Verification and Validation of Transient Stability Models and Results

Thomas J. Overbye, Komal Shetye
University of Illinois at Urbana-Champaign
overbye@illinois.edu, shetye1@illinois.edu

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PowerWorld Corporation

PSERC

Project Synopsis

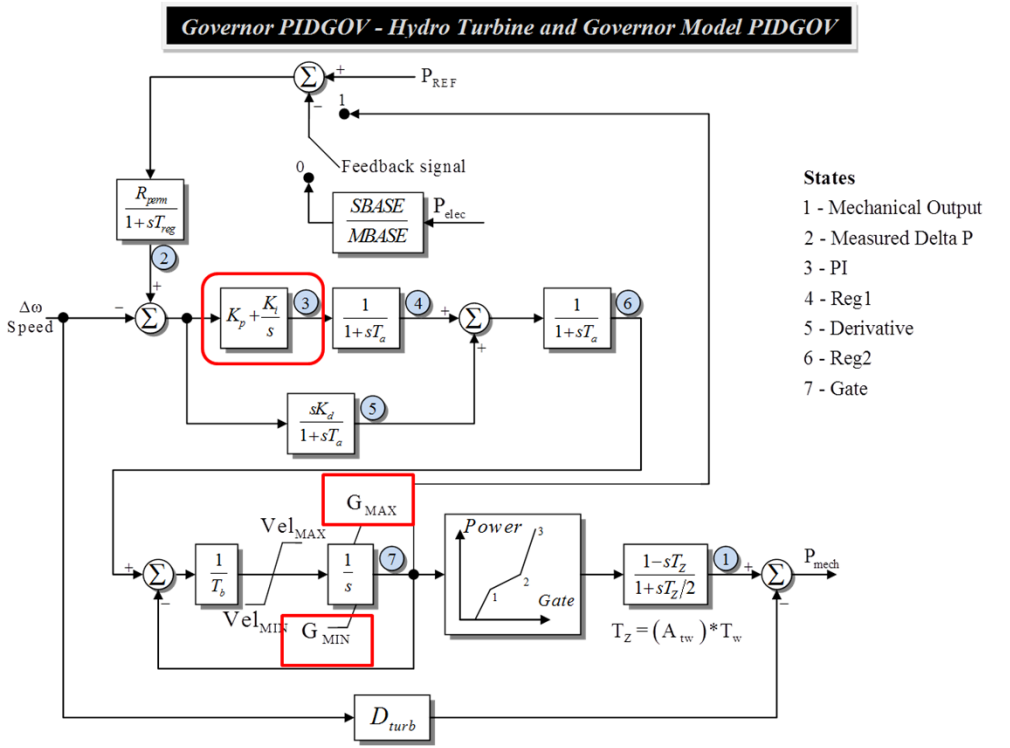
- Over last five years UIUC and WSU have been working with BPA to do transient stability verification, with a primary focus on comparing results between PowerWorld, PSLF, TSAT, and (somewhat) PSSE
  - Verification is defined as making sure the packages have correctly implemented the specified models
  - Over last year the project has also addressed validation, which is defined as determining how well the models represent the actual system
- Verification goal has been to get the packages to give near similar results
  - We believe the goal has been met, particularly between PowerWorld and PSLF

Reason for Project

- Software verification and dynamic model validation should ultimately provide better dynamic analysis tools and models
- Transient stability packages are complex, supporting hundreds of different models, each having many parameters and potentially different modes of operation
  - Errors can be missed, even in code that has been used for decades for studies
  - Multiple packages can also be used to more quickly determine errors in both old and new system models
  - The impact of underlying assumptions can be better considered

Example: Hydro Governor Non-Windup Limits

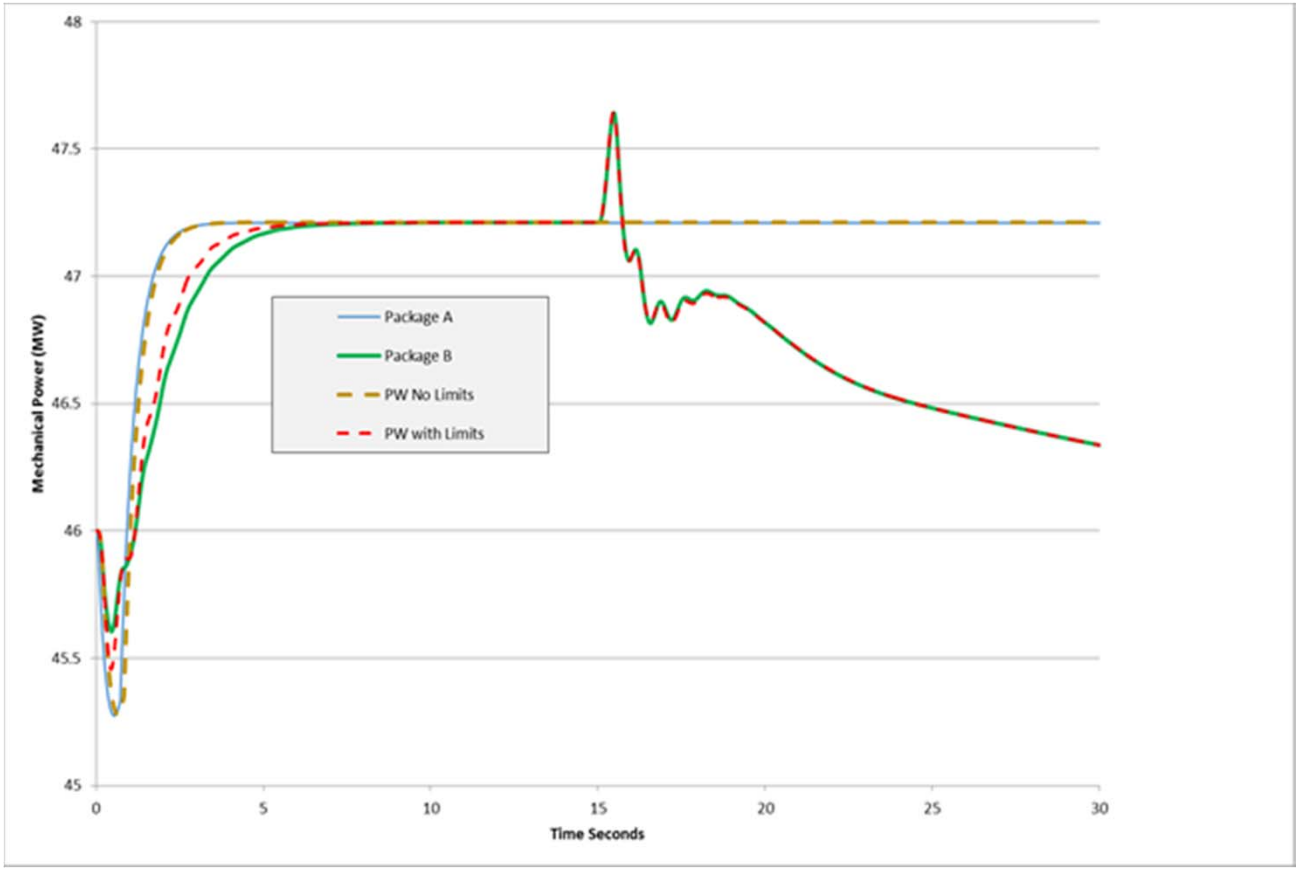
- One issue found during the verification work was the modeling of non-windup limits in hydro governors
  - Handled quite differently in different packages



(G0,0), (G1,P1), (G2,P2), (1,P3) are x,y coordinates of Power vs. Gate function

Example: Hydro Governor Non-Windup Limits

- Seeing differences required a scenario in which governor hit its limit, then backed off its limit



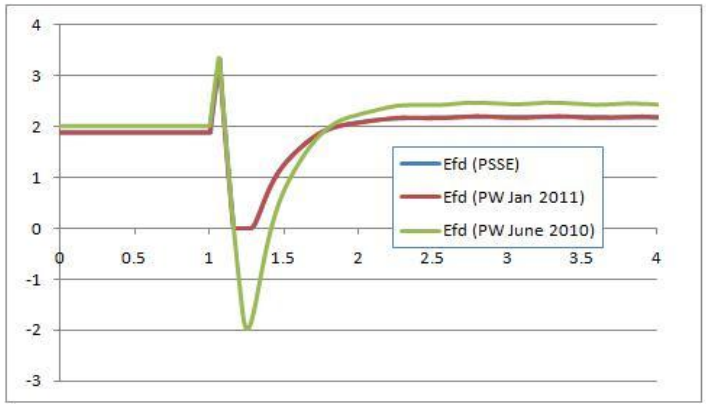
Jamie Weber presented results to MVWG in Spring 2014

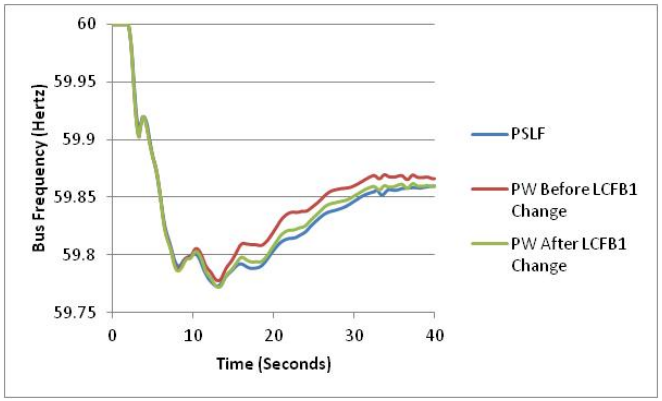
Approach

- Difference transient stability packages can get different results for a variety of reasons
  - Different initial power flow cases; the sharing of generator reactive power among multiple generators is a common difference
  - Slightly different models dynamic models, such as whether a speed multiplier is included in the exciter output
  - Different methods for correcting "bad data"
- Our approach was "zero tolerance" for different results
  - Greatly helped by PowerWorld's implementing all the different models and methods for correcting bad data
- Methodology combined looking at results for full system studies (top-down) and for two bus equivalents (bottom-up)
- Details matter!!

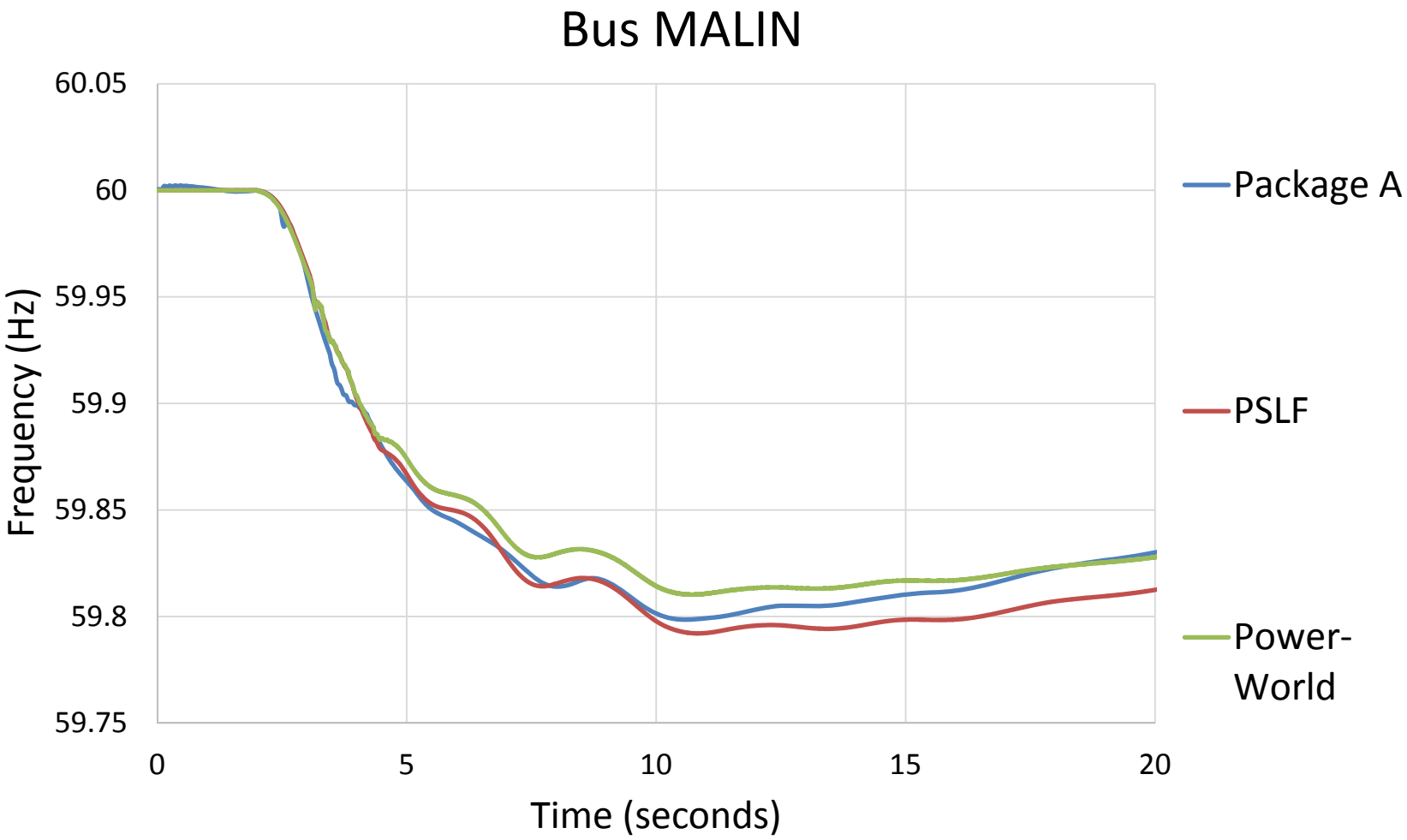
Project Background

- Current BPA project is an out-growth of an earlier (2011) successfully completed PSERC project (S 43-G), conducted by the UIUC and WSU team; funded entirely at BPA (RD53)
  - Project developed prototype mechanism to do software package comparison using the bottom-up approach, but it was done manually, a slow process for thousands of generators

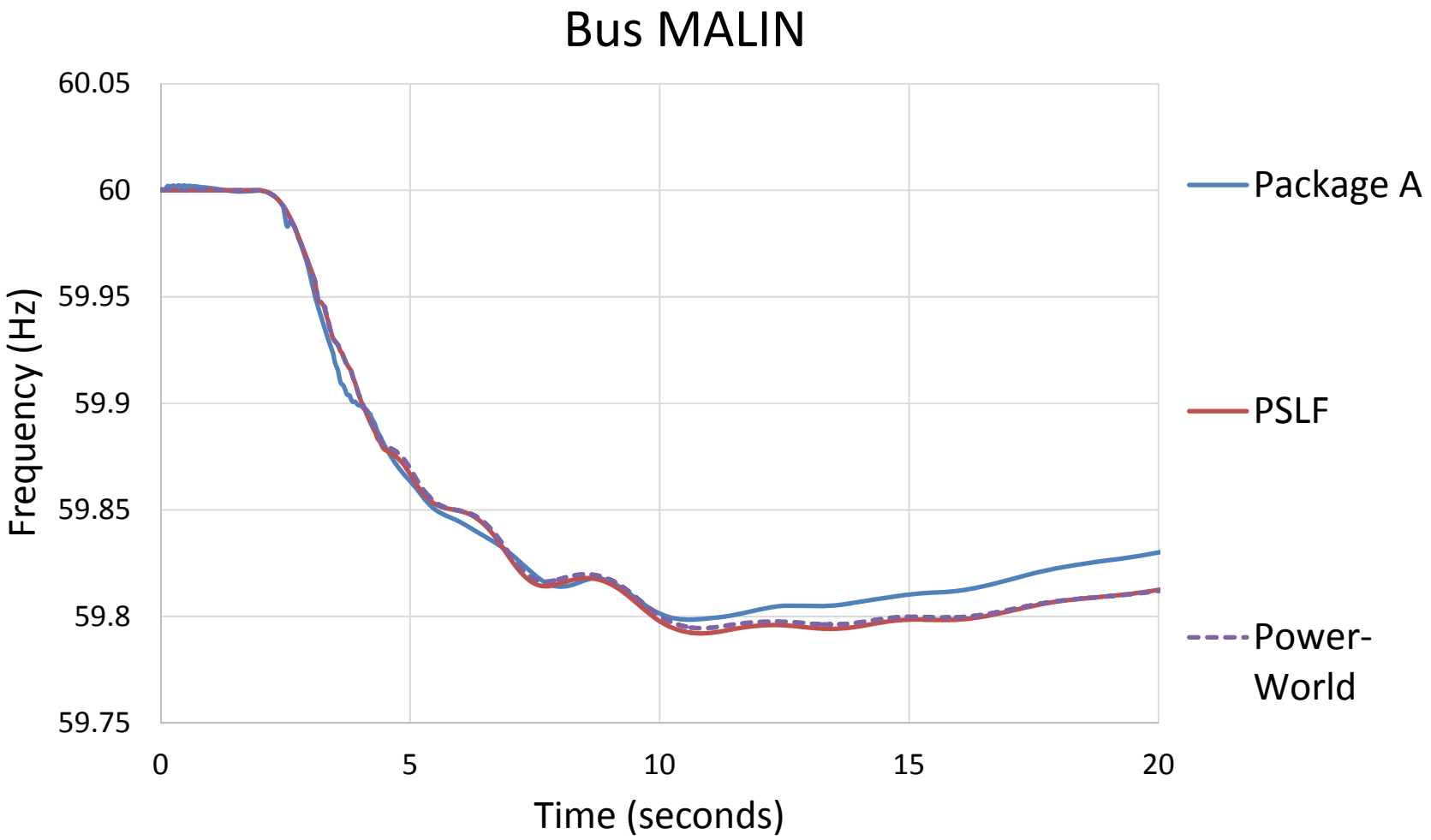




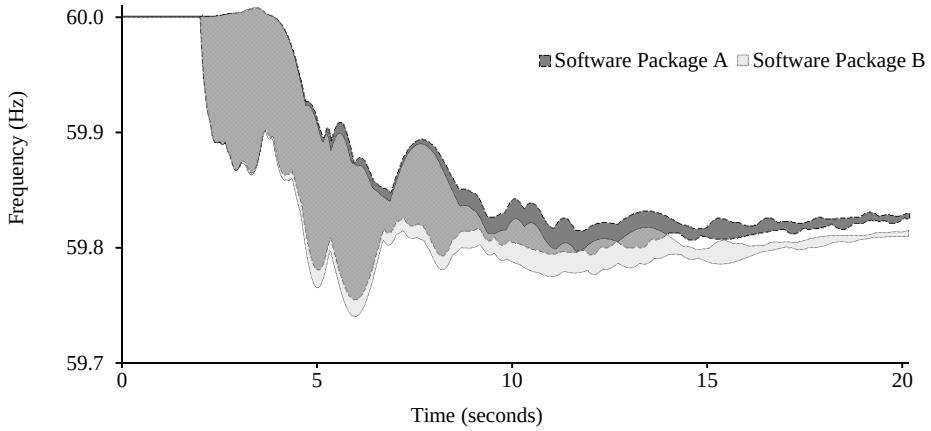
TIP 268 Verification Starting Point



Results of Verification



How this was achieved – Verification Methodology



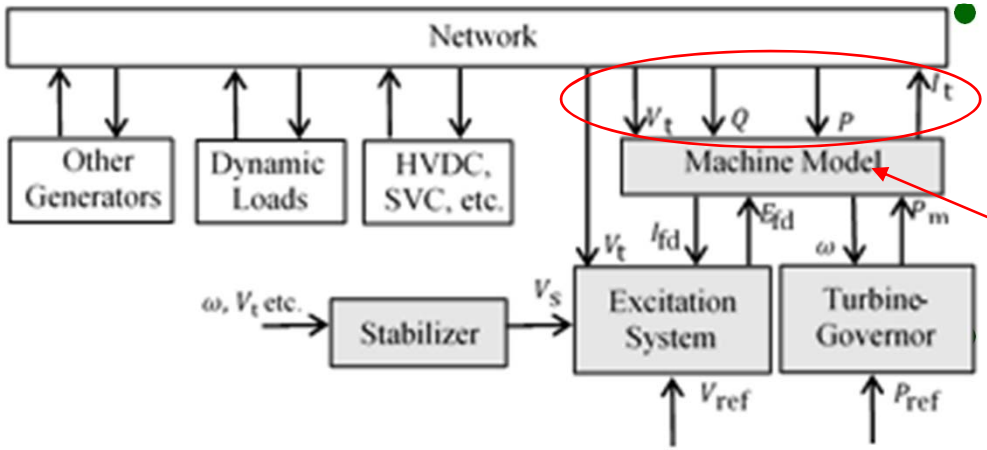
Spread of 18,000 WECC bus frequencies
Software Package A: PowerWorld
Software Package B: PSLF

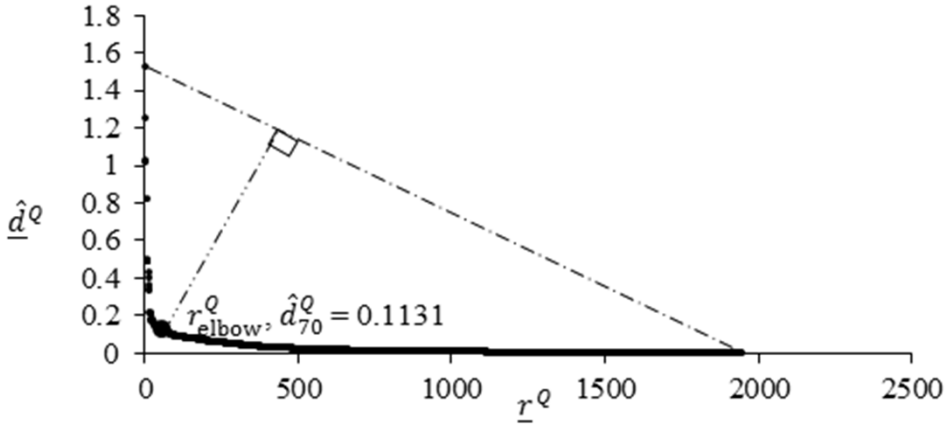
$$d^X = \sum_{i=1}^{N} \left| X^{\mathrm{A}}{}_i - X^{\mathrm{B}}{}_i \right| \left(\sqrt{\left(\sum_{i=1}^{N} |X^{\mathrm{A}}{}_i| \right) \left(\sum_{i=1}^{N} |X^{\mathrm{B}}{}_i| \right)} \right)^{-1}$$

d = distance measure
X = signal being compared (f, P, Q, etc.)
A, B : Software Package

- Analyzed results of the whole system
- Goal: To find the dynamic models causing these system-wide discrepancies
- Automated comparison of large system results
  - Created a metric to compare results analytically rather than manually / visually
  - L1 norm normalized by time and magnitude

Verification Methodology – Hybrid Top Down + Bottom Up Method





69 generators above elbow point for Q comparisons – analyzed further

- Top Down: Analyzing system–wide results and going down systematically to individual dynamic models

  Used Interface Signals: e.g. P and Q for generator buses

- Then, use data partitioning technique called “Elbow Point” to find the most discrepant generators in terms of P and Q comparisons

Verification Methodology – Hybrid Top Down + Bottom Up Method

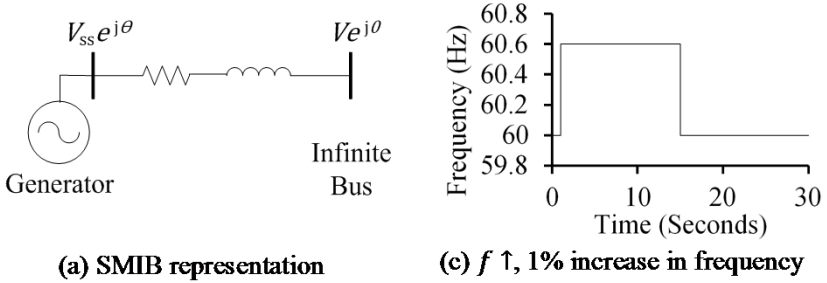


Figure 1. SMIB simulation system and disturbances

TABLE I. Summary of the characteristics of SMIB based simulations

Stage		M	E	G	S	Disturbances	Compared signals
1	M	✓	×	×	×	$V_{SC}, f\uparrow, f\downarrow$	ω, V_t, P, Q
2.a	ME	✓	✓	×	×	V_{SC}	E_{fd}
2.b	MG	✓	×	✓	×	$f\uparrow, f\downarrow$	P_m
3	MEGS	✓	✓	✓	✓	$V_{SC}, f\uparrow, f\downarrow$	V_s

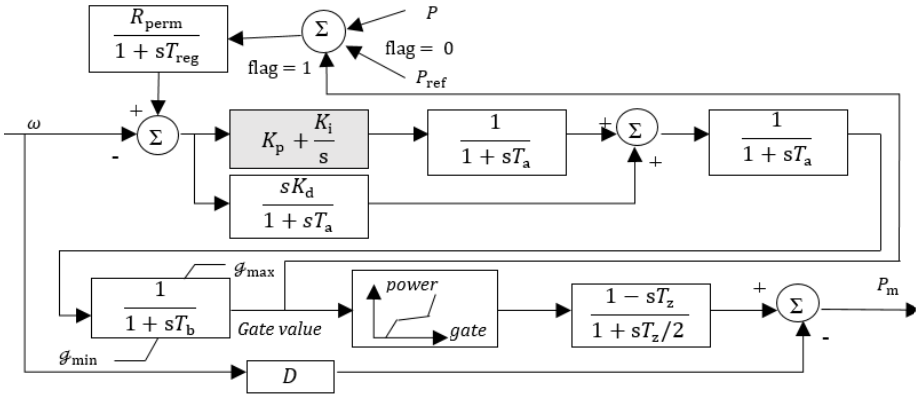
- Once major discrepant generators are identified, compare them in detail by single machine infinite bus (SMIB) analysis
- Creation of SMIB equivalents automated in PowerWorld
- Bottom Up: Simulate SMIB equivalents to isolate discrepancy causing model(s)

TABLE I. Some isolated models, from the large-system example

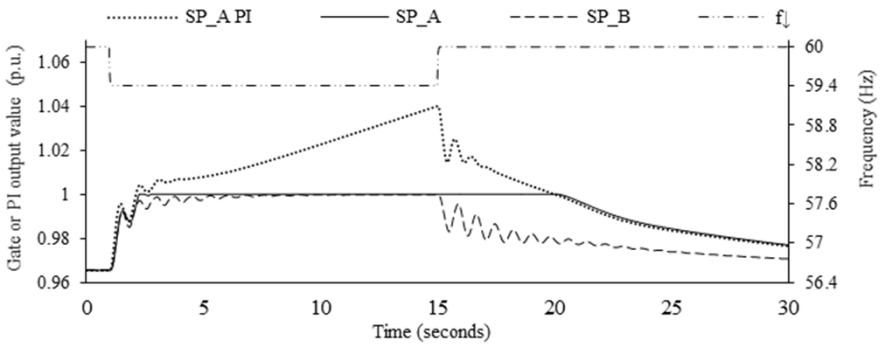
g	M	E	G	S	Failed Stage	Failed Signal(s)
1468	GENTPJ	EXST1	PIDGOV	PSS2A	MG	P_m
1896	GENROU	EXAC1	IEEEG1	IEEEST	ME	E_{fd}
838	GENTPF	EXST1	GGOV1	WSCCST	MEGS	V_s

Verification Methodology – Detection of Causes of Discrepancies

- Method 1: State / Block Diagram Analysis: Comparing states or outputs of blocks as available to narrow the discrepancy to a particular block



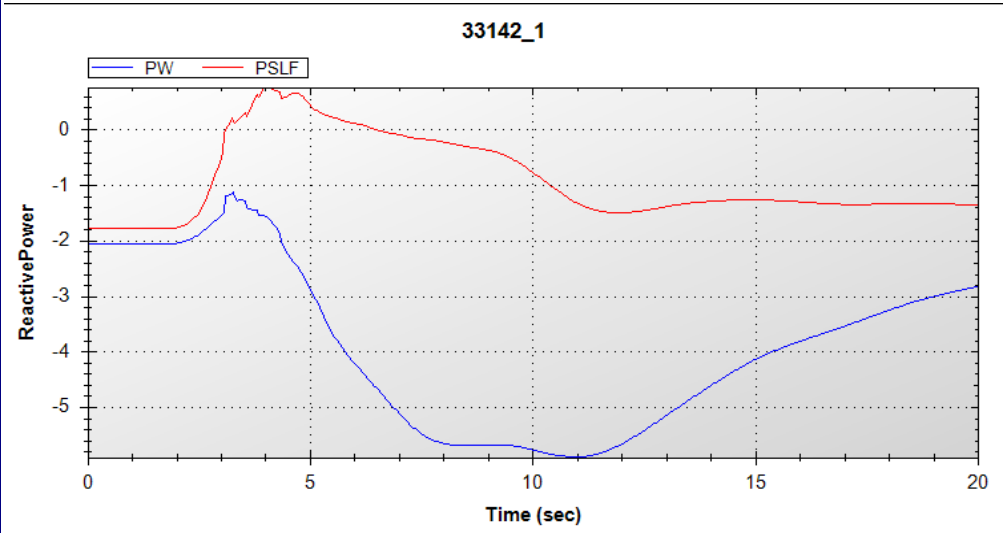
PIDGOV block diagram: PI block in gray



Integral wind-up seen in Package A but not in B, after frequency playback test

Verification Methodology – Detection of Causes of Discrepancies

- Method 2: Clustering parameters: Clustering each parameter of **all** instances of a particular model type to see which parameter cluster aligns with the discrepant models



Now, both PW and PSLF disable this model when Vcutoff = -1, results match

- Eg: Only 3 instances of WSCCST out of total 122 instances in the case showed this discrepancy (Buses 33141, 33142, 33143)
- Clustering all instances showed only these 3 had Vcutoff= -1
- PSLF had unclear documentation on what happens when this is 0

TABLE I. Key WSCCST parameters, with discrepant generators in grey

g	I_{cs}	K_{qs}	T_{qs}	T_q	T_{q1}	T_{pq1}	T_{q2}	T_{pq2}	T_{q3}	T_{pq3}	V_{smax}	V_{cutoff}	V_{slow}
838	1	4.5	0	10	0.05	0.21	0.05	0.21	0	0	1	-1	0
839	1	5.1	0	10	0.025	0.25	0.025	0.25	0	0	1	-1	0
840	1	5.1	0	10	0.025	0.25	0.025	0.25	0	0	1	-1	0
1371	3	6	0.05	2	0	0	0.031	0.2	0.031	0.2	0.07	0	-0.07
1715	2	0.45	0	1.5	2.5	0.35	0.03	0.35	0	0	0.05	0	0
585	1	2.4	0	10	0.02	0.2	0.02	0.2	0.06	0	0.05	0	-0.05
⋮													

Verification Methodology

- Final Step: Reporting error causing models / blocks / parameters to software vendor(s)
  - Helps confirming the error
  - Model updates and bug fixes
  - Re-run with update models to verify if results match
- Commonly found causes of errors
  - Software bugs
  - Incomplete documentation
  - “Bad” model parameters: Values that are not handled by the model, or lack of documentation on how a software package handles them

Verification Results

- Some key models causing simulation result discrepancies identified / fixed in this project
  - Machines: GENTPF, GENTPJ - Fixing the frequency dependent voltage issue drastically improved the system-wide frequency differences between PSLF and PowerWorld
  - Exciters: EXAC1, ST4B, ST6B, AC7B, ESAC, etc.
  - Governors: Hydro governors with PI blocks such as PIDGOV, GPWSCC, HYG3 etc., GGOV1, GGOV3
  - Stabilizer: WSCCST
  - Other Models: OEL1 implementations for different exciter models, LCFB1
  - Loads: Static Load, MOTORW, MOTOR1, LDELEC, LD1PAC, CMPLDW

Current Verification Results

- Verification led to a closer match between software packages

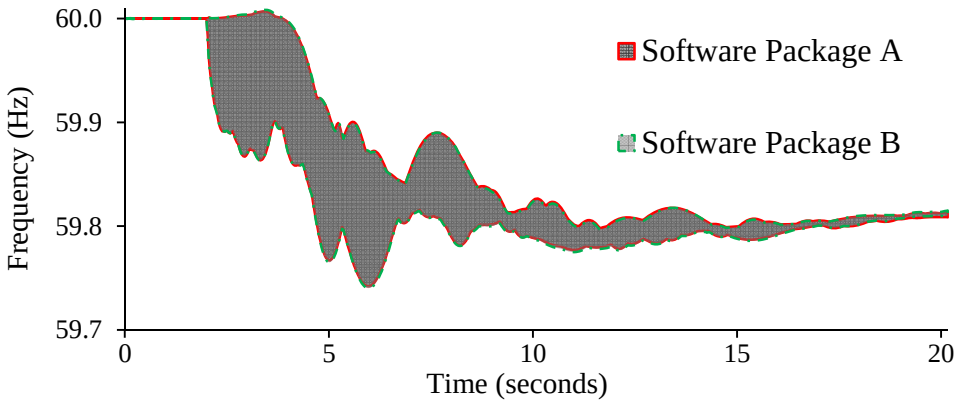
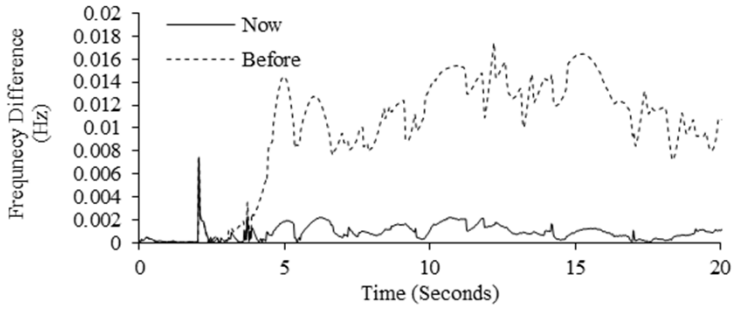
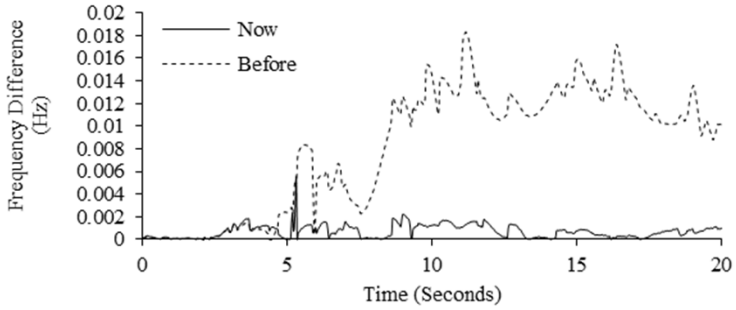


Figure shows where we are now at in package to package comparisons. The largest frequency differences, shown in the figures on the right, are now quite small.



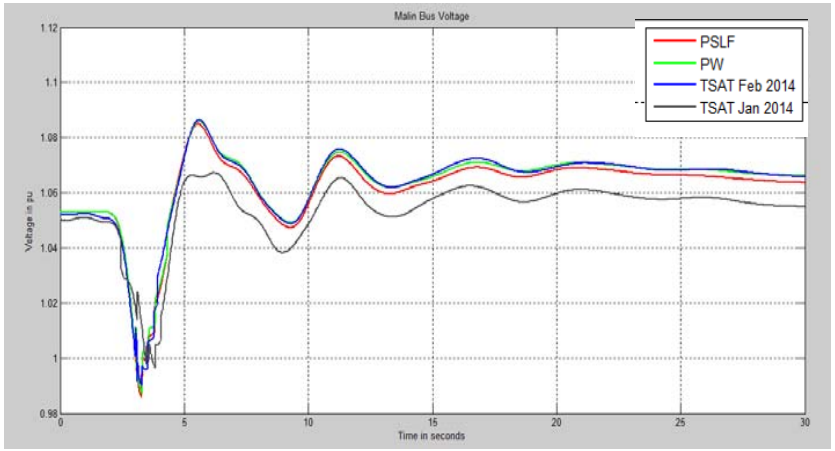
Comparison of differences between the minimum frequency values across18,000 buses

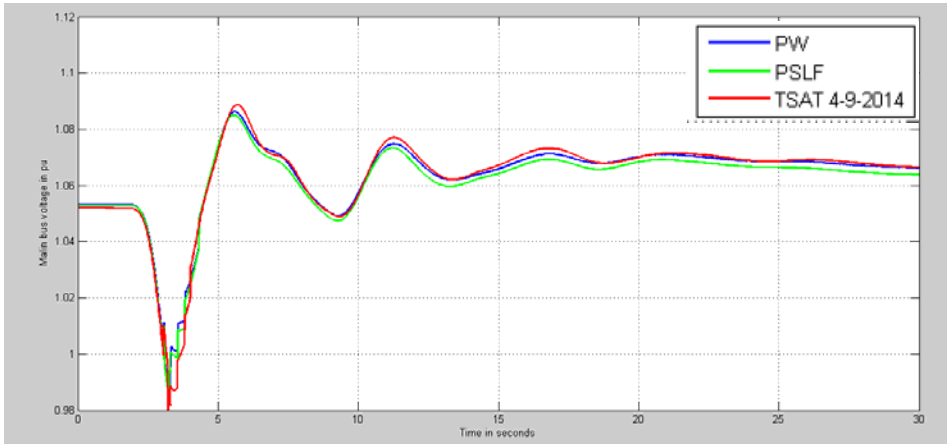


Comparison of differences between the maximum frequency values across18,000 buses

Current Verification Results

- Verification led to a closer match between PowerWorld/PSLF and TSAT as well

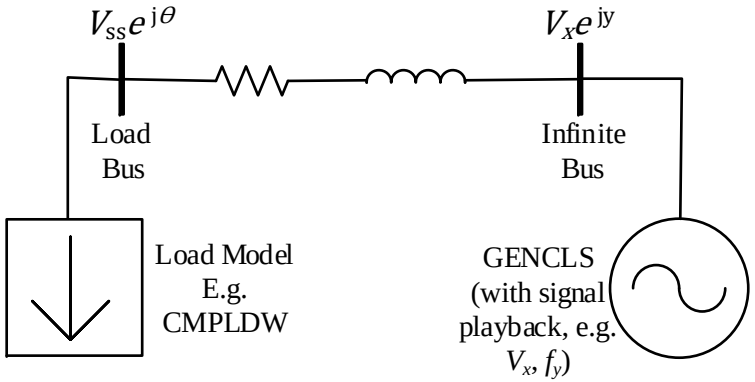


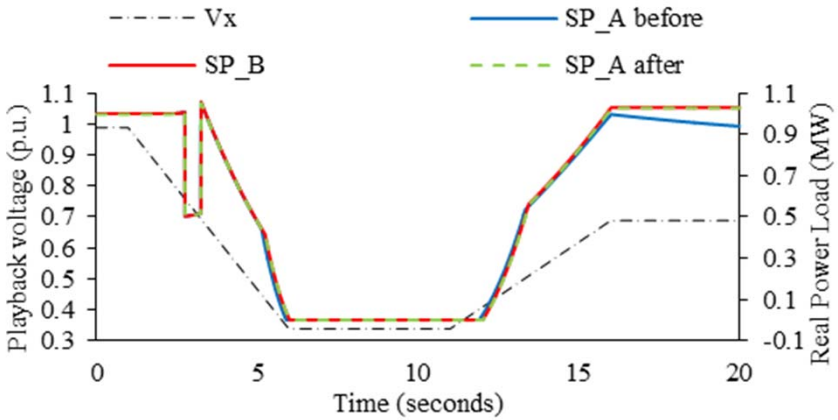


Malin Bus Voltage

Verification of Load Models

- In addition to generator models, performed verification tests for load models such as CMPLDW and its components: 1-ph air conditioner, electronic load, and 3-ph motor models
  - Methodology: Analysis of Single Load Infinite Bus Equivalents (SLIBs). Can create automatically at any bus





Eg: Testing contactor functionality of LD1PAC model. Found discrepancy only when voltage recovers above Vc1on. Issue was incorrect scaling of MVA base of the load above Vc1on. This was fixed in PoweWorld.

Verification of Load Models

- Report on CMPLDW benchmarking submitted to WECC MVWG Load Modeling Task Force in Oct 2014 (co-authored w/ BPA and PowerWorld)

Composite Load Model Benchmarking

PowerWorld Simulator vs. GE PSLF

Prepared for the

WECC MVWG Load Modeling Task Force

Date: October 16, 2014

Prepared By:

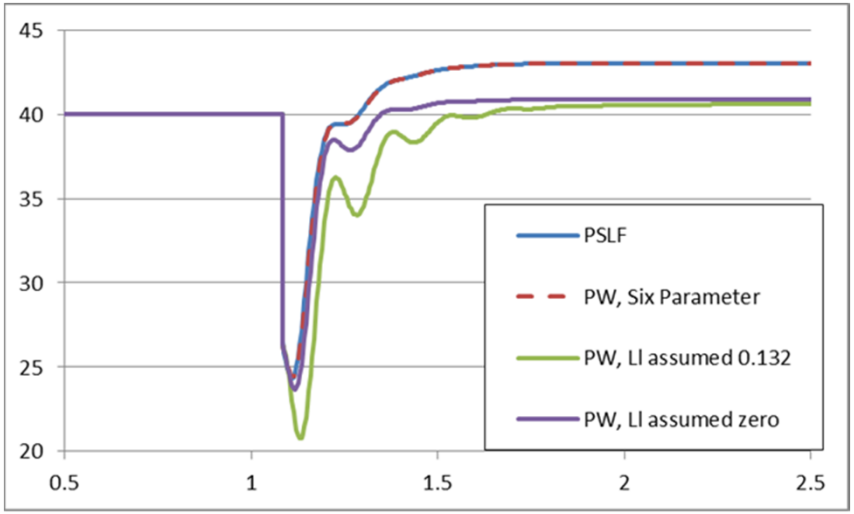
Ran Xu rxxu@bpa.gov (Bonneville Power Administration)

Tom Overbye overbye@illinois.edu (University of Illinois)

Komal Shetye shetye1@illinois.edu (University of Illinois)

Verification of Load Models

- One issue one complex load model verification is whether the underlying 3-phase induction motors are modeled with six parameters (like MOTORW) or seven parameters (like MOTOR1, CIM5)



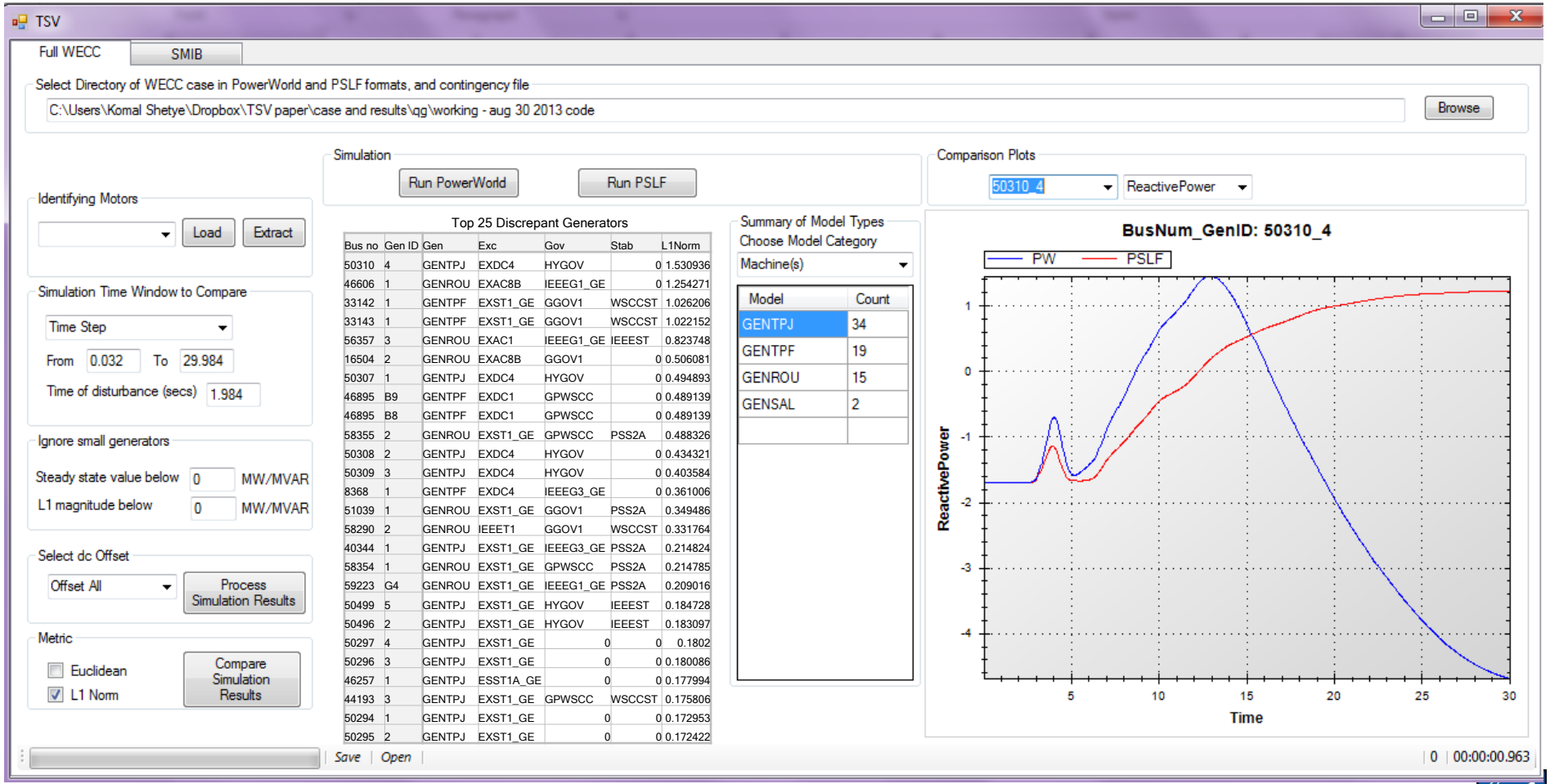
Time (seconds)

Reactive power load comparison for 3-ph induction motor model, with different parameter approaches

The seven parameter models will give different results

Verification Tool Snapshot

- In progress, prototype GUIs shown here



Verification Tool Features

Two parts

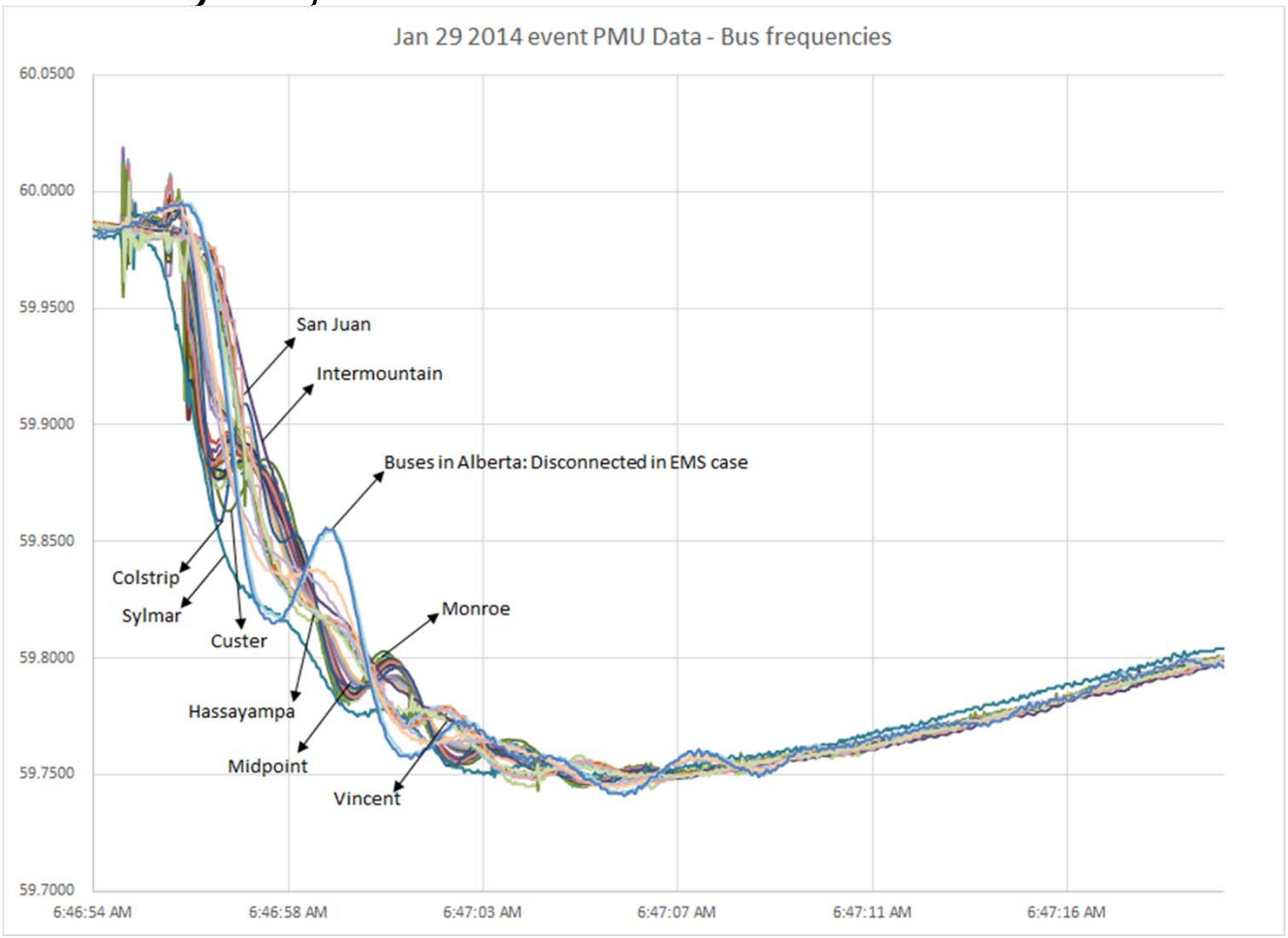
- 1. Large System Analysis (eg. WECC Case)
  - Process simulation results to apply metric: Time alignment, removing duplicates (during switching events), identifying motors (opposite sign convention), removing dc offset, etc.
  - Comparing and displaying most discrepant buses
  - Ability to plot results
- 2. SMIB Analysis
  - Option to simulate all SMIB equivalents of a case or the most discrepant ones identified from large system analysis
  - Simulate with voltage or frequency disturbances to test relevant models
  - Comparing results and finding possible error causing models

Validation

- Actual system validation is more challenging, but many of tools developed for verification are helpful
- Comparing simulation results to PMU data from disturbances
  - Data received
    - State Estimator (SE) Cases for Jan 29 2014 events (John Day - Grizzly fault + Gen Drop)
    - Event logs
    - PMU data for disturbances (50 bus frequencies)
    - Planning cases containing dynamic data
  - Validation Case Set-Up
    - Set-up a procedure to map dynamic data from planning to SE cases (aided by WSM mapping)
    - Fixing “bad data” such as incorrect MVA bases, governors for negative MW generators to address instability issues

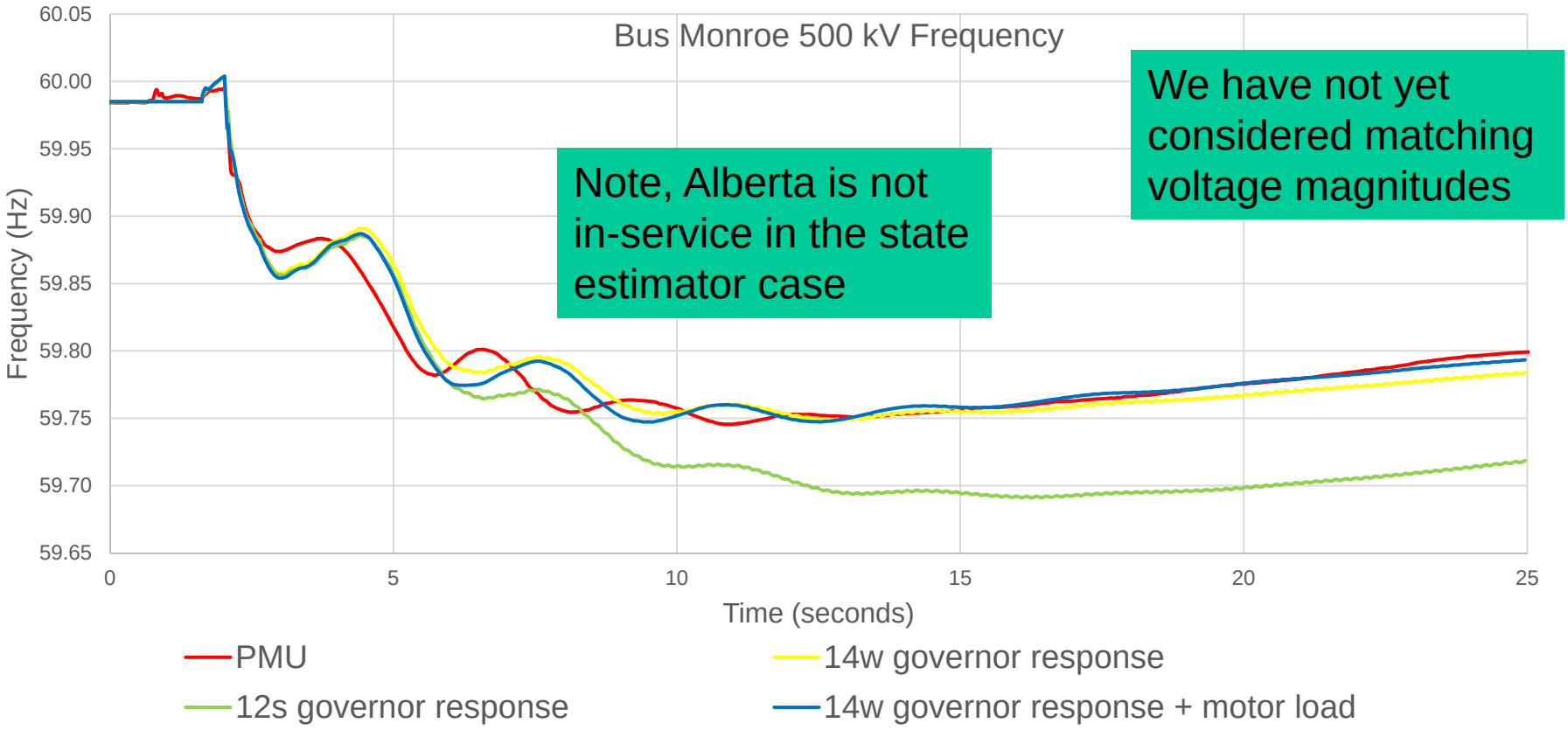
Validation

- January 29, 2014 Event PMU Data



Validation

- Validation Results – Jan 29 2014, 6:46 event



Sensitivity of parameters such as governor response limits and load models, to validation results

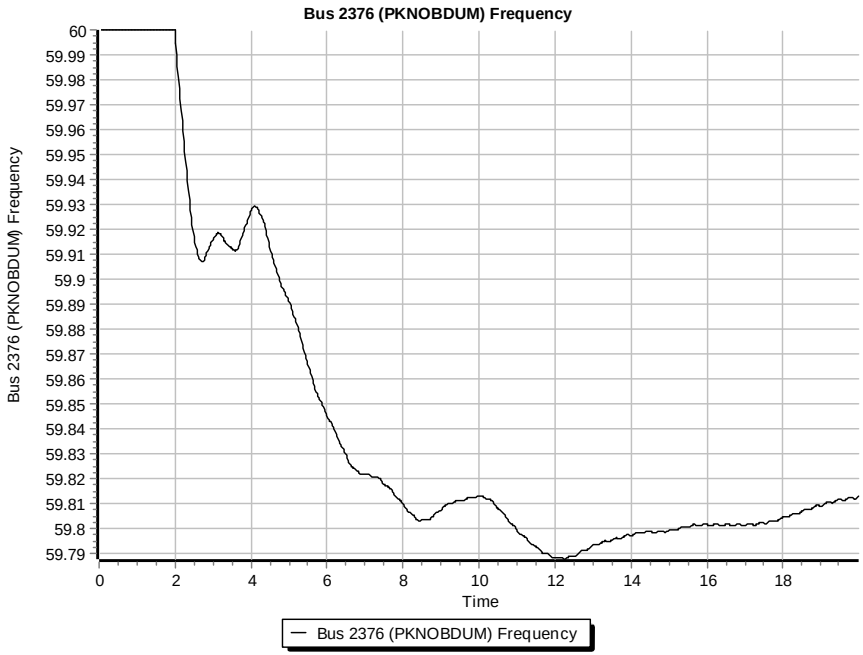
PowerWorld Frequency Analysis Techniques

- Partially based on this project PowerWorld has implemented two frequency domain analysis techniques
  - Fast Fourier Transform (FFT) and modal analysis using the variable projection method (VPM)[1]
  - Frequency domain techniques can be quite helpful in providing information about power system dynamic performance
  - Integrating the tools within transient stability should allow for convenient access

[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 a slight frequency oscillation in a transient stability run
  - The question is to figure out the source of the oscillation (in the bus frequency 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

- 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
- To understand the FFT, it is useful to start with a Fourier series, which seeks to represent any periodic signal, with frequency F=1/T, as a sum of sinusoidals with frequencies that are integer multiples of F, nF
  - DC is n=0, fundamental is n=1, harmonics n > 1

Fourier Series and Nonperiodic Functions

- Often the complete representation requires an infinite number of terms
- Example at right shows the Fourier series for a square wave, showing sequentially the first four terms
- Nonperiodic signals can be represented by letting T go to infinity; this gives a continuous Fourier Spectrum

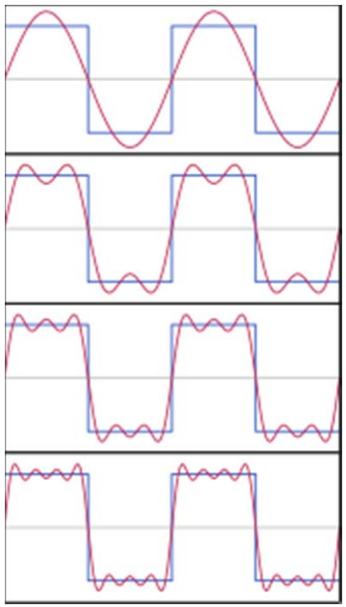
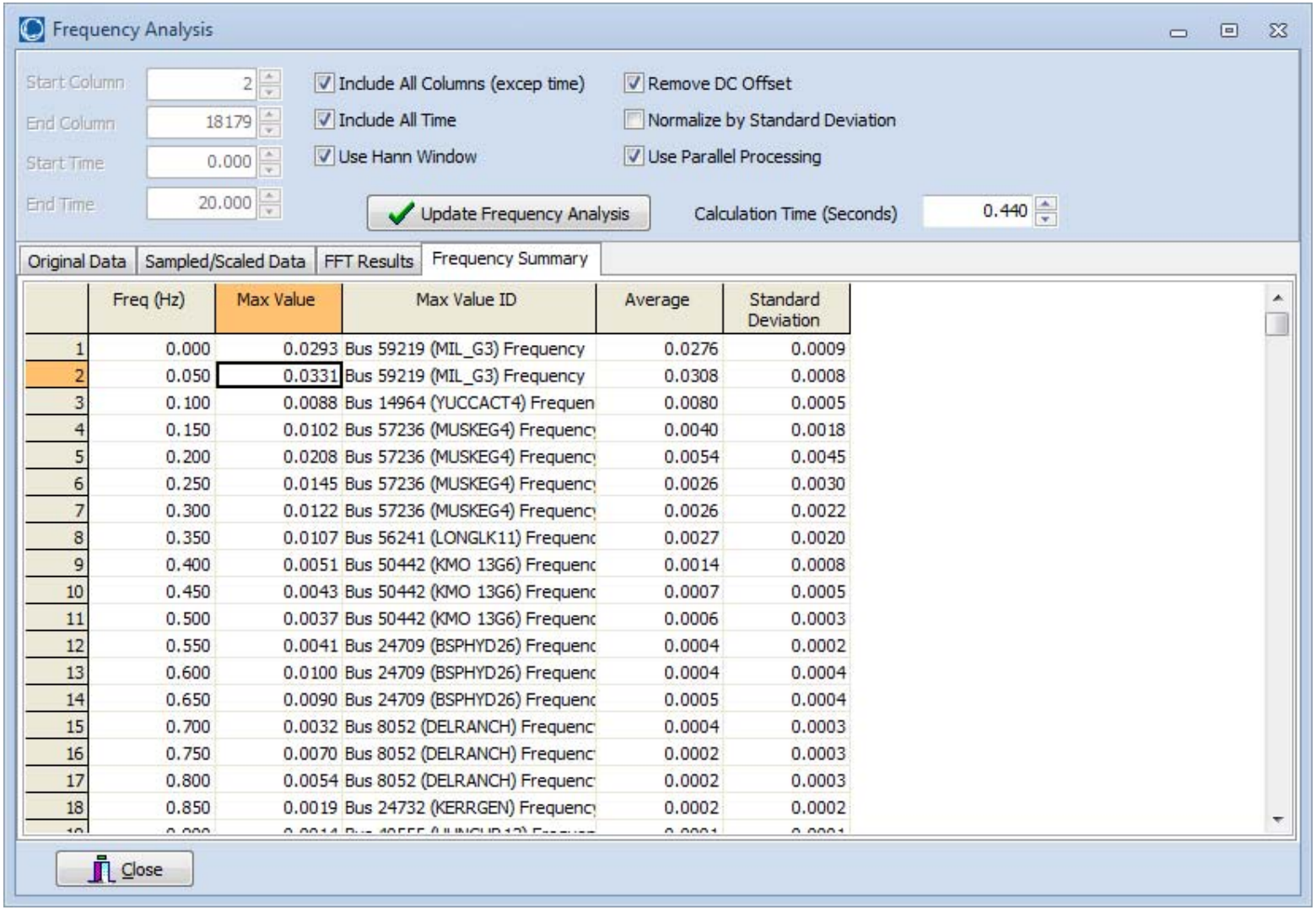


Image Source: wikipedia.org/wiki/Fourier_series

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
  - This works best when all the entries are of the same type, such as bus frequency

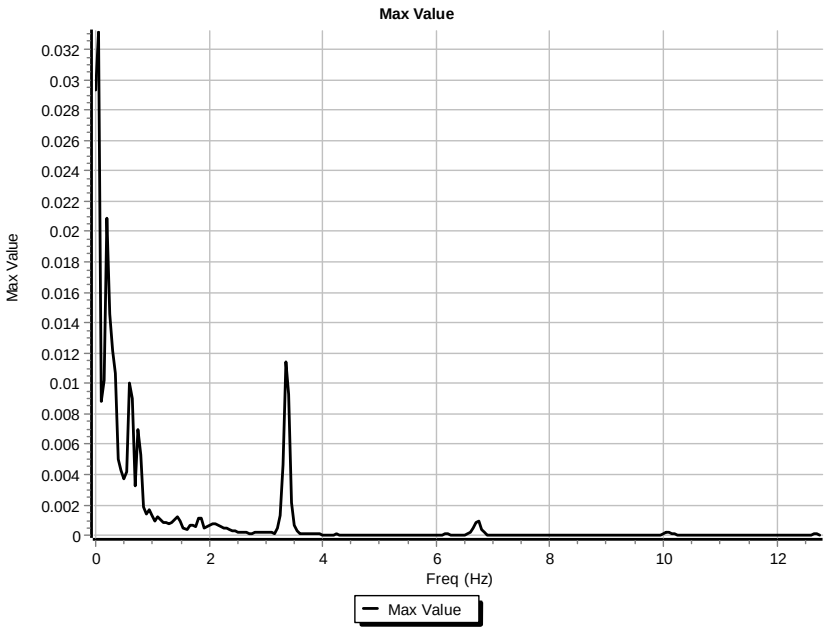
FFT Analysis Display



	Freq (Hz)	Max Value	Max Value ID	Average	Standard Deviation
1	0.000	0.0293	Bus 59219 (MIL_G3) Frequency	0.0276	0.0009
2	0.050	0.0331	Bus 59219 (MIL_G3) Frequency	0.0308	0.0008
3	0.100	0.0088	Bus 14964 (YUCCACT4) Frequen	0.0080	0.0005
4	0.150	0.0102	Bus 57236 (MUSKEG4) Frequenc	0.0040	0.0018
5	0.200	0.0208	Bus 57236 (MUSKEG4) Frequenc	0.0054	0.0045
6	0.250	0.0145	Bus 57236 (MUSKEG4) Frequenc	0.0026	0.0030
7	0.300	0.0122	Bus 57236 (MUSKEG4) Frequenc	0.0026	0.0022
8	0.350	0.0107	Bus 56241 (LONGLK11) Frequenc	0.0027	0.0020
9	0.400	0.0051	Bus 50442 (KMO 13G6) Frequenc	0.0014	0.0008
10	0.450	0.0043	Bus 50442 (KMO 13G6) Frequenc	0.0007	0.0005
11	0.500	0.0037	Bus 50442 (KMO 13G6) Frequenc	0.0006	0.0003
12	0.550	0.0041	Bus 24709 (BSPHYD26) Frequenc	0.0004	0.0002
13	0.600	0.0100	Bus 24709 (BSPHYD26) Frequenc	0.0004	0.0004
14	0.650	0.0090	Bus 24709 (BSPHYD26) Frequenc	0.0005	0.0004
15	0.700	0.0032	Bus 8052 (DELRANCH) Frequenc	0.0004	0.0003
16	0.750	0.0070	Bus 8052 (DELRANCH) Frequenc	0.0002	0.0003
17	0.800	0.0054	Bus 8052 (DELRANCH) Frequenc	0.0002	0.0003
18	0.850	0.0019	Bus 24732 (KERRGEN) Frequenc	0.0002	0.0002

FFT Analysis Display

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



With about 840 time values, and 18,000 signals (bus frequencies in this example), the FFT takes about six seconds

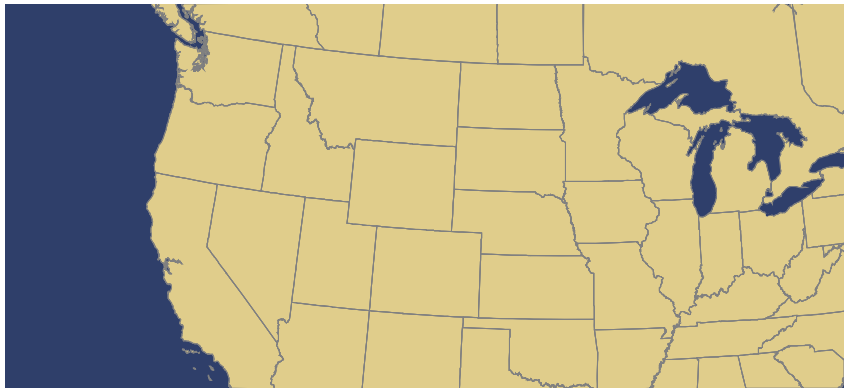
The Frequency Summary Page provides the ID of the signal with the largest component for each frequency

Geographic Data Views

- Since about 2007 PowerWorld Simulator has had functionality for what we call Geographic Data Views (GDVs)
  - Original functionality described in paper, T.J. Overbye, "Wide-area power system visualizations with geographic data views," IEEE PES 2008 General Meeting, Pittsburgh, PA.
- Idea of GDVs is for cases with geographic information for the buses (or substations) the power system information can be visualized on auto-created one-lines
  - Did not catch on because at the time few cases had the necessary geographic information
  - This is now changing, so PowerWorld is refreshing the concept

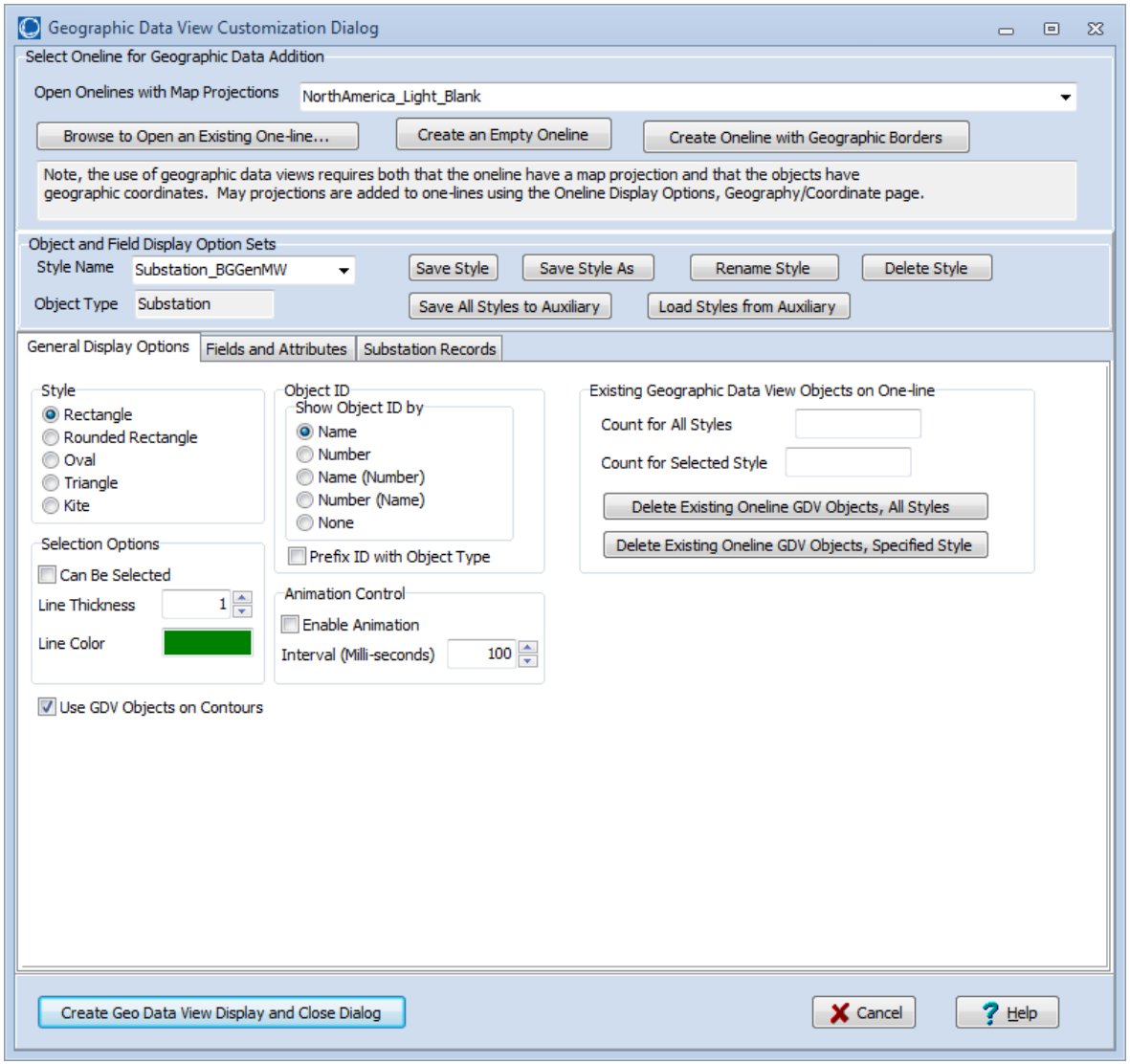
GDV Process

- Starting point is a case with latitude/longitude values, and a map-based usually empty one-line (can be provided by PowerWorld)
- From a case information display with geo-linked objects, like substations, select fields of interest, and then right-click and select Geographic Data View



- This displays the Geographic Data View Customization Display
  - Used to specify the attributes for the auto-inserted GDVs

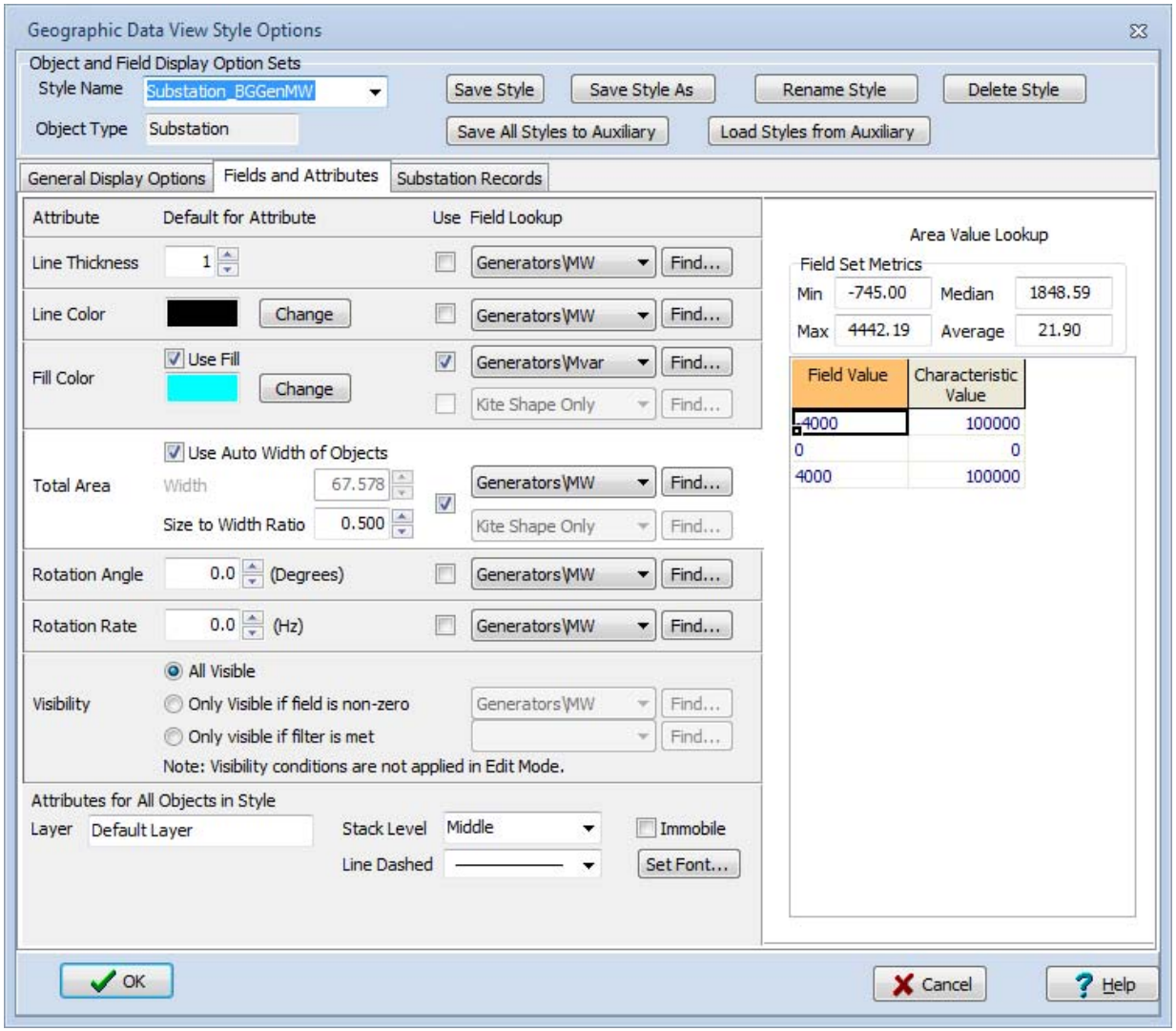
Geographic Data View Customization Display: General Display Options



A one-line needs to be selected, but it need to be initially open

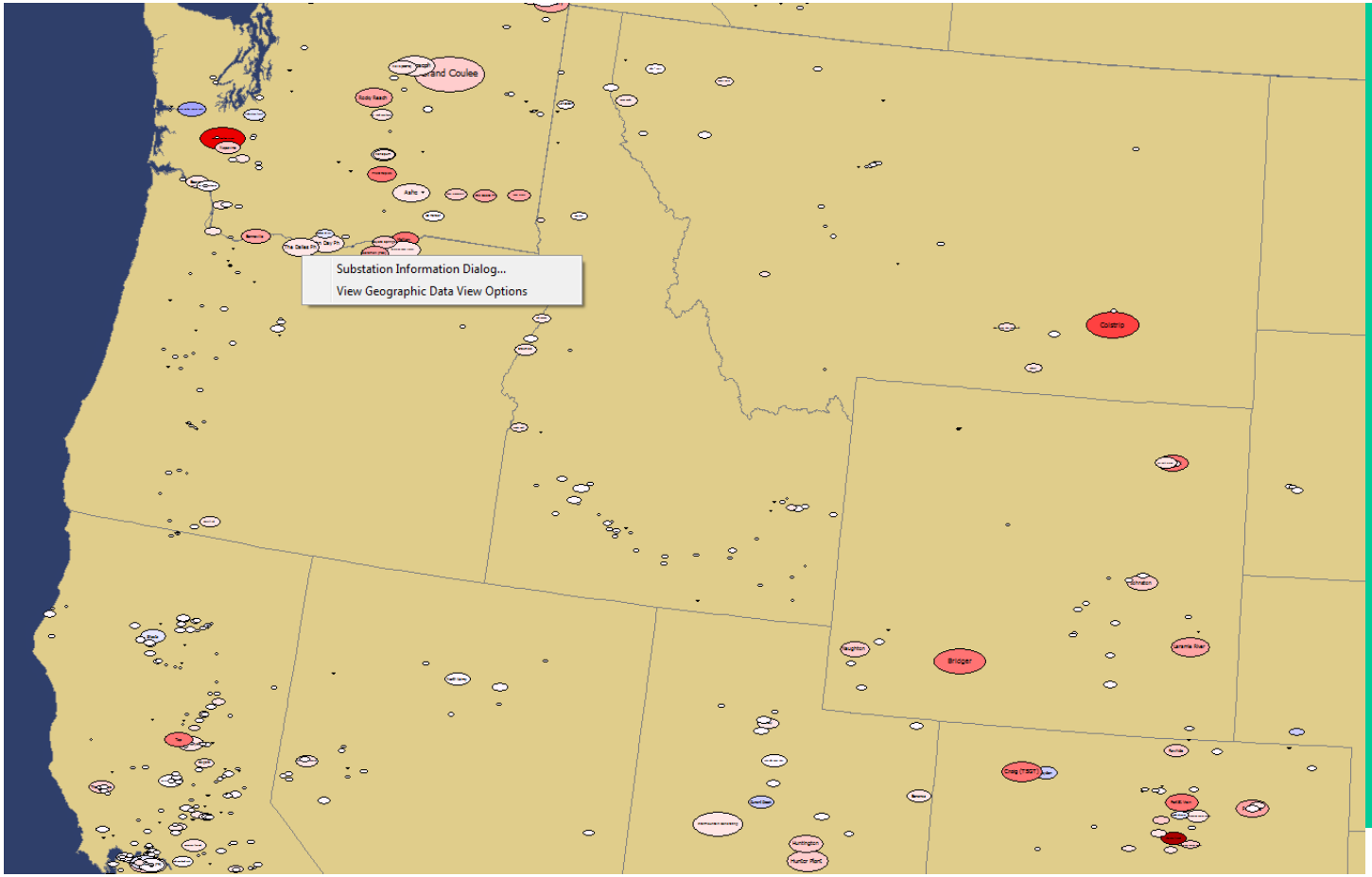
Use the Fields and Attributes Page to customize the display objects

Geographic Data View Customization Display: Fields and Attributes



Different attributes can be used to visualization different object values

Example WECC GDV

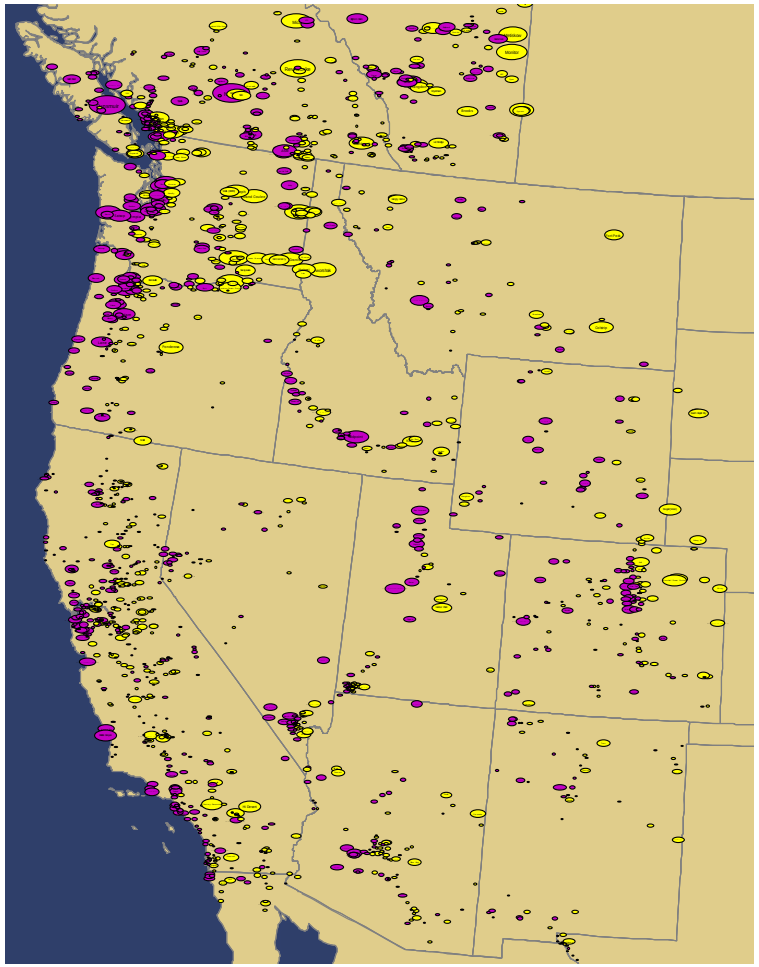


Here the display objects are linked to the substations; size is proportional to MW generation, color to Mvar generation

Right-clicking on an object allows object to either see the substation dialog, or view the Geographic Data View Options

Example WECC GDV Showing GICs

- Below is same display, modified to show substation GIC amps to neutral (size), and direction (color)
- GDVs are standard PowerWorld one-lines, so they can be saved, objects moved around, and reused
- GDV attributes (i.e., the key) are always available by right-clicking
- They also support contouring



North America Load/Generation Map

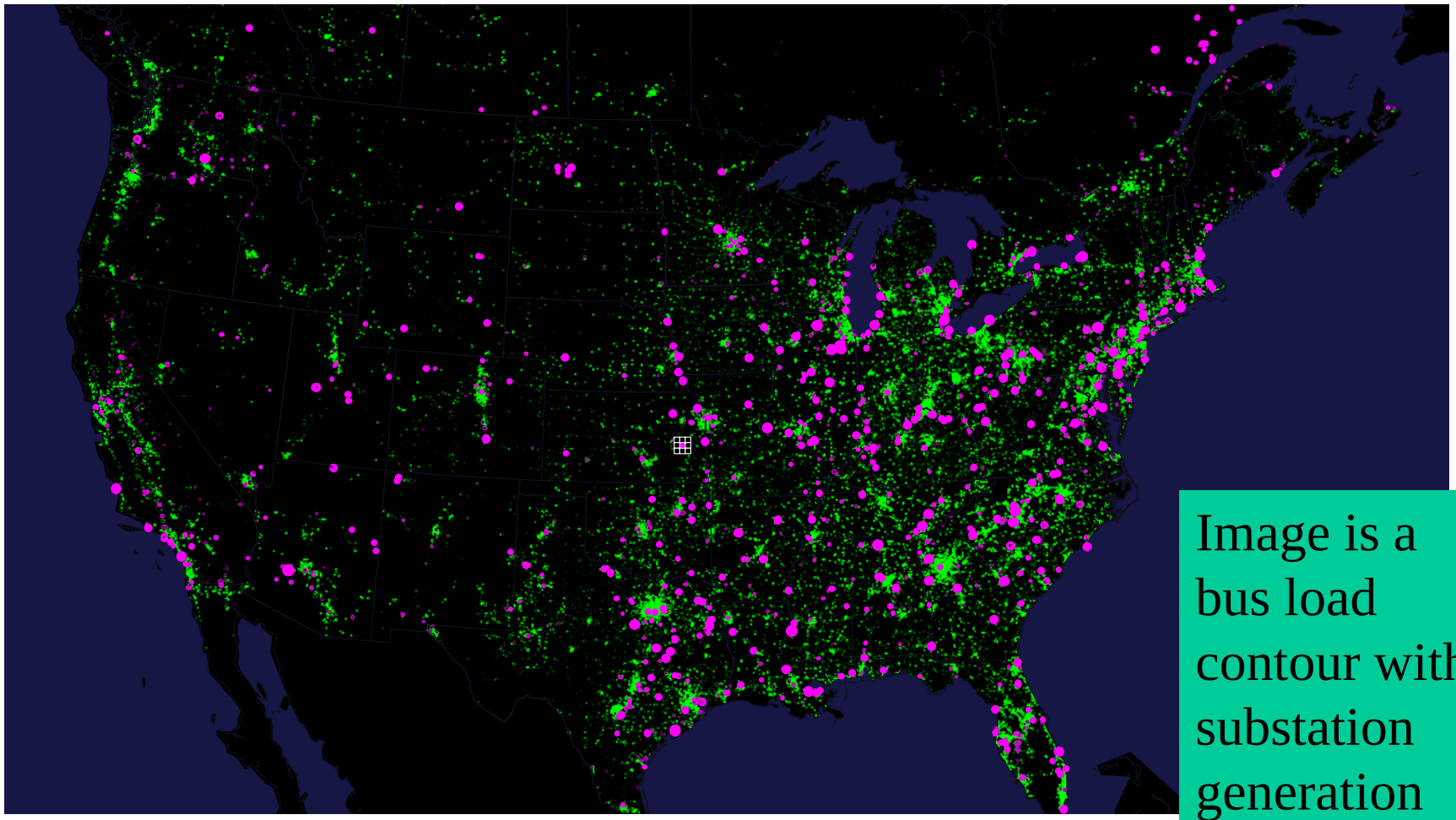


Image is a bus load contour with substation generation GDVs

Thank You!

Questions?