

Iterative Matrix Pencil Method of Electric Grid Modal and Oscillation Analysis and Visualization

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Signal-Based Modal Analysis

- With the advent of large numbers of PMUs, measurement based modal analysis is increasingly used to understand power system behavior
 - The goal is to determine the damping associated with the dominant oscillatory modes in the system
 - Approaches seek to approximate a sampled signal by a series of exponential functions (usually damped sinusoidals)
- Techniques can also be used in dynamic simulation applications
- Several techniques are available
 - Prony is the oldest, dating to 1795, with power system applications from about 1980's



Presentation Overview

- Presentation discusses an approach to quickly handle a large number of signals
 - Goal is to make modal analysis and visualization an easy part of standard engineering studies; fully integrated into PowerWorld Simulator
 - Results can be extended to determine and visualize the source of oscillations
- Many of results are from
 - W. Trinh, K. Shetye, I. Idehen, T.J. Overbye, “Iterative Matrix Pencil Method for Power System Modal Analysis”, Proc. HICSS Jan 2019
 - I. Idehen, B. Wang, K.S. Shetye, T.J. Overbye, J.D. Weber, "Visualization of Large-Scale Electric Grid Oscillation Modes," Proc. 2018 North American Power Symposium, Fargo, ND, September 2018



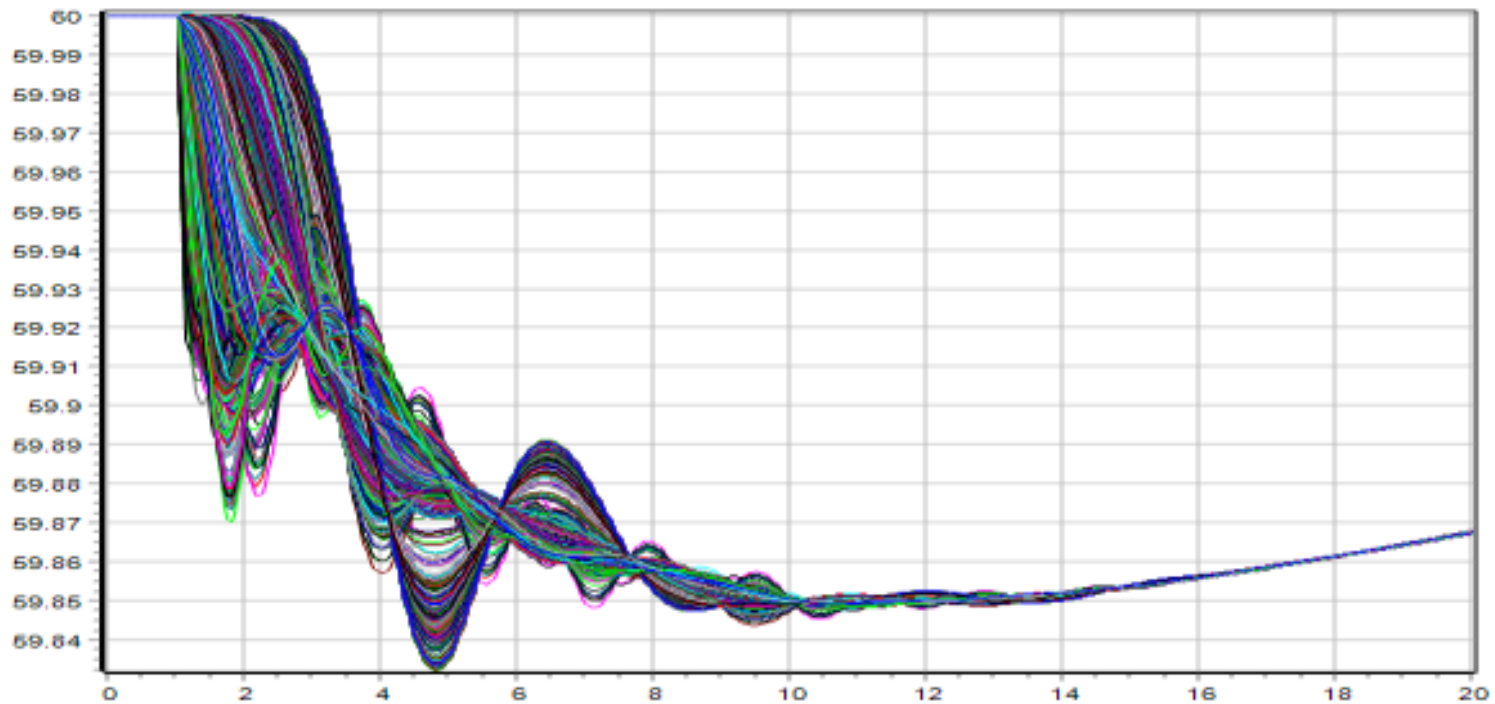
Ring-down Modal Analysis

- A variety of different techniques can be used to approximate a signal, $y_{\text{org}}(t)$, by the sum of other, simpler signals (basis functions)
 - Basis functions are usually exponentials, with linear and quadratic functions used to detrend the signal
 - Properties of the original signal can be quantified from basis function properties
 - Examples are frequency and damping
 - Signal is considered over some time window, with $t=0$ defined as the beginning of the window
- Starting point is time-varying signal, $y_{\text{org}}(t)$, that is then assumed to be uniformly sampled



Example Application

- An example application is to make sense of the frequency response following a contingency
 - Below example at the shows the frequency variation at 8400 substations



Quick Access to Modal Analysis

Transient Stability Analysis

Simulation Status: Not Initialized

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find My Transient Contingency

Select Step

- Simulation
- Options
- Result Storage
- Plots
- Results from RAM
 - Time Values
 - Generator
 - Bus
 - Load
 - Switched Shunt
 - Branch
 - Transformer
 - DC Transmission Line
 - VSC DC Line
 - Multi-Terminal DC Record
 - Area
 - Zone
 - Interface
 - Injection Group
 - Substation
 - Line Shunt
 - Case Information
 - Measurement Model
 - Model Plane
 - Minimum/Maximum Values
 - Summary
 - Events
 - Solution Details
- Transient Limit Monitors
- States/Manual Control
- Validation
 - SMIB Eigenvalues
 - Modal Analysis
 - Dynamic Simulator Options

Results from RAM

Time Values Minimum/Maximum Values Summary Events Solution Details

Generator Bus Load Switched Shunt Branch Transformer DC Transmission Line VSC DC Line Multi-Terminal DC Record

Column Order: Object then Field

Column Filtering: Filter Modify...

Use Area/Zone Filters

Choose Fields to Display

- Frequency Average
- Gen Mvar
- Gen MW
- Gen MW Accel
- Gen MW Mech
- GIC EField Direction
- GIC EField Magnit...
- GIC Mvar
- GIC Neutral Current
- ROCOF (Hz per S...)
- V pu Average
- V pu Max
- V pu Min
- V pu Min Highest ...

Time	Substation 18004	Substation 18005	Substation 18010	Substation 18015	Substation 18028	Substation 18029	Substation 18031
Frequency Average	Frequency Average	Frequency Average	Frequency Average	Frequency Average	Frequency Average	Frequency Average	Frequency Average
1	0	60	60	60	60	60	60
2	0.05	60	60	60	60	60	60
3	0.1	60	60	60	60	60	60
4	0.15	60	60	60	60	60	60
5	0.2	60	60	60	60	60	60
6	0.25	60	60	60	60	60	60
7	0.3	60	60	60	60	60	60
8	0.35	60	60	60	60	60	60
9	0.4	60	60	60	60	60	60
10	0.45	60	60	60	60	60	60
11	0.5	60	60	60	60	60	60
12	0.55	60	60	60	60	60	60
13	0.6	60	60	60	60	60	60
14	0.65	60	60	60	60	60	60
15	0.7	60	60	60	60	60	60
16	0.75	60	60	60	60	60	60
17	0.8	60	60	60	60	60	60
18	0.85	60	60	60	60	60	60
19	0.9	60	60	60	60	60	60
20	0.95	60	60	60	60	60	60
21	1	60	60	60	60	60	60
22	1	60	60	60	60	60	60
23	1.05	59.9907	59.99	59.9928	59.9907	59.9905	59.9909
24	1.1	59.982	59.9811	59.9833	59.9821	59.9818	59.9824
25	1.15	59.9736	59.9725	59.9739	59.9738	59.9734	59.974
26	1.2	59.9656	59.9643	59.9663	59.9658	59.9655	59.966
27	1.25	59.9558	59.9568	59.9602	59.9582	59.958	59.9583
28	1.3	59.9507	59.9496	59.9546	59.9509	59.9508	59.9508
29	1.35	59.9438	59.9429	59.9482	59.944	59.9439	59.9437
30	1.4	59.9373	59.9366	59.9406	59.9374	59.9374	59.9376
31	1.45	59.9314	59.9309	59.9326	59.9315	59.9308	59.9323
32	1.5	59.9264	59.926	59.9253	59.9265	59.9267	59.9265
33	1.55	59.9225	59.9222	59.92	59.9226	59.9228	59.9216
34	1.6	59.9197	59.9194	59.9171	59.9197	59.92	59.9188
35	1.65	59.9179	59.9175	59.9162	59.9179	59.9182	59.9171
36	1.7	59.9168	59.9163	59.9163	59.9168	59.9172	59.9163
37	1.75	59.9162	59.9157	59.9164	59.9162	59.9166	59.916
38	1.8	59.916	59.9155	59.916	59.916	59.916	59.9171
39	1.85	59.9161	59.9156	59.9153	59.9161	59.9163	59.9171
40	1.9	59.9164	59.916	59.9148	59.9164	59.9167	59.9167
41	1.95	59.9169	59.9166	59.915	59.917	59.9172	59.9176
42	2	59.9175	59.9173	59.9162	59.9176	59.9178	59.9179
43	2.05	59.9181	59.9179	59.9178	59.9183	59.9184	59.9186
44	2.1	59.9187	59.9185	59.9193	59.9189	59.919	59.9191
45	2.15	59.9191	59.9188	59.92	59.9193	59.9193	59.9194
46	2.2	59.9192	59.9189	59.9199	59.9195	59.9194	59.9194
47	2.25	59.9192	59.9188	59.919	59.9194	59.9192	59.9194
48	2.3	59.919	59.9187	59.918	59.9192	59.9193	59.9193
49	2.35	59.9189	59.9186	59.9174	59.919	59.9191	59.9189
50	2.4	59.9188	59.9185	59.9173	59.9189	59.919	59.9189

Process Contingencies

- One Contingency at a time
- Multiple Contingencies

Load from Hard Drive File into RAM results specified by Store to RAM Options | Clear Time Values from RAM | Clear Min/Max Values, Summary, Events, and/or Solution Details from RAM

Two click access to modal analysis of a signal or a group of signals



Quick Access to Modal Analysis

Modal Analysis Form

Modal Analysis Status: Solved at 1/15/2020 7:05:49 PM

Data Source Type

- From Plot
- File, WECC CSV 2
- File, JSIS Format
- File, Comtrade CFF
- File, Comtrade CFG
- None, Existing Data

Calculation Method

- Matrix Pencil (Once)
- Iterative Matrix Pencil
- Dynamic Mode Decomposition

Do Modal Analysis

Save in JSIS Format

Save to CSV

Data Source Inputs from Plots or Files

From Plot: Substation_Frequency Average

From File: [Browse]

Just Load Signals

Group Disabled for Existing Data

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 1.000

End Time: 20.000

Maximum Hz: 5,000

Update Sampled Data

Store Results in PWB File

Results

Number of Complex and Real Modes: 4

Lowest Percent Damping: -24.344

Include Detrend in Reproduced Signals

Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	Include Reprodu Signal
1	0.421	6.283	1.8122	Substation 180	-0.1664	YES
2	0.029	-24.344	85.4974	Substation 180	0.0455	YES
3	0.000	100.000	40.8104	Substation 180	-0.8490	YES
4	0.206	49.207	31.9597	Substation 180	-0.7306	YES

Input Data, Actual | Sampled Input Data | Signals | Options | Reproduced Data

Type	Name	Latitude	Longitude	Units	Description	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Average Uns
Substation	Substation 18031 Freq	36.241	-115.085		Average Frequency	YES	YES	59.9021	-0.0034	0	0.021	YES	

Close

Help

One click modal analysis of a single signal with default time period based on simulation events

And to Accuracy Verification

Modal Analysis Signal Dialog

Name: Substation 18031 Frequ
 Type: Substation
 Units:
 Description: Average Frequency, Hz
 Include in Modal Analysis

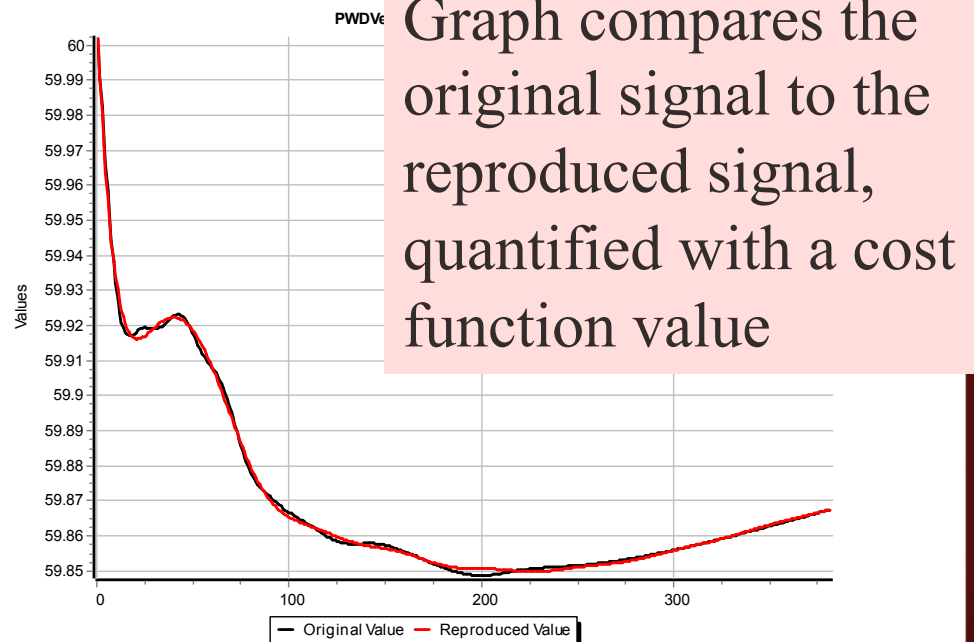
Data Detrend Parameters
 Detrend Model = $A + B*(t-t_0) + C*(t-t_0)^2$ Used Detrend Model: Linear
 Use Case Default Detrend Model
 Signal Specific Detrend Model: None, Linear, Constant, Quadratic
 Parameter A: 59.9021
 Parameter B: -0.0034
 Parameter C: 0.0000
 Standard Deviation (SD): 0.0207

Output Summary
 Average Error, Scaled by SD: 0.0008
 Average Error, Unscaled: 0.0000
 Cost Function Value, Scaled: 0.0036
 Include Detrend in Reproduced Signal
 Update Reproduced

Actual Input | Sampled Input | Fast Fourier Transform Results | Modal Results | Original and Reproduced Signal

	Time (Seconds)	Original Value	Reproduced Value	Difference
1	1.000	60.000	60.002	0.002
2	1.050	59.991	59.991	-0.000
3	1.100	59.982	59.981	-0.002
4	1.150	59.974	59.971	-0.003
5	1.200	59.966	59.963	-0.003
6	1.250	59.959	59.956	-0.003
7	1.300	59.951	59.949	-0.002
8	1.350	59.944	59.944	-0.001
9	1.400	59.938	59.939	0.001
10	1.450	59.932	59.934	0.002
11	1.500	59.927	59.931	0.003
12	1.550	59.924	59.927	0.004
13	1.600	59.921	59.925	0.004
14	1.650	59.919	59.922	0.003
15	1.700	59.918	59.921	0.003
16	1.750	59.917	59.919	0.002
17	1.800	59.917	59.918	0.001
18	1.850	59.917	59.917	0.000
19	1.900	59.917	59.917	-0.001
20	1.950	59.918	59.916	-0.001
21	2.000	59.918	59.916	-0.002

OK Help Print



Issue is How to Handle a Large Number of Signals

Transient Stability Analysis

Simulation Status: Not Initialized

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find | My Transient Contingency

Select Step: Simulation, Options, Result Storage, Plots

Time Values: Minimum/Maximum Values, Summary, Events, Solution Details

Generator | Bus | Load | Switched Shunt | Branch | Transformer | DC Transmission Line | VSC DC Line | Multi-Terminal DC Record | Multi-Terminal DC Record

Column Order: Object then Field

Column Filtering: Filter, Modify...

Choose Fields to Display:

- Frequency Average
- Gen Mvar
- Gen MW Accel
- Gen MW Mech
- Zone
- Interface
- Injection Group
- GIC EField Direction
- GIC EField Magnit...
- GIC Mvar
- GIC Neutral Current
- Load Mvar
- Load MW
- ROCOF (Hz per S...)
- V pu Average
- V pu Max
- V pu Min
- V pu Min Highest ...

Time	Substation 18004 Frequency Average	Substation 18005 Frequency Average	Substation 18010 Frequency Average	Substation 18015 Frequency Average	Substation 18028 Frequency Average	Substation 18029 Frequency Average	Substation 18031 Frequency Average	Substation 18035 Frequency Average	Substation 18053 Frequency Average	Substation 18056 Frequency Average	Substation 18062 Frequency Average	Substation 18064 Frequency Average	Substation 18067 Frequency Average	Substation 18068 Frequency Average	Substation 18069 Frequency Average	Substation 18075 Frequency Average	Substation 18077 Frequency Average	Substation 18080 Frequency Average	Substation 18081 Frequency Average	Substation 18086 Frequency Average
1	0	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
2	0.05	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
3	0.1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
4	0.15	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
5	0.2	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
6	0.25	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
7	0.3	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
8	0.35	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
9	0.4	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
10	0.45	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
11	0.5	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
12	0.55	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
13	0.6	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
14	0.65	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
15	0.7	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
16	0.75	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
17	0.8	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
18	0.85	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
19	0.9	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
20	0.95	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
21	1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
22	1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
23	1.05	59.9907	59.9908	59.9907	59.9905	59.9909	59.9909	59.9909	59.9905	59.9911	59.9905	59.9907	59.9911	59.9906	59.991	59.9908	59.9904	59.9959	59.9908	59.991
24	1.1	59.982	59.9811	59.9833	59.9821	59.9818	59.9824	59.9823	59.9829	59.9805	59.9831	59.9817	59.982	59.9826	59.9819	59.9825	59.9816	59.9868	59.9821	59.9824
25	1.15	59.9736	59.9725	59.9739	59.9738	59.9734	59.974	59.974	59.974	59.9733	59.9747	59.9733	59.9743	59.9735	59.974	59.9744	59.9733	59.9797	59.9738	59.9741
26	1.2	59.9656	59.9643	59.9663	59.9658	59.9655	59.966	59.9661	59.9661	59.9654	59.9666	59.9654	59.9658	59.9664	59.9663	59.9661	59.9655	59.9662	59.9659	59.9654
27	1.25	59.956	59.9568	59.9602	59.9582	59.958	59.9583	59.9586	59.9585	59.9578	59.9583	59.9588	59.9579	59.9586	59.9579	59.9586	59.9579	59.9608	59.9583	59.9585
28	1.3	59.9507	59.9496	59.9466	59.9509	59.9508	59.9508	59.9508	59.9513	59.9511	59.9505	59.9512	59.9507	59.951	59.951	59.9507	59.9512	59.951	59.9507	59.9511
29	1.35	59.9438	59.9429	59.9482	59.944	59.9439	59.9437	59.9444	59.9441	59.9436	59.9438	59.944	59.9444	59.9439	59.9441	59.9437	59.9442	59.9441	59.9439	59.9433
30	1.4	59.9373	59.9366	59.9406	59.9374	59.9369	59.938	59.9374	59.937	59.9366	59.9374	59.9376	59.9379	59.9374	59.9375	59.9374	59.9373	59.9377	59.9378	59.9374
31	1.45	59.9314	59.9309	59.9326	59.9315	59.9316	59.9308	59.9323	59.9315	59.9311	59.9301	59.9316	59.9318	59.9321	59.9315	59.9303	59.9313	59.9317	59.9319	59.9317
32	1.5	59.9264	59.926	59.9253	59.9265	59.9267	59.9256	59.9275	59.9265	59.9261	59.9246	59.9268	59.9269	59.9273	59.9265	59.9264	59.9263	59.9267	59.9269	59.9267
33	1.55	59.9225	59.9222	59.92	59.9226	59.9228	59.9216	59.9237	59.9236	59.9221	59.9205	59.9223	59.9235	59.9226	59.9224	59.9207	59.9228	59.923	59.9231	59.921
34	1.6	59.9197	59.9194	59.9171	59.9197	59.92	59.9188	59.9209	59.9198	59.9194	59.9177	59.9202	59.9203	59.9204	59.9198	59.9226	59.9199	59.9202	59.9204	59.9201
35	1.65	59.9179	59.9175	59.9162	59.9179	59.9182	59.9171	59.9191	59.9181	59.9176	59.9162	59.9184	59.9186	59.9189	59.918	59.9178	59.9164	59.9178	59.9181	59.9183
36	1.7	59.9168	59.9163	59.9163	59.9168	59.9172	59.9163	59.916	59.916	59.9166	59.9156	59.9174	59.9176	59.9178	59.9169	59.9168	59.9158	59.9167	59.9171	59.9173
37	1.75	59.9162	59.9157	59.9164	59.9162	59.9166	59.916	59.9174	59.9167	59.9162	59.9156	59.9168	59.9171	59.9173	59.9164	59.9163	59.9157	59.9162	59.9165	59.917
38	1.8	59.916	59.9155	59.916	59.916	59.9164	59.916	59.9171	59.9166	59.916	59.9159	59.9166	59.9169	59.917	59.9162	59.9161	59.9159	59.916	59.9164	59.9167
39	1.85	59.9161	59.9156	59.9153	59.9161	59.9164	59.9163	59.9171	59.9168	59.9163	59.9161	59.9162	59.9169	59.917	59.9162	59.9161	59.9156	59.9164	59.9167	59.917
40	1.9	59.9164	59.916	59.9148	59.9164	59.9167	59.9167	59.9173	59.9171	59.9164	59.9168	59.9168	59.9171	59.9172	59.9165	59.9166	59.9166	59.9164	59.9167	59.917
41	1.95	59.9169	59.9166	59.915	59.917	59.9172	59.9173	59.9176	59.9176	59.9169	59.9174	59.9172	59.9176	59.9176	59.917	59.9172	59.9172	59.9169	59.9174	59.9174
42	2	59.9175	59.9173	59.9162	59.9176	59.9179	59.9181	59.9181	59.9176	59.9181	59.9176	59.9181	59.9178	59.9181	59.9177	59.9179	59.9175	59.9177	59.9179	59.9177
43	2.05	59.9181	59.9179	59.9178	59.9183	59.9184	59.9186	59.9187	59.9187	59.9182	59.9188	59.9184	59.9187	59.9186	59.9184	59.9186	59.9182	59.9185	59.9183	59.9185
44	2.1	59.9187	59.9185	59.9193	59.9189	59.919	59.9191	59.9191	59.9192	59.9188	59.9193	59.9189	59.9191	59.9191	59.9191	59.9188	59.9191	59.9189	59.9191	59.9191
45	2.15	59.9191	59.9188	59.92	59.9193	59.9193	59.9194	59.9194	59.9194	59.9192	59.9195	59.9193	59.9194	59.9194	59.9194	59.9195	59.9194	59.9192	59.9194	59.9194
46	2.2	59.9192	59.9189	59.9199	59.9195	59.9194	59.9194	59.9194	59.9195	59.9193	59.9194	59.9195	59.9195	59.9196	59.9194	59.9193	59.9195	59.9194	59.9201	59.9195
47	2.25	59.9192	59.9188	59.919	59.9194	59.9192	59.9194	59.9192	59.9191	59.9192	59.9191	59.9192	59.9191	59.9191	59.9191	59.9192	59.9194	59.9192	59.9194	59.9203
48	2.3	59.919	59.9187	59.918	59.9192	59.9193	59.9189	59.9191	59.9189	59.9187	59.9191	59.9187	59.9192	59.9193	59.9192	59.9188	59.919	59.9192	59.9191	59.9192
49	2.35	59.9189	59.9186	59.9174	59.919	59.9191	59.9187	59.9191	59.9189	59.9189	59.9184	59.9191	59.9189	59.9185	59.9189	59.9189	59.9189	59.9191	59.9189	59.9189
50	2.4	59.9188	59.9185	59.9173	59.9189	59.919	59.9186	59.919	59.9188	59.9188	59.9182	59.919	59.9189	59.9189	59.9189	59.9188	59.9188	59.9189	59.9189	59.9188

Process Contingencies:

- One Contingency at a time
- Multiple Contingencies

Load from Hard Drive File into RAM results specified by Store to RAM Options | Clear Time Values from RAM | Clear Min/Max Values, Summary, Events, and/or Solution Details from RAM



There are Now 8400 Signals to Consider

Modal Analysis Form

Modal Analysis Status: Solved at 1/15/2020 7:12:34 PM

Data Source Type:

 From Plot

 File, WECC CSV 2

 File, JSIS Format

 File, Comtrade CFF

 File, Comtrade CFG

 None, Existing Data

Calculation Method:

 Matrix Pencil (Once)

 Iterative Matrix Pencil

 Dynamic Mode Decomposition

Data Source Inputs from Plots or Files:

 From Plot: Substation_Frequency Average

 From File: [Browse]

Buttons: Do Modal Analysis, Save in JSIS Format, Save to CSV

Optimal Matrix Pencil Options:

 Number of Iterations: 10

 Initial All Signals to be Not Included

 Current Iteration: 10

 Store Results in PWB File

Results

Number of Complex and Real Modes: 8

 Lowest Percent Damping: -24.907

 Include Detrend in Reproduced Signals

 Subtract Reproduced from Actual

 Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Weighted Percentage Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	Include in Reproduced Signal
1	0.0221	-24.907	92.1563	Substation 180	0.0361	YES
2	0.221	25.585	39.5733	Substation 337	-0.3680	YES
3	0.000	100.000	38.9543	Substation 337	-0.4767	YES
4	0.614	7.356	25.5609	Substation 337	-0.2844	YES
5	0.344	16.691	18.3366	Substation 337	-0.3655	YES
6	0.553	25.115	17.3504	Substation 337	-0.9019	YES
7	0.823	16.516	13.5647	Substation 337	-0.8660	YES
8	2.600	4.682	5.0753	Substation 337	-0.7657	YES

Input Data, Actual | Sampled Input Data | Signals | Options | Reproduced Data

	Type	Name	Latitude	Longitude	Units	Description	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Average Error, Unscaled	Average Error, Scaled by SD	Maximum Error, Unscaled	Cost Function	Se ^ Refe
1	Substation	Substation 18004 Freq	36.008	-115.213		Average Freq	YES	YES	59.9020	-0.0034	0	0.021	YES	0.0004	0.0000	0.0017	0.0018	NO
2	Substation	Substation 18005 Freq	36.038	-114.999		Average Freq	NO	YES	59.9018	-0.0033	0	0.021	YES	0.0003	0.0000	0.0016	0.0017	NO
3	Substation	Substation 18010 Freq	36.086	-115.049		Average Freq	NO	YES	59.9021	-0.0034	0	0.021	YES	0.0005	0.0000	0.0025	0.0025	NO
4	Substation	Substation 18015 Freq	36.114	-115.214		Average Freq	NO	YES	59.9020	-0.0034	0	0.021	YES	0.0004	0.0000	0.0018	0.0018	NO
5	Substation	Substation 18028 Freq	36.158	-115.279		Average Freq	NO	YES	59.9020	-0.0034	0	0.021	YES	0.0003	0.0000	0.0017	0.0018	NO
6	Substation	Substation 18029 Freq	36.143	-115.049		Average Freq	NO	YES	59.9020	-0.0034	0	0.021	YES	0.0004	0.0000	0.0018	0.0019	NO
7	Substation	Substation 18031 Freq	36.241	-115.085		Average Freq	NO	YES	59.9021	-0.0034	0	0.021	YES	0.0003	0.0000	0.0016	0.0017	NO
8	Substation	Substation 18035 Freq	36.175	-115.115		Average Freq	NO	YES	59.9021	-0.0034	0	0.021	YES	0.0004	0.0000	0.0017	0.0018	NO
9	Substation	Substation 18042 Freq	36.053	-115.121		Average Freq	NO	YES	59.9020	-0.0034	0	0.021	YES	0.0004	0.0000	0.0017	0.0018	NO
10	Substation	Substation 18043 Freq	36.115	-115.056		Average Freq	NO	YES	59.9020	-0.0034	0	0.021	YES	0.0004	0.0000	0.0022	0.0021	NO

Next few slides show how this can be done with good computational efficiency, and the results both quantified and visualized.



Measurement-Based Modal Analysis

- Vector \mathbf{y} consists of m uniformly sampled points from $y_{\text{org}}(t)$ at a sampling value of DT , starting with $t=0$, with values y_j for $j=1 \dots m$
 - Times are then $t_j = (j-1)DT$
 - At each time point j , the approximation of y_j is

$$\hat{y}_j(\mathbf{a}, \mathbf{b}) = \sum_{i=1}^n b_i \phi_i(t_j, \mathbf{a})$$

where \mathbf{a} is a vector with the real and imaginary eigenvalue components,

with $\phi_i(t_j, \mathbf{a}) = e^{\alpha_i t_j}$ for α_i corresponding to a real eigenvalue, and

$$\phi_i(t_j, \mathbf{a}) = e^{\alpha_i t_j} \cos(\alpha_{i+1} t_j) \text{ and } \phi_{i+1}(\mathbf{a}) = e^{\alpha_i t_j} \sin(\alpha_{i+1} t_j)$$

for a complex eigenvector value



Measurement-Based Modal Analysis

- Error (residual) value at each point j is

$$r_j(t_j, \mathbf{a}, \mathbf{b}) = y_j - \hat{y}_j(t_j, \mathbf{a}, \mathbf{b})$$

- Closeness of fit can be quantified using the Euclidean norm of the residuals

$$\frac{1}{2} \sum_{j=1}^m (y_j - \hat{y}_j(t_j, \mathbf{a}, \mathbf{b}))^2 = \frac{1}{2} \|\mathbf{r}(\mathbf{a}, \mathbf{b})\|_2^2$$

- Hence we need to determine \mathbf{a} and \mathbf{b} ; PowerWorld has three techniques for determining \mathbf{a} , and then one for \mathbf{b}
- Approaches can be quickly used with multiple signals



Matrix Pencil Method

- The a vector can be calculated using the Matrix Pencil Method (MPM)
- First, with m samples, let $L=m/2$
- Then form a Hankel matrix, \mathbf{Y} such that

$$\mathbf{Y} = \begin{bmatrix} y_1 & y_2 & \dots & y_{L+1} \\ y_2 & y_3 & \dots & y_{L+2} \\ \dots & \dots & \dots & \dots \\ y_{m-L} & y_{m-L+1} & \dots & y_m \end{bmatrix}$$

The computational complexity increases with the cube of the number of measurements!

- Calculate its singular values with an economy SVD

Matrix Pencil Method (MPM)

- The ratio of each singular value is then compared to the largest singular value; retain the M ones with a ratio greater than a threshold
 - This determines the modal order
 - Assuming \mathbf{V} is ordered by singular values (highest to lowest), let \mathbf{V}_p be then matrix with the first M columns of \mathbf{V}
- Then form the matrices \mathbf{V}_1 and \mathbf{V}_2 such that
 - \mathbf{V}_1 is the matrix consisting of all but the last row of \mathbf{V}_p
 - \mathbf{V}_2 is the matrix consisting of all but the first row of \mathbf{V}_p
 - Discrete-time poles are found as the generalized eigenvalues of the pair $\{\mathbf{V}_2^T \mathbf{V}_1, \mathbf{V}_1^T \mathbf{V}_1\}$
- Then calculate the eigenvalues



Computational Considerations

- MPM can be applied to multiple signals, with computational order scaling according to the cube of the number of samples and linearly with the number of signals
- The MPM can become computationally difficult with large numbers of signals
- A key insight is just a small number of signals are needed to calculate **a**; **b** can then be quickly calculated for each signal



Quick Determination of \mathbf{b}

- A key insight from a technique known as the variable projection method (VPM) is

$$\hat{\mathbf{y}}(\boldsymbol{\alpha}, \mathbf{b}) = \boldsymbol{\Phi}(\boldsymbol{\alpha})\mathbf{b}$$

And then the residual is minimized by selecting

$$\mathbf{b} = \boldsymbol{\Phi}(\boldsymbol{\alpha})^+ \mathbf{y}$$

where $\boldsymbol{\Phi}(\boldsymbol{\alpha})$ is the m by M matrix with values

$\Phi_{ji}(\boldsymbol{\alpha}) = e^{\alpha_i t_j}$ if α_i corresponds to a real eigenvalue,

and $\Phi_{ji}(\boldsymbol{\alpha}) = e^{\alpha_i t_j} \cos(\alpha_{i+1} t_j)$ and $\Phi_{ji+1}(\boldsymbol{\alpha}) = e^{\alpha_i t_j} \sin(\alpha_{i+1} t_j)$

for a complex eigenvalue; $t_j = (j-1)\Delta T$

Finally, $\boldsymbol{\Phi}(\boldsymbol{\alpha})^+$ is the pseudoinverse of $\boldsymbol{\Phi}(\boldsymbol{\alpha})$

M is the number of retained modes, and is usually very small



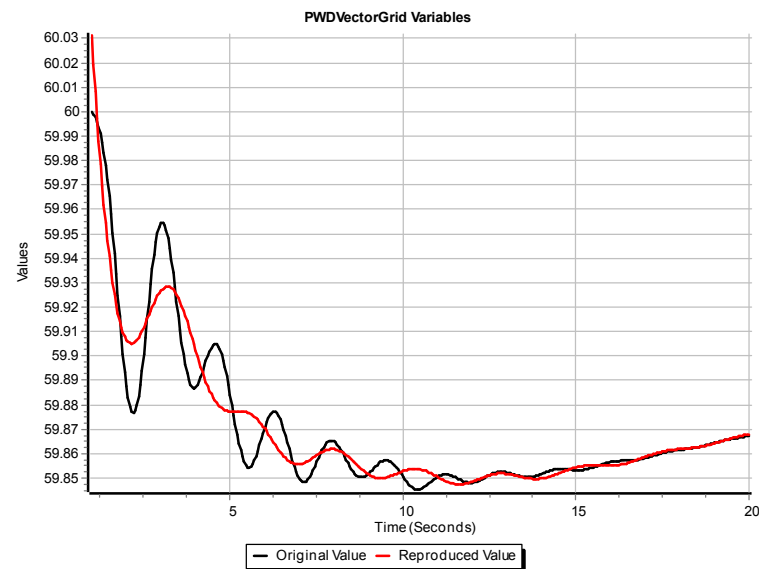
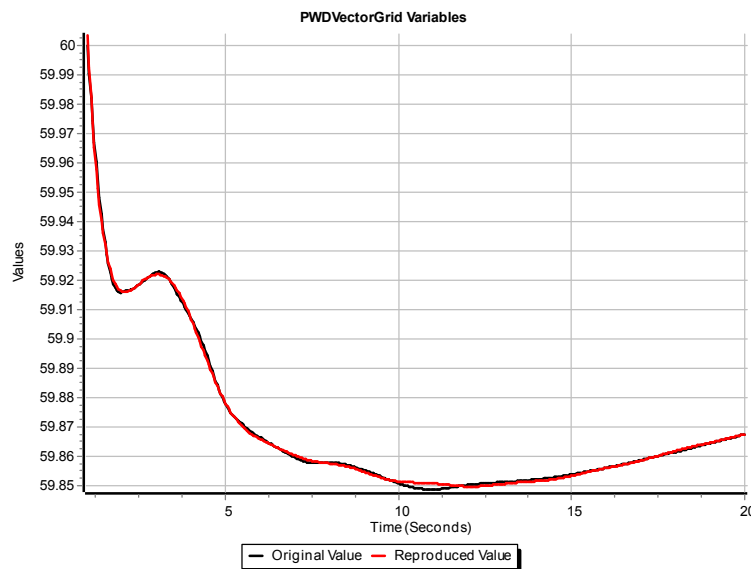
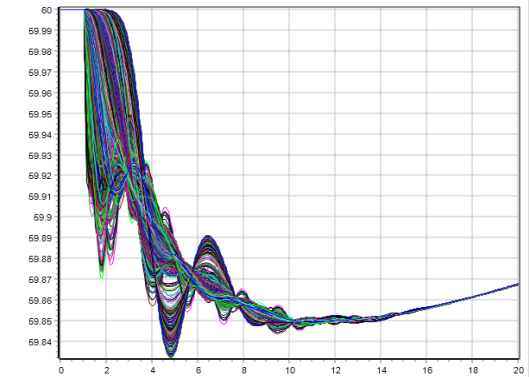
Iterative Matrix Pencil

- The Iterative Matrix Pencil (IMP) is used to iteratively improve \mathbf{a} to better match a large number of signals by sequentially adding signals to be included in the calculation of \mathbf{a}
 - The \mathbf{b} for each signal, and its associated costs function, can be quickly calculated
- The algorithm arbitrarily selects one signal, and then sequentially adds another signal, often the one with the highest cost function (i.e., the worst fit); usually only a small number of signals needs to be considered (approximately 10)



8400 Signal Example

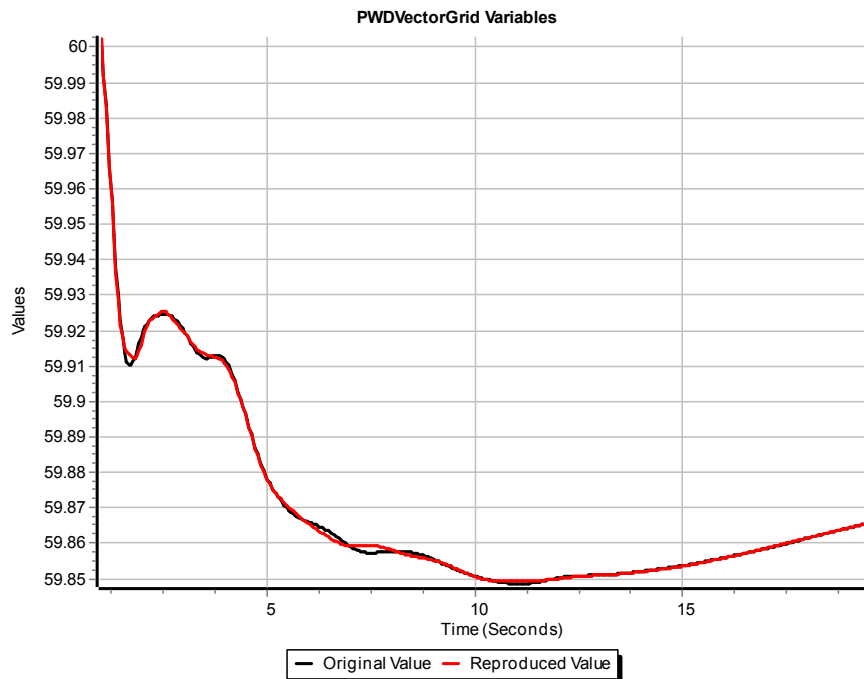
- In previous 8400 signal example if just one signal is included in the calculation of a then just four modes are found: (0, 0.029, 0.21, 0.42Hz)
- The best and worst signal matches are shown



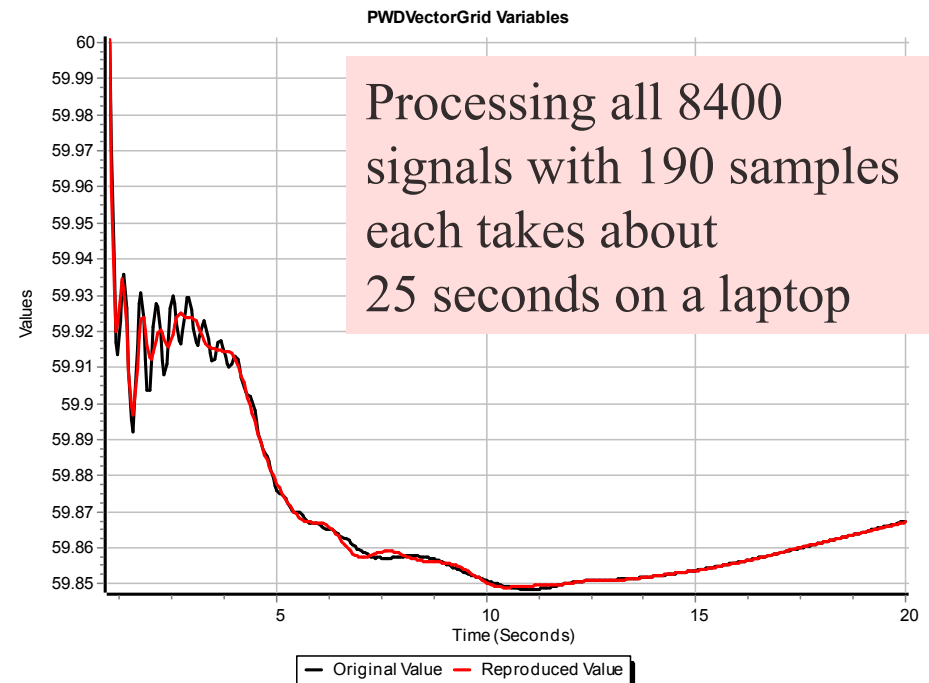
8400 Signal Example

- When ten signals are included there are eight modes, and the overall match for all the 8400 signals is much improved

Average Match



Worst Match



Processing all 8400 signals with 190 samples each takes about 25 seconds on a laptop

Results Screen for the 8400 Signals

Modal Analysis Form

Modal Analysis Status: Solved at 1/15/2020 7:12:34 PM

Data Source Type:

From Plot: Substation_Frequency Average

From File: [Browse]

Just Load Signals | Group Disabled for Existing Data

Calculation Method:

Matrix Pencil (Once)

Iterative Matrix Pencil (Selected)

Dynamic Mode Decomposition

Results:

Number of Complex and Real Modes: 8

Lowest Percent Damping: -24.907

Include Dretrend in Reproduced Signals

Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Weighted Percentage Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	Include in Reproduced Signal
1	0.022	-24.907	92.1563	Substation 180	0.0361	YES
2	0.221	25.585	39.5733	Substation 337	-0.3680	YES
3	0.000	100.000	38.9543	Substation 337	-0.4767	YES
4	0.614	7.356	25.5609	Substation 337	-0.2844	YES
5	0.344	16.691	18.3366	Substation 337	-0.3655	YES
6	0.553	25.115	17.3504	Substation 337	-0.9019	YES
7	0.823	16.516	13.5647	Substation 337	-0.8660	YES
8	2.600	4.682	5.0753	Substation 337	-0.7657	YES

Input Data, Actual | Sampled Input Data | Signals | Options | Reproduced Data

	Type	Name	Latitude	Longitude	Units	Description	Include	Include Reproduced	Dretrend Parameter A	Dretrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Cost Function	Average Error, Unscaled	Scaled by SD	Error, Unsc	Refer
1	Substation	Substation 32000055 F	34.280	-114.240		Average Freq	NO	YES	59.9003	-0.0032	0	0.020	YES	0.0070	0.0011	0.0000	0.0088	NO
2	Substation	Substation 25063957 F	33.314	-114.924		Average Freq	NO	YES	59.9004	-0.0032	0	0.020	YES	0.0052	0.0007	0.0000	0.0087	NO
3	Substation	Substation 337411680	36.594	-106.733		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0059	0.0009	0.0000	0.0086	NO
4	Substation	Substation 337423924	36.582	-106.512		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0050	0.0008	0.0000	0.0074	NO
5	Substation	Substation 30050426 F	36.703	-106.565		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0050	0.0008	0.0000	0.0074	NO
6	Substation	Substation 337409089	36.872	-106.569		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0050	0.0008	0.0000	0.0074	NO
7	Substation	Substation 337431782	33.845	-112.271		Average Freq	NO	YES	59.8995	-0.0032	0	0.019	YES	0.0044	0.0006	0.0000	0.0071	NO
8	Substation	Substation 337408921	36.542	-106.487		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0048	0.0008	0.0000	0.0071	NO
9	Substation	Substation 337423972	34.313	-109.161		Average Freq	NO	YES	59.9001	-0.0032	0	0.020	YES	0.0047	0.0007	0.0000	0.0071	NO
10	Substation	Substation 337405818	36.240	-106.423		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0047	0.0007	0.0000	0.0070	NO
11	Substation	Substation 337410144	36.019	-117.791		Average Freq	NO	YES	59.9029	-0.0034	0	0.022	YES	0.0073	0.0014	0.0000	0.0065	NO
12	Substation	Substation 337413429	36.352	-106.513		Average Freq	NO	YES	59.9017	-0.0033	0	0.021	YES	0.0044	0.0007	0.0000	0.0064	NO
13	Substation	Substation 337419091	36.801	-107.614		Average Freq	NO	YES	59.9016	-0.0033	0	0.021	YES	0.0041	0.0006	0.0000	0.0064	NO
14	Substation	Substation 337420277	33.956	-116.660		Average Freq	NO	YES	59.9018	-0.0033	0	0.020	YES	0.0011	0.0002	0.0000	0.0062	NO
15	Substation	Substation 356867414	36.754	-106.417		Average Freq	NO	YES	59.9018	-0.0033	0	0.021	YES	0.0047	0.0007	0.0000	0.0062	NO

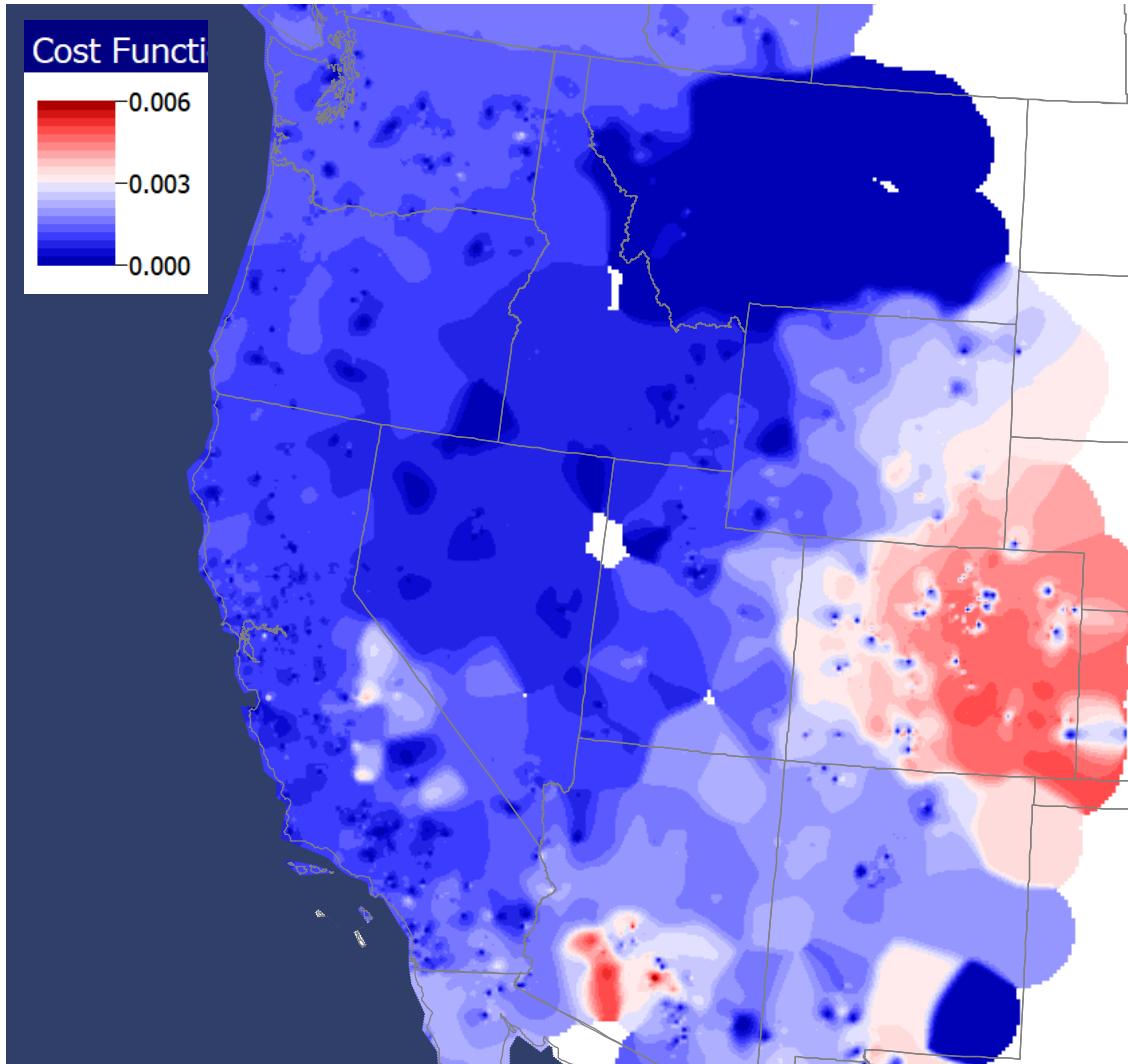
Right-click on row to get the mode details

Each signal is geo-mapped

Results here are sorted by the cost function



8400 Signal Example: Contouring the Cost Functions



The contour shows the locations in which the signals are well matched and where they are less well matched (perhaps indicating bad measurements or unusual system behavior)

Mode Details

Modal Analysis Mode Details

Frequency (Hz) and Damping (%) 0.221 Hz, Damping = 25.585%

Transfer Results from Selected Column to Object
Custom Floating Point Field 1

	Type	Name	Units	Description	Post-Detrend Standard Deviation	Angle (Deg)
1	Substation	Substation 18004 Freq		Average Freq	0.021	115.432
2	Substation	Substation 18005 Freq		Average Freq	0.021	114.974
3	Substation	Substation 18010 Freq		Average Freq	0.021	115.827
4	Substation	Substation 18015 Freq		Average Freq	0.021	115.522
5	Substation	Substation 18028 Freq		Average Freq	0.021	115.540
6	Substation	Substation 18029 Freq		Average Freq	0.021	115.731
7	Substation	Substation 18031 Freq		Average Freq	0.021	115.394
8	Substation	Substation 18035 Freq		Average Freq	0.021	115.651
9	Substation	Substation 18042 Freq		Average Freq	0.021	115.537
10	Substation	Substation 18043 Freq		Average Freq	0.021	116.035
11	Substation	Substation 18047 Freq		Average Freq	0.021	115.503
12	Substation	Substation 18052 Freq		Average Freq	0.021	115.564
13	Substation	Substation 18053 Freq		Average Freq	0.021	115.398
14	Substation	Substation 18056 Freq		Average Freq	0.021	115.584
15	Substation	Substation 18062 Freq		Average Freq	0.021	115.620
16	Substation	Substation 18064 Freq		Average Freq	0.021	115.922
17	Substation	Substation 18067 Freq		Average Freq	0.021	115.469
18	Substation	Substation 18068 Freq		Average Freq	0.021	115.523
19	Substation	Substation 18069 Freq		Average Freq	0.021	115.379
20	Substation	Substation 18075 Freq		Average Freq	0.021	115.527
21	Substation	Substation 18077 Freq		Average Freq	0.021	115.611
22	Substation	Substation 18080 Freq		Average Freq	0.021	115.553
23	Substation	Substation 18081 Freq		Average Freq	0.021	115.552
24	Substation	Substation 18086 Freq		Average Freq	0.021	115.521
25	Substation	Substation 18087 Freq		Average Freq	0.021	115.561

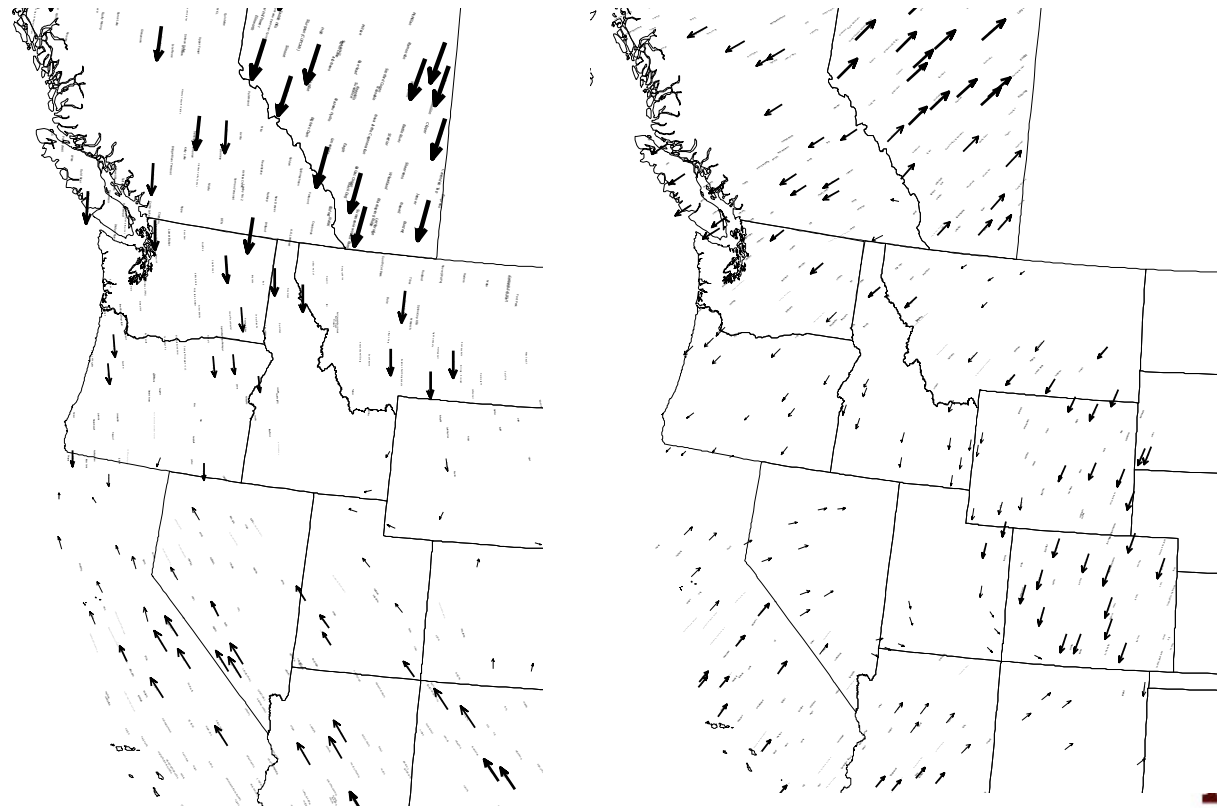
Close

Dialog shows the participation of each signal in the selected mode

Application: Mode Shape Visualization

- Participation of each signal in each mode can then be readily visualized using geographic data views (GDVs)

The displays show the 0.22 and the 0.34 Hz modes; pruning is used to reduce the number of vectors



Oscillation Source Visualization

- When the signals are bus voltage angles the mode j component of the voltage angle at bus k is

$$\theta_{k,j}(t) = A_{k,j} e^{\sigma_j t} \cos(\omega_j t + \phi_{k,j})$$

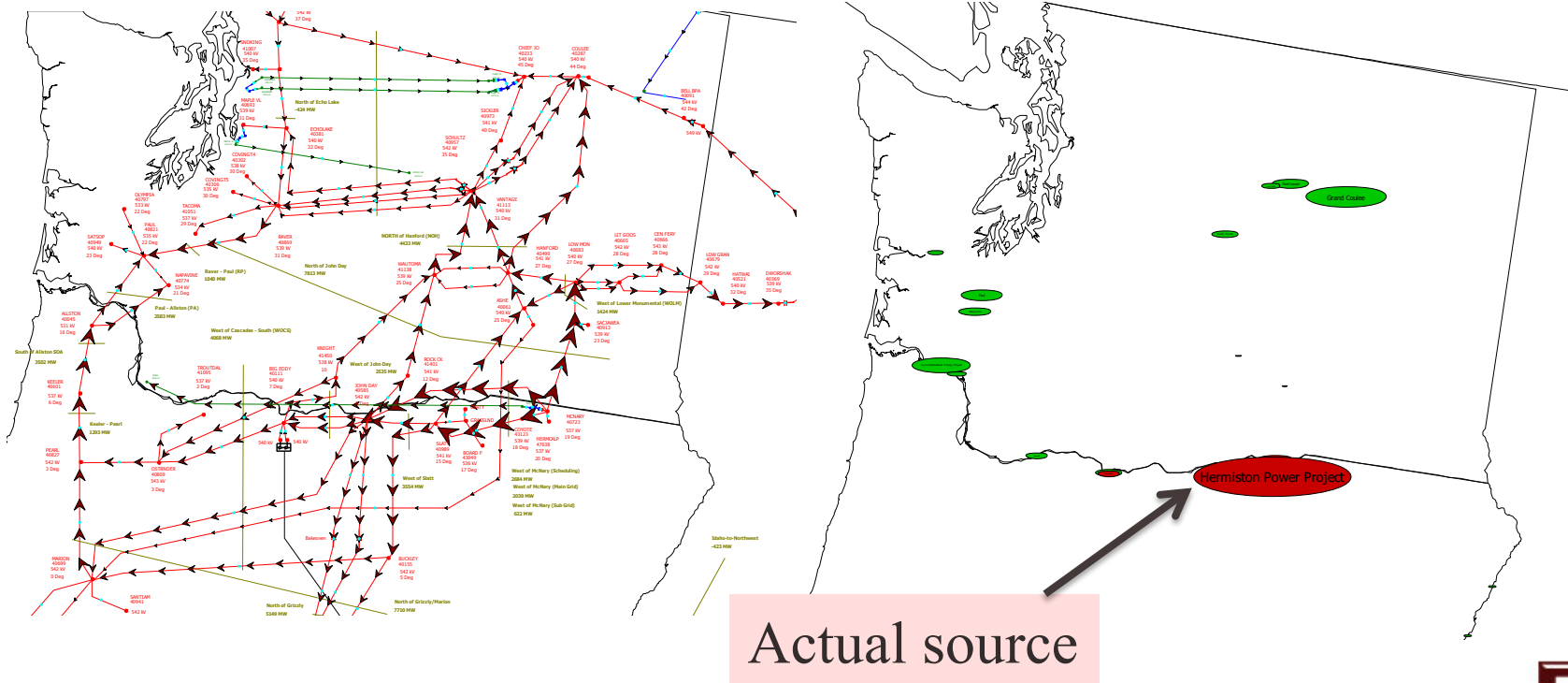
- For an undamped oscillation $s_j = 0$
- Using the dc power flow approximation, the flow of mode j power can be approximated as

$$P_{mn} = \frac{1}{X_{mn}} \left(A_{m,j} \cos(\phi_{m,j}) - A_{n,j} \cos(\phi_{n,j}) \right)$$

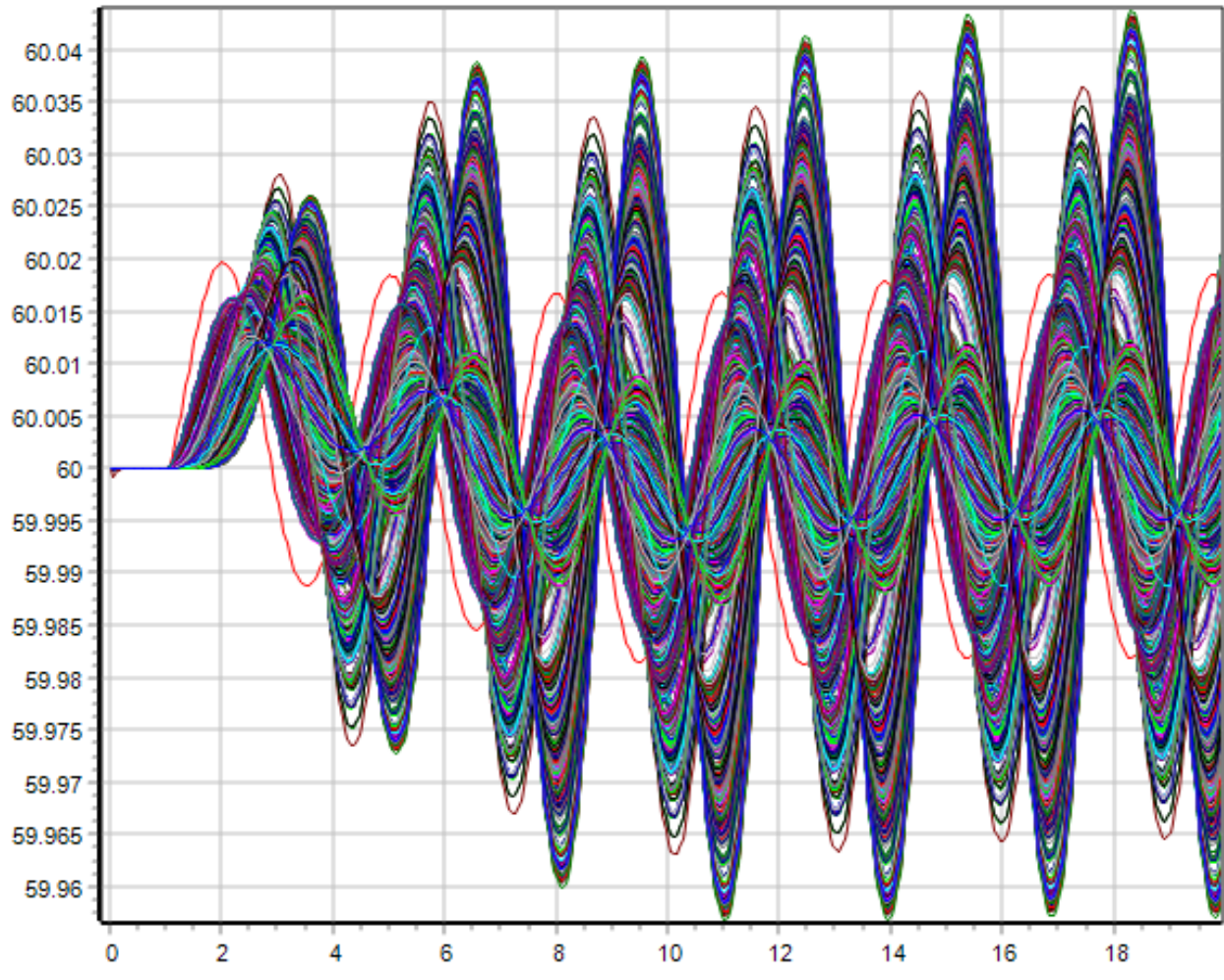
- The source is found by tracing the flows

Application: Visualizing the Source of Oscillations

- The results can also be used to visualize the source of sustained oscillations; images show results for a 1 Hz forced oscillation



Application: Visualizing the Source of Oscillations at 0.34 Hz Forced



Graph shows the frequency response at all 6400 substations

Modal Results, Iterative Matrix Pencil

Modal Analysis Form

Modal Analysis Status: Solved at 4/28/2018 8:36:06 AM

Data Source Type:

From Plot: File, Comtrade CFF

 File, WECC CSV 2

 File, J5IS Format

From File: Browse

Calculation Method:

 Matrix Pencil (Once)

 Iterative Matrix Pencil

 Dynamic Mode Decomposition

Data Source Inputs from Plots or Files:

From Plot: Substation_Frequency Average

From File: Browse

Optimal Matrix Pencil Options:

Number of Iterations: 10

 Initial All Signals to be Not Included

Current Iteration: 10

 Store Results in PWB File

Results

Number of Complex and Real Modes: 2

Lowest Percent Damping: -100.000

 Include Detrend in Reproduced Signals

 Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (Hz)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	Include in Reproduced Signal
1	0.340	0.019	99.6202	Bus 12ST_TAP V	-0.0004	YES
2	0.000	-100.000	8.7076	Bus 12ST_TAP V	0.0031	YES

Input Data, Actual | Sampled Input Data | Signals | Options | Reproduced Data

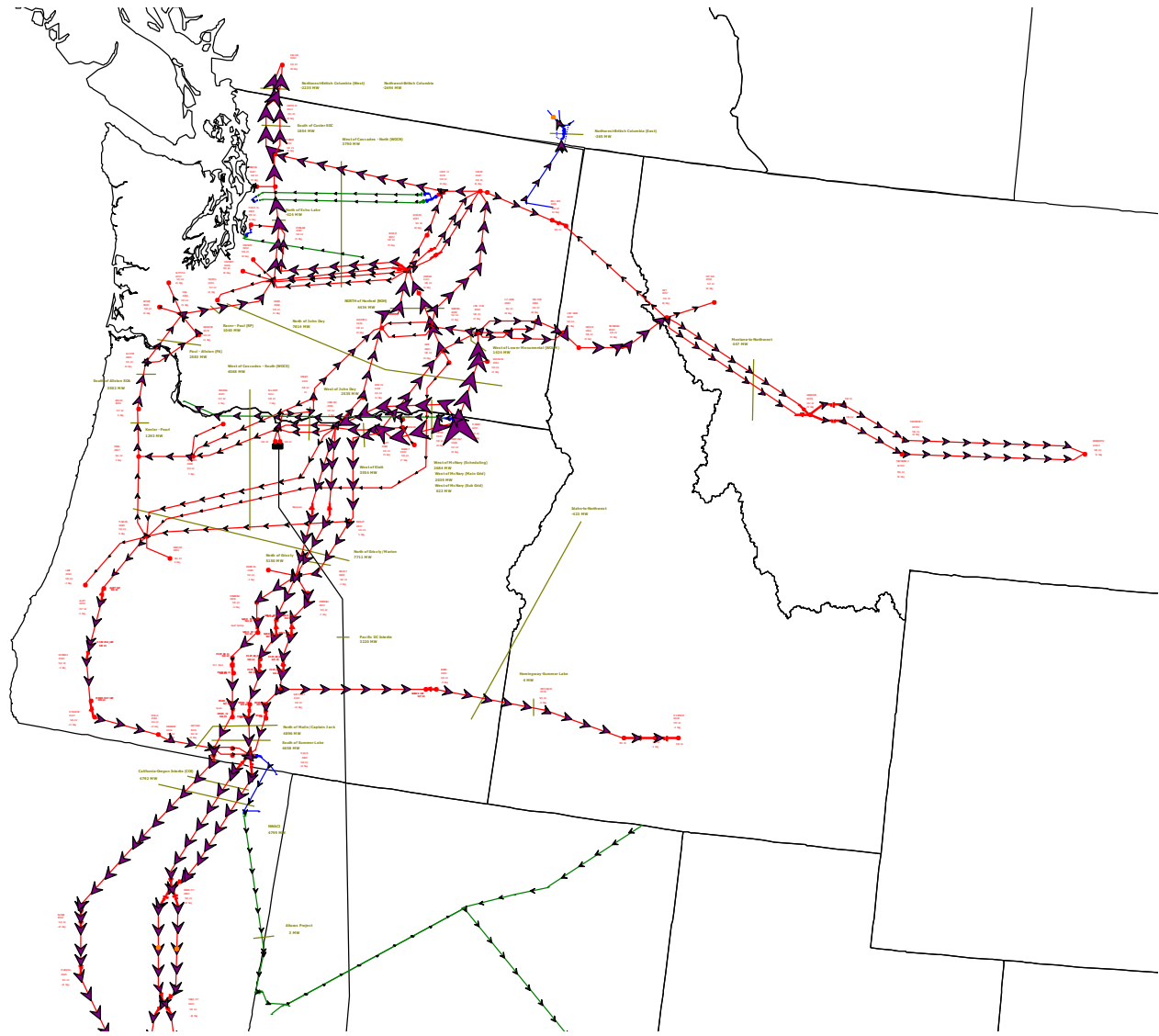
	Type	Name	Units	Description	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Average Error, Unscaled	Average Error, Scaled by SD	Maximum Error, Unscaled	Cost Function	Set as Reference
1	Bus	Bus 0162-WD V angle		Angle (deg)	NO	YES	-41.0877	-0.0009	0	0.514	YES	0.0114	0.0059	0.0358	0.0029	NO
2	Bus	Bus 0162-WD V angle		Angle (deg)	NO	YES	-40.6001	-0.0009	0	0.515	YES	0.0114	0.0059	0.0358	0.0029	NO
3	Bus	Bus 0227-WD V angle		Angle (deg)	NO	YES	-41.6201	-0.0006	0	0.491	YES	0.0109	0.0054	0.0342	0.0029	NO
4	Bus	Bus 0227-WD V angle		Angle (deg)	NO	YES	-41.7410	-0.0006	0	0.491	YES	0.0109	0.0054	0.0342	0.0029	NO
5	Bus	Bus 0354-WD V angle		Angle (deg)	NO	YES	-36.4579	-0.0012	0	0.535	YES	0.0117	0.0063	0.0370	0.0028	NO
6	Bus	Bus 0354-WD V angle		Angle (deg)	NO	YES	-36.4885	-0.0012	0	0.535	YES	0.0117	0.0063	0.0370	0.0028	NO
7	Bus	Bus 1058JOIN V angle		Angle (deg)	NO	YES	40.4402	0.0009	0	3.155	YES	0.0691	0.2181	0.1951	0.0029	NO
8	Bus	Bus 1059A_TP V angle		Angle (deg)	NO	YES	40.1747	0.0009	0	3.161	YES	0.0692	0.2187	0.1953	0.0029	NO
9	Bus	Bus 105S TAP V angle		Angle (deg)	NO	YES	41.0252	0.0007	0	3.137	YES	0.0690	0.2164	0.1948	0.0029	NO
10	Bus	Bus 106S TAP V angle		Angle (deg)	NO	YES	39.4932	0.0010	0	3.178	YES	0.0695	0.2209	0.1967	0.0029	NO
11	Bus	Bus 106TH SO V angle		Angle (deg)	NO	YES	-19.1490	-0.0008	0	0.288	YES	0.0101	0.0029	0.0286	0.0042	NO
12	Bus	Bus 106THSO V angle		Angle (deg)	NO	YES	-24.1978	-0.0007	0	0.287	YES	0.0098	0.0028	0.0278	0.0041	NO
13	Bus	Bus 109ST1 V angle		Angle (deg)	NO	YES	37.3259	0.0018	0	3.360	YES	0.0713	0.2396	0.2011	0.0028	NO
14	Bus	Bus 109ST2 V angle		Angle (deg)	NO	YES	37.3259	0.0018	0	3.360	YES	0.0713	0.2396	0.2011	0.0028	NO
15	Bus	Bus 113JL TP V angle		Angle (deg)	NO	YES	31.4226	0.0054	0	4.262	YES	0.0855	0.3642	0.2667	0.0027	NO

Close Help Print

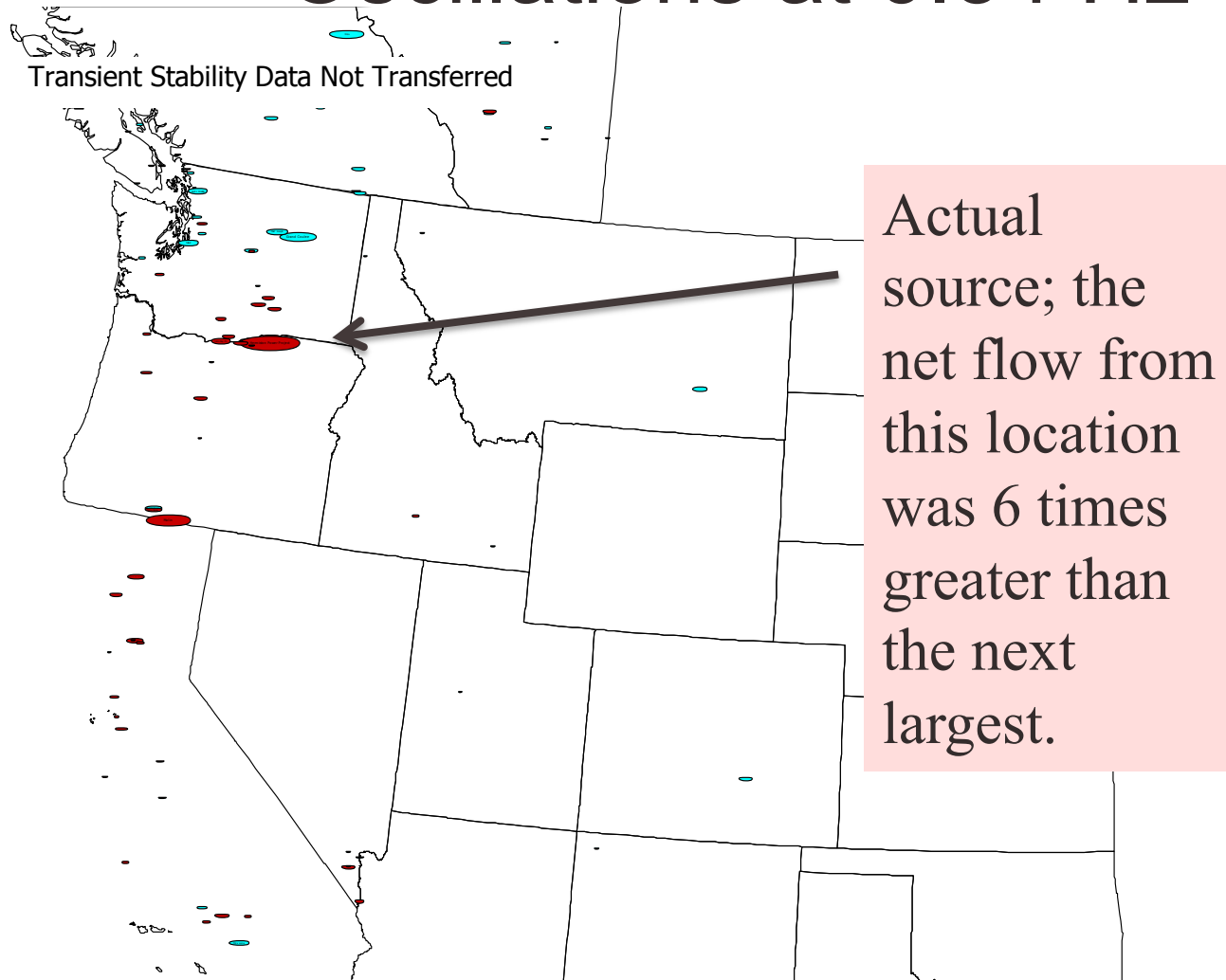
Analysis was done from 10 to 20 seconds



Visualization of Modal Line Flows



Application: Visualizing the Source of Oscillations at 0.34 Hz



Actual source; the net flow from this location was 6 times greater than the next largest.

Conclusion and Questions

- Measurement based modal analysis is becoming widely available for the analysis of power system data, both from actual measurements and simulation results
- Presentation has shown an iterative matrix pencil approach that can be used to quickly calculate values
- Results can also be easily visualized
- A simple but seemingly quite useful approach for locating the source of oscillations was presented