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A TESTBED AND METHODS FOR IMPROVED POWER PLANT MODEL
VALIDATION VIA PMU TERMINAL MEASUREMENTS

by
Jacob Eisenbarth

A thesis submitted in partial fulfillment of the
requirements for the degree of

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Abstract

The power industry requires the validation and sharing of the models for generators and controlling equipment to other utilities within North America. Accurate simulation of the electric grid is essential when setting operation and control strategies during various conditions present on the grid. An industry accepted method for performing model validation involves using the voltage and frequency measurements during an event, typically recorded by a phasor measurement unit, to perform a dynamic simulation on the system. The output real and reactive powers from the dynamic simulation and the actual event are then compared to each other. If the real and reactive powers closely match, the overall model is considered validated. Otherwise, the process of model calibration is performed to make improvements to the model. Least-squares fitting is an industry recognized method used during model calibration. No measurement of uncertainty is provided for individual parameters when sharing models between generator owners, utilities, and regulatory bodies. This thesis proposes a methodology for finding a measurement of uncertainty for each model parameter in the form of the standard deviation of the parameter value by means adding measurement noise and least-squares fitting.

Keywords: model validation, model calibration, transient stability simulation, dynamic simulation, least-squares fitting

Dedication

This thesis is dedicated to my family, specifically my grandparents, Joan and Carey Eisenbarth, who supported me through the entirety of my life and academic career.

Acknowledgements

I'd like to thank Josh Wold, Matt Donnelly, and Dan Trudnowski for offering their expertise and guidance toward my research. Josh Wold went above and beyond for me by being my advisor and answering my countless questions. Also, thank you to Curtis Link for being on my graduate school committee.

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Glossary of Terms

Term	Definition
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulation
MVAR	Mega Volt-Ampere(s) Reactive
MW	Mega Watt(s)
NERC	North American Energy Reliability Corporation
PDCI	Pacific DC Intertie
PMU	Phasor Measurement Unit
PSLF	Positive Sequence Load Flow
PU	Per Unit
WECC	Western Electricity Coordinating Council

1. Introduction

Operations and control are essential to the reliability of the nation's power grid, and the basis of the operation and control strategy results from the simulation of grid response to possible contingencies. The simulations do not provide useful operation and control strategies without having accurate models. The 1996 Western grid outage illustrates the consequences of inadequate modeling resulting in the failure to predict and replicate the outage within simulation [1]. As the national power grid continues to add more renewable generation sources, the ability to use dynamic modeling becomes increasingly important for meeting new challenges and plays a key role in the evolution of the power grid.

Traditional rotating generators and surrounding control equipment have relatively mature models which are provided in extensive libraries containing the standardized models by software vendors [2]. Wind and photovoltaic generation facilities have basic models, but the evolution of the models will continue with changing technology [3]. The behavior of the actual equipment must be validated against the simulation of the model for the model to be considered useful. For mature models, the validation process reduces to ensuring the correct model structure and the selection of parameters for a given piece of equipment.

Models for generation equipment are physically parameterized, and these parameters can be reliably obtained via a combination of offline and online tests performed on the piece of equipment. However, performing these tests is expensive (in terms of both the downtime cost and the equipment or consulting costs of the tests themselves) and the North American Energy Reliability Corporation (NERC) requires that all power plant models be validated periodically. The NERC standards [4, 5] allow for a more cost-effective means of validating power plant models by using measurements taken at the terminal of the plant (or individual generators) while

the plant is in operation. The measurements are typically taken by a phasor measurement unit (PMU). The validation strategy attempts to replicate the conditions on the actual power system by “playing-in” the voltage and frequency measurements to the simulation model and comparing the simulated model response (typically real and reactive power) to actual measured data [6, 7]. A simulation producing results significantly different from the measured response indicates the model parameters may need adjustment. The process of adjusting the model parameters is called model calibration.

1.1. Current Industry Practices

The North American Electrical Reliability Corporation (NERC) oversees six regional reliability entities and encompasses all the interconnected power systems of the contiguous United States, Canada, and Mexico. NERC is responsible for developing standards for power system operation and monitoring and enforcing compliance with those standards [8]. Currently, NERC has 2 standards, MOD-026-1 and MOD-027-1 [4, 5], requiring that each company owning a generator must validate that the simulation of the generator and its controlling equipment matches actual events occurring on the grid. If the model provides a good representation of the event data, the models are considered to be validated, otherwise the models are not valid and need to undergo model calibration. Systematic parameter tuning which minimizes the least-squares error between the simulation and the event is commonly used for model calibration. The resulting models will provide a better representation of the actual generating unit and controlling equipment due to model calibration. The generator and controlling equipment models are shared between transmission and generator owners so accurate planning studies can be conducted. The current industry practice when sharing models provides

no information on the uncertainty of individual parameters. It simply labels the overall model as validated or not validated.

1.2. Model Validation via Play-In Simulation

One method used to validate a generator model is to compare an event recorded by a PMU on the actual system to the same event simulated using the generator and controlling equipment models. Software programs such as PSLF (Positive Sequence Load Flow), PowerWorld, and PSS/E (Power System Simulator for Engineering) are used to perform the transient stability simulations. A transient stability simulation allows for the accurate analysis of power system dynamics and transients during system disturbances and other events. An accurate model will provide a transient stability simulation with similar power system dynamics to the ones recorded by the PMU.

The generator and controlling equipment models are validated against an actual event occurring on the actual system. The model validation setup process begins by having the entire power system within the software program of choice. Typically, the measurements of the event come from a PMU which measures the voltage and current phasors taken at a known point in the electrical system. The bus where the PMU is located needs to be identified within the software program, then all of the models outside of the power plant under validation and the PMU bus are eliminated. A reduced section of the power system will remain in the software to perform model validation. The validation is conducted by adding a generator model that behaves like a Thevenin voltage source to the PMU bus so the voltage magnitude and frequency can be inputted into the simulation from an actual event occurring on the power system. The Thevenin voltage source is used to control the voltage magnitude and angle at a specific bus during a transient stability simulation. The setup of the system in this manner for external signal usage is called hybrid

dynamic simulation. It is referred to as “hybrid” in the sense it bridges the measurement world with the simulation world [7]. The authors in [7] outline the model validation process using hybrid dynamic simulations. The reduced system with the addition of a Thevenin voltage source is referred to in this text as a Play-In system. An illustration of the Play-In system to the actual power system is shown in Figure 1. The real and reactive power is compared for the Play-In simulation and data recorded by the PMU to determine if a power plant model is validated. If model does not match the PMU data, improvements to the model need to be made so the model provides an accurate representation of the actual system which is referred to as model calibration.

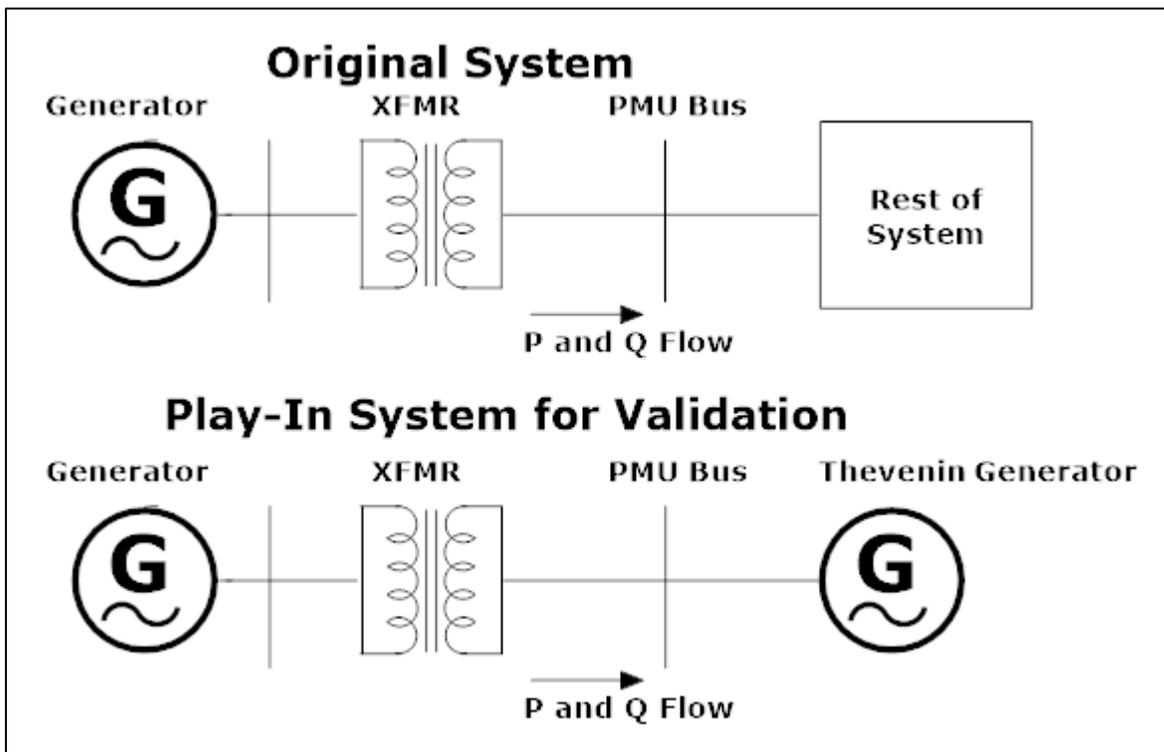


Figure 1: Play-In and original system comparison.

1.3. Additions to Industry Practices

Using the methods developed in this thesis, information quantifying the level of uncertainty for each individual parameter within the generator and controlling equipment models given the measured data set can be added to the model validation procedure. The standard deviation of the parameter distribution will be used to quantify the uncertainty for each parameter. Each parameter can be classified as either a sensitive or insensitive parameter based on the standard deviation of the parameter distribution. A parameter with a distribution with a smaller standard deviation signifies the parameter is a more sensitive parameter than a parameter with a distribution with a larger standard deviation. A sensitive parameter has a tighter distribution because the change in parameter value has a large effect on the output simulation. Conversely, an insensitive parameter has little effect on the output simulation due to a parameter value change.

The level of uncertainty will change based on which events are used during the model validation process. For example, the generator inertia constant, H , would have a greater level of certainty when validated on power transferring events than on voltage disturbance events. Knowing the level of uncertainty for each parameter provides useful information when sharing generator and controlling equipment model information between utilities. Other work has been done [9, 10] to quantify parameter uncertainty in the model validation problem. These methods rely on advanced statistical and computational techniques that represent a significant departure from the standard play-in simulation framework. In the papers where they are presented, they are only evaluated on simulation data. It is not clear how they will perform on real data.

2. Limitations of PSLF for Play-In Simulations

The commercial software package created by General Electric named Positive Sequence Load Flow (PSLF) was used to begin research for the topics within this thesis. The PSLF software package was used to perform model validation by running transient stability simulations with a Play-In generator. The Play-In generators allowed for an external signal such as a PMU voltage and frequency measurement to be used as an input during a transient stability simulation. The initial goal was to verify that the built-in PSLF Play-In generator behaved as described in the documentation. A simulation case was run using the PSLF case making sure to record the data necessary for a Play-In simulation, then a Play-In simulation was run using the previously recorded simulation data. Since the data was ideal simulation data, it should have been possible to exactly match the full case to the Play-In case. PSLF has been found to contain certain dynamic simulation flaws hindering the attempt to get a perfectly matching Play-In simulation when simulation data was used as the input to the Play-In generator. The encountered flaws are explained in detail in the following sections

2.1. Small Time-Step Problems

When running PSLF transient stability simulations, unknown behavior and oscillations in the output data of the PSLF simulations have been encountered when running simulations at extremely small time steps. Decreasing the time step for transient stability simulations was a troubleshooting technique used to diagnose potential problems within the transient stability simulation. A test to illustrate the output at small time steps was made on the wsc_9bus system shown in Figure 2. The wsc_9bus is a sample case provided by PowerWorld within [11]. The wsc_9bus system is a small testing system that has three generators with the same type of

exciter and machine models. The `ieeet1` exciter model and the `genrou` generator model are the models used for each generator.

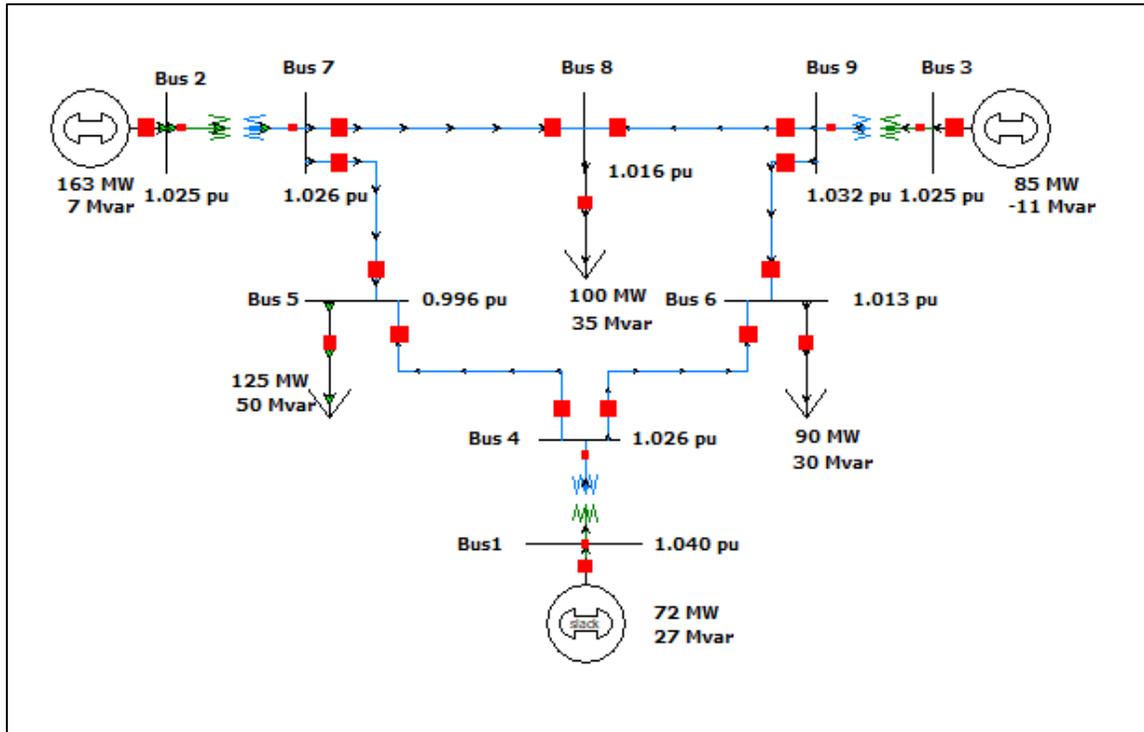


Figure 2: Diagram of the wsc9bus system.

A transient stability case was programmed where the load at Bus 5 within the wsc9bus system was shed at one second within the simulation. The case was run three different times with only the time steps changing. The three time steps used were 0.005, 0.0005, and 0.00005 seconds. The real power flow from Bus 2 to 7 was used to illustrate the oscillations at different simulation time steps. In Figure 3, the yellow line which represents the simulation with the smallest time step has erratic oscillations occurring near the end of the simulation. The oscillations also occur in other types of output measurements such as voltage, frequency, and reactive power. All buses within the system contain measurements with oscillations at the smallest time step. The source of what is creating the oscillations is unknown because the PSLF

software code is not accessible since it is proprietary. More plots of different output measurements illustrating oscillating effects are provided in Appendix C.

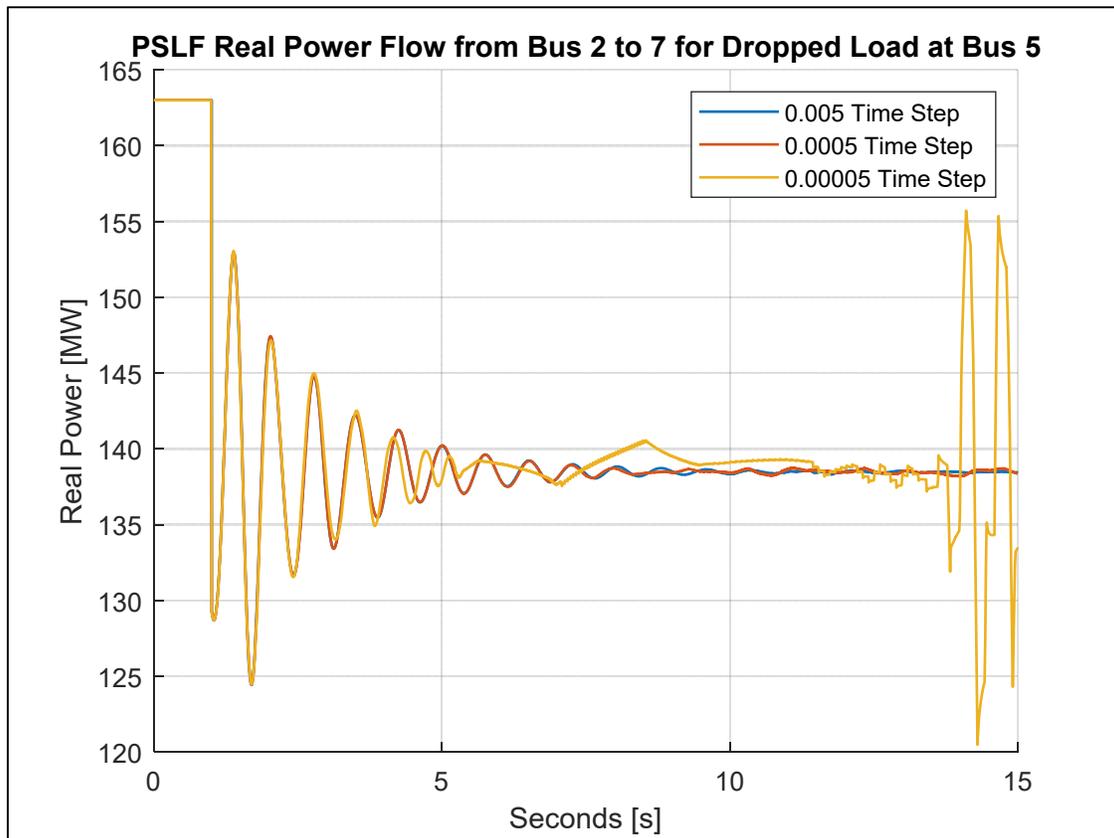


Figure 3: Real power plots for PSLF time step testing.

2.2. PSLF's imetr Model on Small Impedance Branches

For model validation, it is crucial to compare the real and reactive power for a physical event recorded on the grid, then compare the simulated real and reactive power provided by a transient stability simulation of models for the grid. Within the PSLF software, the imetr dynamic model is used to record the power flow at a branch of the electrical system during a simulation. A branch can either be a transformer or a line within the system. The imetr model places the branch power and current flow into the output channel of the PSLF transient stability simulation. Problems have been encountered when using the imetr model on branches with small

impedances. When the impedance gets too small, PSLF provides the error shown in Figure 4 cancelling the transient stability simulation because the imetr model is unable to initialize on the branch.

```

There are      1 models with data check warnings or actions
Can't initialize [imetr] on line from  40821 [PAUL      ] 500.00  47741 [CENTR P1  ] 500.00Error during
initialization of [imetr] with id [1 ] at bus  40821 [PAUL      ] 500.00|
Fatal errors detected during while initializing dynamic models -- aborting command

```

Figure 4. PSLF imetr terminal error for small impedance branch.

Increasing the impedance of the branch allows for the imetr model to properly initialize and the transient stability to run until completion. The transmission line branch that provided the error in Figure 4 had the reactance set to 0.0001 per unit with both the resistance and susceptance set to zero. The imetr initialization error did not occur on the transformer when the transmission line reactance was increased to 0.001 per unit. It can be inferred that the threshold for the transmission line reactance being too small to initialize is somewhere between the two reactance values.

2.3. Unexpected Model Behavior

Unexpected model behavior has been noticed within the PSLF software package. Identical parameters were found within a power system stabilizer but when each are changed to different values the output transient stability simulations do not match. For example, the pss2a power system stabilizer model shown in Figure 5 has three cascaded blocks before the output performing the same function. The parameters within the three blocks were the same making each block identical. This means that numerator time constants, T_1 , T_3 , and T_a , were equal and the denominator time constants, T_2 , T_4 , and T_b , were equal.

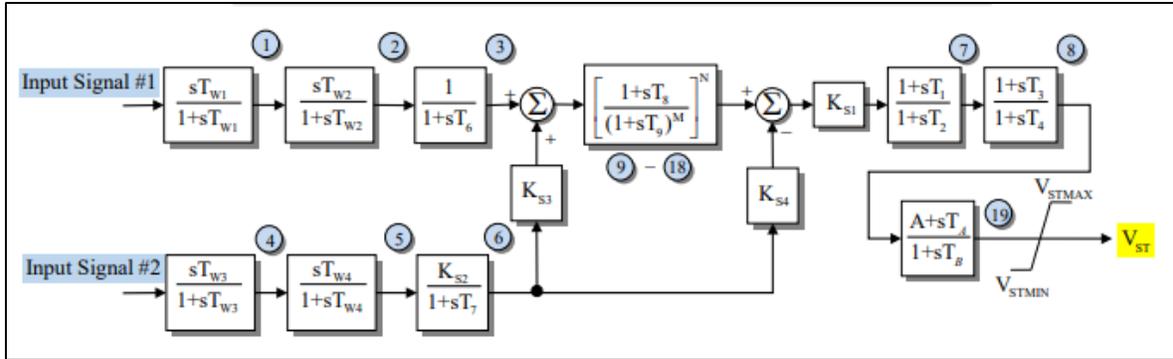


Figure 5. IEEE pss2a power system stabilizer model [12].

If the T_1 parameter was increased by 10 percent, the same output should be expected if either T_3 or T_A was increased by 10 percent while all other simulation setting and parameters remain constant. A test was performed to verify that the pss2a model acted in the expected behavior. A transient stability simulation was run on the WECC where the Chief Joseph resistive brake was energized for 0.5 seconds. The voltage, frequency, real power, and reactive power were recorded at the PAUL bus nearby the CENTR G1 generator bus. The Play-In system used during the testing is shown in Figure 6. Multiple Play-In transient stability simulations were made on the Centralia G1 generator where the T_1 , T_2 , T_3 , T_4 , T_A , and T_B parameters were each incremented by 10 percent of the original value. The results of simulations were compared to the Play-In simulation with the parameters at the original value. The real and reactive power comparison for the incremented pss2a parameters to the original simulation are shown in Figure 7 and 8, respectively. Note that the direction of the real and reactive power flow is defined in Figure 6. The default PSLF time-step of 0.0042 seconds was used for each of the simulations.

parameters each have a similar real power flow but are not exactly the same as expected. Denominator parameters have similar results as the numerator parameters where the three simulated real powers are not identical. A closer comparison for real power differences for both the numerator and denominator parameters is shown in Figure 9.

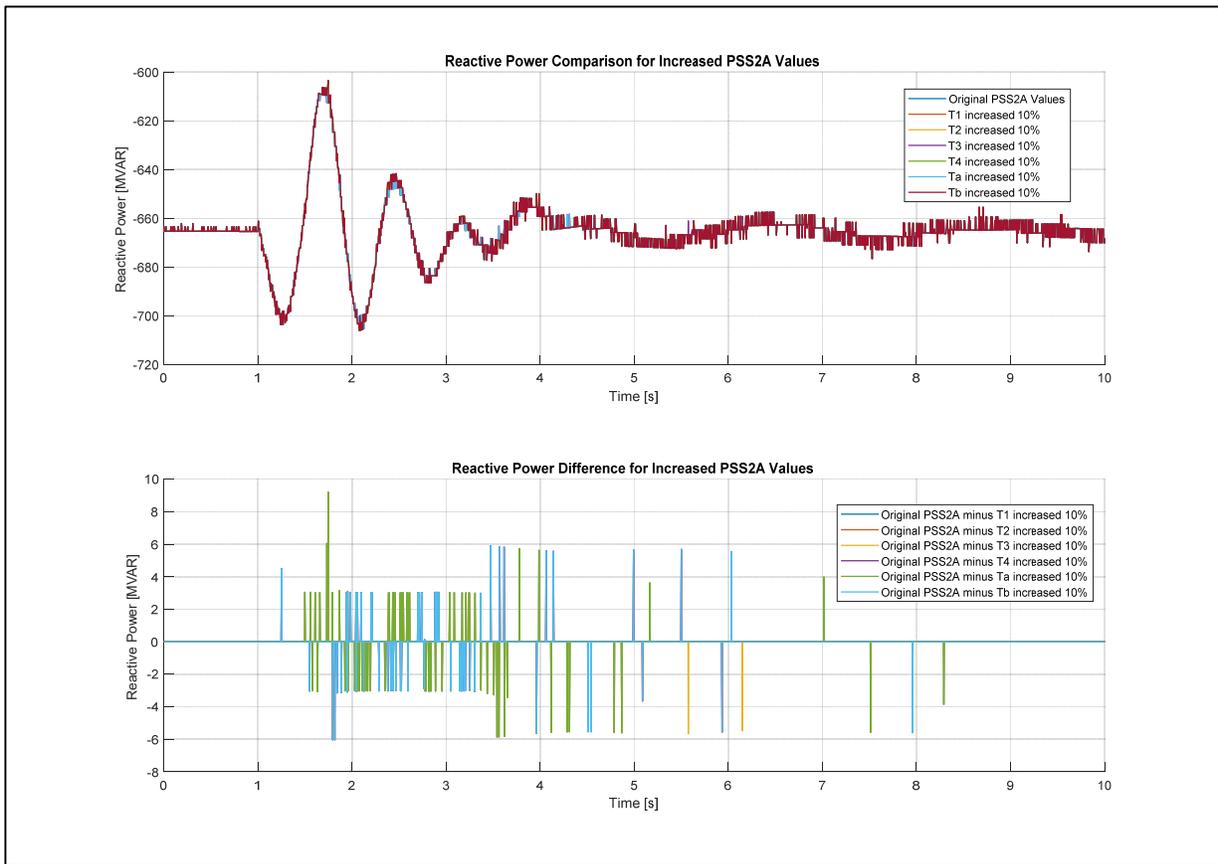


Figure 8. Reactive power for PSLF pss2a testing.

The PSLF reactive power simulations shown in the first subplot of Figure 8 are very noisy. The source of this noise is unknown but is not significant to the test because only a relative comparison of the outputs is needed to verify the pss2a model behavior. The 10 percent increase of numerator parameters should provide the same simulation results since the last three blocks are identical. The same expectations apply to the denominator parameters. Differences

between the groups of parameters in the denominator are apparent in the second subplot of Figure 8 and are shown in detail in Figure 9.

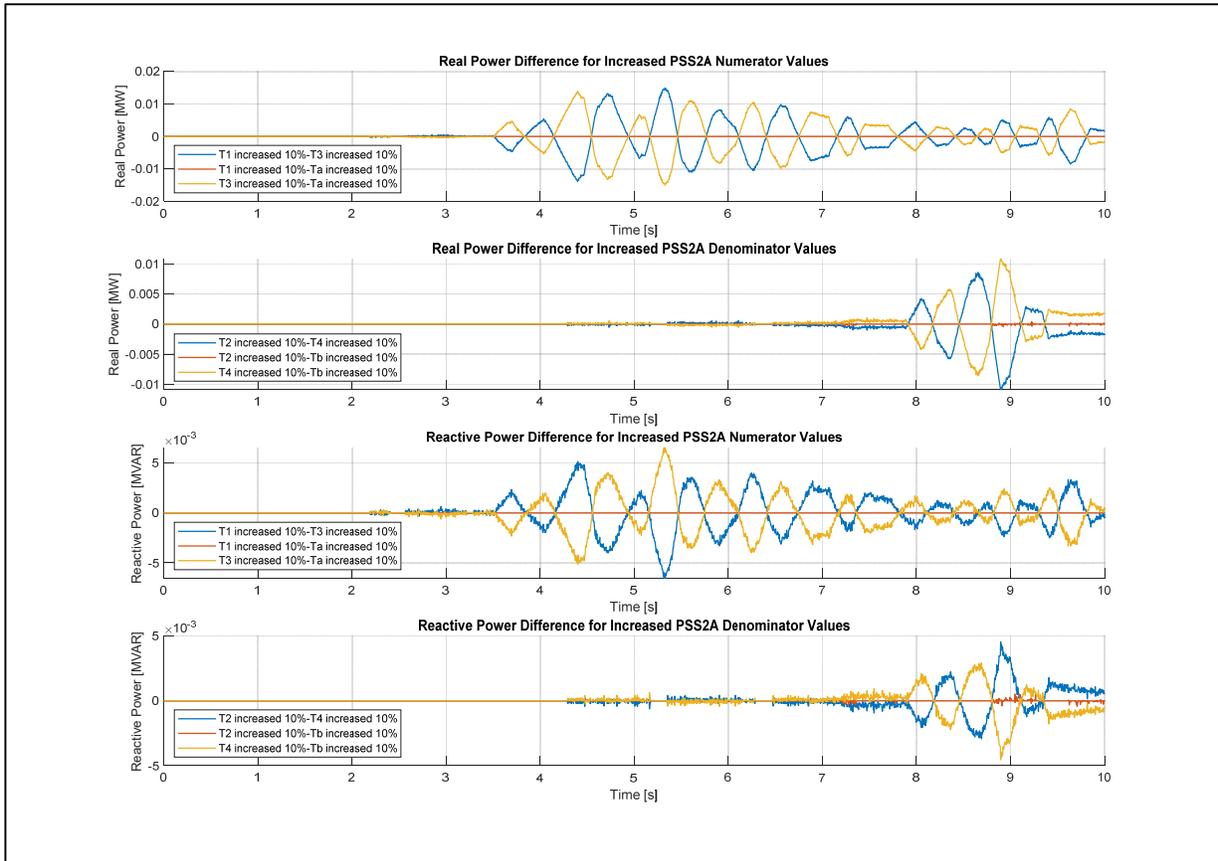


Figure 9. P and Q group comparison for PSLF pss2a testing.

The results shown in Figure 9 confirm unexpected model behavior occurring in PSLF for the pss2a model. Each simulation of the numerator parameters increased by 10 percent should provide the same output in real and reactive power. The same was expected for the denominator parameters. Figure 9 shows that the difference between the parameters was not zero indicating a flaw for the pss2a model.

The test verified that this behavior occurs in the pss2a model within PSLF but many other models have a similar construction which could create the same problems. The source of the error was not found since the source code for the PSLF software is not accessible. This means

that other models could potentially contain similar errors. Caution should be used when using the PSLF software to perform transient stability simulations since similar flaws could exist.

2.4. Unable to Turn off Filtering for fmetr Model

When verifying the Play-In feature within PSLF, a simulation was run on the full WECC case, then a Play-In simulation was run on a small portion of the system where the voltage magnitude, frequency, real power, and reactive power were recorded. The goal was to perform a model validation case where the event data was simulated in PSLF. The expectation was that if the Play-In feature was working correctly then the event and Play-In simulations would overlap perfectly. Differences were found between the two simulations and led to a detailed investigation into portions of PSLF software.

One revelation was made regarding the fmetr model used in PSLF to measure frequency. The block diagram for the fmetr is shown in Figure 10. The bus frequency is calculated by the numerical differentiation of the bus voltage angle after the result is passed through a low pass filter with a time constant T_f [12]. When setting up the fmetr model, the time constant T_f was set to zero with the hopes to avoid the low pass filtering. The PSLF user manual stated when the time constant T_f is set to a value less than five times the simulation time step the fmetr model uses the `netw[i].f` frequency which uses a time constant of 0.05 seconds for low pass filtering [12]. This means that it is not possible to turn off the low pass filtering that occurs in the fmetr model. The closest action to turning off the low pass filter is choosing the smallest filter time constant to minimize frequencies filtered.

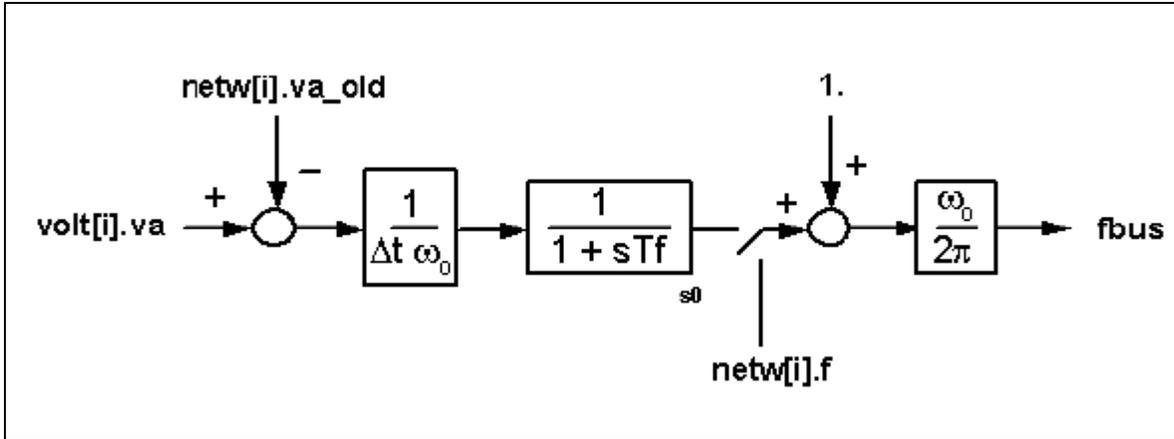


Figure 10. PSLF fmetr model block diagram [2].

2.5. Voltage Angle for Play-In Simulations

The Play-In feature for PSLF is accomplished by using the gthev model in combination with data from an external file to be used during the simulation. The model acts as a Thevenin source of defined voltage amplitude and frequency with the inputs to the model being voltage amplitude and frequency [2]. The block diagram for the gthev model is shown in Figure 11.

From the PSLF manual, [2], or the block diagram of gthev, it is not clearly shown how the input voltage amplitude and frequency are implemented in the Thevenin voltage source.

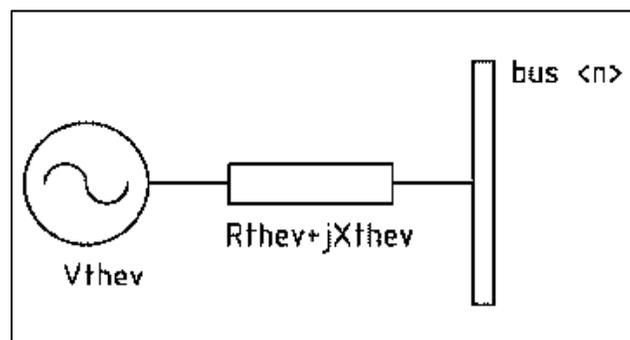


Figure 11. PSLF gthev model block diagram [2].

The PowerWorld software package uses a Thevenin voltage source, PlayInGen, during a Play-In transient stability simulation. The block diagram for the PlayInGen model for

PowerWorld is shown in Figure 12. In PowerWorld, the input frequency and voltage amplitude data are both passed through a low pass filter. The low pass filter can be turned off by setting the filter time constant to zero as shown in Appendix B. The voltage magnitude is then set directly to the voltage magnitude of the Thevenin source. The frequency undergoes integration which calculates the change in voltage angle used by the Thevenin source. The Thevenin source in PowerWorld works by controlling the voltage magnitude and angle at the connected bus.

The details of implementation for the gthev model within PSLF are unknown due to limited documentation found in the user manual. Since both PowerWorld and PSLF use a Thevenin source in the Play-In, it can be inferred that PSLF has a similar implementation as PowerWorld where the Thevenin source controls the voltage magnitude and angle given a voltage magnitude and frequency input. The calculation for voltage angle from frequency could be avoided entirely if the voltage angle was available to be used during a Play-In simulation. Expanding the Play-In feature in both PSLF and PowerWorld to accepting either frequency or voltage angle inputs for the Thevenin source could be very beneficial.

For example, the frequency output provided by the fmetr model in PSLF is passed through an unavoidable low pass filter. This means some of the frequency content is unavoidably attenuated by the low pass filter. A Play-In case in PSLF using a frequency input provided from an event case using the fmetr frequency measurement would not be the same since the frequency was filtered due to the fmetr model. If PSLF could use voltage angle as an input to the Thevenin source, the low pass filtering could be bypassed and the Play-In would match the event simulation.

3. PowerWorld Play-In Setup

3.1. Description of PowerWorld Test Bed

After testing the PSLF software package, model validation was conducted using the PowerWorld software package. The PowerWorld software has an add-on named Simulator Automation Server (SimAuto) which allows access to the PowerWorld Simulator functionality within a program written externally by the user. The Simulator Automation Server acts as a COM object, which can be accessed from various programming languages with COM compatibility [13]. MATLAB was used during this project to access the PowerWorld Simulator through the SimAuto add-on.

The Transient Stability add-on was crucial to this project because it allowed for the dynamic simulation of the system within PowerWorld. For model validation, the PowerWorld Play-In model called PlayInGen allowed for the input of PMU voltage and frequency data into a transient stability simulation. The PlayInGen model acts as a Thevenin voltage source which controls the voltage magnitude and angle at the bus the PlayInGen model is attached to [14]. The PlayInGen model integrates the input frequency vector to get the voltage angle. The Thevenin resistance and the reactance of the PlayInGen model are set to negligibly small values for model validation to not affect the system by adding reactance. The PlayInGen model is illustrated in Figure 12.

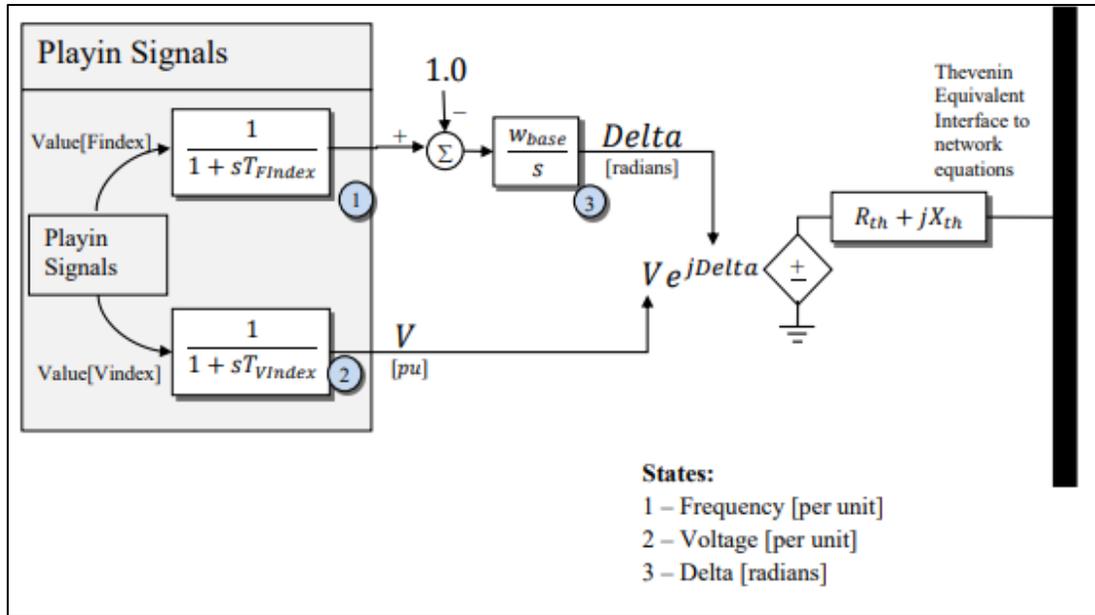


Figure 12: PowerWorld PlayInGen Model [4]

Instead of using the entire WECC model, the system used for Play-In is reduced to only the system between the PMU and generator being validated. The models outside the PMU and generator are unnecessary and just adds computation time. Reducing the computation time is essential when running many simulations where only slight changes are made between simulations.

3.2. Resolution of PSLF Problems in PowerWorld

Previously, the software package that was going to be used during this research was PSLF but due to previously described flaws the research was transitioned to PowerWorld. It was important to make sure that the same flaws existing in PSLF were not present in the PowerWorld software. The following sections outline the problems found in the PSLF software package and the testing conducted to verify the same problems don't appear in the PowerWorld software.

3.2.1. Small Time-Step Problems

The PSLF software encountered problems with small time steps causing oscillations in the output of the simulation. More oscillations appeared as the time step decreased within the PSLF transient stability simulation. The same wsc_9bus system used to test the PSLF software was used to test the PowerWorld software. The wsc_9bus system is shown in Figure 2 and can be found in the PowerWorld training material [11]. The shedding of the load connected to Bus 5 at one second remained the contingency within the transient stability case. The same time steps of 0.005, 0.0005, and 0.00005 seconds were used when testing the PowerWorld software. The real power flow from Bus 2 to 7 for the PowerWorld software is shown in Figure 13. The smaller time steps do not exhibit any oscillations in the PowerWorld output. Comparing the PSLF plots available in Appendix C to the PowerWorld plots in Appendix D show that the small time step issue is nonexistent in the PowerWorld software.

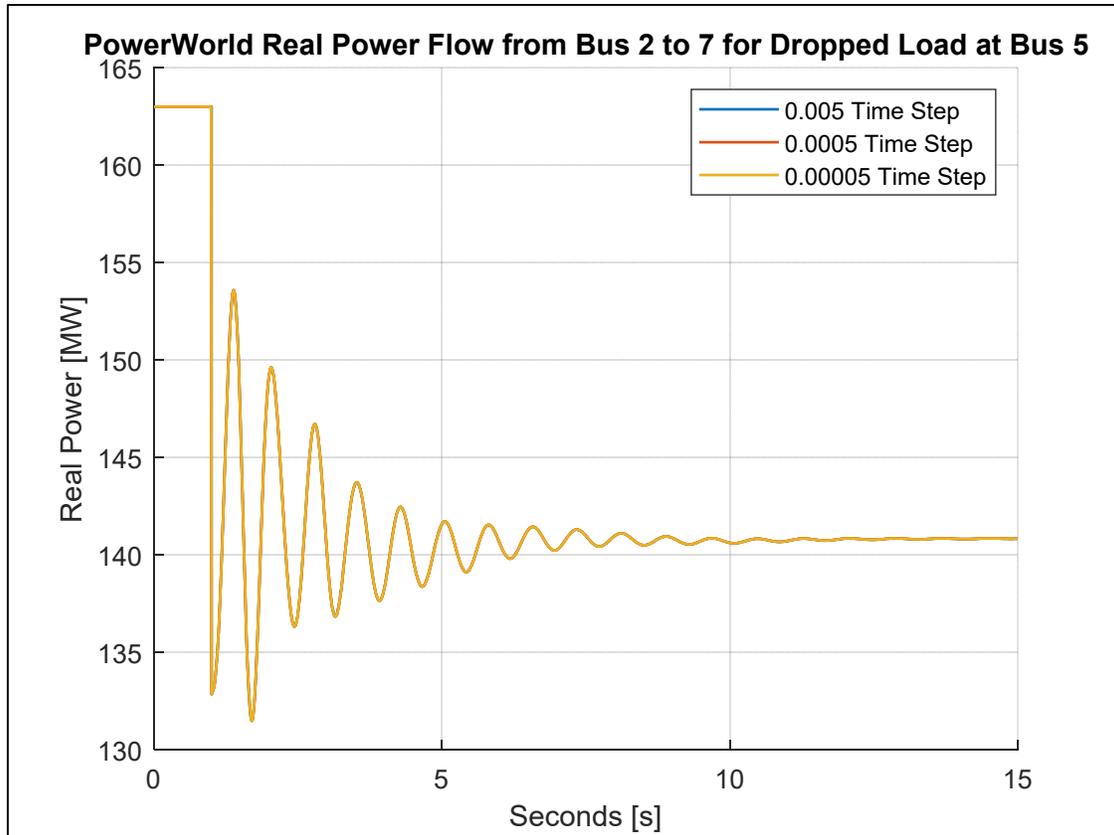


Figure 13: Real power plots for PowerWorld time step testing.

3.2.2. Unexpected Model Behavior

A problem encountered within PSLF was that blocks in the power system stabilizer pss2a model did not give the expected results based on the block diagram for the model. The pss2a model is shown in Figure 5. For example, the numerator and denominator values for the last three blocks of the pss2a model are the same so T_1 , T_3 , and T_a are equal and T_2 , T_4 , and T_b are equal. The expectation for this model is that each block would provide the same effect on a simulation which was not the case in PSLF. The PowerWorld simulation software was tested the same way as the PSLF software. A test was run where the time constant, T_1 , in the numerator was increased by 10 percent to run a simulation, then separate simulations were ran with each other numerator time constants increased by 10 percent. Each of the simulations should have the

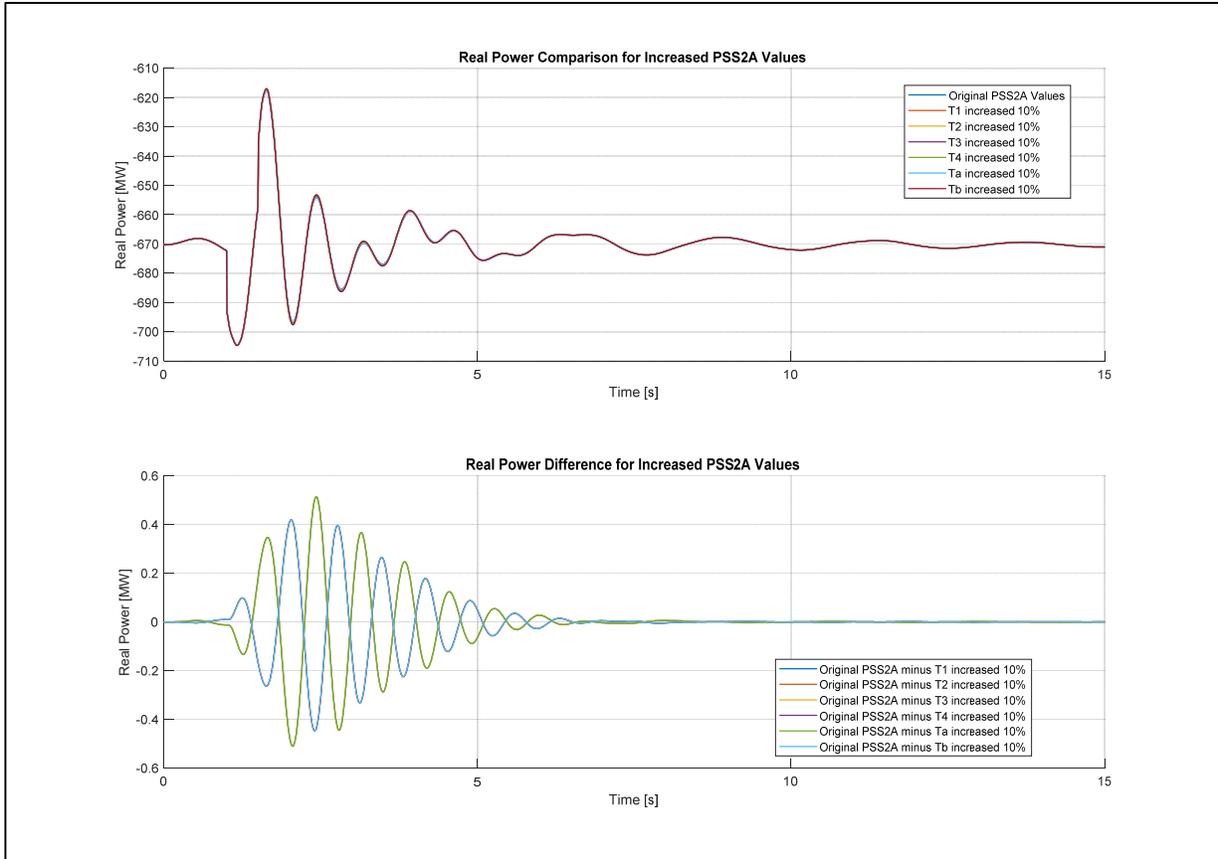


Figure 15. Real Power for PowerWorld pss2a Testing.

Similarly, the reactive power plots for this test are shown in Figure 16. Like the real power plots, the 10 percent increase in parameter values show small differences in reactive power for varying pss2a parameter values in the first subplot. The simulation changes due to the parameter values are shown in the second subplot by taking the difference between the original and the 10 percent increased parameter simulations. The second subplot has two groups of plots for the changing parameter values. The increased numerator time constants, T_1 , T_3 , and T_a , in the second subplot overlap on the green line. The increased denominator time constants, T_2 , T_4 , and T_b , in the second subplot overlap the on the blue line. Since the numerator and denominator parameters simulate to the same group of reactive power, the pss2a model is working as expected from the block diagram in Figure 5. A plot showing the differences between each case where the

parameter is increased by 10 percent is shown in Figure 17. The four subplots show the difference between parameters over the entire simulation. The results of pss2a testing prove that PowerWorld does not have the same problem for unexpected model behavior as PSLF.

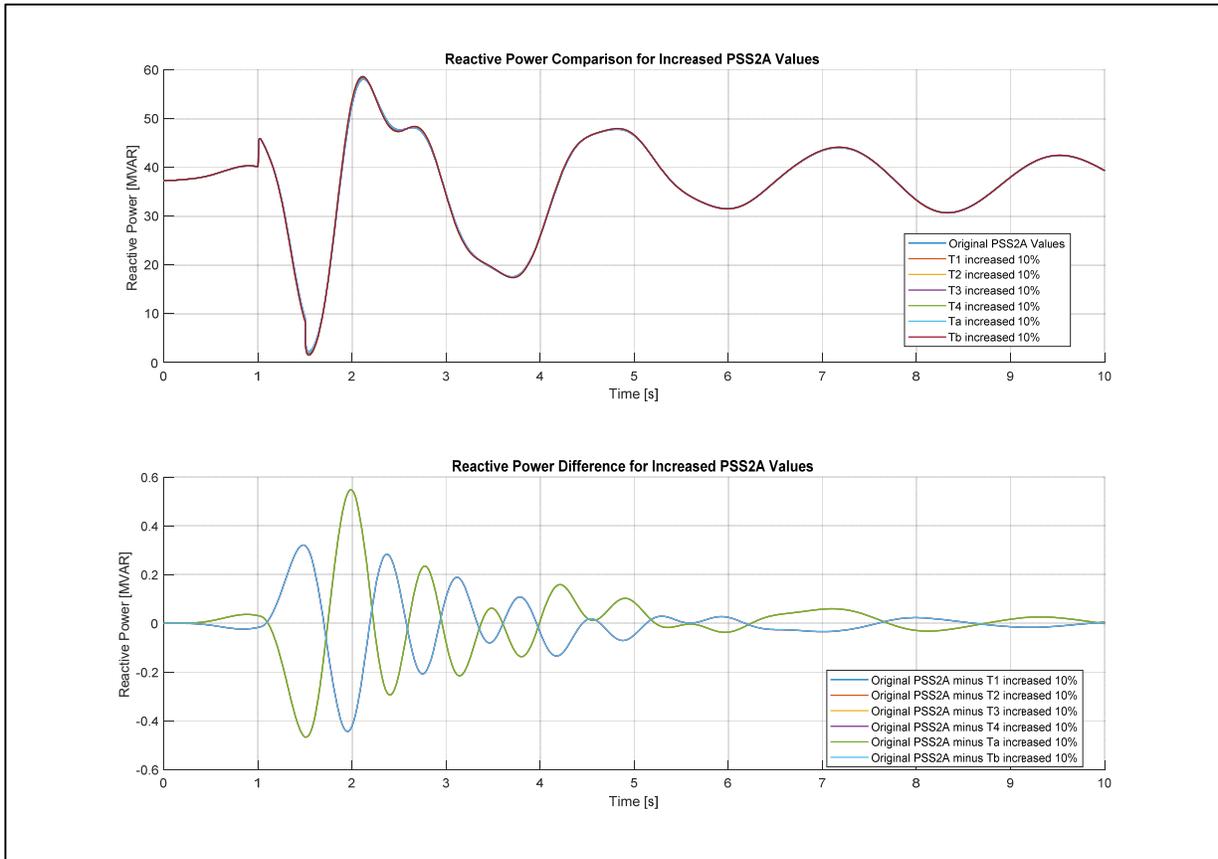


Figure 16. Reactive Power for PowerWorld pss2a Testing.

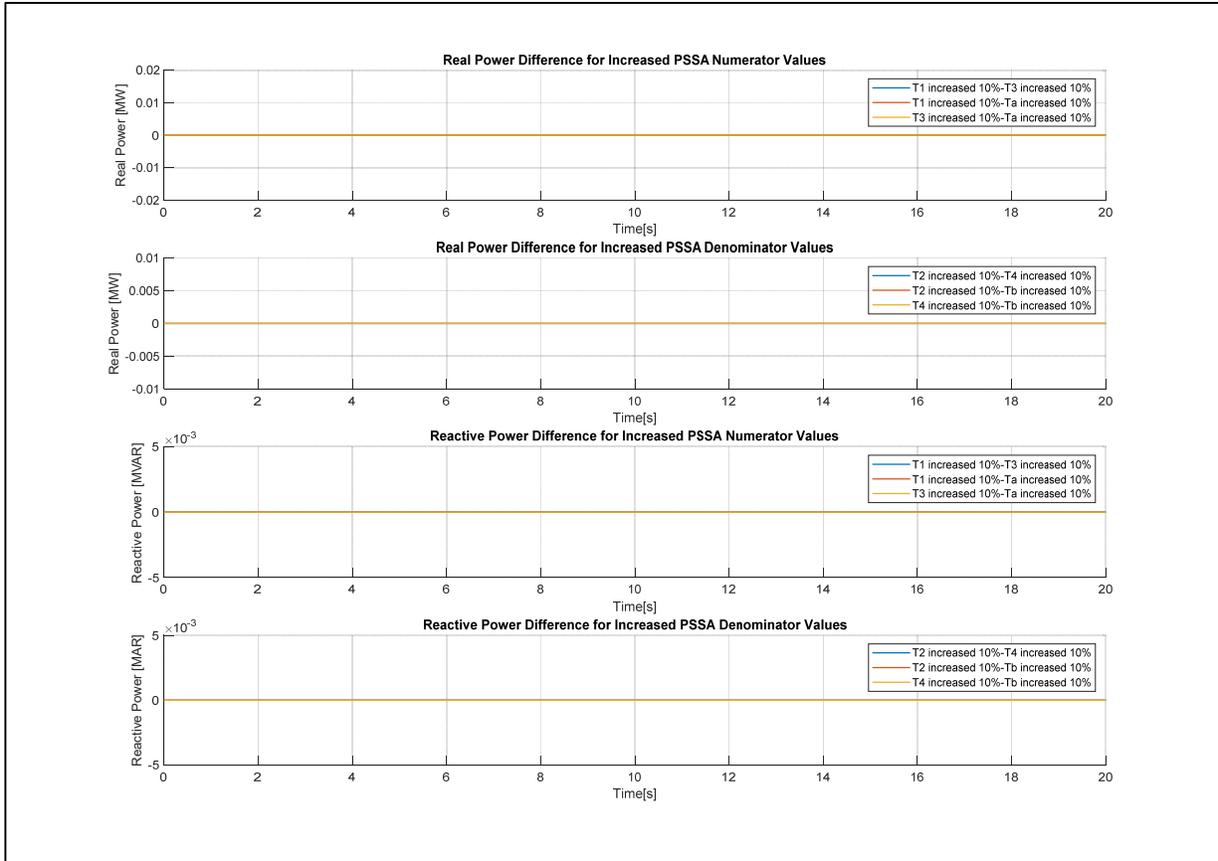


Figure 17. P and Q group comparison for PowerWorld pss2a testing.

3.3. PowerWorld Play-In Simulation Verification

Before starting parameter tuning within the PowerWorld software, it was crucial to verify that the transient stability simulation using the PlayInGen model worked correctly. A transient stability simulation using the wsc_9bus system shown in Figure 2 was used for event data. The wsc_9bus system is a system provided in the training materials for PowerWorld in [11]. During the simulation, the load at Bus 5 was increased from 125 to 160 MW. The simulated voltage, frequency, and real and reactive power at Bus 7 were recorded for the entire transient stability simulation. The measurements at Bus 7 are the same measurements a PMU would record during an actual event occurring on the grid.

The goal is to use a Play-In system where the PlayInGen model at Bus 7 plays in the recorded frequency and voltage magnitude to just the generator and transformer models attached at Bus 2, then compare the real and reactive power for the event and the Play-In simulation. Since the models are exactly the same in both the event and Play-In, the real and reactive power should be the same if the PlayInGen model works correctly. Results showed that simply playing in the measured voltage and frequency at Bus 7 does not produce the same real and reactive powers. The following sections provide details to perform a simulation within PowerWorld then a Play-In simulation using frequency and voltage to get a near perfect Play-In simulation.

3.3.1. Bus Frequency Low Pass Filter

The original frequency vector used as input into the Play-In simulation was the output frequency for the wsc_9bus system. The resulting Play-In simulation did not provide the perfect Play-In as expected. The real and reactive powers from the Play-In simulation followed the general response of the event data as shown in Figure 18.

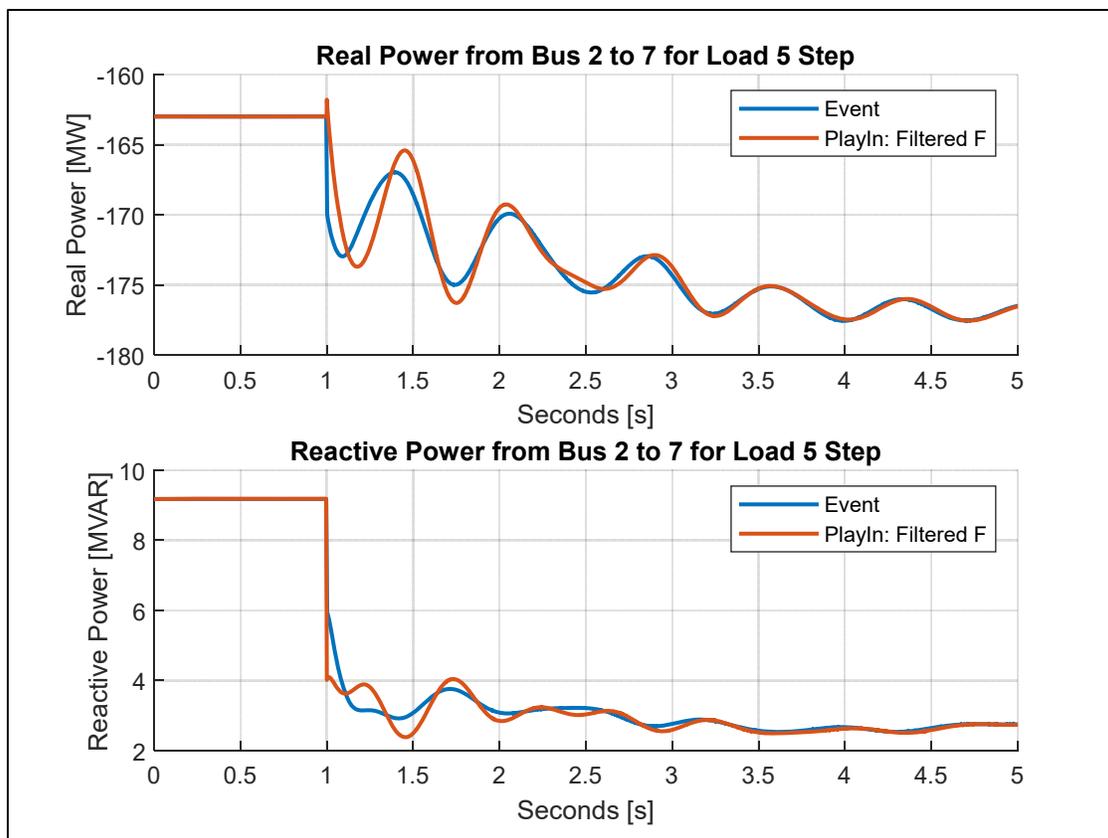


Figure 18. PQ comparison for filtered input frequency.

At this point, the cause of the poorly matching Play-In real and reactive power was unknown so voltage magnitude and frequency vectors were compared since those are the quantities played into the PlayInGen model. The comparison for the voltage magnitude and frequency is illustrated in Figure 19. The expectation for the voltage magnitude and frequency would be the same in both the event and Play-In cases. The voltage magnitude comparison was near perfect (a single time step delay at one second because the event had two points at one second) but the flaws existed in the frequency comparison. The differences in frequency are highlighted in detail in Figure 20 which is a zoomed-in version of the frequency plotted within Figure 19. Since only the frequency measurements contained differences, the real and reactive power differences were attributed to the input frequency vector.

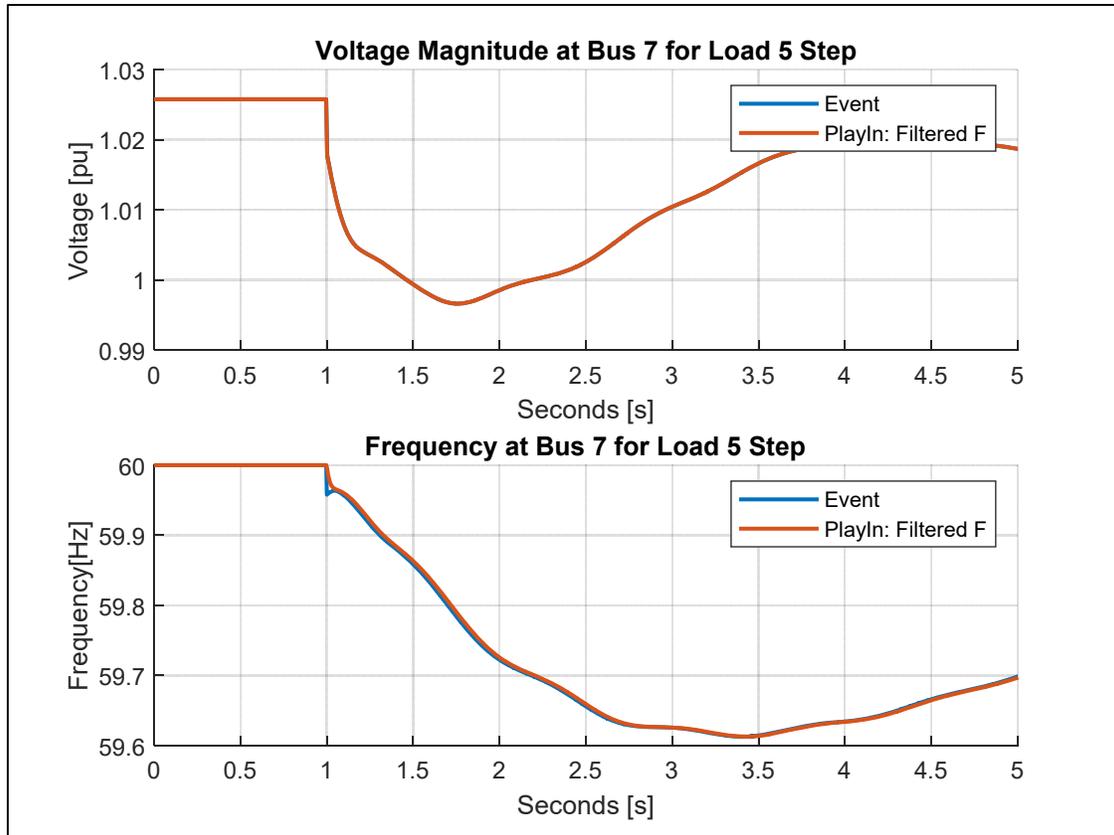


Figure 19. VF comparison for filtered input frequency.

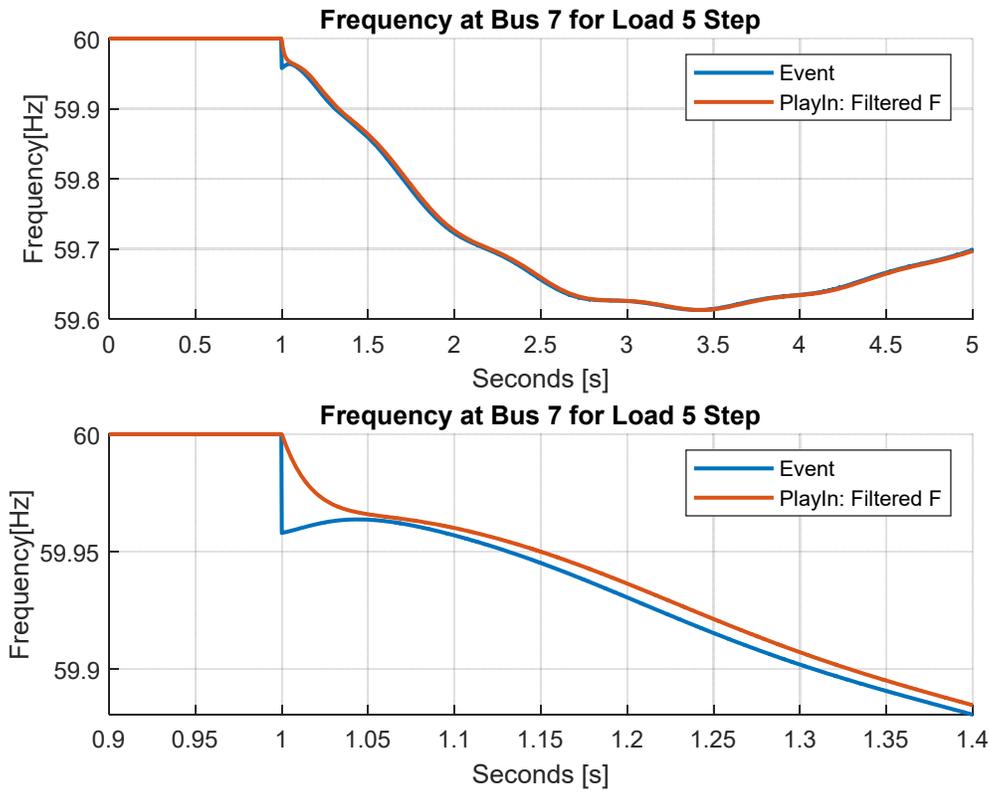


Figure 20. Frequency for filtered input frequency.

As mentioned earlier, the PlayInGen model acts as a Thevenin voltage source which controls the voltage magnitude and angle given the input voltage magnitude and frequency. The PlayInGen model integrates the frequency to get the voltage angle at the bus. The voltage angle was also compared for both the event and Play-In shown in Figure 21. Since the frequency comparison had differences, the voltage angle also contained differences.

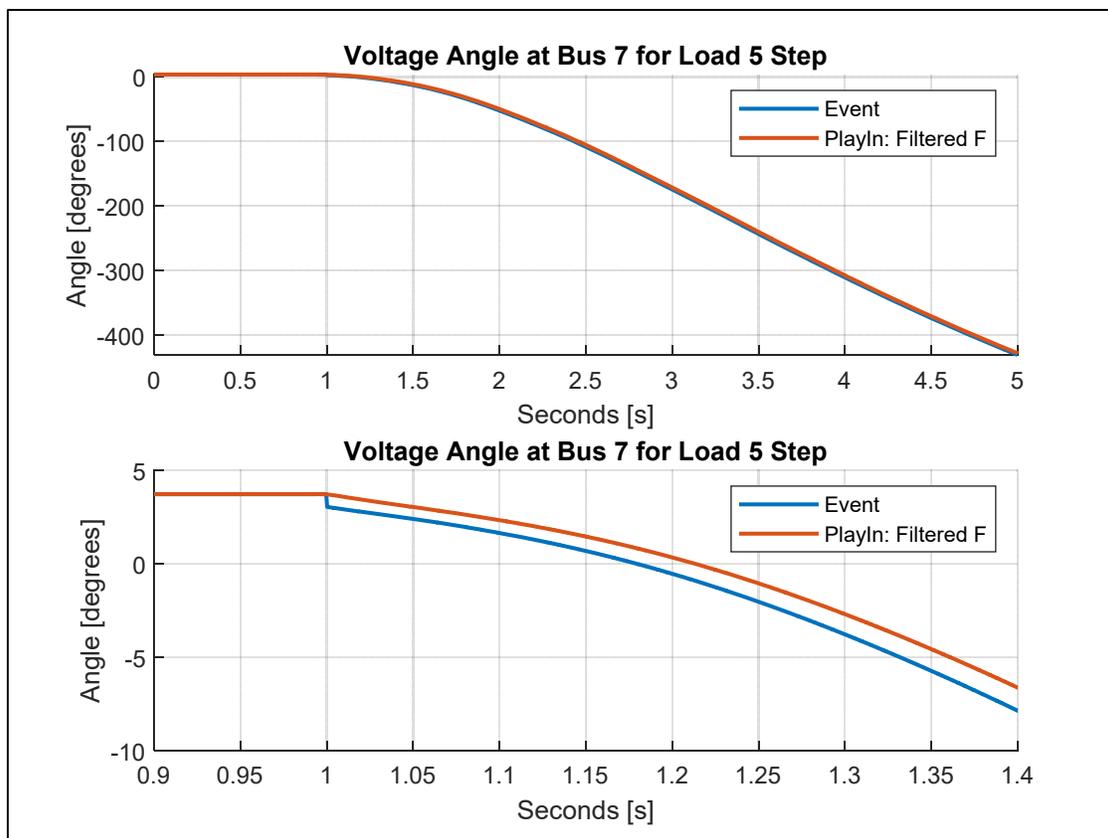


Figure 21. Voltage angle comparison for filtered input frequency.

While attempting to determine the source of error for the frequency, the PowerWorld manual in Figure 22 revealed that a time-constant was associated with the frequency calculation. The frequency was calculated by taking the derivative of the voltage angle then low pass filtering [15]. This means that the input frequency of the Play-In simulation was a filtered version of the event frequency which created a source of error. Since the measured frequency is filtered, the voltage angle will be used to diagnose differences in the Play-In simulation.

Common: Frequency Measurement Options
Bus Frequency Measurement Time Constant (Sec.)
 Bus frequency in a transient stability simulation is a value which is calculated by performing a special calculation similar to taking the derivative of the bus angle. This means there is a time-constant associated with calculating this frequency and this value can be specified here. Also note that Bus frequency is calculated at all buses during a transient stability simulation.

Figure 22. Frequency measurement options in PowerWorld [15]

3.3.1.1. Low Pass Filter Pole Cancellation

The next step going forward is an attempt to cancel the low pass filtering performed by PowerWorld when calculating the bus frequency. The setup for the process for low pass cancelling is illustrated in Figure 23. The time constant used for the low pass filter is a setting that is shown in Figure 24. The setting changes the cutoff frequency for the low pass filter. The setting can be made to be any value between 0.01 and 1 seconds. During these tests, the time constant setting was made to be the minimum value of 0.01 seconds. Making the time constant small increases the cutoff frequency which allows higher frequency content of the signal to be passed without attenuation. Since no way has been found to turn off the low pass filtering, the goal is to minimize the low pass filtering effects on the frequency signal by changing the cutoff frequency of the low pass filter. Cascading the low pass filter with a filter with a zero at the pole of the low pass filter and a pole with an extremely large cutoff essentially cancels the low pass filtering effects. The cancelling filter time constant, T_{small} , was set to two time steps which for this simulation was 0.0001. The overall calculation shifts the filter cutoff frequency to a frequency that is 100 times the previous frequency.

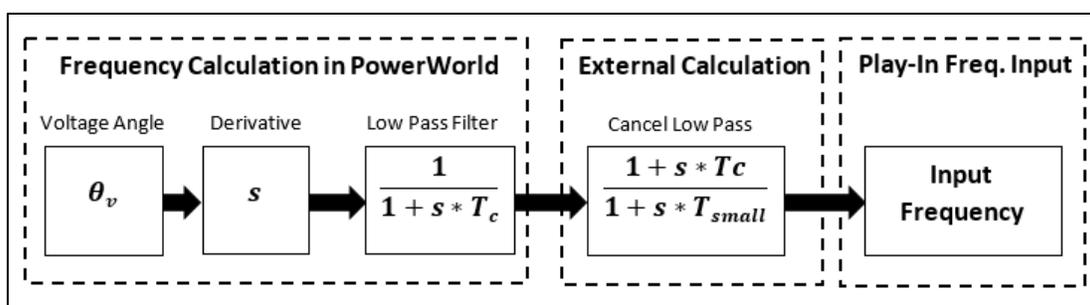


Figure 23. Block diagram of cancelling of low pass filter.

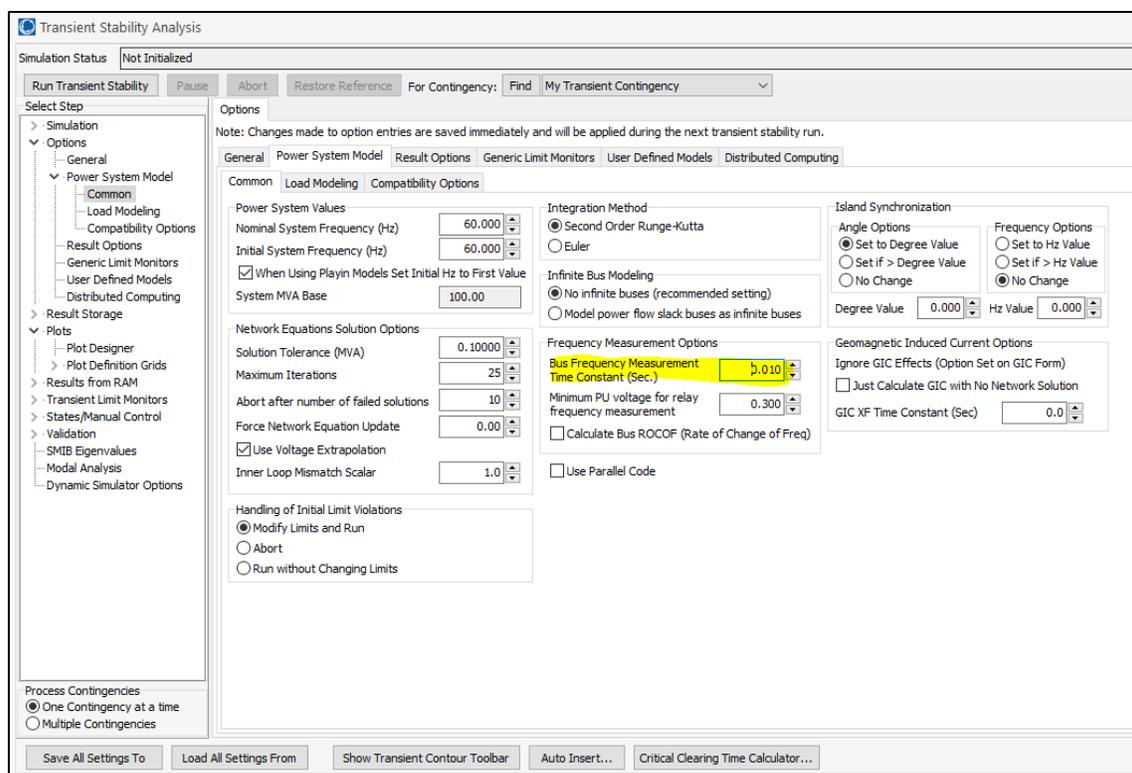


Figure 24. Time constant frequency measurement option.

The new frequency vector was used in a Play-In simulation with the voltage magnitude. In Figure 25, the real and reactive power comparison with the cancelled low pass filter shows improvements on the Play-In simulation. Since differences remain between the event and Play-In real and reactive power, this indicates an error remains with the Play-In simulation.

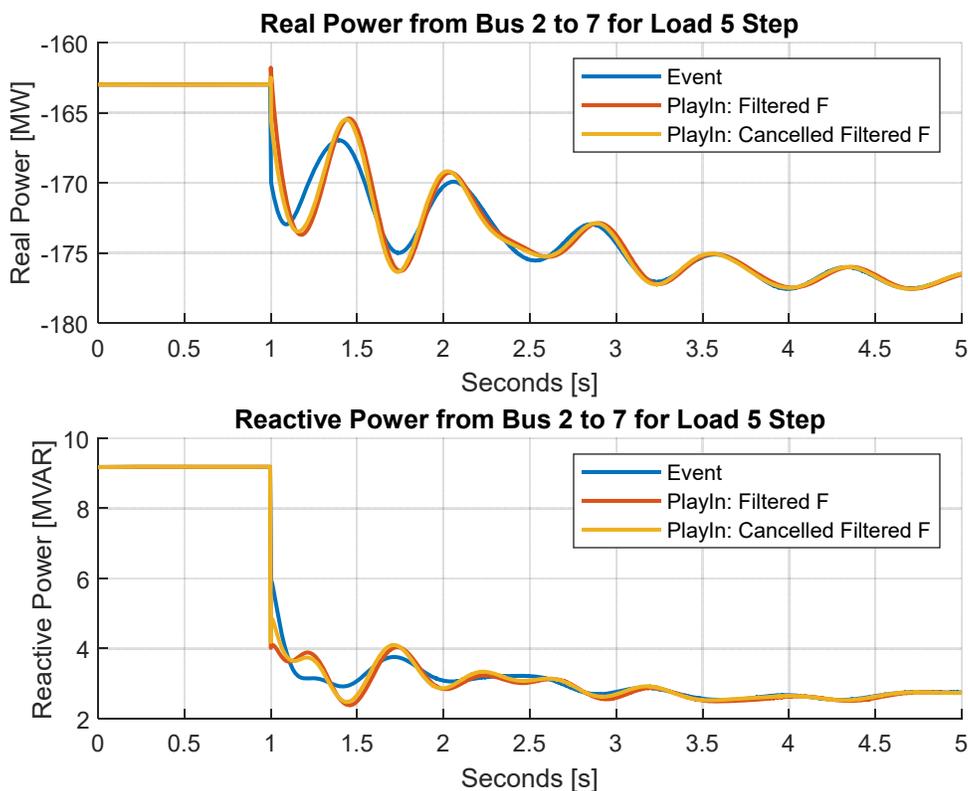


Figure 25. PQ comparison for cancelled filtered frequency.

The voltage angle plot in Figure 26 illustrates the improvements that cancelling the low pass filter had on the Play-In simulation. As shown by the differences in the voltage angle, the integration of frequency vector used for the input of the Play-In simulation does not contain the same voltage angle information as the event. At this point, the frequency calculation provided through PowerWorld does not contain all the voltage angle information for reasons that will be apparent in the following section.

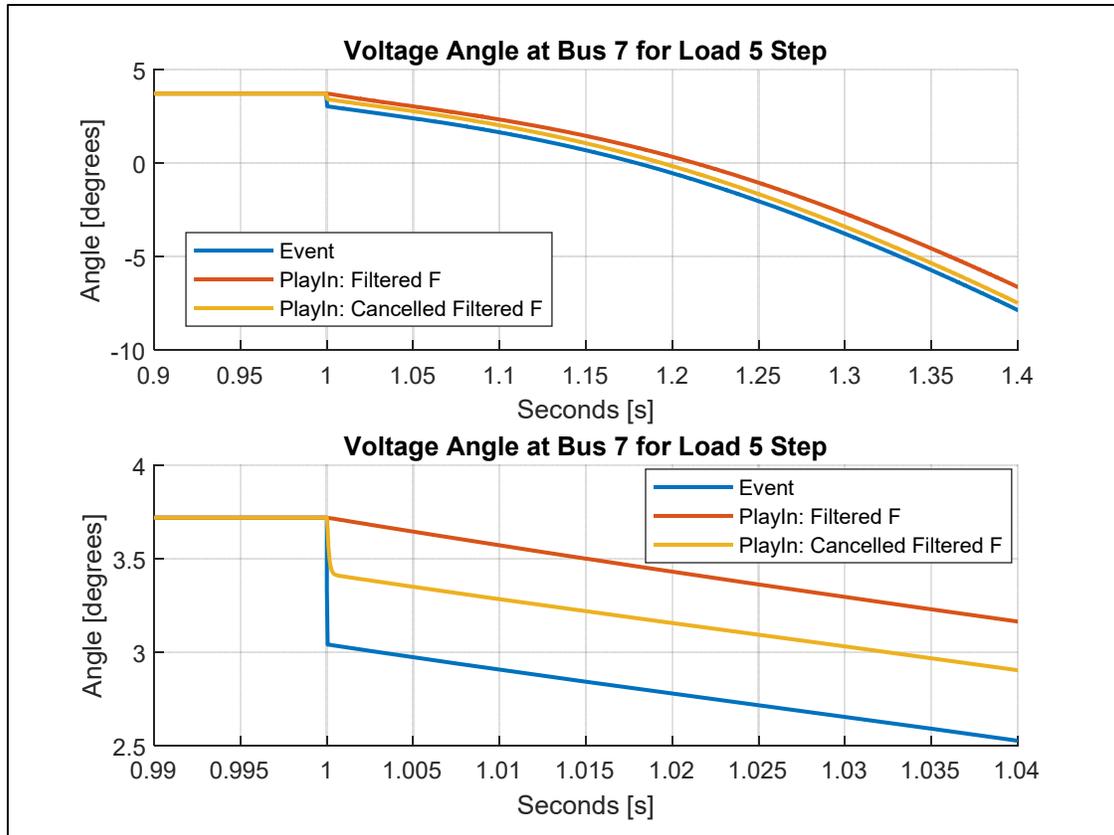


Figure 26. Voltage angle comparison for cancelled filtered frequency.

3.3.2. Voltage Angle Differentiation for Frequency

To achieve a perfect Play-In simulation, the voltage angle from both the event and Play-In simulations need to match. Since the frequency output from PowerWorld does not contain all the voltage angle information, the voltage angle derivative will be performed external to PowerWorld to provide a frequency input for a Play-In simulation. The goal is to fully represent all of the voltage angle information in the Play-In simulation.

3.3.2.1. Euler Differentiation

The Euler differentiation method called the finite difference method was used to calculate the frequency given the voltage angle. The derivative of the voltage angle, $\dot{\phi}_v$, also known as frequency is calculated from the voltage angle, ϕ_v , by

$$\dot{\phi}_v(k) = \frac{\phi_{v(k+1)} - \phi_{v(k)}}{\Delta_t} \quad (1)$$

where Δ_t is the time difference between samples and k is sample number [16]. The calculated input frequency is shown in Figure 27. PowerWorld at 1 second has two samples for voltage angle so to avoid having a Δ_t of zero seconds, the second repeated point is deleted. The steep decline in frequency is a result of the instantaneous change of voltage angle that occurs at 1 second.

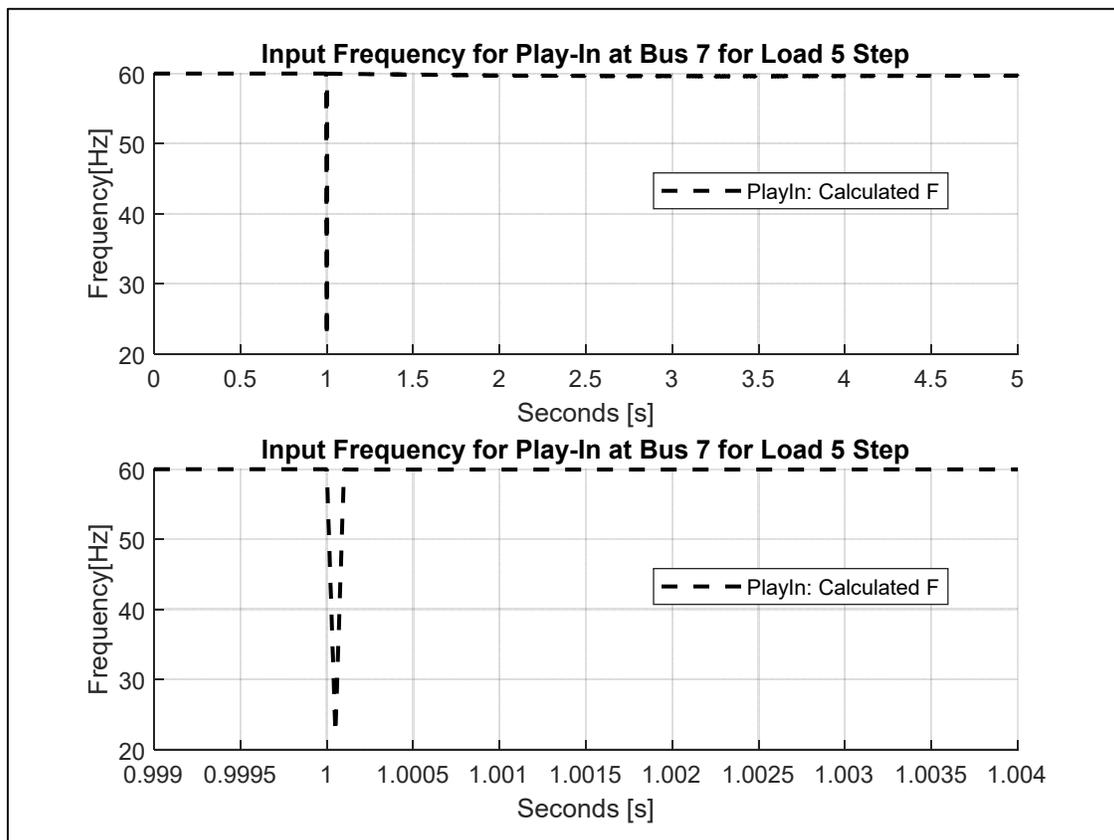


Figure 27. Calculated input frequency from voltage angle.

The resulting real and reactive power from the Play-In using the externally calculated input frequency compared to the event is shown in Figure 28. The real and reactive power from Play-In using calculated frequency overlaps the event data nearly perfectly. The only flaw in the simulation is the one time step delay for the real and reactive power which results from the

deletion of the repeated point when calculating frequency. Overall, the Play-In simulation using the calculated input frequency verifies it is working correctly, and the output of a Play-In simulation will provide the same output as an event simulation if the same models are used in both cases as long as the frequency is calculated using the above method. The two voltage angle simulations match for both the event and Play-In cases in Figure 29. The logic used to deduce the Play-In simulation problem was proven correct because if the voltage angle of both the event and Play-In voltage angle simulations match, then the real and reactive power simulations would match, provided the voltage magnitude simulations matched each other.

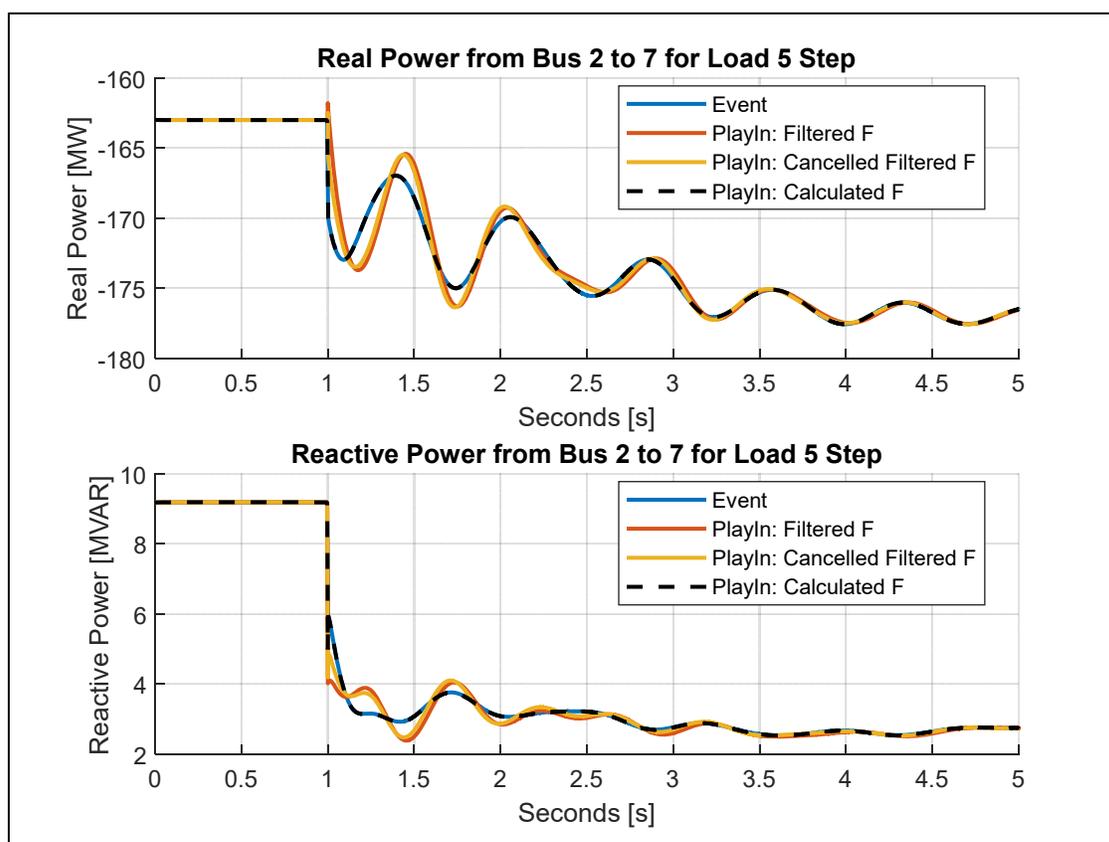


Figure 28. PQ comparison calculated frequency.

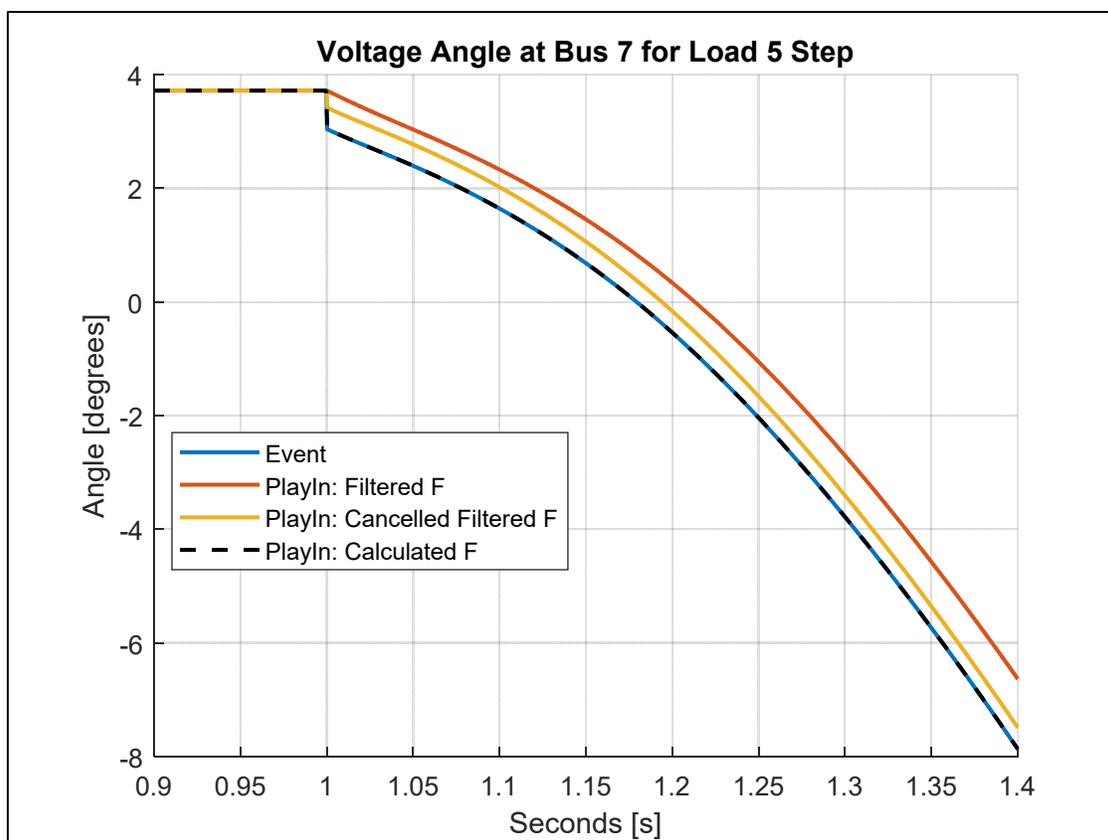


Figure 29. Voltage angle comparison calculated frequency.

3.3.2.2. Voltage Angle Information Lost when Power Flow Resolves

The reason that the input frequency for the Play-In needs to be calculated outside of PowerWorld is due to the way PowerWorld calculates frequency during a transient stability simulation. During a transient stability simulation, each time step has at least one voltage angle measurement value to use in a frequency calculation but when a contingency occurs, in this case an increase in load by 45 MW, a second voltage angle measurement is added to the same time step. The reason why there is a second voltage angle measurement at the same time step is inferred to be the result of the PowerWorld software resolving the power flow due to different system loading conditions. The two voltage angle measurements at 1 second can be seen in Figure 29 which represent an instantaneous change in voltage angle. The resulting derivative of

an instantaneous voltage angle change is an infinite frequency. To avoid infinite spikes in frequency, the instantaneous voltage angle changes are not included in frequency measurement for PowerWorld.

In conclusion, the PowerWorld Play-In and event simulations were exact matches when the frequency vector was calculated externally from PowerWorld using the output voltage angle signal. The reasoning behind this was due to a portion of the voltage angle signal being neglected during the frequency calculation during an instantaneous voltage angle change. The event simulation provides two voltage angle samples at a single time step when a contingency occurs during the simulation (a load step in this case). Also, the frequency signal output from PowerWorld is unavoidably low pass filtered which creates error when running a Play-In simulation. The PSLF software package likely contains similar issues when attempting to achieve a perfect Play-In simulation since both use similar Thevenin voltage sources. Due to encountered errors such as the unexpected model behaviors and small time-step problems in PSLF, the point was never reached to verify the Play-In simulation. A user can utilize the information provided in this thesis and apply it to the PSLF software package to improve the Play-In simulation.

4. Parameter Fitting and Adding Measurement Noise

The setup for power plant model validation begins with starting with the entire system within the software program of choice. The power plant model is validated against an actual event occurring on the actual electrical system. Typically, the measurements of the event come from a PMU measurement which measures the voltage and current phasors taken at a known point in the electrical system. The bus where the PMU is located needs to be identified in the software, then all of the models outside of the power plant under validation and the PMU bus need to be eliminated. A small section of the system will remain in the software to perform model validation. The validation is conducted by adding a generator model that behaves like a Thevenin voltage source to the PMU bus so the voltage magnitude and frequency can be inputted into the simulation. The reduced system with the addition of a Thevenin voltage source is referred to in this text as a Play-In system. The real and reactive power is compared for the Play-In simulation and data recorded by the PMU to determine if a power plant model is validated. If the model does not match the PMU data, improvements to the model need to be made so the model provides an accurate representation of the actual system which is referred to as model calibration.

4.1. Least-Squares Fitting

A commonly used method of model calibration is an iterative approach taken to minimize the least-squared error between the measured and simulated powers. The nonlinear dynamic equations that are solved during the Play-In simulation are summarized by the following equations

$$\dot{x}(t) = f(x(t), |V(t)|, f(t), \theta) \quad (2)$$

$$y(t) = g(x(t), |V(t)|, f(t), \theta) \quad (3)$$

where $x(t)$ is the state vector, $|V(t)|$ and $f(t)$ are the PMU voltage magnitude and frequency, $y(t)$ is the simulation output vector containing real and reactive power, and θ is a vector of model parameters. The error between the model and the measured data is

$$e_k(\theta) = \bar{y}_k - y_k(\theta) \quad (4)$$

where the subscript k denotes the discrete sample number and \bar{y} is the real and reactive power recorded by the PMU. The sum of the squared error is

$$V(\theta) = \sum_{k=1}^N e_k(\theta)^2 \quad (5)$$

where $V(\theta)$ is also called the cost function. The parameters that minimize the cost function are defined as the best-fit parameters. The usage of nonlinear least-squares fitting in combination with PMU data is accepted in industry for model validation and calibration [17].

An algorithmic approach is taken to minimize the cost function when performing least-squares fitting. The *lsqnonlin* function within MATLAB was used for a nonlinear least-squares solver used to perform least-squares fitting on generator parameters during this research. The MATLAB solver was setup to use the Trust-Region-Reflective Least Squares Algorithm since this algorithm provided the ability to set bounds on the parameter. Other algorithms available to be used with the MATLAB solver did not have the capabilities to set parameter bounds. A detailed explanation on the Trust-Region-Reflective Least Squares Algorithm used by MATLAB is provided in [18].

4.2. Measurement Noise

Bonneville Power Administration (BPA) operates the federally-owned portion of the northwest US transmission system. BPA routinely conducts system tests in which the grid is

intentionally perturbed. The activation of a large resistive brake (at the Chief Joseph substation) and a bipolar power pulse produced by the Pacific DC Intertie (PDCI) (see [19] and references therein) are two tests conducted by BPA. The PMU data set recorded during BPA testing provides a series of the same events repeated on the power system at similar loading condition. Performing least-squares fitting on parameters for each event provides an actual parameter distribution. The goal is to add many realizations of measurement noise to a single PMU event, then the resulting parameter distribution from least-squares fitting replicates the parameter distribution from the series of events conducted on the actual power system. The measurement noise is added to the four PMU quantities to test the effects on parameter distribution after least-squares fitting, then comparing parameter distribution to the actual distribution. The starting point for the measurement noise is to begin with a realistic noise model that could be represent a PMU. The measurement noise would then be tuned to provide similar parameter distributions found during the actual events.

This method can be described as Monte Carlo analysis [20]. The basic strategy is to quantify the identifiability of each parameter by performing many simulations, each with random measurement noise. Models can contain parameters that are more identifiable than other parameters. For example, consider the two-pole system with two widely different time constant parameters

$$G(s) = \frac{p_1 p_2}{(s + p_1)(s + p_2)} \quad (6)$$

where s is the Laplace variable, $p_1=1$, and $p_2=100$. The step response of the system will be dominated by the slower pole $-p_1$ for the system, so the cost function should show a much higher sensitivity to p_1 than p_2 . The step response to the two pole system was calculated, then a

small amount of Gaussian noise was added to it. The cost function was calculate for a range of the model parameters for three separate realizations of noise. The results are shown in Figure 30. The p_1 value that minimized the cost function is much closer to the correct value than the values minimizing p_2 in each of the three cases. The p_1 parameter varies over a range of $\pm 1\%$ but the p_2 parameter fluctuates by $\pm 50\%$ of the original value.

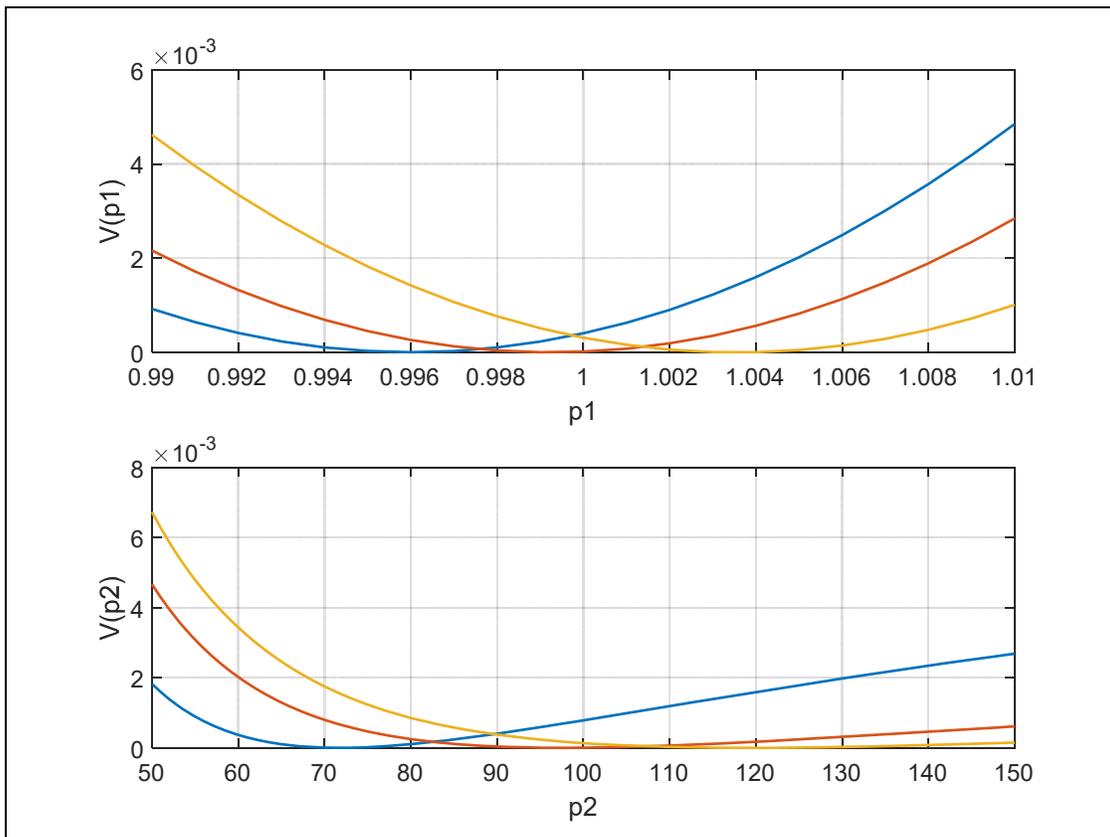


Figure 30. Normalized cost functions for two pole system noisy step response for three noise realizations.

A realistic model of the measurement noise could be found by analysis of the PMU itself. Knowing the hardware and components along with the algorithm used to compute the electrical phasors would provide key insight to the potential measurement noise for a certain PMU. This method for finding a measurement noise vector would not be effective since it requires gathering

proprietary or difficult to obtain information regarding the PMU installation and calculation methods. A second potential method to find the measurement noise could be found through the statistical analysis of the recorded data from the PMU. In this method, it would be difficult to differentiate between the measurement noise and the random switching/ load noise which is always present on the grid. The method used during this research is a combination of the two methods. A plausible model for the measurement noise is developed that should apply to most PMUs, then the noise model is calibrated using a unique PMU data set. The same logic and methodology is used in [21].

Simply adding four different independent vectors of noise to the frequency, voltage magnitude, real power, and reactive power signals would not be an effective way to add measurement noise since the four quantities correlate. For example, the voltage signal is used to calculate the real and reactive power signals. The plausible model for measurement noise needs to capture the proper correlation between each of the signals. Therefore, the strategy used was to add independent noise to the complex voltage and current phasors V and I , then compute the voltage magnitude, frequency, real power, and reactive power quantities from the noisy phasors. The proper correlation between quantities is captured in this methodology.

The method begins with four mutually independent sequences of zero-mean Gaussian noise, v_i , for $i = 1..4$. The variance of the each will be described afterwards. The sequences are passed through a low-pass Butterworth filter with a cutoff frequency of 5 Hz. The cutoff frequency was selected to provide a bandwidth close to standard PMUs. The filtered noise sequences are referred to as $v_{i,f}$. The models for the noisy voltage and current phasors are

$$V = (|V_{pmu}| + v_{1,f})e^{j(\angle V_{pmu} + v_{2,f})} \quad (7)$$

$$I = (|I_{pmu}| + v_{3,f})e^{j(\angle I_{pmu} + v_{4,f})} \quad (8)$$

where V_{pmu} and I_{pmu} are the voltage and current phasors actually measured by the PMU, and V and I are the phasors with the artificial noise to be used during a Play-In simulation. The real and reactive power are calculated from the noisy voltage and current phasors by

$$P = \Re(3VI^*) \quad (9)$$

$$Q = \Im(3VI^*). \quad (10)$$

The noisy frequency, f , is calculated by using an Euler derivative of the voltage angle with the added filtered noise sequence. An actual PMU may not compute frequency by differentiating angle, but other methods would have similar noise profiles.

To determine the appropriate variances $\sigma_i^2 = VAR(v_i)$ for each of the noise sequences before filtering, the method utilizes a unique PMU data set taken during BPA's routine testing. The PMU data collected during these events can be used for, among other things, validating power plant models. Because both the PDCI and the resistive brake pulse at the Chief Joseph substation effectively result in small real power imbalances on the grid, they can be expected to excite any nearby power plant similarly. The PMU data set contains three days of data from a single day in 2016, 2017, and 2018 where multiple PDCI and resistive brake pulses perturbed the grid. The data includes measurements from 21 different PMUs located near power plants in the region. The goal of adding noise and performing repeated simulations is to mimic what would happen if many actual events happen over a short period of time. The data set considered here with multiple events occurring over the course of a single day provide the desired statistical

sample of actual events that might be expected to be available. This data set is used to “calibrate” the variance of added noise.

A global noise scale factor m is used to scale the noise variances appropriately as follows:

$$\sigma_1^2 = m|V_{avg}| \quad (11)$$

$$\sigma_2^2 = m\pi \quad (12)$$

$$\sigma_3^2 = m|I_{avg}| \quad (13)$$

$$\sigma_4^2 = m\pi \quad (14)$$

where $|V_{avg}|$ and $|I_{avg}|$ are the average voltage and current magnitudes for the data sets in question. Notice the magnitude noise variance is scaled by the appropriate magnitude and the angle noise variance is scaled by π (full-scale angle is $\pm\pi$). The only remaining quantity to be determined to fully characterize the noise is now m , which is selected such that the parameter variance observed in the many artificial noise simulations matches the variance observed in the actual events. This was done for the generator inertia parameter, H , which plays an important role in the response to power imbalance events. An example of what the actual PMU data (thick black line) measured for one 125 MW PDCI pulse event along with four noise realizations is shown in Figure 31. Note that the noise level is large enough to be noticeable but reasonable in the sense that the major features of each signal are still prominent.

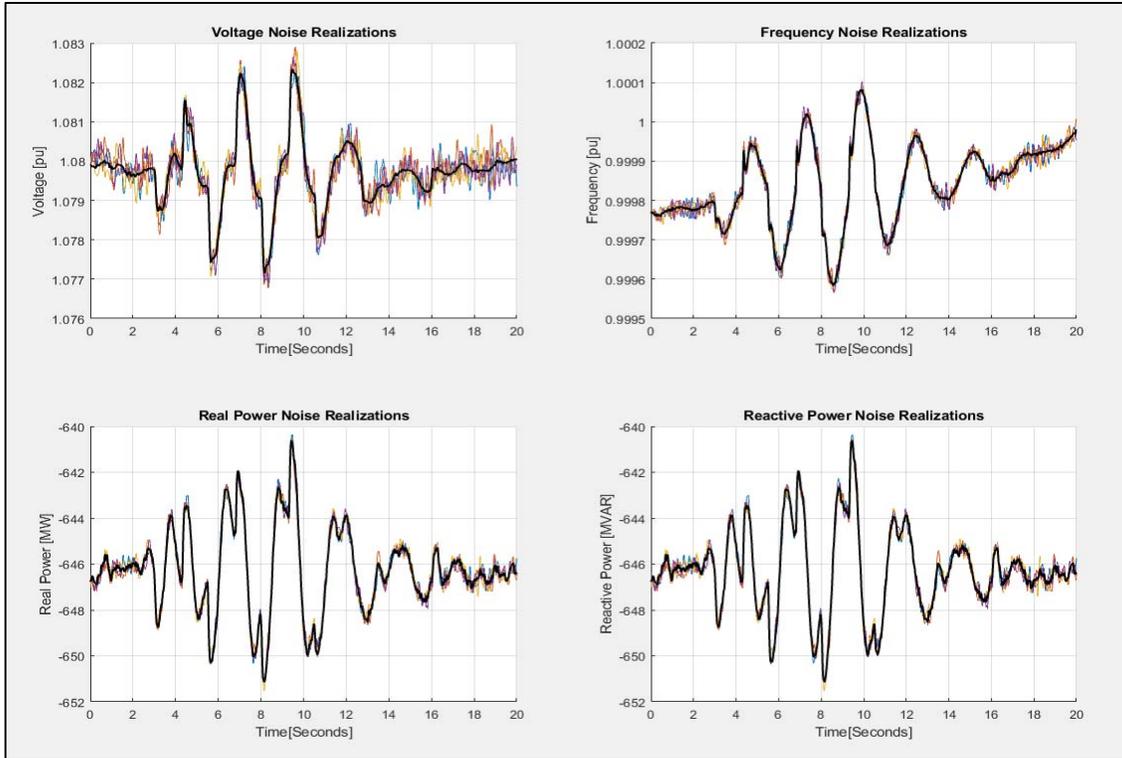


Figure 31. Centralia G1 PDCI pulse recorded by PMU along with four noise realizations of artificial noise with $m=0.0006$.

Since the repetition of the same exact event is unlikely to occur on the grid during normal system operating conditions, the addition measurement noise to a single PMU event is an attempt to approximate what would happen if the event was repeated many times by artificially reproducing or resampling the stochastic portion of the measurement. A well-known statistical method for resampling the data is bootstrapping [22]. A large amount of techniques fall under the bootstrapping category, and a simple version of it is utilized in this research. Bootstrapping techniques have been applied to study the wide-area behavior of the Western Interconnect [23], but application to a power system dynamic simulation is considered new. The literature containing the application of bootstrapping to dynamic models is quite limited. Typically, a “residual-based” strategy is used to bootstrap a single data set to many by resampling the error

between the best-fit model output and the measured data when using dynamic models. The error is made to capture the same frequency-domain characteristics [24].

5. MATLAB Description

A software interface between MATLAB and PowerWorld was developed to utilize the computational and analysis capabilities of MATLAB with the PowerWorld Simulator. The user sets up a *.PWB file containing the power system data in PowerWorld for the desired Play-In system (shown in detail in Appendix A), and then using a series of MATLAB functions and scripts, the entire process of least-squares fitting is controlled from the MATLAB software. The interface allows for the automated setup of the power system and running of a transient stability simulation within the PowerWorld Simulator based on model parameters and events defined in MATLAB. The transient stability simulation results are transferred from the PowerWorld Simulator to MATLAB to perform calculations for the least-squares fitting of parameters.

5.1. Automated Play-In Setup and Running PowerWorld from MATLAB

A single MATLAB script controls the PowerWorld transient stability simulation through a series of PowerWorld auxiliary files and SimAuto functions. An auxiliary file is simply a text file with the .AUX extension that is recognized by the PowerWorld software. The auxiliary file can contain a combination of data and scripting sections which can be used by the PowerWorld simulator. A data section within an auxiliary file may provide data for a specific type of object [25]. For example, a data section can be used to set a generator terminal voltage to a different per unit value or changing the reactance of a transformer in the system. The scripting section of an auxiliary file is a list of scripting actions for the PowerWorld simulator to perform [25]. Some examples of script commands are commands used to open or close cases and commands to run transient stability simulations. To see all the available scripting commands and the proper scripting and data section formatting, [26] outlines the auxiliary file format in detail.

The automated setup of Play-In transient stability cases from MATLAB is crucial to the research since so many iterations of transient stability simulations with different parameter values are needed to find the best fit parameter via the least-squares method. The diagram in Figure 32 shows the process of running a PowerWorld transient stability simulation from MATLAB. The first step is to create an auxiliary file SetupAux.aux which changes the voltage, real power, and reactive power flow of the Play-In system to match the initial conditions of the PMU data provided for the event being used during model validation. An example of the SetupAux.aux auxiliary file for the Coulee 24 power plant is provided in Appendix E. A calculation is performed in MATLAB which finds the desired voltage magnitude and real power output at the PV bus, then calculates the voltage magnitude for the slack bus of the Play-In system. The voltage angle at the slack bus is set to zero. The SetupAux.aux auxiliary file is also used to change the impedance values of the branches in the Play-In system.

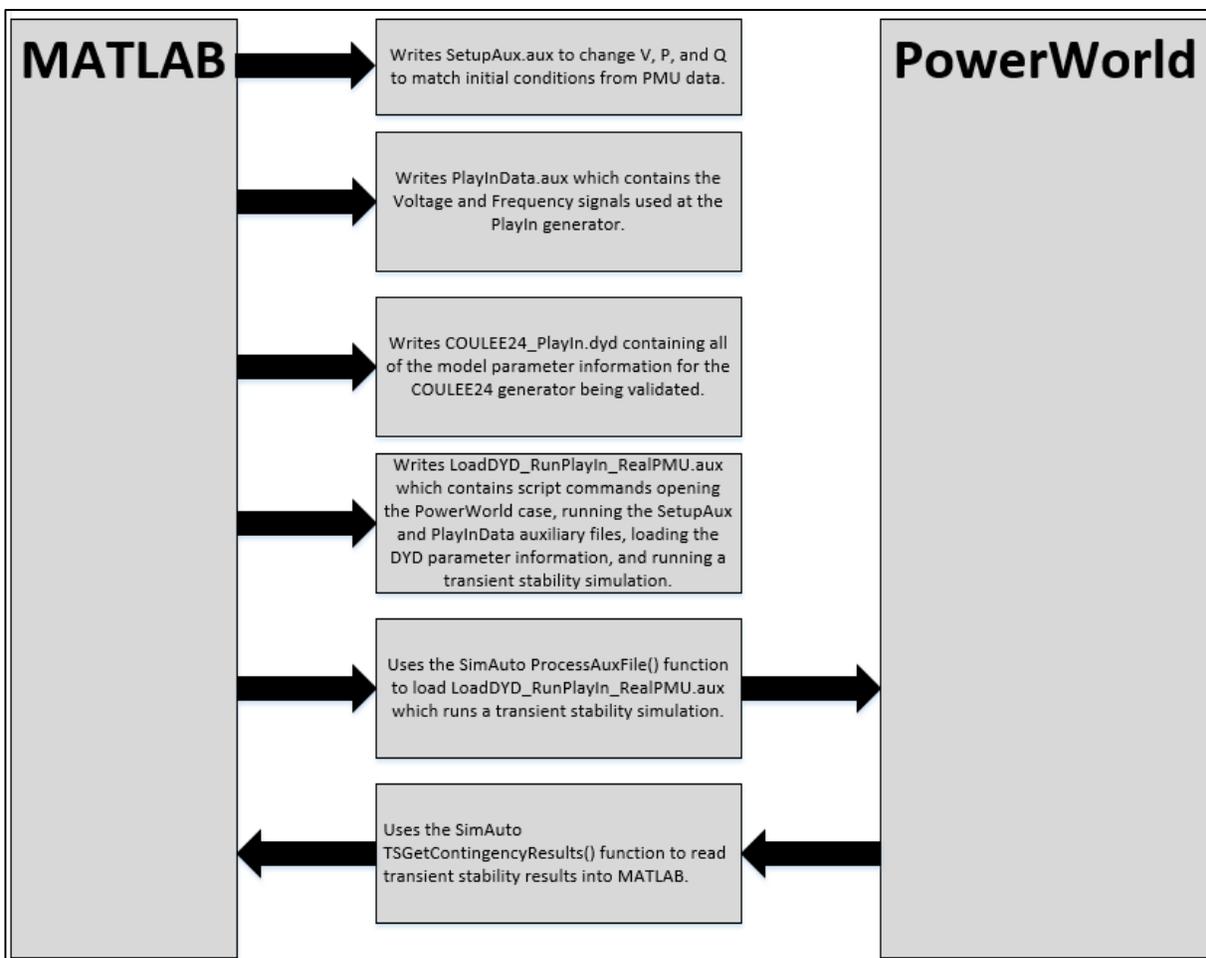


Figure 32. Diagram of running a PowerWorld simulation from Matlab for Coulee 24 Generator.

The next step is to setup the `PlayInData.aux` auxiliary file which contains the voltage and frequency signals to be used during each time step by the `PlayInGen` model which behaves as a Thevenin voltage source. An example of the auxiliary file containing the data for the `PlayInGen` is shown in Appendix B.

The `COULEE24_PlayIn.dyd` contains all the transient stability parameter values for the models within the power plant. The appropriate formatting for each model in the file can be found in [2]. The least-squares parameter fitting is the iterative process of changing the parameter values within this file to improve the overall power plant model.

The LoadDYG_RunPlayIn_RealPMU.aux is an auxiliary file that first opens up the PowerWorld case, then loads the previously mentioned auxiliary files, and runs the transient stability simulation. The LoadDYG_RunPlayIn_RealPMU.aux is shown in Appendix G. The SimAuto function called *ProcessAuxFile* is ran from MATLAB to load the LoadDYG_RunPlayIn_RealPMU.aux file to set up the Play-In system to the correct power flows to match the PMU data, loads the voltage and frequency data to be used by the PlayInGen, loads the transient stability parameter values for the models, and runs a transient stability simulation. The results of the simulation are transferred from PowerWorld to MATLAB after running the *TSGetContingencyResults* function.

6. New Generator Testing Case Setup Procedure

The following section describes issues that may not be apparent when setting up a power plant model to conduct the experiments contained in this research and provides suggestions to resolve each issue.

6.1. Best Initialization Point

It is crucial to pick a good initial frequency and voltage magnitude point within the auxiliary data file for the PlayInGen model because these values affect the output of dynamic simulation. The initial frequency and voltage magnitude define the starting voltage magnitude and angle at the PlayInGen bus for the simulation. Small changes in the voltage magnitude and angle can drastically change the real and reactive power flowing in the system. During model validation, the real and reactive power for the PMU and model simulation are compared, then the model is calibrated based on the differences. Therefore, picking an initial frequency and voltage magnitude point which minimizes the differences between the real and reactive power for the PMU and the model simulation is essential before performing model calibration.

The method used to pick the best initialization point was running a single event with many different starting points within the auxiliary data file. Instead of running every starting point for an event, intervals of 0.05 seconds were used when changing the starting point. For each simulation with different starting points, the real and reactive power was combined into a single vector for both the PMU and model simulation. The difference between the combined vectors for PMU and model simulation is referred to as the residual. The mean of the absolute value of the residual was calculated which gives a measurement of how well the simulation fits the PMU real and reactive power. The starting point which has the lowest mean was used as the starting point for that event. This process was repeated for each event used for model validation.

6.2. Tune Parameters to Get Good Initial Fit

Before performing least square fittings with added measurement noise on parameters within the power plant, it is important to verify that the overall power plant model provides an accurate representation of the physical event. The initial power plant models provided in this research were from 2016 but the events were from 2016, 2017, and 2018. In some cases, slight changes were made to the parameter values within the power plant model to improve the initial model. The goal was to tune the initial model to provide an accurate simulation of the provided PMU data.

The methodology used for tuning parameters to have a good initial fit began by identifying sensitive parameters, then trying least-squares fitting on different combinations of sensitive parameters checking to see the improvements made to the fit on the PMU events. The sensitive parameters were identified by using an aggregate of methods coded into a MATLAB script. The first method identifies sensitive parameters by sorting the singular values of the Jacobian matrix which is detailed in [27]. The second method uses the QR decomposition of the Hessian matrix in [28]. The third method based on [29] outlines a method that computes the correlation coefficient between the residual vector and the columns of the Jacobian. The fourth and fifth methods are two simple methods sorting sensitive parameters by the largest step size taken by two iterative optimization algorithms.

The sensitive parameters identified by the multiple methods above were selected to be tuned by using least-squares fitting to improve the initial model. A trial and error combination of single and multiple parameter fittings were ran using some of the identified sensitive parameters. The fittings were started with single parameter fittings of the sensitive parameters. If no single parameter fitting provides a good initial fit, combinations of different two parameter fittings of sensitive parameters were made. The process of adding a sensitive parameter to the number of

parameters fitting was continued until a fitting provided an adequate initial fit. The same fitting was conducted on each PMU event, then the final fitted values were averaged to provide a good initial starting point for each event.

6.3. Setting Parameter Upper and Lower Simulation Bounds

Within PowerWorld, some model parameters have a specific domain constraining the potential parameter value. If a parameter is set to a value outside the PowerWorld defined domain, an error will be generated which cancels the transient stability simulation. The PowerWorld *TSAutoCorrect* script command runs the auto correction of model parameters for a transient stability simulation. The parameters are changed to acceptable values for a PowerWorld transient stability simulation. The *TSAutoCorrect* script command cannot be used during this research because direct control of the parameter values is needed when least-square fitting. Therefore, the domain must be controlled in MATLAB where the least-square fitting is conducted which constrains each parameter to acceptable PowerWorld values to avoid transient stability errors canceling simulations.

The *lsqnonlin* function within MATLAB is utilized within this research to solve the nonlinear least-squares problems while fitting parameters for a model. The *lsqnonlin* function has many options allowing a user to setup the solver. For example, the numerical algorithm used by the solver can be changed to the desired algorithm by adjusting the options. The default Trust-Region-Reflective algorithm was used during the research. A detailed explanation of the Trust-Region Reflective algorithm can be found in [30].

The *lsqnonlin* options allow for the domain of each parameter to be defined by setting an upper and lower bound for the numerical algorithm. The appropriate setup for the *lsqnonlin* bounds can be found in [31]. The upper bound would correspond to the largest acceptable

parameter value that PowerWorld would allow for the given parameter. Similarly, the lower bound would be the smallest acceptable parameter value PowerWorld would allow for a given the parameter. PowerWorld provides documentation which explains the changes made during *AutoCorrection* for each parameter within a model. This essentially defines the domain of each parameter. For example, the exciter model ESST5B which has the block diagram shown in Figure 33 has the *AutoCorrection* properties shown in Figure 34. The second portion of the *AutoCorrection* properties for the T_r time constant would be used when determining the bound for $lsqnonlin$ since the first portion turns the parameter off. The lower bound for T_r would be set to the minimum number of time step (typically four) times the fixed time step for the transient stability simulation. The upper bound for T_r would be infinite since no information is provided constraining the maximum value of the parameter.

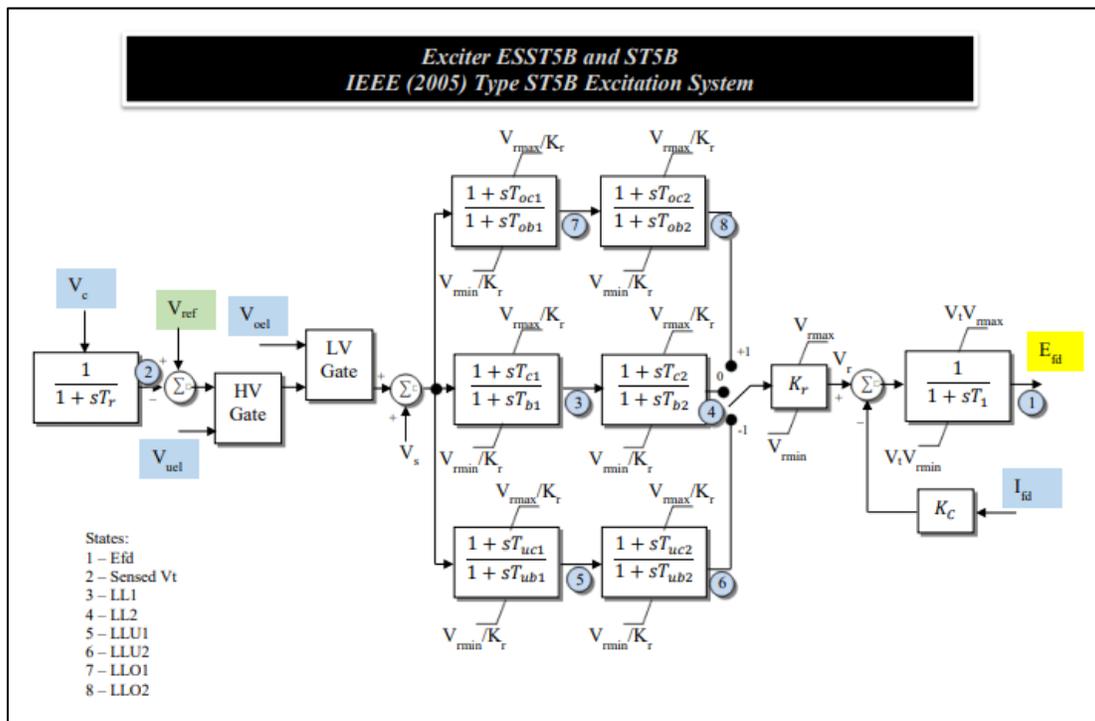


Figure 33. IEEE ESST5B model [32].

Exciter Model: ESST5B and ST5B	
AutoCorrection Properties	
Following checks and corrections are applied during Validation and AutoCorrection.	
<ul style="list-style-type: none"> • If $0.0 < Tr < 0.5 * Mult * TimeStep$ then $Tr = 0$, Elseif $0.5 * Mult * TimeStep < Tr < Mult * TimeStep$ then $Tr = Mult * TimeStep$ • If $0.0 < Tb1 < 0.5 * Mult * TimeStep$ then $Tb1 = 0$, Elseif $0.5 * Mult * TimeStep < Tb1 < Mult * TimeStep$ then $Tb1 = Mult * TimeStep$ • If $0.0 < Tb2 < 0.5 * Mult * TimeStep$ then $Tb2 = 0$, Elseif $0.5 * Mult * TimeStep < Tb2 < Mult * TimeStep$ then $Tb2 = Mult * TimeStep$ • If $0.0 < Tob1 < 0.5 * Mult * TimeStep$ then $Tob1 = 0$, Elseif $0.5 * Mult * TimeStep < Tob1 < Mult * TimeStep$ then $Tob1 = Mult * TimeStep$ • If $0.0 < Tob2 < 0.5 * Mult * TimeStep$ then $Tob2 = 0$, Elseif $0.5 * Mult * TimeStep < Tob2 < Mult * TimeStep$ then $Tob2 = Mult * TimeStep$ • If $0.0 < Tub2 < 0.5 * Mult * TimeStep$ then $Tub2 = 0$, Elseif $0.5 * Mult * TimeStep < Tub2 < Mult * TimeStep$ then $Tub2 = Mult * TimeStep$ • If $0.0 < Tub1 < 0.5 * Mult * TimeStep$ then $Tub1 = 0$, Elseif $0.5 * Mult * TimeStep < Tub1 < Mult * TimeStep$ then $Tub1 = Mult * TimeStep$ • T1: If $Mult * TimeStep > 4$ then $T1 = 0.25 * Mult * TimeStep$, else $1 < T1 < Mult * TimeStep$ • If $V_{rmax} < V_{rmin}$ then swap the values 	
Mult represents the user-specified value Minimum time constant size as multiple of time step option on the Validation page of the Transient Stability Dialog	
TimeStep represents the integration time step being used as described on TimeStep	

Figure 34. PowerWorld ESST5B AutoCorrection properties [32].

Not all parameters are included in the PowerWorld *AutoCorrection* documentation so it is necessary to be aware that other parameter values can cause an error canceling the transient stability simulation. Finding the domain to set the *lsqnonlin* bounds for other parameter can be roughly accomplished by setting the parameter to a series of values, then checking to see if any of those values provide an error. A good series of values to check would be an extremely large negative number, a negative number close to zero, zero, a positive number close to zero, and a large positive number. Checking the simulation log during an error will provides insight into the desired bound for each parameter.

7. Results Single Generator Parameter Testing with Artificial Measurement Noise

A single parameter fitting is a least-squares fitting where only a single parameter is changed to improve the model. The least-squares fitting procedure uses an iterative process to minimize the error between the PMU recorded event and the Play-In simulation. A multiple parameter fitting with least-squares fitting can be performed where multiple parameters are changed at a time to improve the model. The research conducted in this thesis focusses on single parameter fittings and does not investigate multiple parameter fittings. The following results are from Play-In systems with a single generator.

7.1. Centralia G1 Generator

The first power plant analyzed under this research was the Centralia power plant which is located in western Washington. The power plant has two identical coal-fired generating units which have a combined capacity of 1,340 MW [33]. This research focused on the first unit located at the bus named CENTR G1. This unit was chosen to conduct testing on because the PMU data was readily available for this unit and the radial setup of the system making Play-In simulations easier to setup. The CENTR G1 Play-In system is shown in Figure 35. The Centralia system is simpler than other potential generators available in the PMU data during the BPA testing since only a single generator and transformer are in the system downstream of the PMU. Other power plants within the PMU data have multiple generators and transformers making for a more complex Play-In system.

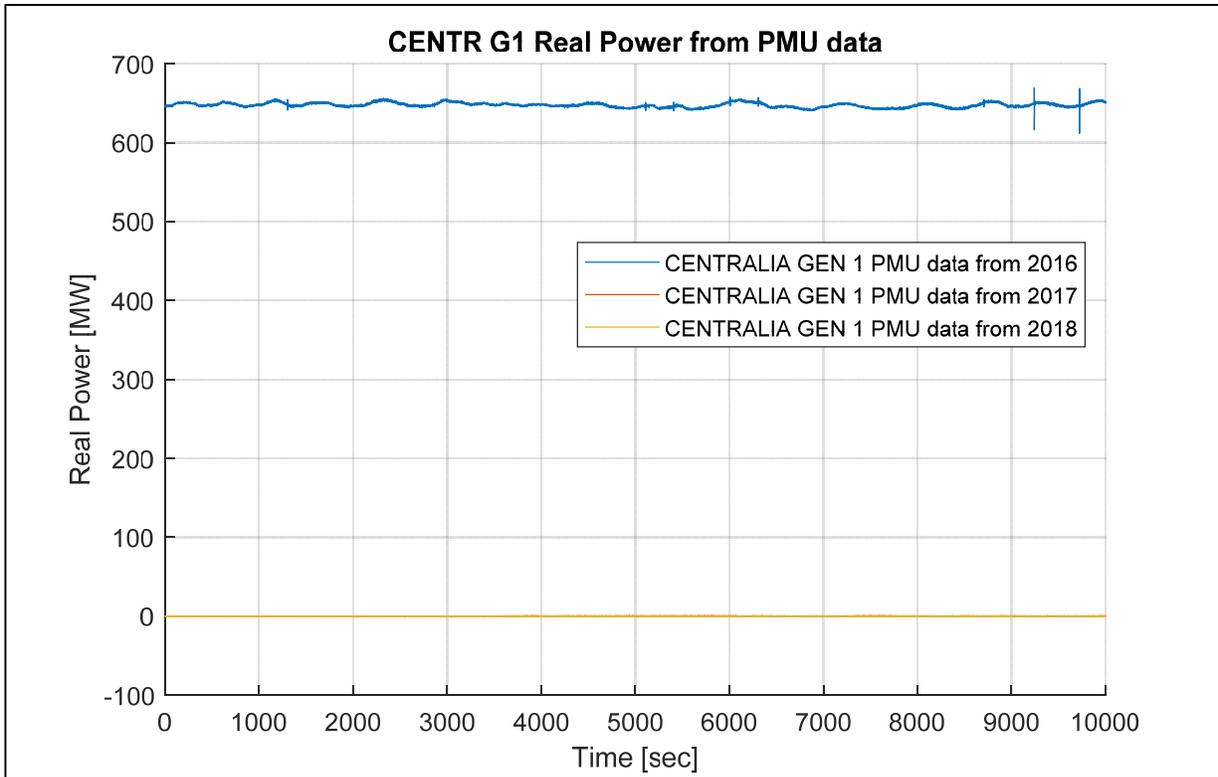


Figure 36: Real power from multiple years of PMU data for CENTR G1 generator.

The PMU data from 2016 contains 11 PDCI pulses and 4 resistive brake pulses at the Chief Joseph brake. Only the 11 PDCI pulses occurring on a single day were the events used for parameter fitting since it was deemed that four resistive brake pulses did not provide enough distribution information. Ideally, a large number of PDCI pulses at the same exact system loading conditions would be used to approximate the parameter distribution due to measurement noise, but the 11 PDCI pulses on a single day with similar system loading conditions is the best available approximation.

The CENTR G1 model provided for research did not provide a good initial fit for to the PDCI pulses. Through the process described in Section 6.2, the parameters of the model were tuned to provide a good initial fit for the model. The four parameters that were changed are documented in Table I. The improved initial fit is illustrated in Figure 37.

Table I. Tuned CENTR G1 parameters to provide good initial fit.

Model	Parameter	Initial Value	Value to Improve Fit
genrou	H	3.25	3.042533480
genrou	Ld	2.05	7.448166598
XFMR	X	0.024309	0.031234032

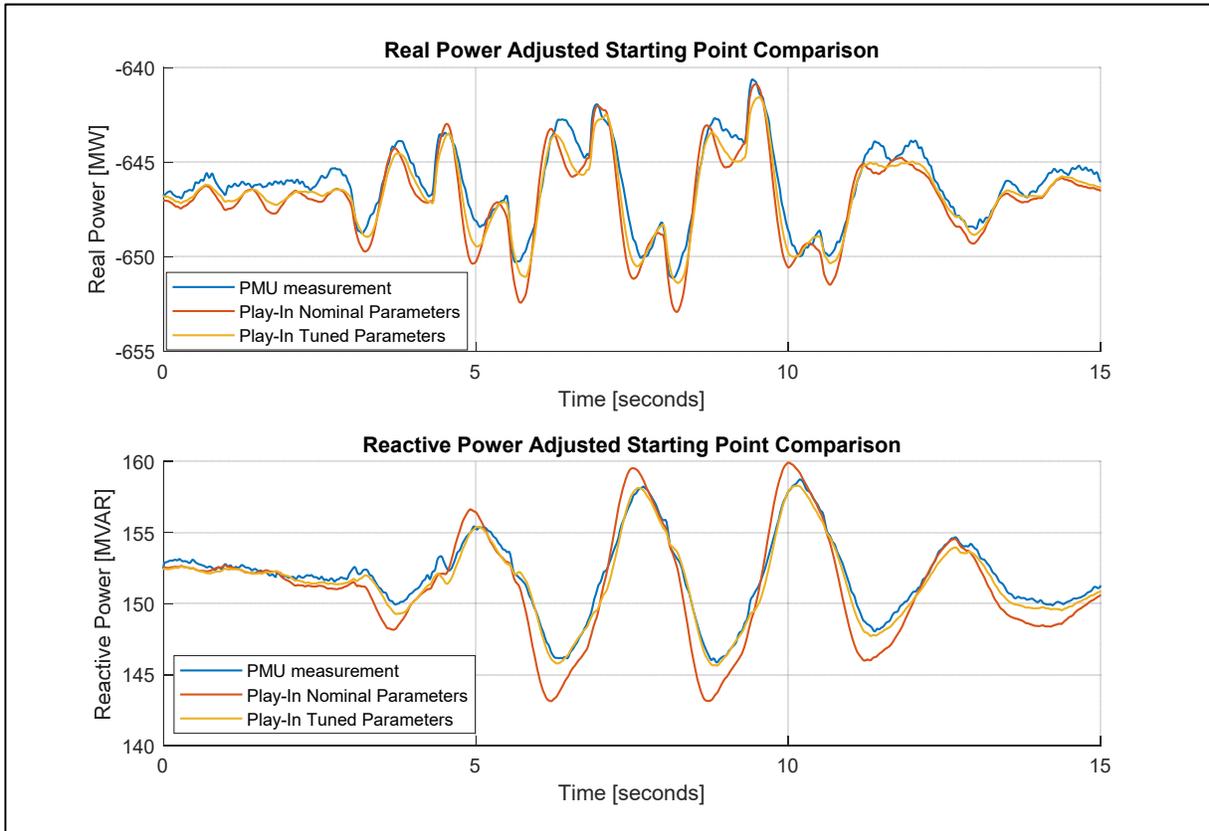


Figure 37: CENTR G1 improved initial fit.

After getting a good initial fit between the model and the actual event, a single parameter fit for each tunable parameter (generator and transformer) was conducted on each PDCI pulse. Parameters that were originally set to zero within the models were excluded from fitting. The models used by the generator unit are shown in Figure 35. A total of 54 parameters (two of

which were transformer parameters) were ran over 11 PDCI pulses so 594 single parameter fittings were conducted to provide a parameter distribution for each parameter.

The artificial measurement noise was setup and calibrated based on the generator inertia parameter distribution. Refer to Section 4.2 for the measurement noise model. $|V_{avg}|$ and $|I_{avg}|$ were calculated from the average voltage and current magnitudes at the PMU for the entire day of data occurring during BPA testing in 2016. The global noise scale factor m was found to be approximately 0.0006 for the CENTR G1 unit for the 11 PDCI pulses. This means the standard deviation for the single parameter fittings of generator inertia constant for the 11 PDCI events during BPA testing were the same as 250 realizations of noise with a noise scale factor of 0.0006 added to the first PDCI event. Four realizations of the measurement noise added to the first PDCI event with the calibrated noise scale factor are shown in Figure 31. A histogram comparing the actual distribution to the simulated distribution is provided in Figure 44.

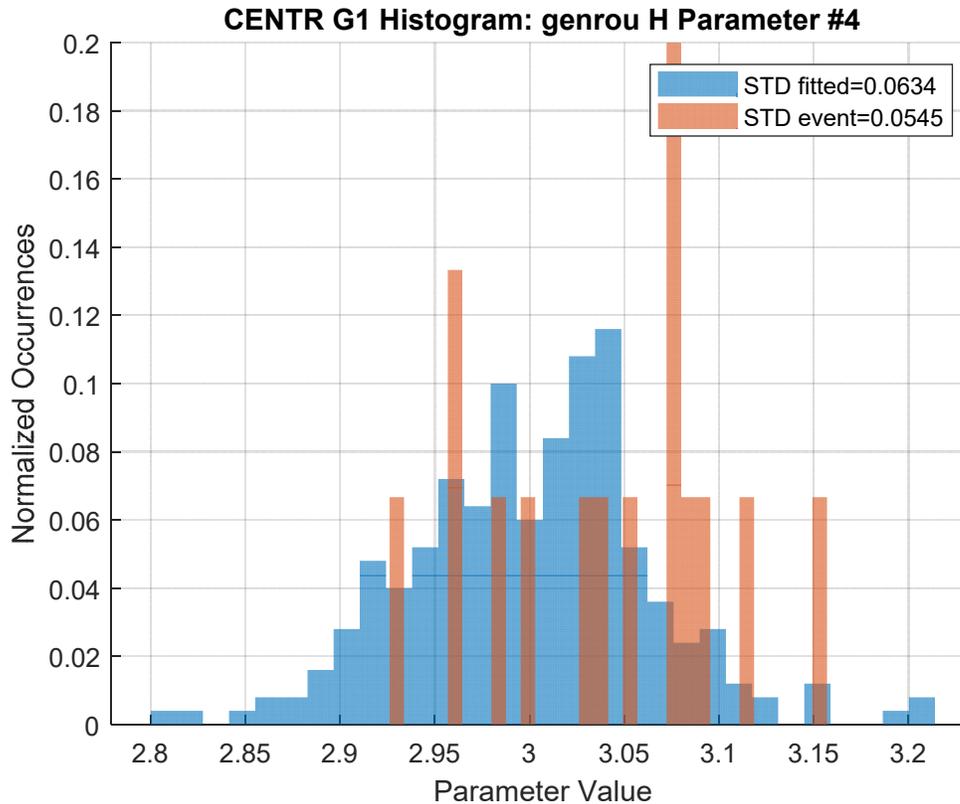


Figure 38: CENTRG1 single parameter genrou H histogram.

The single parameter fitting with the addition of artificial measurement noise was continued using the same method for measurement noise on different parameters. Note that the 250 realizations of noise were different for each parameter. Selected histograms for the fittings with artificial noise are shown in Figures 39, 40, and 41. Additional histograms are included in Appendix J. The histograms illustrate well-matching parameter distributions for other parameters, even though the measurement noise was only calibrated for the inertia constant H . The closely matching histograms is reason to believe the method works.

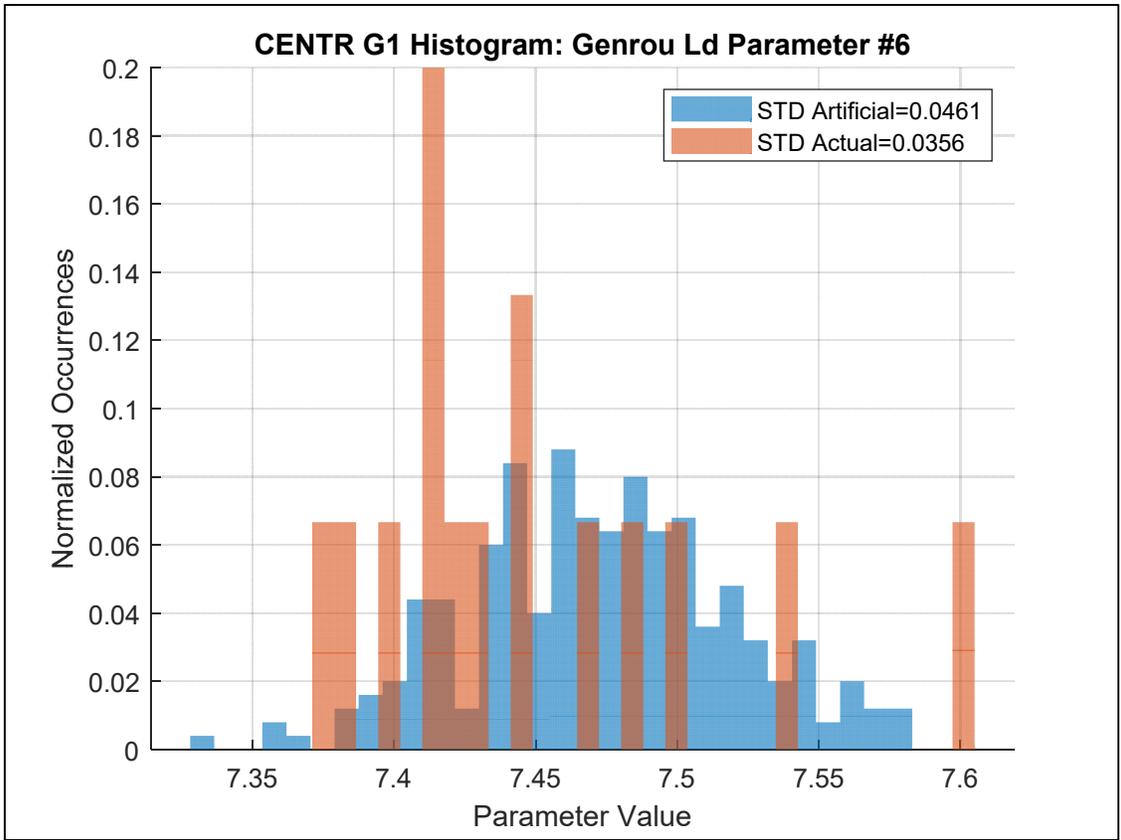


Figure 39: CENTRG1 single parameter genrou Ld histogram.

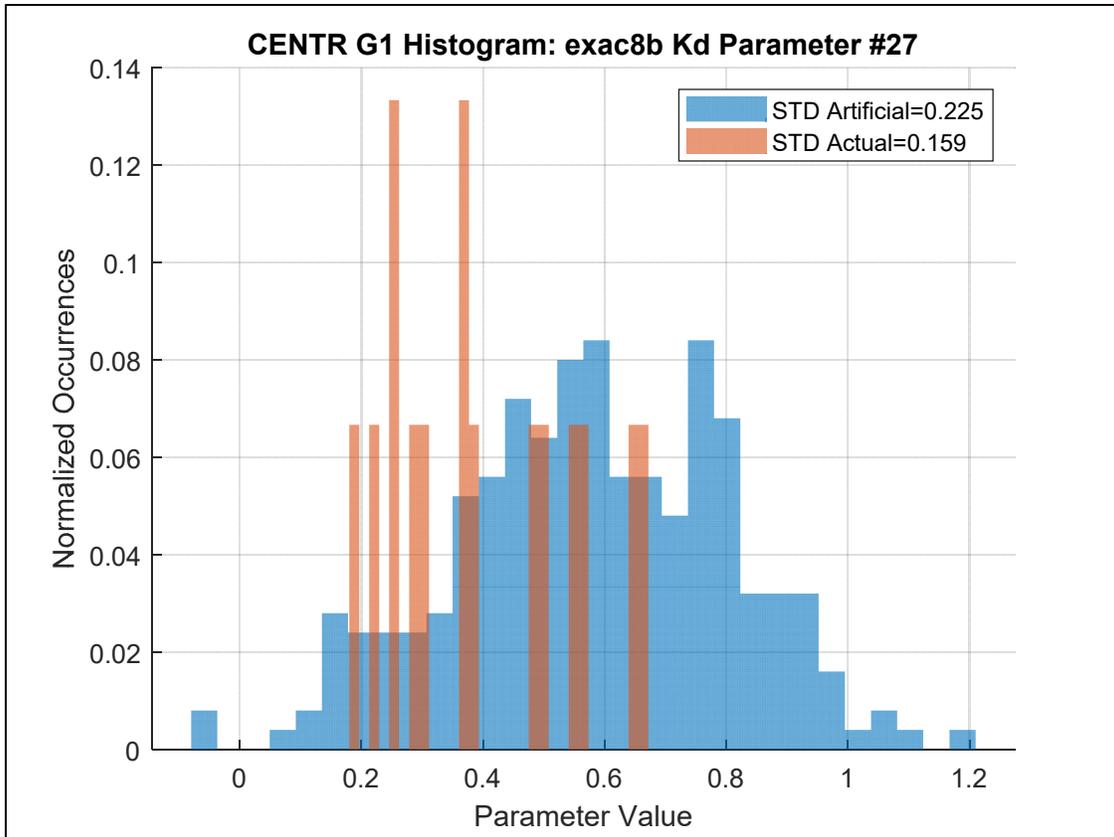


Figure 40: CENTRG1 single parameter exac8b Kd histogram.

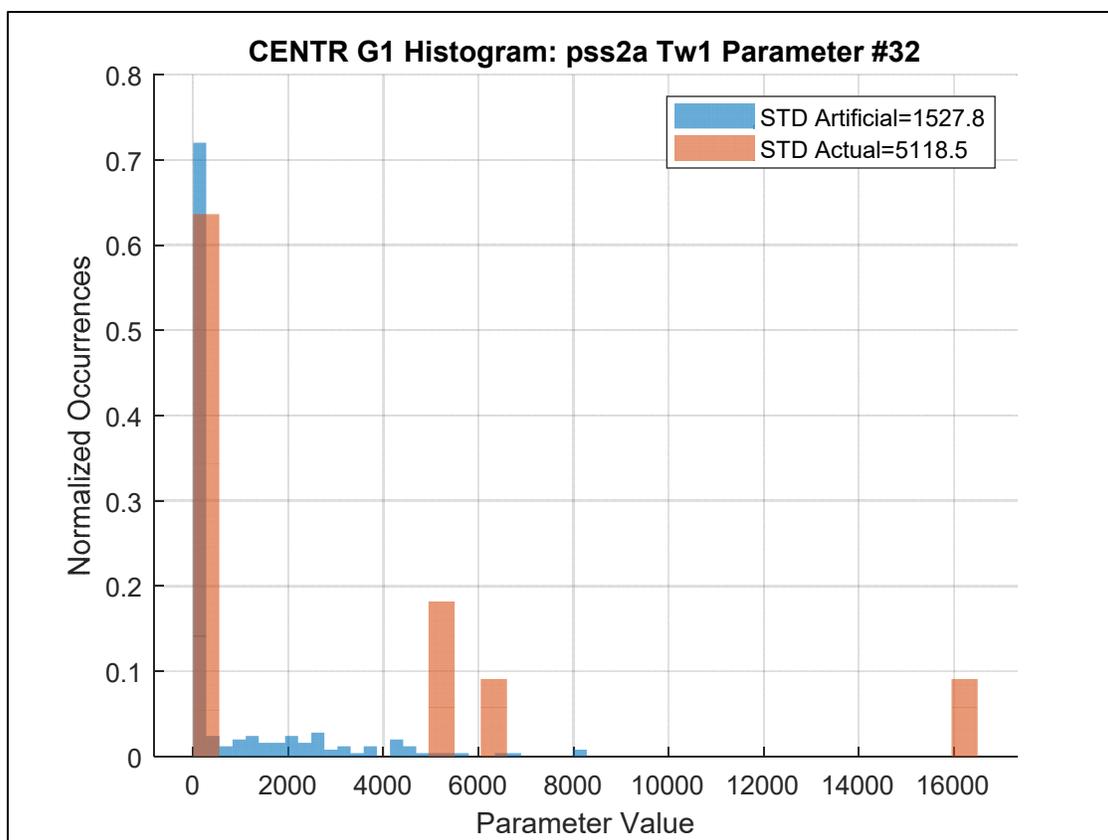


Figure 41: CENTRG1 single parameter pss2a Tw1 histogram.

The addition of 250 realizations of measurement noise to a single PMU event provides closely matching distributions for some parameter but others do not perform as well. For example, the pss2a Tw1 parameter distribution from the CENTR G1 generator illustrated in Figure 41 has a largely different standard deviation between fitting from the 250 noise realizations and the 11 PDCI pulses. A deeper investigation was made into the effects of changing the pss2a Tw1 parameter during a PDCI Play-In simulation. The states of the pss2a model after the Tw1 parameter and the output of the model were compared for two different parameter values. See Figure 5 for a reference of the pss2a power system stabilizer model. The two parameter values used for Tw1 were 15 and 5000. Since the output of the power system stabilizer goes to the exciter, states within the exac8b exciter model were compared at the

different parameter values. The exac8b exciter model is provided in Figure 42 for reference. A plot of each of the states at different Tw1 values is shown in Figure 43.

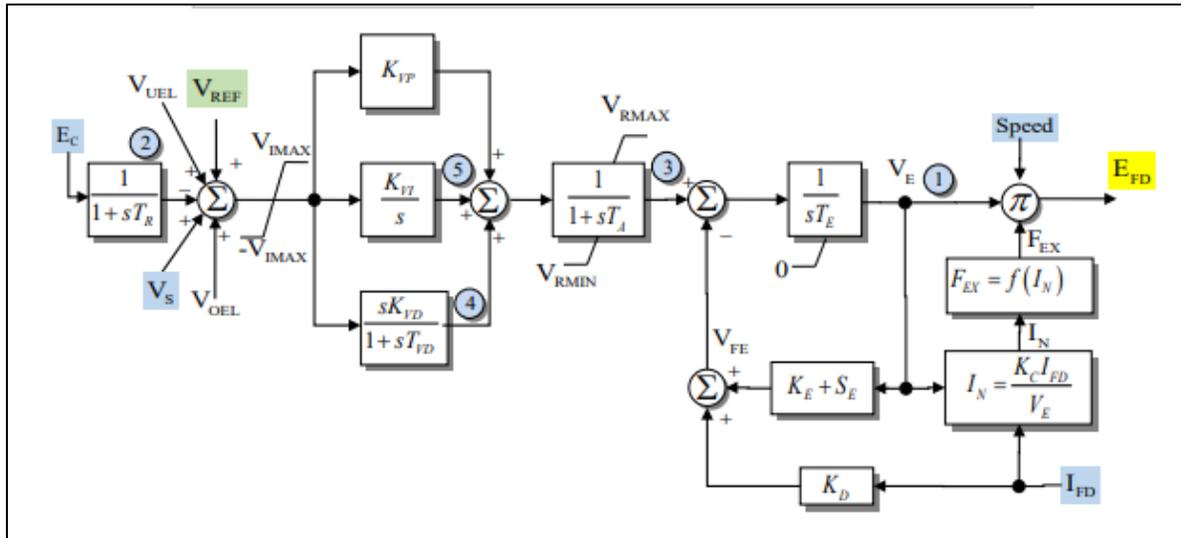


Figure 42: IEEE exac8b exciter model [34].

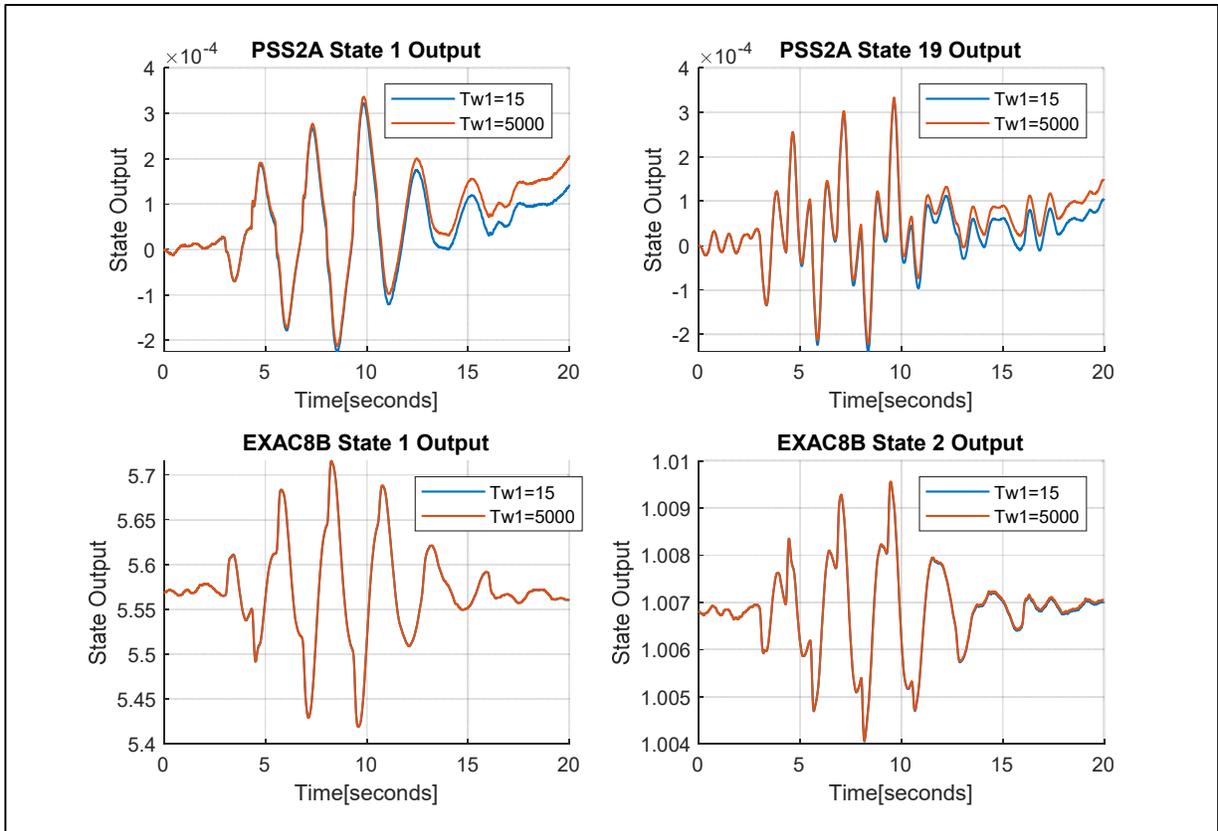


Figure 43: Pss2a and exac8b states at different Tw1 values.

The changing of the $Tw1$ parameter has little effect on the output of the pss2a power system stabilizer model which in turn had little effect on the output of the exac8b exciter model. The pss2a $Tw1$ parameter is considered an insensitive parameter since the changing of the parameter has little effect on the output of the simulation. The reason the histograms in Figure 41 have large disparities in standard deviation is likely due to the $Tw1$ parameter being insensitive. When a parameter is insensitive, the finally value for a fitting is a function of stopping conditions for the *lsqnonlin* MATLAB nonlinear least-squares solver and the algorithm implemented within the solver. For this reason, very insensitive parameters may not provide a good estimation of the parameter distributions.

7.2. Coulee 24 Generator

The second power plant analyzed within this research was the COULEE 24 unit which is part of the Grand Coulee Dam. The Grand Coulee Dam is the largest hydropower producer in the United States and generates 21 billion kilowatt-hours of electricity each year. The 24th generator is a hydroelectric unit located in Northern Washington on the Columbia River and rated for 805 MW [35]. This unit was chosen from the PMU data since the generator was operating during each of the three years of BPA testing and had a Play-In system configuration similar to the previous CENTR G1 system. The Play-In system contains the models between the COULEE bus where the PMU measurements are recorded and the COULEE24 generator. The Play-In system is shown in Figure 44.

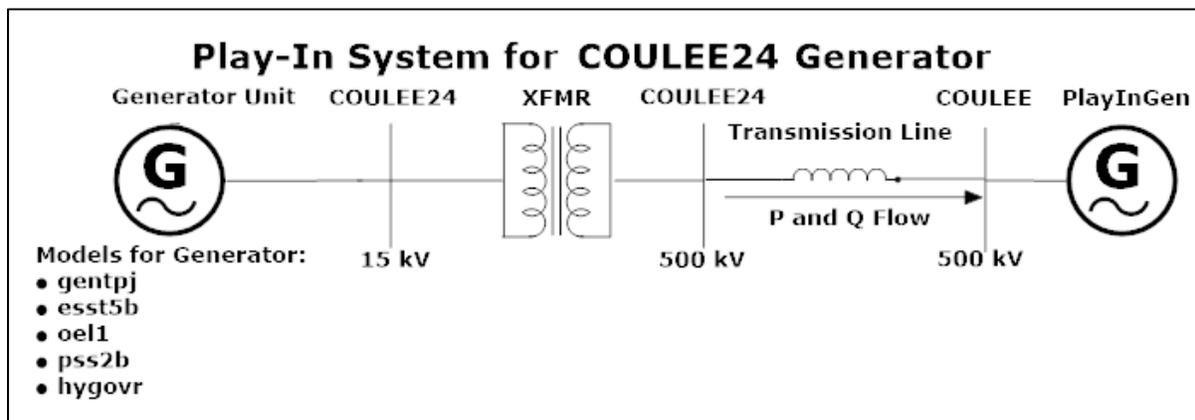


Figure 44: Play-In system for COULEE 24 generator.

Although three years of PMU data were available for the COULEE24 Play-In system, it was found the only usable PMU data for this system was from the 2017 and 2018 BPA testing. The PMU data from the 2016 BPA testing was not used since it displayed a high level of oscillating noise compared to other generators and other years for the same generator. The source

of the oscillating noise within the PMU data is unknown but can be clearly observed when comparing different years of data from the same PMU. The real power for the COULEE24 generator is shown in Figure 45.

The PMU data from 2017 and 2018 together have 8 resistive brake pulses at the Chief Joseph brake and 17 PDCI pulses. The PDCI pulses are not used for the COULEE24 generator because the resulting oscillations are not large enough. The Grand Coulee Dam is not as close in proximity to the PDCI as the Centralia generator which explains the smaller oscillations due to the PDCI pulsing. Instead, the 8 resistive brake pulses at the Chief Joseph brake were used for the event data set since the event resulted in larger oscillations.

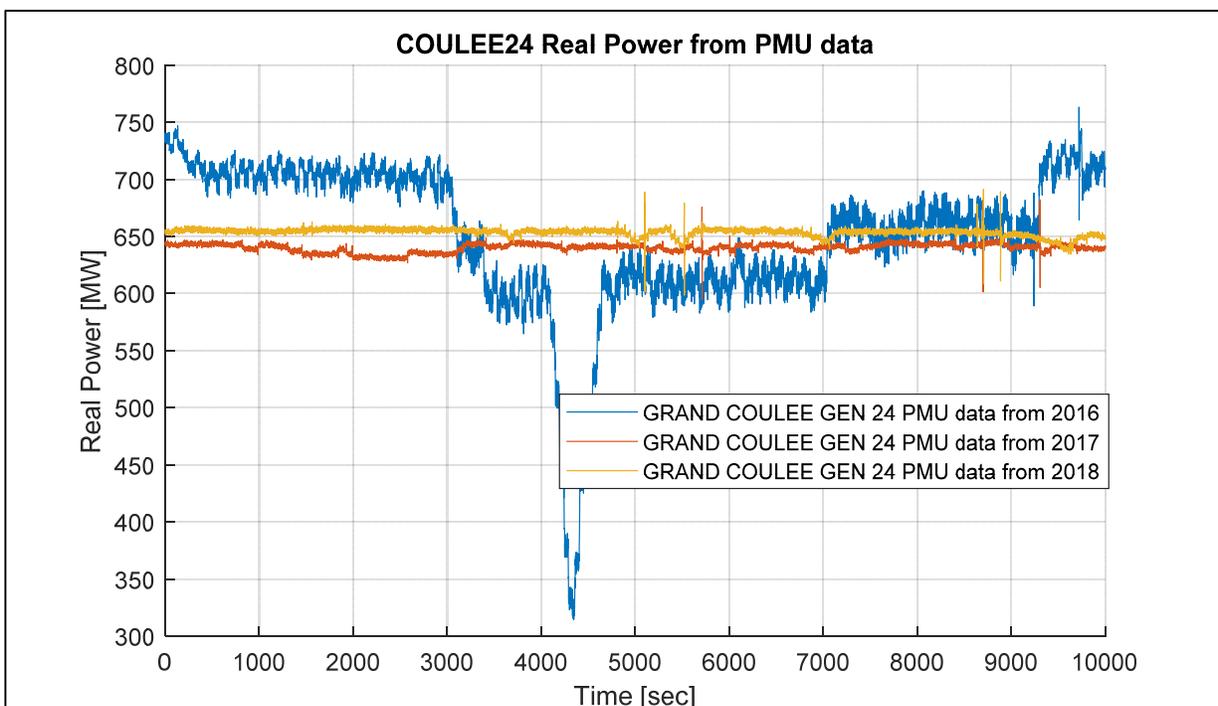


Figure 45: Real power from multiple years of PMU data for COULEE24 power plant.

The COULEE24 model provided for research did not provide a good initial fit for to the Chief Joseph brake pulses. Through the process described in Section 6.2, the parameters of the

model were tuned to provide a good initial fit for the model. The four parameters that were changed are documented in Table II. The improved initial fit is illustrated in Figure 46.

Table II. Tuned COULEE24 parameters to provide good initial fit.

Model	Parameter	Initial Value	Value to Improve Fit
gentpj	H	4.9722	4.7818527474472300
pss2b	Ks1	10	8.9063082890300300
pss2b	T1	0.5	0.4139950005881630
XFMR	X	0.02089	0.0297318251450101

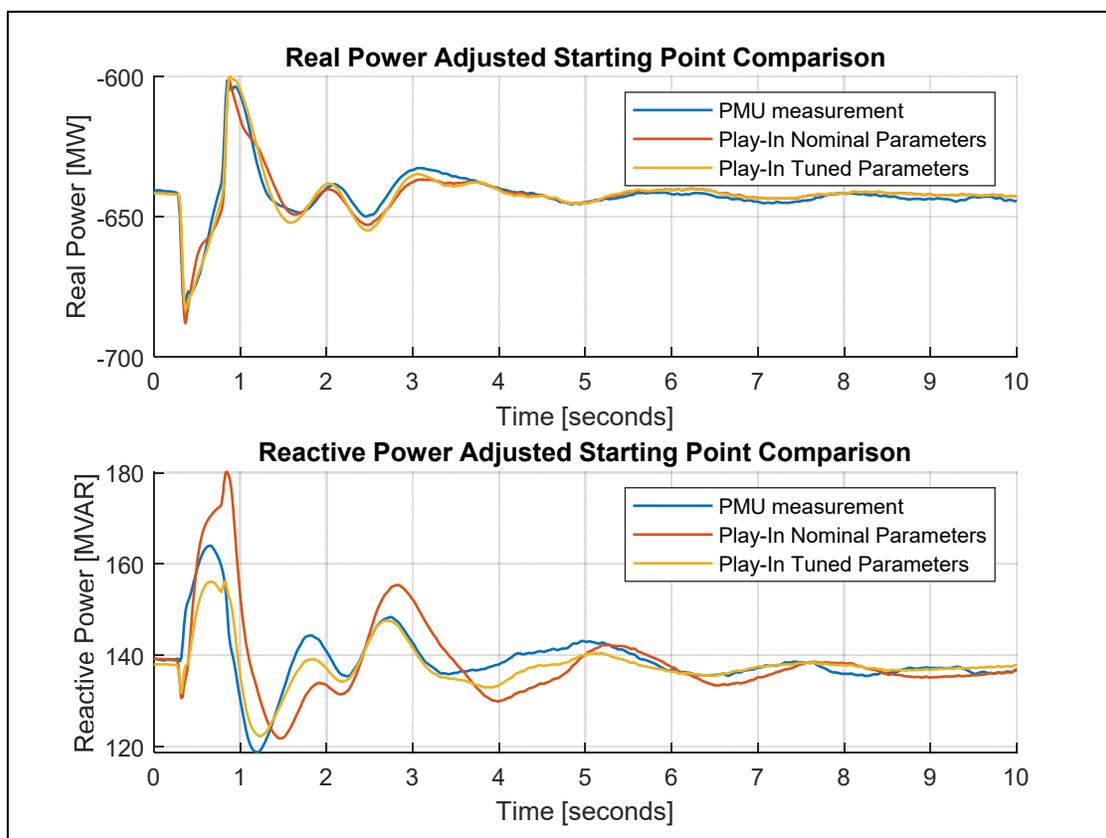


Figure 46: COULEE24 improved initial fit.

After getting a good initial fit between the model and the actual event, a single parameter fit for each tunable parameter (generator, transformer, and transmission line) was conducted on each Chief Joseph brake pulse. Parameters that were originally set to zero within the models

were excluded from fitting. The models used by the power plant are shown in Figure 44. A total of 100 parameters (three transformer parameters and three line parameters) were ran over 8 Chief Joseph brake pulses so 800 single parameter fittings were conducted to provide a parameter distribution for each parameter.

The artificial measurement noise was setup and calibrated based on the parameter distribution. Refer to Section 4.2 for the measurement noise model. $|V_{avg}|$ and $|I_{avg}|$ were calculated from the average voltage and current magnitudes at the PMU from the BPA testing in 2017 and 2018. The global noise scale factor m was found to be approximately 0.0042 for the COULEE24 unit for the 8 Chief Joseph pulses. This means the standard deviation for the single parameter fittings of generator inertia constant for the eight Chief Joseph brake pulses events during BPA testing were the same as 250 realizations of noise with a noise scale factor of 0.0042 added to the selected event. Four realizations of the measurement noise added to the first Chief Joseph brake pulse event with the calibrated noise scale factor are shown in Figure 47. A histogram comparing the actual distribution to the simulated distribution is provided in Figure 48.

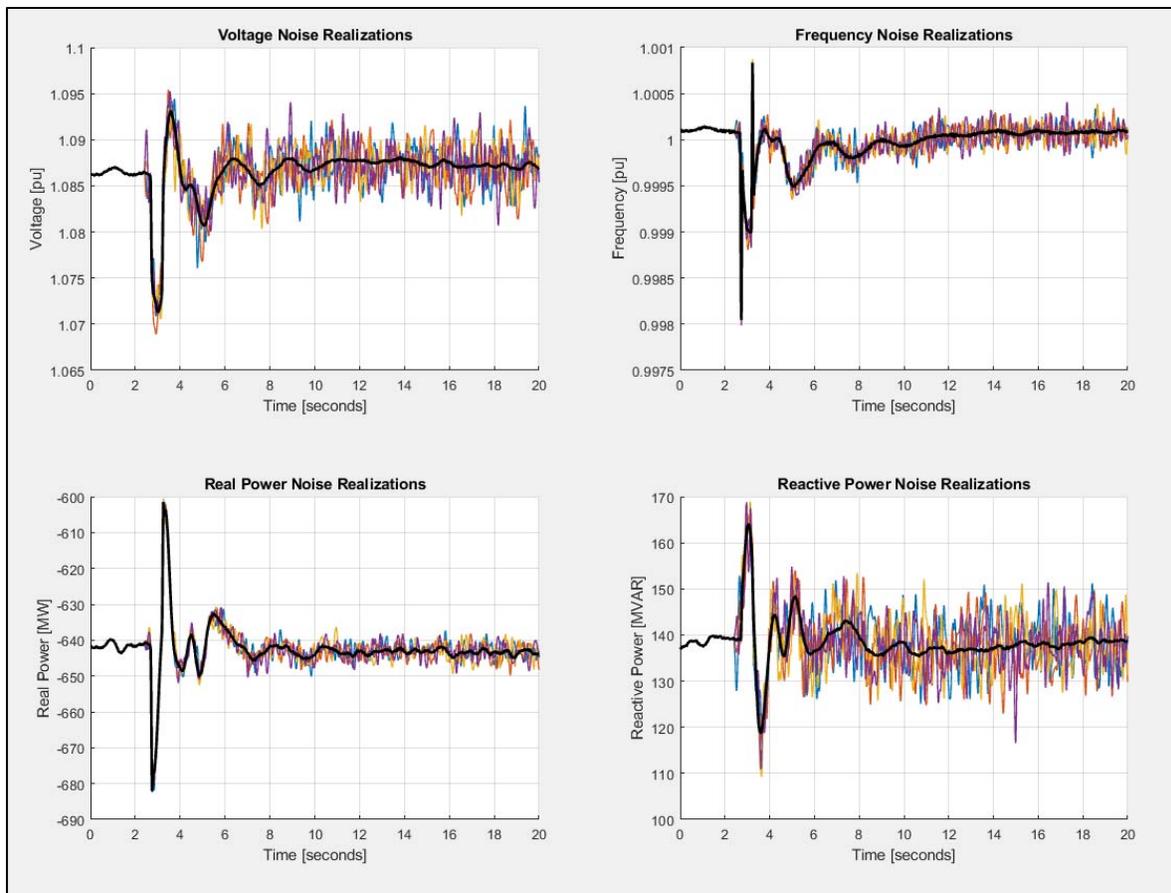


Figure 47. COULEE24 Chief Joseph pulse recorded by PMU along with four noise realizations of artificial noise with $m=0.0042$.

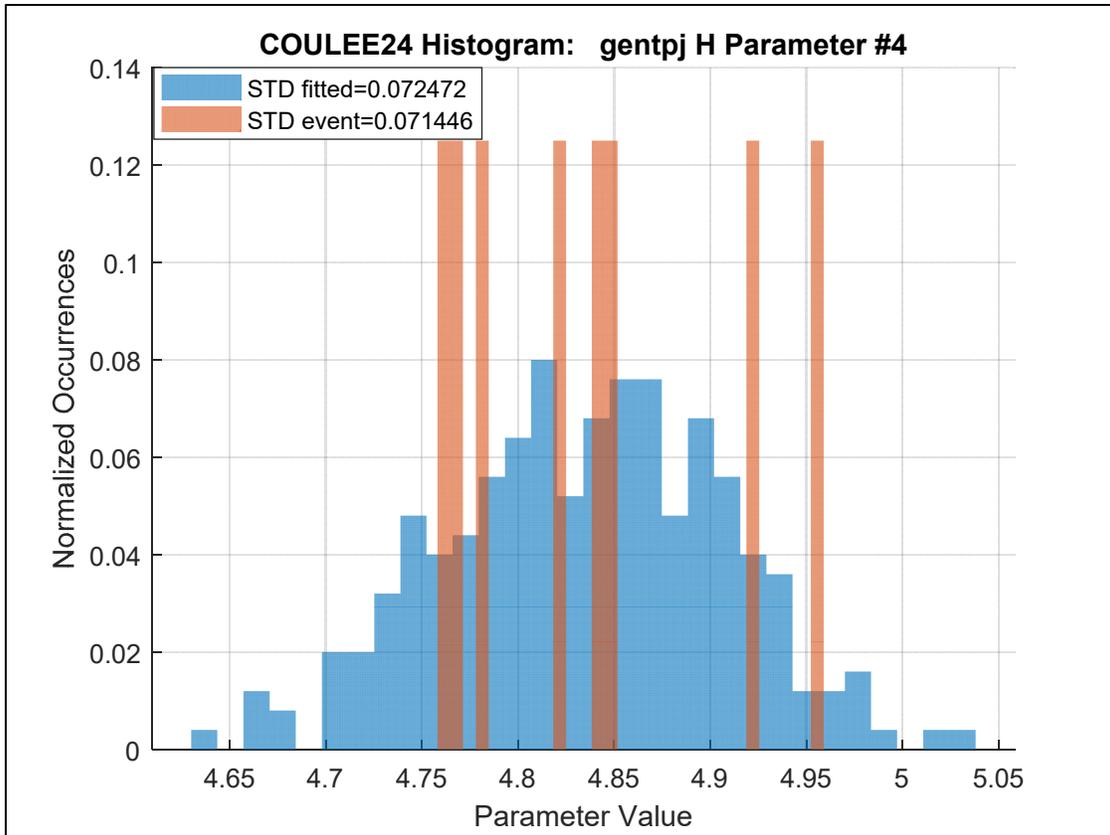


Figure 48: COULEE24 single parameter gentpj H histogram.

The single parameter fitting with the addition of artificial measurement noise was continued using the same method for measurement noise on different parameters. Note that the 250 realizations of noise were the same for each parameter which differs from the CENTR G1 case. A few histograms of parameters comparing the single parameter fittings with addition of artificial measurement noise to the actual parameter distribution are provided in Figures 49, 50, and 51. Additional histograms for more parameters are provided in Appendix I. The histograms illustrate well-matching parameter distributions for other parameters, even though the measurement noise was only calibrated for the inertia constant H. The closely matching histograms is reason to believe the method works.

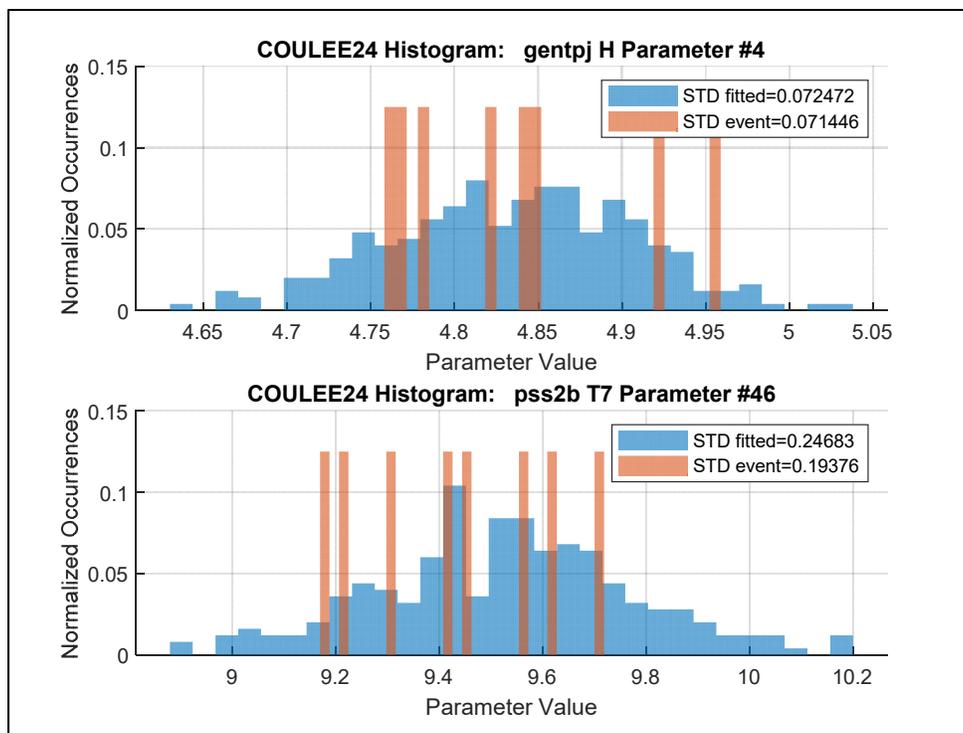


Figure 49: COULEE24 single parameter gentpj H and pss2b T7 histograms.

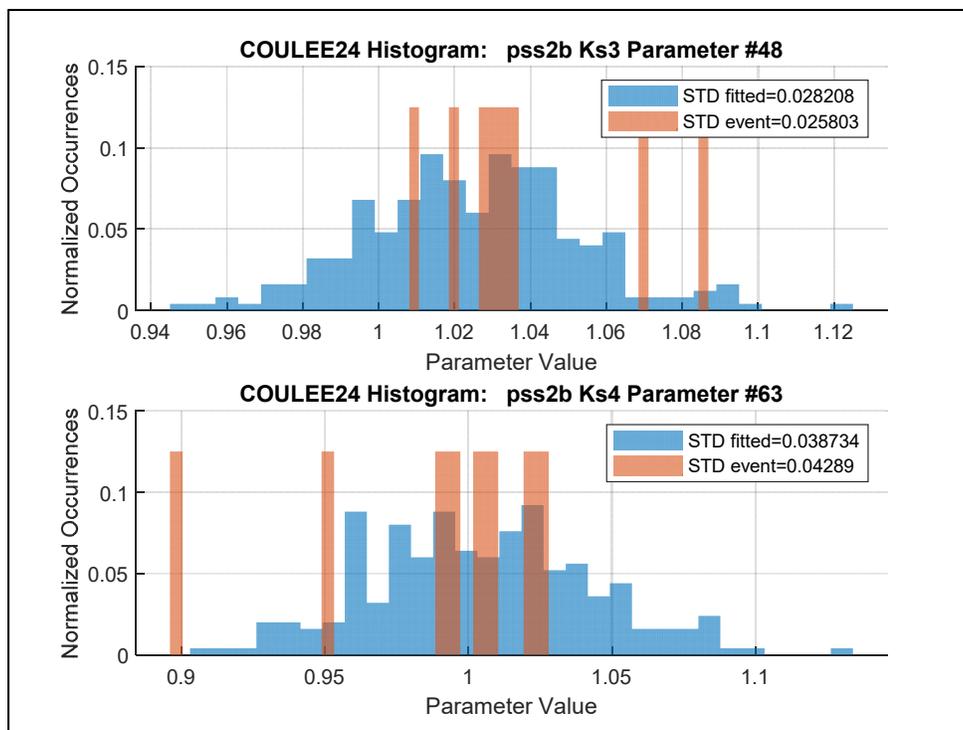


Figure 50: COULEE24 single parameter pss2b Ks3 and pss2b Ks4 histograms.

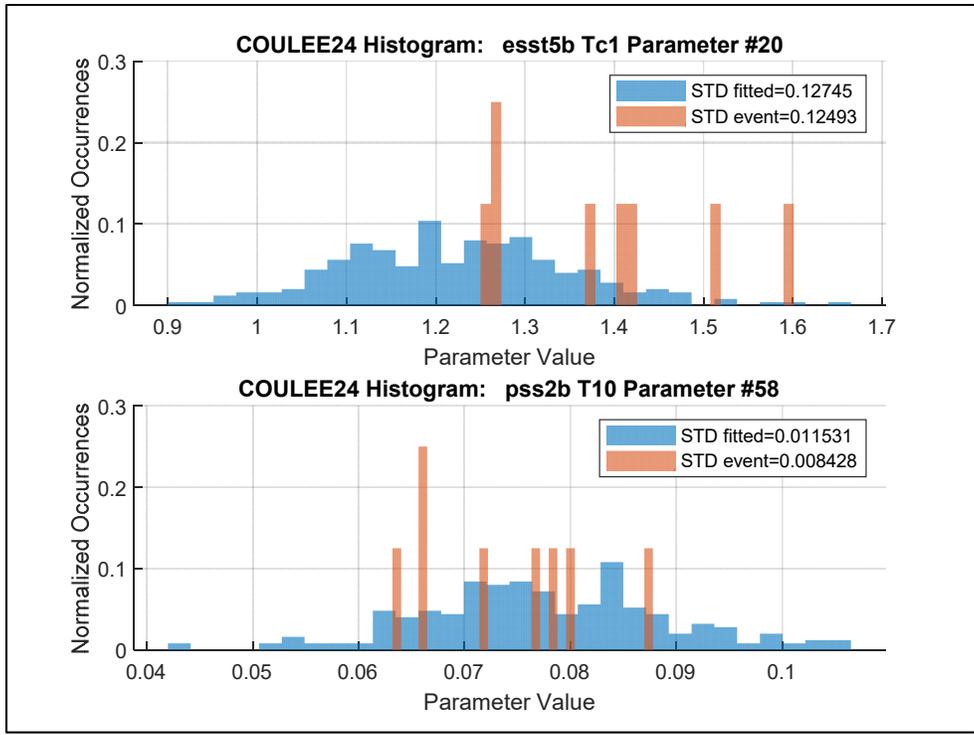


Figure 51: COULEE24 single parameter esst5b Tc1 and pss2b T10 histograms.

8. Results Multiple Generator Parameter Testing with Artificial Noise

The following section focusses on the parameter testing with multiple generators within the Play-In system. A single parameter fitting to minimize the least-squared error was used to make improvements to the models just like in Play-In system with a single generator. The PMU data recorded during these cases has multiple generators operating downstream of the PMU which creates uncertainty to which generator model needs to be tuned to provide a simulation to closely match the actual event. Having a PMU recording two or more generators outputs is a common occurrence within the system, and the effects of adding artificial noise while performing parameter fitting on such system need to be tested.

8.1. Chief Joseph PH 1

The Chief Joseph Dam is the second largest producer of hydropower within the United States. The dam is located in northern Washington. The energy in the water from the Columbia River is harnessed through the 27 generators at the Chief Joseph Dam to produce electricity to be used in the Western United States [36]. A subset of the generators are used for this research. The four generators used are the ones connected downstream of the CHJ PH1 bus where a PMU was located to measure the events occurring during BPA testing. The Play-In system for the CHJ PH1 PMU bus is shown in Figure 52. The same models are used for each of the generators within the Play-In system. All the parameters are the same within the models for each generator except the `hyg3 Relec` parameter varies slightly for each generator. Although the four generators have almost identical models, the XFMR 2 and XFMR 3 transformers in the Play-In system have different impedances changing the system response based on which generators are online.

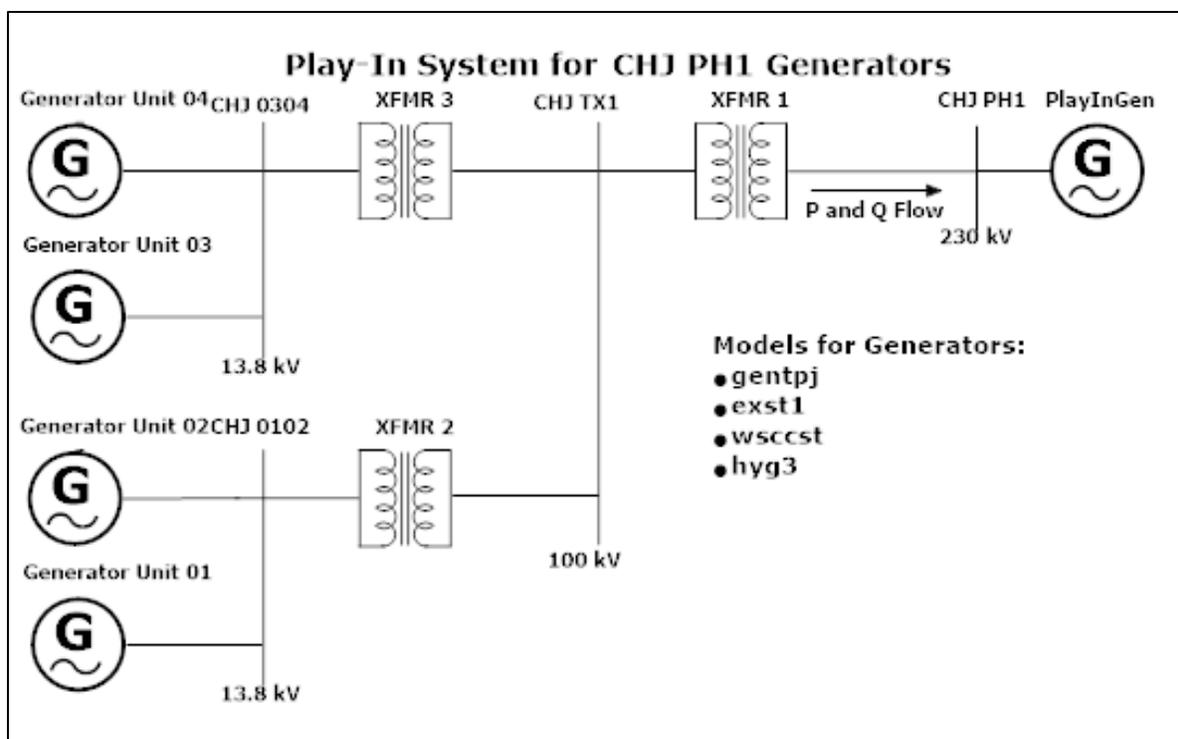


Figure 52: Play-In system for Chief Joseph Pump House 1 generators.

Three years of PMU data during BPA testing was recorded at the CHJ PH1 PMU bus but not all the events in this data set could be utilized due to varying operating conditions on the days of testing. The goal was to identify the same events occurring at similar operating conditions, then use the events to provide a parameter distribution that can be compared to the parameter distribution from added measurement noise. The real power output measured by the PMU was used to determine if the operating conditions were similar enough. A plot of the real power measured at the CHJ PH1 PMU bus from each year of BPA testing is shown in Figure 53. Since each generator shown in Figure 52 has a maximum real power output of 88 MW, it is possible to estimate how many generators in the Play-In system were online during the BPA testing. The 2016 and 2017 years appear to have two units on during the Chief Joseph brake pulses (large four spikes in each year of data) because the real power is at about 150 MW during those times.

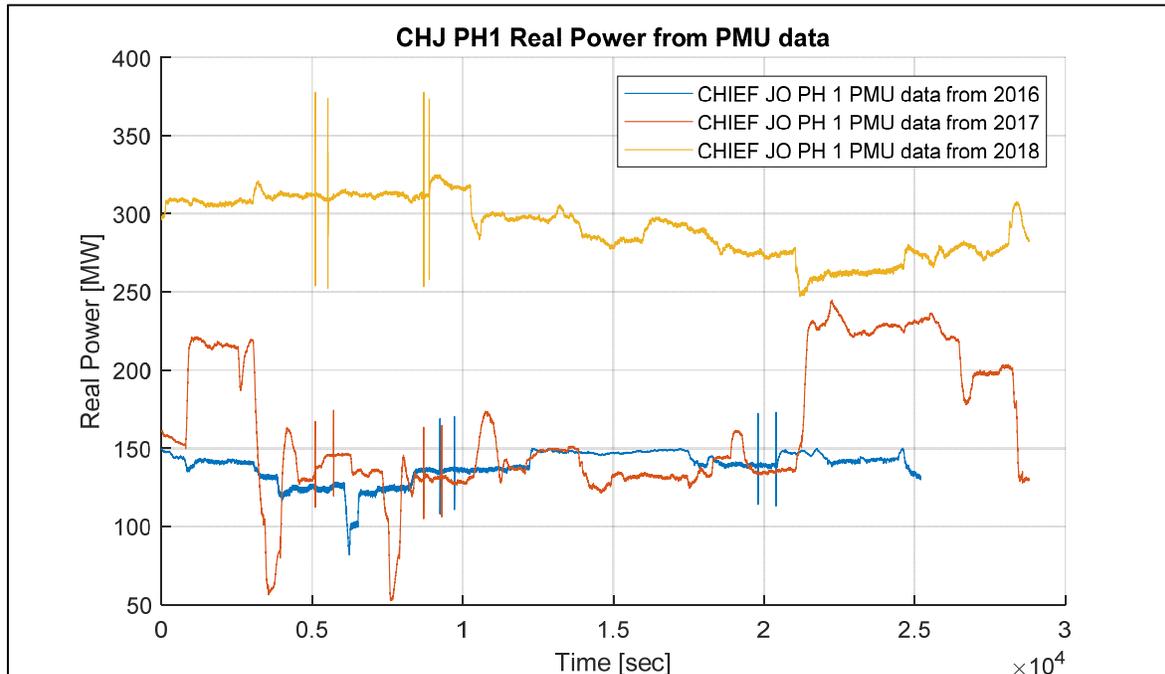


Figure 53: Real power from multiple years of PMU data at the CHJ PH1 bus.

Determining which generators are on during each of the Chief Joseph brake pulse was the next step. The blue line in Figure 53 shows no indication that the combination of generators changed between events in the 2016 data since the real power remains steady. The 2017 data shown by the red plot indicates that the combination of units online may have changed between the first two and the last two Chief Joseph brake pulses since the power ramps down to about 50 MW then back up to about 130 MW. The real power from the eight Chief Joseph brake pulses from 2016 and 2017 were plotted on the same plot to compare the events to each other in Figure 54. The initial real power point was subtracted from response to a Chief Joseph brake pulse to make the plots overlap. The first four events correspond to the brake pulses from 2016 in chronological order and the last four are the brake pulses from 2017. The fifth and sixth events have obvious differences in the PMU data which indicate a different combination of generators

operating during these events. These two events would be excluded from the data set leaving the remaining six Chief Joseph brake pulses.

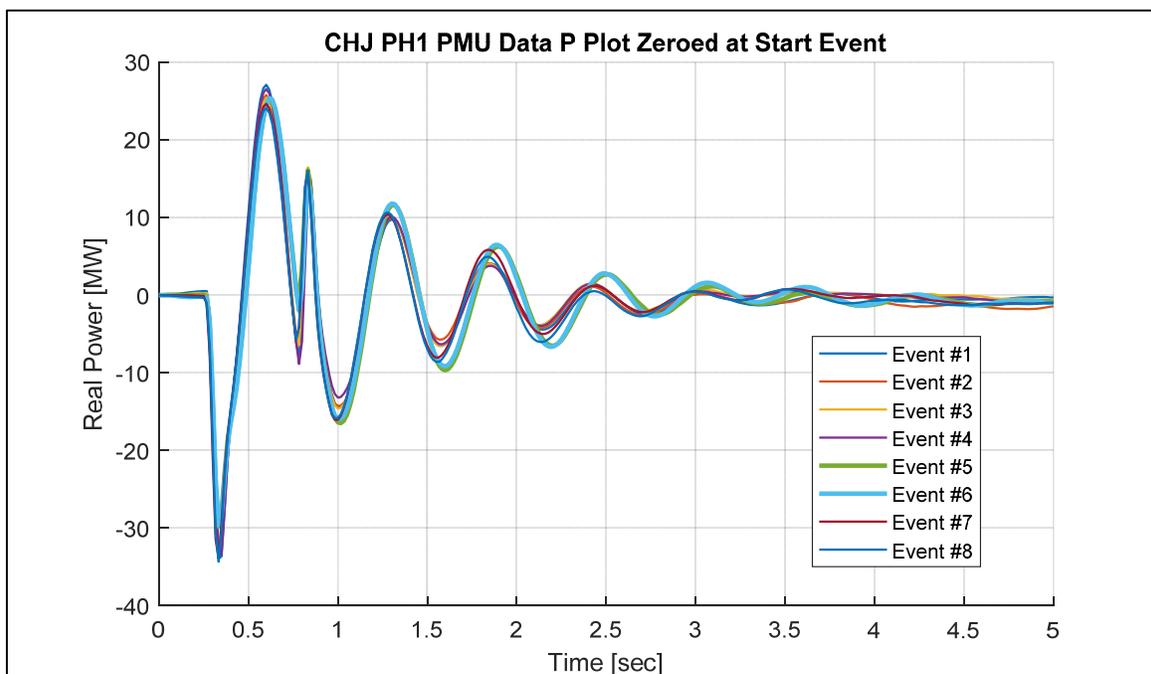


Figure 54: Real power of 2016 and 2017 Chief Joseph brake pulse events from PMU data.

Play-In simulations were conducted where the combination of two generators online were changed. All the possible combinations for two generators were tried for each Chief Joseph brake pulse. The combination with generator 1 and 3 online provided the least error between the PMU and Play-In simulation so it is reasonable that these generators were on during the BPA testing for the six events.

Since the models already provided an adequate initial fit, the procedure in Section 6.2 was skipped. A single parameter fitting was conducted over each all of the parameters deemed tunable within the Play-In system for all six Chief Joseph brake pulse events. The resulting distribution provided a parameter distribution for all the parameters. This provided a distribution

for both inertia for the first and third generators to be used during setup and calibration of the measurement noise to be added during a simulation. Refer to Section 4.2 for the measurement noise model. The global noise scale factor m was found to be approximately 0.0008 for the CHJ PH1 system for the 6 Chief Joseph pulses. This means the standard deviation for the single parameter fittings of generator inertia constants for the 8 Chief Joseph brake pulses events during BPA testing were the same as 250 realizations of noise with a noise scale factor of 0.0008 added to the selected event. Four realizations of the measurement noise added to the first Chief Joseph brake pulse event with the calibrated noise scale factor are shown in Figure 55. A histogram comparing the actual distribution to the simulated distribution is provided in Figure 56.

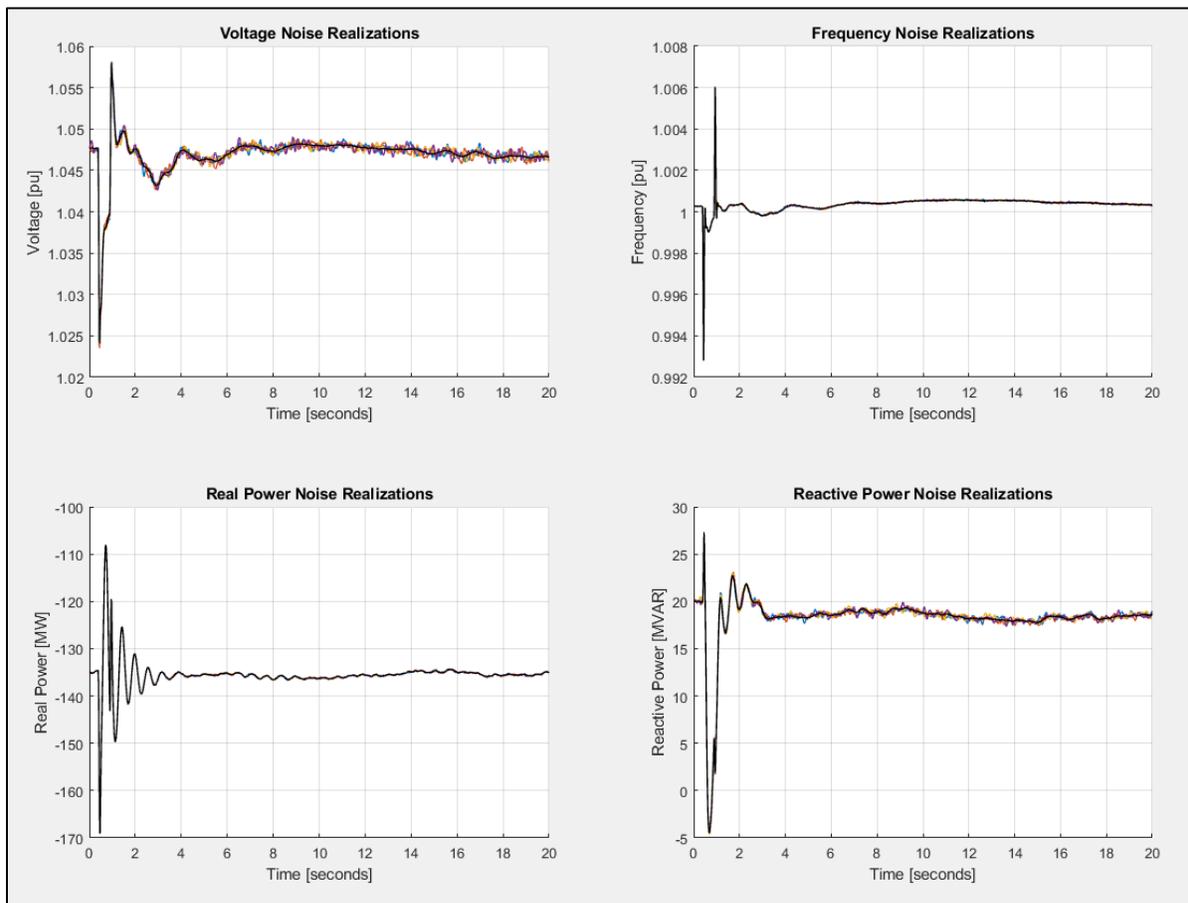


Figure 55. CHJ PH1 Chief Joseph pulse recorded by PMU along with four noise realizations of artificial noise with $m=0.0008$.

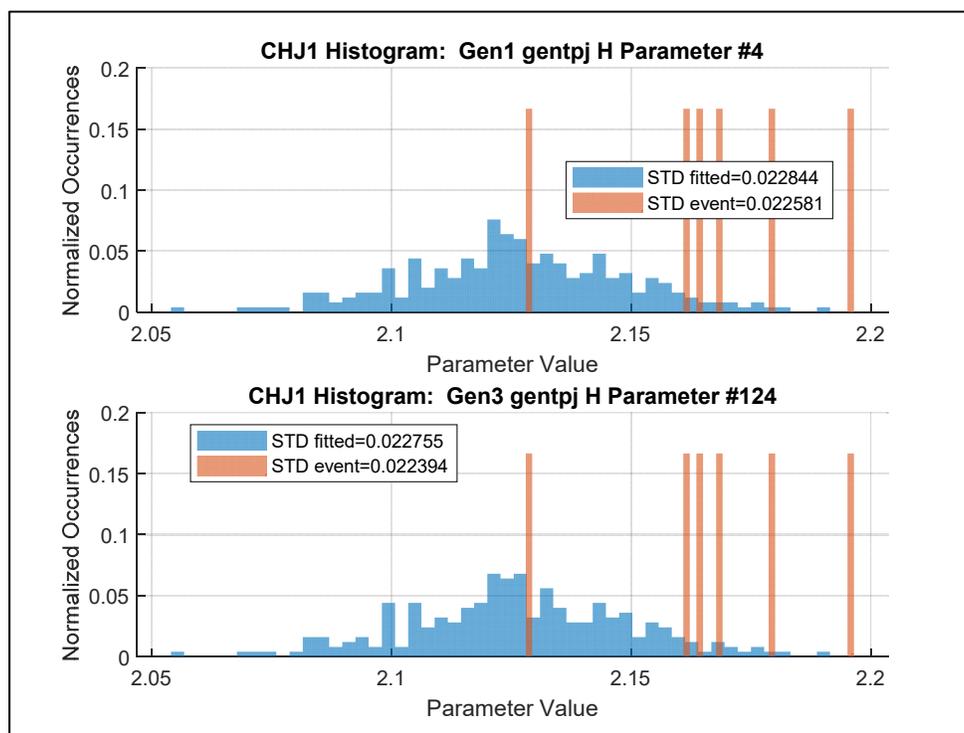


Figure 56: CHJ1 single parameter gentpj H histogram comparison.

The single parameter fitting with the addition of artificial measurement noise was continued using the same method for measurement noise on different parameters. Note that the 250 realizations of noise were the same for each parameter. Histograms illustrating the comparison of the single parameter fitting distributions for each operating generator are shown in Figures 57, 58, 59, and 60. Additional histograms for more parameters are provided in Appendix I. The histograms illustrate well-matching parameter distributions for other parameters, even though the measurement noise was only calibrated for the inertia constant H . The similarity of the histograms is reason to believe the method works.

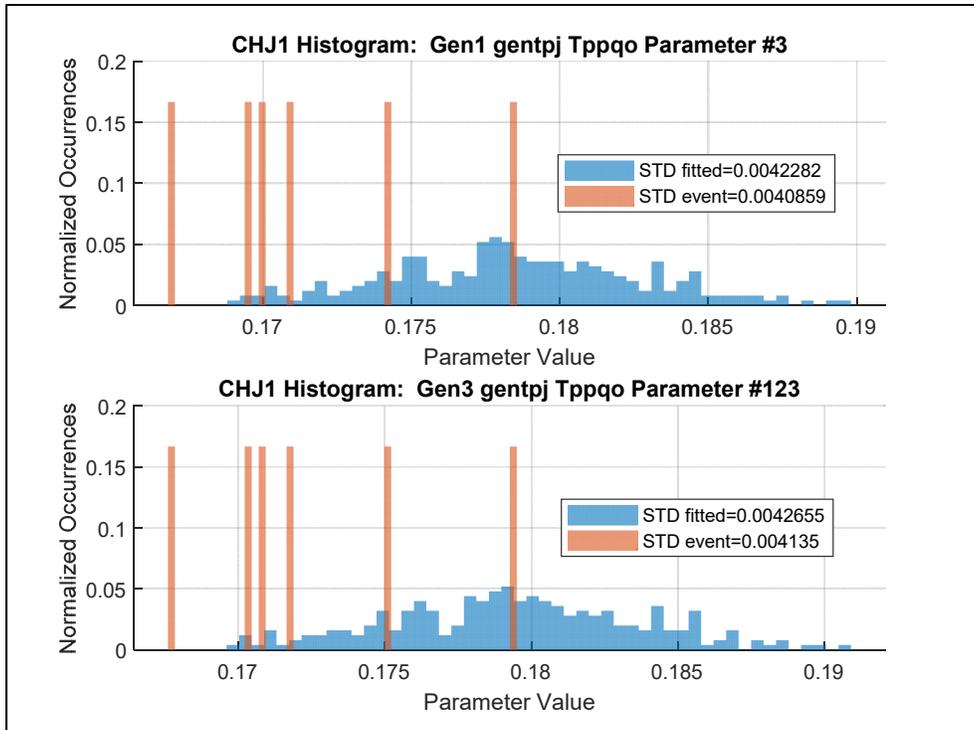


Figure 57: CHJ1 single parameter gntpj Tppqo histogram comparison.

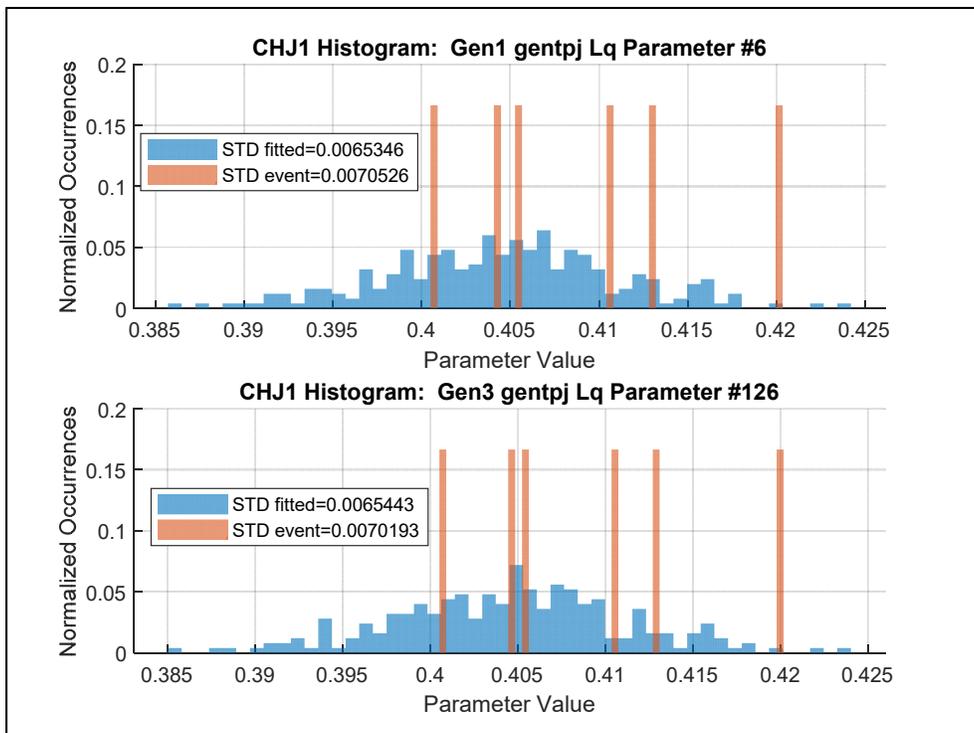


Figure 58: CHJ1 single parameter gntpj Lq histogram comparison.

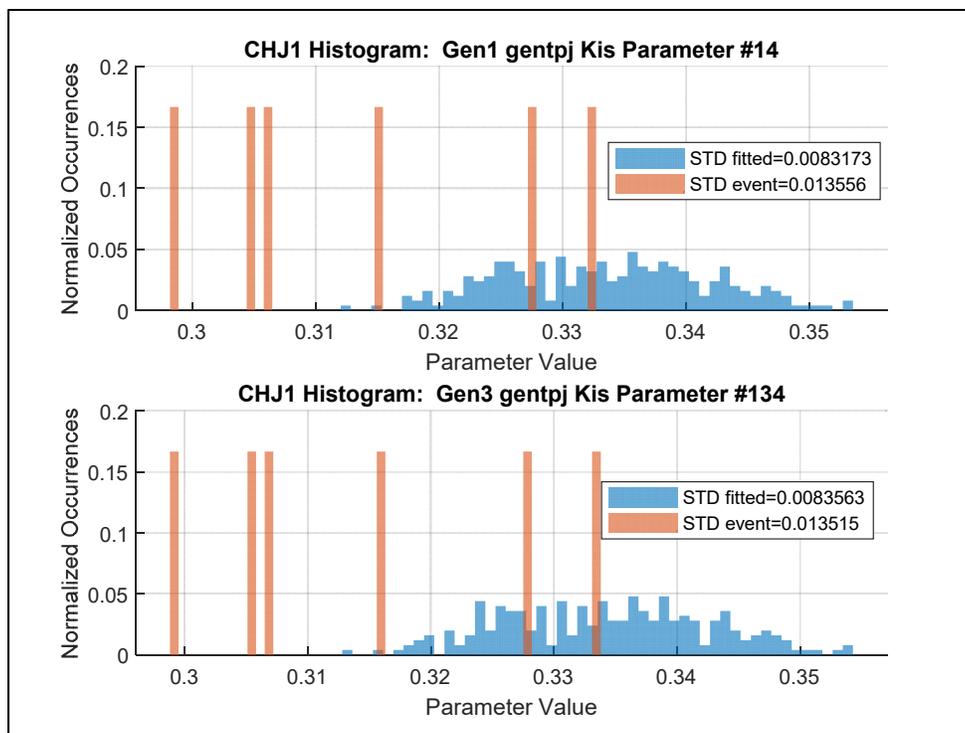


Figure 59: CHJ1 single parameter gentpj Kis histogram comparison.

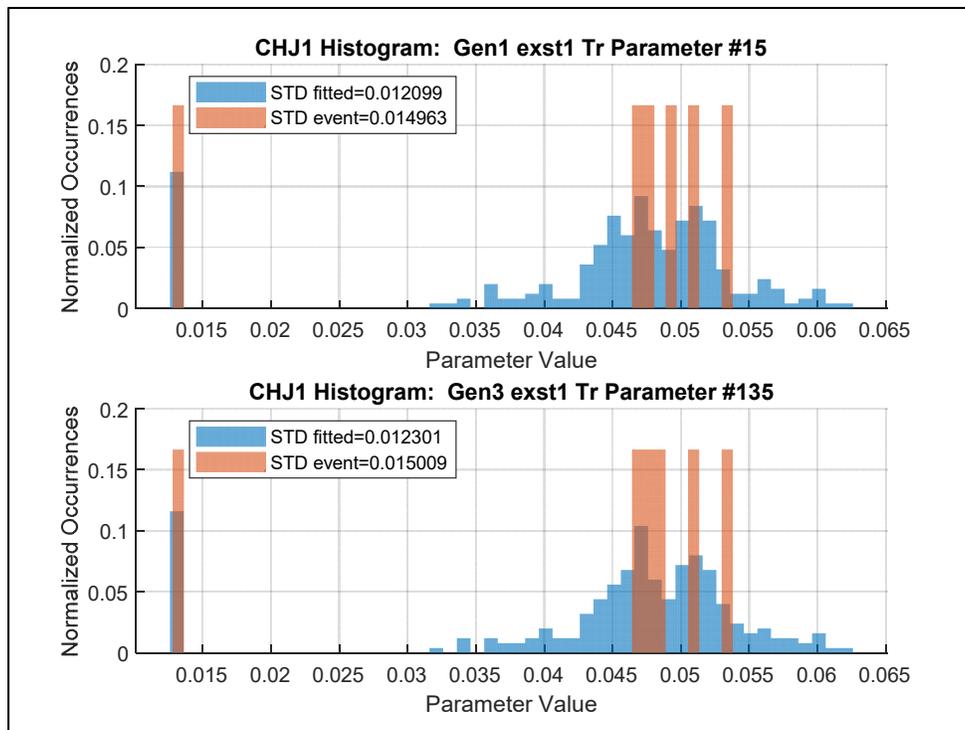


Figure 60: CHJ1 single parameter exst1 Tr histogram comparison.

9. Conclusions

The resulting distributions after least-squares fitting for each parameter can be qualitatively grouped into two parameter types. The first type is a sensitive parameter which has a large effect on the output simulation due to changes in the parameter value. Oppositely, an insensitive parameter plays little effect on the output simulation due to a parameter value change. The resulting distribution for a sensitive parameter is tighter since small parameter changes drastically affect the output of the simulation. A histogram of a sensitive parameter is shown in Figure 38. The insensitive parameter would have a distribution spread out over a larger range of values since small parameter changes hardly affect the output of the simulation. An example of a distribution for an insensitive parameter is shown in Figure 41. The standard deviation of the parameter values is much larger for the insensitive parameter compared to the sensitive parameter.

A large number of parameters have very close distributions between the noise realizations and the events. The standard deviations remain the same order of magnitude between the noise realizations and the events. This indicates that the addition of the measurement noise can be used to provide an estimate of the parameter uncertainty given an event recorded by a PMU if a history of the event has been previously recorded. Knowing the uncertainty for each parameter based on the validation event is useful information when calibrating the generator model. The measurement of uncertainty identifies parameters that may not have been properly excited to during the validation event warning of potential inaccuracies in the existing model.

10. Future Work

This research outlines initial methodology to estimate parameter uncertainty while performing PMU model validation. The research remains incomplete and needs additional work. The following are future work suggestions to further improve and advance the research conducted in this thesis.

First, expansion and trial of this technique on other generators is needed to determine parameter uncertainty and verification to real-life events on the system. Since the methodology is data-driven, it is important to provide verification that this technique is applicable to many generators within the grid. The trials on different generators could be used to determine if there are any limitations due to different generator types and models.

The second suggestion for future work is to use different event types while using the same methodology. The PDCI and Chief Joseph brake pulses were the two event types used for this research. The two events create similar power imbalances on the grid so various events creating different conditions need to be explored.

Improvements to the research can be made by increasing the amount of events available for the event distribution. For example, the testing in this research had only six Chief Joseph brake pulse events to use on the Chief Joseph Pump House system. Having such a small number of events may not provide the best representation for the expected parameter distribution so having more events would be desirable. Since this event is regularly conducted during BPA testing, generating and recording more pulses at a single operating condition would provide more events. For some events, it is not possible to increase the event sample size because the events are a result of a random occurrence on the grid that is not easily repeated.

Another suggestion to the research involves running multi-parameter fitting simulations to discover when parameters are correlated to each other. A pair of correlated parameters affect the output of the simulation similarly. Identifying correlated parameters is crucial during model calibration because extra deliberation needs to be used when changing the values of correlated parameters.

Lastly, the final suggestion is to determine why certain parameters perform better than other parameters. The additional information would provide beneficial information regarding the limitations from the methodology in this thesis. The limitations would be known when applying this technique to models containing similar parameters.

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11. Appendix A: Setup for PowerWorld .PWB File for Model Validation

- 1) Start with a working .PWB file for PowerWorld. This can be created from scratch or opened from other file formats shown below.

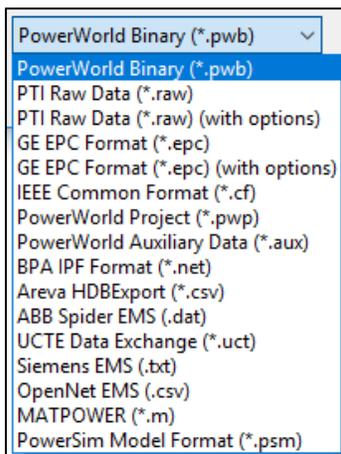


Figure 61: Optional file formats to open in PowerWorld

- 2) The first step to setting up a case within PowerWorld to be used during a power plant model validation is determining the bus at which the PMU measurements are taken. Once the bus is determined, the models are kept between the PMU and the power plant, but the models outside of the plant are deleted from the PowerWorld file.
- 3) Change the system slack bus to the bus where the PMU is located. An example of how this should appear within PowerWorld is shown in Figure 63.

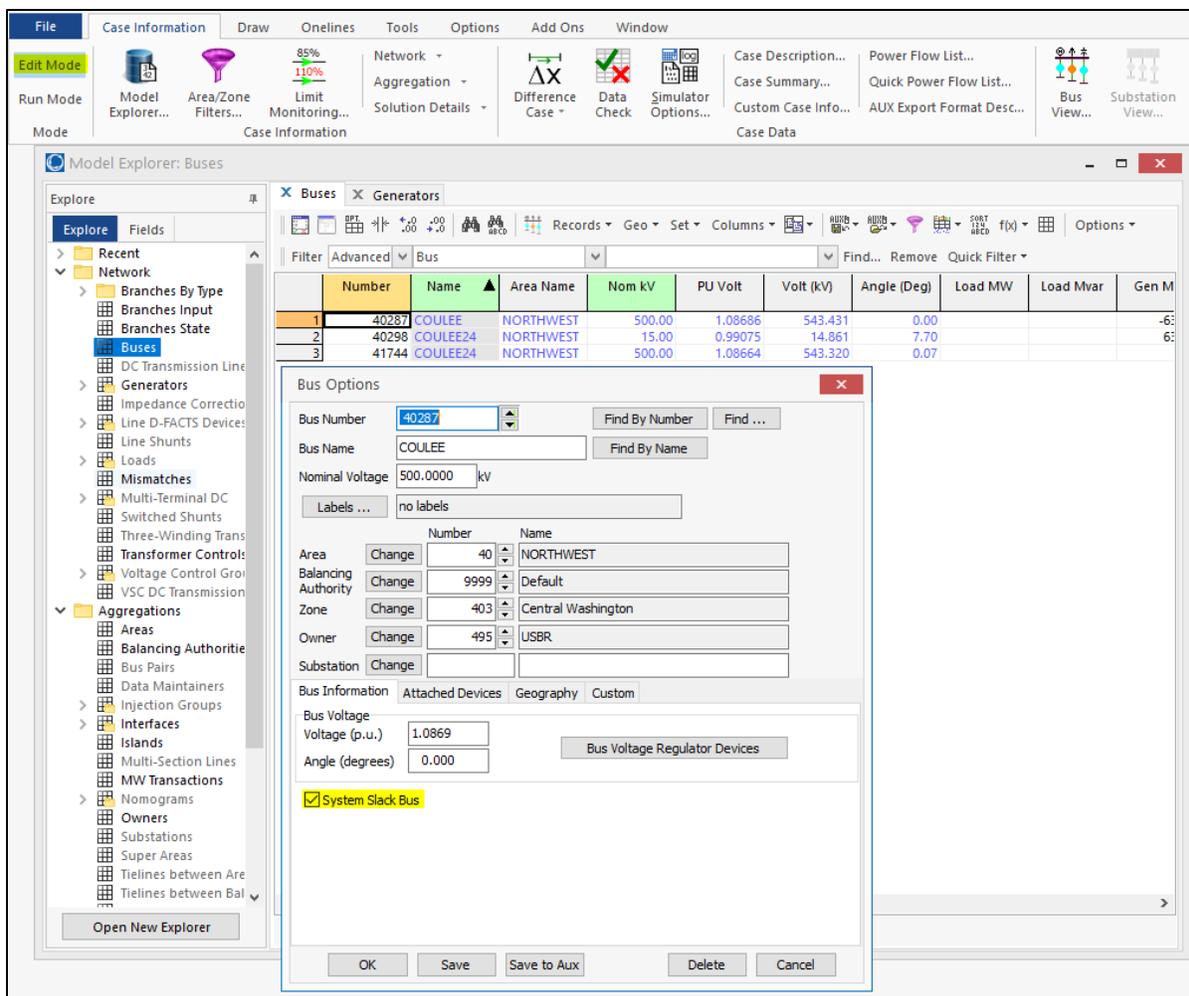


Figure 62: How to change bus to a slack bus in PowerWorld

- 4) The next step is to add a generator to the bus where the PMU is located. The generator located at the PMU bus will be referred to as the Play-In generator. The settings for the “Max and Min MW Output” and the “Max and Min MVAR Output” for the Play-In generator should be set to values that won’t be reached during the simulation. The AGC setting for all the generators should be set to “NO”. The AVR setting for all the generators should be set to “YES”. Refer to Figure 63 for an example of how the Play-In generator should appear in PowerWorld.

The screenshot shows the 'Model Explorer: Generators' window. The left pane shows a tree view with 'Generators' selected. The main pane displays a table with the following data:

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set V	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	40298 COULEE24	1	Closed	635.82	-47.48	0.99075	NO	YES	0.00	825.70	-312.57	306.76	None	825.70
2	40287 COULEE	1	Closed	-635.78	132.35	1.08686	NO	YES	-999999.02	999999.02	-999999.02	-999999.02	None	10.00

Figure 63: Example settings for Play-In generator

- 5) Under the “File” tab, click the “Load Auxiliary” then select a PowerWorld Auxiliary file containing voltage and frequency data to be used during a transient stability simulation at the Play-In generator bus. The setup for the Auxiliary file is shown in Appendix B:
Example PowerWorld PlayInGen Data Auxiliary File.
- 6) Under the Stability tab for the Play-In generator, insert the machine model called “PLAYINGEN”. Choose the name of the Play-In data loaded during the previous step. Make sure the “Vindex” and “Findex” are set to the corresponding numbers for the “TSSignals” from the Auxiliary file. Also, set the output impedance of the Thevenin voltage source in per unit in the “Rth” and “Xth” boxes. Typically, the values would want to be small compared to the impedances within your system so that the voltage at the Thevenin source would equal the voltage at the bus it is connected. Acceptable values for

“Rth” and “Xth” are 0 and 0.00001 pu, respectively. Note that when making “Xth” equal zero simulation errors have been encountered. Refer to Figure 64 to see the completed stability settings for Play-In Generator.

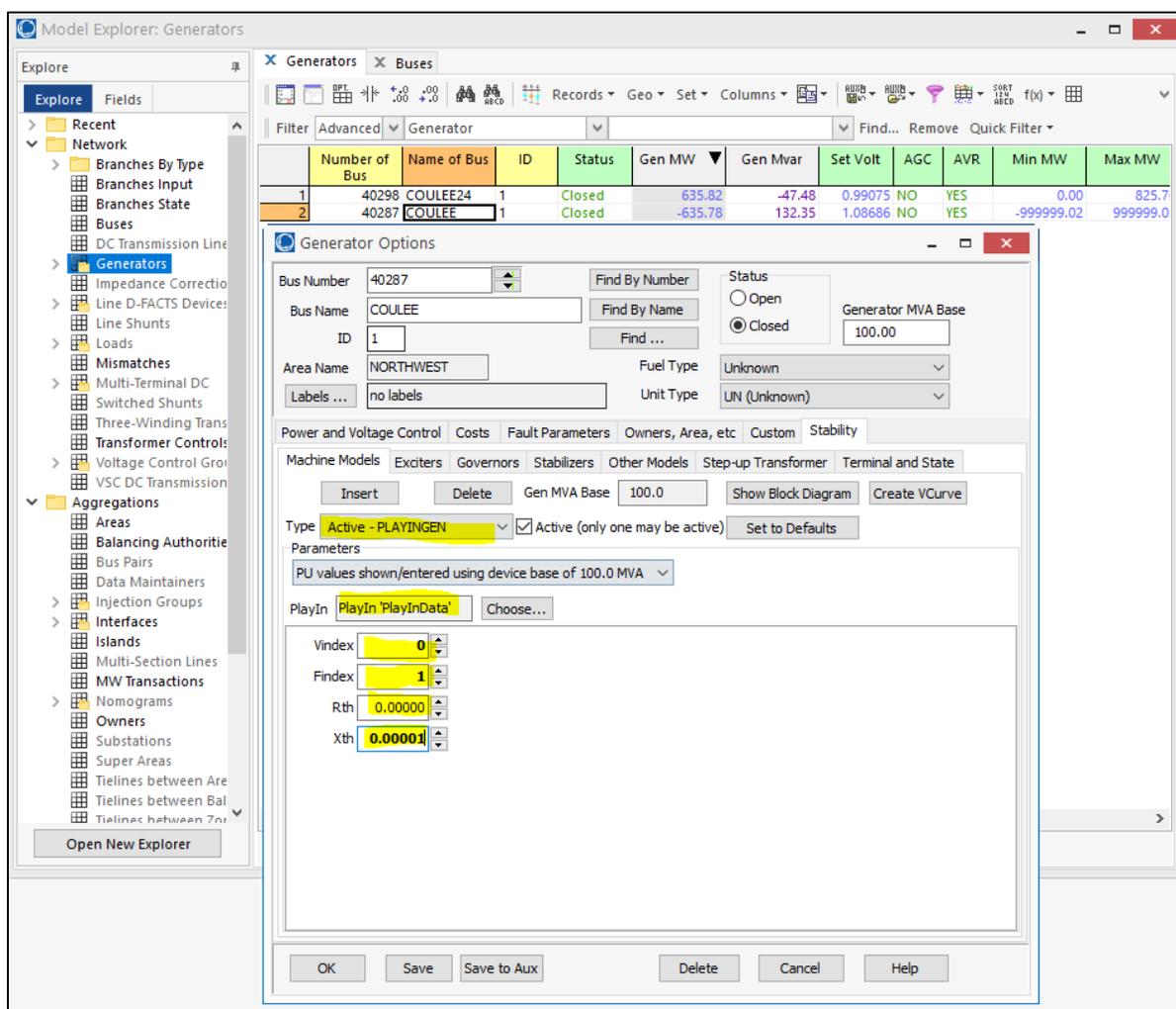


Figure 64: Example stability settings for Play-In Generator

- 7) Next open the “Transient Stability Analysis” tab while in “Run Mode”. Under the “Simulation” tab, specify the “Start” and “End Times” for the simulation along with the desired “Time Step”. If a time step smaller than the Play-In data loaded in Step 93 is desired, consider picking a multiple of the previous time step. Refer to Figure 65 to see the locations of these settings.

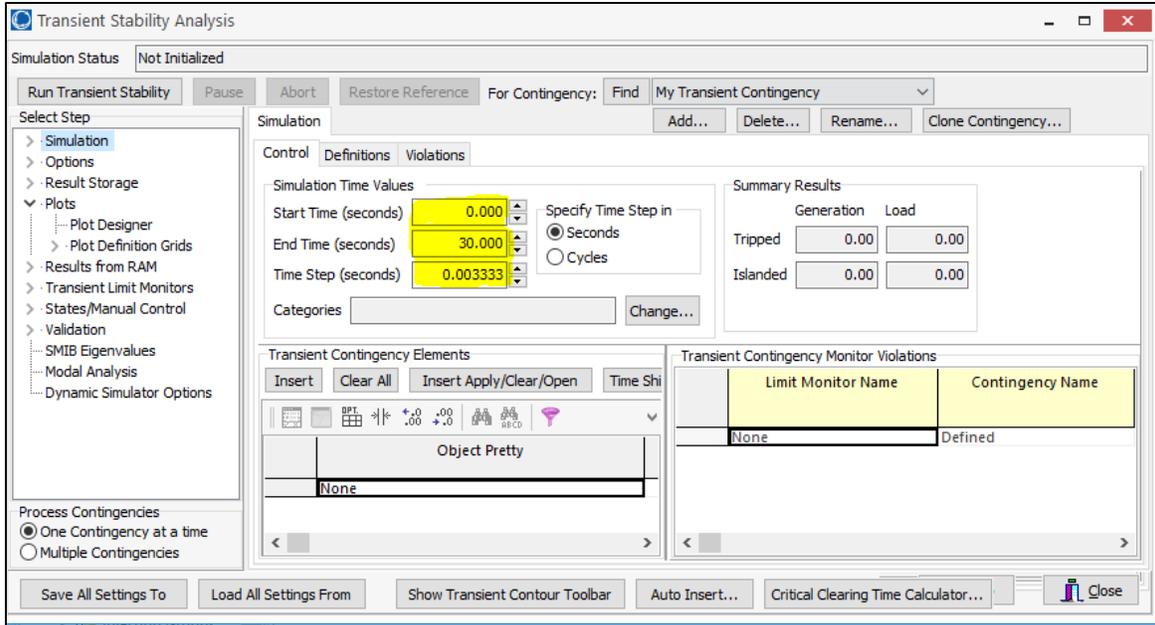


Figure 65: Example transient stability time settings

- 8) The next step is setting up the plot definitions to get the desired output from a transient stability simulation. Under the “Plots” tab, open the “Plot Designer” subtab. To add a plot, choose a “Device Type”, “Field”, and the “Name” of the bus then drag the “Field” to the desired plot. An example of the plots for an output of the simulation are shown in Figure 66.

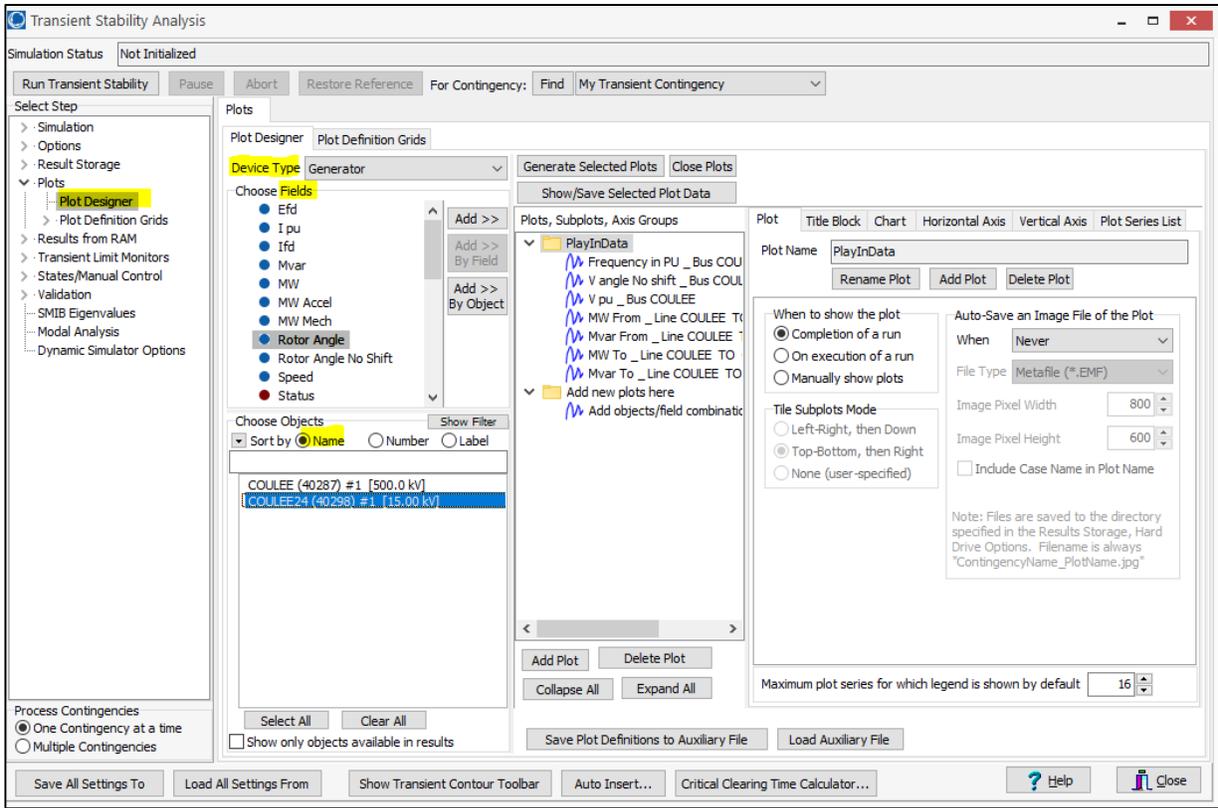


Figure 66: Example transient stability plot settings

12. Appendix B: Example PowerWorld PlayInGen Data Auxiliary File

The following code is an example of an auxiliary file containing voltage and frequency data to be used during a PowerWorld transient simulation at a PlayInGen model. Note that the voltage and frequency values need to be in per unit.

```

DATA (PlayIn, [TSName,          TSTimeOffSet], AUXDEF, YES)
{
"PlayInData" 0.0
}

DATA (PlayInInfo, [TSName, TSSignalIndex, TSInfoName, TSScale, TSFilter], AUXDEF, YES)
{
"PlayInData" 0          "V pu"          1          0.0
"PlayInData" 1          "Frequency pu" 1          0.0
}

DATA (PlayInSignal, [TSName,          TSTime, TSSignal, TSSignal:1], AUXDEF, YES)
{
"PlayInData" 0.0000000 1.081253176475036 0.999784298831461
"PlayInData" 0.01666667 1.081322367234318 0.999779143699626
"PlayInData" 0.03333333 1.081441203449071 0.999776812205052
"PlayInData" 0.05000000 1.081571674825383 0.999777976517394
"PlayInData" 0.06666667 1.081645784747786 0.999779723251635
"PlayInData" 0.08333333 1.081637350883430 0.999780315120021
"PlayInData" 0.10000000 1.081555295646725 0.999780446149369
"PlayInData" 0.11666667 1.081427051770444 0.999781687655380
"PlayInData" 0.13333333 1.081266607826894 0.999782172701757
"PlayInData" 0.15000000 1.081055969337511 0.999779826650135
"PlayInData" 0.16666667 1.080828543136643 0.999776738985893
"PlayInData" 0.18333333 1.080672252802262 0.999773710590606
"PlayInData" 0.20000000 1.080632891769272 0.999767452308479
"PlayInData" 0.21666667 1.080695822992016 0.999756580899672
"PlayInData" 0.23333333 1.080821181470950 0.999745268563754
"PlayInData" 0.25000000 1.080961151497710 0.999739080380172
"PlayInData" 0.26666667 1.081076250003715 0.999739848140396
"PlayInData" 0.28333333 1.081163425441463 0.999745554758656
"PlayInData" 0.30000000 1.081234267061405 0.999752189365072
"PlayInData" 0.31666667 1.081284070448024 0.999757148818256
"PlayInData" 0.33333333 1.081282159912158 0.999759546395549
"PlayInData" 0.35000000 1.081199045367679 0.999759888057085
"PlayInData" 0.36666667 1.081065149458132 0.999758756704912
"PlayInData" 0.38333333 1.080945016720838 0.999756669668745
"PlayInData" 0.40000000 1.080867518673206 0.999755777586434
"PlayInData" 0.41666667 1.080834659693024 0.999757852345667
"PlayInData" 0.43333333 1.080853997878825 0.999760255023960
"PlayInData" 0.45000000 1.080914129902444 0.999759518923435
"PlayInData" 0.46666667 1.080966435224879 0.999757379320501
"PlayInData" 0.48333333 1.080981276554504 0.999756020291832
"PlayInData" 0.50000000 1.080974705341692 0.999756872503898
}

```

13. Appendix C: PSLF wsc_9bus Small Time Step Plots

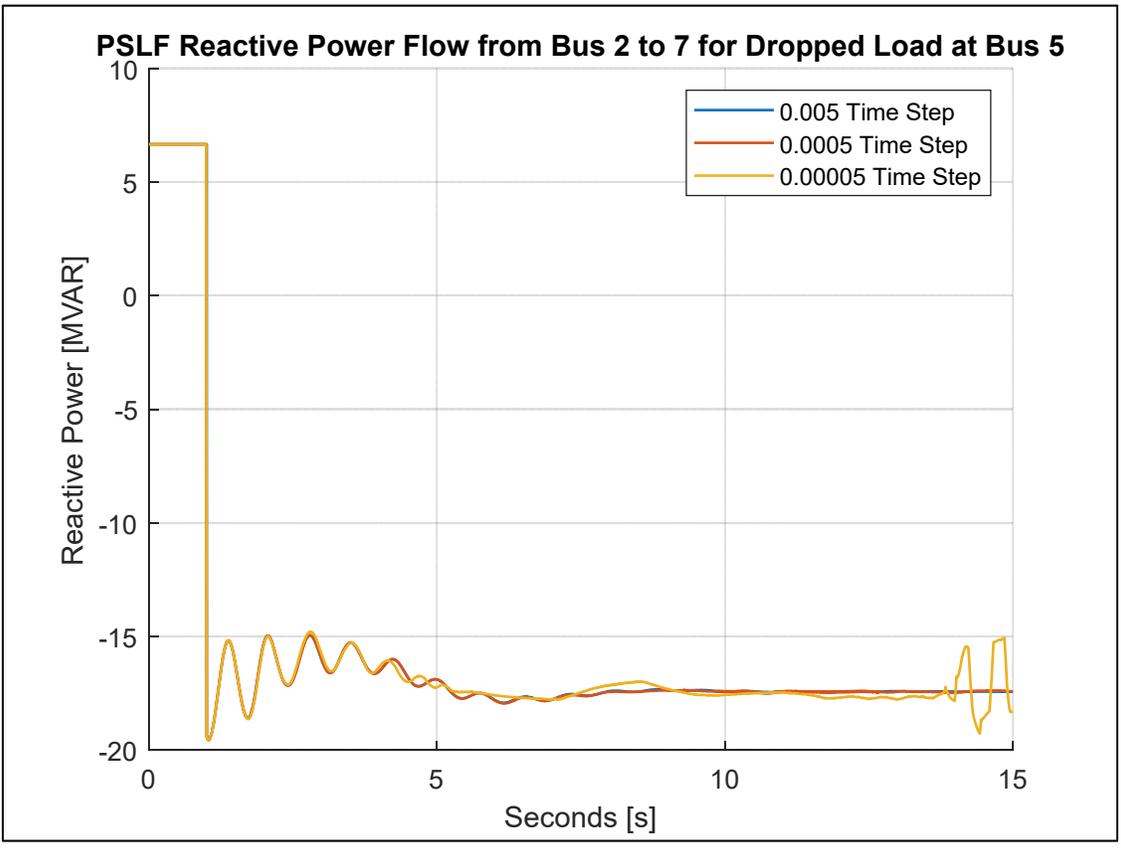


Figure 67: Reactive power plot for PSLF time step testing

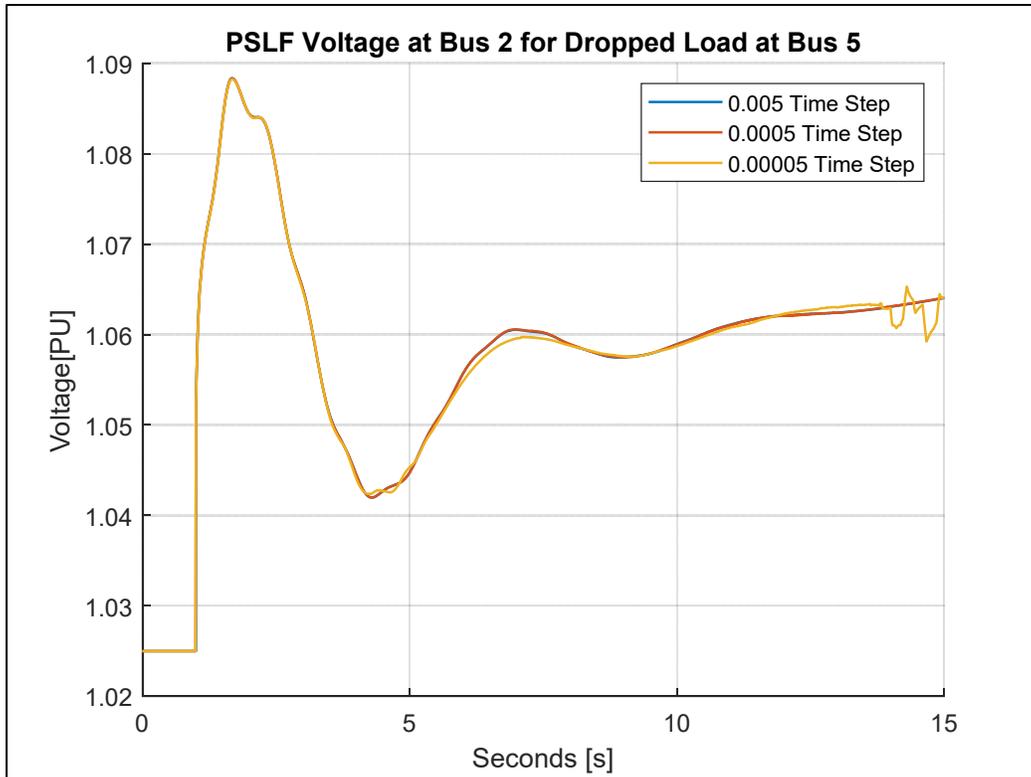


Figure 68: Voltage plot for PSLF time step testing

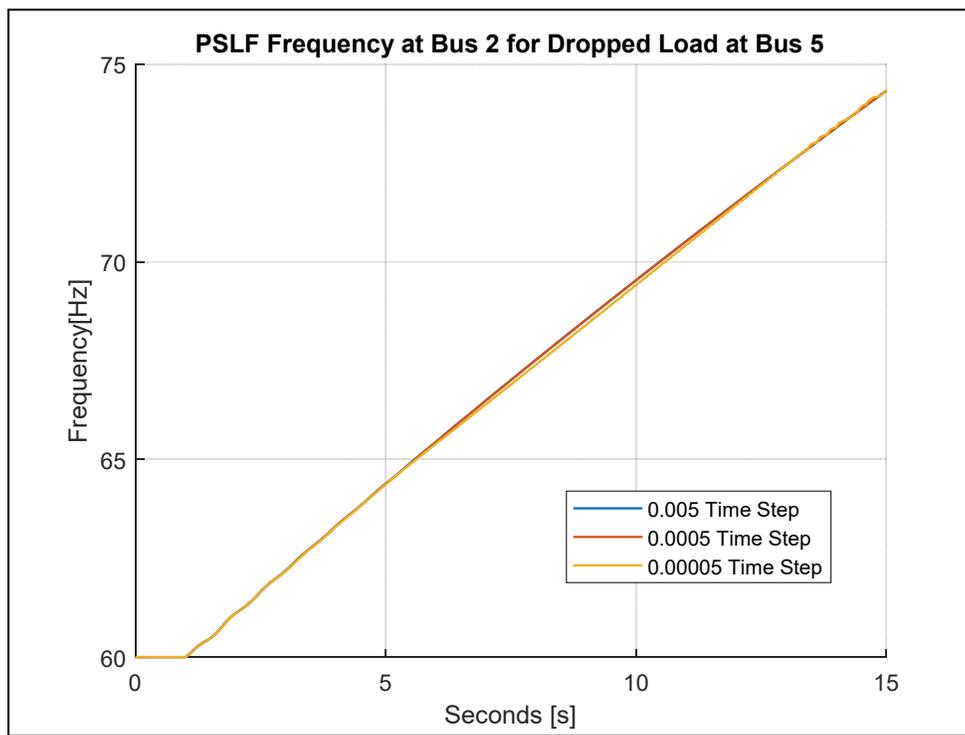


Figure 69: Frequency plot for PSLF time step testing

14. Appendix D: PowerWorld wsc_9bus Small Time Step Plots

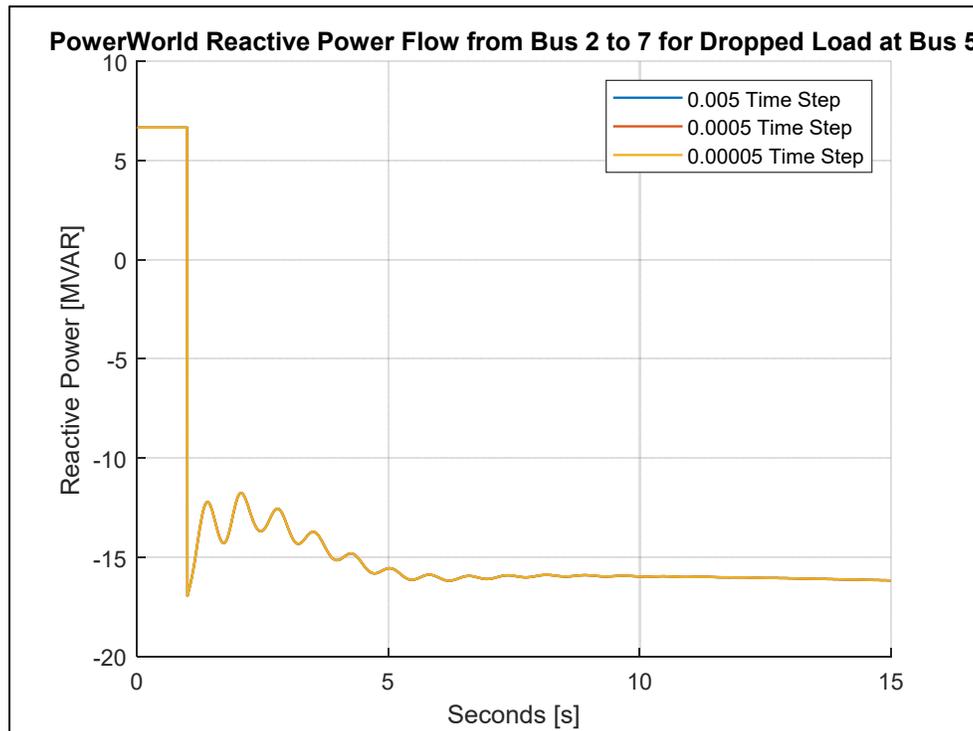


Figure 70: Reactive power plot for PSLF time step testing

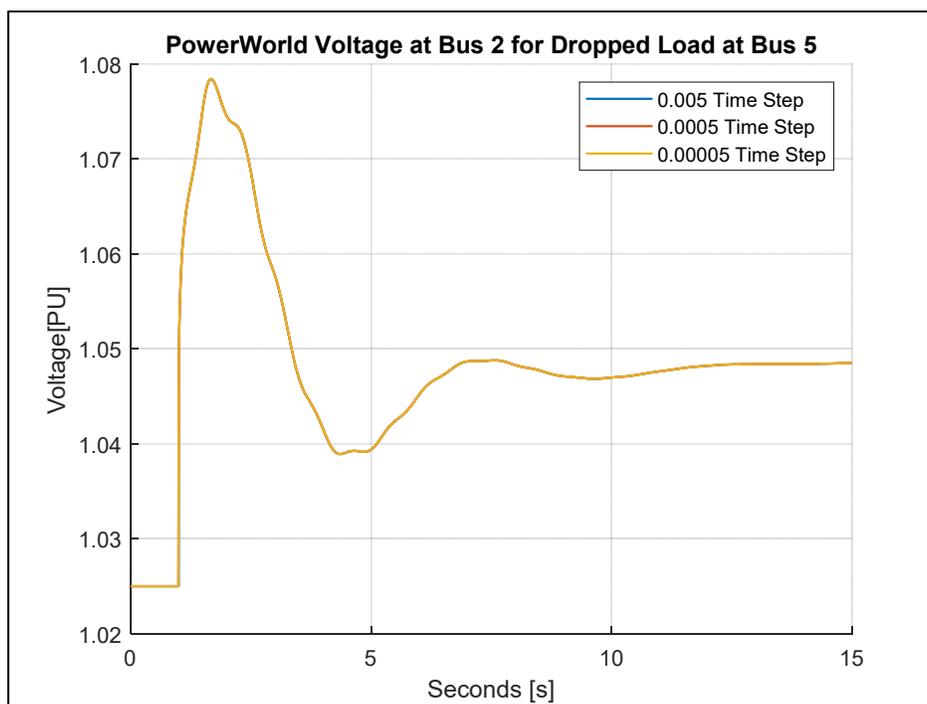


Figure 71: Voltage plot for PSLF time step testing

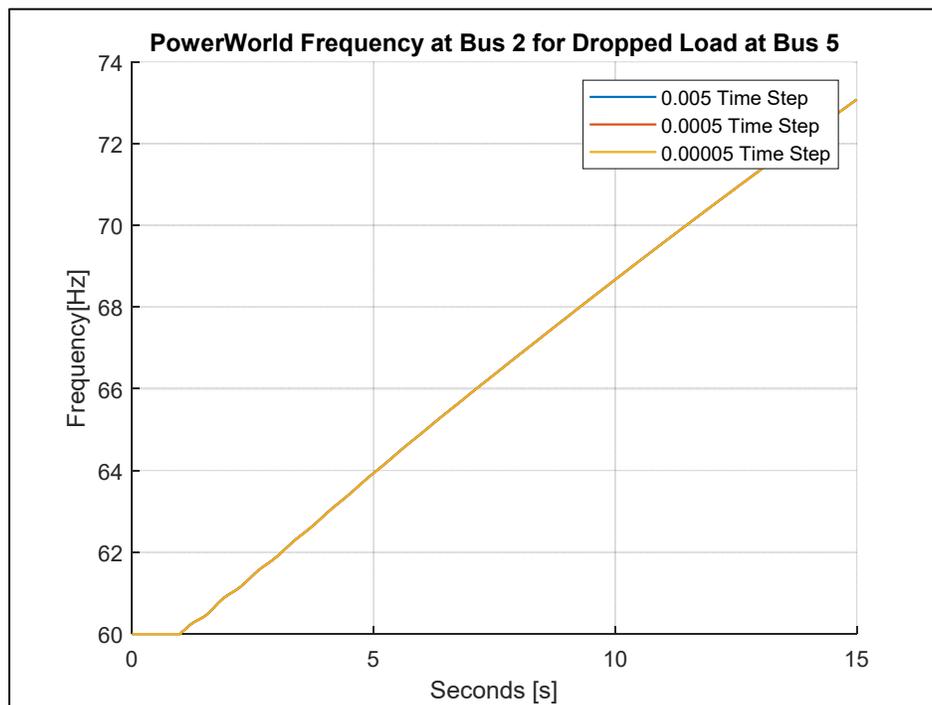


Figure 72: Frequency plot for PSLF time step testing

15. Appendix E: Example "SetupAux.aux" for Coulee 24 Generator

```

SCRIPT
{
OpenCase("COULEE24_PlayIn_RealPMU.PWB",PWB);
EnterMode(EDIT);
}

DATA (Branch,
[BusNum,BusName,BusNum:1,BusName:1,LineCircuit,LineR,LineX,LineC])
{
40287 "COULEE" 41744 "COULEE24" 1 1e-05 0.00023 0.02096
}

DATA (Branch, [BusNum,BusName,BusNum:1,BusName:1,LineCircuit,LineR,LineX])
{
41744 "COULEE24" 40298 "COULEE24" 1 0 0.029731825145
}

DATA (GEN, [BusNum,BusName,GenID,VoltSet])
{
40287 "COULEE" 1 1.08633068342
}

DATA (Bus, [BusNum,BusName,BusPUVolt,BusAngle])
{
40287 "COULEE" 1.08633068342 0
}

DATA (GEN, [BusNum,BusName,GenID,VoltSet,GenMW])
{
40298 "COULEE24" 1 0.986660890656 641.712914387
}

SCRIPT
{
EnterMode(RUN);
SolvePowerFlow (RECTNEWT,"","");
}

```

16. Appendix F: Example "COULEE24.dyd"

```

models
gentpj      40298 "COULEE24" 15.00 "1" : #0 mva=825.6 7.6 0.08 0 0.04
4.781852747 0 1.02 0.7 0.32 0.7 0.25 0.25 0.15 0.08 0.24 0.0028 0 0.08 0 0.08
esst5b      40298 "COULEE24" 15.00 "1" : #0 0 200 0.004 0.004 9.5 -8.6 1.2
2.667 0.01 0.017 1.52 3.378 0.1 0.15 1.5 3.33 0.1 0.15
oell        40298 "COULEE24" 15.00 "1" : #0 1.89 2.87 10 0 999 999 1.8 0 0
pss2b       40298 "COULEE24" 15.00 "1" : #9 1 0 3 0 999 -999 10 10 999 -999 10
0 0.017 10 1.006 1 0.3 0.15 4 2 8.906308289 0.4139950006 0.05 0.04 0.017 0.06
0.017 0.1 -0.1 1 0 0 1
hygovr      40298 "COULEE24" 15.00 "1" : #0 mwcap=826.0 1 0 0.05 0.05 0.017
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.0714 -0.0552 0.5 4 1.05 -0.05 0 0 0 0 2 1 1
0 1 0.16 0 0.61 0.64 0.7 0.75 0.85 0.91 0.98 0.99 1 1

```

17. Appendix G: Example “LoadDYD_RunPlayIn_RealPMU.aux” File

```
SCRIPT LoadDYD_RunPlayIn
{
//Clear Log
LogClear;
//Load Case
OpenCase("COULEE24_PlayIn_RealPMU.PWB",PWB);
//Load SetupAux Aux File
LoadAux("SetupAux.aux");
//Load Aux File with PlayInData
LoadAux("PlayInData.aux");
//Enter Edit Mode
EnterMode(EDIT);
//Load Dyd File
TSLoadGE("COULEE24_PlayIn.dyd", NO, YES);
//Enter Run Mode
EnterMode(RUN);
//Solve Dynamic Simulation
TSSolveAll;
//Save to Log
LogSave("Log_PowerWorld.txt");
}
```

18. Appendix H: Extensive Results Single Parameter Fitting for Chief Joseph PH1

The following single parameter fittings were conducted on two generators connected downstream of the CHJ PH1 PMU bus. The Play-In simulation was found to provide the closest fit to the PMU data with only Gen1 and Gen3 operating. The Gen1 generator is the generator connected to the CHJ 0102 bus with the ID 01 and the Gen3 generator is the generator located at the CHJ 0304 bus with the ID 03. Only the PMU data from the pulsing of the braking resistor located at the Chief Joseph substation were used as events in this case. The noise multiplier was calibrated to provide a matching distribution for the gentpj H parameter which represents the inertia constant of the generator. The 0.0008 multiplier provides a closely matching distribution between the event data and the 250 realizations of noise added to the single Event 1 case.

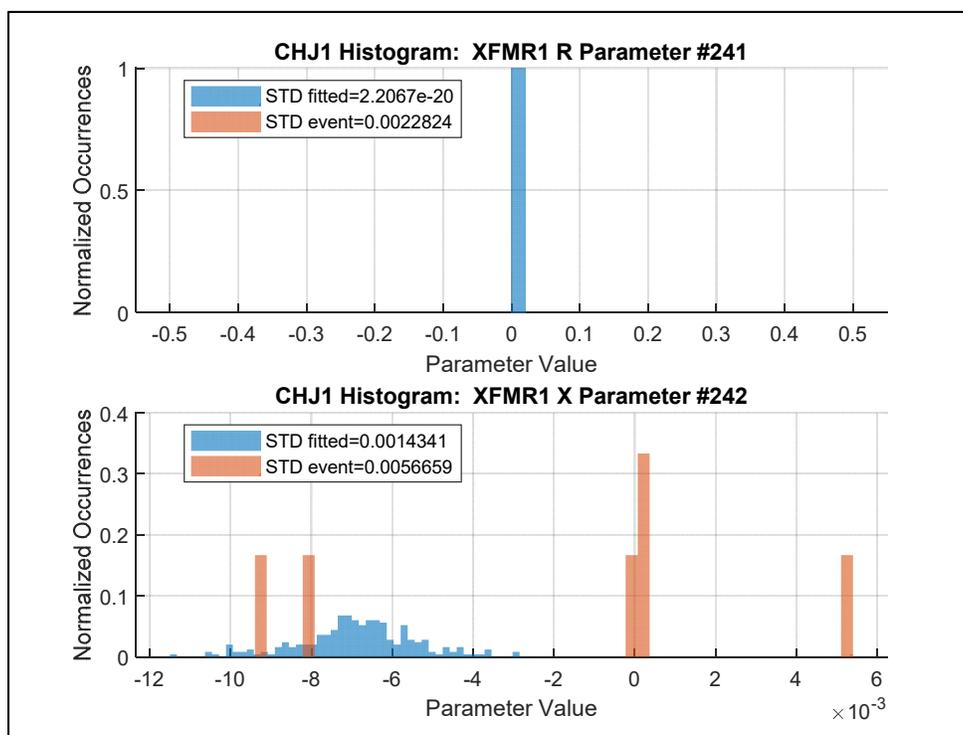


Figure 73: CHJ1 single parameter XFMR 1 R and X histograms.

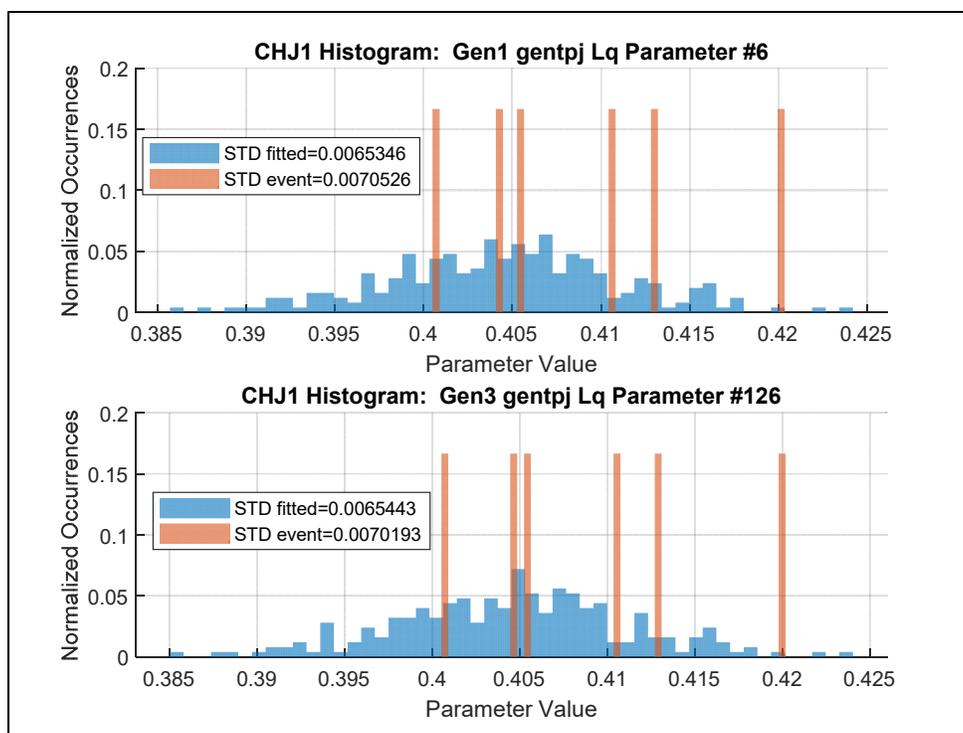


Figure 74: CHJ1 single parameter gentpj Lq histogram comparison.

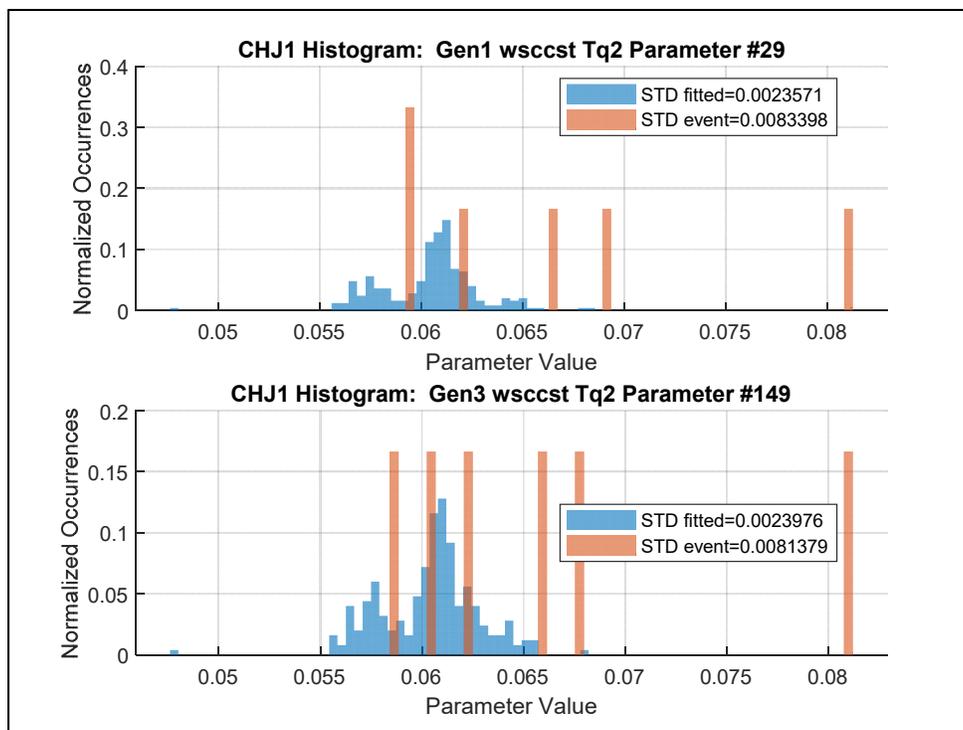


Figure 75: CHJ1 single parameter wscst Tq2 histogram comparison.

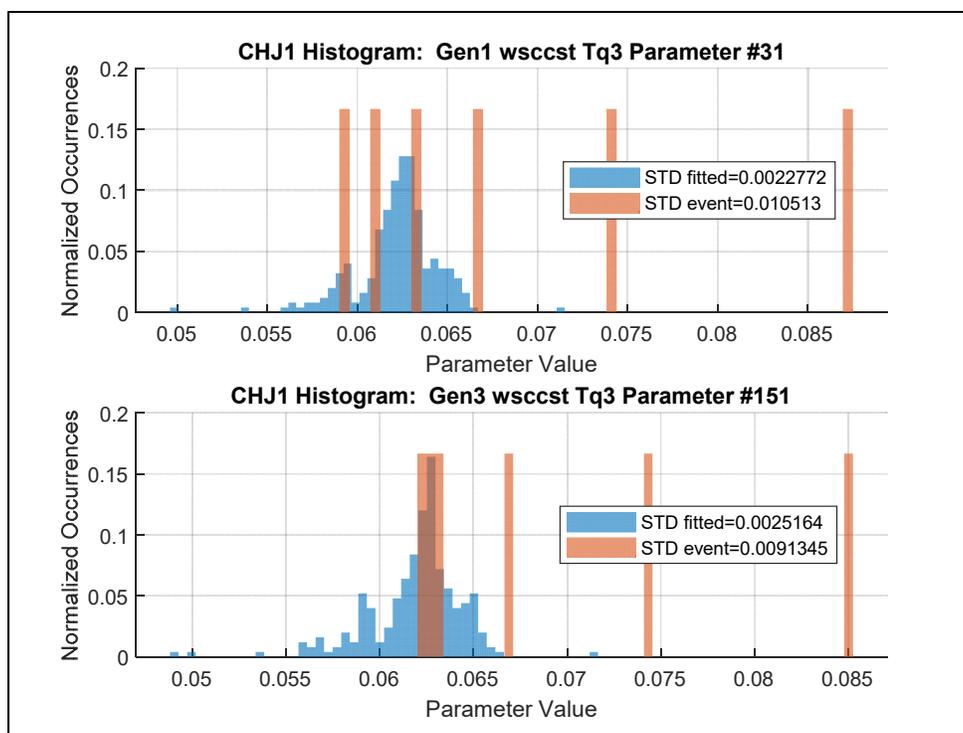


Figure 76: CHJ1 single parameter wscst Tq3 histogram comparison.

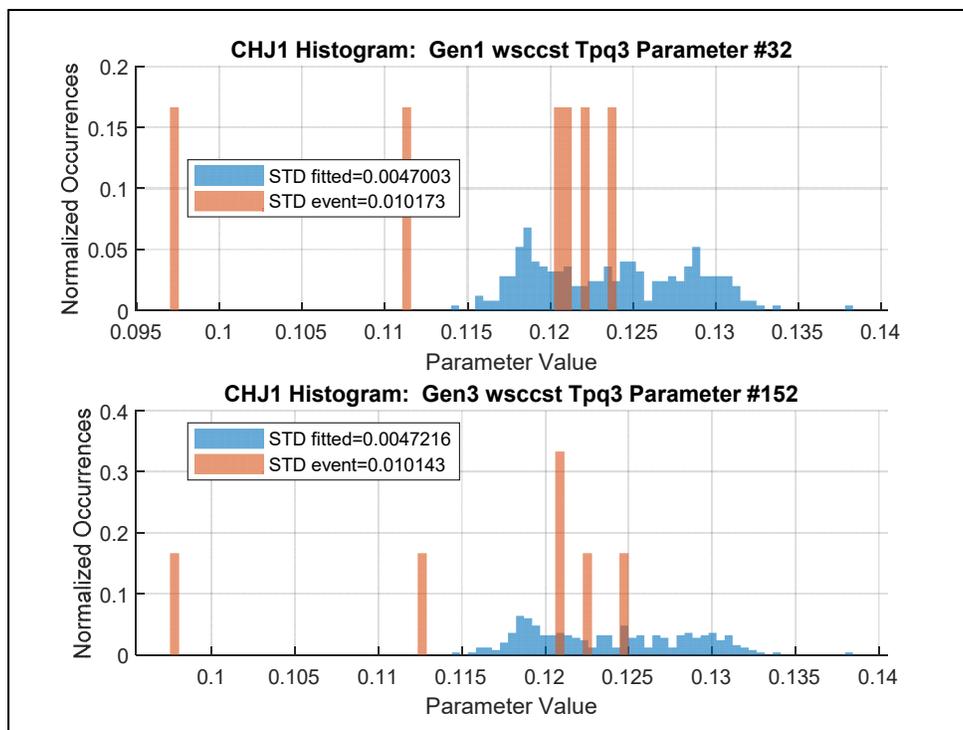


Figure 77: CHJ1 single parameter wscst Tp3 histogram comparison.

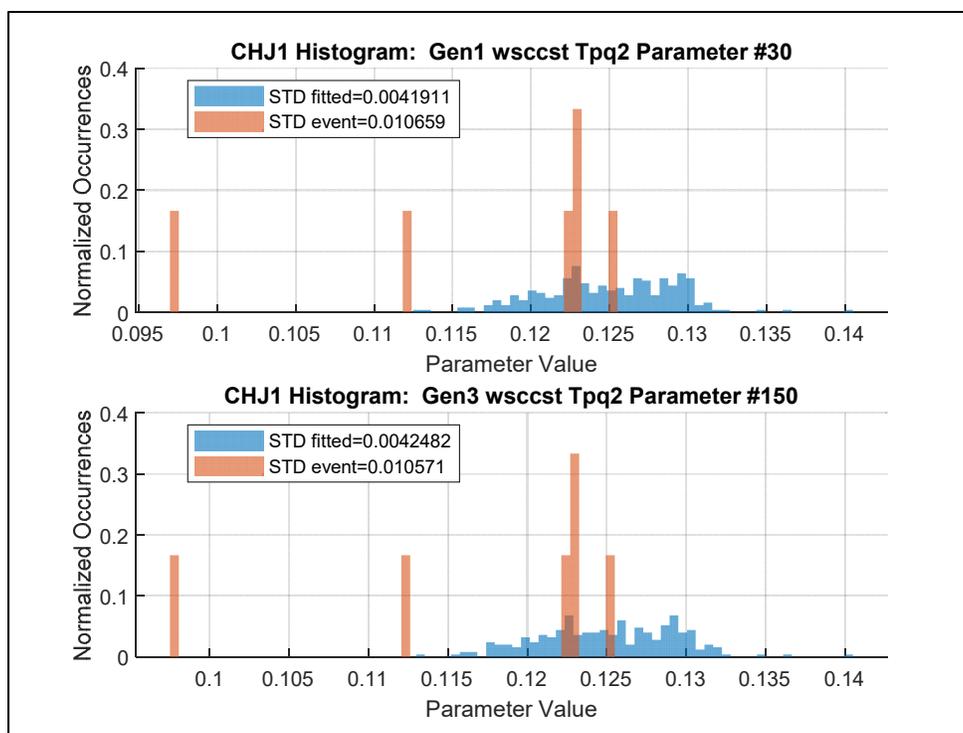


Figure 78: CHJ1 single parameter wscst Tpq2 histogram comparison.

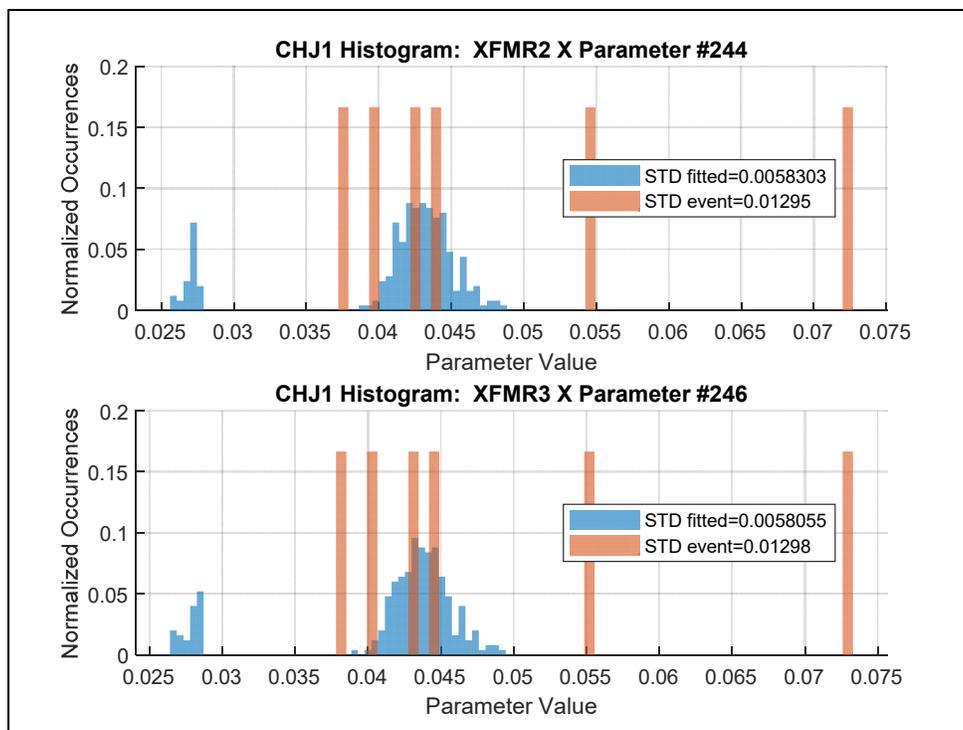


Figure 79: CHJ1 single parameter XFMR2 X and XFMR3 X histograms.

19. Appendix I: Extensive Results Single Parameter Fitting for COULEE 24 Generator

The system used to run Play-In simulations contained the models between the COULEE PMU bus and the COULEE24 generator bus. The single parameter fittings are used to test the COULEE24 power plant model. Only the PMU data from the pulsing of the braking resistor located at the Chief Joseph substation were used as events in this case. The noise multiplier was calibrated to provide a matching distribution for the gentpj H parameter which represents the inertia constant of the generator. The 0.0042 multiplier provides a closely matching distribution between the event data and the 250 realizations of noise added to the single Event 7 case. The Event 7 case is the seventh brake pulse recorded by the PMU.

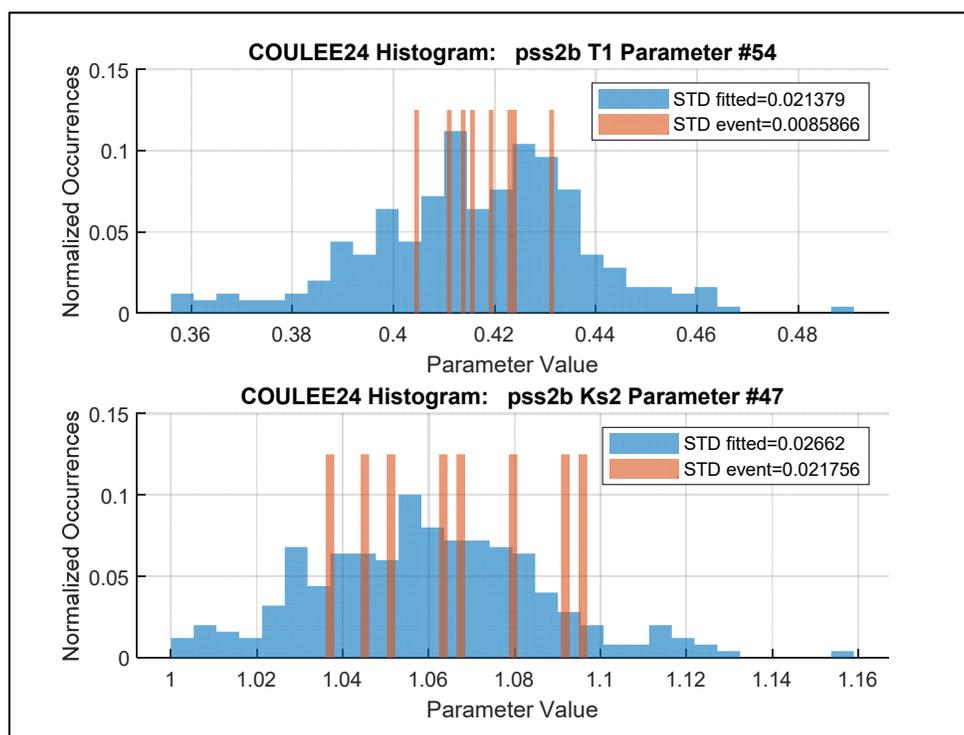


Figure 80: COULEE24 single parameter pss2b T1 and pss2b Ks2 histograms.

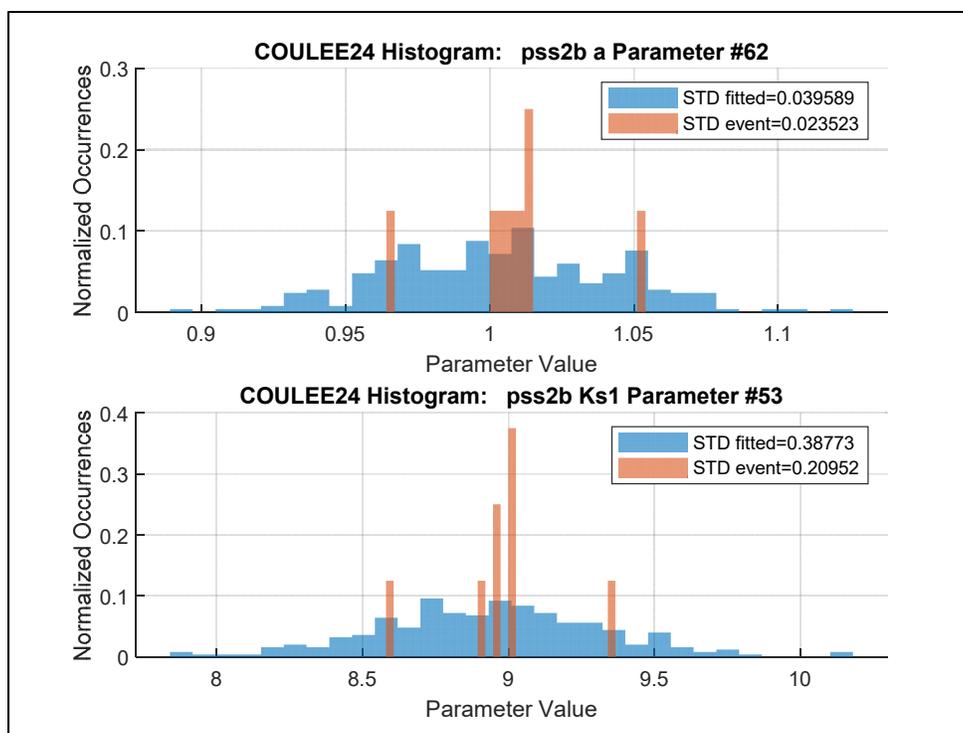


Figure 81: COULEE24 single parameter pss2b a and pss2b Ks1 histograms.

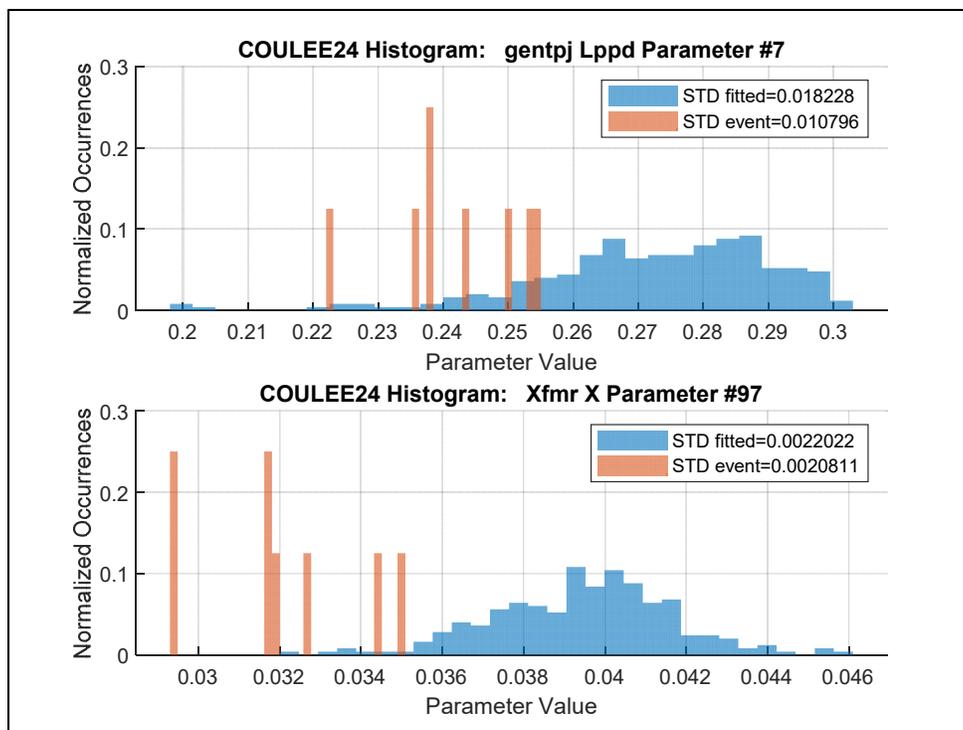


Figure 82: COULEE24 single parameter gentpj Lppd and XFMR X histograms.

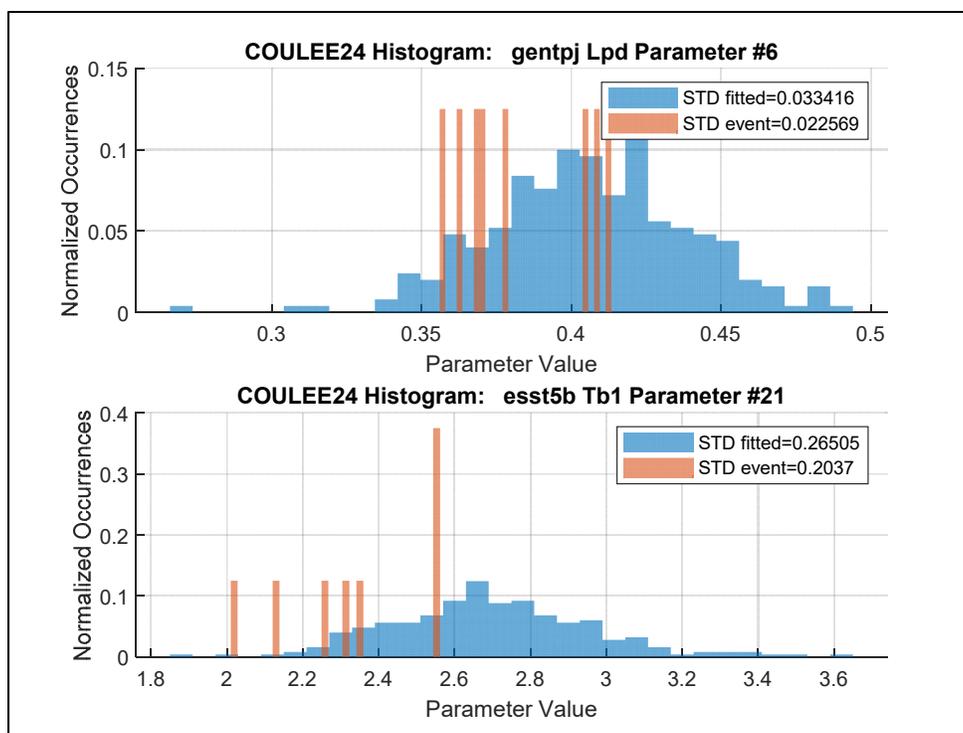


Figure 83: COULEE24 single parameter gentpj Lpd and esst5b Tb1 histograms.

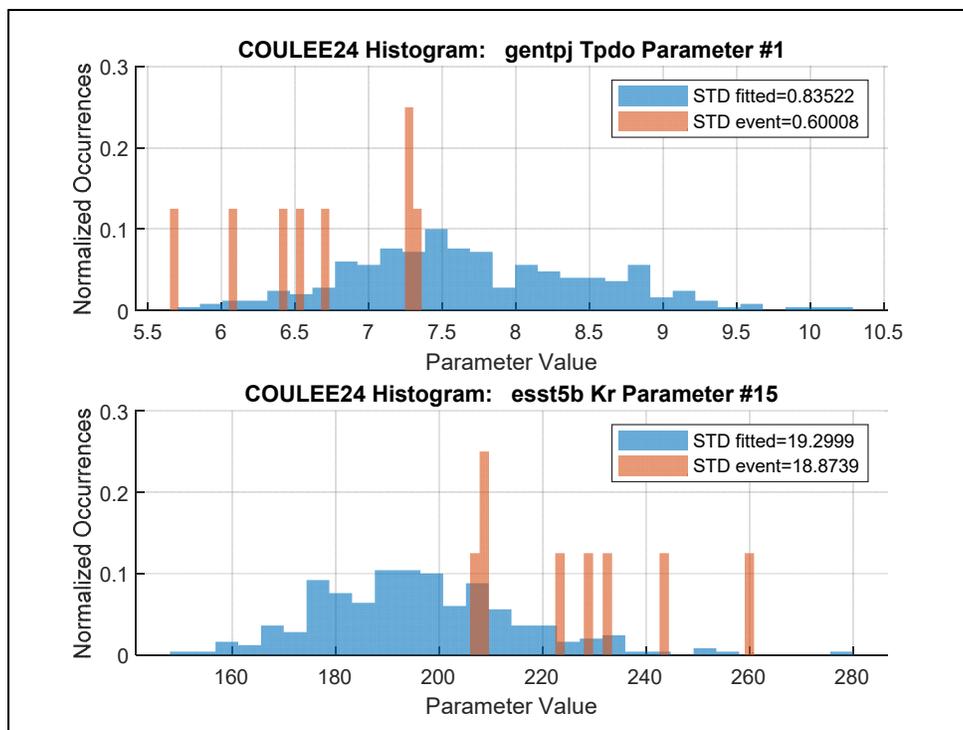


Figure 84: COULEE24 single parameter gentpj Tpdo and esst5b Kr histograms.

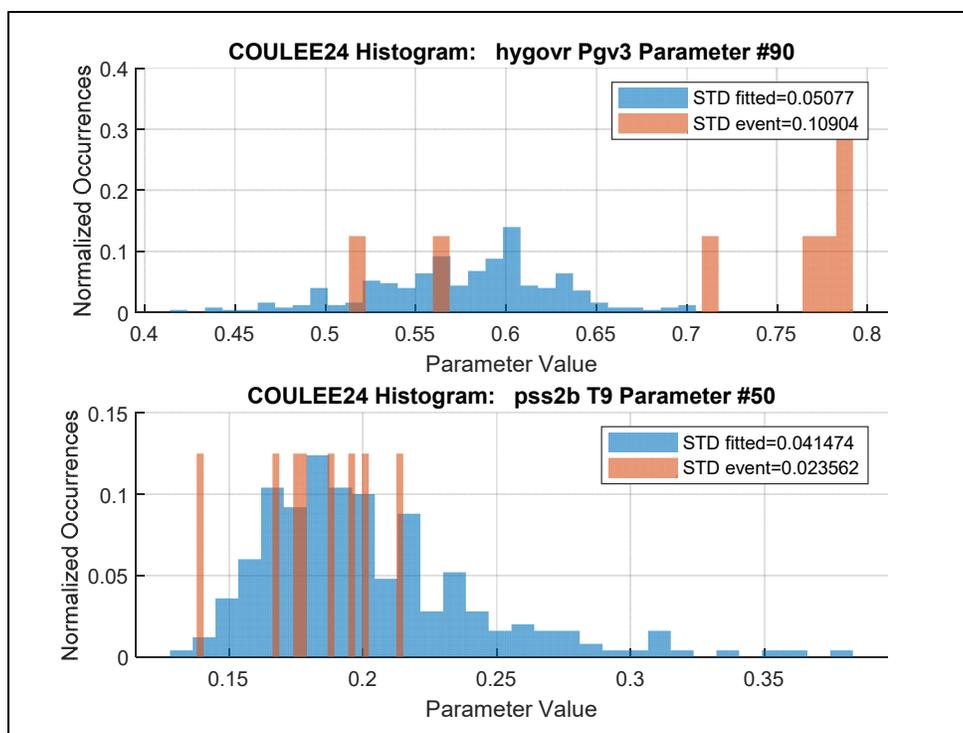


Figure 85: COULEE24 single parameter hygovr Pgv3 and pss2b T9 histograms.

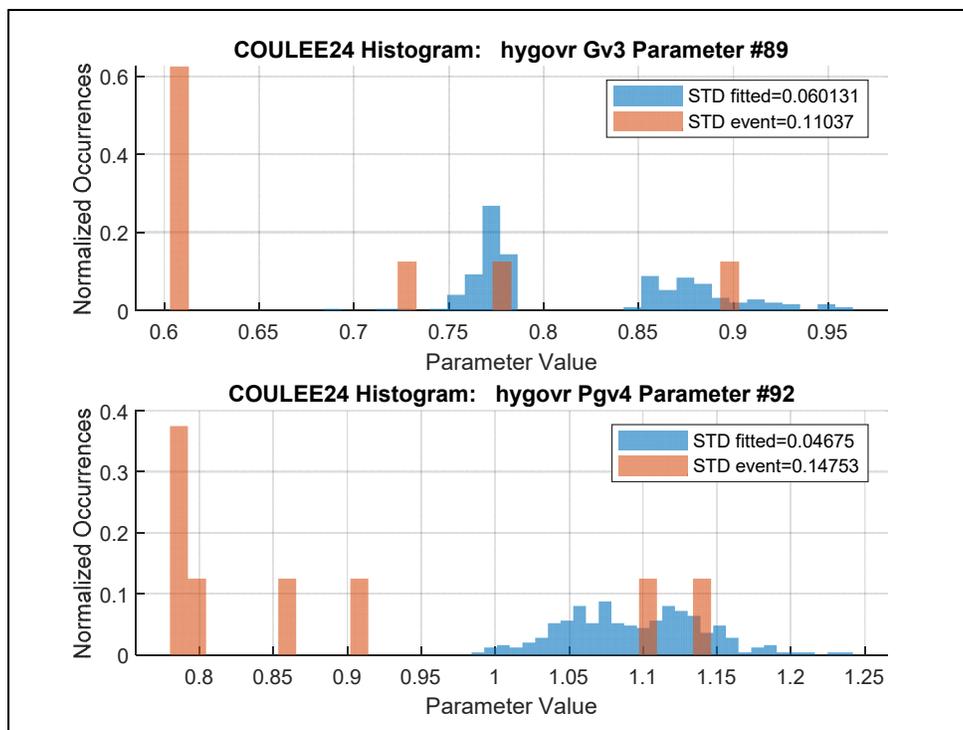


Figure 86: COULEE24 single parameter hygovr Gv3 and hygovr Pgv4 histograms.

20. Appendix J: Extensive Results Single Parameter Fitting for CENTR G1 Generator

The system used to run Play-In simulations contained the models between the CENTR P1 PMU bus and the CENTR G1 generator bus. The single parameter fittings are used to test the CENTR G1 power plant model. Only the PMU data from the pulsing PDCI were used as events in this case. The noise multiplier was calibrated to provide a matching distribution for the genrou H parameter which represents the inertia constant of the generator. The 0.0006 multiplier provides a closely matching distribution between the event data and the 250 realizations of noise added to the single Event 1 case. The events were all recorded by the PMU in 2016.

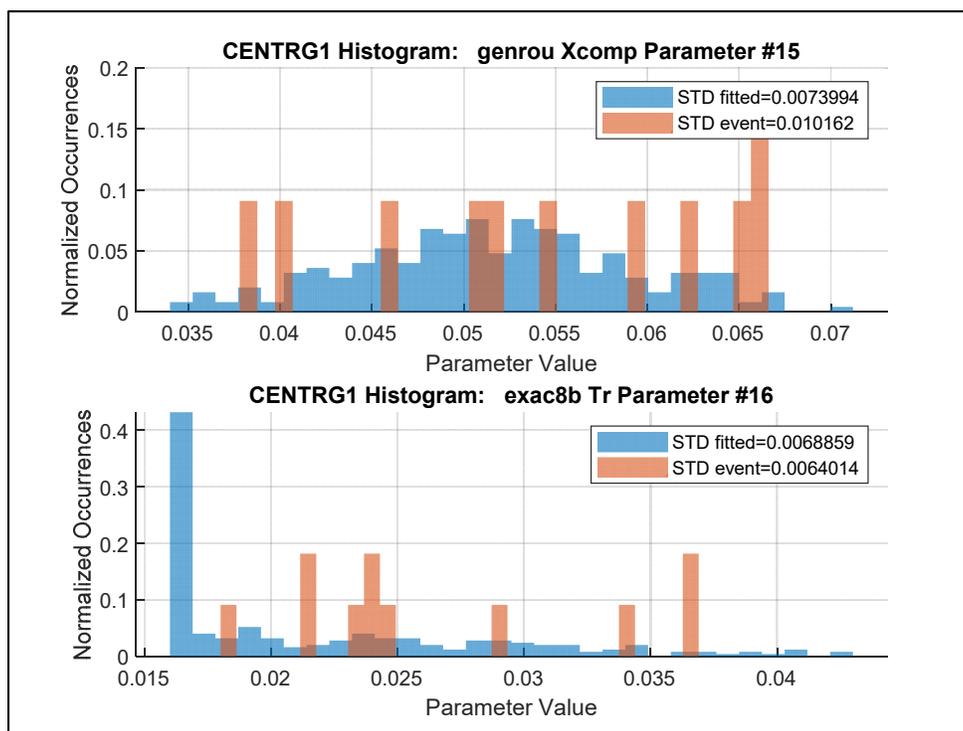


Figure 87. CENTRG1 single parameter genrou Xcomp and exac8b Tr histogram.

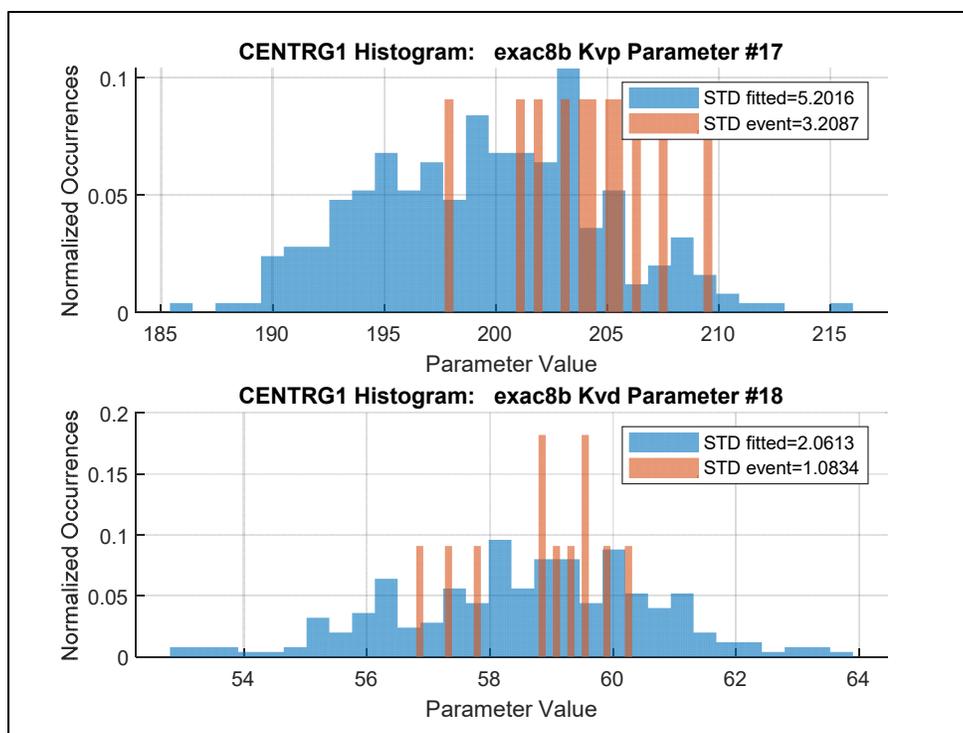


Figure 88.CENTRG1 single parameter exac8b Kvp and Kvd histogram.

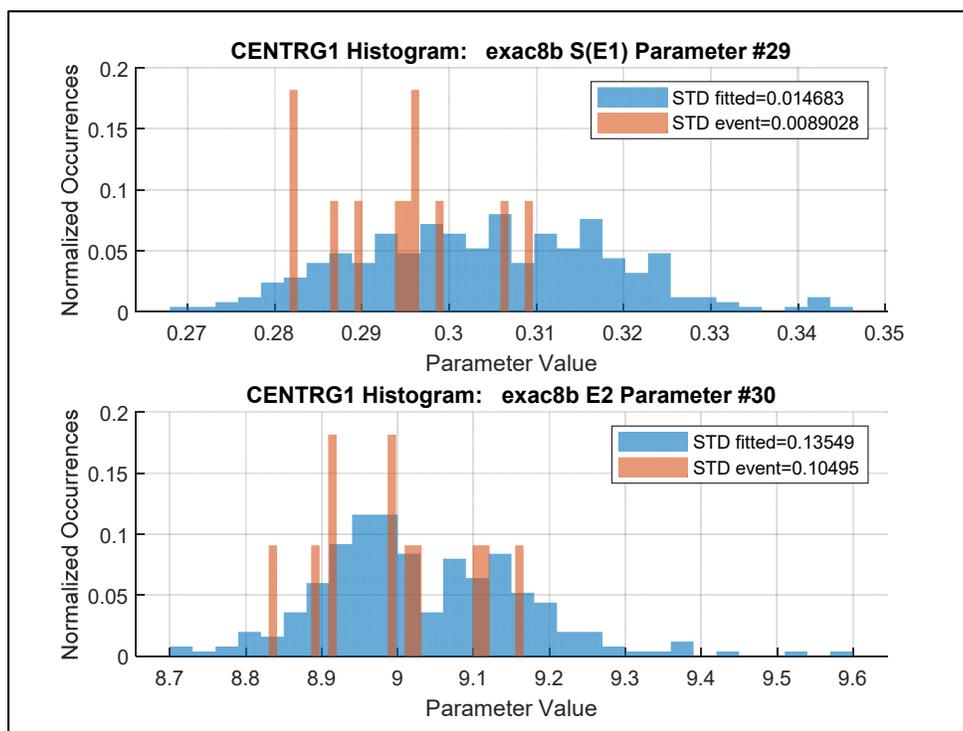
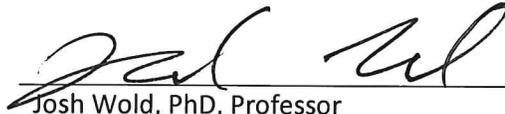


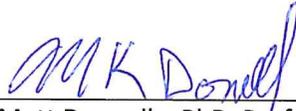
Figure 89.CENTRG1 single parameter exac8b S(E1) and E2 histogram.

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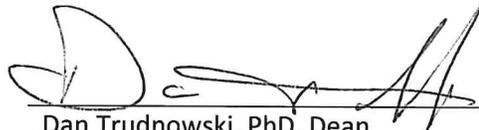
This is to certify that the thesis prepared by Jacob Eisenbarth entitled "A TESTBED AND METHODS FOR IMPROVED POWER PLANT MODEL VALIDATION VIA PMU TERMINAL MEASUREMENTS" has been examined and approved for acceptance by the Department of Electrical Engineering, Montana Technological University, on this 30th day of July, 2020.



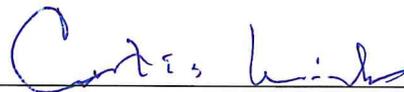
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