PowerWorld FFT and Modal Analysis Tools

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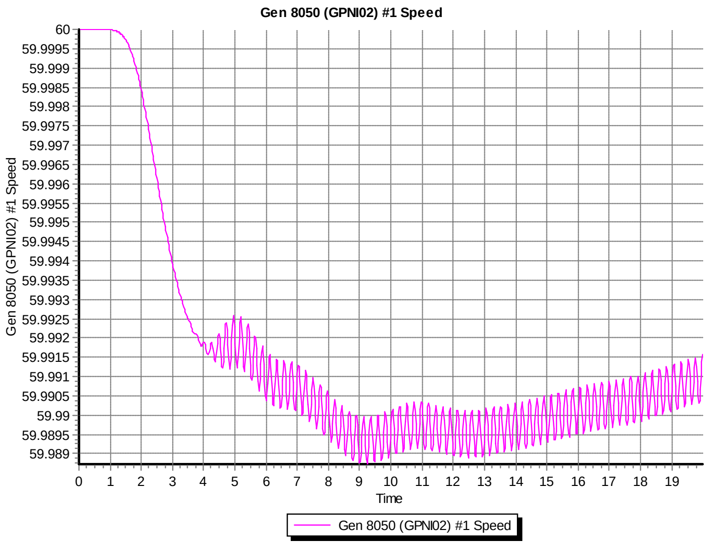
Overview

- Frequency domain techniques can be quite helpful in providing system information
- With version 18 PowerWorld is including two tools with its transient stability package
  - Fast Fourier Transform (FFT) and modal analysis using the variable projection method (VPM)[1]
  - Integrating the tools within transient stability should allow for convenient access
- **Your feedback is desired on needed features!!**

[1]A. Borden, B.C. Lesieutre, J. Gronquist, "Power System Modal Analysis Tool Developed for Industry Use," *Proc. 2013 North American Power Symposium*, Manhattan, KS, Sept. 2013

Motivational Example

- The below graph shows an unusual high frequency oscillation in a transient stability run
  - The question is to figure out the source of the oscillation (in the generator speed here)
  - Plotting all the speed values is one option, but sometimes small oscillations could get lost
  - A solution is to do an FFT

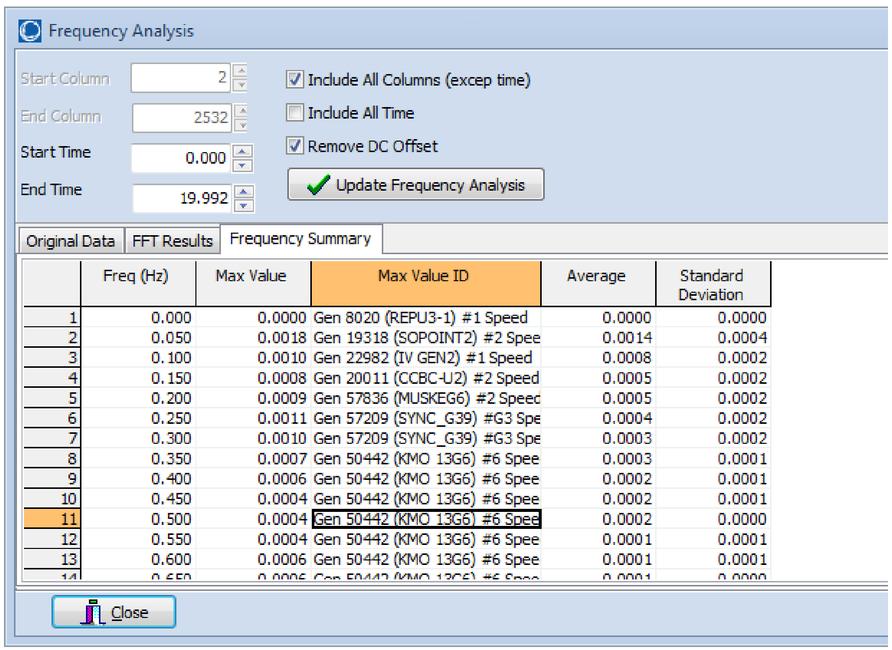


Fast Fourier Transform (FFT) Overview

- Discrete Fourier Transforms (DFTs) can be used to provide frequency information about sampled, non-periodic signals
- The FFT is just a fast DFT – with N_0 points its computational order is $N_0 \ln(N_0)$
  - This allows it to be applied to many signals
- In version 18 quick access to an FFT is available in the transient stability time values (or plot) case information displays by selecting "Frequency Analysis" from the right-click menu

Frequency Analysis Display

- The frequency analysis display shows the original data, the FFT for each time result, and a frequency summary



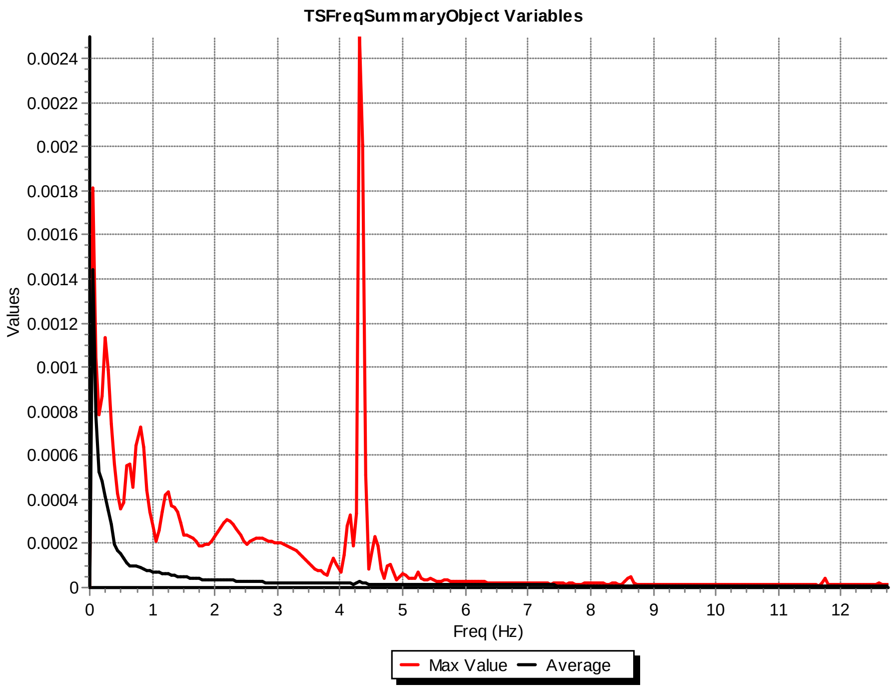
	Freq (Hz)	Max Value	Max Value ID	Average	Standard Deviation
1	0.000	0.0000	Gen 8020 (REPU3-1) #1 Speed	0.0000	0.0000
2	0.050	0.0018	Gen 19318 (SOPOINT2) #2 Spee	0.0014	0.0004
3	0.100	0.0010	Gen 22982 (IV GEN2) #1 Speed	0.0008	0.0002
4	0.150	0.0008	Gen 20011 (CCBC-U2) #2 Speed	0.0005	0.0002
5	0.200	0.0009	Gen 57836 (MUSKEG6) #2 Speed	0.0005	0.0002
6	0.250	0.0011	Gen 57209 (SYNC_G39) #G3 Spe	0.0004	0.0002
7	0.300	0.0010	Gen 57209 (SYNC_G39) #G3 Spe	0.0003	0.0002
8	0.350	0.0007	Gen 50442 (KMO 13G6) #6 Spee	0.0003	0.0001
9	0.400	0.0006	Gen 50442 (KMO 13G6) #6 Spee	0.0002	0.0001
10	0.450	0.0004	Gen 50442 (KMO 13G6) #6 Spee	0.0002	0.0001
11	0.500	0.0004	Gen 50442 (KMO 13G6) #6 Spee	0.0002	0.0000
12	0.550	0.0004	Gen 50442 (KMO 13G6) #6 Spee	0.0001	0.0001
13	0.600	0.0006	Gen 50442 (KMO 13G6) #6 Spee	0.0001	0.0001

With about 500 time values, and 2500 signals (generator speeds in this example), the FFT takes about one second

The Frequency Summary Page provides the ID of the signal with the largest component for each frequency

Frequency Summary Plot of Maximum and Average Values

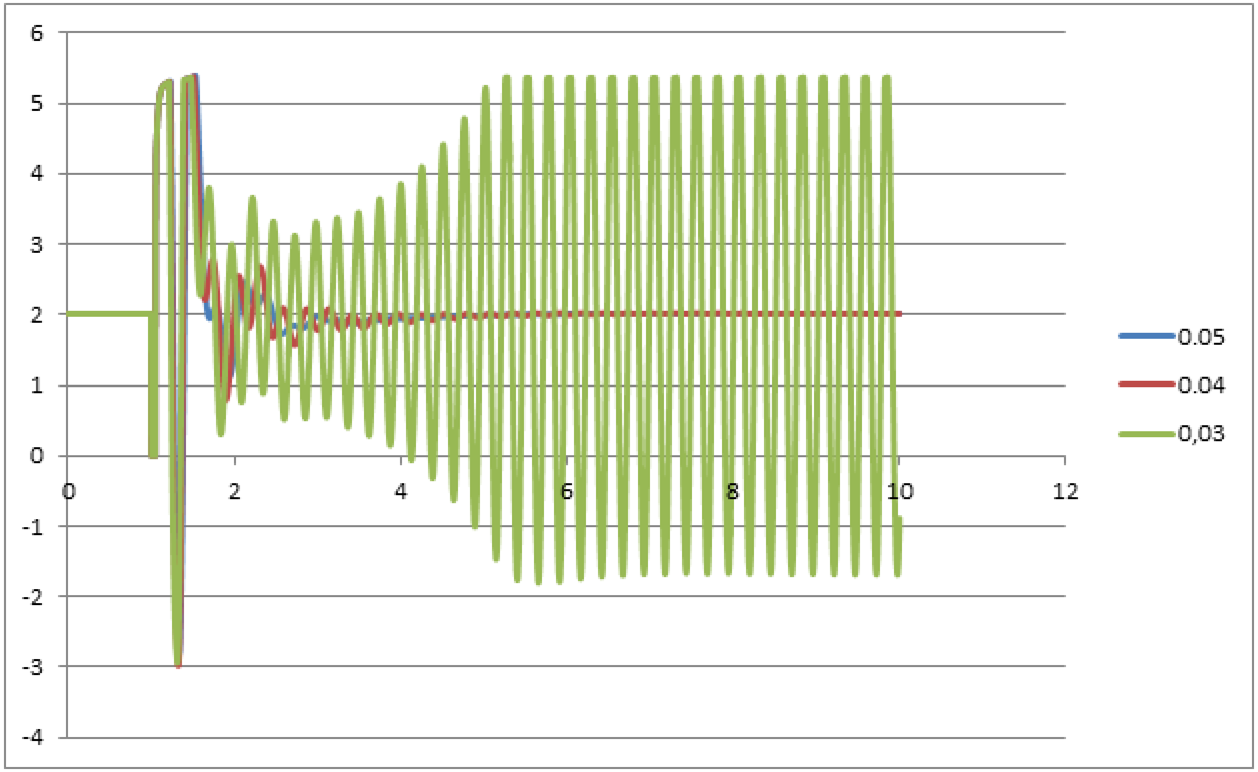
- The maximum values summary makes the source of the observed 4.3 Hz oscillation readily apparent (here at gen 19318)



The cause was actually due to a small ΔT value of 0.02 seconds being used in the bus frequency calculation. Since the bus frequency was an input to the 19318 stabilizer, this was causing the stabilizer to cycle between its limits. The default value has been increased to 0.05 seconds.

Example of the Impact of Assumed Parameters on Stability

- Graph shows SMIB results for a fault at generator 19318 for varied ΔT frequency values



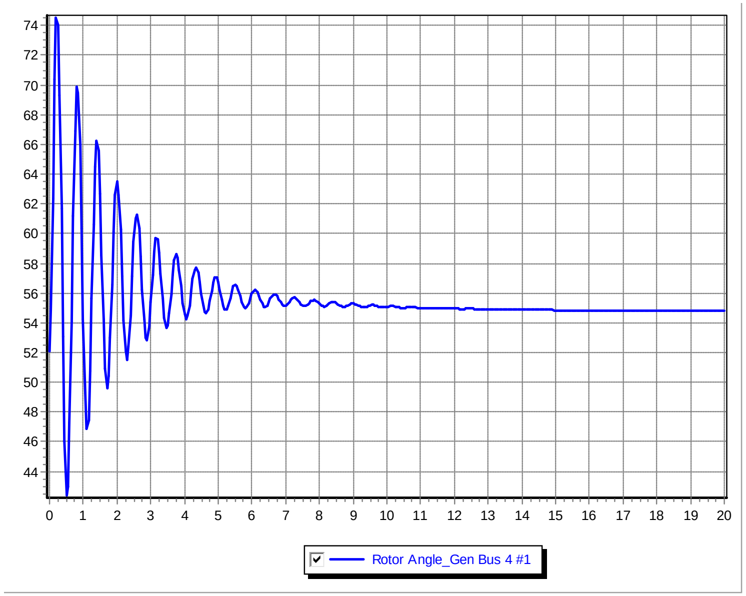
Similar results were obtained using another transient stability pacakge

FFT Characteristics

- The key FFT advantage is it is fast and robust, allowing consideration of a many signals
  - Possibly detecting otherwise unnoticed issues
- The frequency resolution of $1/(T_{end}-T_{start})$ is usually not high
- Currently results are not normalized (by say standard deviation), so it is best to compare similar values (such as speed, pu voltage, etc)
- Results are sensitive to the time window

FFT Characteristics

- Not ideally suited for damped signals, but results can still be useful



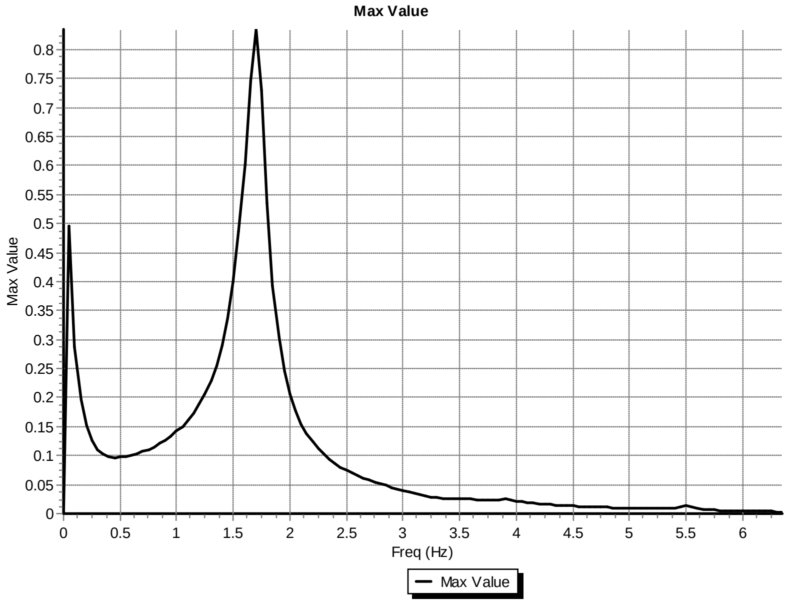


Figure on right is the FFT for the signal on the left

Modal Analysis using the Variable Projection Method (VPM)

- Goal of the VPM is do determine the frequency and damping of modes in a signal
- The application of the variable projection method to transient stability was developed at UW-Madison through DOE funding
- PowerWorld saw the method at the 2013 NAPS[1], and subsequently worked with Alex Borden to get it implemented

[1]A. Borden, B.C. Lesieutre, J. Gronquist, "Power System Modal Analysis Tool Developed for Industry Use," *Proc. 2013 North American Power Symposium*, Manhattan, KS, Sept. 2013

Variable Projection Method Overview

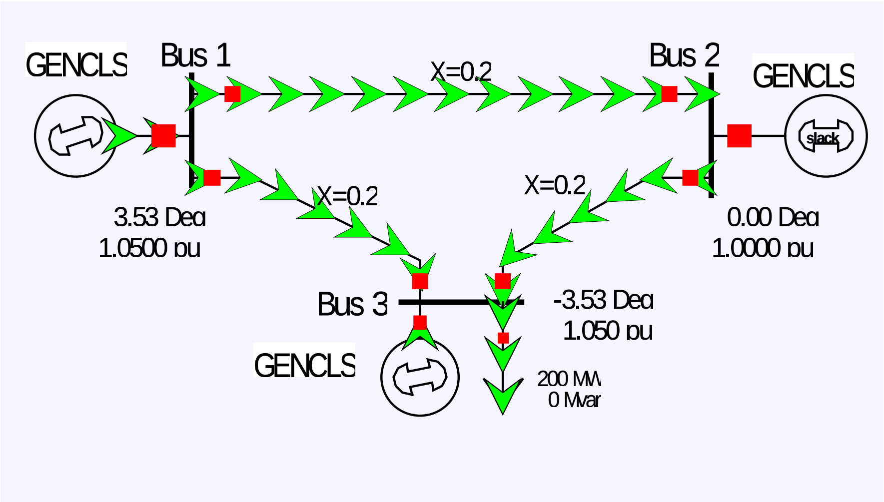
- Idea is to approximate a signal or signals by the sum of other, simpler signals (basis functions)
  - Basis functions are usually exponentials; signal can be detrended with linear or quadratic functions added
  - Properties of the original signal can be quantified from basis function properties (such as frequency and damping)
  - Signal is considered over an interval, with the specified interval quite important

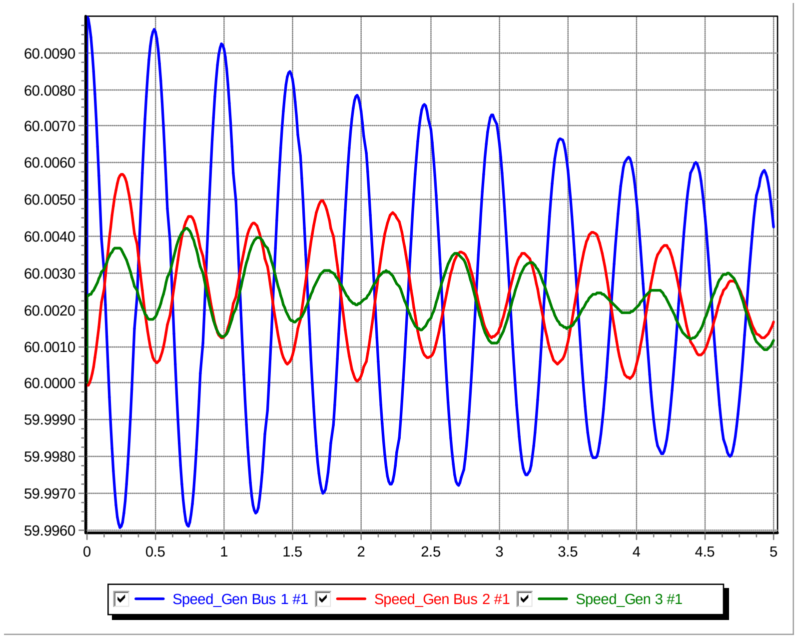
VPM in PowerWorld

- We're working to make the VPM as easy to use as possible with presently two ways to access it
  - On the Transient Stability Analysis form left menu, immediately below SMIB Eigenvalues
    - Does modal analysis for signals from either plot groups or stored in JSIS format files
  - By right-clicking on a transient stability or plot case information display, and selecting "Modal Analysis"
    - Works directly with the time data in the associated case information display

Simple VPM Three Generator Example

- A short fault at t=0 gets the below three generator case oscillating; clearly multiple modes in the oscillations (mostly clearly visible for the red and the green curves)





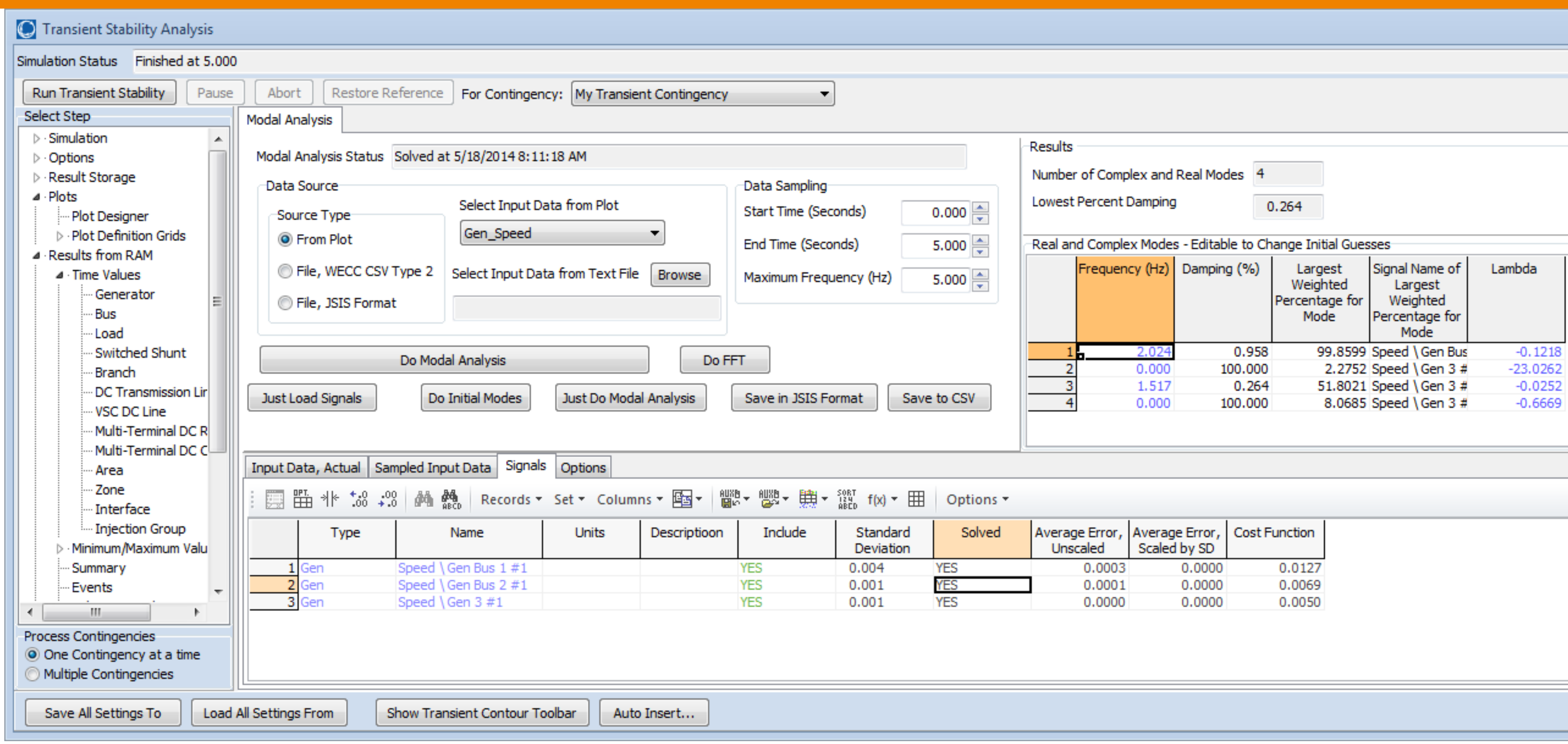
Simple VPM Three Generator Example

- One way to do modal analysis is on the Transient Stability Display select **Modal Analysis** to display the Modal Analysis page, load the data from the Gen_Speed Plot and click **Do Modal Analysis**
  - This does modal analysis simultaneously for all three generator speed curves (signals)

Transient Stability Modal Analysis Page

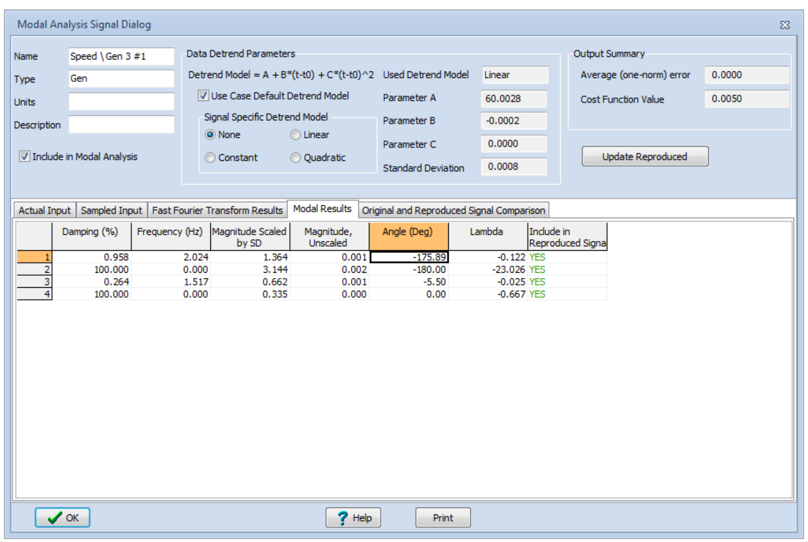
Key results are shown in upper-right. There are two main models, one at 2.024 Hz with 0.958% damping, and one at 1.517 with 0.264% damping.

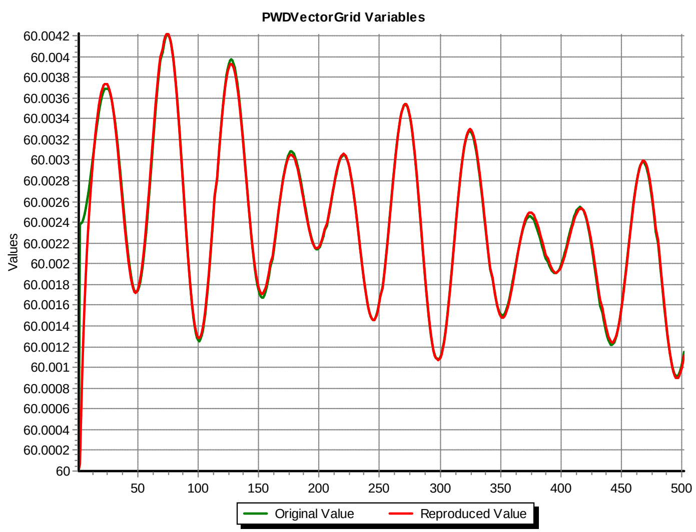
The bottom portion of the display provides a summary of how well each signal was matched, and by right-clicking on the signal, provides more details



Three Generator Example: Signal Dialog

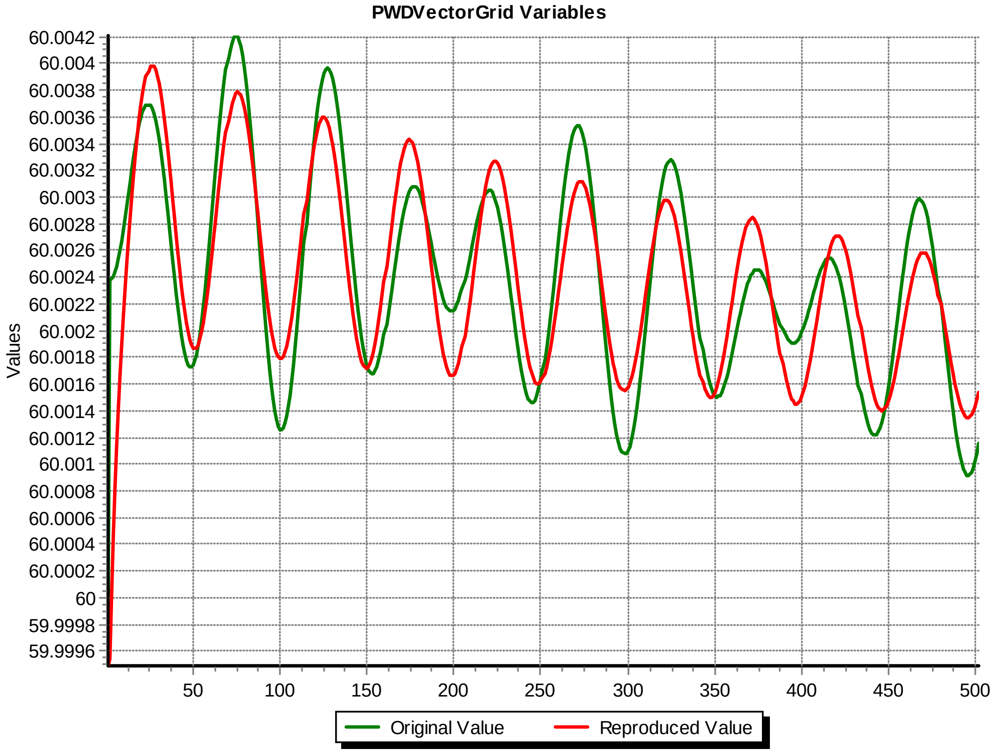
- The Signal Dialog provides details about each signal, including its modal components and a comparison between the original and reproduced





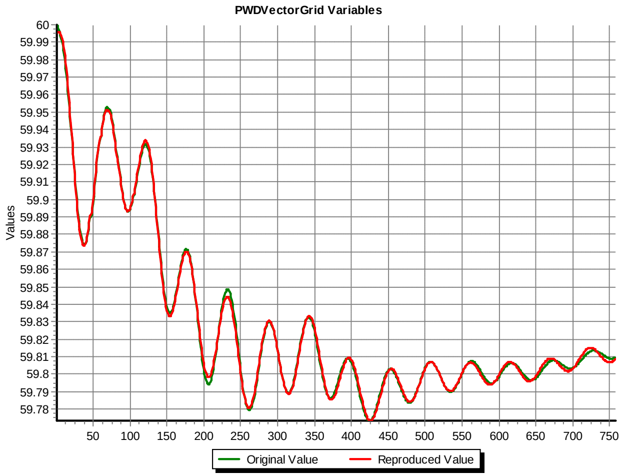
Three Generator Example: Signal Dialog

- The impact of individual frequencies can also be viewed
  - Graph on the right compares the previous signal with the 1.5 Hz portion of the signal removed



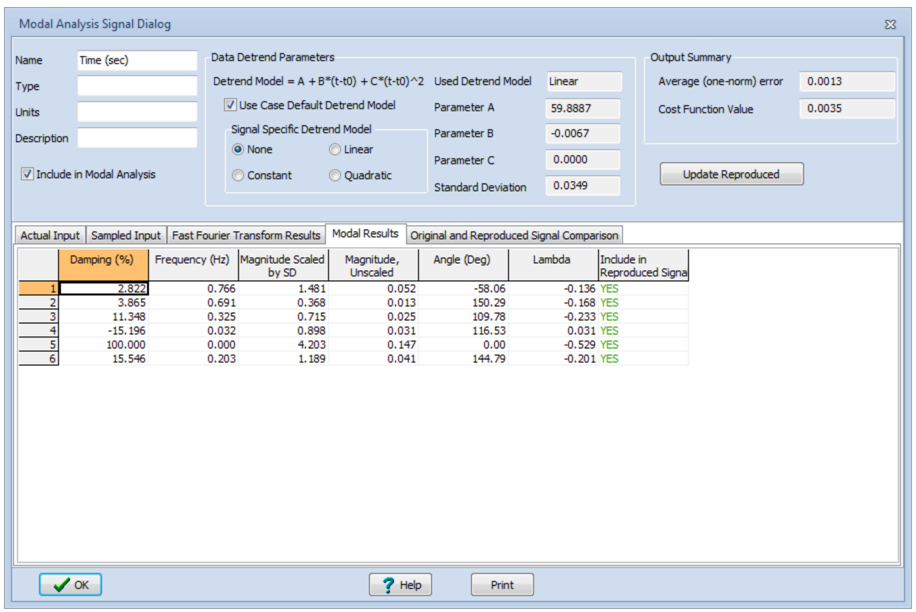
WECC Example with Access from Case Information Displays

- Modal analysis can also be easily done from the Transient Stability Time Values case information display
  - Right-click on a column and select Modal Analysis
  - By default analysis is from last event to end
  - Graph on the right shows results for a bus frequency, with the result having six modes

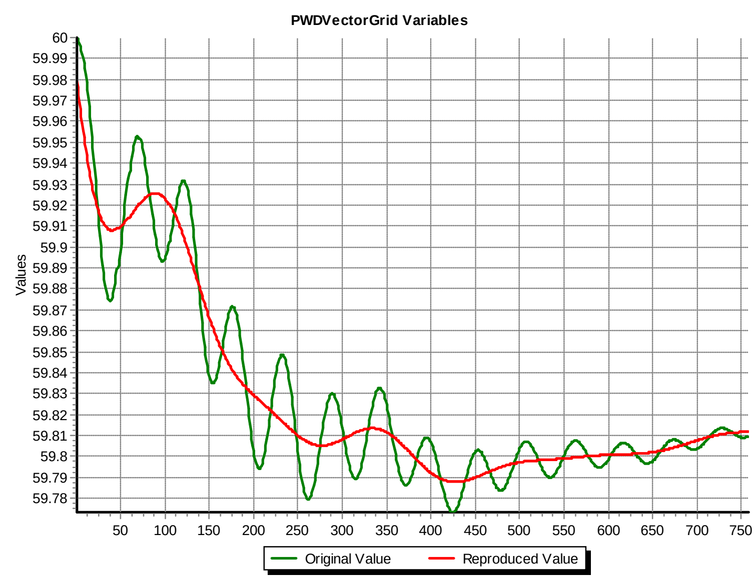


WECC Example with Access from Case Information Displays

- Below figures show the dialog, and the original/reproduced comparison with just the four lower frequency modes



	Damping (%)	Frequency (Hz)	Magnitude Scaled by SD	Magnitude, Unscaled	Angle (Deg)	Lambda	Include in Reproduced Signa
1	2.822	0.766	1.481	0.052	-58.06	-0.136	YES
2	3.865	0.691	0.368	0.013	150.29	-0.168	YES
3	11.348	0.325	0.715	0.025	109.78	-0.233	YES
4	-15.196	0.032	0.898	0.031	116.53	0.031	YES
5	100.000	0.000	4.203	0.147	0.00	-0.529	YES
6	15.546	0.203	1.189	0.041	144.79	-0.201	YES

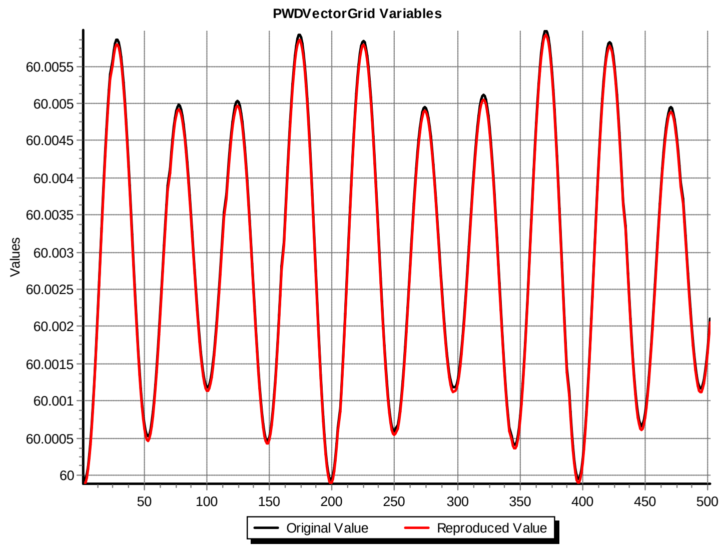


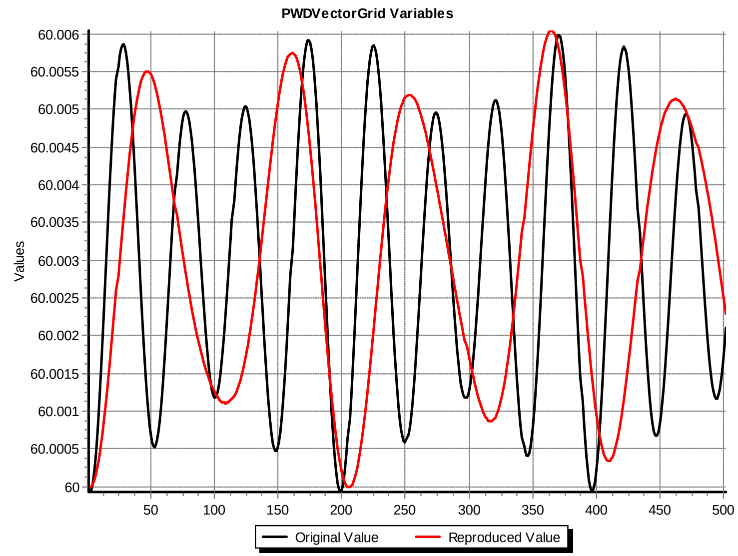
A Few Comments VPM

- VPM uses an algorithm the iteratively refines the modes
  - Algorithm requires an initial guess of the modes, which is automatically calculated
  - However, this is an $O(N^3)$ process, where N is the number of sample points
  - 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)

Results Can be Poor if Too Low a Frequency is Used

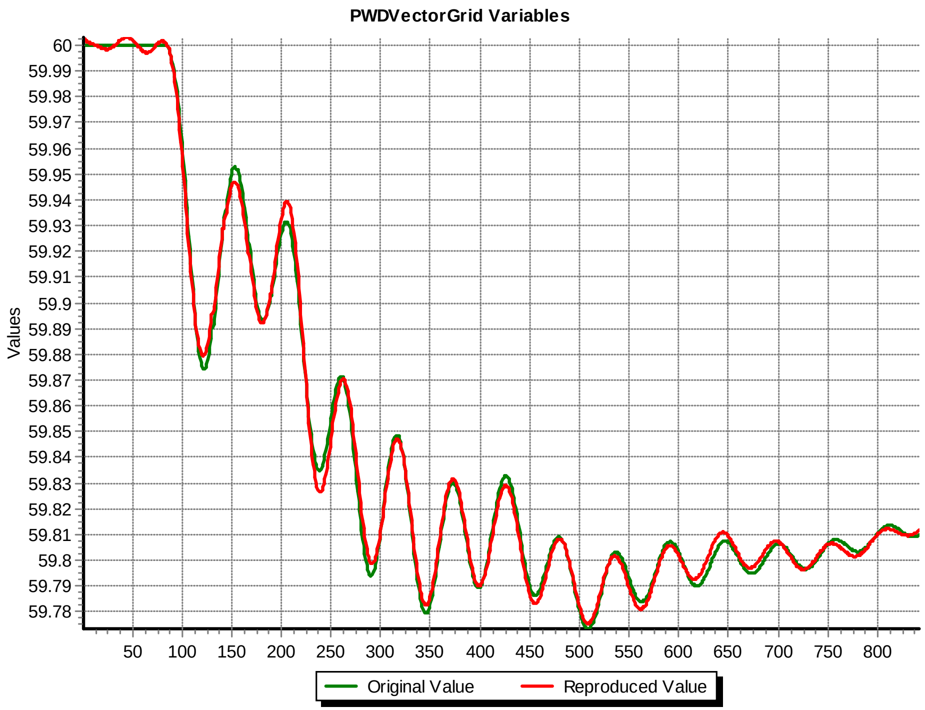
- Graph on left shows example from three generator case sampled at 10 Hz, while graph on right shows results with a 1.5 Hz sampling
  - Signal has modes at 1.51 and 2.03 Hz





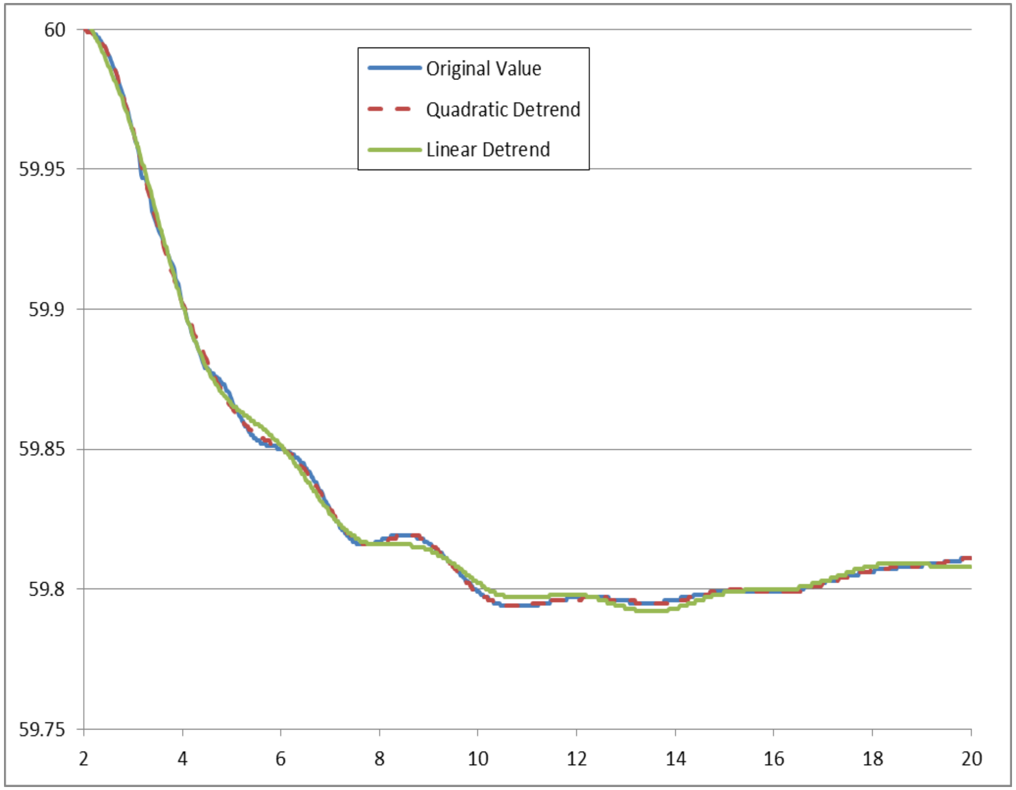
The Starting Time is Also Quite Important

- A take away is don't start trying to reproduce a signal until sometime interesting is happening
  - Graph shows the results for the previous WECC speed signal when the algorithm is asked to also match the first 2 seconds of 60 Hz frequency



Impact of Data Detrending

- In general it is a good idea to use either a linear or quadratic data detrending
- Figure compares reproducing the Malin frequency with either a quadratic (five modes) or linear detrend



Summary

- FFT and Variable Projection Method (VPM) modal analysis provide easy access to signal frequency information
- FFT is fast but less precise
- VPM is newer and can be quite precise
  – Testing seems to indicate that is works quite well
  – PowerWorld will be working to further develop this implementation
- **Feedback is always desired!!!**

PowerWorld Transient Stability Verification

- In addition to internal testing, there is a BPA funded project involving University of Illinois and Washington State to verify the PowerWorld transient software against the PSLF and TSAT packages
  - A second part of this project is integrating the dynamic models into the state estimator cases to validate the simulated results vs. the actual system

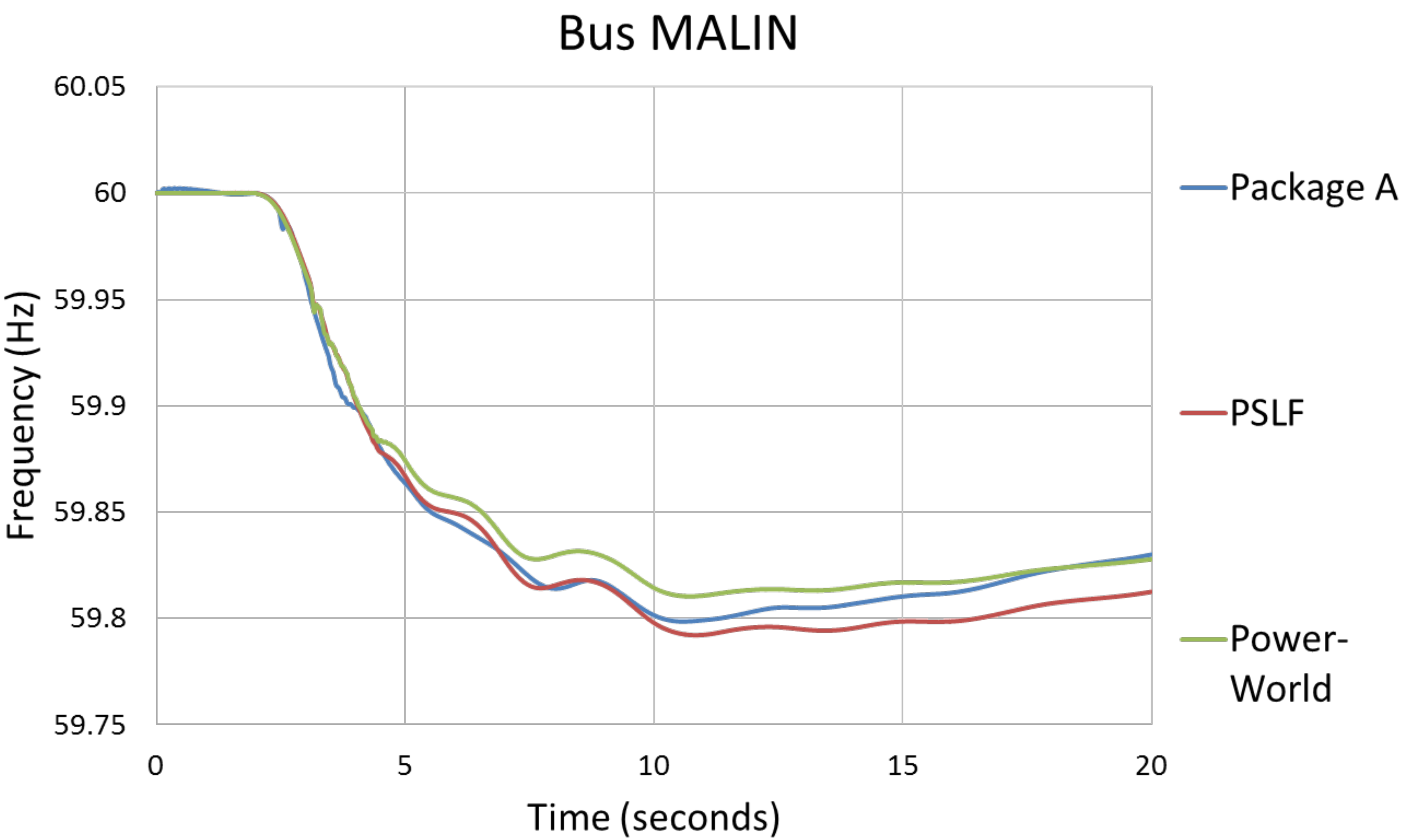
Accomplishments: Simulation Automation

- Developed mechanism to simulate all individual generators of a planning case in PowerWorld and PSLF, using automation routines
  - SimAuto in PowerWorld, EPCL in PSLF
- In addition to simple bus faults last year, added capability to simulate voltage and frequency playback for individual generator simulations
  - This has helped to find and resolve issues with several generator, exciter, and governor models

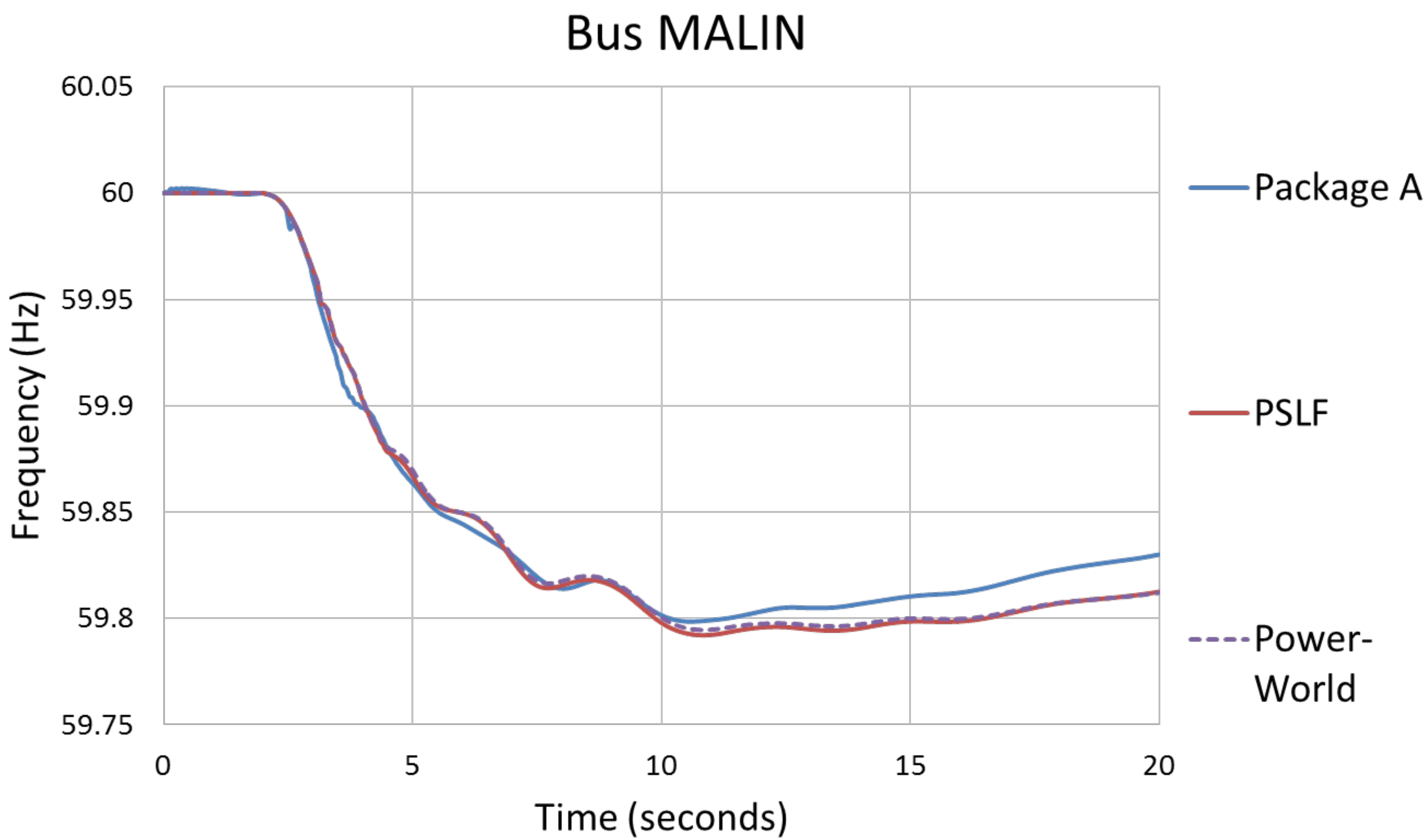
Accomplishments: Verification Tool

- Developed verification tool which compares dynamic responses and quantifies differences
  - Extended to compare full system responses
  - Developed better metrics to compare responses
    - L1 norm (area between two curves, which is perceived visually)
    - L2 norm or Euclidean distance is also a good measure
  - Added data pre-processing methods
- Tool helps automatically identify problematic buses/generators from the thousands in a case

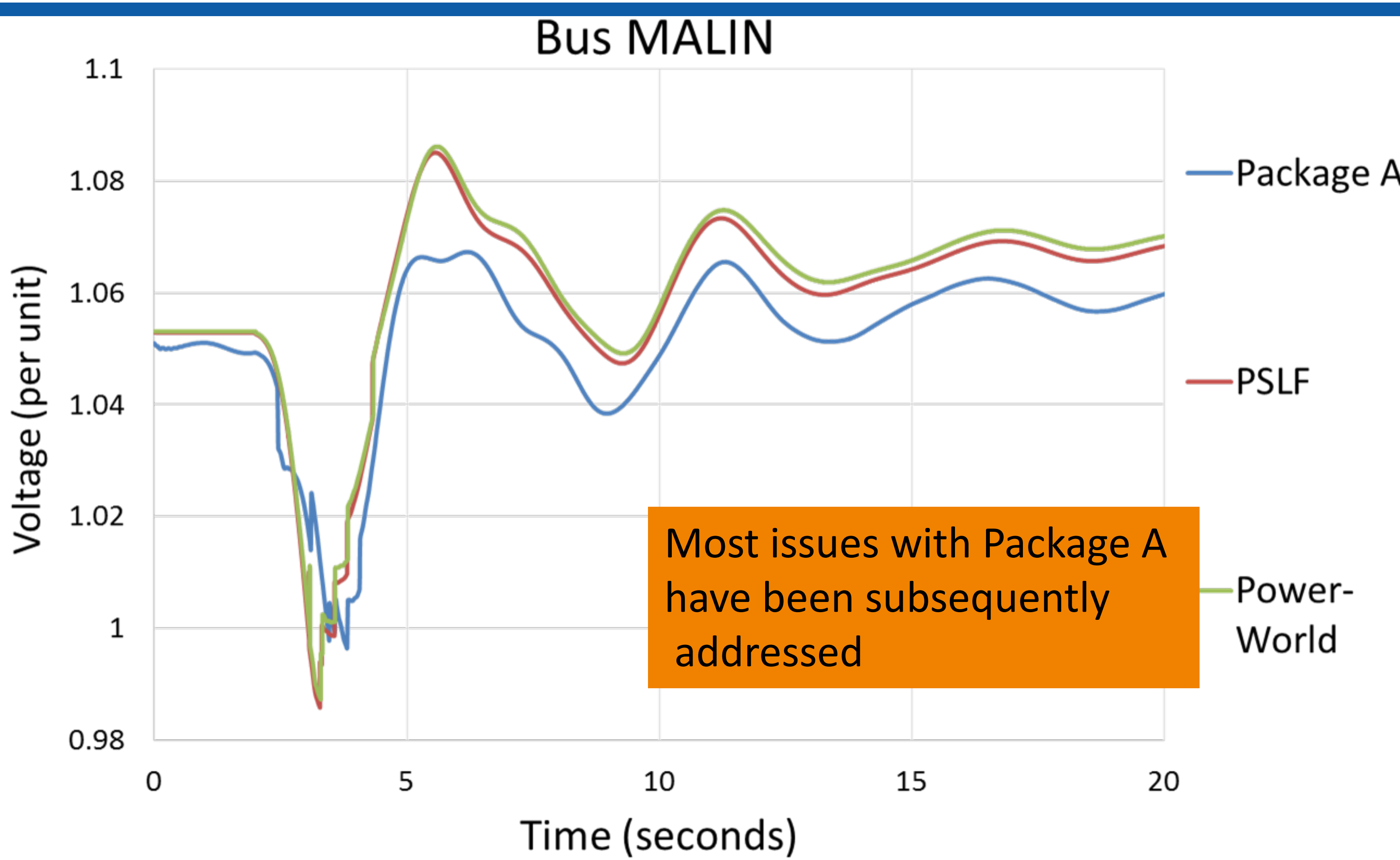
Accomplishments: Results Last Year



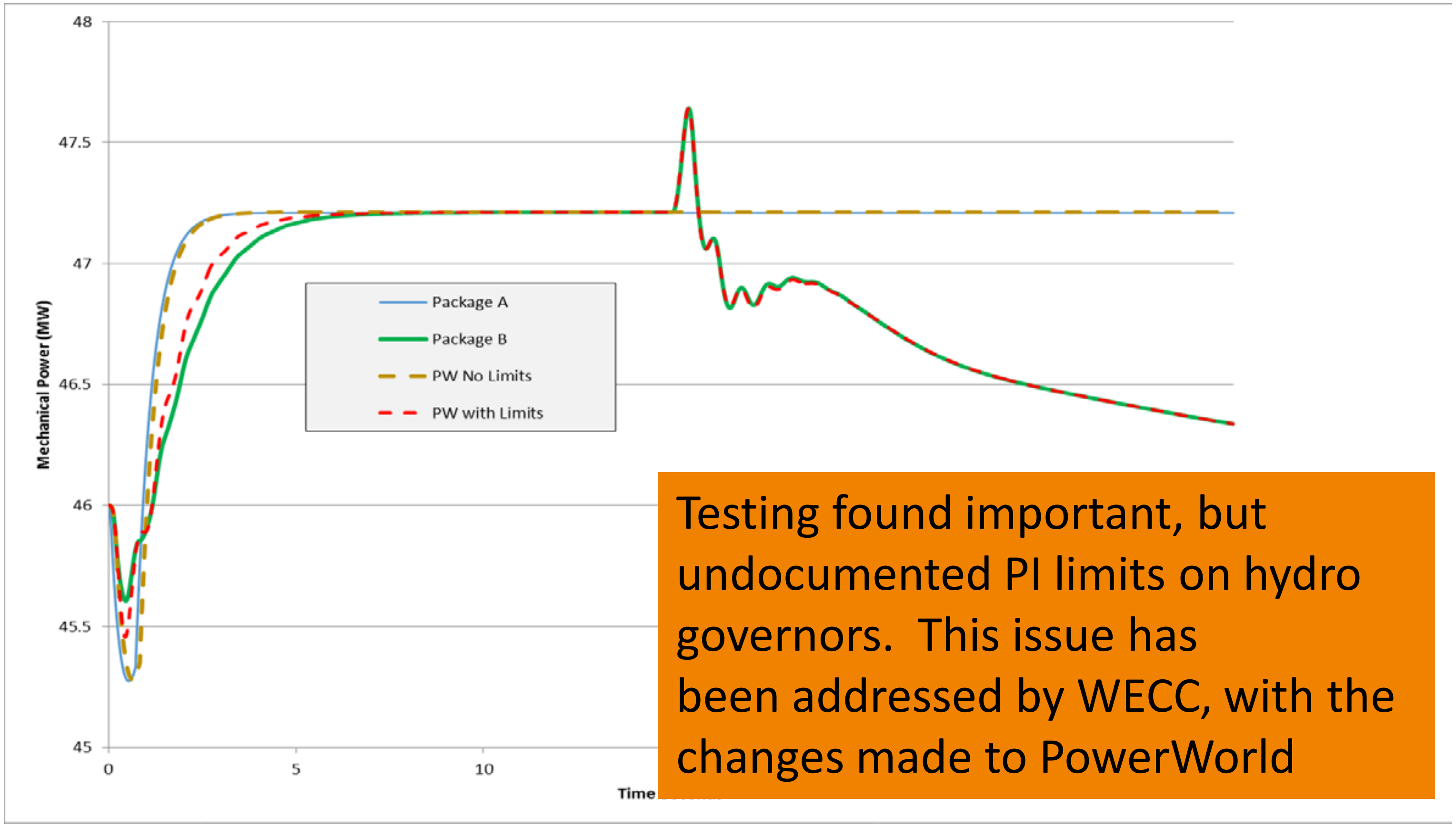
Accomplishments: Results Now



Accomplishments: Results Now



Hydro governors Undocumented PI limits



Testing found important, but undocumented PI limits on hydro governors. This issue has been addressed by WECC, with the changes made to PowerWorld

Moving Forward

- Continuing to work on verification of newer models, such as the composite load
- Project is also now moving into validation between state estimator cases (with dynamic models) and the actual system
  - Several issues are being addressed, such as how to handle generators that are operating as condensors (and hence consuming real power) that have governors with zero power lower limits

Questions?