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

\[ e^{\alpha t} \left( a \cos(\omega t) + b \sin(\omega t) \right) = e^{\alpha t} C \cos(\omega t + \theta) \]

where \( C = \sqrt{A^2 + B^2} \) 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.

![Graph showing observed and simulated COI power during a blackout](image-url)
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

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 sinusoidals (modes).

\[ y(t) = \sum_{i=1}^{q} A_i e^{\sigma_i t} \cos(\omega_i t + \phi_i) \]

\[ \text{Damping (\%)} = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \omega_i^2}} \times 100 \]
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 $\Delta T$, starting with $t=0$, with values $y_j$ for $j=1...m$
  - Times are then $t_j = (j-1)\Delta T$
  - At each time point $j$, the approximation of $y_j$ is

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

where $\alpha$ is a vector with the real and imaginary eigenvalue components, with $\phi_i(t_j, \alpha) = e^{\alpha_i t_j}$ for $\alpha_i$ 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.
Signal Based Modal Analysis

- Error (residual) value at each point $j$ is
  \[ r_j(t_j, \alpha) = y_j - \hat{y}_j(t_j, \alpha) \]

- Closeness of fit can be quantified using the Euclidean norm of the residuals
  \[
  \frac{1}{2} \sum_{j=1}^{m} (y_j - \hat{y}_j(t_j, \alpha))^2 = \frac{1}{2} \| r(\alpha) \|_2^2
  \]

- Hence we need to determine $\alpha$ and $b$; PowerWorld has three techniques for determining $\alpha$, and then one for $b$

- 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
First click on Do Modal Analysis to run the modal analysis.

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.

Right-click on signal to view its dialog.
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).

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

Start time default value

Mode frequency, damping, and largest contribution of each mode in the signals
GENROU Example with Damping

- Left image shows 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, \( Y \) such that

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

Algorithm Details, cont.

- Then calculate $Y$’s singular values using an economy singular value decomposition (SVD):
  $$Y = U\Sigma V^T$$

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

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

\[ Y = UV^T \]

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

The original concept is more than 100 years old, but has founds lots of recent applications
Images can be represented with matrices. When an SVD is applied and only the largest singular values are retained the image is compressed.
Algorithm Details, cont.

- Then form the matrices $V_1$ and $V_2$ such that
  - $V_1$ is the matrix consisting of all but the last row of $V_p$
  - $V_2$ is the matrix consisting of all but the first row of $V_p$

- Discrete-time poles are found as the generalized eigenvalues of the pair $(V_2^T V_1, V_1^T V_1) = (A, B)$

- 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 $B$ is nonsingular (the situation here) then the generalized eigenvalues are the eigenvalues of $B^{-1}A$
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 $Y_k$ matrix for each signal $k$ using the measurements for that signal and then combining the matrices so that for $N$ signals:

$$Y = \begin{bmatrix} Y_1 \\ \vdots \\ Y_N \end{bmatrix}$$

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

The required computation scales linearly with the number of signals.
Matrix Pencil Method with Many Signals

• However, when dealing with many signals, usually the signals are somewhat correlated, so very few of the signals actually need to be included to determine the desired modes

• Recall we are ultimately finding

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

where \( \alpha \) is a vector with the real and imaginary eigenvalue components, with \( \phi_i(t_j, \alpha) = e^{\alpha_{ij}t_j} \) for \( \alpha_i \) corresponding to a real eigenvalue, and

\[ \phi_i(t_j, \alpha) = e^{\alpha_{ij}t_j} \cos(\alpha_{i+1}t_j) \quad \text{and} \quad \phi_{i+1}(\alpha) = e^{\alpha_{ij}t_j} \sin(\alpha_{i+1}t_j) \]

for a complex eigenvector value

The \( \alpha \) is found using the matrix pencil method and is common to all the signals; the \( b \) vector is signal specific.
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 \( k \)

\[
\hat{y}_k(\alpha) = \Phi(\alpha)b_k
\]

Where \( m \) is the number of measurements and \( n \) is the number of modes

And then the residual is minimized by selecting \( b_k = \Phi(\alpha)^+y_k \)

where \( \Phi(\alpha) \) is the \( m \) by \( n \) matrix with values

\[
\Phi_{ji}(\alpha) = e^{\alpha_it_j} \text{ if } \alpha_i \text{ corresponds to a real eigenvalue},
\]

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

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

Finally, \( \Phi(\alpha)^+ \) is the pseudoinverse of \( \Phi(\alpha) \)

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 \( A \) is \( A^+ \)
- Satisfies \( AA^+A = A \)
- If \( A \) is a square matrix, then \( A^+ = A^{-1} \)
- Quite useful for solving the least squares problem since the least squares solution of \( Ax = b \) is \( x = A^+b \)
- Can be calculated using an SVD
  \[
  A = U \Sigma V^T
  \]
  \[
  A^+ = V \Sigma^+ U^T
  \]
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 \(A\mathbf{x} = \mathbf{b}\)

\[
\begin{bmatrix}
1 & 1 \\
2 & 1 \\
6 & 1 \\
\end{bmatrix}
\begin{bmatrix}
m \\
b \\
\end{bmatrix}
= 
\begin{bmatrix}
1 \\
4 \\
4 \\
\end{bmatrix}
\]

so \(A = \begin{bmatrix}
1 & 1 \\
2 & 1 \\
6 & 1 \\
\end{bmatrix}\)
Least Squares Matrix
Pseudoinverse Example, cont.

• Doing an economy SVD

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

• Computing the pseudoinverse

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

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

In an economy SVD the \( \Sigma \) matrix has dimensions of \( m \) by \( m \) if \( m < n \) or \( n \) by \( n \) if \( n < m \)
Least Squares Matrix
Pseudoinverse Example, cont.

• Computing \( \mathbf{x} = [m \ b]^\top \) gives

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

• 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 $\alpha$ 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 $\alpha$
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
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

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.
2000 Bus System Example, Comparing the Other Signals

- Sort on the cost function to see the worst match

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.
2000 Bus System Example, Iterative Matrix Pencil

- Now run the Iterative Matrix Pencil method
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.
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 oneline 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**...
GDV Display Customization

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

The GDV Styles can also be shown by selecting Onelines, List Display, Geo Data View Styles.
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 options to control the contour and the storage of images for movies

Only objects with associated time-varying data should be selected

Use to control time
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)
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 it 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
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.

Transient Stability Time (Sec): 15,000
Visualizing the Source of Oscillations in PowerWorld Example

![Modal Analysis Form]

- Data Source Type: From Plot, File, WECC CSV 2, File, Contraf CFF, File, JSIS Format, None, Existing Data
- Calculation Method: Variable Projection, Matrix Pencil (Once), Derivative Matrix Pencil, Dynamic Mode Decomposition
- Data Source Inputs from Plots or Files: Bus Frequency Ten
- Start Time: 0.000
- Maximum Hz: 0.000

![Results]

- Number of Complex and Real Modes: 8
- Lowest Percent Damping: 0.039

![Input Data Table]

| Type   | Name            | Latitude | Longitude | Description | Units | Include | Include Reproduced | Defend Parameter A | Defend Parameter B | Post-Defend Number Zeros | Post-Defend Standard Deviation | Solved | Annual Un
|--------|-----------------|----------|-----------|-------------|-------|---------|-------------------|---------------------|---------------------|-------------------------------|---------------------------------|--------|---------
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.
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 lines’ Custom Float1 fields shows the flow of the oscillation.