

Modal and Signal Analysis



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Oscillations



- An oscillation is just a repetitive motion that can be either undamped, positively damped (decaying with time) or negatively damped (growing with time)
- If the oscillation can be written as a sinusoid then

$$e^{\alpha t} (a \cos(\omega t) + b \sin(\omega t)) = e^{\alpha t} C \cos(\omega t + \theta)$$

$$\text{where } C = \sqrt{A^2 + B^2} \text{ and } \theta = \tan\left(\frac{-b}{a}\right)$$

- And the damping ratio is defined as (see Kundur 12.46)

$$\xi = \frac{-\alpha}{\sqrt{\alpha^2 + \omega^2}}$$

The percent damping is just the damping ratio multiplied by 100; goal is sufficiently positive damping

Power System Oscillations

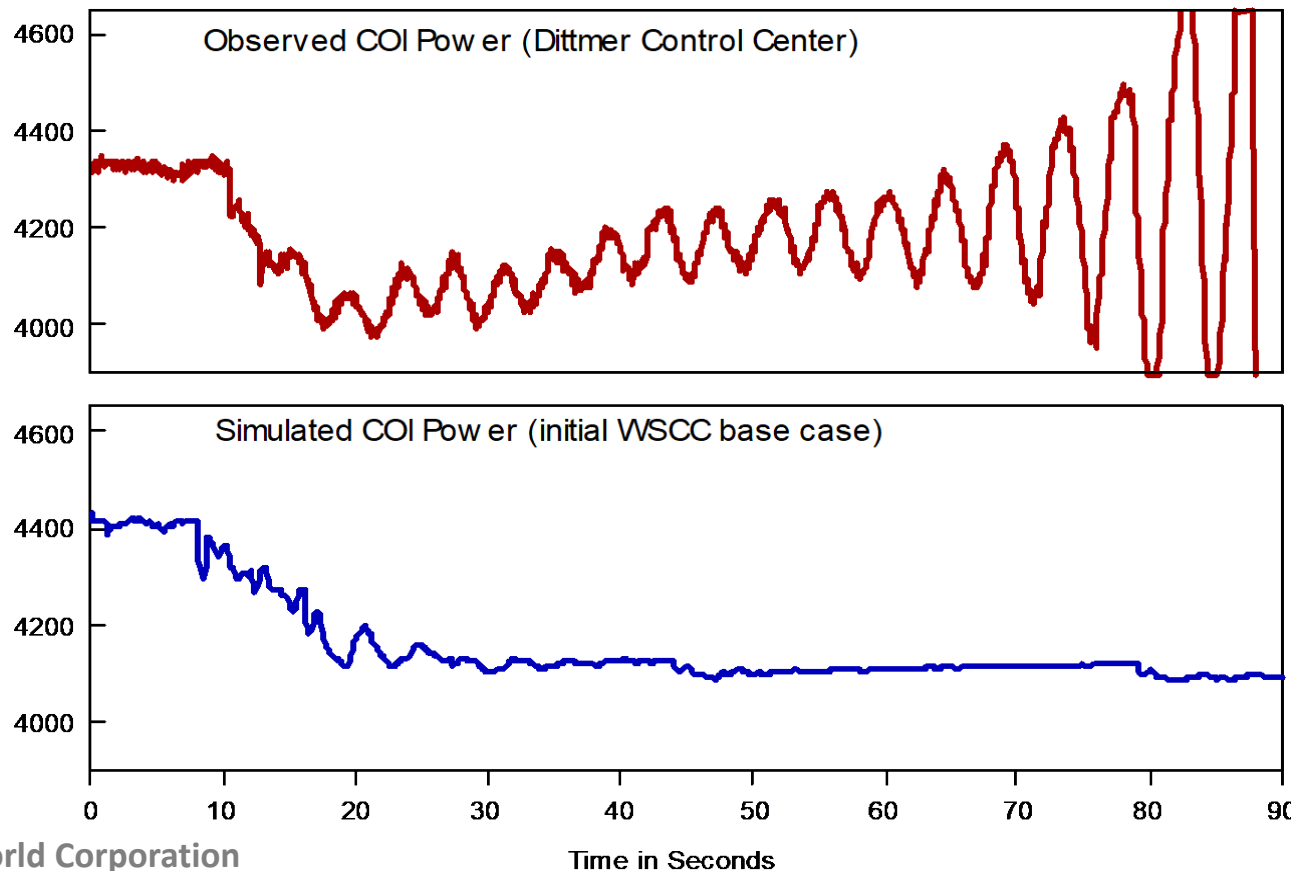


- Power systems can experience a wide range of oscillations, ranging from highly damped and high frequency switching transients to sustained low frequency (< 2 Hz) inter-area oscillations affecting an entire interconnect
- Types of oscillations include
 - Transients: Usually high frequency and highly damped
 - Local plant: Usually from 1 to 5 Hz
 - Inter-area oscillations: From 0.15 to 1 Hz
 - Slower dynamics: Such as AGC, less than 0.15 Hz
 - Subsynchronous resonance: 10 to 50 Hz (less than synchronous)

Example Oscillations



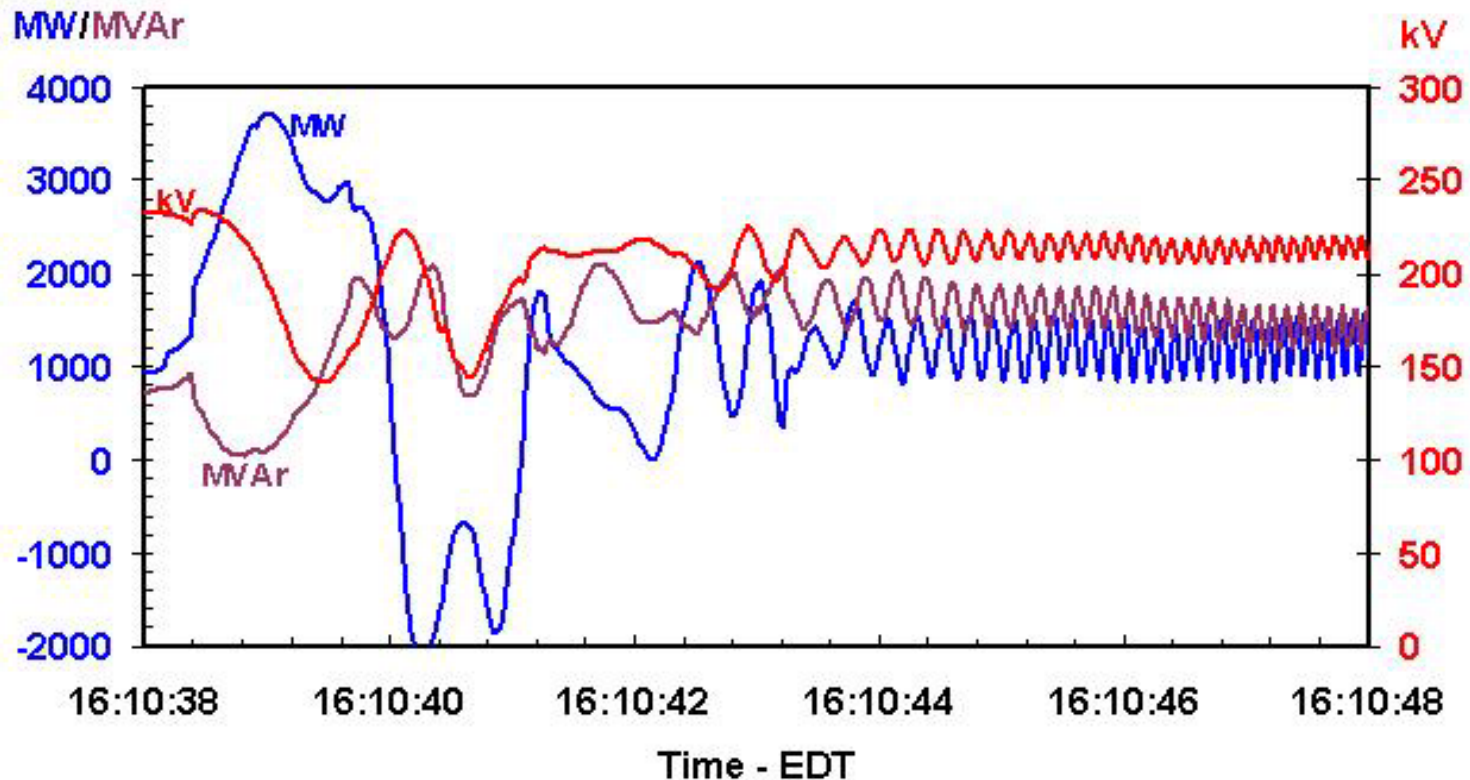
- The below graph shows an oscillation that was observed during a 1996 WECC Blackout



Example Oscillations



- The below graph shows oscillations on the Michigan/Ontario Interface on 8/14/03



More General Signal Analysis



- More generally we may wish to better understand the dynamic behavior of the power grid, either following a disturbance or during ambient conditions
 - Events are more common in studies

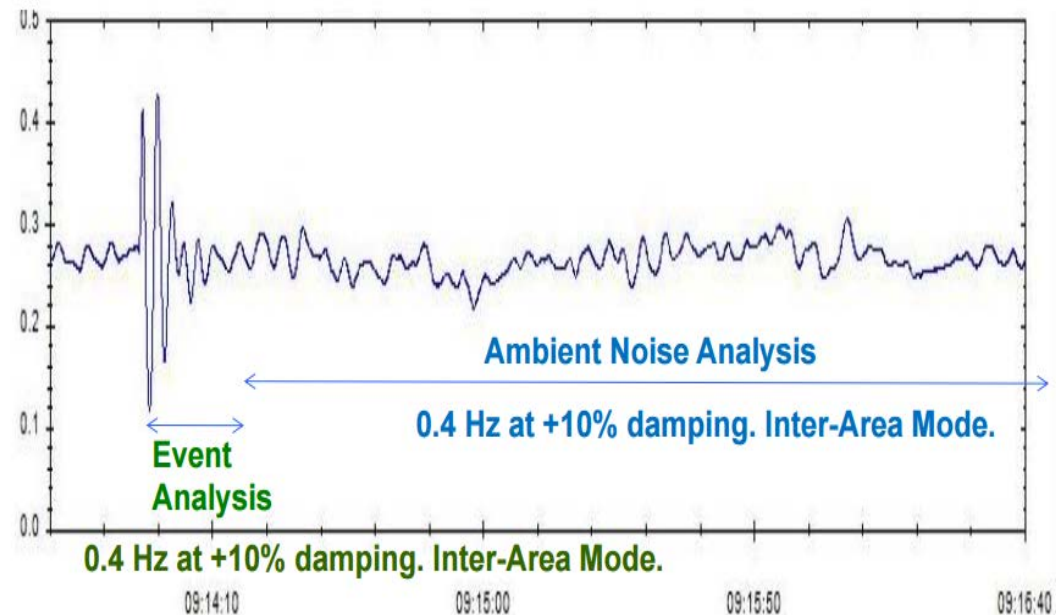
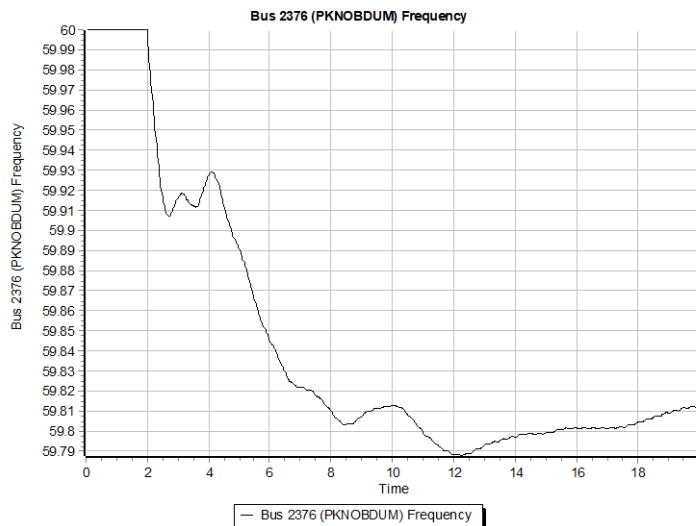


Image Source: M. Venkatasubramanian, "Oscillation Monitoring System", June 2015

<http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf>

Small Signal Analysis and Measurement-Based Modal Analysis



- Small signal analysis has been used for decades to determine power system frequency response
 - It is a model-based approach that considers the properties of a power system, linearized about an operating point
 - PowerWorld Simulator does single-machine, infinite bus (SMIB) small signal analysis but does not do general small signal analysis
- Measurement-based modal analysis determines the observed dynamic properties of a system
 - Input can either be measurements from PMUs or transient stability results
 - This is now more common, and has been implemented in PowerWorld Simulator

Ring-down Modal Analysis



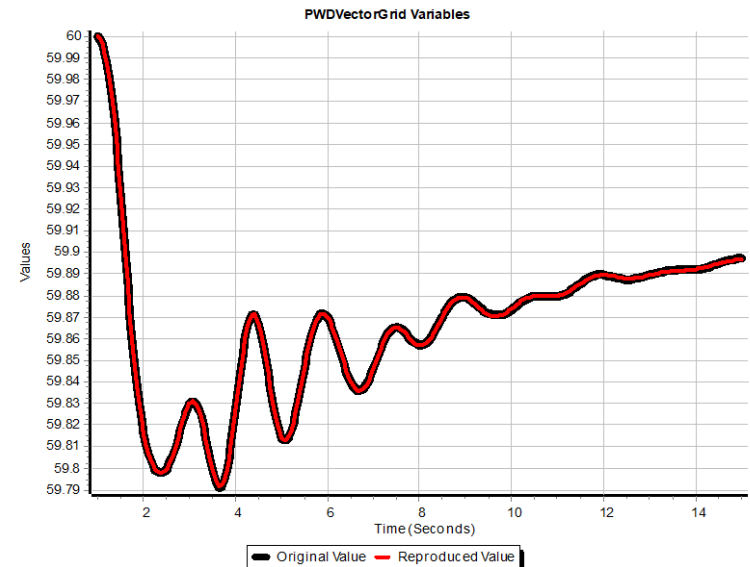
- Ring-down analysis seeks to determine the frequency and damping of key power system modes following some disturbance
- There are several different techniques, with the Prony approach the oldest (from 1795)
- Regardless of technique, the goal is to represent the response of a sampled signal as a set of exponentially damped sinusoids (modes)

$$y(t) = \sum_{i=1}^q A_i e^{\sigma_i t} \cos(\omega_i t + \phi_i) \quad \text{Damping (\%)} = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \omega_i^2}} \times 100$$

Ring-down Modal Analysis Example



- The image on this slide shows an example in which the frequency response at a bus for 15 seconds after a contingency (thick black line) is approximated by a set of exponentially decaying sinusoids (thinner red line)
 - In this example six sinusoids and a linear detrend are used
- This approach assumes the system behavior is linear during the time period of interest
 - It isn't fully linear, but it can be a quite useful approximation



Signal-Based Modal Analysis



- Idea of all techniques is to approximate a signal, $y_{org}(t)$, 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 time with $t=0$ as the start
- Approaches sample the original signal $y_{org}(t)$

Signal-Based Modal Analysis



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

$$\hat{y}_j(\boldsymbol{\alpha}) = \sum_{i=1}^n b_i \phi_i(t_j, \boldsymbol{\alpha})$$

where $\boldsymbol{\alpha}$ is a vector with the real and imaginary eigenvalue components,

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

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

for a complex eigenvector value

Signal Based Modal Analysis



- Error (residual) value at each point j is

$$r_j(t_j, \boldsymbol{\alpha}) = y_j - \hat{y}_j(t_j, \boldsymbol{\alpha})$$

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

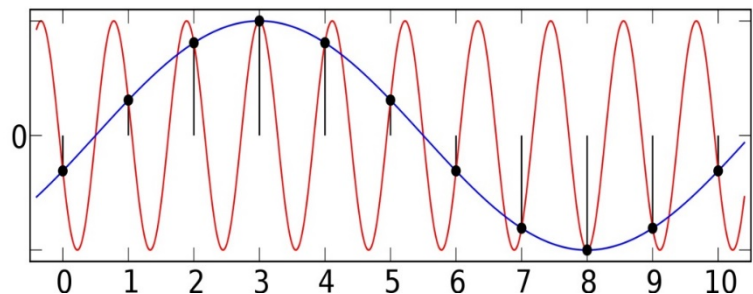
$$\frac{1}{2} \sum_{j=1}^m (y_j - \hat{y}_j(t_j, \boldsymbol{\alpha}))^2 = \frac{1}{2} \|\mathbf{r}(\boldsymbol{\alpha})\|_2^2$$

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

Sampling Rate and Aliasing



- The Nyquist-Shannon sampling theory requires sampling at twice the highest desired frequency
 - For example, to see a 5 Hz frequency we need to sample the signal at a rate of at least 10 Hz
- Sampling shifts the frequency spectrum by $1/T$ (where T is the sample time), which causes frequency overlap
- This overlapping of frequencies is known as aliasing, which can cause a high frequency signal to appear to be a lower frequency signal
 - Aliasing can be reduced by fast sampling and/or low pass filters



Modal Analysis in PowerWorld

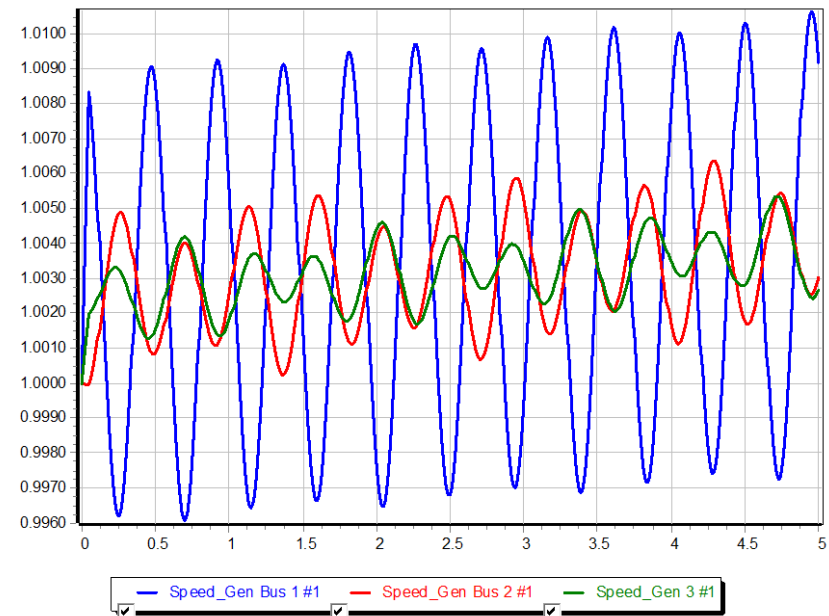
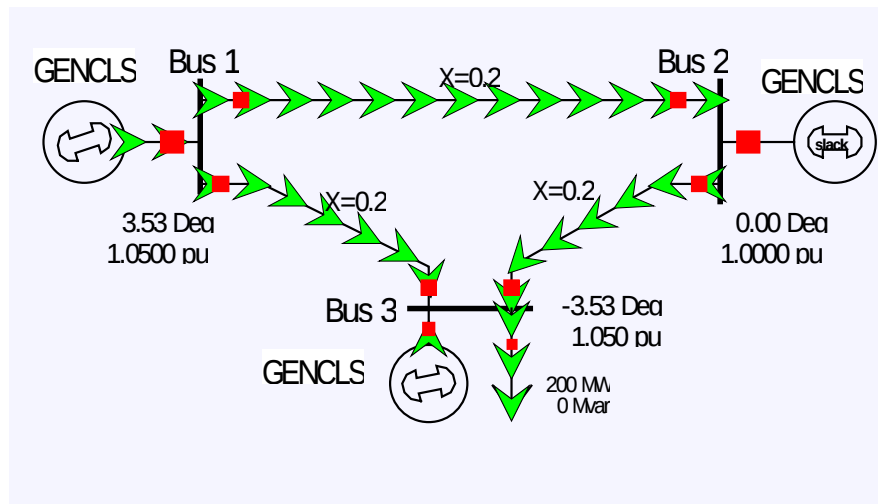


- Goal is to make modal analysis easy to use, and easy to visualize the results
- Provided tool can be used with either transient stability results or actual system signals (e.g., from PMUs)
- Two ways to access in PowerWorld (with a quicker third way coming soon!)
 - On the Transient Stability Analysis form left menu, **Modal Analysis** (right below SMIB Eigenvalues)
 - By right-clicking on a transient stability or plot case information display, and selecting **Modal Analysis Selected Columns** or **Modal Analysis All Columns**

Modal Analysis: Three Generator Example



- A short fault at $t=0$ gets the below three generator case oscillating with multiple modes (mostly clearly visible for the red and the green curve)



Modal Analysis:

Three Generator Example



- Open the case **B3_CLS_UnDamped**
 - This system has three classical generators without damping; the default event is a self clearing fault at bus 1
- Run the transient stability for 5 seconds
- To do modal analysis, on the Transient Stability page select Results from RAM, view just the generator speed fields, right-click and select **Modal Analysis All Columns**
 - This display the Modal Analysis Form

Modal Analysis Form



First click on Do Modal Analysis to run the modal analysis

Modal Analysis Form

Modal Analysis Status: Solved

Data Source Type

- ☐ From Plot
- ☐ File, Comtrade CFF
- ☐ File, WECC CSV 2
- ☐ File, Comtrade CFG
- ☐ File, J5IS Format
- ☒ None, Existing Data

Calculation Method

- ☐ Variable Projection
- ☒ Matrix Pencil (Once)
- ☐ Iterative Matrix Pencil
- ☐ Dynamic Mode Decomposition

Do Modal Analysis

Save in J5IS Format

Save to CSV

Data Source Inputs from Plots or Files

From Plot: Gen_Speed

From File: Browse

Just Load Signals

Group Disabled for Existing Data

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 0.050 End Time: 5.000

Maximum Hz: 5.000

Update Sampled Data

Results

Number of Complex and Real Modes: 2

Lowest Percent Damping: -0.013

☒ 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 Reproduced Signal
1	2.233	-0.009			0.0012 YES	
2	1.511	-0.013			0.0013 YES	

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

	Type	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Average Unsolved
1	Gen	Gen Bus 1 #1 Speed			Speed		YES	YES	1.0024	0.0004	0	0.005	NO	
2	Gen	Gen Bus 2 #1 Speed			Speed		YES	YES	1.0024	0.0003	0	0.001	NO	
3	Gen	Gen 3 #1 Speed			Speed		YES	YES	1.0025	0.0003	0	0.001	NO	

Close

Help

Right-click on signal to view its dialog

Key results are shown in the upper-right of the form. There are two main modes, one at 2.23Hz and one at 1.51; both have very little damping.

Three Generator Example: Signal Dialog



- The Signal Dialog provides details about each signal, including its modal components and a comparison between the original and reproduced signals (example for gen 3)

Modal Analysis Signal Dialog

Name: Gen 3 #1 Speed
Type: Gen
Units:
Description: Speed

☒ 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: 1.0025
Parameter B: 0.0003
Parameter C: 0.0000
Standard Deviation (SD): 0.0008

Output Summary

Average Error, Scaled by SD: 0.0000
Average Error, Unscaled: 0.0000
Cost Function Value, Scaled: 0.0000

☒ Include Detrend in Reproduced Signal

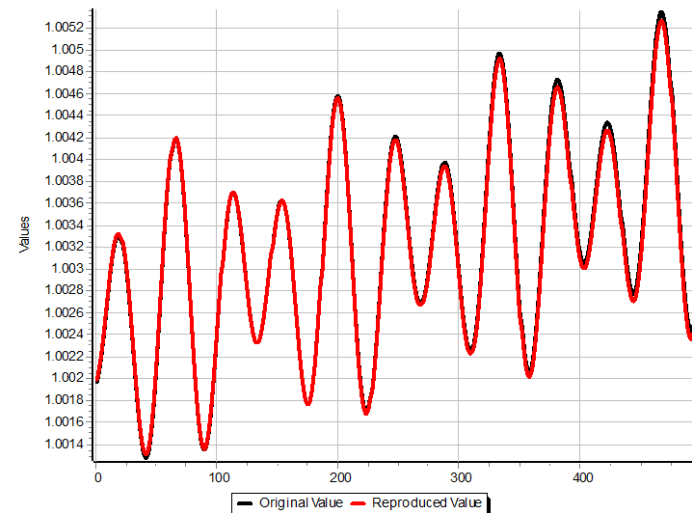
Update Reproduced

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

	Time (Seconds)	Original Value	Reproduced Value	Difference
1	0.050	1.002	1.002	0.000
2	0.060	1.002	1.002	0.000
3	0.070	1.002	1.002	0.000
4	0.080	1.002	1.002	0.000
5	0.090	1.002	1.002	0.000
6	0.100	1.002	1.002	0.000
7	0.110	1.002	1.002	0.000
8	0.120	1.003	1.003	0.000
9	0.130	1.003	1.003	0.000
10	0.140	1.003	1.003	0.000
11	0.150	1.003	1.003	0.000
12	0.160	1.003	1.003	0.000
13	0.170	1.003	1.003	0.000
14	0.180	1.003	1.003	0.000
15	0.190	1.003	1.003	0.000
16	0.200	1.003	1.003	0.000
17	0.210	1.003	1.003	0.000
18	0.220	1.003	1.003	0.000
19	0.230	1.003	1.003	0.000
20	0.240	1.003	1.003	0.000
21	0.250	1.003	1.003	0.000

OK Help Print

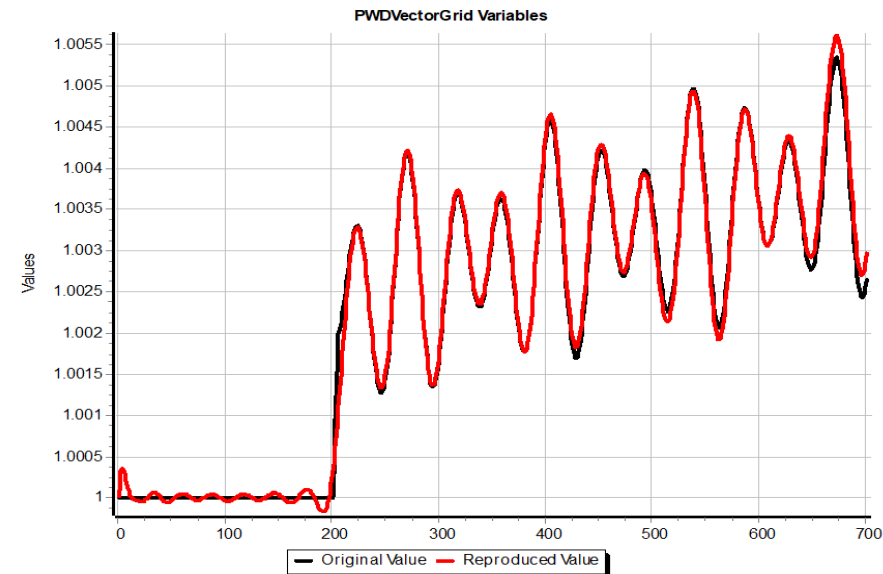
Plotting the original and reproduced signals shows a near exact match



Caution: Setting Time Range Incorrectly Can Result in Unexpected Results!



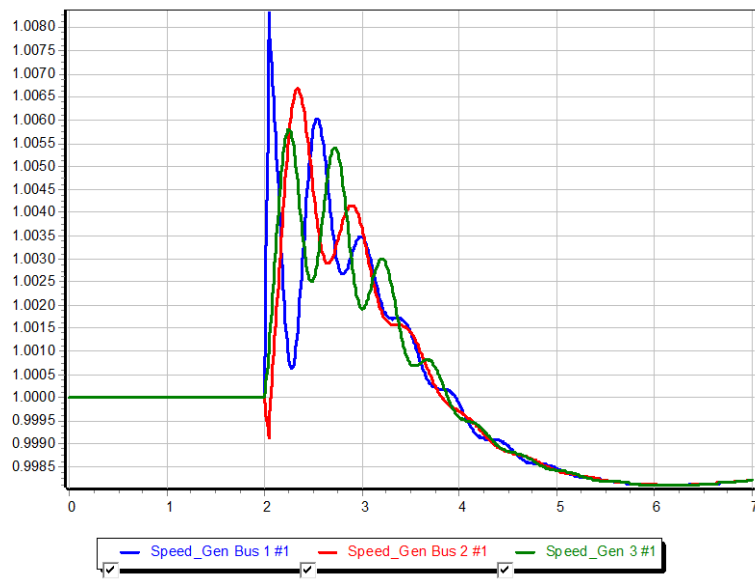
- Assume the system is run with no disturbance for two seconds, and then the fault is applied and the system is run for a total of seven seconds (five seconds post-fault)
 - The incorrect approach would be to try to match the entire signal; rather just match from after the fault
 - Trying to match the full signal between 0 and 7 seconds required eleven modes!
 - By default the Modal Analysis Form sets the default start time to immediately after the last event



GENROU Example with Damping



- Open the case **B3_GENROU**, which changes the GENCLS to GENROU models, adding damping
 - Also each has an EXST1 exciter and a TGOV1 governor
 - The simulation runs for seven seconds, with the fault occurring at two seconds; modal analysis is done from the time the fault is cleared until the end of the simulation.



The image shows the generator speeds. The initial rise in the speed is caused by the load dropping during the fault, causing a power mismatch; this is corrected by the governors. Note the system now has damping; modal analysis tells us how much.

GENROU Example with Damping

Modal Analysis Form

Modal Analysis Status: Solved at 9/15/2019 7:28:01 AM

Data Source Type

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

Calculation Method

- ☐ Variable Projection
- ☒ 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: Gen_Speed

From File: Browse

Just Load Signals

Group Disabled for Existing Data

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 2.050 End Time: 7.000

Maximum Hz: 5.000 Update Sampled Data

Results

Number of Complex and Real Modes: 4

Lowest Percent Damping: -34.022

☒ 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	2.053	11.353	25.5481	Gen 3 #1 Speed	-1.4737	YES
2	1.649	19.638	23.5452	Gen Bus 2 #1 S	-2.0754	YES
3	0.236	65.427	55.7050	Gen Bus 2 #1 S	-1.2833	YES
4	0.098	-34.022	83.2537	Gen Bus 1 #1 S	0.2224	YES

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

	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Average Error, Unscaled	Average Error, Scaled
1	Gen Bus #1 Speed			Speed		YES	YES	1.0037	-0.0014	0	0.001	YES	0.0000	
2	Gen Bus #1 Speed			Speed		YES	YES	1.0034	-0.0014	0	0.001	YES	0.0000	
3	Gen 3 #1 Speed			Speed		YES	YES	1.0035	-0.0014	0	0.001	YES	0.0000	

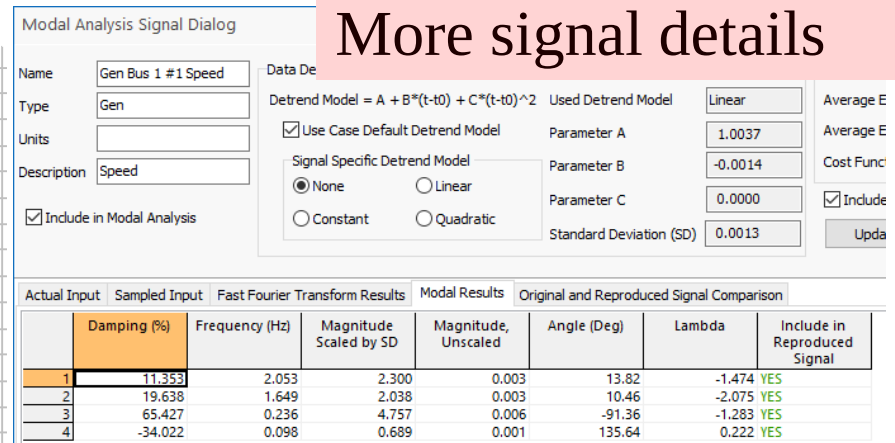
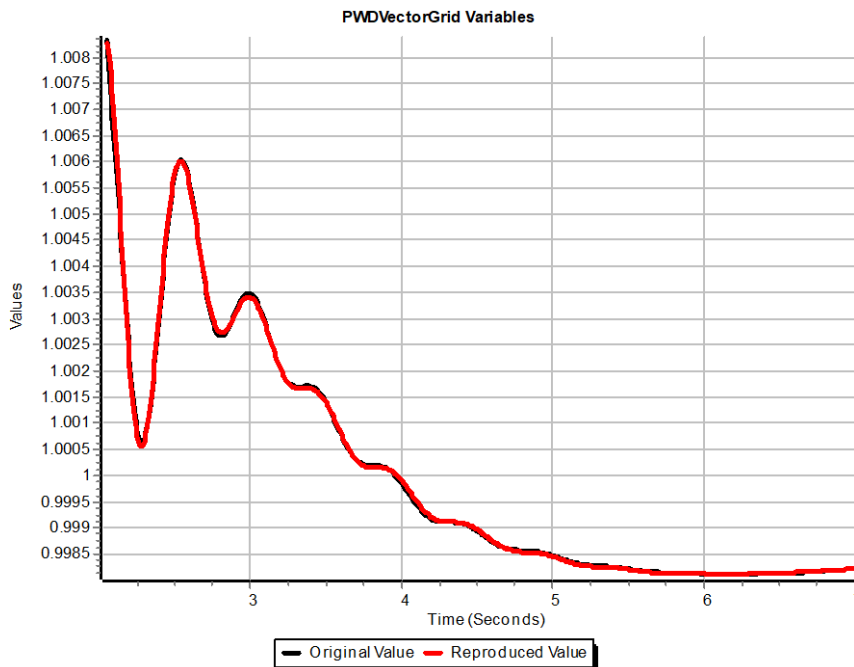
Start time
default value

Mode frequency, damping, and
largest contribution of each
mode in the signals

GENROU Example with Damping



- Left image show how well the speed for generator 1 is approximated by the modes



More signal details

Just the 2.05 Hz mode



Algorithm Details



- The modes are found using the Matrix Pencil method
 - This is a newer technique for determining modes from noisy signals (from about 1990, introduced to power system problems in 2005); it is an alternative to the Prony Method (which dates back to 1795, introduced into power in 1990 by Hauer, Demeure and Scharf)
- Given m samples, with $L=m/2$, the first step is to form the Hankel Matrix, $\mathbf{Y}$ such that

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

Algorithm Details, cont.



- Then calculate $\mathbf{Y}$'s singular values using an economy singular value decomposition (SVD)

$$\mathbf{Y} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T$$

- The ratio of each singular value is then compared to the largest singular value σ_c ; retain the ones with a ratio $>$ than a threshold (e.g., 0.16)
 - This determines the modal order, M
 - Assuming $\mathbf{V}$ is ordered by singular values (highest to lowest), let $\mathbf{V}_p$ be then matrix with the first M columns of $\mathbf{V}$

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

This threshold is a value that can be changed; decrease it to get more modes.

Aside: Matrix Singular Value Decomposition (SVD)



- The SVD is a factorization of a matrix that generalizes the eigendecomposition to any m by n matrix to produce

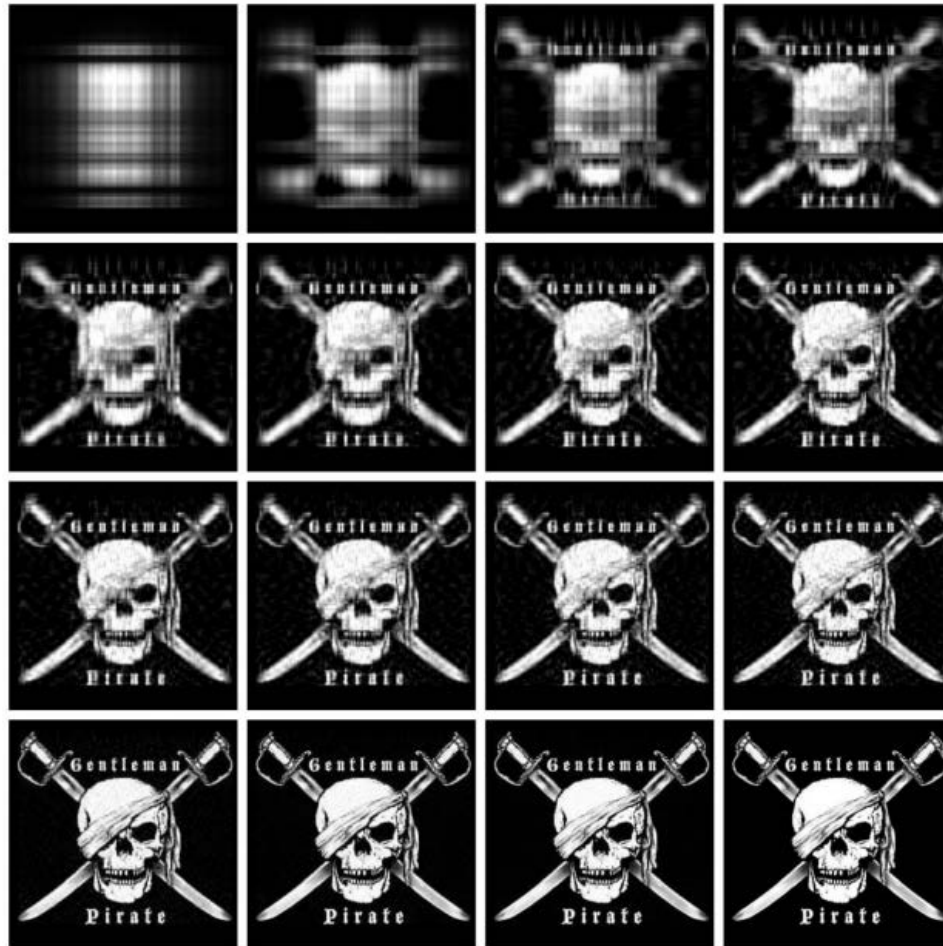
$$\mathbf{Y} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T$$

The original concept is more than 100 years old, but has found lots of recent applications

where S is a diagonal matrix of the singular values

- The singular values are non-negative real numbers that can be used to indicate the major components of a matrix (the gist is they provide a way to decrease the rank of a matrix)
- A key application is image compression

SVD Image Compression Example



Images can be represented with matrices. When an SVD is applied and only the largest singular values are retained the image is compressed.

Figure 3.1: Image size 250x236 – modes used
 $\{\{1,2,4,6\},\{8,10,12,14\},\{16,18,20,25\},\{50,75,100,\text{original image}\}\}$

Algorithm Details, cont.



- 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 $(\mathbf{V}_2^T \mathbf{V}_1, \mathbf{V}_1^T \mathbf{V}_1) = (\mathbf{A}, \mathbf{B})$
- These eigenvalues are the discrete-time poles, z_i with the modal eigenvalues then

$$\lambda_i = \frac{\ln(z_i)}{\Delta T}$$

The log of a complex number $z=r\angle\theta$ is $\ln(r) + j\theta$

If $\mathbf{B}$ is nonsingular (the situation here) then the generalized eigenvalues are the eigenvalues of $\mathbf{B}^{-1}\mathbf{A}$

Matrix Pencil Method with Many Signals



- The Matrix Pencil approach can be used with one signal or with multiple signals
- Multiple signals are handled by forming a $\mathbf{Y}_k$ matrix for each signal k using the measurements for that signal and then combining the matrices so that for N signals

$$\mathbf{Y}_k = \begin{bmatrix} y_{1,k} & y_{2,k} & \cdots & y_{L+1,k} \\ y_{2,k} & y_{3,k} & \cdots & y_{L+2,k} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m-L,k} & y_{m-L+1,k} & \cdots & y_{m,k} \end{bmatrix}$$

The required computation scales linearly with the number of signals

$$\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_1 \\ \vdots \\ \mathbf{Y}_N \end{bmatrix}$$

Matrix Pencil Method with Many Signals



- However, when dealing with many signals, usually the signals are somewhat correlated, so vary few of the signals actually need to be included to determine the desired modes
- Recall we are ultimately finding

The α is found using the matrix pencil method and is common to all the signals; the b vector is signal specific.

$$\hat{y}_{j,k}(\alpha) = \sum_{i=1}^n b_{i,k} \phi_i(t_j, \alpha)$$

where α is a vector with the real and imaginary eigenvalue components,

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

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

for a complex eigenvector value

Quickly Determining the b Vectors



- A key insight is from an approach known as the variable projection method (from Borden, 2013) that for any signal k

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

Where m is the number of measurements and n is the number of modes

And then the residual is minimized by selecting $\mathbf{b}_k = \boldsymbol{\Phi}(\boldsymbol{\alpha})^+ \mathbf{y}_k$

where $\boldsymbol{\Phi}(\boldsymbol{\alpha})$ is the m by n 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 $\boldsymbol{\Phi}(\boldsymbol{\alpha})$

Aside: Pseudoinverse of a Matrix



- The pseudoinverse of a matrix generalizes concept of a matrix inverse to an m by n matrix, in which $m \geq n$
 - Specifically this is a Moore-Penrose Matrix Inverse
- Notation for the pseudoinverse of $\mathbf{A}$ is $\mathbf{A}^+$
- Satisfies $\mathbf{A}\mathbf{A}^+\mathbf{A} = \mathbf{A}$
- If $\mathbf{A}$ is a square matrix, then $\mathbf{A}^+ = \mathbf{A}^{-1}$
- Quite useful for solving the least squares problem since the least squares solution of $\mathbf{A}\mathbf{x} = \mathbf{b}$ is $\mathbf{x} = \mathbf{A}^+ \mathbf{b}$
- Can be calculated using an SVD

$$\mathbf{A} = \mathbf{U} \mathbf{\Sigma} \mathbf{V}^T$$

$$\mathbf{A}^+ = \mathbf{V} \mathbf{\Sigma}^+ \mathbf{U}^T$$

Least Squares Matrix Pseudoinverse Example



- Assume we wish to fix a line ($mx + b = y$) to three data points: (1,1), (2,4), (6,4)
- Two unknowns, m and b ; hence $\mathbf{x} = [m \ b]^T$
- Setup in form of $\mathbf{Ax} = \mathbf{b}$

$$\begin{bmatrix} 1 & 1 \\ 2 & 1 \\ 6 & 1 \end{bmatrix} \begin{bmatrix} m \\ b \end{bmatrix} = \begin{bmatrix} 1 \\ 4 \\ 4 \end{bmatrix} \quad \text{so} \quad \mathbf{A} = \begin{bmatrix} 1 & 1 \\ 2 & 1 \\ 6 & 1 \end{bmatrix}$$

Least Squares Matrix Pseudoinverse Example, cont.



- Doing an economy SVD

$$\mathbf{A} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T = \begin{bmatrix} -0.182 & -0.765 \\ -0.331 & -0.543 \\ -0.926 & 0.345 \end{bmatrix} \begin{bmatrix} 6.559 & 0 \\ 0 & 0.988 \end{bmatrix} \begin{bmatrix} -0.976 & -0.219 \\ 0.219 & -0.976 \end{bmatrix}$$

- Computing the pseudoinverse

$$\mathbf{A}^+ = \mathbf{V}\mathbf{\Sigma}^+\mathbf{U}^T = \begin{bmatrix} -0.976 & 0.219 \\ -0.219 & -0.976 \end{bmatrix} \begin{bmatrix} 0.152 & 0 \\ 0 & 1.012 \end{bmatrix} \begin{bmatrix} -0.182 & -0.331 & -0.926 \\ -0.765 & -0.543 & 0.345 \end{bmatrix}$$

$$\mathbf{A}^+ = \mathbf{V}\mathbf{\Sigma}^+\mathbf{U}^T = \begin{bmatrix} -0.143 & -0.071 & 0.214 \\ 0.762 & 0.548 & -0.310 \end{bmatrix}$$

In an economy SVD the $\mathbf{\Sigma}$ matrix has dimensions of m by m if $m < n$ or n by n if $n < m$

Least Squares Matrix Pseudoinverse Example, cont.



- Computing $\mathbf{x} = [m \ b]^T$ gives

$$\mathbf{A}^+ \mathbf{b} = \begin{bmatrix} -0.143 & -0.071 & 0.214 \\ 0.762 & 0.548 & -0.310 \end{bmatrix} \begin{bmatrix} 1 \\ 4 \\ 4 \end{bmatrix} = \begin{bmatrix} 0.429 \\ 1.71 \end{bmatrix}$$

- With the pseudoinverse approach we immediately see the sensitivity of the elements of $\mathbf{x}$ to the elements of $\mathbf{b}$
 - New values of m and b can be readily calculated if $\mathbf{y}$ changes
- Computationally the SVD is order m^2n+n^3 (with $n < m$)

Iterative Matrix Pencil Method

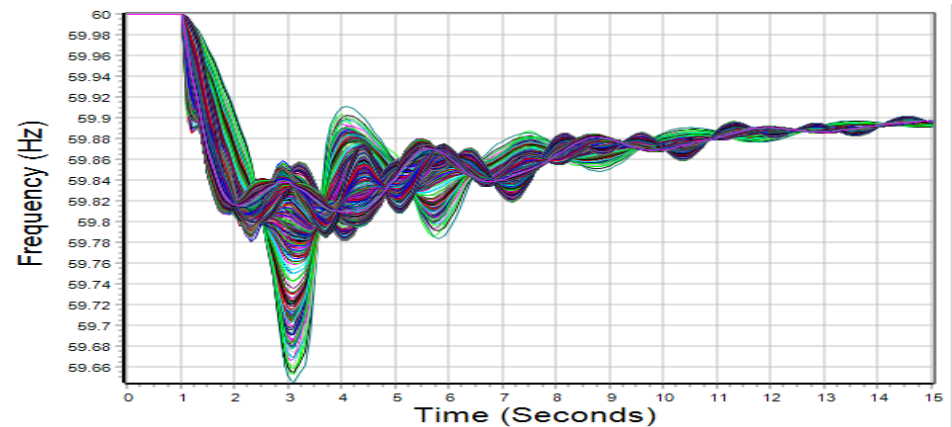
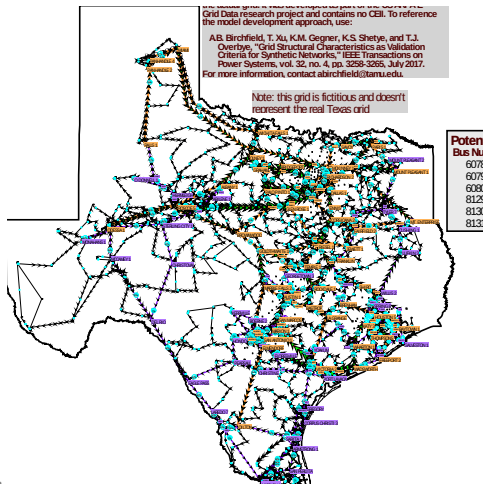


- When there are a large number of signals the iterative matrix pencil method works by
 - Selecting an initial signal to calculate the α vector
 - Quickly calculating the $\mathbf{b}$ vectors for all the signals, and getting a cost function for how closely the reconstructed signals match their sampled values
 - Selecting a signal that has a high cost function, and repeating the above adding this signal to the algorithm to get an updated α

2000 Bus System Example



- In PowerWorld open the case **ECEN460_TSGC_GenDrop**
 - This is a 2000 bus synthetic electric grid on the ERCOT footprint that we use in our undergraduate and graduate classes to study larger power systems
- Run the predefined transient stability contingency
 - Response following the loss of two generators



2000 Bus System Example



- On the Transient Stability page select **Results from RAM**, view the Bus page display just the bus frequencies, right-click and select **Modal Analysis All Columns**

We'll work with frequencies in Hz rather than per unit

Transient Stability Analysis

Simulation Status: Not Initialized

Run Transient Stability | Pause | Abort | Restore Reference | For Contingency: Find | Gen Drop 2700 MW Together

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 R
 - Multi-Terminal DC C
 - Area
 - Zone
 - Interface
 - Injection Group
 - Substation
 - Line Shunt
 - Case Information
 - Measurement Mode
 - Model Plane
 - Minimum/Maximum Values
 - Summary
 - Events
 - Solution Details

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 | Multi-Terminal DC Converter | Area | Zone | Interface | Injection Group | Substation | Line Shunt | Case Information

Column Order

Object then Field

Column Filtering Filter Modify...

Use Area/Zone Filters

Choose Fields to Display

- ☒ Frequency
- ☐ Frequency in PU
- ☐ Gen Mvar
- ☐ Gen MW
- ☐ Load Mvar
- ☐ Load MW
- ☐ ROCOF (Hz per Seco...
- ☐ Status
- ☐ V (kV)
- ☐ V angle
- ☐ V angle (rad)
- ☐ V angle No shift
- ☐ V pu

Check All | Uncheck All

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

Save All Settings To | Load All Settings From | Show Transient Contour Toolbar | Auto Insert... | Critical Clearing Time Calculator... | Help | Close

Time	Bus ODESSA 2 0 Frequency	Bus PRESIDIO 2 0 Frequency	Bus DONNELL 1 1 Frequency	Bus BIG SPRING 5 0 Frequency	Bus BIG SPRING 5 1 Frequency	Bus VAN HORN 0 Frequency	Bus IRAAN 2 0 Frequency	Bus IRAAN 2 1 Frequency	Bus PRESIDIO 1 0 Frequency	Bus PRESIDIO 1 1 Frequency	Bus SANDERSO 0 Frequency	Bus MONAHAN 2 0 Frequency	Bus GRANDFAL 0 Frequency	Bus MARFA 0 Frequency	Bus GARDEN CITY 0 Frequency	Bus ODES 0 Frequency
1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
2	0.1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
3	0.2	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
4	0.3	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
5	0.4	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
6	0.5	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
7	0.6	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
8	0.7	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
9	0.8	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
10	0.9	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
11	1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
12	1	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
13	1.1	59.9942	59.9935	59.993	59.993	59.993	59.993	59.9938	59.9917	59.9918	59.9934	59.9934	59.9888	59.9946	59.9938	59.9936
14	1.2	59.9875	59.9869	59.9842	59.9838	59.9855	59.9856	59.9874	59.9841	59.9845	59.9868	59.9869	59.9782	59.9885	59.9873	59.9871
15	1.3	59.9778	59.978	59.9709	59.97	59.9749	59.9752	59.9766	59.9742	59.975	59.9779	59.9781	59.9651	59.9799	59.9784	59.9782
16	1.4	59.9657	59.9675	59.9541	59.9525	59.962	59.9626	59.9601	59.9631	59.9643	59.9674	59.9678	59.9513	59.9693	59.9678	59.9677
17	1.5	59.9521	59.9557	59.9347	59.9324	59.9475	59.9483	59.9562	59.9509	59.9525	59.9556	59.9561	59.9371	59.9573	59.9558	59.9505
18	1.6	59.9373	59.9426	59.914	59.9111	59.9319	59.9329	59.943	59.9376	59.9395	59.9425	59.9432	59.9224	59.9439	59.9426	59.936
19	1.7	59.9221	59.9285	59.8933	59.8898	59.9157	59.9169	59.9289	59.9233	59.9256	59.9284	59.9292	59.9069	59.9295	59.9283	59.9286
20	1.8	59.9069	59.9138	59.8737	59.8698	59.8996	59.901	59.9142	59.9085	59.9111	59.9138	59.9147	59.8907	59.9147	59.9136	59.914
21	1.9	59.8922	59.8994	59.856	59.8518	59.8842	59.8858	59.8997	59.894	59.8968	59.8994	59.9003	59.8746	59.9001	59.8991	59.8995
22	2	59.8784	59.8854	59.8406	59.8364	59.8698	59.8715	59.8857	59.88	59.883	59.8854	59.8863	59.8593	59.886	59.8855	59.8764
23	2.1	59.8653	59.8718	59.8278	59.8238	59.8565	59.8581	59.8721	59.8667	59.8697	59.8719	59.8728	59.8456	59.8724	59.8715	59.872

2000 Bus System Example



- Initially our goal is to understand the modal frequencies and their damping
- Initially we'll consider just one of the 2000 signals

Modal Analysis Form

Modal Analysis Status: Data Loaded for 2000 Signals

Data Source Type:

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

Calculation Method:

- ☐ Variable Projection
- ☐ File, Comtrade CFG
- ☒ 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: Bus Frequency Ten

From File: [Browse]

Just Load Signals

Group Disabled for Existing Data

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 1.000 End Time: 15.000

Maximum Hz: 5.000 Update Sampled Data

Results

Number of Complex and Real Modes: 0

Lowest Percent Damping: 0.000

Include Detrend in Reproduced: ☒

Subtract Reproduced from: ☐

Update Reproduced Sign

Frequency (Hz)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage Mode	Lambda
None	None	None	None	None

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

Type	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	
1	Bus ODESSA 2 0 Freq	31.907	-102.262	Frequency		YES	YES	59.8423	0.0034	0	0.046	NC
2	Bus PRESIDIO 2 0 Freq	29.888	-104.519	Frequency		NO	YES	59.8423	0.0034	0	0.049	NC
3	Bus O DONNELL 1 0 Freq	32.926	-101.648	Frequency		NO	YES	59.8409	0.0036	0	0.035	NC
4	Bus O DONNELL 1 1 Freq	32.926	-101.648	Frequency		NO	YES	59.8408	0.0036	0	0.034	NC
5	Bus BIG SPRING 5 0 Freq	32.208	-101.388	Frequency		NO	YES	59.8418	0.0035	0	0.043	NC
6	Bus BIG SPRING 5 1 Freq	32.208	-101.388	Frequency		NO	YES	59.8418	0.0035	0	0.043	NC
7	Bus VAN HORN 0 Freq	31.093	-104.625	Frequency		NO	YES	59.8424	0.0034	0	0.049	NC
8	Bus IRAAN 2 0 Freq	30.931	-102.201	Frequency		NO	YES	59.8419	0.0035	0	0.046	NC
9	Bus IRAAN 2 1 Freq	30.931	-102.201	Frequency		NO	YES	59.8420	0.0035	0	0.047	NC
10	Bus PRESIDIO 1 0 Freq	29.600	-104.300	Frequency		NO	YES	59.8423	0.0034	0	0.049	NC
11	Bus PRESIDIO 1 1 Freq	29.600	-104.300	Frequency		NO	YES	59.8423	0.0034	0	0.049	NC
12	Bus SANDERSON 0 Freq	30.028	-101.970	Frequency		NO	YES	59.8408	0.0036	0	0.038	NC

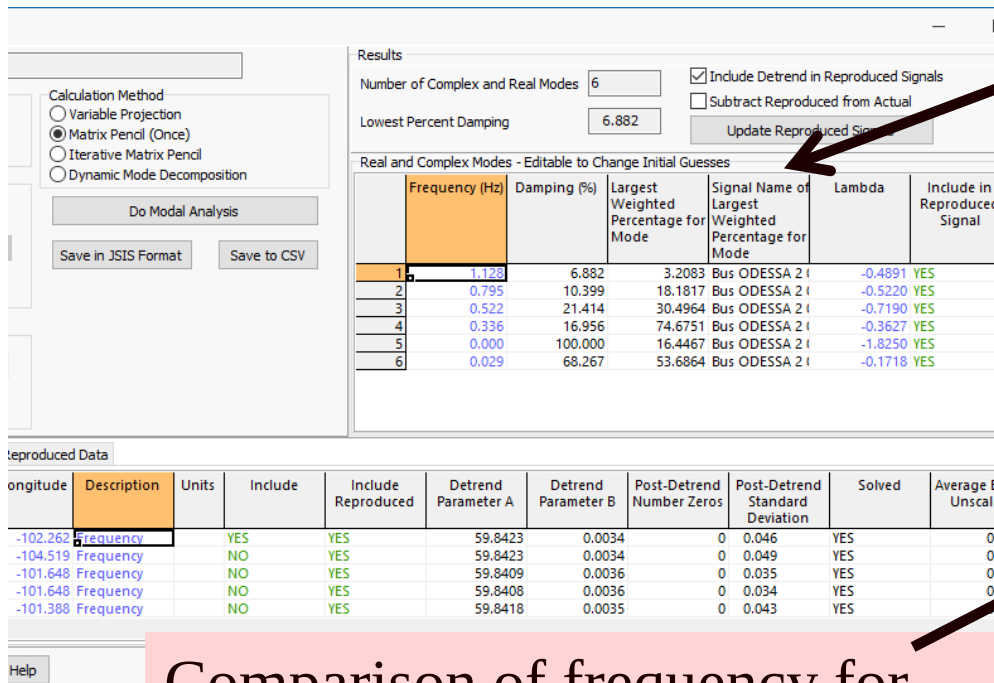
Toggle the **Include** to “No” for all the 2000 signals, except set the first one to “Yes”

Once only the first signal is selected, click the **Do Modal Analysis**

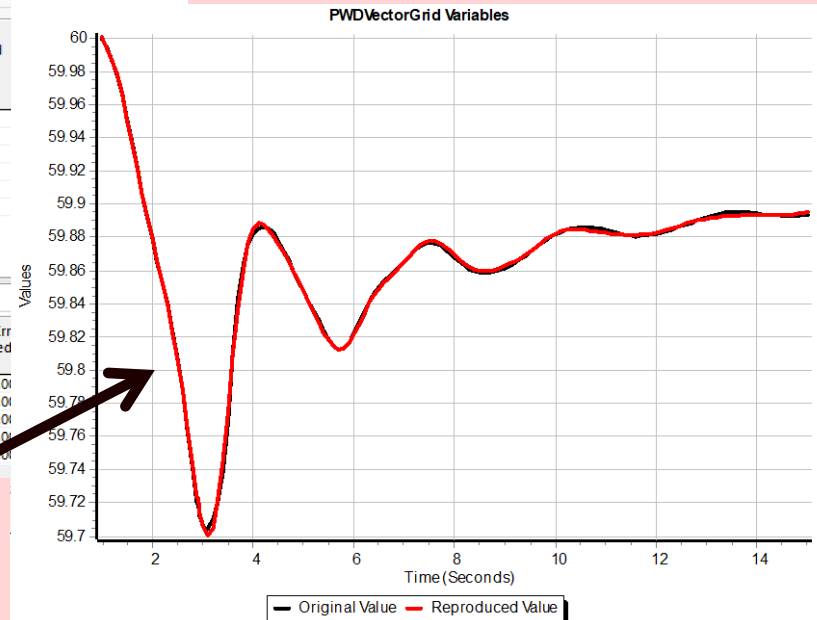
2000 Bus System Example, One Signal



- Note the modes and their damping. The signal dialog indicates that we have fairly accurately reproduced the first signal



Calculated mode information



Comparison of frequency for the first bus

2000 Bus System Example, Comparing the Other Signals



- Sort on the cost function to see the worst match

Modal Analysis Form

Modal Analysis Status: Solved at 9/15/2019 9:38:16 AM

Data Source Type

- ☐ From Plot
- ☐ File, WECC CSV 2
- ☐ File, JESIS Format
- ☐ File, Comtrade CFF
- ☐ File, Comtrade CFG
- ☒ None, Existing Data

Calculation Method

- ☐ Variable Projection
- ☒ Matrix Pencil (Once)
- ☐ Iterative Matrix Pencil
- ☐ Dynamic Mode Decomposition

Do Modal Analysis

Save in JESIS Format

Save to CSV

Data Source Inputs from Plots or Files

From Plot: Bus Frequency Ten

From File: Browse

Just Load Signals

Group Disabled for Existing Data

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 1.000 End Time: 15.000

Maximum Hz: 5.000 Update Sampled Data

Results

Number of Complex and Real Modes: 6

Lowest Percent Damping: 6.882

☒ 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	1.128	6.882	3.2083	Bus ODESSA 2	-0.4891	YES
2	0.795	10.399	18.1817	Bus ODESSA 2	-0.5220	YES
3	0.522	21.414	30.4964	Bus ODESSA 2	-0.7190	YES
4	0.336	16.956	74.6751	Bus ODESSA 2	-0.3627	YES
5	0.000	100.000	16.4467	Bus ODESSA 2	-0.8250	YES
6	0.029	68.267	53.6864	Bus ODESSA 2	-0.718	YES

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

	Type	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Average Error Unscaled	Ave
1	Bus	Bus MT. ENTERPRISE 4	32.018	-94.620	Frequency		NO	YES	59.8406	0.0037	0	0.034	YES	0.0073	
2	Bus	Bus MT. ENTERPRISE 3	32.018	-94.620	Frequency		NO	YES	59.8406	0.0037	0	0.034	YES	0.0073	
3	Bus	Bus MT. ENTERPRISE 6	32.018	-94.620	Frequency		NO	YES	59.8406	0.0037	0	0.034	YES	0.0073	
4	Bus	Bus PARIS 1 7 Frequency	33.631	-95.590	Frequency		NO	YES	59.8410	0.0036	0	0.035	YES	0.0073	
5	Bus	Bus PARIS 1 2 Frequency	33.631	-95.590	Frequency		NO	YES	59.8411	0.0036	0	0.035	YES	0.0073	

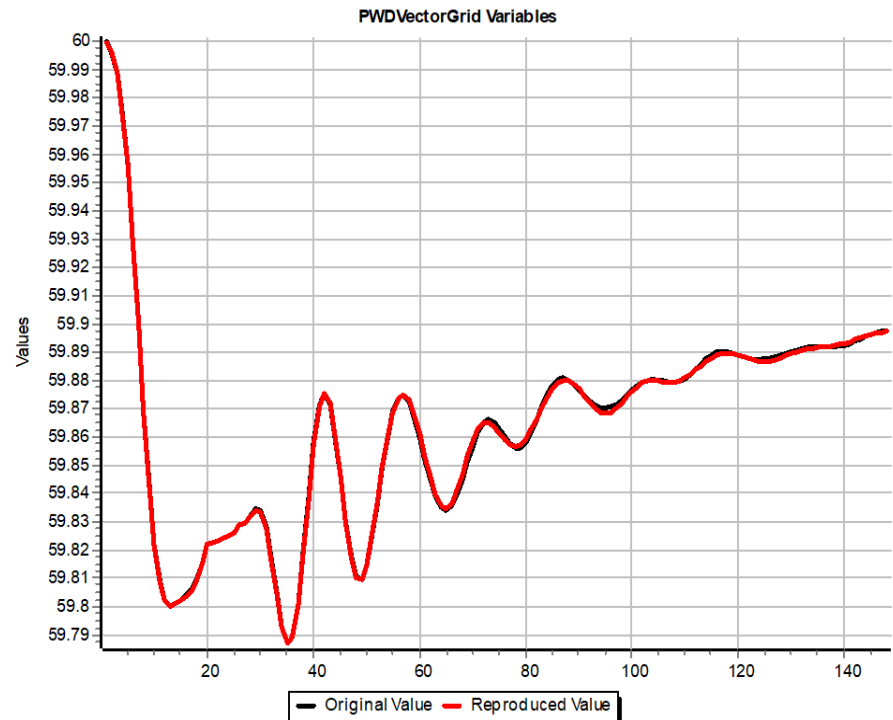
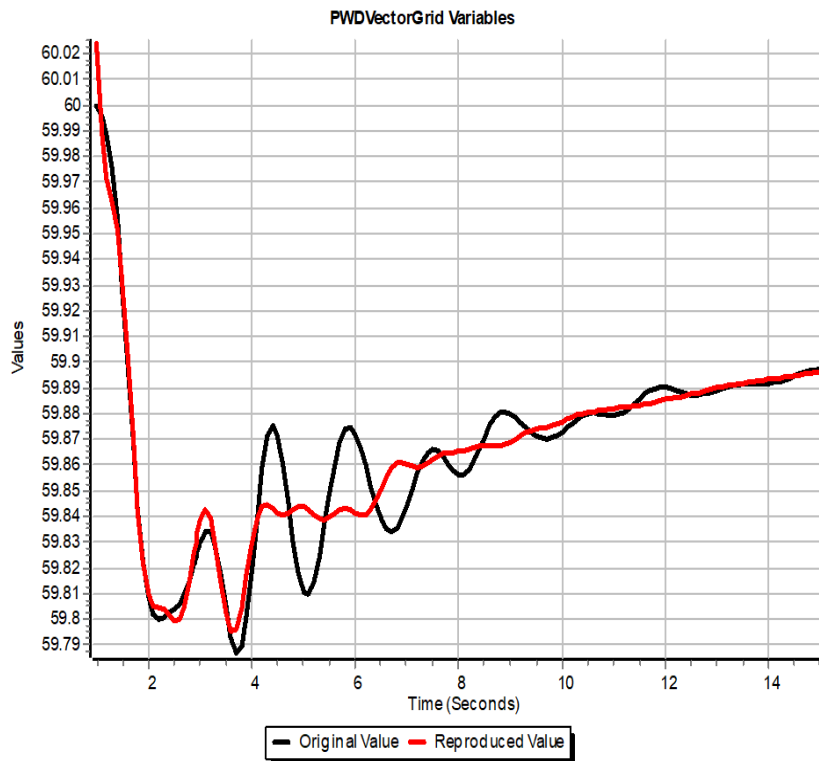
Bus 8078 has the worst match

- Now we will rerun it including this bus frequency signal as well; that is, now a total of two signals

2000 Bus System Example, Now With Two Signals



- The left image shows the original match for bus 8078 (when not included), and the right when included



Updated Modes

- The calculated modes and damping have changed slightly with the additional signal

Modal Analysis Form

Modal Analysis Status: Solved at 9/15/2019 10:05:04 AM

Data Source Type

From Plot: ☐ From Plot ☐ File, WECC CSV 2 ☐ File, JSIS Format ☐ File, Comtrade CFG ☐ File, Comtrade CFG ☒ None, Existing Data

Calculation Method

☐ Variable Projection ☒ 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: Bus Frequency Ten

From File: Browse

Just Load Signals Group Disabled for Existing Data

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 1.000 End Time: 15.000

Maximum Hz: 5.000 Update Sampled Data

Results

Number of Complex and Real Modes: 7

Lowest Percent Damping: 9.198

☒ 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	1.008	9.198	11.8378	Bus MT. ENTER	-0.5849	YES
2	0.803	16.940	23.9593	Bus ODESSA 2 I	-0.8676	YES
3	0.662	9.370	62.8500	Bus MT. ENTER	-0.3917	YES
4	0.597	28.539	49.8091	Bus ODESSA 2 I	-1.1168	YES
5	0.363	34.909	54.7157	Bus ODESSA 2 I	-0.8496	YES
6	0.328	13.521	49.8000	Bus ODESSA 2 I	-0.2812	YES
7	0.046	44.591	37.1872	Bus ODESSA 2 I	-0.1435	YES

Input Data, Actual Sampled Input Data Signals Options Reproduced Data

	Type	Name	Latitude	Longitude	Description	Units	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	Maxim Error, U
1	Bus	Bus MT. ENTERPRISE 4	32.018	-94.620	Frequency		YES	YES	59.8406	0.0037	0	0.034	YES	0.0005	0.0000	
2	Bus	Bus ODESSA 2 0 Freq	31.907	-102.262	Frequency		YES	YES	59.8423	0.0034	0	0.046	YES	0.0012	0.0001	
3	Bus	Bus O DONNELL 1 0 Freq	32.926	-101.648	Frequency		NO	YES	59.8409	0.0036	0	0.035	YES	0.0005	0.0000	
4	Bus	Bus BIG SPRING 5 0 Freq	32.208	-101.388	Frequency		NO	YES	59.8418	0.0035	0	0.043	YES	0.0009	0.0000	
5	Bus	Bus BIG SPRING 5 1 Freq	32.208	-101.388	Frequency		NO	YES	59.8418	0.0035	0	0.043	YES	0.0009	0.0000	
6	Bus	Bus VAN HORN 0 Freq	31.093	-104.625	Frequency		NO	YES	59.8424	0.0034	0	0.049	YES	0.0015	0.0001	
7	Bus	Bus IRAAN 2 1 Freq	30.931	-102.201	Frequency		NO	YES	59.8420	0.0035	0	0.047	YES	0.0011	0.0001	
8	Bus	Bus ODESSA 4 0 Freq	31.725	-102.414	Frequency		NO	YES	59.8424	0.0034	0	0.047	YES	0.0012	0.0001	
9	Bus	Bus PRESIDIO 1 0 Freq	29.600	-104.300	Frequency		NO	YES	59.8423	0.0034	0	0.049	YES	0.0014	0.0001	
10	Bus	Bus PRESIDIO 1 1 Freq	29.600	-104.300	Frequency		NO	YES	59.8423	0.0034	0	0.049	YES	0.0014	0.0001	
11	Bus	Bus SANDERSON 0 Freq	30.028	-101.970	Frequency		NO	YES	59.8408	0.0036	0	0.038	YES	0.0008	0.0000	
12	Bus	Bus MONAHAN 2 0 Freq	31.485	-103.161	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0016	0.0001	
13	Bus	Bus GRANDFALLS 0 Freq	31.170	-103.085	Frequency		NO	YES	59.8423	0.0034	0	0.049	YES	0.0014	0.0001	
14	Bus	Bus MARFA 0 Freq	30.285	-104.006	Frequency		NO	YES	59.8423	0.0034	0	0.049	YES	0.0014	0.0001	
15	Bus	Bus MCC&MFP 1 1 Freq	31.209	-102.242	Frequency		NO	YES	59.8416	0.0035	0	0.042	YES	0.0009	0.0000	

Close Help Print

2000 Bus System Example, Iterative Matrix Pencil

- Now run the Iterative Matrix Pencil method

Modal Analysis Form

Modal Analysis Status: Solved at 9/15/2019 10:01:17 AM

Data Source Type

☐ From Plot ☐ File, Comtrade CFF

☐ File, WECC CSV 2 ☐ File, Comtrade CFG

☐ File, J3IS Format ☒ None, Existing Data

Calculation Method

☐ Variable Projection

☐ Matrix Pencil (Once)

☒ Iterative Matrix Pencil

☐ Dynamic Mode Decomposition

Data Source Inputs from Plots or Files

From Plot: Bus Frequency Ten

From File: Browse

Just Load Signals **Group Disabled for Existing Data**

Data Sampling Time (Seconds) and Frequency (Hz)

Start Time: 1.000 End Time: 15.000

Maximum Hz: 5.000 Update Sampled Data

Do Modal Analysis

Save in J3IS Format Save to CSV

Optimal Matrix Pencil Options

Number of Iterations: 10

☒ Initial All Signals to be Not Included

Current Iteration: 10

Results

Number of Complex and Real Modes: 11

Lowest Percent Damping: 6.722

☒ 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
3	0.654	9.871	56.1534	Bus MT. ENTER	-0.4077	YES
4	0.791	11.215	41.7318	Bus MONAHAN	-0.5606	YES
5	0.600	6.722	41.5305	Bus BROWNSVI	-0.2540	YES
6	0.784	49.446	36.1120	Bus POINT CON	-2.8034	YES
7	0.054	42.916	34.5740	Bus CHRISTINE	-0.1614	YES
8	0.958	8.747	24.7812	Bus CHRISTINE	-0.5286	YES
9	0.000	100.000	18.0149	Bus POINT CON	-6.0794	YES
10	1.362	8.987	13.7990	Bus CHRISTINE	-0.7723	YES
11	1.607	9.667	11.1401	Bus FANNIN 2 F	-0.9807	YES

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

	Name	Latitude	Longitude	Description	Units	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 ST
3	Bus ODESSA 1 1 Frequency	31.840	-102.326	Frequency		NO	YES	59.8431	0.0033	0	0.053	YES	0.0018	0.001
4	Bus ODESSA 1 4 Frequency	31.840	-102.326	Frequency		NO	YES	59.8431	0.0034	0	0.054	YES	0.0018	0.001
5	Bus ODESSA 1 7 Frequency	31.840	-102.326	Frequency		NO	YES	59.8430	0.0034	0	0.053	YES	0.0017	0.001
6	Bus ODESSA 1 6 Frequency	31.840	-102.326	Frequency		NO	YES	59.8431	0.0034	0	0.055	YES	0.0017	0.001
7	Bus MONAHANS 1 4 Frequency	31.584	-102.963	Frequency		YES	YES	59.8429	0.0034	0	0.054	YES	0.0017	0.001
8	Bus MONAHANS 1 3 Frequency	31.584	-102.963	Frequency		NO	YES	59.8428	0.0034	0	0.052	YES	0.0016	0.001
9	Bus ODESSA 1 5 Frequency	31.840	-102.326	Frequency		NO	YES	59.8426	0.0034	0	0.050	YES	0.0015	0.001
10	Bus MONAHANS 1 5 Frequency	31.584	-102.963	Frequency		NO	YES	59.8427	0.0034	0	0.053	YES	0.0015	0.001
11	Bus GOLDSMITH 0 Frequency	31.995	-102.828	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
12	Bus MONAHANS 1 0 Frequency	31.584	-102.963	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
13	Bus MONAHANS 1 2 Frequency	31.584	-102.963	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
14	Bus MONAHANS 1 1 Frequency	31.584	-102.963	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
15	Bus KERMIT 0 Frequency	31.696	-103.139	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
16	Bus PECOS 0 Frequency	31.804	-103.600	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
17	Bus MONAHANS 2 0 Frequency	31.485	-103.161	Frequency		NO	YES	59.8425	0.0034	0	0.050	YES	0.0014	0.001
18	Bus ODESSA 1 0 Frequency	31.840	-102.326	Frequency		NO	YES	59.8423	0.0034	0	0.046	YES	0.0014	0.001
19	Bus ODESSA 1 9 Frequency	31.840	-102.326	Frequency		NO	YES	59.8423	0.0034	0	0.046	YES	0.0014	0.001
20	Bus ODESSA 6 0 Frequency	31.969	-102.631	Frequency		NO	YES	59.8425	0.0034	0	0.049	YES	0.0014	0.001
21	Bus ODESSA 2 0 Frequency	31.907	-102.262	Frequency		YES	YES	59.8423	0.0034	0	0.046	YES	0.0013	0.001
22	Bus ANDREWS 0 Frequency	32.336	-102.697	Frequency		NO	YES	59.8424	0.0034	0	0.048	YES	0.0013	0.001
23	Bus ODESSA 3 0 Frequency	32.001	-102.312	Frequency		NO	YES	59.8423	0.0034	0	0.046	YES	0.0013	0.001

Close ? Help Print

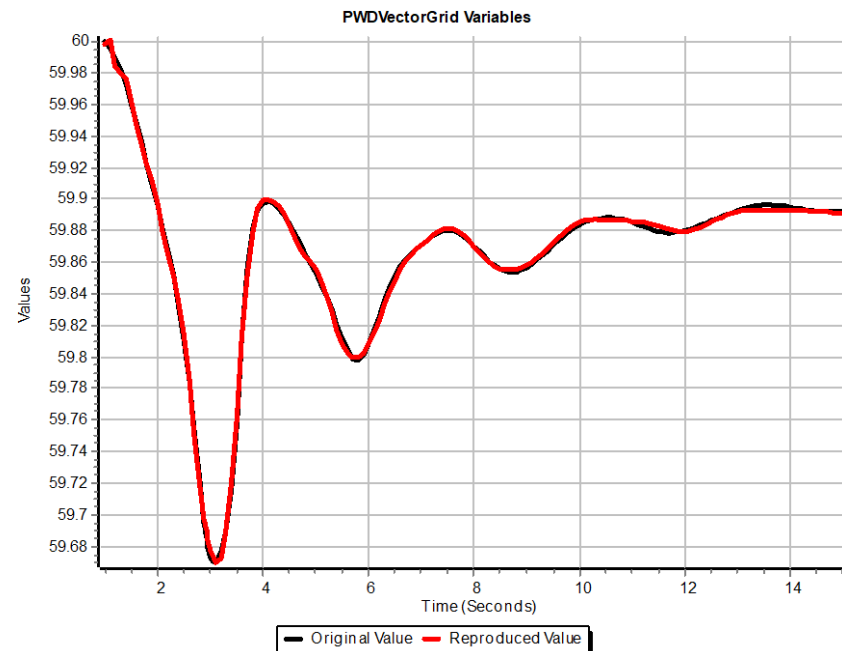


2000 Bus System Example, Iterative Matrix Pencil



- With the inclusion of just ten signals (out of 2000) quite accurate modal information is obtained for all 2000 frequency signals

**This is the worst match
(at bus 1072)**



Takeaways So Far



- Modal analysis can be quickly done on a large number of signals
 - Computationally is an $O(N^3)$ process for one signal, where N is the number of sample points; it varies linearly with the number of included signals
 - Number of sample points is automatically determined from the highest desired frequency (The Nyquist-Shannon sampling theory requires sampling at twice the highest desired frequency)
 - Determining how signals are manifested in modes is fast (done when **Include Reproduced** is Yes)

Getting Mode Details

- Detailed information about each mode is available by right-clicking on mode and selecting Show Dialog

Results

Number of Complex and Real Modes: 11

Lowest Percent Damping: 0.722

☒ Include Detrend in Reproduced Signals

☐ Subtract Reproduced from Actual

Update Reproduced Signals

Real and Complex Modes - Editable to Change Initial Guesses

	Frequency (▲)	Damping (%)	Largest Weighted Percentage for Mode	Signal Name of Largest Weighted Percentage for Mode	Lambda	In Rep
1	0.000	10.000	18.0149	Bus POINT COM	-6.0794	YES
2	0.054	42.916	34.5740	Bus CHRISTINE	-0.1614	YES
3	0.320	14.185	72.9017	Bus NEWGULF	-0.2879	YES
4	0.344	30.433	71.2927	Bus ODESSA 2	-0.6915	YES
5	0.600	6.722	41.5305	Bus BROWNSVI	-0.2540	YES
6	0.654	9.871	56.1534	Bus MT. ENTER	-0.4077	YES
7	0.784	49.446	36.1120	Bus POINT COM	-2.8034	YES
8	0.791	11.215	41.7318	Bus MONAHAN	-0.5606	YES

Include Reproduced Detrend Parameter A Detrend Parameter B Post-Detrend Number Zeros Post-Detrend Standard Deviation Solved A U

Modal Analysis Mode Details

Frequency (Hz) and Damping (%) 0.654 Hz, Damping = 9.871%

Transfer Results from Selected Column to Object Custom Floating Point Field

Custom Floating Point Field 1 Transfer Results

Type	Name	Units	Description	Post-Detrend Standard Deviation	Angle (Deg)	Magnitude, Unscaled	Magnitude Scaled by SD	Cost Function
1 Bus	Bus ODESSA 2 0 Freq		Frequency	0.046	2.643	0.029	0.626	0.0029
2 Bus	Bus PRESIDIO 2 0 Freq		Frequency	0.049	14.459	0.015	0.302	0.0026
3 Bus	Bus O DONNELL 1 0 Freq		Frequency	0.035	-64.584	0.059	1.680	0.0022
4 Bus	Bus O DONNELL 1 1 Freq		Frequency	0.034	-66.995	0.065	1.876	0.0023
5 Bus	Bus BIG SPRING 5 0 Freq		Frequency	0.043	-25.908	0.030	0.704	0.0024
6 Bus	Bus BIG SPRING 5 1 Freq		Frequency	0.043	-22.868	0.030	0.684	0.0024
7 Bus	Bus VAN HORN 0 Freq		Frequency	0.049	14.954	0.014	0.275	0.0027
8 Bus	Bus IRAAN 2 0 Freq		Frequency	0.046	3.964	0.020	0.436	0.0025
9 Bus	Bus IRAAN 2 1 Freq		Frequency	0.047	10.167	0.020	0.432	0.0025
10 Bus	Bus PRESIDIO 1 0 Freq		Frequency	0.049	14.635	0.015	0.311	0.0026
11 Bus	Bus PRESIDIO 1 1 Freq		Frequency	0.049	17.211	0.015	0.314	0.0026
12 Bus	Bus SANDERSON 0 Freq		Frequency	0.038	-21.924	0.021	0.537	0.0023
13 Bus	Bus MONAHANS 2 0 Freq		Frequency	0.050	15.529	0.010	0.210	0.0028
14 Bus	Bus GRANDFALLS 0 Freq		Frequency	0.049	12.851	0.013	0.270	0.0027
15 Bus	Bus MARFA 0 Freq		Frequency	0.049	14.724	0.015	0.295	0.0026
16 Bus	Bus GARDEN CITY 0 Freq		Frequency	0.045	-11.481	0.027	0.593	0.0024
17 Bus	Bus ODESSA 4 0 Freq		Frequency	0.047	3.762	0.023	0.487	0.0027
18 Bus	Bus NOTREES 0 Freq		Frequency	0.048	7.842	0.022	0.449	0.0027
19 Bus	Bus MIDLAND 4 0 Freq		Frequency	0.046	1.104	0.029	0.622	0.0029
20 Bus	Bus BIG SPRING 1 0 Freq		Frequency	0.042	-31.814	0.032	0.764	0.0024
21 Bus	Bus BIG SPRING 1 1 Freq		Frequency	0.043	-22.833	0.030	0.694	0.0024
22 Bus	Bus O DONNELL 2 0 Freq		Frequency	0.035	-64.883	0.060	1.697	0.0022
23 Bus	Bus O DONNELL 2 1 Freq		Frequency	0.036	-62.317	0.054	1.506	0.0022
24 Bus	Bus ODESSA 6 0 Freq		Frequency	0.049	11.978	0.021	0.427	0.0027
25 Bus	Bus BIG SPRINGS 0 Freq		Frequency	0.042	-28.413	0.031	0.731	0.0024
26 Bus	Bus BIG SPRINGS 1 Freq		Frequency	0.045	-14.551	0.029	0.648	0.0024
27 Bus	Bus MIDLAND 2 0 Freq		Frequency	0.045	-12.787	0.029	0.645	0.0026
28 Bus	Bus COAHOMA 0 Freq		Frequency	0.035	-66.342	0.063	1.813	0.0023
29 Bus	Bus MIDLAND 3 0 Freq		Frequency	0.045	-11.663	0.026	0.571	0.0026
30 Bus	Bus ALPINE 0 Freq		Frequency	0.048	11.994	0.017	0.355	0.0026
31 Bus	Bus FORT DAVIS 0 Freq		Frequency	0.050	15.376	0.012	0.242	0.0027
32 Bus	Bus MCCAMEY 1 0 Freq		Frequency	0.045	-4.640	0.021	0.470	0.0025
33 Bus	Bus MCCAMEY 1 1 Freq		Frequency	0.042	-17.847	0.023	0.535	0.0025

Close



Quickly Visualizing Results: Geographic Data Views (GDVs)



- GDVs were introduced into PowerWorld about twelve years back to provide a quick way of visualizing geographic information; they are ideally suited for modal results
- To create a GDV online of the substations, go to **Case Information, Aggregation, Substations**. Then right-click in any column (Gen MW here) and select **Geographic Data View, Select Column then Geographic Data View**
- This displays the Geographic Data View Customization Dialog

GDV Customization Dialog



- Select Browse to Open Existing Oneline select NorthAmerica_Blank
- The Fields and Attributes page can be used to customize the GDV appearance
- As an example of a GDV showing the substation gen MW, select the Total Area field
- Select **Add Geographic Data View Objects...**

The screenshot shows the 'Geographic Data View Style Options' dialog box with the 'Fields and Attributes' tab selected. The 'Object and Field Display Option Sets' section at the top shows 'Style Name' as 'Substation_GenMW' and 'Object Type' as 'Substation'. Below this are buttons for 'Change Linked Style', 'Rename Style', 'View Different Style', 'Load Styles from Auxiliary', and 'Save All Styles to Auxiliary'. The main area is divided into several sections: 'General Display Options' (Line Thickness: 1, Line Color: black, Fill Color: cyan), 'Fields and Attributes' (Total Area: Width 66.007, Size to Width Ratio 0.500, Rotation Angle 0.0, Rotation Rate 0.0), 'Linked Objects' (Generators/MW, Kite Shape Only), 'Pseudo-Geographic Mosaic Display', and 'Pruning'. On the right, the 'Area Value Lookup' table shows 'Field Set Metrics' (Min: 0.00, Max: 3673.49, Median: 1836.75, Average: 55.12) and a 'Field Value' table with 'Characteristic Value' 0. The 'Attributes for All Objects in Style' section at the bottom shows 'Layer' as 'Default Layer', 'Stack Level' as 'Middle', and 'Line Dashed' as 'None'. There are buttons for 'Send All to Back', 'Send All to Front', 'OK', 'Save Style Changes', 'Cancel', and 'Help'.

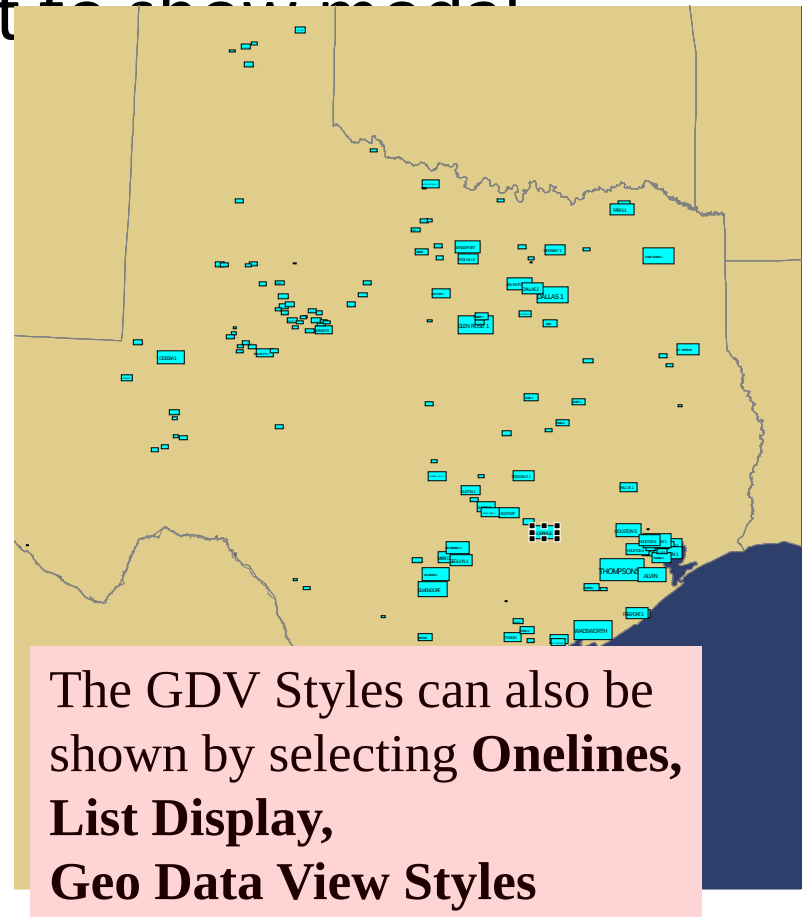
Area Value Lookup	
Field Set Metrics	
Min	0.00
Max	3673.49
Median	1836.75
Average	55.12

Field Value	Characteristic Value
0.000000	0
4000	40000

GDV Display Customization



- As created the GDV shows substation generation, but we will shortly modify it to show model information
- Save the display with a different name – say ECEN460_SubGen
- To modify a GDV online, just right-click on any GDV display object and select View Geographic Data View Options



Transient Stability Toolbar



- One application of GDVs is wide area visualization of time-sequenced results using the transient stability toolbar
- These displays can then be made into a movie by either
 - Capturing the screen as the contours are creating using screen recording software such as Camtasia
 - Or having Simulator automatically store the contour images as jpegs and then creating a movie using software such as Microsoft Movie Maker

Transient Stability Toolbar



- The toolbar uses stored transient stability results, and hence it is used only after the transient stability solution has finished
 - It can be used with results that are either saved RAM or saved to the hard drive
 - It has recently been updated to show PMU and modal analysis data
- It requires having a oneline with objects associated with the desired results (such as buses, generators, substations, etc)
 - Again these can be auto-created with GDVs

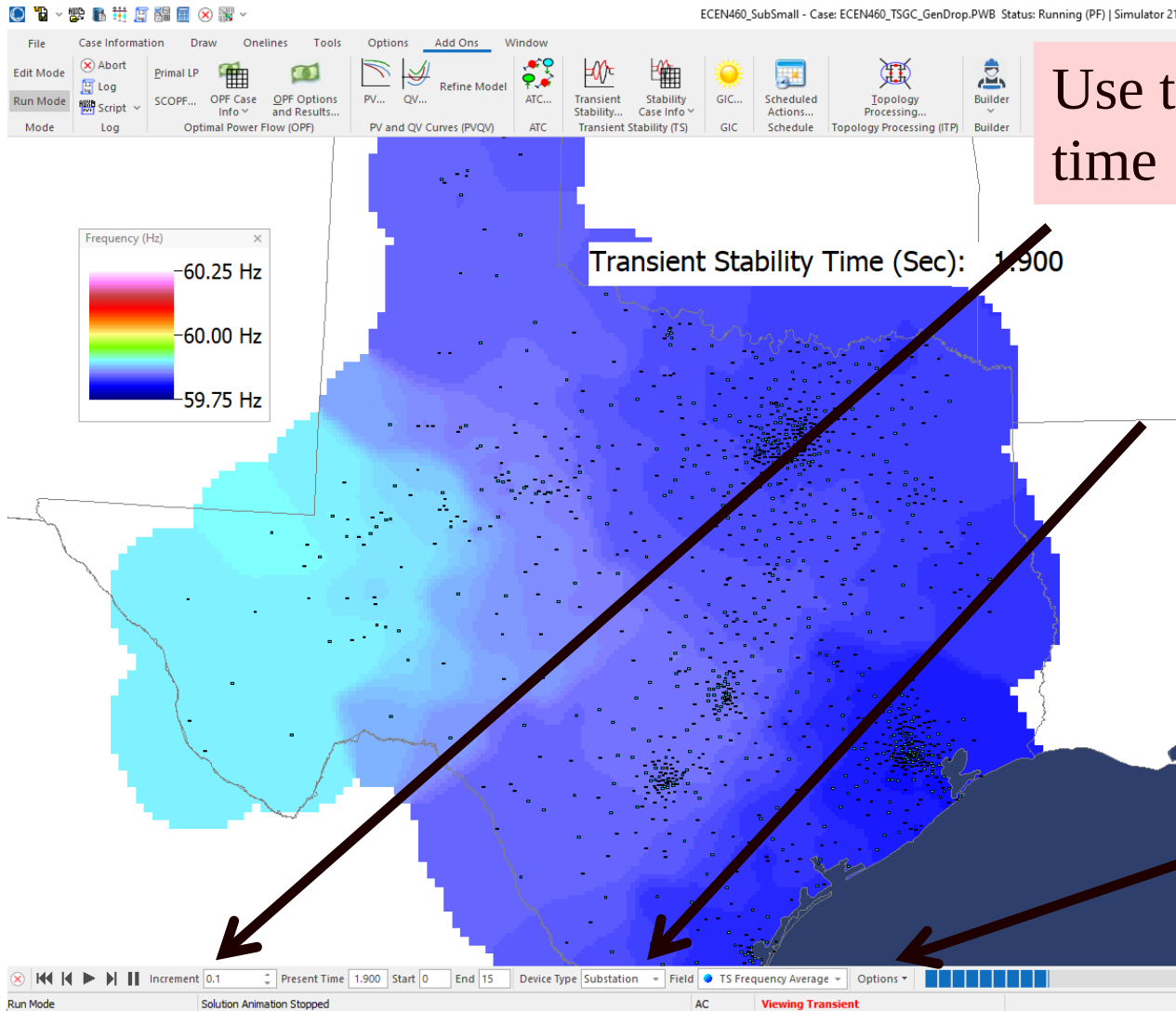
Showing the Toolbar



- The toolbar is shown by either
 - Selecting **Add-ons, Stability Case Info, Show Transient Contour Toolbar**
 - On the Transient Stability Analysis Form select the **Show Transient** Contour Toolbar button at the bottom of the form
- The toolbar is only fully enabled if there are results to contour
- We'll demonstrate it using the previous GDV, except changing the object size to be almost not visible

The oneline is saved as ECEN460_SubSmall

Toolbar

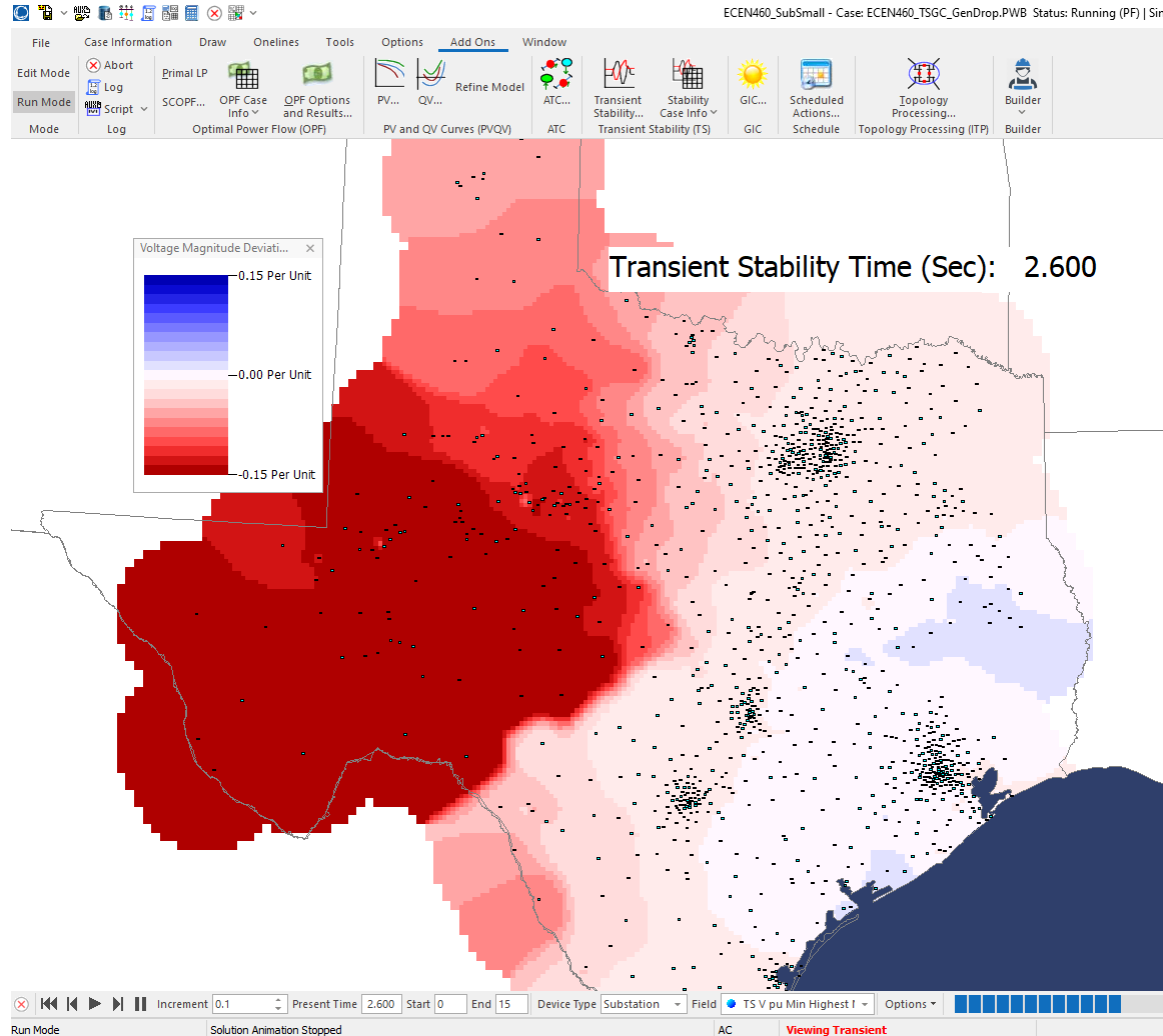


Use to control time

Only objects with associated time-varying data should be selected

Use options to control the contour and the storage of images for movies

Toolbar: Voltage Deviation



Sometimes the best field to visualize is the deviation from the initial values (here the figure shows voltage magnitude deviation)

Designing synthetic grids helps to highlight the complexities in designing the actual grid!!

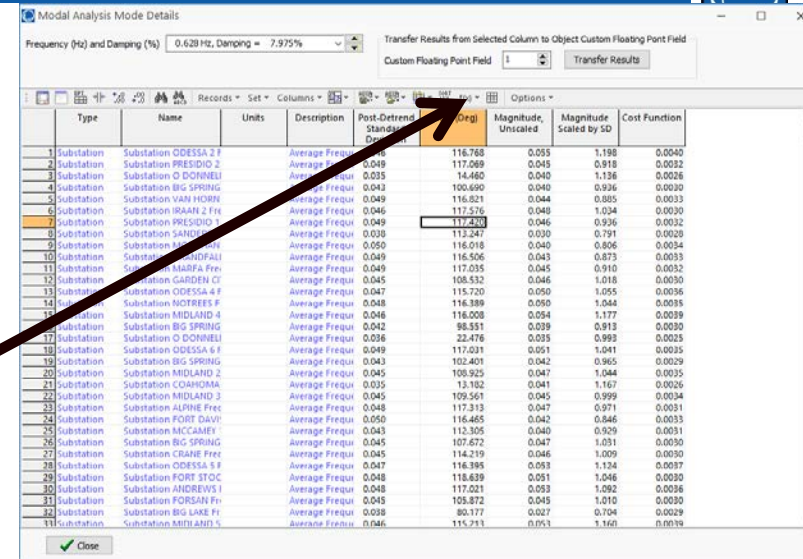
Visualizing Mode Magnitude and Angle Components



- GDVs can be used to quickly visualize information about the modes
- To visualize mode magnitude and angles, we'll use the substation custom fields to store the mode values
- Rerun modal analysis using the substation average frequency field. That is,
 - Start from the **Results From RAM, Substation display**
 - Show just Frequency Average field
 - Right-click to select “Modal Analysis All Columns” to show the **Modal Analysis Form**
 - Select the Iterative Matrix Pencil method and click on **Do Modal Analysis**; view the **Mode Details** dialog for 0.63 Hz

Visualizing Mode Magnitude and Angle Components

- We'll use the custom fields to tell the substation objects about this mode's data
 - Select the Angle field, set the Custom **Floating Point** Field to 1; click Transfer Results
 - Repeat, except click on the Magnitude Unscaled field and set the Custom Floating field to 2
- Create a new GDV display using the ECEN460_SubSmall display (the customizations are on the next slide)



Modal Analysis Mode Details

Frequency (Hz) and Damping (%): 0.628 Hz, Damping = 7.975%

Transfer Results from Selected Column to Object Custom Floating Point Field

Custom Floating Point Field: 1

Transfer Results

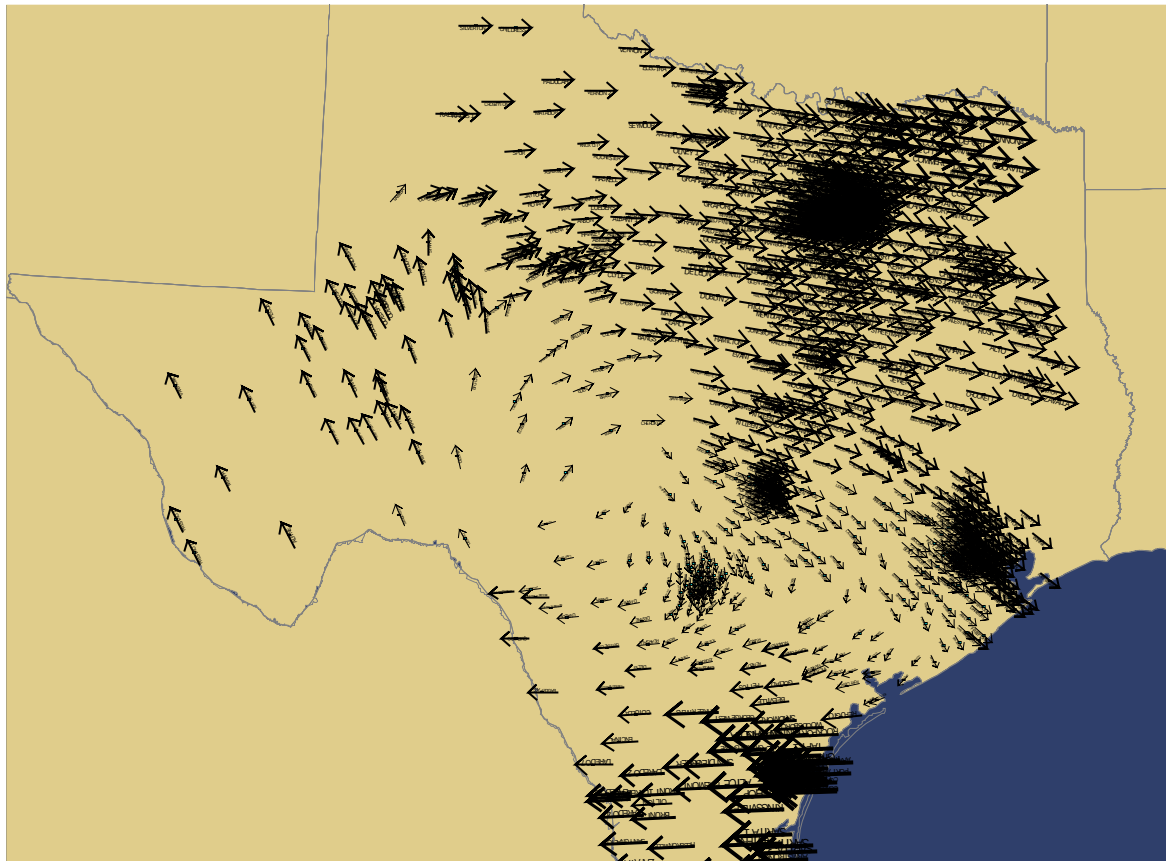
Type	Name	Units	Description	Post-Processed Standard Deviation	Angle	Magnitude, Unscaled	Magnitude Scaled by SD	Cost Function
1	Substation	Substation ODESSA 2 F	Average Freq	0.045	116.768	0.055	1.198	0.0040
2	Substation	Substation PRESIDIO 2	Average Freq	0.049	117.069	0.045	0.918	0.0032
3	Substation	Substation O DONNELL	Average Freq	0.035	14.460	0.040	1.138	0.0026
4	Substation	Substation BIG SPRING	Average Freq	0.043	100.690	0.040	0.936	0.0030
5	Substation	Substation VAN HORN	Average Freq	0.049	116.821	0.044	0.885	0.0033
6	Substation	Substation WAKARUSA 2 F	Average Freq	0.046	117.576	0.040	1.034	0.0030
7	Substation	Substation PRESIDIO 1	Average Freq	0.049	117.230	0.046	0.936	0.0032
8	Substation	Substation SANDHURST	Average Freq	0.038	113.247	0.030	0.791	0.0028
9	Substation	Substation LINDSEY	Average Freq	0.050	116.018	0.040	0.806	0.0034
10	Substation	Substation MCGRAW	Average Freq	0.049	116.506	0.043	0.873	0.0033
11	Substation	Substation MARFA Free	Average Freq	0.049	117.035	0.045	0.910	0.0032
12	Substation	Substation GARDEN CT	Average Freq	0.045	108.532	0.046	1.018	0.0030
13	Substation	Substation ODESSA 4 F	Average Freq	0.047	115.720	0.050	1.055	0.0036
14	Substation	Substation NOTRE DAME	Average Freq	0.048	116.389	0.050	1.044	0.0035
15	Substation	Substation MIDLAND 4	Average Freq	0.046	116.008	0.054	1.177	0.0039
16	Substation	Substation BIG SPRING	Average Freq	0.042	98.531	0.039	0.913	0.0030
17	Substation	Substation O DONNELL	Average Freq	0.038	22.476	0.035	0.993	0.0025
18	Substation	Substation ODESSA 6 F	Average Freq	0.049	117.031	0.051	1.041	0.0035
19	Substation	Substation BIG SPRING	Average Freq	0.043	102.401	0.042	0.965	0.0029
20	Substation	Substation MIDLAND 2	Average Freq	0.045	108.925	0.047	1.044	0.0035
21	Substation	Substation CICHANARA	Average Freq	0.035	13.182	0.041	1.167	0.0036
22	Substation	Substation MIDLAND 3	Average Freq	0.045	109.561	0.045	0.999	0.0034
23	Substation	Substation ALPINE Free	Average Freq	0.048	117.313	0.047	0.971	0.0031
24	Substation	Substation FORT DAVIS	Average Freq	0.050	116.485	0.042	0.846	0.0033
25	Substation	Substation MCCAMEY	Average Freq	0.043	112.305	0.040	0.929	0.0031
26	Substation	Substation BIG SPRING	Average Freq	0.045	107.672	0.047	1.031	0.0030
27	Substation	Substation CRANE Free	Average Freq	0.045	114.219	0.046	1.009	0.0030
28	Substation	Substation ODESSA 1 F	Average Freq	0.047	116.395	0.051	1.134	0.0037
29	Substation	Substation FORT STOK	Average Freq	0.048	118.639	0.051	1.046	0.0030
30	Substation	Substation ANDREWS I	Average Freq	0.048	117.021	0.053	1.092	0.0036
31	Substation	Substation FORTSMAN Free	Average Freq	0.045	105.872	0.045	1.010	0.0030
32	Substation	Substation BIG LAKE Free	Average Freq	0.038	80.177	0.027	0.704	0.0029
33	Substation	Substation MIDLAND 5	Average Freq	0.046	115.213	0.053	1.160	0.0039

GDV Visualization of Mode Magnitude and Angle Components



- Set the GDV Style as
 - On the **General Display Options** page set the **Style** to Arrows and the **Text to Show** field to None.
 - On the **Fields and Attributes** page
 - Total Area uses the Custom Float 2 field (magnitude); a ballpark largest size should be 50000.
 - Rotation Angle uses the Custom Float 1 field (angle)
 - Line Thickness uses the Custom Float 2 field (magnitude)
- Once a oneline has been setup, it can be saved for repeated use
- Save the oneline as ECEN460_Modes

Visualization of 0.63 Hz Mode



In this display the arrows show the magnitude and angle (direction) for the mode at each substation.

However, the problem is there are too many arrows! The solution is so dynamically prune the display using the GDV Options, Pruning command

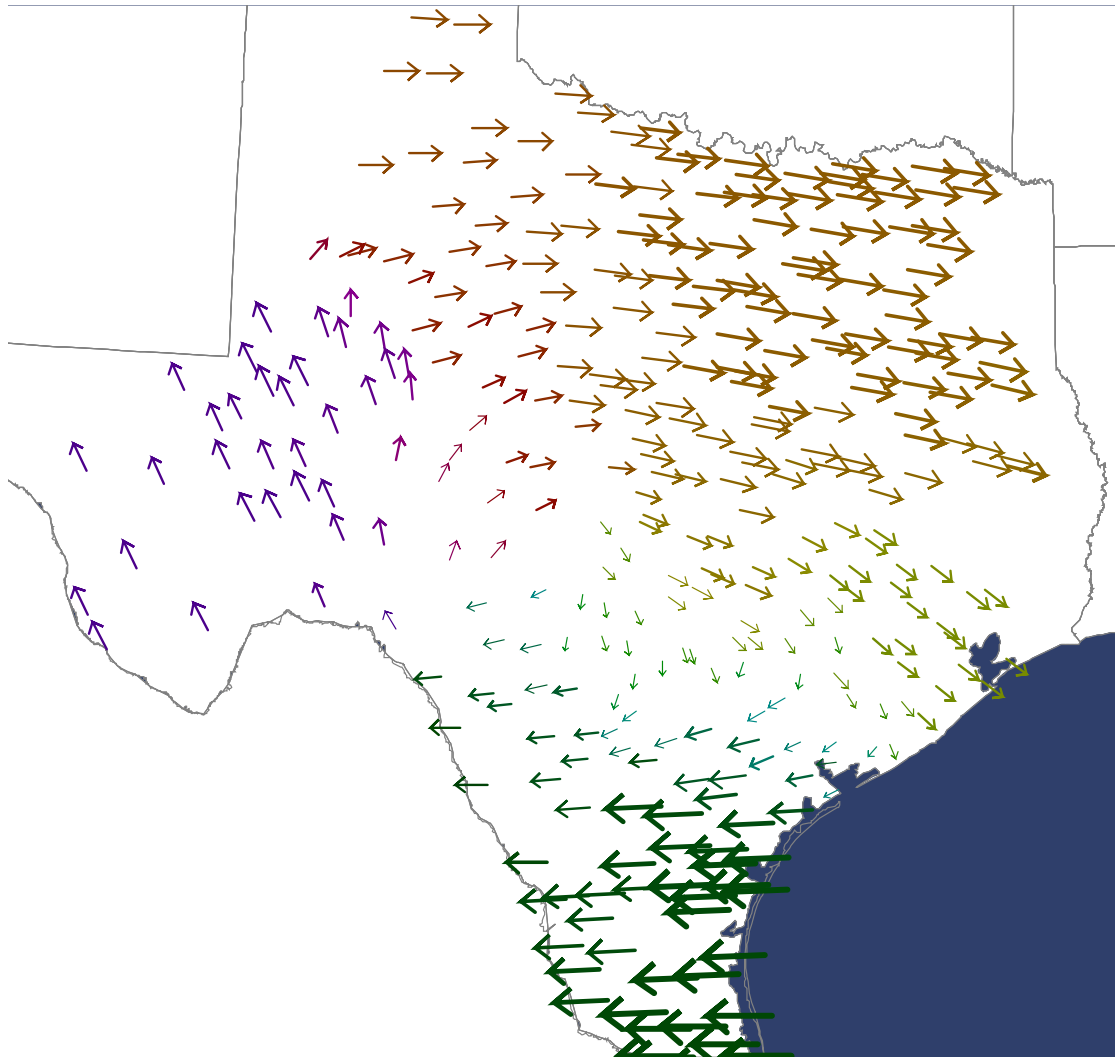
GDV Display Pruning



- This page allows GDVs to be selectively displayed
- Select **Do Pruning** to modify the oneline so an invisible grid is added to the display and only one GDV arrow is visible in each grid area
- I also added some color, using a circular color map to highlight the angles

The screenshot shows the 'Geographic Data View Style Options' dialog box with the 'Pruning' tab selected. The 'Object and Field Display Option Sets' section shows 'Style Name' as 'Substation_GenMWMax' and 'Object Type' as 'Substation'. Below this, the 'General Display Options' tab is active, showing 'Current Layout Extent' with X Min: 17517.6189, X Max: 21943.1163, Y Min: 8610.8366, and Y Max: 14067.2629. The 'Object Pruning to No More than One Per Grid Element' section shows 'X Axis Columns (East-West)' and 'Y Axis Rows (North-South)' both set to 30. There is an unchecked checkbox for 'Align Retained GDVs with Grid Centers'. At the bottom of this section are two buttons: 'Do Pruning' (highlighted in blue) and 'Remove Pruning'. The bottom of the dialog box has 'OK', 'Save Style Changes', 'Cancel', and 'Help' buttons.

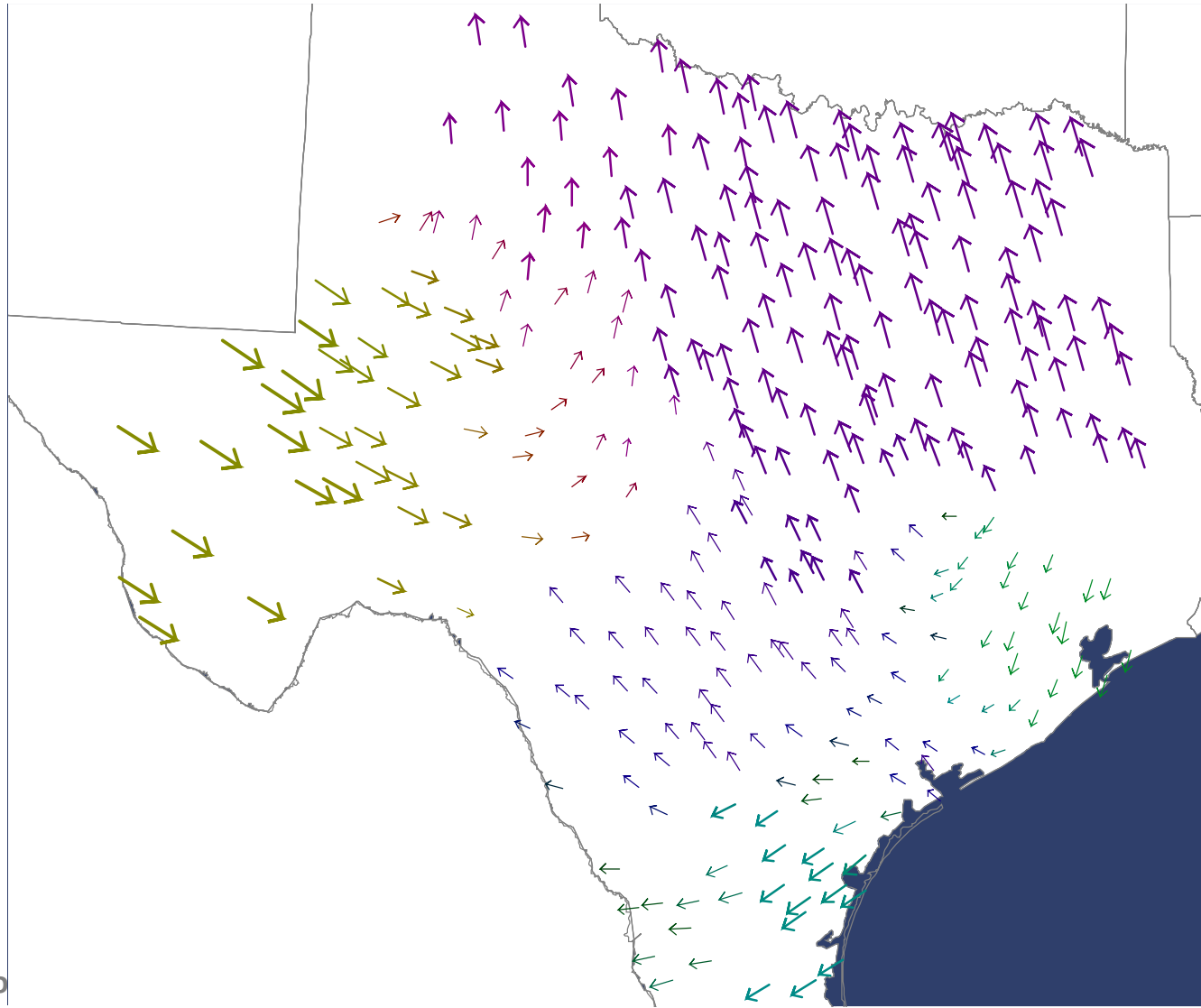
Visualization of 0.63 Hz Mode



Again save the oneline, now as ECEN460_Modes; it can then be used to quickly visualize the other modes

To show other modes, just go to the Mode Details dialog for a different frequency and again transfer the angle and magnitude

Visualization of 0.76 Hz Mode



Visualizing the Source of Oscillations



- For showing the source of sustained oscillations assume zero damping and recognizing that the source of the oscillation will have a leading phase angle, shift all the $\phi_{k,j}$ so it is zero at the bus with the largest $A_{k,j}$ and set $t=0$. Then

$$\theta_{k,j} = A_{k,j} \cos(\phi_{k,j})$$

- Then approximate the mode j power flow on all lines between buses m and n as

$$P_{mn} \approx \frac{1}{X_{mn}} (A_{k,m} \cos(\phi_{k,m}) - A_{k,n} \cos(\phi_{k,n}))$$

- The location of the oscillation has positive net power

Visualizing the Source of Oscillations in PowerWorld

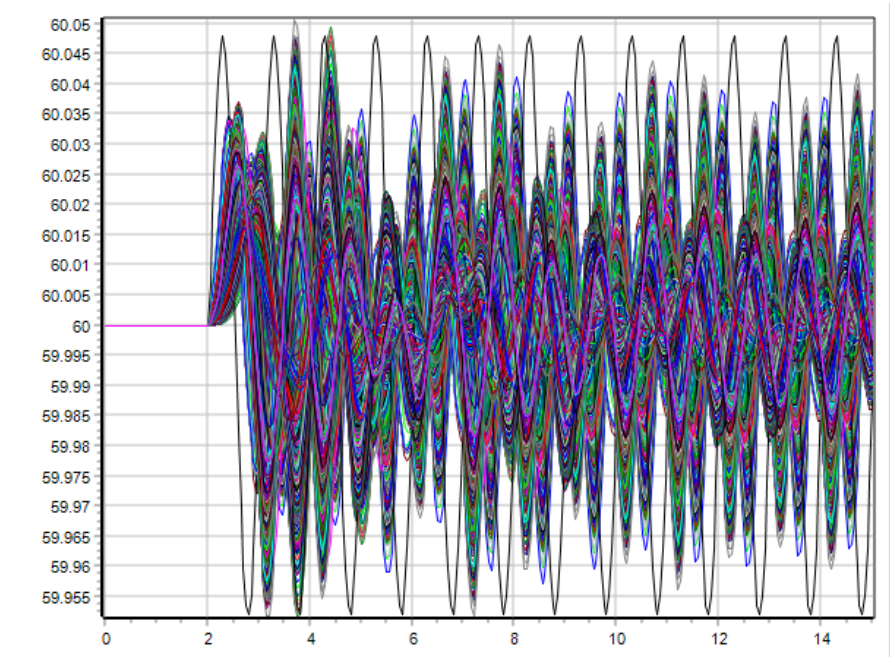
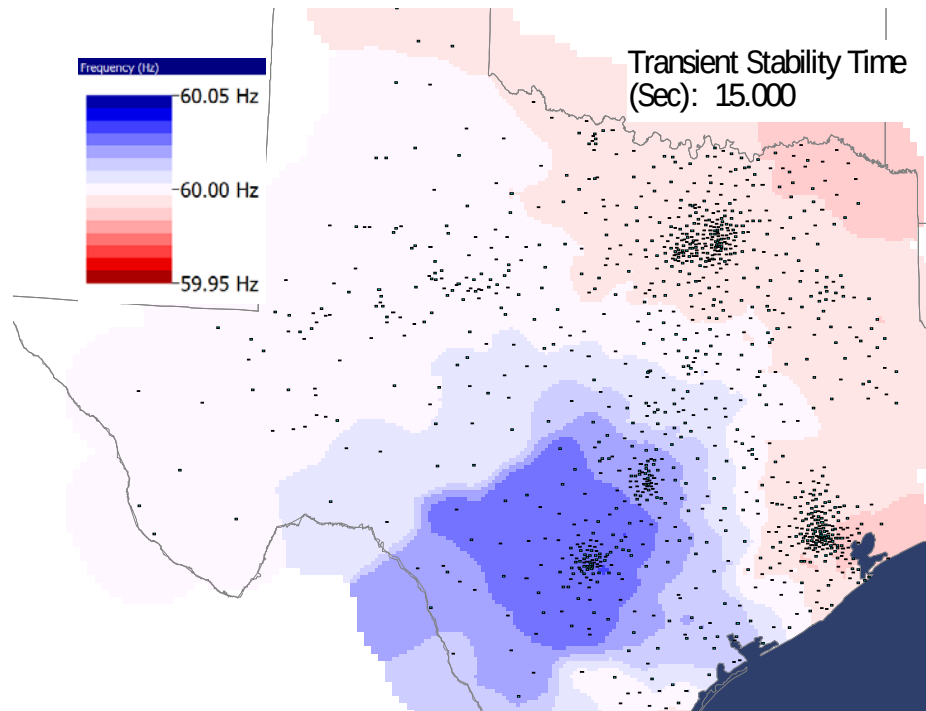


- Now done mostly automatically in PowerWorld
- To apply the approach with transient stability
 - Run the transient stability storing the bus angles
 - Do modal analysis on the bus angles; technique is only applicable if there are lightly or negatively damped modes
 - Select the desired mode to display the **Mode Analysis Mode Details Dialog**
 - When analyzing just bus angles a **Visualization Source of Oscillations** button appears; click to transfer flows to line and substation custom float1

Visualizing the Source of Oscillations in PowerWorld Example



As an example, a 1Hz sustained oscillation was introduced into the 2000 bus system



Visualizing the Source of Oscillations in PowerWorld Example



Modal Analysis Form

Modal Analysis Status: Solved at 9/15/2019 10:01:17 AM

Data Source Type:
☐ From Plot
☐ File, WECC CSV 2
☐ File, JSIS Format
☐ File, Comtrade CFF
☐ File, Comtrade CFG
☒ None, Existing Data

Calculation Method:
☐ Variable Projection
☐ Matrix Pencil (Once)
☒ Iterative Matrix Pencil
☐ Dynamic Mode Decomposition

Data Source Inputs from Plots or Files
 From Plot: Bus Frequency Ten
 From File: Browse

Just Load Signals **Group Disabled for Existing Data**

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

Data Sampling Time (Seconds) and Frequency (Hz)
 Start Time: 1.000 End Time: 15.000
 Maximum Hz: 5.000 Update Sampled Data

Results

Number of Complex and Real Modes: 8
 Lowest Percent Damping: 0.039
☒ 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 Reproduced Signal
1	0.998	0.039	85.7439	Bus THOMPSON	-0.0025	YES
2	0.732	3.886	64.7912	Bus TAFT 1 1 V	-0.1789	YES
3	0.259	5.613	76.2008	Bus ODESSA 1	-0.0915	YES
4	0.918	9.280	28.9139	Bus LOLITA 0 V	-0.5375	YES
5	0.616	12.946	36.1365	Bus TAFT 1 1 V	-0.5052	YES
6	1.036	13.185	10.2268	Bus LOLITA 0 V	-0.8658	YES
7	0.469	18.814	43.9190	Bus ODESSA 1	-0.5651	YES
8	0.000	100.000	2.4483	Bus THOMPSON	-0.1019	YES

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

	Type	Name	Latitude	Longitude	Description	Units	Include	Include Reproduced	Detrend Parameter A	Detrend Parameter B	Post-Detrend Number Zeros	Post-Detrend Standard Deviation	Solved	Avr Un
1	Bus	Bus THOMPSONS 10 V	29.483	-95.631	Angle (deg)		NO	YES	-27.2084	-0.0218	0	2.365	YES	
2	Bus	Bus SAN ANTONIO 1 6	29.429	-98.343	Angle (deg)		NO	YES	-47.1900	-0.0103	0	1.634	YES	
3	Bus	Bus ODESSA 1 2 V angl	31.840	-102.326	Angle (deg)		YES	YES	-14.0054	-0.0019	0	1.033	YES	
4	Bus	Bus SAN ANTONIO 1 4	29.429	-98.343	Angle (deg)		NO	YES	-45.4576	-0.0095	0	1.526	YES	
5	Bus	Bus SAN ANTONIO 1 5	29.429	-98.343	Angle (deg)		NO	YES	-45.6143	-0.0093	0	1.503	YES	
6	Bus	Bus NEW BRAUNFELS 1	29.737	-98.023	Angle (deg)		NO	YES	-47.6190	-0.0090	0	1.453	YES	
7	Bus	Bus SAN ANTONIO 1 8	29.429	-98.343	Angle (deg)		NO	YES	-49.0701	-0.0090	0	1.439	YES	
8	Bus	Bus ELMENDORF 10 V i	29.257	-98.382	Angle (deg)		NO	YES	-44.9591	-0.0089	0	1.414	YES	
9	Bus	Bus PEARSALL 5 V angl	28.928	-99.092	Angle (deg)		NO	YES	-53.2741	-0.0080	0	1.384	YES	
10	Bus	Bus NEW BRAUNFELS 1	29.737	-98.023	Angle (deg)		NO	YES	-47.5842	-0.0088	0	1.426	YES	
11	Bus	Bus SEGUIN 1 3 V angl	29.593	-97.973	Angle (deg)		NO	YES	-46.5314	-0.0088	0	1.409	YES	
12	Bus	Bus ELMENDORF 5 V ar	29.257	-98.382	Angle (deg)		NO	YES	-44.8342	-0.0088	0	1.393	YES	
13	Bus	Bus ELMENDORF 6 V ar	29.257	-98.382	Angle (deg)		NO	YES	-45.2297	-0.0086	0	1.380	YES	
14	Bus	Bus ELMENDORF 3 V ar	29.257	-98.382	Angle (deg)		NO	YES	-45.8765	-0.0087	0	1.381	YES	
15	Bus	Bus NEW BRAUNFELS 1	29.737	-98.023	Angle (deg)		NO	YES	-48.0853	-0.0086	0	1.407	YES	

Close ? Help Print

Visualizing the Source of Oscillations in PowerWorld Example

Modal Analysis Mode Details

Frequency (Hz) and Damping (%) 0.998 Hz, Damping = 0.039%

Transfer Results from Selected Column to Object Custom Floating Point Field

Custom Floating Point Field 1 Transfer Results

Visualize Source of Oscillations (Research Only Now)

	Type	Name	Units	Description	Post-Detrend Standard Deviation	Angle (Deg)	Magnitude, Unscaled	Magnitude Scaled by SD	Cost Function
1	Bus	Bus ODESSA 2 0 V angl		Angle (deg)	0.812	-156.370	0.684	0.842	0.0046
2	Bus	Bus PRESIDIO 2 0 V angl		Angle (deg)	0.852	-153.242	0.674	0.791	0.0045
3	Bus	Bus O DONNELL 1 0 V angl		Angle (deg)	0.711	-164.530	0.748	1.053	0.0037
4	Bus	Bus O DONNELL 1 1 V angl		Angle (deg)	0.714	-165.651	0.760	1.065	0.0037
5	Bus	Bus BIG SPRING 5 0 V angl		Angle (deg)	0.765	-154.405	0.695	0.908	0.0045
6	Bus	Bus BIG SPRING 5 1 V angl		Angle (deg)	0.772	-153.976	0.691	0.896	0.0045
7	Bus	Bus VAN HORN 0 V angl		Angle (deg)	0.858	-154.601	0.672	0.784	0.0044
8	Bus	Bus IRAAN 2 0 V angl		Angle (deg)	0.800	-147.447	0.696	0.870	0.0046
9	Bus	Bus IRAAN 2 1 V angl		Angle (deg)	0.813	-147.270	0.688	0.846	0.0047
10	Bus	Bus PRESIDIO 1 0 V angl		Angle (deg)	0.850	-152.839	0.674	0.793	0.0045
11	Bus	Bus PRESIDIO 1 1 V angl		Angle (deg)	0.856	-152.746	0.672	0.785	0.0045
12	Bus	Bus SANDERSON 0 V angl		Angle (deg)	0.714	-140.947	0.781	1.094	0.0042
13	Bus	Bus MONAHANS 2 0 V angl		Angle (deg)	0.871	-157.738	0.671	0.771	0.0043
14	Bus	Bus GRANDFALLS 0 V angl		Angle (deg)	0.854	-154.605	0.674	0.790	0.0044
15	Bus	Bus MARFA 0 V angl		Angle (deg)	0.854	-153.594	0.673	0.789	0.0045
16	Bus	Bus GARDEN CITY 0 V angl		Angle (deg)	0.792	-152.181	0.685	0.865	0.0046
17	Bus	Bus ODESSA 4 0 V angl		Angle (deg)	0.830	-156.561	0.679	0.818	0.0045
18	Bus	Bus NOTREES 0 V angl		Angle (deg)	0.843	-156.563	0.674	0.800	0.0045
19	Bus	Bus MIDLAND 4 0 V angl		Angle (deg)	0.810	-156.249	0.684	0.845	0.0046
20	Bus	Bus BIG SPRING 1 0 V angl		Angle (deg)	0.749	-154.306	0.703	0.939	0.0044
21	Bus	Bus BIG SPRING 1 1 V angl		Angle (deg)	0.767	-153.012	0.692	0.903	0.0045
22	Bus	Bus O DONNELL 2 0 V angl		Angle (deg)	0.711	-164.666	0.749	1.053	0.0037
23	Bus	Bus O DONNELL 2 1 V angl		Angle (deg)	0.704	-162.167	0.734	1.042	0.0038
24	Bus	Bus ODESSA 6 0 V angl		Angle (deg)	0.855	-156.495	0.670	0.784	0.0045
25	Bus	Bus BIG SPRINGS 0 V angl		Angle (deg)	0.757	-154.080	0.699	0.923	0.0044
26	Bus	Bus BIG SPRINGS 1 V angl		Angle (deg)	0.785	-152.160	0.682	0.869	0.0047
27	Bus	Bus MIDLAND 2 0 V angl		Angle (deg)	0.791	-156.180	0.689	0.871	0.0045
28	Bus	Bus COAHOMA 0 V angl		Angle (deg)	0.715	-165.969	0.756	1.058	0.0037
29	Bus	Bus MIDLAND 3 0 V angl		Angle (deg)	0.800	-156.156	0.686	0.858	0.0044
30	Bus	Bus ALPINE 0 V angl		Angle (deg)	0.837	-150.900	0.679	0.811	0.0046
31	Bus	Bus FORT DAVIS 0 V angl		Angle (deg)	0.864	-156.164	0.671	0.777	0.0044
32	Bus	Bus MCCAMEY 1 0 V angl		Angle (deg)	0.786	-148.813	0.703	0.894	0.0045
33	Bus	Bus MCCAMEY 1 1 V angl		Angle (deg)	0.757	-149.412	0.720	0.952	0.0043

Close

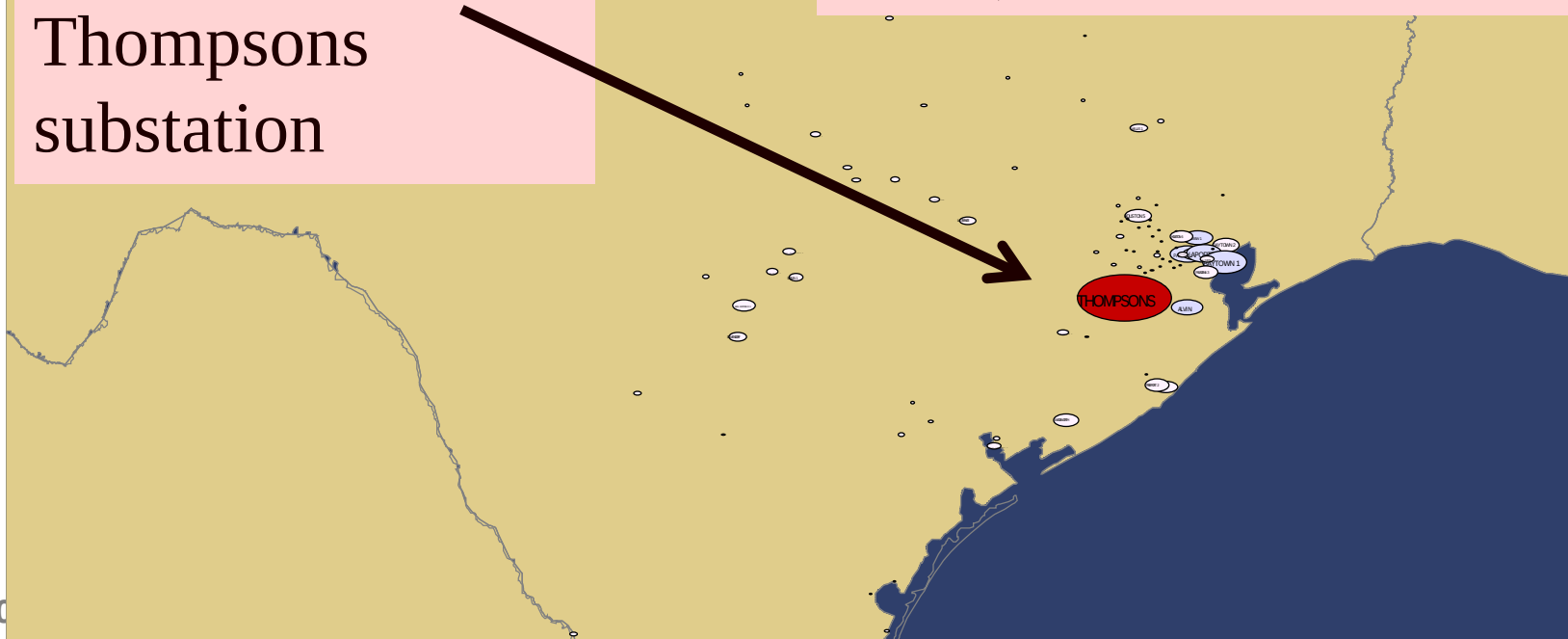
This button only appears when doing modal analysis on bus angles. Clicking on it 1) calculates the mode power flow on each line and places the value in the line's custom float 1 field, 2) calculates the net mode power injection at each substation and stores it in the substation's custom float 1 field.

Visualizing the Source of Oscillations in PowerWorld Example



The source of the forced oscillation is correctly identified (bus 7356) at the Thompsons substation

This is a substation GDV, in which size of objects is proportional to the custom float 1 field; a red/blue color map shows the direction (red is the source)



Visualizing the Source of Oscillations in PowerWorld Example



Visualizing the lines' Custom Float1 fields shows the flow of the oscillation

