RECLAMATION
Managing Water in the West

NERC and WECC Generator Testing and Modeling Requirements

Final Research Report

U.S. Department of the Interior
Bureau of Reclamation

July 2014

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Abstract

The Power System Analysis and Controls Group performed research on behalf of the Program Services Office. Hydropower generation is the foundation for grid stability; therefore, hydro generator control systems need to become even more reliable than in the past. To accurately simulate the dynamic response of a generator under disturbance conditions, it is essential to have accurate models of machines and their control systems. The development of new digital signal processing techniques and computer tools will drastically improve the computer modeling needed to benefit generator and grid stability.

Disclaimer

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1.0 INTRODUCTION

The Power Systems Analysis and Control Group performed research in the area of improved power generation "North American Electric Reliability Corporation (NERC) and Western Electricity Coordinating Council (WECC) Generator Testing and Modeling Requirements". The research questions asked consisted of: Can we increase the efficiency in obtaining data and validating models, thereby saving Reclamation a significant amount of money and resources? More specifically, can common digital signal processing techniques and/or computer software tools, which are currently being used in other applications and arenas, be applied to generator control systems for better determining powerplant model structure and parameters? Also, can the data required for model validation be collected by online monitoring systems instead of sending test engineers to collect the data? This would ultimately save money by not needing to take generation outages to collect the data.

The role of power generation in power system reliability is becoming increasingly complex as the power grid grows and diversifies. Hydropower generation is the foundation for grid stability in Western North America; therefore, hydro generator control systems need to become even more reliable than in the past. Reclamation operates many hydropower generators that can benefit from better signal processing techniques and computer software tools to keep up with current and future standards and to help better support the western power system (or grid). These new techniques/software tools will improve current practices of data collection and signal manipulation for easier tuning and generator/controller modeling. These techniques/software tools are custom designed to be more precise for generator control system testing than anything that can be purchased "off the shelf." This will benefit generator and grid stability as well as computer modeling of these systems.

To accurately simulate the dynamic response of a generator under disturbance conditions, it is essential to have accurate models of machines and their control systems. In response to this, research has been performed on model parameter identification of excitation and governing systems. However, the current and future standards implemented by NERC/WECC for modeling are becoming more stringent and demand better data collected from field testing. The development of new digital signal processing techniques/software tools will drastically improve the computer modeling.

2.0 ONLINE FREQUENCY RESPONSE

One of the standard field tests when commissioning a new excitation system at a hydroelectric powerplant is to perform frequency response measurements of the generator control systems while running both offline and online under load. For this test, a variable frequency signal is fed into the exciter input and the resulting ratios of this input to the generator output provides valuable information that is unique to each generator-excitation control system. This data can then be used to develop or verify computer models of the system. In the past, frequency response data of a generating unit running offline has been very valuable in the model validation process, however, it offers an incomplete validation of the plant model since its reaction with the power system is not examined.

This year, code was developed for simulating the online frequency response test. The code is used in a software package which simulates large power interconnections, so the tests of a single unit connected to the power system can be simulated with the same conditions as when the tests were actually conducted. The developed code creates a swept sine (variable frequency) signal which is inserted into the appropriate exciter model input and the corresponding generator output is recorded. The data is mathematically manipulated at each time step and the final product is data that can be graphed on a Bode plot and compared to field test data. The figures below show the raw simulated data as well as the calculated model data versus measured field test data.

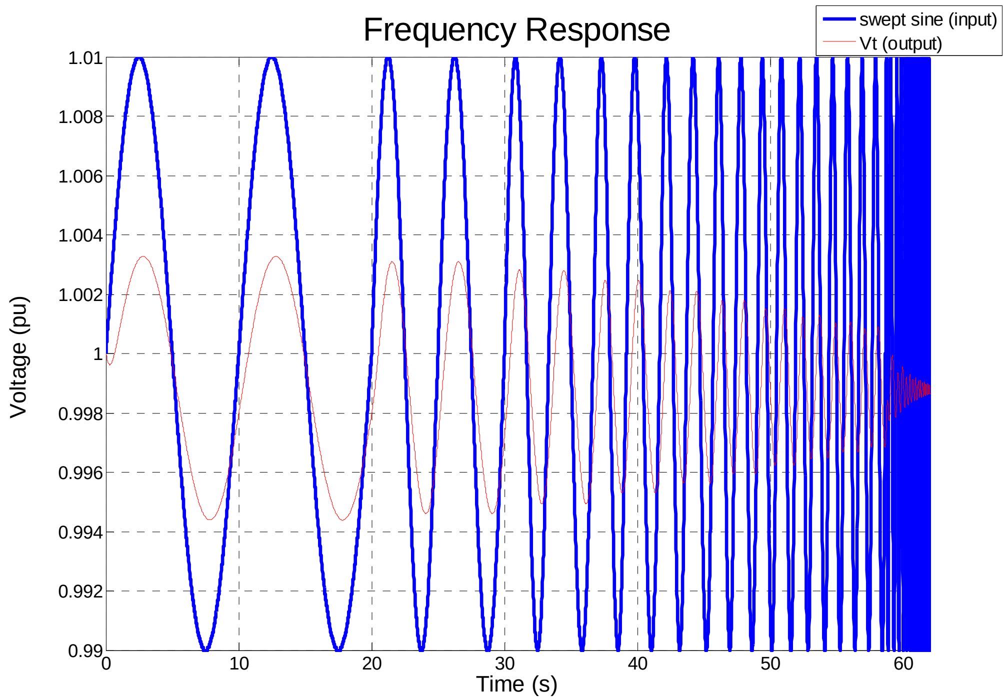

Figure 1 - Raw input and output simulated data

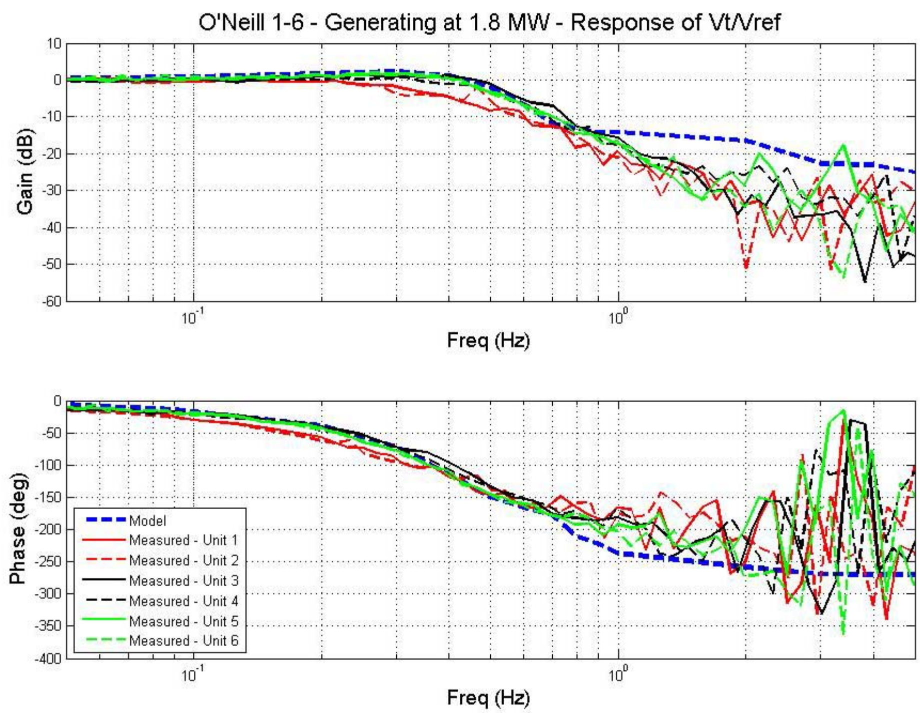

Figure 2 - Online Frequency Response model data versus measured data

3.0 MODEL VALIDATION FROM ONLINE DISTURBANCE DATA

According to requirements from WECC, models of powerplant generators, governors, exciters, and turbines must be developed, validated, and submitted for all generators 10 MVA and larger or for facilities 20 MVA and larger. These models must also be updated every 5 years or when equipment is modified. Typical model validation work includes sending a team of test engineers to the facility to run a series of tests on each piece of equipment, record the data, and bring it back to the office for processing. This data is used to develop models for each piece of equipment and each field test is replicated in the models and compared to the field test data. However, if models have been previously developed and just need to be re-confirmed, less field data is necessary. All that is needed is a situation that causes a dynamic response from the piece of equipment that can be replicated with the models. This can be done through the traditional manner of sending a team of test engineers to the field to collect data, followed by replicating all field tests using the models. However, if the powerplant has online “disturbance” monitoring systems that record critical data (power, voltage, current, frequency, etc.), snapshots of power system disturbances can be used for comparison to simulations of the same disturbances to re-confirm the existing models.

This new process was developed using disturbance data from online monitors at Yellowtail Powerplant. Disturbance data used in this process included:

- Chief Joseph Brake test (an extremely large resistor in the Pacific Northwest is closed for a few cycles and then reopened): this type of disturbance results in a response in the exciter and generator and therefore can be used to validate both models.
- Various loading and ramping points: this data was used to develop the turbine gate versus power curve as well as the saturation factor (Kis) for the generator.
- Large generation trips: this results in a system frequency drop to which the governor control system responds to by increasing power.

Unfortunately, this newly developed process could not be fully tested as it was determined that the recorded signals from the online monitors were inaccurate (incorrect scaling and/or offsets) and too slow (sampling rate was too low). Therefore, while the development of the process has been performed, it could not be fully tested due to poor quality data. There are now plans to recalibrate and improve the existing online monitoring system at Yellowtail Powerplant. After this has been performed, this process can be fully tested.

Below are examples of measured disturbance data compared to model replicated data for Yellowtail Powerplant. Some of the plots do not match well, but this is due to the poor quality of the measured data from the online monitors. These plots are included to illustrate the process that has been developed and the type of disturbance data that is used.

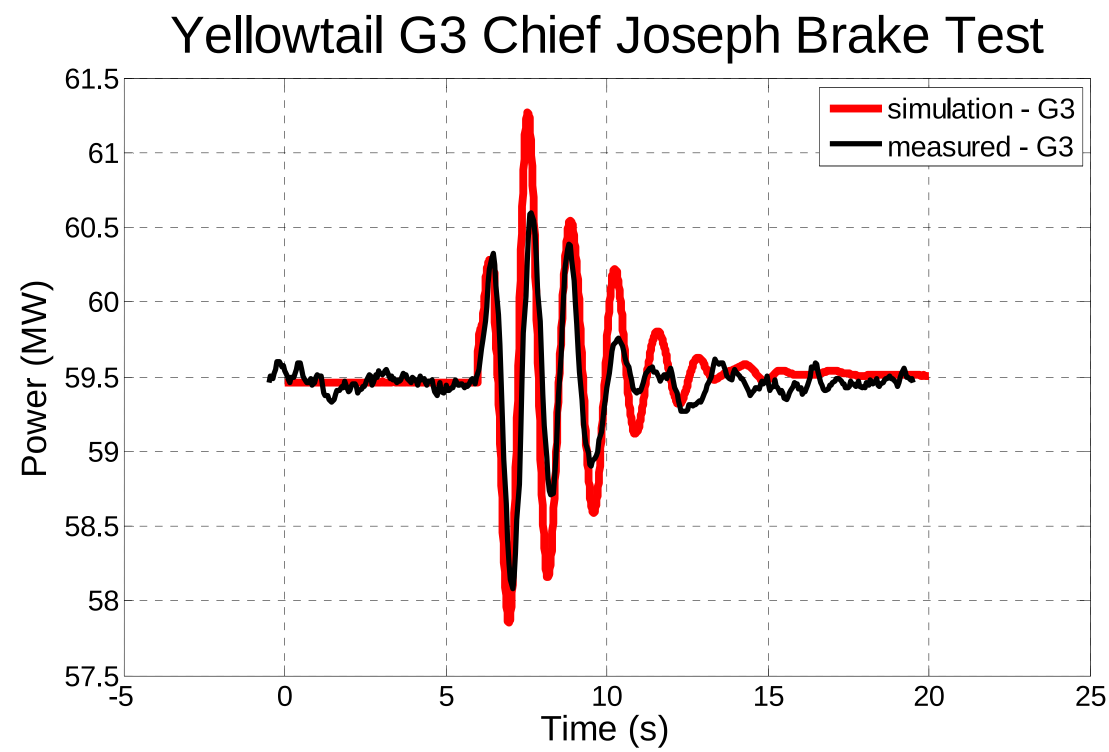

Figure 3: Chief Joseph Brake Test - Measured data compared to simulated data – Generator power (MW).

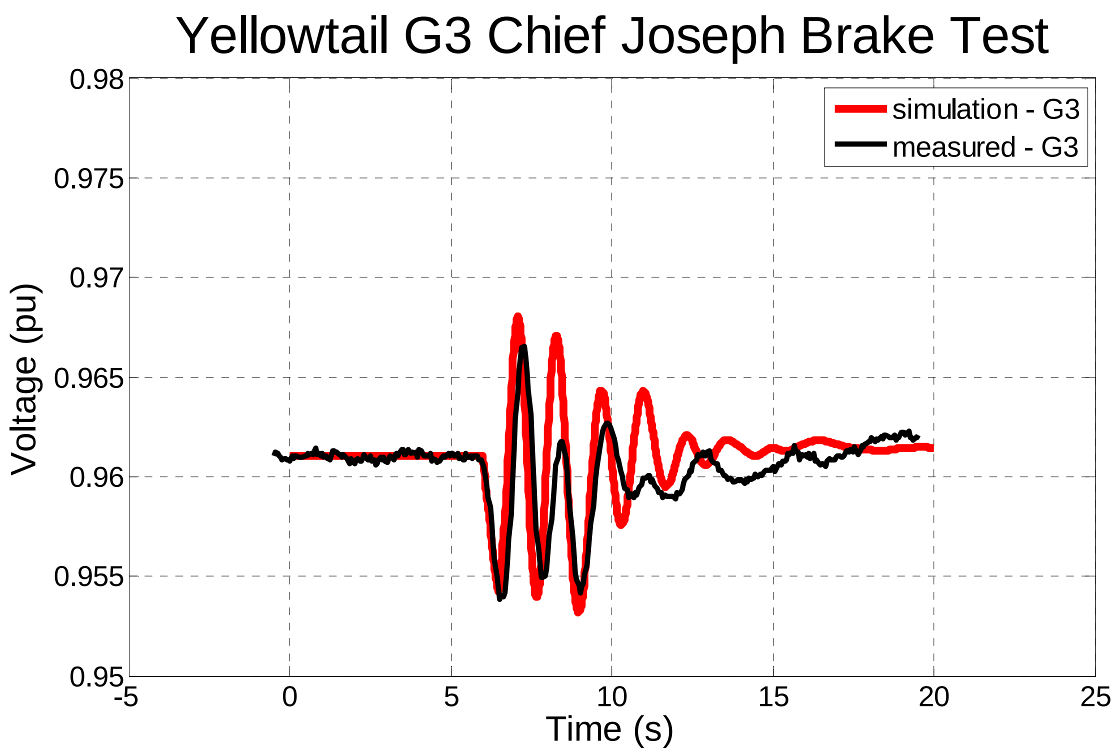

Figure 4: Chief Joseph Brake Test - Measured data compared to simulated data – Generator terminal voltage.

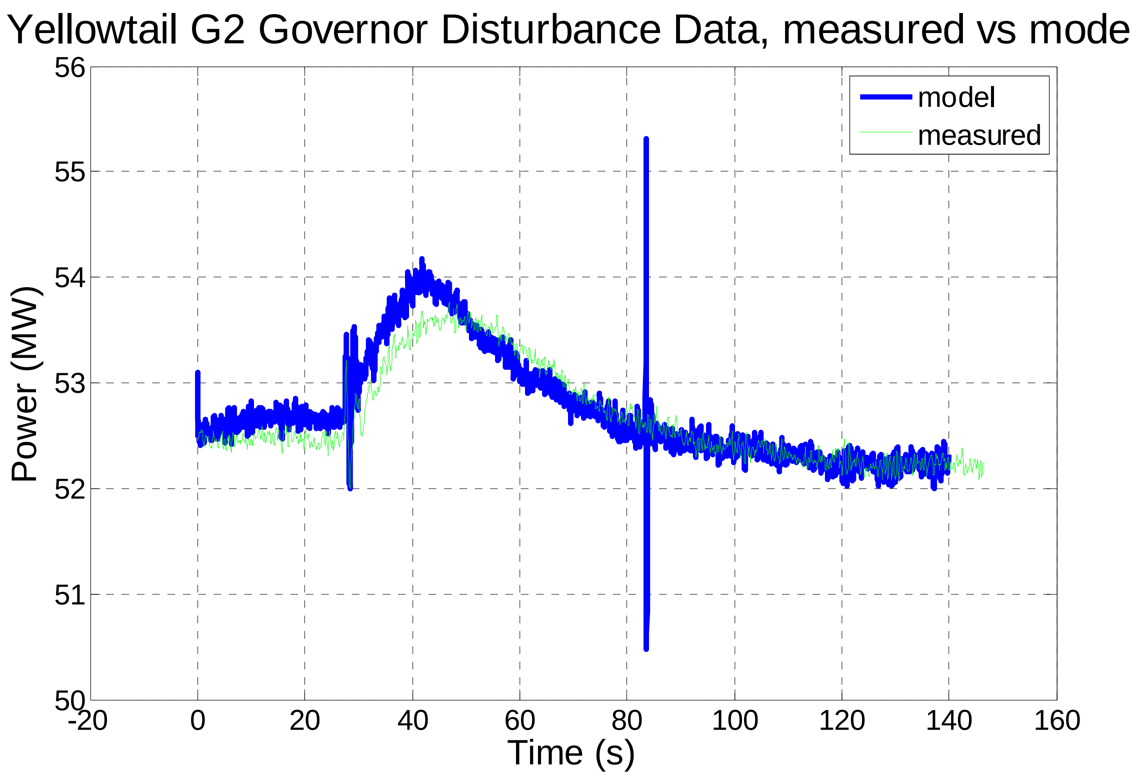

Figure 5: Local drop in generation resulting in a drop in frequency which results in a governor response - Measured data compared to simulated data – Generator power.

4.0 MODEL VALIDATION EXCITER STEP RESPONSE

During normal WECC testing for model validation (described in the section on "Model Validation from Online Disturbance Data", above), step response tests are performed by inserting a 1% change in voltage into the exciter input and measuring the exciter field voltage and generator terminal voltage responses. At Nimbus Powerplant, this typical 1% step response test was performed as well as additional research tests of 2%, 3%, and 4% magnitudes. This was done in an effort to determine if simulated model step responses match measured data just as well for larger step responses as they do for the standard 1% step response.

The results in this particular case illustrate that there are some subtle differences for variation in step sizes, likely due to nonlinear behavior of the power electronics. In this case, the differences are tolerable, and it is possible that the control circuitry in this model of equipment corrects for some of the nonlinear behavior, as it ideally should. However, examples have been found, such as the Glen Canyon excitation equipment, where the control circuitry does not compensate for the bridge circuit nonlinearity, which results in slightly different responses for different input magnitudes, and is also very apparent when comparing positive responses against negative ones, as shown.

The comparison of the measured versus modeled data for the various step sizes proved that the standard 1% step size is adequate for most model validation work. This must be ascertained for each model of equipment that we encounter in the future. Additional information can be gained by also recording larger step responses, namely, the ceiling and floor limits of the exciter.

When larger step responses were performed, the exciter hit upper or lower limits. These values are typically calculated, but not tested during model validation work. By performing additional larger step responses these values can be proven in the test results and then used in the models.

Below are examples of varying sizes of step responses for measured and modeled data:

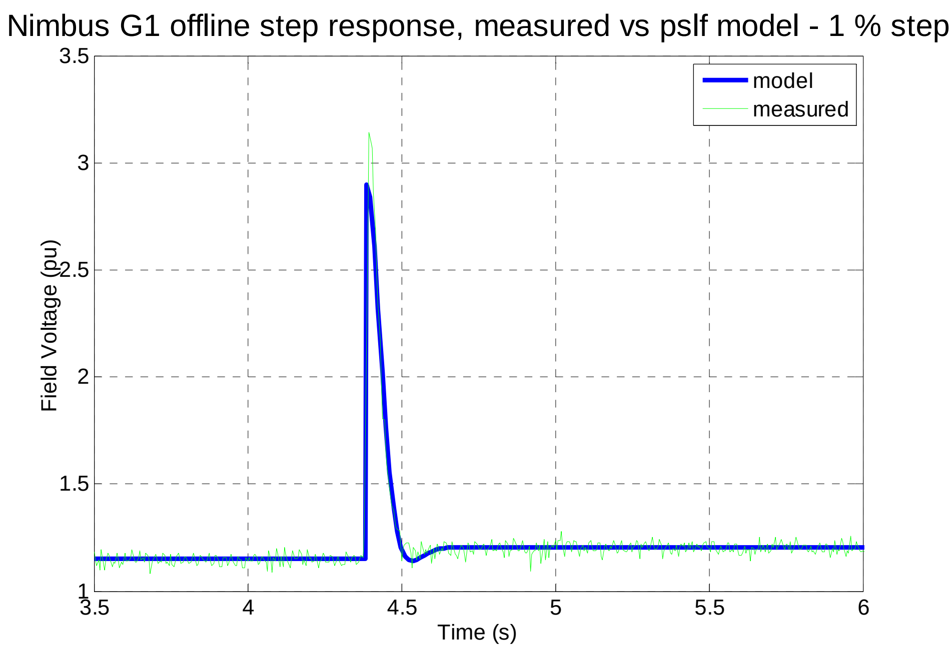

Figure 6 - 1% Step Response - Measured Test Data versus Calculated Model Data – Field Voltage Response

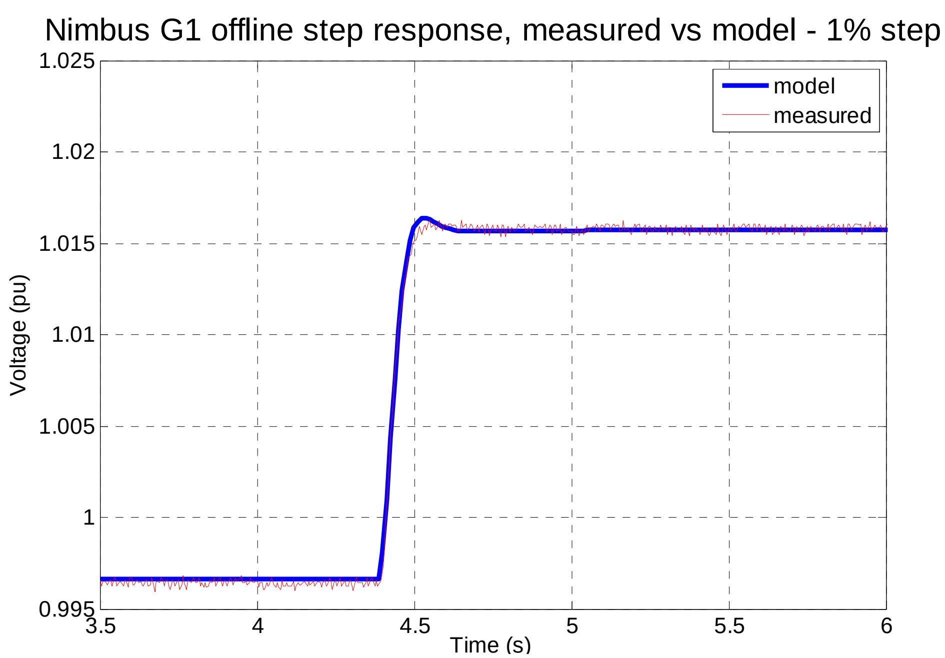

Figure 7 - 1% Step Response - Measured Test Data versus Calculated Model Data – Terminal Voltage Response

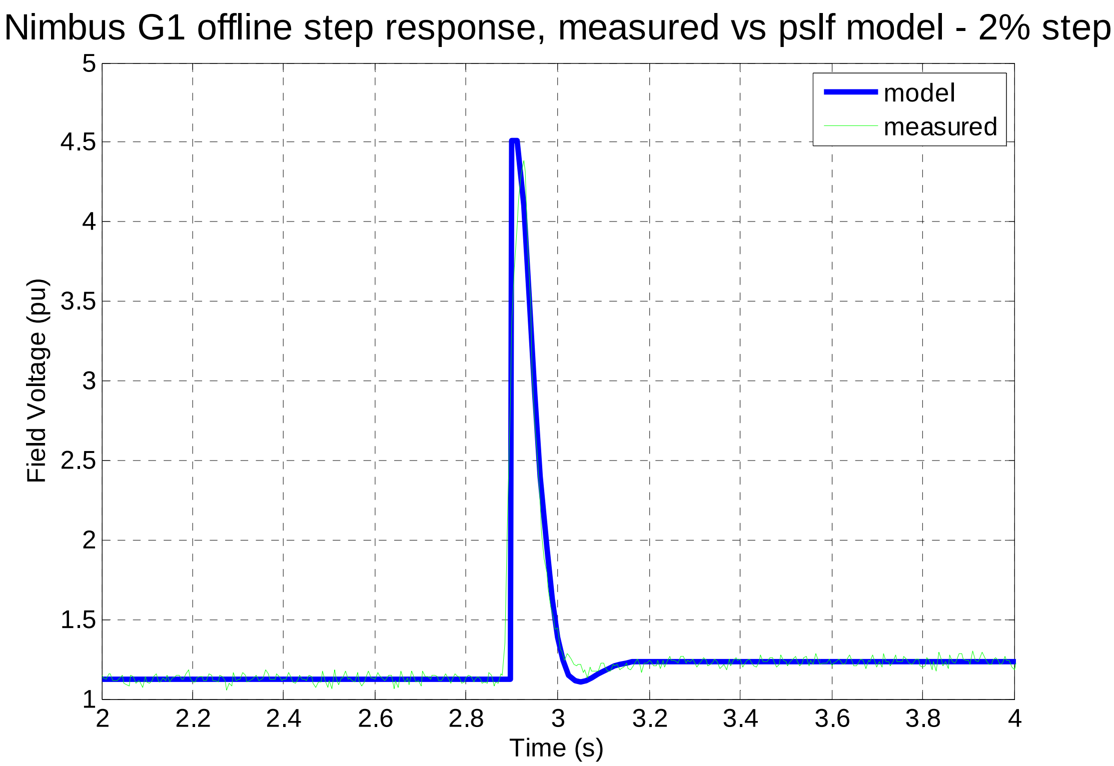

Figure 8 - 2% Step Response - Measured Test Data versus Calculated Model Data – Field Voltage Response

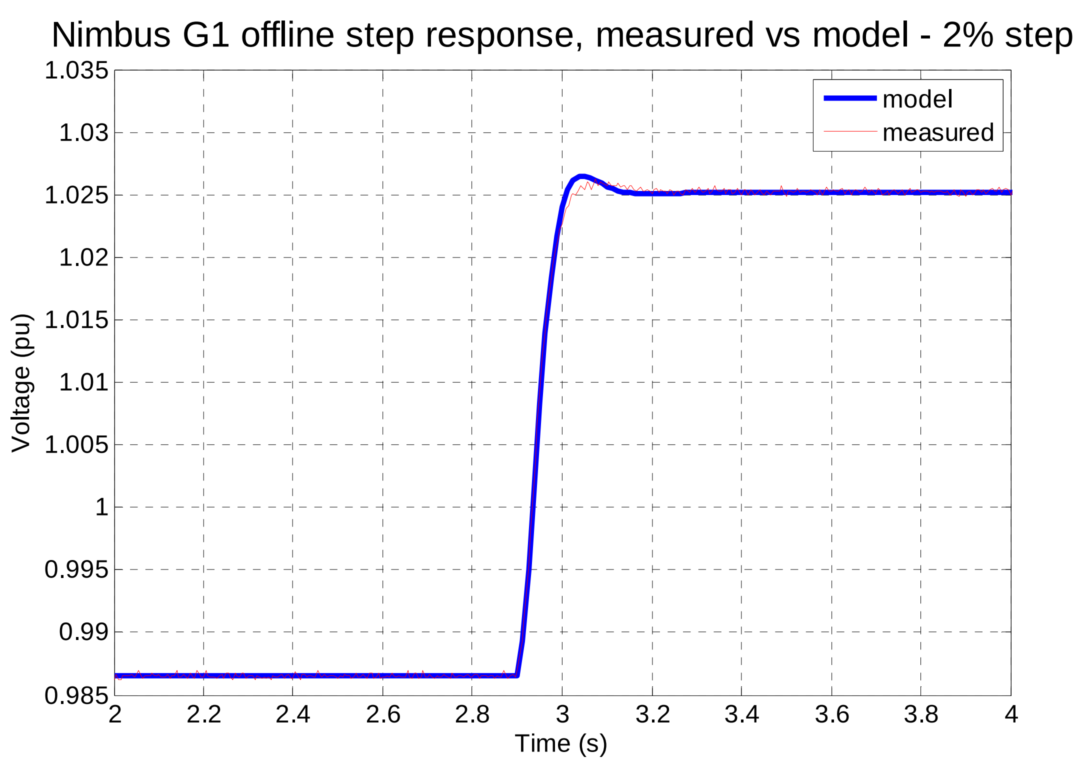

Figure 9 - 2% Step Response - Measured Test Data versus Calculated Model Data – Terminal Voltage Response

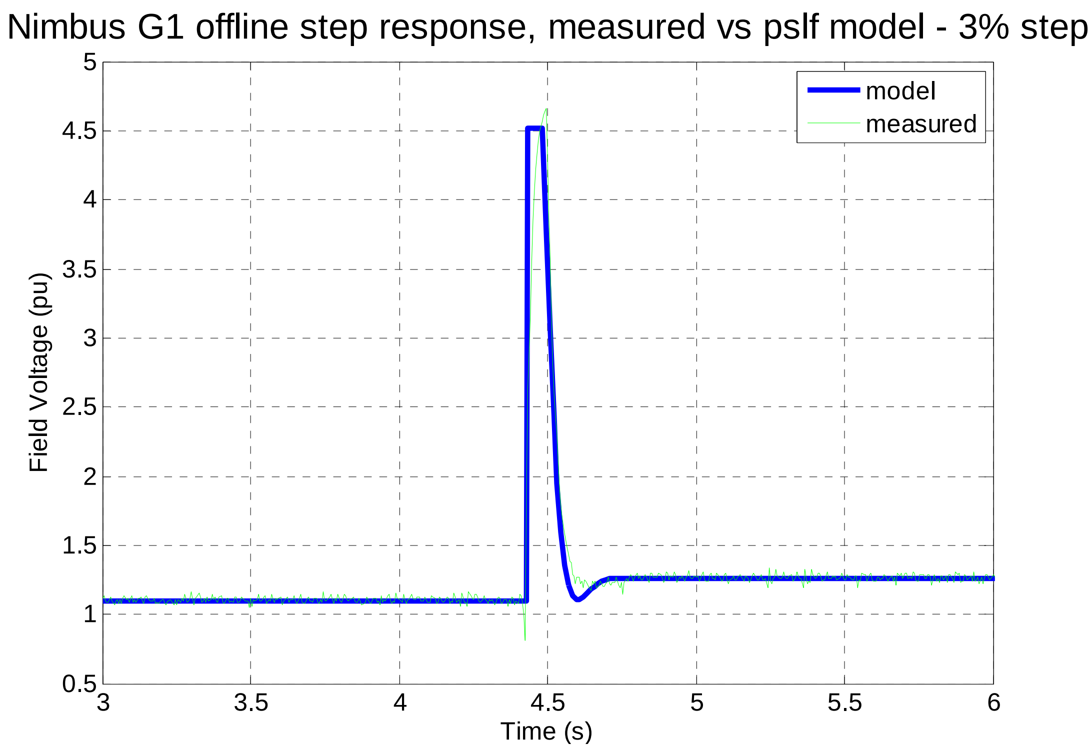

Figure 10 - 3% Step Response - Measured Test Data versus Calculated Model Data – Field Voltage Response

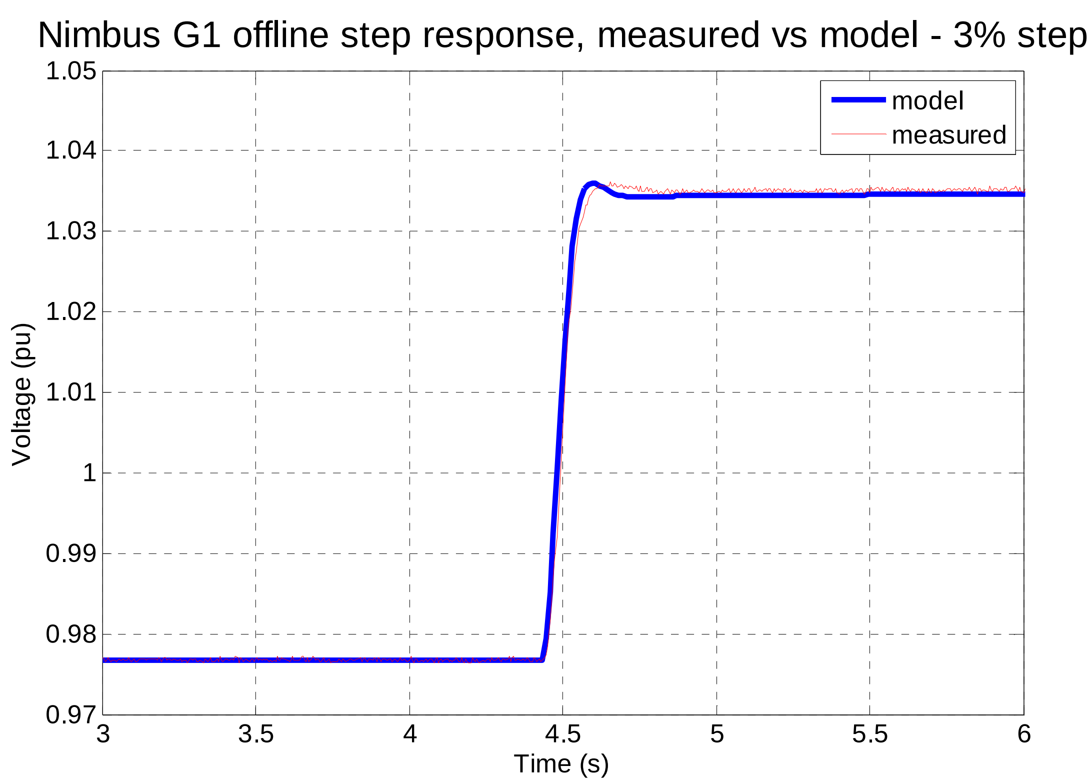

Figure 11 - 3% Step Response - Measured Test Data versus Calculated Model Data – Terminal Voltage Response

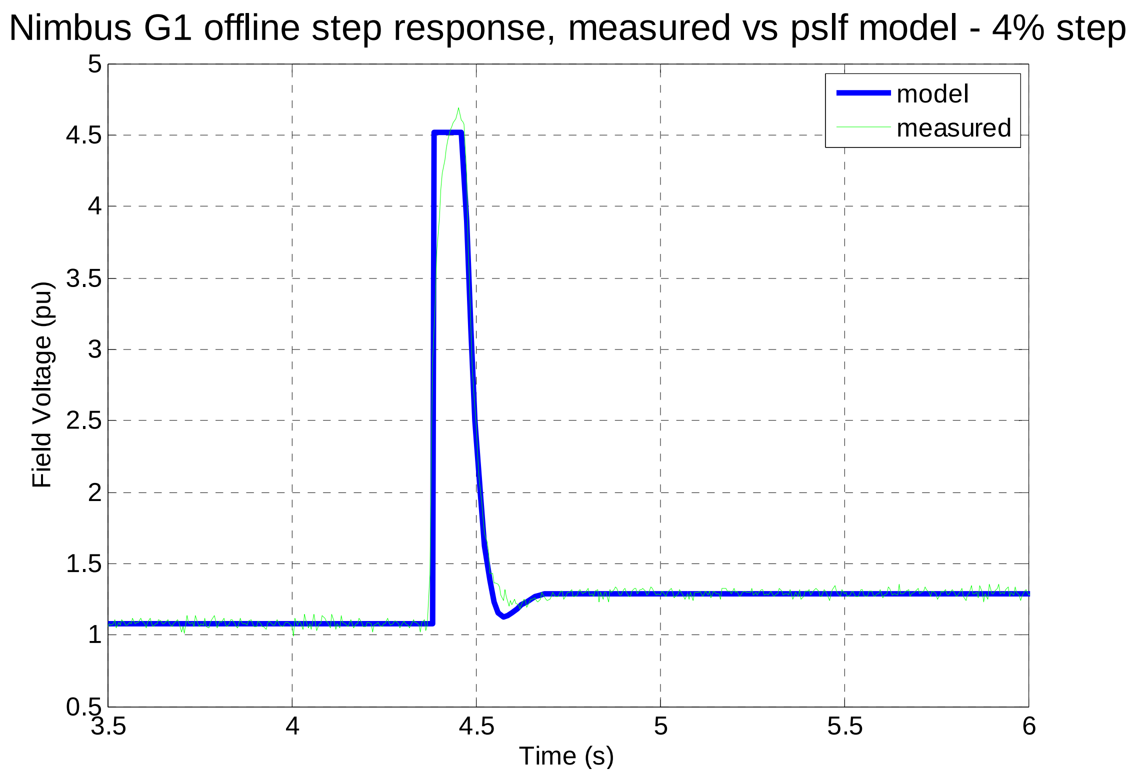

Figure 12 - 4% Step Response - Measured Test Data versus Calculated Model Data – Field Voltage Response

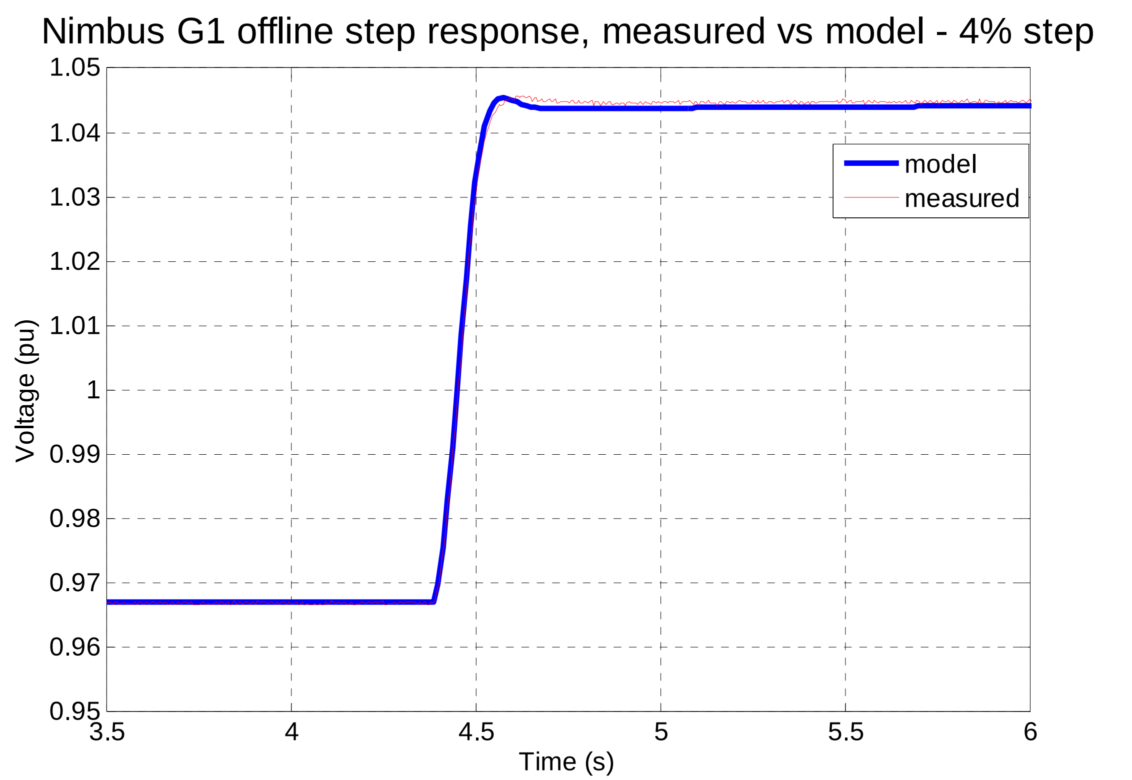

Figure 13 - 4% Step Response - Measured Test Data versus Calculated Model Data – Terminal Voltage Response

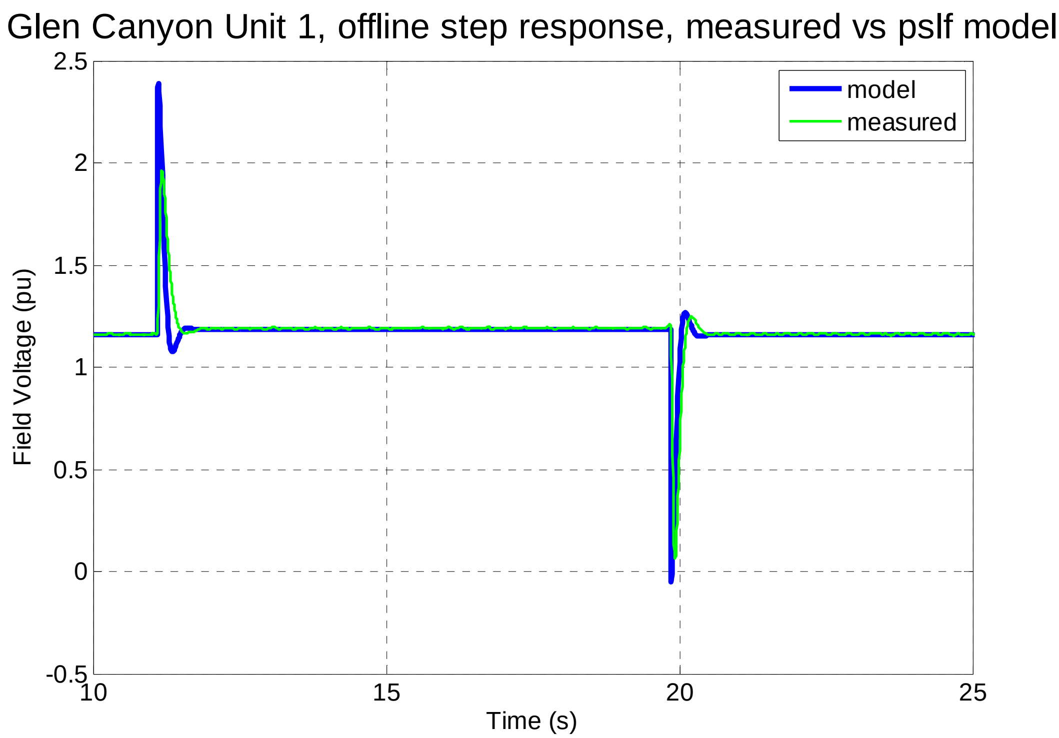

Figure 14 - Offline Step Response - Measured Test Data versus Calculated Model Data - Field Voltage Response

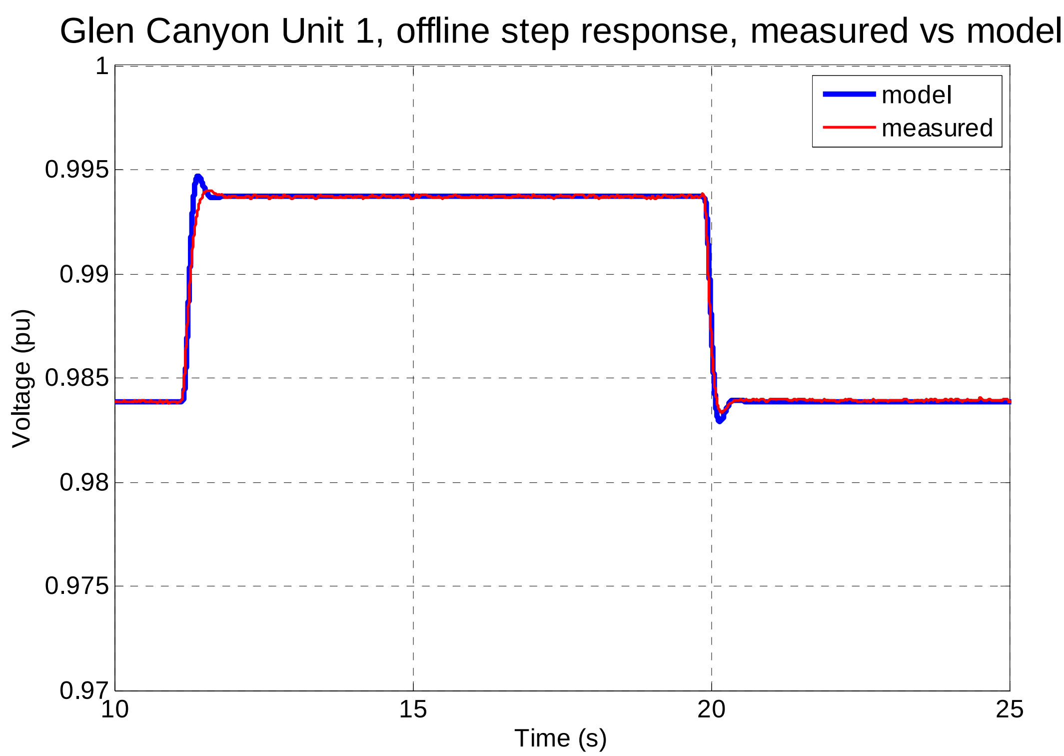

Figure 15 - Offline Step Response - Measured Test Data Versus Calculated Model Data - Terminal Voltage Response

5.0 DATA ANALYSIS TOOLS – TIME DOMAIN AVERAGING TECHNIQUE

One area that presents problems during the data analysis portion of generator model validation is choosing a step response from recorded data that closely represents the actual response of the generator. Many step responses can be recorded, but all may vary due to system disturbances and/or random noise that can occur while collecting the data. Typically the step response that appears to be the best quality is extracted, but many times it does not represent the actual settings very well. When examined more closely looking for the general shape of the majority of the step responses, then choosing one that follows that trend, the model seems to match the step response data more closely. Based on this process we developed a digital processing technique to eliminate power system disturbances and random noise in the step response data. The technique also helps to determine what the actual step response should look like to closely resemble the generator to be modeled. The time domain averaging technique we developed operates by taking a series of step responses, all recorded at the same operating point, lining the data up based on each reference step signal, overlaying the data as shown in Figure 16, and applying an averaging algorithm. One key feature of this algorithm is that it does not affect the phase response or overall shape of the response as would occur by simply filtering each response individually.

Figure 16 - Multiple Step Responses Overlaid

5.1 Time Domain Averaging Technique Algorithm

1. Locate all step responses included in the bounds of the data set to be analyzed.

2. Precisely align all step responses and sort the data to later be used to calculate the average signals.

3. Calculate the average values for each signal of the step response. The average value for each index can be calculated by simply summing the data points for each step response at a specific index and dividing the result by the number of step responses used to calculate the average value. This process is then repeated across all indices of the signal data sets.

4. The results consist of an array containing average values for each signal of the step response.

5. Save and/or plot the averaged time-domain step response.

5.2 Time Domain Averaging Technique Examples

Three examples have been included to illustrate the effectiveness of the time-domain averaging algorithm. In each example the first figure shows the raw responses in the plot furthest to the left and shows the average response of all the selected responses in the plot on the right. The left hand plot is intended to provide the user with the ability to quickly determine any outlying responses that may need to be removed from the average response to eliminate any unnecessary noise caused by random noise and/or power system disturbance signals. The user can discard responses by simply unchecking the check box in the upper right hand corner of the window that corresponds to the response(s) to be discarded. Then the step response averaging tool can be run again without the obvious outlying responses.

The first figure for each example shows all the raw responses on the left plot and the average response on the right plot. All responses were included in this figure to show what the raw responses and average response look like before the user discards the outlying response(s).

The second figure for each example shows only the selected raw responses on the left plot and the average response for the selected responses on the right plot. This figure was included to show the average response of only the consistent trending responses containing no or very minor outlying data points.

The first example is shown in Figures 17 (All Responses) and 18 (Selected Responses) and contains a minor system disturbance in the dark blue Field Current trace on the left plot of Figure 17. Close observation of the average Field Current trace on the right plot yields a slight dip in the response just after the increasing step begins to settle out. Whereas, in Figure 18 the dark blue response has been discarded and the slight dip in the average Field Current response has been removed as a result.

The second example is shown in Figures 19 (All Responses) and 20 (Selected Responses) and contains system disturbance signals in the Terminal Voltage traces and large random noise signals in the Field Current traces. As in the first example these figures clearly illustrate the effectiveness of removing these noise signals yielding a cleaner average response.

The third example is shown in Figures 21 (All Responses) and 22 (Selected Responses) and contains moderate levels of random noise and severe levels of system disturbance signals on both the Bridge Voltage and Terminal Voltage traces. These figures also illustrate the effectiveness of the tool for even removing more severe levels of system disturbance noise signals. It should be noted that, better results can be obtained by including a higher number of responses to be averaged to remove more of the noise signals.

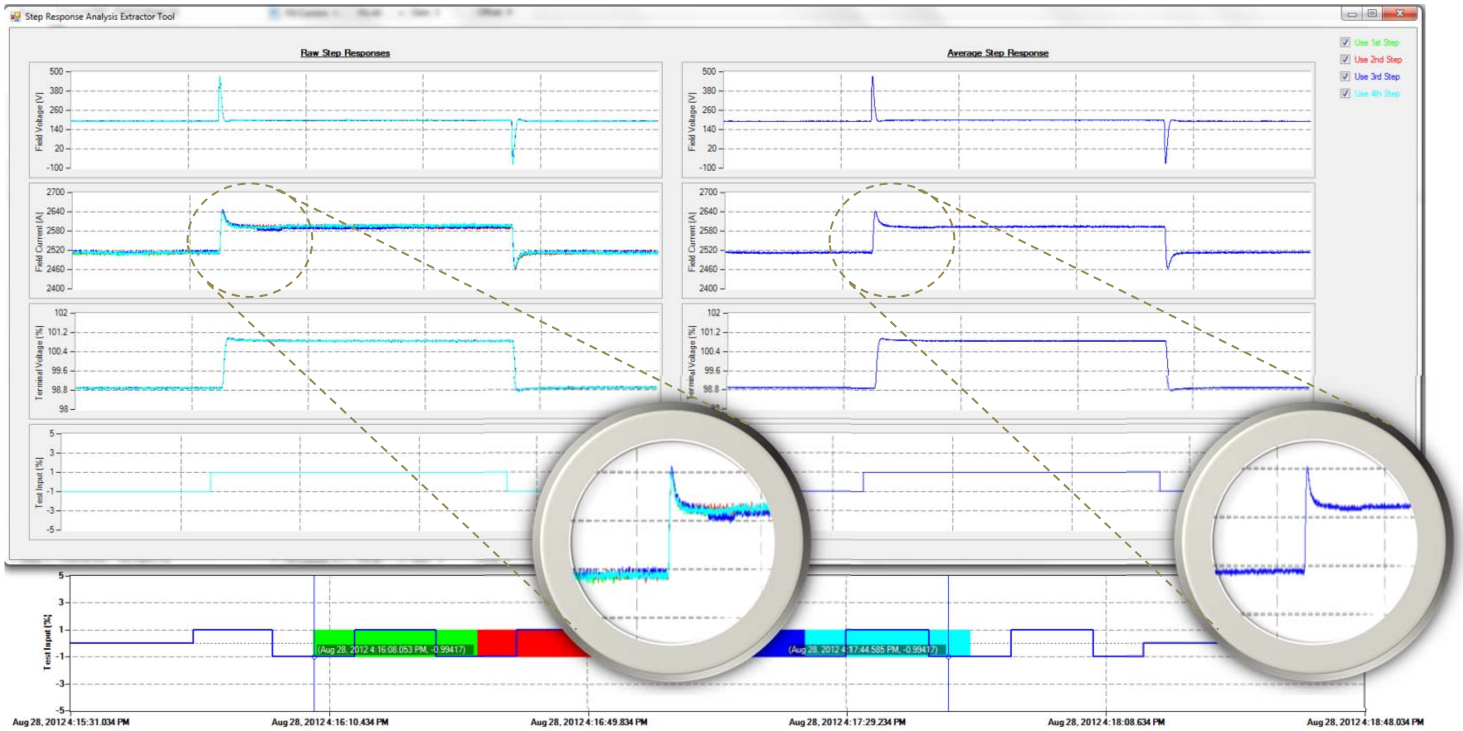

Figure 17 - Multiple Step Responses With System Disturbance (All Responses)

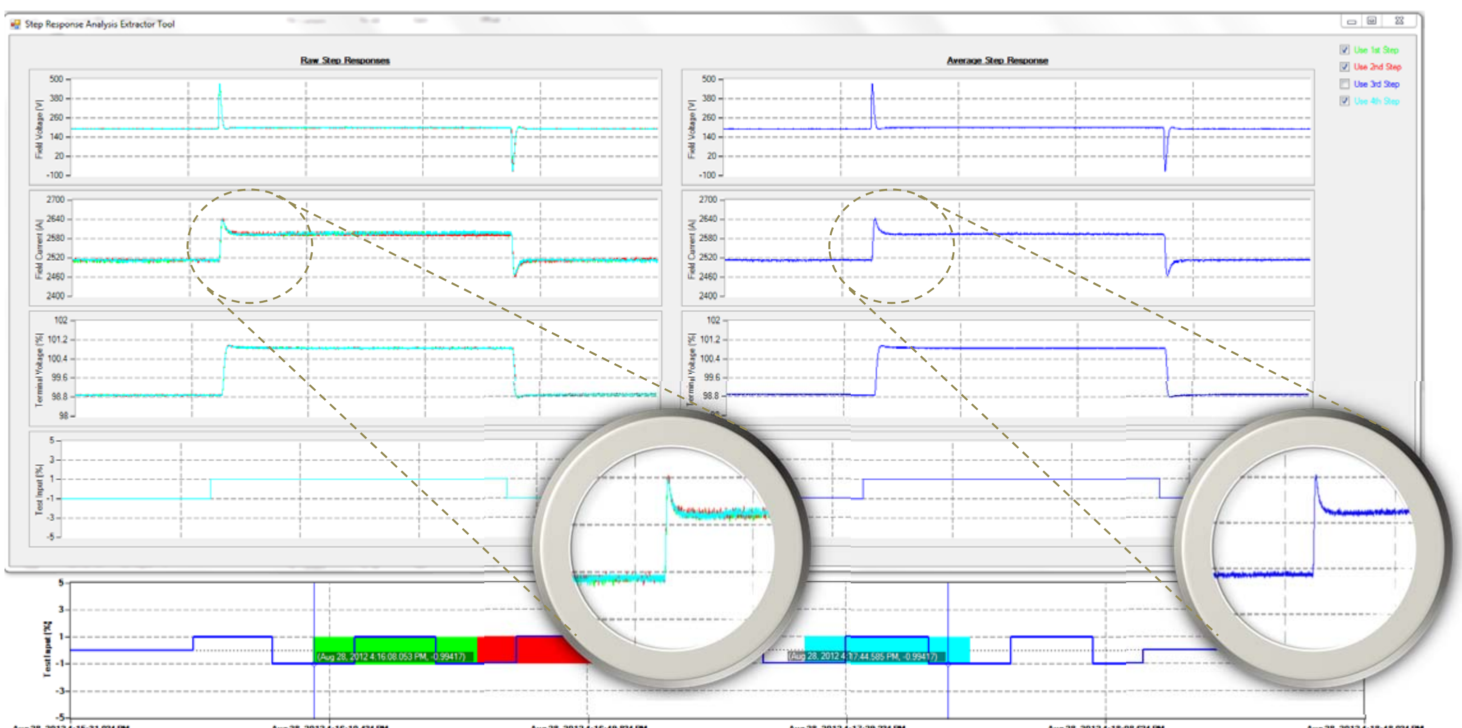

Figure 18 - Multiple Step Responses With System Disturbance (Selected Responses)

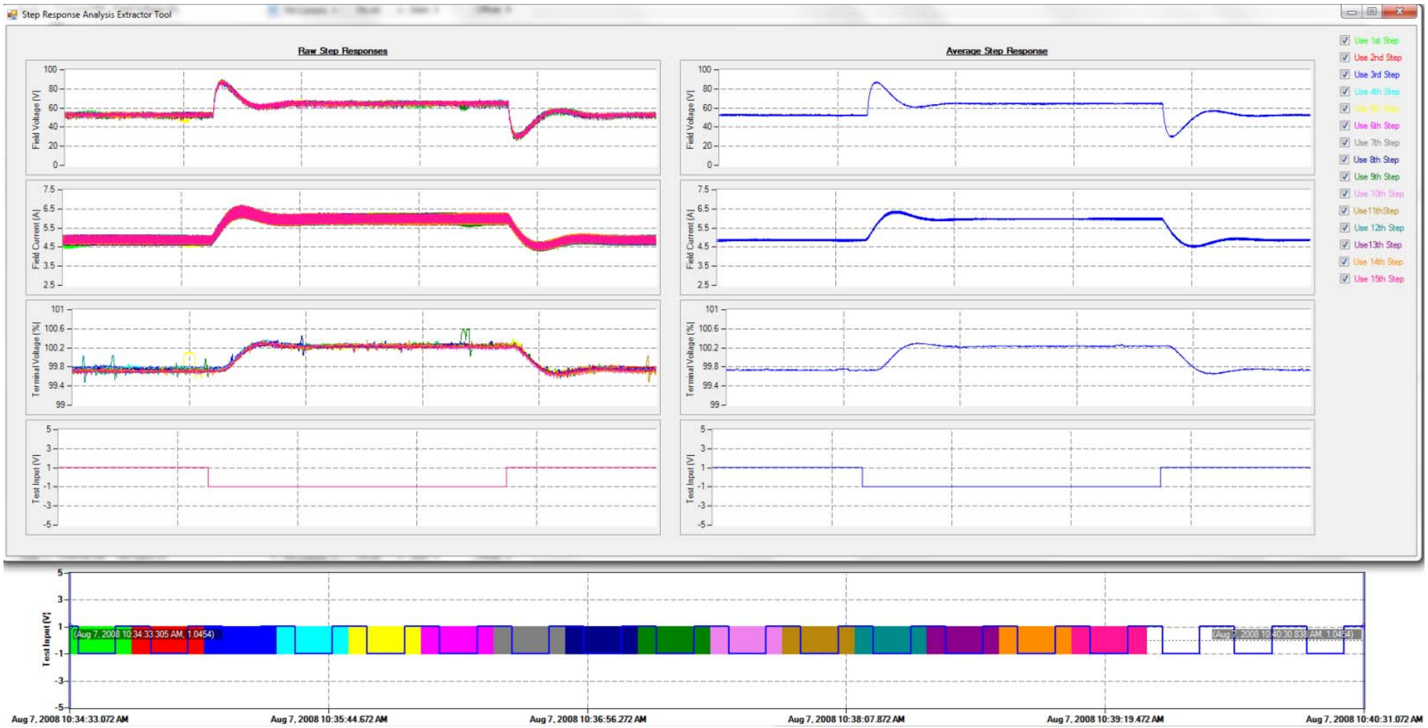

Figure 19 - Multiple Step Responses With System Disturbance/Random Noise (All Responses)

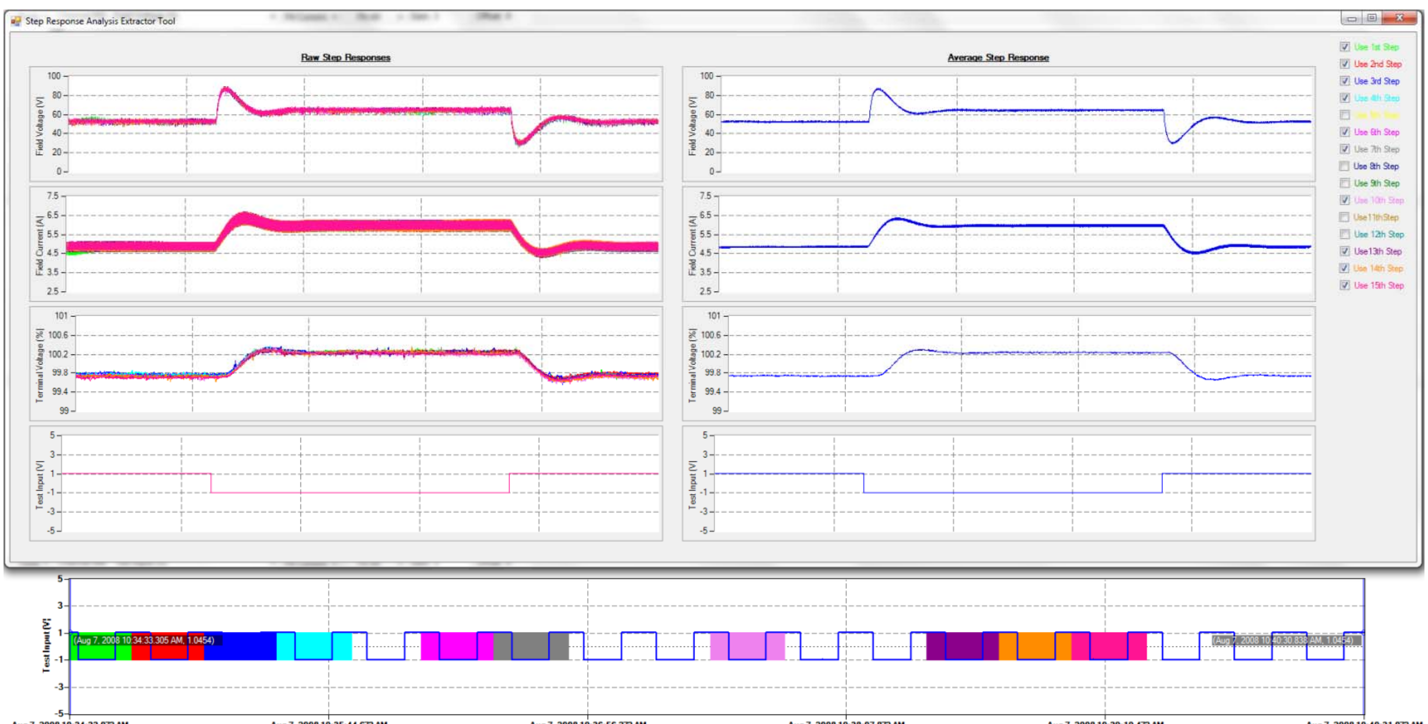

Figure 20 - Multiple Step Responses With System Disturbance (Selected Responses)

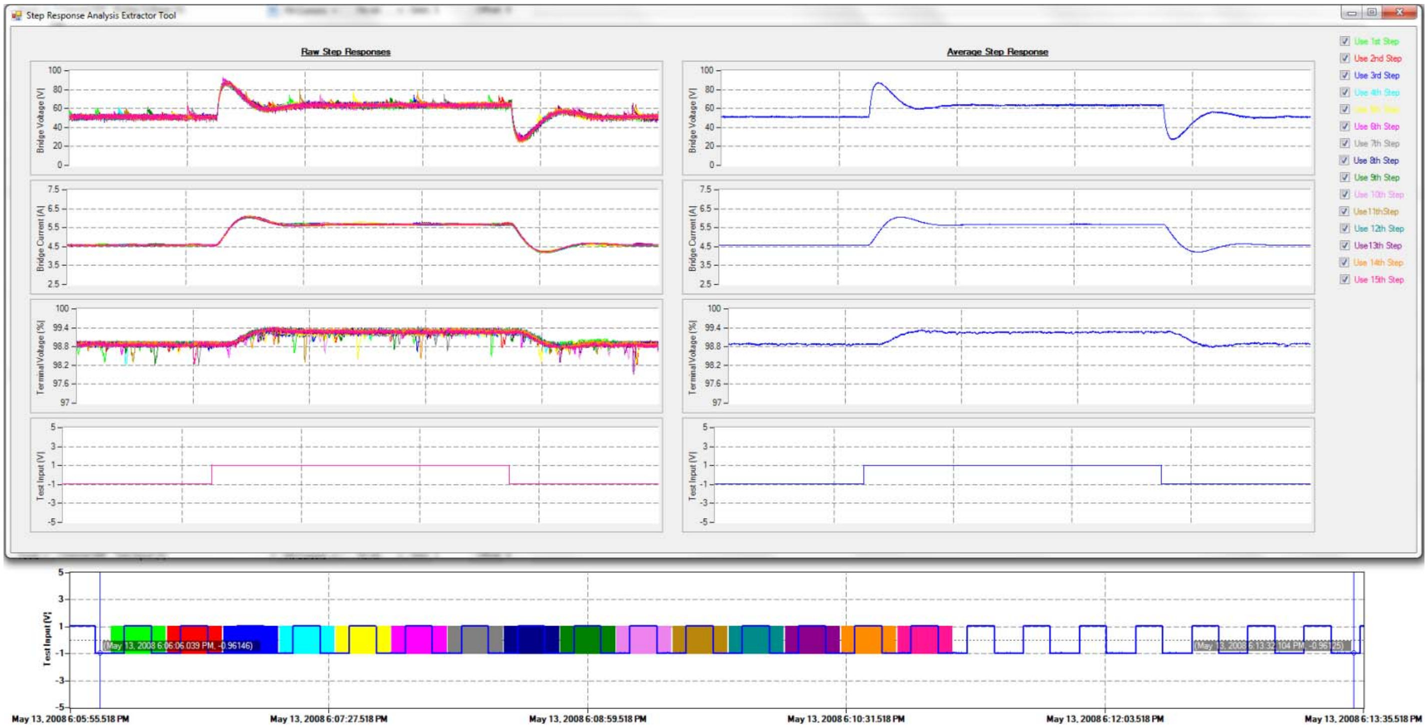

Figure 21 - Multiple Step Responses With System Disturbance/Random Noise (All Responses)

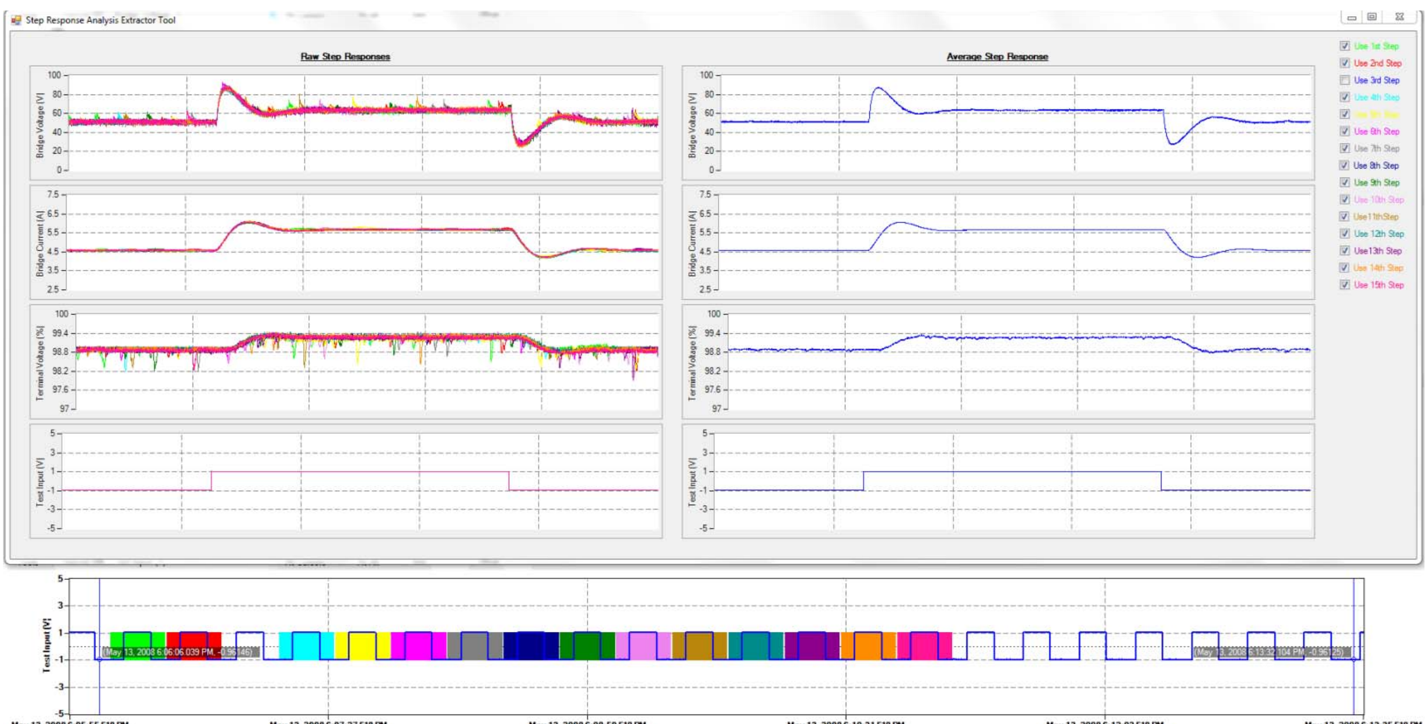

Figure 22 - Multiple Step Responses With System Disturbance (Selected Responses)

5.3 Time Domain Averaging Technique Future Ideas

Additional modifications to the algorithm could be made to increase the effectiveness of the ability of this tool to remove random noise and power system disturbance signals by implementing algorithms that automatically identify outlying data points that should be ignored while calculating the average responses.

One simple concept for accomplishing this task consists of calculating the error of each data point for each signal of the response against the data point for the corresponding signal of the average response and automatically ignoring these outlying data points when calculating the average responses. This concept assumes the power system disturbance and/or random noise does not occur exactly at the same point on each of the responses causing the noise to cancel upon averaging the signals. This assumption seems to be a safe assumption when looking closely at the previous figures and noticing the randomness of noise for the different responses.

6.0 CONCLUSIONS

Frequency responses play an important role in uniquely characterizing the response of a power system. Up until this research project, we were only able to simulate, compare, and validate offline frequency responses. (We were not able to simulate online frequency responses because the software tools that simulated the generator response with the unit connected to the power system did not support frequency responses.) As part of this research we wrote software so the online software tool could provide a simulated frequency response with the generator attached to the power system while under load. Now we can take advantage of utilizing the offline and online frequency responses for validating generator models because of the work we completed with this research project.

The process of performing model validation from online disturbance data could result in significant cost savings. Unit outages could be avoided by no longer needing to collect detailed data for each piece of equipment to perform a detailed model validation study. Instead, snapshots of power system disturbances can be used for comparison to modeled replications of the same disturbances to re-confirm the existing models. However, we found out the dependability of this process greatly depends on the quality, accuracy, and bandwidth of the critical data signals being measured.

Model validation exciter step response tests are typically performed by inserting a 1% change in voltage into the exciter input and measuring the responses of the exciter field voltage and generator terminal voltage. We also tried using 2%, 3%, and 4% magnitudes, as part of this research project, to see if the simulated model step responses would still match the measured data. Our results showed some subtle differences for variation in step sizes that were tolerable and were likely due to nonlinear behavior in the power electronics. This comparison also showed that additional information can be gained by also recording larger step responses (exciter ceiling and floor limits). By performing additional larger step response tests these values can be proven in the tests and used in the models. The time domain averaging technique has successfully removed random noise and power system disturbance signals while also providing users with the tools to determine step responses that contain outlying data properties to be removed by the user to provide a more accurate representation of the actual step response. One key feature of this algorithm is that it does not affect the phase response or overall shape of the response, it merely removes random and power system disturbance-based noise signals. This technique can be further refined by using standard deviations and/or other data point comparison techniques to remove outlying data points from the time-domain averaging algorithms automatically.