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High Wind/Solar Grid Stability Study

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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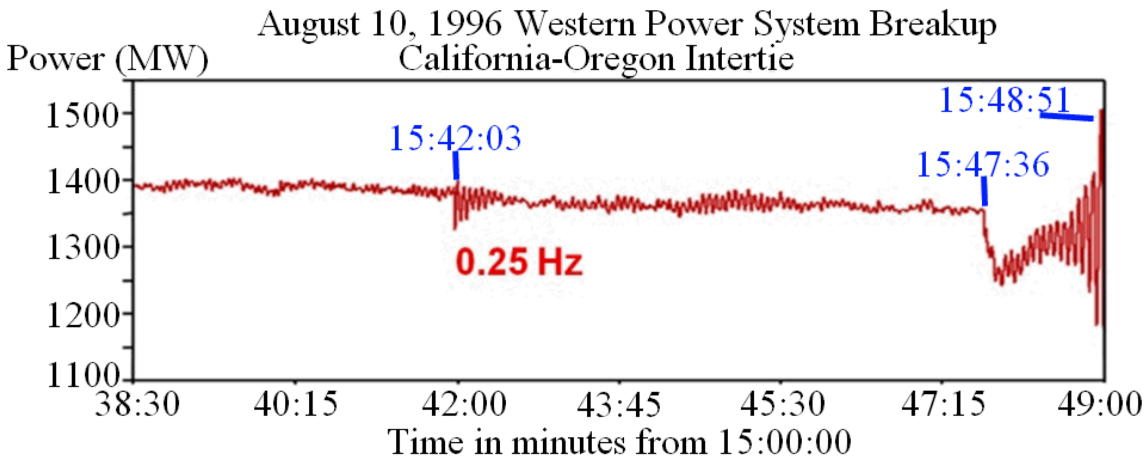
About Me

- Missouri University of Science and Technology
  - Formerly University of Missouri-Rolla
- PhD Student
- Electrical Engineering
- Expected Graduation Date: May 2014

Low Frequency Power System Oscillations

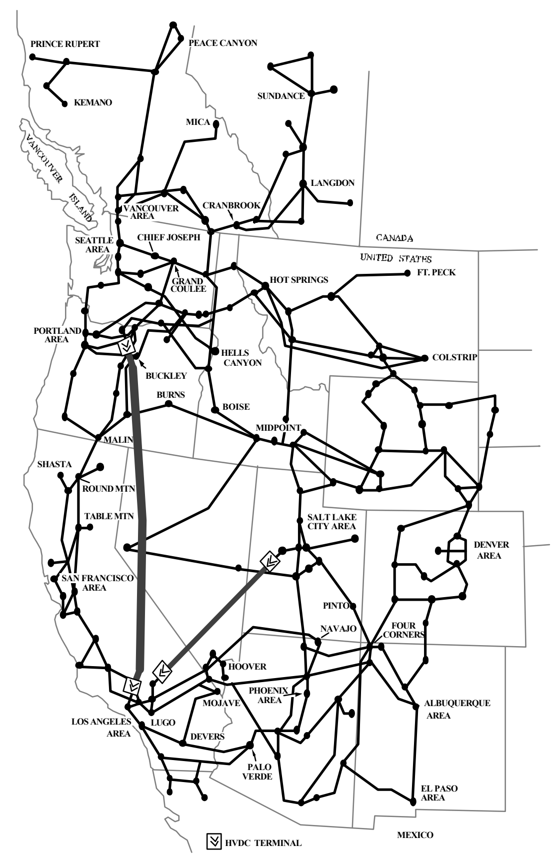
- Project Goal: Evaluate the small signal and transient stability of the WECC with high penetrations of wind and solar in 2022
  - The western United States are more susceptible to low frequency power system oscillations caused by generators separated by long transmission lines that oscillate against each other
  - These oscillations are not as well damped as higher frequency “local” oscillations

1996 breakup caused by low-frequency oscillations



Oscillations in the WECC

- There are several low frequency oscillation modes in the Western Electricity Coordinating Council (WECC) region
  - “North-South” mode nominally near 0.25 Hz;
  - “Alberta-BC” mode nominally near 0.4 Hz;
  - “BC” mode nominally near 0.6 Hz; and,
  - “Montana” mode nominally near 0.8 Hz.
- System Inertia
  - Large conventional generators provide a significant amount of inertia to the system, which improves transient response
  - Increased renewable penetration (e.g. wind and solar) has the potential to greatly reduce system inertia and lead to stability issues



My Part of the Project

- Develop test cases based on WECC base case models (in PSLF)
- Generate statistics for each test case
- Perform modal analysis on the data to characterize the system stability
- PSLF (Positive Sequence Load Flow)
  - GE software for analyzing power systems
  - “epcl” language for writing scripts and new models
- Power system modal analysis
  - If you have the equations, eigenvalue analysis
  - For real data or large systems
    - Prony analysis
    - Matric pencil

Base Case Statistics

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- 2022 Light Spring TEPPC Scenario Case
  - Renewable penetrations consistent with state RPS requirements in 2022
  - Grouped into 21 Areas
  - Total Generation: 116,971 MW
  - Installed Generation: 290,764 MW
- Metrics on Dispatch and Commitment
  - GR – Governor Responsive
  - BL – Base Load
  - NG – No Governor
  - Kt – ratio of power generation capability of units with governor response to the MW capability of all generation units

Generation Summary	
GR Pgen (MW)	89,317
GR MWCAP (MW)	117,768
GR Headroom (MW)	28,451
BL Pgen (MW)	6,444
NG Pgen (MW)	3,085
Wind Pgen (MW)	**17,559**
Solar Pgen (MW)	**102**
# GR Units	1,348
# BL Units	244
# NG Units	521
# Wind/Solar Units	**496**
MW Capability	144,958
CU Pgen (MW)	**98,847**
Total Pgen	**116,971**
Total Pload	91,294
Wind Pgen/Total Pgen	**15.0%**
Solar Pgen/Total Pgen	**0.1%**
Kt	**81.2%**
GR Pgen/CU Pgen	90.4%
GR Pgen/Total Pgen	76.4%
GR Headroom/CU Pgen	28.8%
GR Headroom/Total Pgen	24.3%

*California ISO (CAISO) Frequency Response Study, GE Energy Consulting, N. W. Miller, 2011

**John Undrill, “Power and Frequency Control as it Relates to Wind-Powered Generation”, Lawrence Berkeley National Laboratory Report, LBNL-4143E, December 2010.

Base Case Statistics

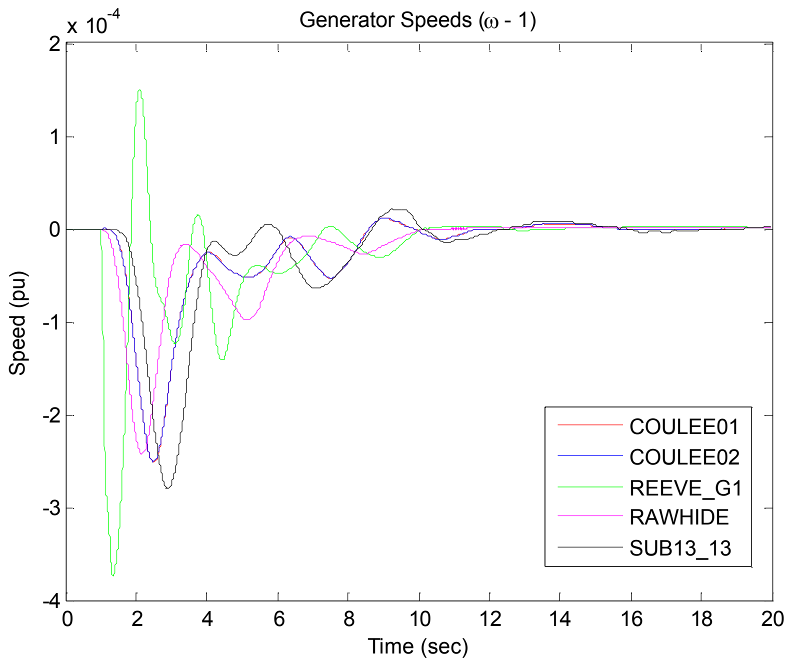
Area	# of Units	Renewable Generation (MW)	Renewable Installed (MW)	% Generation
10	9	1,035.16	1,668.31	62%
11	0	-	-	-
14	1	50.40	50.40	100%
18	2	-	586.00	0%
20	0	-	-	-
21	0	-	-	-
22	79	330.40	726.20	46%
24	176	3,791.05	7,720.14	49%
26	4	150.00	430.50	35%
30	89	693.28	1,314.78	53%
40	92	8,357.92	11,272.40	74%
50	0	-	-	-
52	0	-	-	-
54	5	50.00	81.60	61%
60	16	458.00	849.90	54%
62	0	-	-	-
63	0	-	-	-
64	2	129.99	351.60	37%
65	1	40.02	99.00	40%
70	15	1,906.99	2,275.50	84%
73	5	666.99	667.20	100%

- Wind/Solar Generation
  - Wind: Gen – 17,558 MW; Installed – 27,918 MW (61%)
  - Solar: Gen – 101 MW; Installed – 175 MW (58%)
  - 496 Renewable Units, 88% of Wind is from types 3 & 4

	Total Generation (MW)	Renewable Generation (MW)
Light Spring 2022 (Original WECC Case)	116,970	17,660
Nominal Renewable Output	116,970	12,696
Increased Solar	116,970	18,152
Low Load / High Renewable Output	114,618	18,152
High Load / High Renewable Output	125,526	17,660

Modal Analysis

- In order to evaluate the modes of the system, different "impulse" stimulus are applied
  - A 0.5 second change in output power of a generator (e.g. Palo Verde)
  - A 0.5 second increase in load (e.g. Chief Joseph brake)
- The resulting ringdown in generator speeds (system frequency) are analyzed to pull out the modes of the system



Modal Analysis Techniques

$$\hat{y}(t) = \sum_{i=1}^{n} B_i e^{\lambda_i t} \longrightarrow \hat{y}(k) = \sum_{i=1}^{n} B_i z^k$$

- **Prony Analysis**
  - Construct a discrete linear prediction model from the measured signal

$$\begin{bmatrix} y(n-1) & y(n-2) & \cdots & y(0) \\ y(n-0) & y(n-1) & \cdots & y(1) \\ \vdots & \vdots & \vdots & \vdots \\ y(N-2) & y(N-3) & \cdots & y(N-n-1) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} y(n) \\ y(n+1) \\ \vdots \\ y(N-1) \end{bmatrix}$$

  - Find the roots of the characteristic polynomial of the model

$$\begin{bmatrix} z_1^0 & z_2^0 & \cdots & z_n^0 \\ z_1^1 & z_2^1 & \cdots & z_n^1 \\ \vdots & \vdots & \vdots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \cdots & z_n^{N-1} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = \begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix}$$

  - Solve for modal parameters using the roots as the complex modal frequencies for the signal

- **Matrix Pencil**
  - Choose pencil parameter *L*
  - Construct Hankel matrix [*Y*]

$$[Y] = \begin{bmatrix} y(0) & y(1) & \cdots & y(L) \\ y(1) & y(2) & \cdots & y(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L) & y(N-L+1) & \cdots & y(N) \end{bmatrix}$$

  - Perform Singular Value Decomposition of [*Y*]

$$[Y] = [U][S][V]^T$$

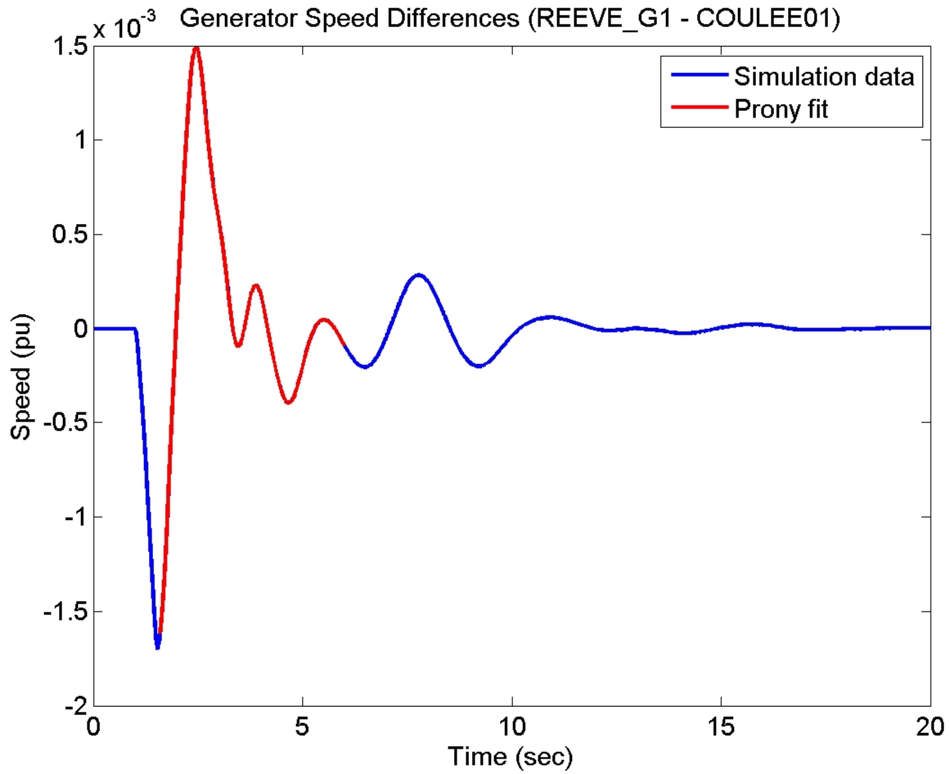
  - Set up generalized eigensystem for pole computation

$$[V_1] = [v_1 \quad v_2 \quad v_3 \quad \cdots \quad v_{n-1}] \qquad [Y_1] = [V_1]^T [V_1]$$
$$[V_2] = [v_2 \quad v_3 \quad v_4 \quad \cdots \quad v_n] \qquad [Y_2] = [V_2]^T [V_1]$$

  - Solve for modal parameters using poles *z* as in Prony method

Source: *Computational Methods for Electric Power Systems*, M. L. Crow, CRC Press, 2010

Prony Analysis



1 |Residue| = 3.9878e+36, pole = -62.239059 345.85j, damping = 0.177114

2 |Residue| = 3.9878e+36, pole = -62.239059 -345.85j, damping = 0.177114

3 |Residue| = 5.8935e+18, pole = -33.134991 0.00j, damping = 0.177114

4 |Residue| = 1.0757e+17, pole = -33.072341 79.82j, damping = 0.382786

5 |Residue| = 1.0757e+17, pole = -33.072341 -79.82j, damping = 0.382786

6 |Residue| = 3.6599e+13, pole = -29.397770 554.68j, damping = 0.052925

7 |Residue| = 3.6599e+13, pole = -29.397770 -554.68j, damping = 0.052925

8 |Residue| = 5.9204e+07, pole = -22.714937 747.99j, damping = 0.030354

9 |Residue| = 5.9204e+07, pole = -22.714937 -747.99j, damping = 0.030354

Next Steps

- Modal information gives us insight into stability of the system under different penetration scenarios
- This information can be applied to control techniques to improve grid stability with high wind/solar penetrations:
  - Power modulation (two schemes, proportional to: local frequency error and wide area frequency measurements)
    - With energy storage
    - With curtailment
  - Emulated Inertia (virtual rotor angle)
  - Brake resistor damping
  - VAR modulation
- From an Energy Surety perspective:
  - Renewable sources improve Sustainability
  - Improved Stability from optimized control techniques will help with Reliability and Cost concerns