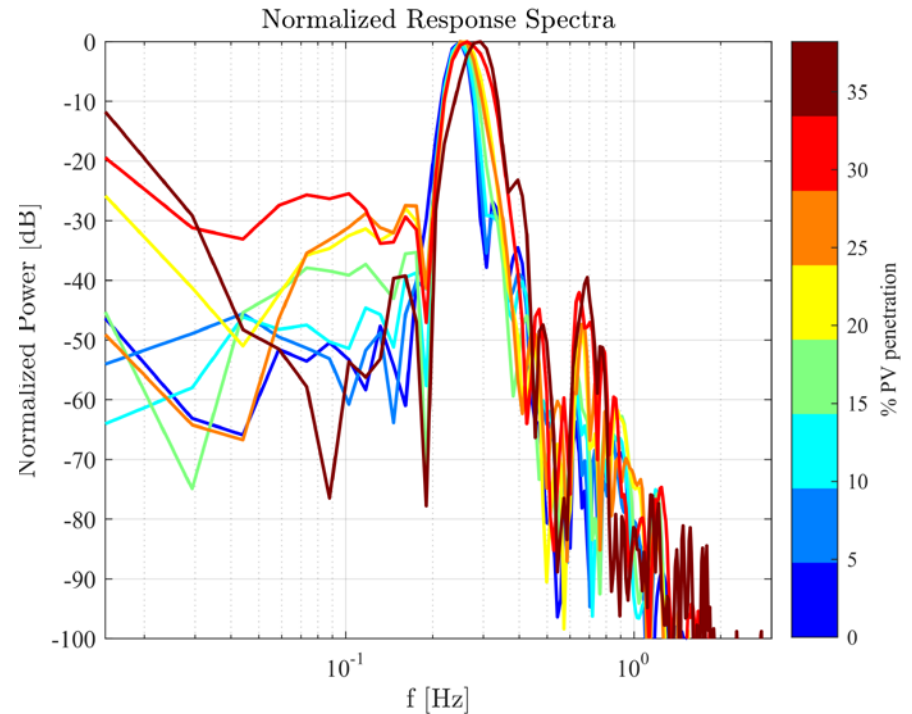
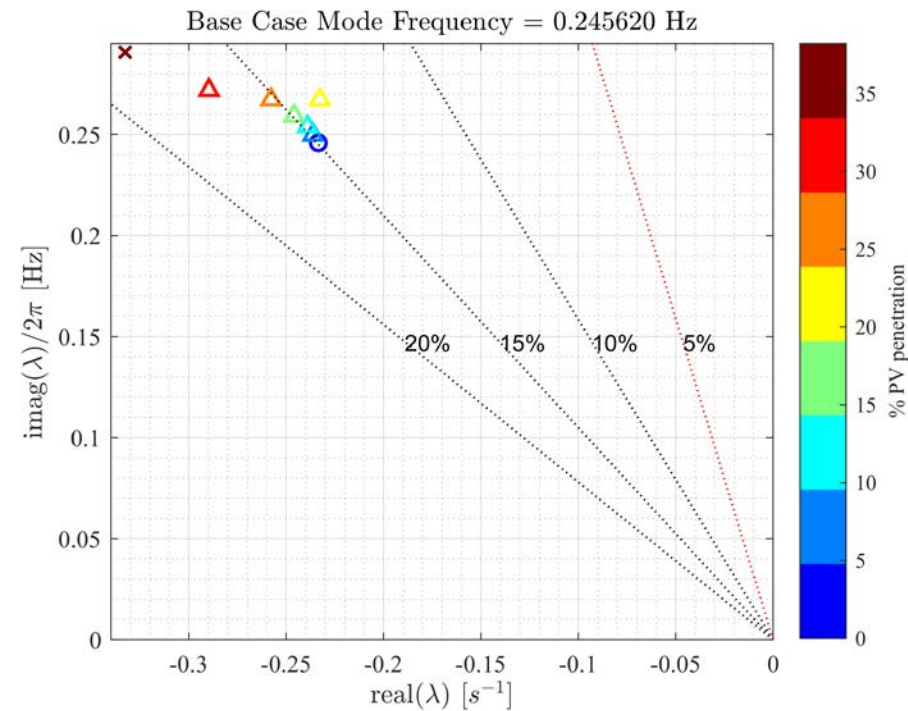


# Why are we concerned?

- 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



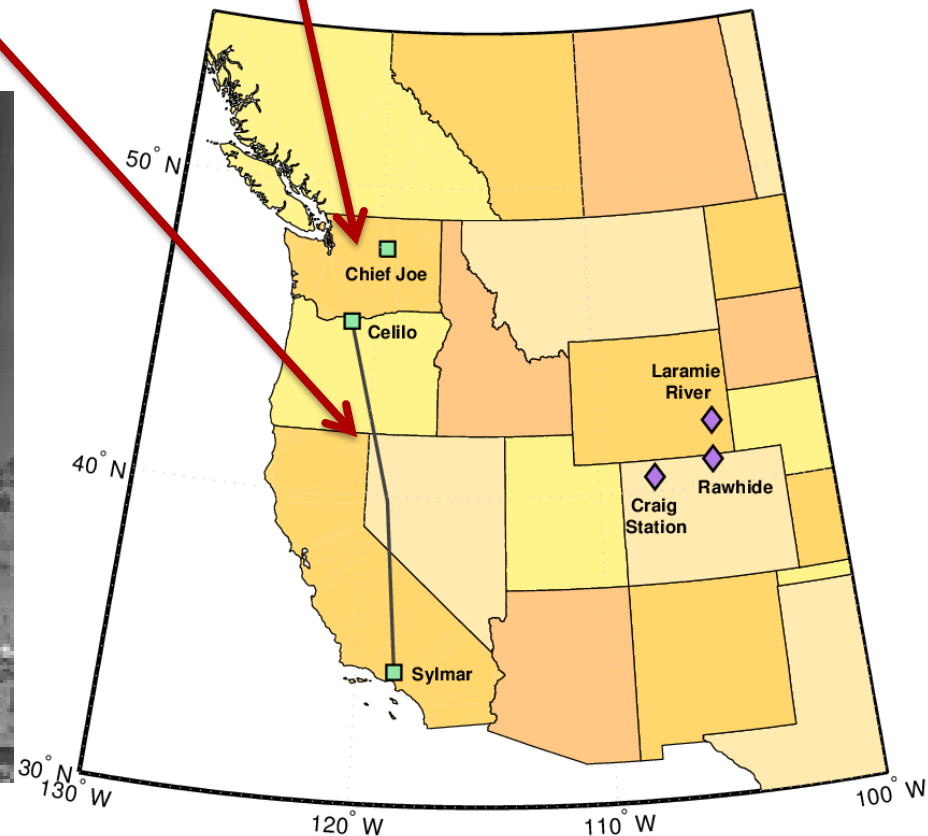
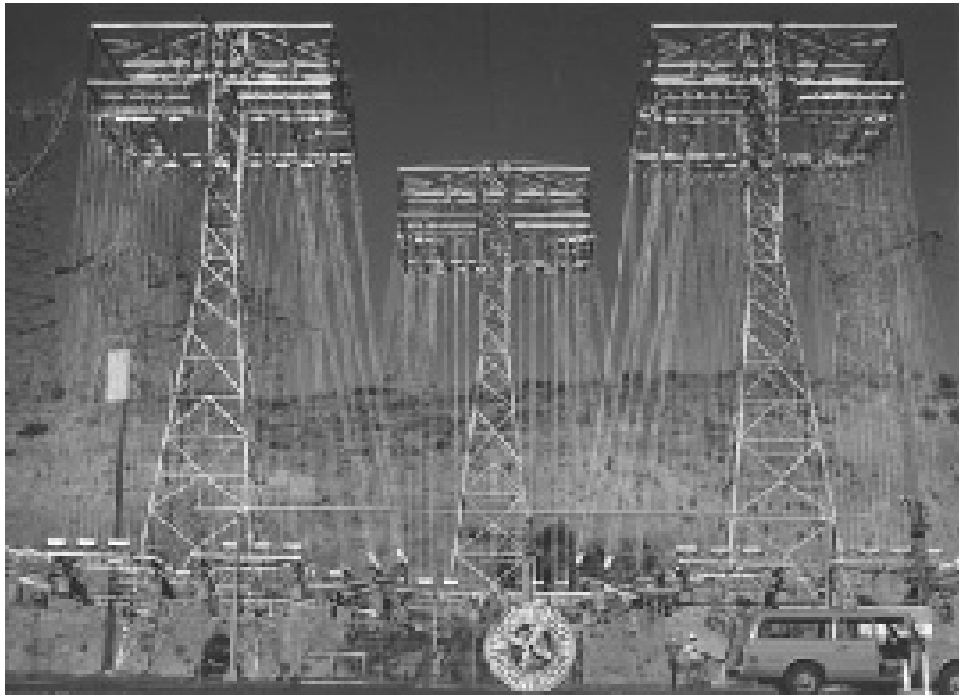
# What happens with Increased Renewables?



- 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):

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

- Partition the system into N-interconnected systems:

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

- $e_{ij}$  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<sup>1</sup>

<sup>1</sup>D. D. Siljak, Decentralized Control of Complex Systems. Academic Press, 1991.

# Power System 2-area Model

- Partition the system

$$A = \begin{bmatrix} \boxed{-\frac{D_1}{M_1} & -\frac{T}{M_1}} & 0 & \frac{T}{M_1} \\ 1 & 0 & 0 & 0 \\ 0 & \frac{T}{M_2} & \boxed{-\frac{D_2}{M_2} & -\frac{T}{M_2}} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \boxed{\frac{1}{M_1}} & 0 \\ 0 & 0 \\ 0 & \boxed{\frac{1}{M_2}} \\ 0 & 0 \end{bmatrix}$$

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

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

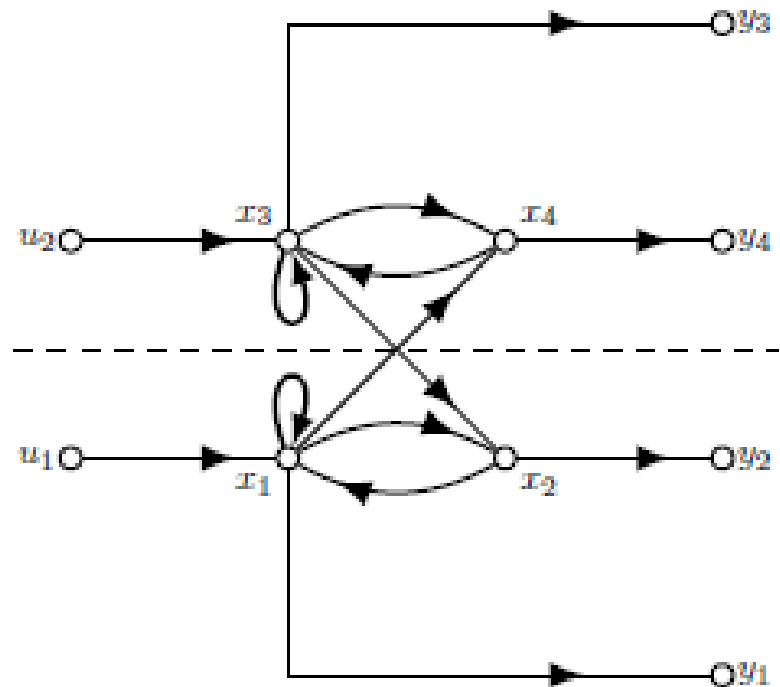


Fig. 2. Two-area system digraph.

# 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:

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

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

# Power System n-area Model

- Local feedback – uncertainty in coupling

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

- Global feedback – uncertainty in coupling and communications

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

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



# 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

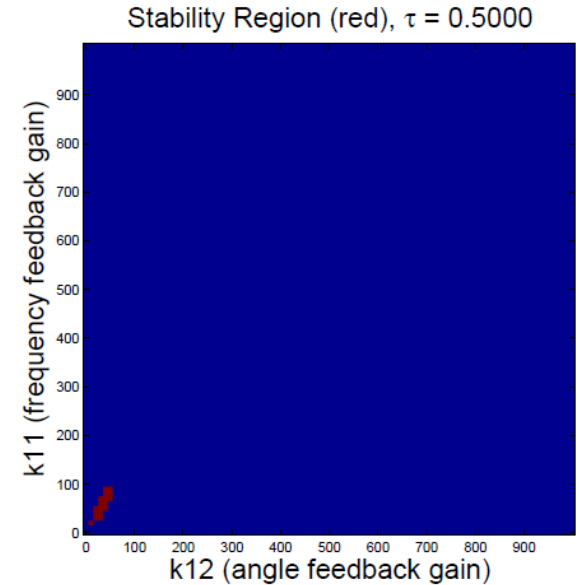
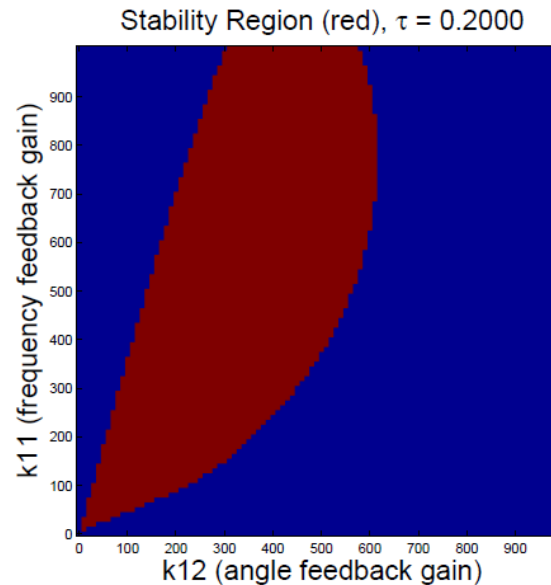
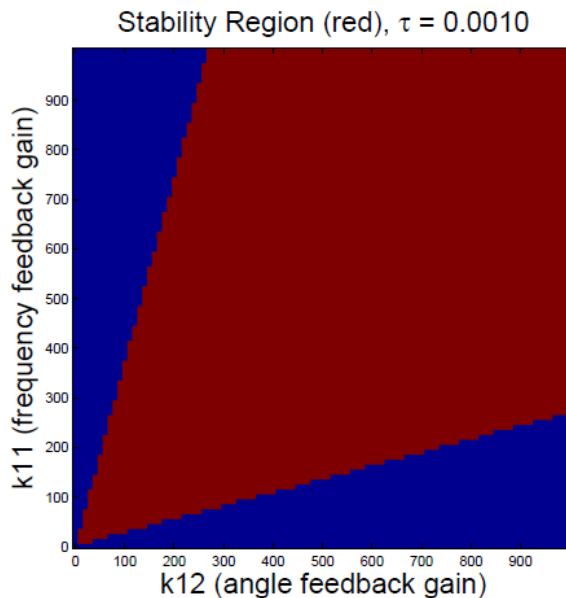
- where

the matrices  $H_i$  and  $G_i$  satisfy the Lyapunov matrix equation

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

- 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

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

- 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