NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Reliability Guideline

Power Plant Dynamic Model Verification using PMUs

September 2016

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Table of Contents

Preamble

It is in the public interest for NERC to develop guidelines that are useful for maintaining or enhancing the reliability of the Bulk Electric System (BES). The Technical Committees of NERC; Operating Committee (OC), Planning Committee (PC) and the Critical Infrastructure Protection Committee (CIPC) per their charters[1] are authorized by the NERC Board of Trustees (Board) to develop Reliability (OC and PC) and Security Guidelines (CIPC). These guidelines establish a voluntary code of practice on a particular topic for consideration and use by BES users, owners, and operators. These guidelines are coordinated by the technical committees and include the collective experience, expertise and judgment of the industry. The objective of this reliability guideline is to distribute key practices and information on specific issues critical to maintaining the highest levels of BES reliability. Reliability guidelines are not to be used to provide binding norms or create parameters by which compliance to standards is monitored or enforced. While the incorporation of guideline practices are strictly voluntary, reviewing, revising, or developing a program using these practices is highly encouraged to promote and achieve the highest levels of reliability for the BES.

NERC as the FERC certified ERO[2] is responsible for the reliability of the BES and has a suite of tools to accomplish this responsibility, including but not limited to: lessons learned, reliability and security guidelines, assessments and reports, the Event Analysis program, the Compliance Monitoring and Enforcement Program and mandatory reliability standards. Each entity as registered in the NERC compliance registry is responsible and accountable for maintaining reliability and compliance with the mandatory standards to maintain the reliability of their portions of the BES. Entities should review this guideline in detail in conjunction with the periodic review of their internal processes and procedures and make any needed changes to their procedures based on their system design, configuration and business practices.

---

[1] http://www.nerc.com/comm/OC/Related%20Files%20DL/OC%20Charter%2020131011%20(Clean).pdf
http://www.nerc.com/comm/CIPC/Related%20Files%20DL/CIPC%20Charter%20(2)%20with%20BOT%20approval%20footer.pdf
http://www.nerc.com/comm/PC/Related%20Files%202013/PC%20Charter%20-%20Board%20Approved%20November%202013.pdf

[2] http://www.ferc.gov/whats-new/comm-meet/072006/E-5.pdf

Purpose

This Reliability Guideline is intended to raise industry awareness and utilization of dynamic disturbance recorders (DDRs) such as Phasor Measurement Units (PMUs) and synchrophasor data for dynamic model verification of power plant models. This guideline presents one method of disturbance based verification that may be used to perform verification of dynamic models and focuses on the use of synchrophasor data as one form of DDR data for performing power plant model verification (PPMV); it does not discuss the use of PMUs for system-wide model verification or comparison, and briefly discusses other complementary methods such as generator baseline testing[3] for completeness. It is meant to provide utilities that have PMUs located at the terminals of generating units or the Point of Interconnection (POI) of power plants with guidance and appropriate technical reference material such that they can effectively and efficiently pursue model verification using synchronized measurement data. While the use of PMU data is the primary focus of this guideline, it is noted that other techniques for model verification exist. The methodologies outlined herein also apply to other types of disturbance monitoring data such as data from triggered digital fault recorders (DFR) and digital relays that provide this measurement function.

The concepts presented here are generic and do not necessarily pertain to specific implementations or software tools; however, the appendix material highlights some of the commercially available tools that enable PMU-based model verification. The Reliability Guideline, as mentioned, does not provide binding norms or create parameters by which compliance to NERC Reliability Standards is monitored or enforced. However, it does provide insight into those standards for which PMUs can be used for verifying that the model performance matches actual response for system events.

The Reliability Guideline applies primarily to Transmission Planners (TP) and Generator Owners (GO). While the GO is ultimately responsible for ensuring accuracy and usability of the dynamic models, both the TP and GO play a key role in developing and verifying these models used for planning and operating the bulk power system (BPS). The TP, in coordination with the Transmission Owner (TO) and/or the GO, may own the PMU that measures the plant performance to grid events. Transmission Operators (TOP) and Generator Operations (GOP) are also involved in unit dispatch and operation of the power plant, particularly during generator testing, and can play an important role in supporting responsible entities' activities under Reliability Standards MOD-026 and MOD-027.

---

[3] Generator baseline testing refers to performing select tests (such as step tests, V-curve tests, rejection tests, etc.) and capturing response with instrumentation within the plant. This guideline provides high-level supplementary material on this type of testing as background; however, this type of verification is not the main focus of this guideline.

Fundamental Need for Representative Dynamic Models

The power system is planned and operated using dynamic models that are expected to represent the transient behavior of system elements when subjected to reasonable grid disturbances. Figure 1 shows the predominant example of the necessity of accurate models. In August 1996, a cascading sequence of events led to small signal instability (red) where undamped oscillations grew on the California-Oregon Intertie (COI), leading to large blackouts in California. When simulated to recreate the disturbance (blue), the system model in use at the time showed the system was well damped and did not represent the actual dynamic nature of the grid. This led to the Western Systems Coordinating Council (WSCC) launching a modeling initiative to improve the current state of transient stability models used for planning and operating the grid. Today, the Western Electricity Coordinating Council (WECC), Peak Reliability, and the WECC operating entities are continually monitoring dynamic model performance through accelerated power plant testing and certification as well data quality checks and disturbance-based model verification efforts.

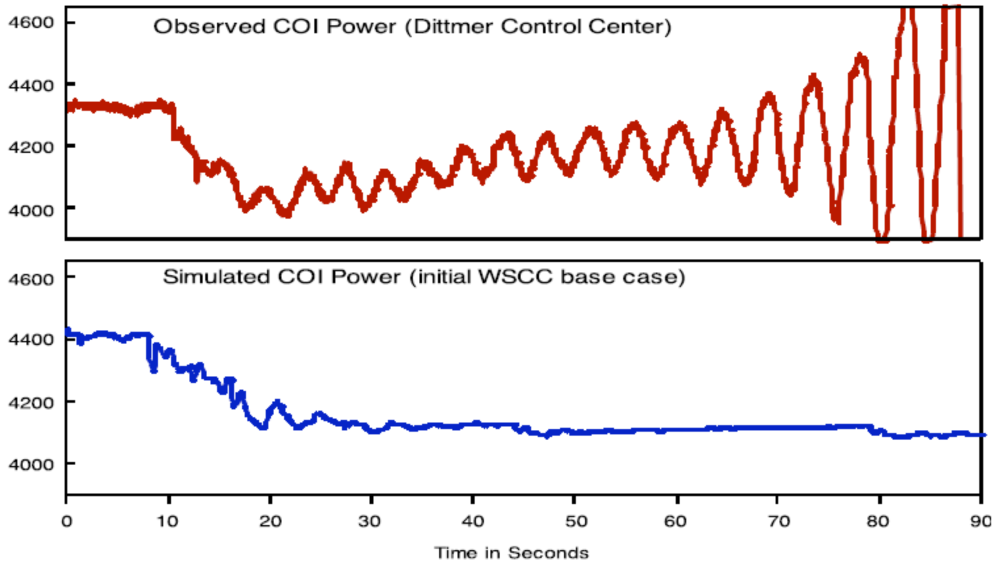


FIGURE 1: August 1996 Simulated vs. Actual System Response

Power Plant Dynamics and Dynamic Model Verification

Power plant model verification (PPMV) involves verifying the model structure and model parameters associated with the building blocks of a generating facility. Figure 2 shows the interconnectivity of the functional blocks of a power plant for a conventional generator; however, the techniques also apply to renewable energy facilities.

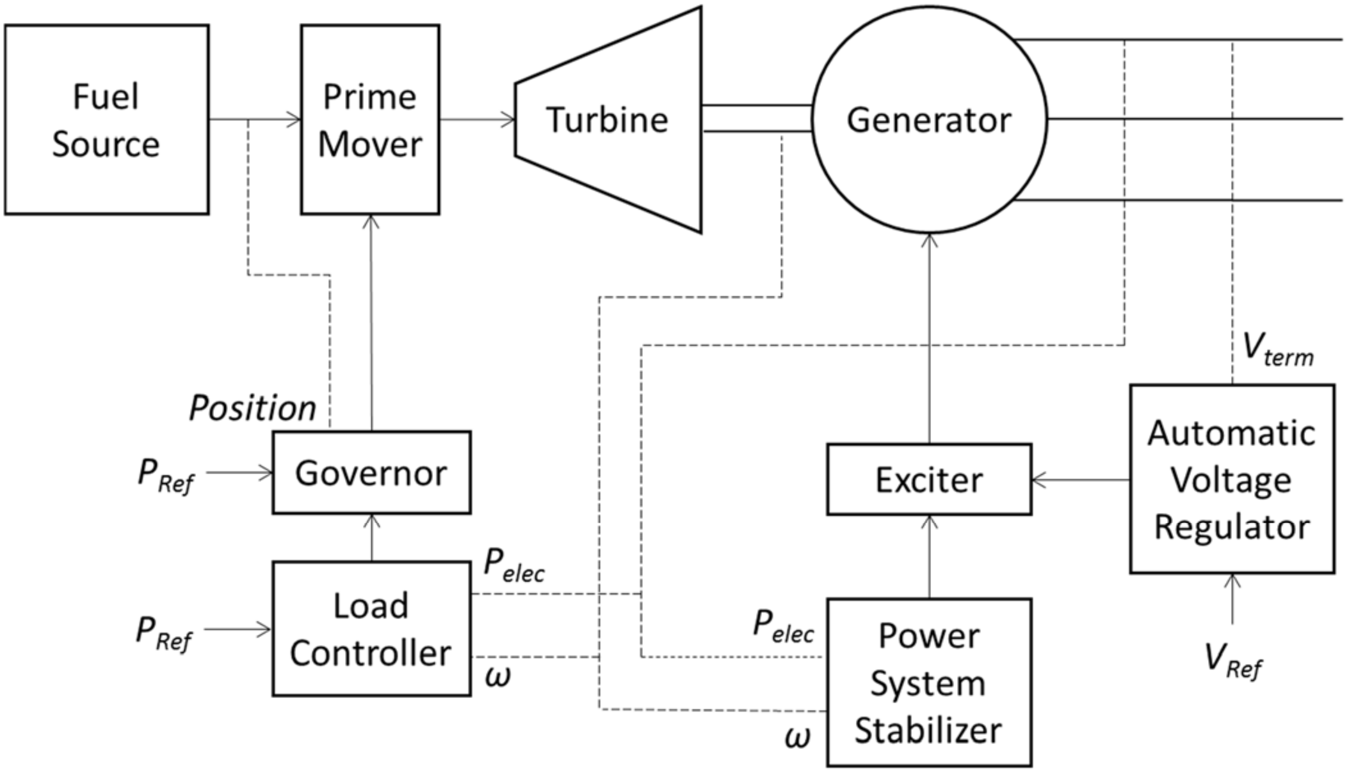


FIGURE 2: Power Plant Model Structure

Whether performing baseline generator testing or disturbance-based power plant model verification, the test or disturbance events may excite features of the model that can be used to verify the validity of the model structure and parameters selected.

The following power plant models can be verified using disturbance data:

- Generator
- Turbine-Governor[4]
- Excitation System-Automatic Voltage Regulator (AVR)[5]
- Power System Stabilizer (PSS)
- Limiters[6] & Compensators (if modeled)
- Turbine Load Controller (if modeled)
- Relays & Protection (if modeled)

---

[4] For reference, see IEEE PES Technical Report PES-TR1 “Dynamic Models for Turbine-Governors in Power System Studies”, January 2013.

[5] For reference, see IEEE Std. 421.5-2016 “IEEE Approved Draft Recommended Practice for Excitation System Models for Power System Stability Studies”.

[6] Events that trigger operation of components such as limiters, load controllers, or other changes to operation mode are useful events for verifying these types of components.

The mathematical models used to represent the behavior of a power plant are typically derived from the physical nature of the plant. That is, the model structure and key parameters are derived from the actual plant characteristics such as the type of electrical generator, turbine, control systems, etc. These models are expected to represent the actual nature of the equipment being represented over a range of conditions in which the model is valid. For power system stability analysis typically performed in positive sequence simulation tools the range of validity is discussed in the NERC Special Report, Standard Models for Variable Generation, May 18, 2010. As stated in that document:

> *“Stability analysis is traditionally performed using positive-sequence models. This includes models that focus on system simulation under assumed perfect balanced conditions (i.e., no imbalance in the 3-phase system voltages and currents). Furthermore, the primary stability issues that are investigated (angular stability, voltage stability, frequency control/stability) for bulk power systems tend to be bounded within a small frequency band around the system fundamental frequency. Positive sequence models are typically required to be valid in a range of roughly 0.1 Hz to about 3 Hz, with the control system having validity up to 10 to 15 Hz to allow for investigating general control loop stability. With these simplifying assumptions, it has been historically easy to establish generic, non-proprietary models for representing conventional generation and its controls.”*

Offline Testing and Online Performance Monitoring

It is imperative to clarify the scope of potential model validation and verification practices, particularly with respect to offline testing and online measurement-based verification. This section describes how baseline testing and online verification tools complement one another, and describes considerations for each.

Baseline Generator Testing

The goal of baseline testing is to characterize the dynamic behavior of the generator and its control systems, providing performance information capturing the continuously acting feedback controls such as the voltage regulators[7] and turbine controls. The specific tests performed excite a response of the unit that is associated with a parameter(s) in the model, thus deriving or validating parameter values. Those performing baseline generator testing should understand the equipment being tested and understand modeling the equipment at the grid simulation level. At a high level, generator performance testing can be broken down to the following major efforts:

1. **Instrumentation and Test Equipment:** Test equipment and any temporary instrumentation is set up to measure the response of the power plant components for various tests.
2. **Generator Testing:** A suite of tests are performed on the generating unit that capture the dynamics of the generator and its controls. These tests require that the unit be running, carrying current, and maneuvered to varied levels of loading including unusual or unfamiliar operating conditions for most plant operators.
3. **Model Selection and Parameter Derivation:** The appropriate model structure should be selected from the Transmission Planner's list of acceptable models such that the performance of the equipment and controls can accurately be modeled. With an appropriate model, the correct parameters should be chosen based on the testing results and data collected from the plant such as equipment drawings, nameplate ratings, and control set points.
4. **Verification of Baseline Model:** Simulations are performed to verify that the model matches the actual unit response. These types of simulations typically mirror the tests performed in the baseline study.
5. **Monitoring Model Validity:** The model can be continuously monitored using disturbance data by comparing modeled response to grid disturbances versus actual response. This is the focus of this Reliability Guideline.

Selection of a quality testing organization or engineer is critical to ensure a high level of accuracy and understanding of the tests. Overall, the following expertise is required:

- Fundamental understanding of the equipment within the plant at the level of its dynamic behavior;
- Understanding of dynamic simulation processes and tools;
- Understanding of and ability to model control system (block diagrams);
- Expertise with test equipment and signal processing software; and
- Power plant equipment operation.

Prior to actual testing, the following processes are recommended upon arriving at the test plant location:

1. Search for all available documentation (e.g., circuit schematics, fuel flow drawings, factory testing data);
2. Scan and read all documentation for reference – this is challenging for older plants that have gone through multiple owners with varying levels of data retention;

---

[7] For reference, see IEEE Std. 421.2-2014 "IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems".

3. Photograph the nameplate ratings of the equipment including the generator and auxiliary transformer(s);
4. Review and record base values including generator MVA, turbine rated/nominal power, and turbine head (if applicable);
5. Select pro-forma (suitable) models with generic, expected, or manufacturer supplied parameters;
    a. What type of excitation system exists? (e.g., DC exciter, brushless exciter, static exciter, etc.)
    b. What type of turbine exists? (e.g., Francis or Kaplan turbine)
    c. Is there a PSS? Is it integrated in the excitation controller? (e.g. modern digital module or old analog standalone unit)
    d. What operating mode is each component using? Ensure those are in effect both in operation and in the model.
    e. Typically these models and/or parameters are supplied by the manufacturer and are expected to accurately represent plant performance, particularly for newer digital control systems.
6. Run pre-test simulations to ensure a functional model;
7. Have defined test plans with step by step actions for the control room and operators; and
8. Ensure an active power (MW) chronogram for power scheduling (to ensure sufficient fuel supply and testing times) – anything resulting with off-schedule testing incurs cost to the Generator Owner (GO).

Data is collected and the initial model and model parameters are selected during commissioning. Baseline testing is performed to verify that the model actually represents reality. Many new, modern digital excitation control systems have a direct mapping between actual construction and model parameters. Generally, the digital logic within the controller can be analyzed and parameters can be put directly into the model and tested as a good starting point. Experience shows that this works very well most of the time with newly constructed plants with correctly selected pro-forma models. However, there is not always a direct mapping and the parameters should also not be trusted at face value. For example, incorrect scaling factors can skew the model and cause issues with PID gain ratios.

Testing varies depending on the type of generating unit under test and the conditions in which testing is allowed. Test plans must be developed for each specific plant or resource being tested, and must take into account limitations and specifications as well as current operating conditions on the day of the test. This could even alter which tests can physically be performed on that testing day. Table 1 provides an illustrative example of the tests that may be performed for a hydroelectric generating unit (which are relatively easy and flexible to test), and the model parameters that are derived or verified for each test[8]. Similar test plans[9] can be developed for other types of resources such as gas and steam turbine generators.

Table 1: Baseline Tests for Hydro Generating Unit

Test Procedure	Parameters Derived
Open Circuit Saturation Test – With the unit open circuit, adjust terminal voltage and monitor field current. Must only travel in one direction to limits.	s1 s12 air gap line

---

[8] While the parameters will change for the different types of models, conventional thermal units use relatively similar tests. Hence, only the table of tests used for hydro units is provided for illustrative purposes.

[9] IEEE Task Force on Generator Model Validation Testing of the Power System Stability Subcommittee, "Guidelines for Generator Stability Model Validation Testing," *Power Engineering Society General Meeting, 2007. IEEE*, Tampa, FL, 2007, pp. 1-16.

Table 1: Baseline Tests for Hydro Generating Unit

Test Procedure	Parameters Derived
V-curve Test – With the unit at no-load, partial load, and near full load, adjust field current to under-excitation limiter and as far past the over-excitation limiter as practical and monitor reactive power output.	Ld – d-axis synchronous reactance Lq – q-axis synchronous reactance Ll – leakage reactance Kis – saturation factor OEL function and verification UEL function and verification
Exciter Step Test[10] – With Power System Stabilizer (PSS) OFF and unit offline, perform voltage reference step tests and monitor terminal voltage, field voltage and field current. With PSS OFF and unit online, perform step tests at near full load and no load. With PSS ON and unit online, perform terminal voltage step test. NOTE: PSS OFF tests verify excitation system models while PSS ON tests verify PSS models.	T'do – d-axis rotor open-circuit time constant T'qo – q-axis rotor open-circuit time constant Ka – gain Lead/lag parameter verification PSS functionality verification only – require digital set points or a swept frequency test to verify PSS parameters.
Load Rejection Test[1] – With unit loaded at some load level (typically 25%, 50%, or near full load), open the breaker and observe the unit speed (frequency) with respect to time at an extremely high sample rate. Plot the tangential component of the frequency to get the initial acceleration to derive the inertia value.	H – Inertia constant[2]
Power-Gate Test – Accounting for the rated vs. actual head, the gate position is adjusted across its allowable range and active power is monitored.	Nonlinear gain points – power Nonlinear gain points – Gate Droop (if not digital) Qnl – no-load flow at nominal head Gmax/Gmin – if sufficient operational capability available.
Blade-Gate Test – The gate position is adjusted across its allowable range and blade position is monitored; this is a subtest of the power-gate test on Kaplan turbines	Nonlinear gain points – Blade

---

[10] For additional reference, see IEEE Std. 421.2-2014 "IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems".

Table 1: Baseline Tests for Hydro Generating Unit

Test Procedure	Parameters Derived
Speed Reference Test – A 0.5% change in speed reference is applied and removed with the unit online above the rough zone with sufficient operating range to not reach the maximum gate or stator output limit and active power, gate position, and blade position are monitored.	Kp – Governor Proportional Gain Ki – Governor Integral Gain Kd – Governor Derivative Gain Ldref – Load limiter reference Velop – maximum gate opening velocity (may require larger step) Velcl – maximum gate closing velocity (may require larger negative step) Tp – gate servo time constant Tw – verification of water time constant
Pre-test Calculations – Requires Operations and Maintenance Manuals, test records, inlet and outlet works drawings.	PSS settings – use as-left tested settings, potentiometer set points, or digital parameters as a starting point Tw – calculate from penstock/inlet configuration Ld – use as-tested value from commissioning or previous verification tests Vamax, Vrmax – maximum exciter control element output from manual Vamin, Vrmin – minimum control element output from manual T’’qo – q-axis rotor open-circuit sub-transient time constant (may also be verified by VAR rejection test depending on exciter model) T’’do – d-axis rotor open-circuit sub-transient time constant (may also be verified by VAR rejection test depending on exciter model) Gmax/Gmin – should be verified via calculation or observation depending on available head or other unit restrictions Verify unit limitations – shaft limits, rough zones, relaying set points, thermal limits, stator voltage limits, and any other possible dangerous, trip, or limiting conditions.

[1] Using Load Rejection Test at 0 MW with the unit underexcited is not used because many units do not hold field voltage (E_{fd}) constant; rather, they hold field current (I_{fd}) constant and therefore one cannot discern T'_{d0}.

[2] The Load Rejection Test should only be used as a sanity check for the inertia constant. The inertia constant should be derived by the manufacturer data and the physical characteristics of the machine.

Thermal units are much more difficult to perform baseline testing on due to their complexity, particularly around fuel availability, shutdown windows, and plant maneuverability. For example, these types of units often have controls that will trip the automatic voltage regulator when the generator is tripped. Therefore, the protection system would have to be bypassed for testing which is discouraged and may not be allowed by the power plant operator. Further, testing requires the plant operator to burn fuel at no revenue, which may require advanced purchase of fuel supply. Also, the Generator Operator (GOP) should coordinate with the Transmission Operator (TOP) regarding voltage and reactive power scheduling and unit status.

In situations where it may be difficult or not feasible to perform the baseline testing, disturbance monitoring approaches can complement the staged tests. For example, one option is to start with the manufacturer supplied data and perform bench tests (e.g., testing the excitation system using auxiliary supply with the unit shut down during scheduled outage). These tests can be used to select the baseline model and parameters along with manufacturer data. With disturbance monitoring data available, grid event can be collected and the model can be verified using the recordings. The process has been used to substitute some of the baseline testing that could not be performed such as load rejection tests and current interruption tests. This can minimize the impact on the units' commercial operations and not exhibit the unit to abnormal conditions during testing.

The following recommendations are made regarding baseline testing:

1. Protection system should remain in service with normal settings for all tests. Generator protection has advanced over the past 10-15 years, enabling testing of the unit with little to no change to protection.
2. The magnetization curve is the normalizing basis for all electrical modeling and should be established first based on test data. A typical value for V/Hz relay is 1.08 pu (voltage/frequency); therefore, one must extrapolate up to 1.2 pu voltage to identify the S(1.2) parameter per standard model requirements.
3. Generator tested V-curve is usually the best basis for estimating synchronous reactance.
4. The accuracy of the excitation system model depends on the accuracy of the generator model.
5. Parameter changes should be tested on the full suite of simulations, not just fit to one test; all test simulations should be reproduced for every parameter change.

Baseline testing provides a comprehensive look into the generator performance and can isolate tests to excite features of the model that can be used to verify specific parameters. When significant mismatches between modeled response and actual response exist, these types of tests are often required to establish a high quality baseline. When known or expected errors exist in the model, the other techniques such as disturbance-based parameter derivation can be used to identify discrete changes in operation or bad parameter values. This is the focus of the remainder of this guideline.

Online Performance Monitoring

Online performance monitoring of power plants using synchrophasor data or other high resolution disturbance monitoring data acts as a recurring test to ensure that the modeled response to system events matches actual response of the power plant or generating unit. Thus, online monitoring-based model verification using synchronized measurement data is used as a binary check ("yes/no") that the model is performing as expected. Online performance monitoring provides a cost effective and efficient means of ensuring that the model is accurate. From the Transmission Planner's perspective, online performance monitoring provides expeditious verification that the modeled performance is actually how the unit operates; any differences can be used to instigate a model correction by the Generator Owner (GO), and can also be used to guide the modeler towards potential corrections to the model. From the GO's perspective, online verification using high resolution measurement data can provide evidence of compliance by demonstrating the validity of the model by online measurement. Therefore, the GO may not have to take the unit offline for testing of model parameters. Taking the unit offline as well as bringing in an outside contractor to perform the model verifications can be costly for the GO.

Online performance monitoring for the purposes of power plant dynamic model verification requires that some form of Disturbance Monitoring Equipment (DME) such as a PMU be located at the terminals of an individual generator or Point of Interconnection (POI) of a power plant. Figure 3 provides a high-level illustration of the monitoring requirements that will be discussed in detail in subsequent sections.

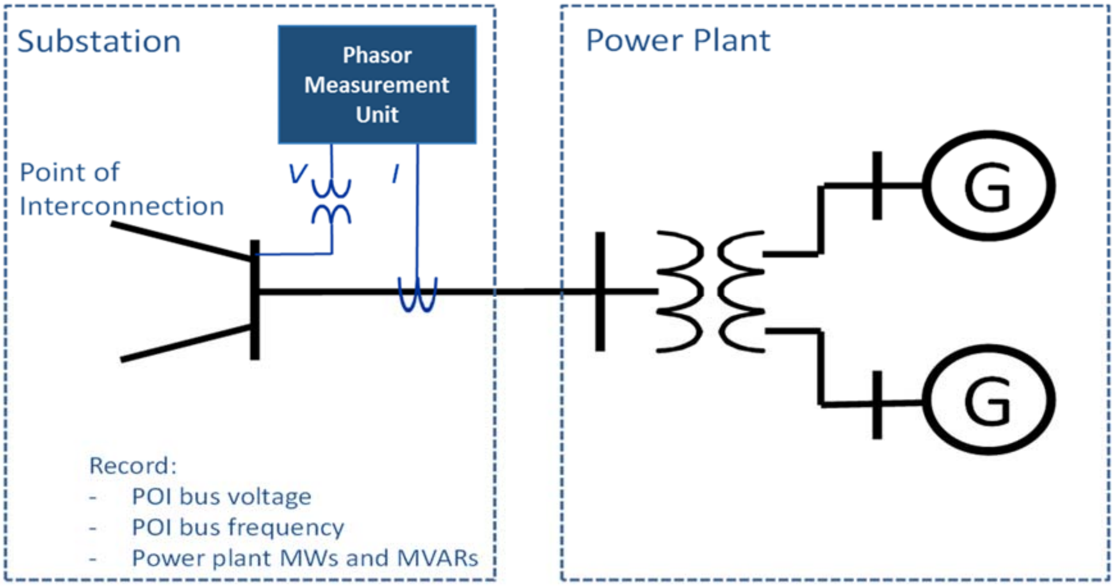


FIGURE 3: Online Disturbance Monitoring (Source: BPA)

Process for Model Validation

Model validation is the overarching process of deriving a given set of models and ensuring that those models accurately represent the nature of which they are intended to model. Understanding the overall process, and each step of the process, is critical for accurate development and maintenance of dynamic models. Figure 4 is a high-level flowchart of power plant model validation, including both baseline testing and disturbance-based analysis.

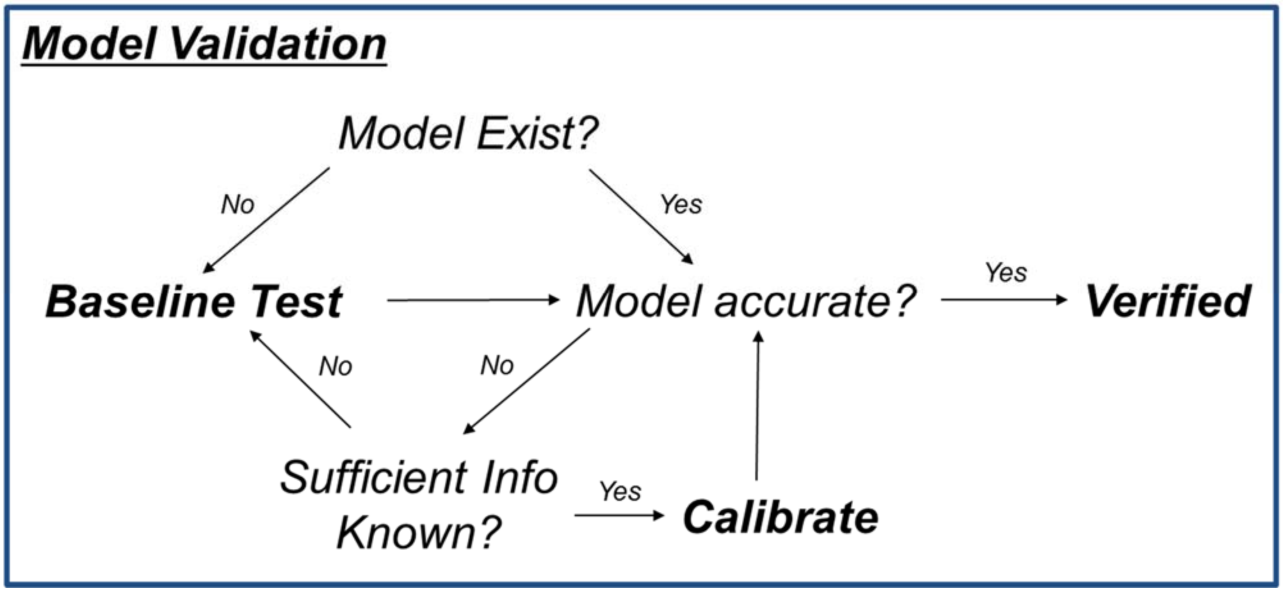


FIGURE 4: Model Validation Process Flowchart

Model validation starts with identification of whether a model exists for the unit under test. Either a model already exists or a pro forma model with expected parameters that must be validated is used. If no model exists, baseline studies are performed to derive or verify manufacturer supplied information. Model accuracy is tested by comparing simulated response versus actual baseline testing (i.e., voltage reference or speed reference step tests). If the model matches[11] actual response, the unit can be considered verified. Otherwise, the model should be either calibrated or additional information obtained by working with the plant owner or additional testing. Calibration is suitable only when sufficient information about the power plant and dynamic model representing that plant are well understood. Gaps in baseline data or unexplainable differences in response need to be verified using baseline analysis and testing. However, if the model and baseline data are well understood, model calibration ("tuning") is a viable option to obtain an accurate model using a database of events to compare against.

Disturbance-based analysis falls under the "Model Accurate?" section of model validation, acting as a recurring check on performance. If the model matches reality, then the model can be considered verified. If not, one should make the determination of whether sufficient information is known to perform calibration or if baseline testing is necessary. Regardless, close collaboration between the model users and plant-level staff is necessary to ensure accurate development of a model that represents the physical equipment within the plant.

---

[11] Engineering judgment should be applied to consider what an acceptable match is. This will account for tolerances in equipment, operating conditions, model tolerances, and any other potential sources for minor errors. These are expected since the dynamic models can closely represent the characteristic shape of response but likely will not match identically. This document does not prescribe acceptable levels of mismatch because engineering judgment should be applied first and foremost.

Value Proposition for PMU-Based Model Verification

Disturbance-based model verification provides a number of benefits both for the asset owners and the system operators and planners that use the models of these power plants. From the asset owner (Generator Owner) perspective:

- Cost-effective method of compliance with NERC Reliability Standards MOD-026 and MOD-027
- Effective means of recertification of power plant models
- Reduces costs and potentially mitigates shutdowns needed for offline, physical testing
- Identification of oscillatory behavior (plant-driven or system-driven)
- Early detection of generator control issues

From the Planning Coordinator, Transmission Planner, and Transmission Operator perspectives:

- Independent verification of model accuracy for NERC MOD-026 and MOD-027
- Supporting model accuracy work for NERC MOD-033 system model validation studies
- More accurate models for stability analysis
- More accurate calculation of system operating limits, and potentially higher system operating limits
- Early detection of generator control issues
- Identification of plants which are frequency responsive, under load control, or base-loaded; identification of models improvements to capture this behavior.
- Continual monitoring of system-wide unit performance to identify modeling deficiencies or trends in power plant dynamic performance and controls

Related NERC Reliability Standards

There are predominantly two (2) NERC Reliability Standards where disturbance monitoring-based model verification can be used to help responsible entities demonstrate compliance or effectively meet the requirements set forth in the standards. These standards include:

- **MOD-026-1:** Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions

  Purpose: *"To verify that the generator excitation control system or plant volt/var control function model (including the power system stabilizer model and the impedance compensator model) and the model parameters used in dynamic simulations accurately represent the generator excitation control system or plant volt/var control function behavior when assessing Bulk Electric System (BES) reliability."*

- **MOD-027-1:** Verification of Models and Data for Turbine/Governor and Load Control or Active Power/Frequency Control Functions

  Purpose: *"To verify that the turbine/governor and load control or active power/frequency control model and the model parameters, used in dynamic simulations that assess the Bulk Electric System (BES) reliability, accurately represent generator unit real power response to system frequency variations."*

MOD-026 and MOD-027 both apply to the same Functional Entities: GOs and TPs. Facilities considered as "applicable unit[s]" must meet the following characteristics based on the interconnection in which the generating resource connects to the power system:

Table 2: MOD-026 and MOD-027 Applicability

Interconnection	**"Individual generating unit"… (gross nameplate rating)**	**"Individual generating plant consisting of multiple generating units that are directly connected at a common BES bus with total generation"… (gross aggregate nameplate rating)**
Eastern or Quebec	> 100 MVA	> 100 MVA
Western	> 75 MVA	> 75 MVA
ERCOT	> 50 MVA	> 75 MVA

The TP defines the list of acceptable models for use in dynamic simulation, and the GO is responsible for providing a verified model to its Transmission Planner. Requirement 2.1.1 explicitly defines that the verification shall include demonstrating the unit's model response, and clearly mentions using a measured "system disturbance" as an acceptable means of verification. For MOD-026, "voltage excursion[s]" can be used; however, in MOD-027, the definition of a frequency excursion event is defined as shown in Table 3.

Table 3: Frequency Event Criteria

Interconnection	Frequency Deviation from Scheduled Frequency
Eastern	≥ 0.05 Hz
ERCOT and Western	≥ 0.10 Hz
Quebec	≥ 0.15 Hz

Overall Process for Model Verification per MOD-026 and MOD-027

MOD-026 and MOD-027 have a "checks and balances" structure that includes GO model verification and TP oversight that the model functions correctly and accurately. Upon receiving information regarding appropriate and allowable models by the TP (Requirement R1), the GO must provide a verified model including documentation and all necessary data (Requirement R2). The remaining Requirements address situations where either the model is shown to not be usable (Requirement R6), to not to accurately represent actual response (Requirements R3 and R5), or changes within the power plant require revisions to the model or plans for verification (Requirement R4).

Figure 5 illustrates the overall process of these Standards and the interactions between the Requirements with respect to model verification and oversight of model performance. Model accuracy (R3 and R5) and validity (R6) can be reviewed at any time by the Transmission Planner. Disturbance-based model verification applies to three specific steps within the standards, identified in Figure 5 by a (*):

- **Requirement R2:** The GO can use disturbance-based model verification as a form of demonstrating that the modeled response matches actual response. However, this must also be accompanied by the other documentation and data required by Requirements R2, including manufacturer data, model structure and data, compensation settings, etc.
- **Requirement R3:** The TP can use results from disturbance-based model verification to demonstrate that the current model being used does not accurately represent actual response.
- **Requirement R5:** The TP can submit a request for model review using "technically justified" results "demonstrating that the simulated unit or plant response does not match the measured unit or plant response."

This overall process can apply to all types of power plant models, whether generic models or "black box" proprietary models. Requirements R1 and R2 ensure that sufficient documentation regarding the model structure, parameters, and functional behavior of the governor or excitation system are provided. Requirements R3 and R5 ensure that the Transmission Planner has sufficient oversight of the model performance in terms of proper functionality but also accuracy as compared with real-time disturbance data, if available. The goal of these standards is to ensure sufficient understanding of the model and that the model performs as expected to ensure reliability of the BPS[12].

---

[12] *See*, purpose statements of MOD-026-1 and MOD-027-1 respectively: "To verify that the generator excitation control system or plant volt/var control function model (including the power system stabilizer model and the impedance compensator model) and the model parameters used in dynamic simulations accurately represent the generator excitation control system or plant volt/var control function

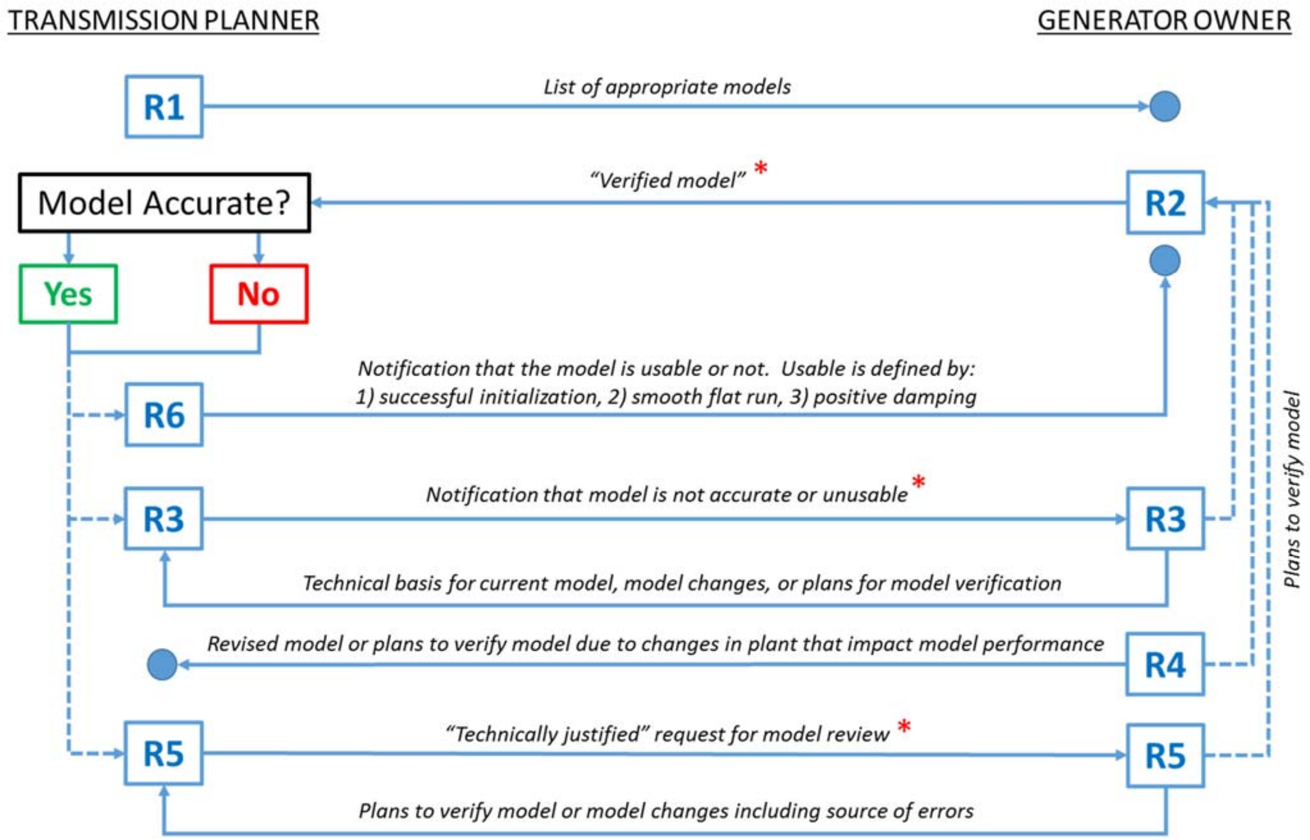


FIGURE 5: MOD-026-1 and MOD-027-1 Process Flowchart

Ongoing Discrepancies between Modeled and Actual Performance

In particular, it is clear that Requirements R3 and R5 of MOD-026 and MOD-027 create feedback loops between the Transmission Planner and Generator Owner. While beneficial for ensuring an accurate model is developed, there could arise a situation where the model structure and parameters derived by the Generator Owner through their verification process do not match the Transmission Planner's verification of those models' accuracy using disturbance-based verification. In these situations, it is imperative that the TP and GO work collaboratively to develop a model that does represent reality. Often times, the transmission planning engineers familiar with grid simulation tools do not have the opportunity to interact with the generating plant staff particularly during generator testing. However, this interaction between grid simulation experts and generating plant experts is incredibly valuable.

For situations where ongoing discrepancies exist between modeled and actual performance, the GO should work with the TP to derive a model that is usable and accurate. This is based on Requirements R3 and R5 of MOD-026 and MOD-027 enabling the TP to provide oversight on model performance and accuracy using actual response data from system events, and the GO addressing identified issues or discrepancies in a timely manner.

---

behavior when assessing Bulk Electric System (BES) reliability." and "To verify that the turbine/governor and load control or active power/frequency control model and the model parameters, used in dynamic simulations that assess Bulk Electric System (BES) reliability, accurately represent generator unit real power response to system frequency variations."

Regardless of the number of iterations between model derivation and model performance comparison, the following high-level process aids in addressing issues with model performance.

IF: *Quality* baseline testing has been performed to develop an accurate and sufficient model to represent the power plant equipment dynamic behavior;

AND: Measurement data used in disturbance-based model verification is of good quality and trusted;

AND: The measurement data and simulated response continue not to match;

THEN: It is recommended to physically go to the plant;

- AND: Check data historian readings, controller statuses (on/off), failure or abnormal operation of equipment (e.g., PSS), transformer tap position(s), digital logic within the controllers, and so on, and the GO;
- MAY: Not have to perform baseline testing if errors or setting issues are identified and proven to address the discrepancies identified; or
- MAY: Have to (re)test the generator to establish a new baseline model and parameters.

Performing PMU-Based Model Verification

This section outlines the process for performing PMU-based[13] model verification, modeling and measurement considerations that should be accounted for, and types of events that should be considered for model verification. It is important to note that the quality of PPMV analysis and review of modeled vs. actual performance is of utmost importance; qualified engineering judgment for reviewing and analyzing results should be applied throughout the process.

PMU-Based Model Verification Procedure Overview

Regardless of the tools used, the following high-level procedure is followed for performing disturbance-based power plant dynamic model verification using PMU data.

System Disturbance Measurement:

1. Collect pre-disturbance operating conditions for the generator(s) under test[14].
2. Monitor for the major grid disturbances (local, regional, and interconnection-wide) that evoke a transient response of the generator active and reactive power.
3. Convert disturbances to format required for playback model file structure (i.e., positive sequence).

Steady-State Case Creation:

1. Extract the steady-state model representing the generator(s) under test and the associated network elements up to the point of PMU measurement. This model may include:
   a. Generator step up (GSU) transformer
   b. Radial transmission circuits interconnecting the generator(s) to the rest of the grid
   c. Loads – plant-level or local distribution
   d. Static and dynamic reactive resources
2. Add a system equivalent generator (high MVA Base and low internal impedance) and interconnecting equivalent transmission circuit[15] (very low impedance) to this reduced model.
3. Perform state estimate to match initial conditions with actual PMU (or SCADA) data, including:
   a. Voltage magnitude at point of measurement[16]
   b. Active power[17] and reactive power at point of measurement[18]

Dynamics Case Creation:

1. Extract dynamics data records from interconnection-wide dynamics case. Include all dynamic records necessary based on the steady-state model elements.

---

[13] Different types of disturbance data can be used for measurement-based model verification – DFRs triggered to capture disturbances, continuously recorded PMU data, data from transient fault recorders built into modern power plant digital control systems, etc.

[14] In the case of a multiple generator plant, SCADA data may be needed to dispatch the initial conditions appropriately for each individual generator's power outputs and status.

[15] Generally optional (for efficient data extraction); equivalent impedance should be less than the jumper threshold in the solution settings.

[16] Play-in equivalent generator is modeled at the point of measurement and is a "slack generator" so it controls voltage magnitude and sets relative voltage angle.

[17] Entails modifying the active power output of the generator under test until the measurement location active power flow matches; the equivalent generator is defined as the "slack bus" to pick up any differences.

[18] Entails modifying the scheduled terminal voltage of the equivalent "slack bus" generator until the measurement location reactive power flow matches.

2. Add the models associated with the playback generator.

3. Add any additional models or channels to capture the response of the power plant or generator at the same location as the PMU measurement – bus voltage magnitude, frequency, and active and reactive power flows.
4. Ensure that playback data base values match PMU data (i.e., per unit vs. physical units).

Transient Stability Simulation:

1. Initialize stability run.
    a. Perform a "flat run" simulation with no playback model to confirm successful initialization prior to performing verification simulations.
2. Perform stability run[19] using playback model – voltage and frequency or voltage and angle measurements are played into the stability run.

PMU and Model Comparison:

1. Extract the channel data from the simulation which represents the measurement location.
2. Compare[20] the PMU active and reactive power flows with the simulated power flows.
    b. If the simulation sufficiently matches the actual PMU data, the model is verified.
    c. If there are noticeable discrepancies between the simulated data and actual PMU data, the model is not verified. Further investigation is required.

Appendix A[21] provides more details regarding particular software tools available for performing this analysis.

Measurement & Modeling Considerations

When developing the model used for playback of synchrophasor data, the following items should be considered:

- **Measurement Data Quality:** The measurements should be sufficiently accurate to perform verification. Data should be at least 30-60 samples per second[22] with proper time synchronization and reasonable errors introduced by the instrument transformers and measurement device.
- **Measurement Location**: The location in which the PMU is measuring electrical quantities drives the size of the subset model used for playback. For power plant dynamic model verification, PMU measurements at the high- or low-side of the generator step-up transformer are recommended or required.
- **Signal Measurements[23]**: The actual signals being measured should be considered; adjustments should be made to the data to account for unit conversions.
    - **Voltage Magnitude**: Playback voltage magnitude should be the positive sequence bus (or line) voltage, and can be reported in volts [kV] or per unit.

---

[19] Also a "flat run" simulation (no disturbance) – playback model injects disturbance data into the program, emulating an actual grid event.

[20] The comparison of simulated vs. actual response must include engineering judgment. In most cases, the simulation will not exactly match the actual response of the plant. This guideline does not prescribe a tolerance level to be used for all circumstances because each case must be considered uniquely on an individual basis.

[21] This is not an exhaustive list of tools, platforms, and methods. It is likely there are other tools for measurement-based model verification; however, the software platforms listed in Appendix A are widely used in the electric utility industry and provided here for reference.

[22] Generally recommended to be 10 times the highest frequency for which the model is adequate; excitation models are acceptable up to 3 Hz per IEEE Std. 421.5-2005.

[23] Governor verification may be accomplished solely with frequency; however, excitation system verification requires both voltage and frequency if a power system stabilizer is involved.

  - **Frequency:** Playback frequency should be the frequency of the voltage phasor measured, reported in Hertz. Some tools use bus voltage angle instead of frequency.
  - **Active and Reactive Power:** Active and reactive power should be expressed on a three-phase (total line flow) basis, reported in megawatts [MW] and megavars {Mvar].
  - **In-Plant Analog Quantities[24]:** Measurement quantities within the power plant such as field voltage, field current, generator speed, gate position, and other control signals.
- **Signal Polarity**: PMUs may be measuring the line flow into or out of the generator (polarity difference). Data may need to be modified to account for directionality of line current.
- **Generator Step-Up (GSU) Transformer**: If the measurement location is at the high-side of the GSU, then the GSU must be explicitly modeled. Any loads off the tertiary of the GSU must also be explicitly modeled.
- **Station Service Load & Auxiliary Load**: Station service load does not necessarily have to be modeled explicitly; however, when the low-side load is modeled, consideration must be taken to the dynamic load model used to represent the load. These plant loads are generally large induction motor loads, and therefore need a motor model designation. For implicit modeling, any station service load should be accounted for in the model appropriately with respect to net versus gross power outputs.
- **Measurement Duration**: The duration of captured measurements from the PMU depends on the power plant's response to the system disturbance. Data collected should capture the entire system event, such that sufficient model comparison can be made. Generally, the following time durations are considered:
  - **Pre-Disturbance**: Sufficient[25] pre-disturbance data to ensure steady-state modeled response matches actual response.
  - **Post-Disturbance**: Sufficient[26] data to capture the disturbance as well as unit response following the disturbance until a new steady-state is reached or secondary controls[27] begin acting on the unit.

Event Selection

Besides the disturbance size criteria outlined in MOD-026 and MOD-027, the following considerations can be made for selecting events for online performance monitoring:

- **Event Compilation:** Online performance monitoring should be performed sequentially for multiple events rather than a single event. Any modification to model parameters or structure should accurately represent the power plant's behavior under a range of (transmission and generation) operating conditions.
- **Type of Disturbance:** Different types of system disturbances will induce a different dynamic behavior from the electrical machines interconnected to the power system. Frequency excursions are predominantly used to verify turbine-governor models while voltage excursions are used to verify the excitation system and power system stabilizer models. Examples of different types of events include:
  - Transmission system faults[28] – three-phase, single-phase, multi-phase, normal or delayed clearing, or other low voltage conditions;
  - Transmission system switching;
  - Protection system operations near terminals of a generator;

---

[24] While not required to perform disturbance-based PPMV, these quantities can improve the analysis of model performance.

[25] Typically, around 10 seconds of pre-disturbance data is collected and used.

[26] Typically, around 15-45 seconds depending on how long the unit takes to find a new steady-state operating conditions and when secondary controls may begin acting on the unit.

[27] Such as Automatic Generation Control (AGC), assuming the unit is on AGC control.

[28] PMU filtering needs to be considered when using fault event near the terminals of the generating unit(s) under test.

  - HVDC tripping or run backs;
  - AC or DC controls (mis)operations;
  - Planned or unexpected large load tripping, load shedding, or other overfrequency events;
  - Generator tripping or other underfrequency events;
  - Large FACTS device switching, failure, or operation;
  - System islanding or loss of synchronism events; and
  - Other large system swings exhibiting voltage or frequency fluctuations, particularly with low damping ratio and high amplitude.
- **System Topology:** Changes in system topology, particularly near a generating facility, can change the dynamic behavior of the machine[29]. While topology changes can be classified as an event itself, different topologies pre-contingency will also drive different electrical dynamic behavior of the unit. Various operating conditions worth considering include:
  - All lines in service – system topology intact near area of generator under consideration;
  - Single (N-1), double (N-2), or multi- (N-k) line outage near generator pre-contingency;
  - HVDC modes of operation (monopolar, bipolar, metallic return, back-to-back, parallel converter);
  - Nearby generation dispatch online or out-of-service, with additional considerations for renewable generation, where applicable;
  - Capacitor, reactor, FACTS device, or synchronous condenser statuses; and
  - Multi-unit operations at power plant under consideration.
- **Operating Conditions:** The operating conditions, along with system configuration, play a major role in the response of dynamic resources within a power plant. These need to be accounted for during the verification process. Examples include:
  - Ambient temperature (can drastically limit transient response of a power plant, and events during extreme temperatures may not be as useful for testing model performance);
  - Maximum generator plant output (plant may exhibit oscillations when the gate/power are at limits);
  - Minimum generator plant output
  - Significant underexcitation of the generating unit (consuming reactive power) resulting in weaker magnetic field;
  - Units operating at or near the rough zone (turbine cavitation) may produce forced oscillations;
  - Hydraulic or boiler control considerations; and
  - Changes in protection system settings or controls.

In general, these events are examples that may induce a change or perturbation to the terminals of a power plant or generating unit. Frequency deviations are a wide-area phenomena and can be used to verify a larger range of units' models. In addition, frequency changes due to power-load imbalance on the system result in changes in power flow across the system. These fluctuations in active power can result in changes in reactive power demands and voltage fluctuations as well. Therefore, frequency events may be useable for both turbine-governor and excitation system model verification. On the other hand, fault events that cause a substantial change in voltage

---

[29] System topology changes outside the explicitly modeled plant under test will not require changes to the initial base case; however, the dynamic response may change and hence provide more or less useful events for verification purposes.

are prime candidates for verifying power plant models in a more local area. These events are useful for ensuring the excitation system and power system stabilizer models are sufficiently accurate for more severe perturbations that are generally studied by Transmission Planning engineers for stability studies. For example, a fault resulting in changes in positive sequence voltage below 0.8 pu generally induces a significant demand and perturbation in generator reactive power as well as active power fluctuations as the generator unit responds.

As utilities gain more experience with disturbance-based model verification, selection of events can become automated. There is no need to be selective with the events chosen; however, the user must ensure that the event causes sufficient perturbation to terminal voltage and/or frequency for the event to be used for verifying a particular power plant. For example, an underfrequency event may be useable on an entire fleet of generators while a fault event may only be applicable for verifying power plant models in that local area of the event. This requires applying engineering judgment when assessing the verification results, but the process of performing the verification can become automated.

The measurement error introduced during dynamic events should be considered when determining which events are good candidates for the purposes of PPMV. Faults very close to the measurement location (terminals or Point of Interconnection of generating unit, for example) may be attenuated by the measurement device in the calculation of the phasor estimate. Additionally, the response-time of the controls for electronically-coupled resources is significantly faster than other types of controls and of the phasor measurements themselves. These sub-cycle controls may impact the response of the plant, may not be explicitly modeled in positive sequence simulation models, and can affect the post-contingency conditions after the fault has cleared (for example, the mode of operation could change mid-contingency that impacts the post-contingency performance. Common practice is to discard events where attenuation may be prevalent. Past experience has shown that frequency excursion events are slow enough such that dynamics are accurately captured by recording devices. Similarly, many fault events that are a couple buses away in the local network have proved effective for verification purposes. The industry is working towards quantifying these impacts.

Model Calibration Practices

Model calibration is the process of tuning or modifying the model to match measured event data. Common industry practice for model calibration includes applying engineering judgment to determine the parameters or models which require modification. Sensitivities around these parameters are tested, and the change in modeled response compared with actual are observed. Parameter values are modified until a fit is obtained. The following guidance is provided for performing model calibration:

- Numerical curve fitting that is not guided by engineering judgment should be avoided at all cost; the results are a non-unique set of parameters (i.e. many different sets of parameters will provide the same results), and the determination of these parameters must use engineering judgment[30].
- Controller failure should be considered prior to modifying any parameters, including:
  - Governor: Unit modeled with governor active but unit base loaded or operated in different mode (operating mode can change from one event to another).
  - Load Control: Load control model acting on a functional governor but not modeled in the dynamics database.
  - Power System Stabilizer (PSS): Power system stabilizer turned off or malfunctioning, resulting in increased oscillatory behavior.
- Engineering judgment must be used to ensure that the correct model is used to represent the generator and its controls. Inappropriate models include:
  - Static exciter to represent a rotating DC exciter
  - Single input PSS to represent a dual input PSS
- Engineering judgment must be used to understand the parameters which have a higher likelihood of being incorrect. Examples include:
  - Wrong value for AVR gain
  - Bad turbine-governor data
  - Incorrect settings in the PSS
  - Wrong generator inertia[31] and time constant
- A level of accuracy should be defined that accounts for accuracy of the instrument transformers and measurement transducers.

Figure 6 shows an example of sensitivity analysis, calibrating the power system stabilizer gain, K_{S1}, for the PSS2B dual-input stabilizer model. The original model provided by the Generator Owner responds optimistically to a nearby fault event, where in reality the unit is not as well damped. Using engineering judgment, sensitivities were performed to match the oscillatory behavior and amplitude of the modeled behavior compared with the actual response. The PSS gain was reduced to a reasonable level, expected for this type of unit and excitation system, and the model was updated accordingly. While the results do not exactly match the PMU data, this is an example of a model fit that is significantly better than the original model, verifying performance of the model. In this case, the Transmission Planner is working with the Generator Owner to ensure the parameters match with what is in service at the power plant. The Transmission Planner may also be able to collect additional events to verify the parameter changes function accurately over a wide range of event types and magnitudes.

---

[30] Parameter estimation tools should incorporate a significant amount of engineering judgment.

[31] Manufacturer data for inertia constant is generally the best source.

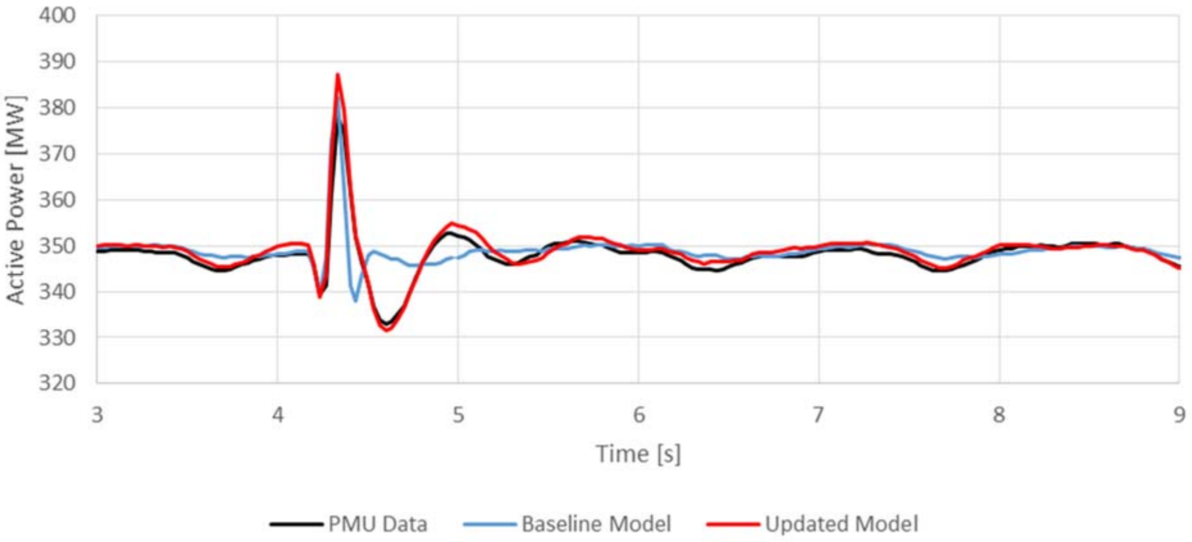


FIGURE 6: Calibration of 630 MW Coal-Fired Generator Power System Stabilizer Gain

Model Accuracy Tolerance

Ideally, a calibrated model would accurately match disturbance data for a wide range of system disturbances. In most cases, calibration can accurately represent one or a subset of events and can capture the general characteristics of the model for other events. It is hard to quantify when a model is defined as "calibrated"; however, the following aspects of the simulated waveform should have fairly close match with the actual data.

- **Phase Shift:** The model should accurately capture phase shift, as defined by the model time constants, such that oscillation phase should align between measurement and model.
- **Amplitude:** The amplitude of the modeled response should accurately match the measured data. Differences in amplitudes are generally attributed to controller gains, droop settings, or action of a load controller.
- **Damping Ratio:** The model should accurately capture the oscillation ringdown and damping ratio for active and reactive power output. This includes capturing any growing or relatively undamped oscillatory modes throughout the playback time duration.

Modeling Improvements Feedback Loop

A feedback loop between the Generator Owner (model owner) and Transmission Planner (model user) is incredibly valuable for ensuring accurate and representative modeling of generating resources. While not required in MOD-026 and MOD-027, a collaborative feedback process and communication between the GO and TP would enhance model verification efforts and help ensure any model changes are agreed upon by both entities. The following steps can support developing this feedback loop to make any changes to the model, model parameters, or generator controls.

1. The entity performing model verification should test the performance of the model on multiple events[32]. These events can be used for deriving new model parameters or a new model entirely. An additional set of events[33] should be used to test that the model performs as expected and as intended. These events need to be mutually exclusive from the calibration data set to test the modified model.
2. Any outlier events where the model does not accurately match should be identified, with reasons why the model did not perform appropriately or as expected.
3. The Transmission Planner can work with the Generator Owner, and vice versa, to discuss verification findings and any potential modeling discrepancies. The TP should verify model parameters and model structure with the GO including controller settings, statuses, etc.
4. Both the TP and GO should determine whether to make any changes to the model or whether changes to plant settings is more appropriate[34]. This likely requires additional transient stability studies to ensure stable and secure dynamic performance of the power plant.
5. Once any changes have been made by the GO and agreed upon by the TP, these changes should be updated in the local models and interconnection-wide models. This involves both the TP and GO helping to ensure that future models accurately reflect the changes made by working with the MOD-032 designees for building interconnection-wide base cases.

The overall process described here, in conjunction with the guidance provided in this Reliability Guideline, provides the foundation for helping ensure accurate power plant dynamic models for reliable planning and operation of the Bulk-Power System moving forward.

---

[32] This generally consists of at least 3-5 distinct events to test the model.

[33] This generally consists of at least 5-8 more events to verify the calibration dataset against.

[34] For example, if the power system stabilizer gain in the physical plant was identified to not match the model used for planning and operations, the TP and GO should coordinate to ensure the most effective setting is used to ensure stability of the unit and BPS.

Disturbance-Based Model Verification Benefits & Examples

Disturbance-based model verification using dynamic disturbance recording (DDR) data such as PMU data can be a powerful tool for ensuring models used in grid stability studies accurately represent the actual response of the power plant or generating unit being modeled. The following examples illustrate the benefits of using this recurring check.

Nuclear Power Plant Model Calibration

Figure 7 depicts the model performance before and after model calibration for a large nuclear power plant steam turbine generator. Figure 7 (left) shows the active power response and Figure 7 (right) shows reactive power response. The top figures represent pre-calibration response and the bottom figures represent post-calibration response. In this example, the generator excitation system and power system stabilizer gains and time constants were modified to obtain an accurate match. The newly derived model parameters were then tested on multiple events to ensure the updated model matched actual response under a range of expected operating conditions.

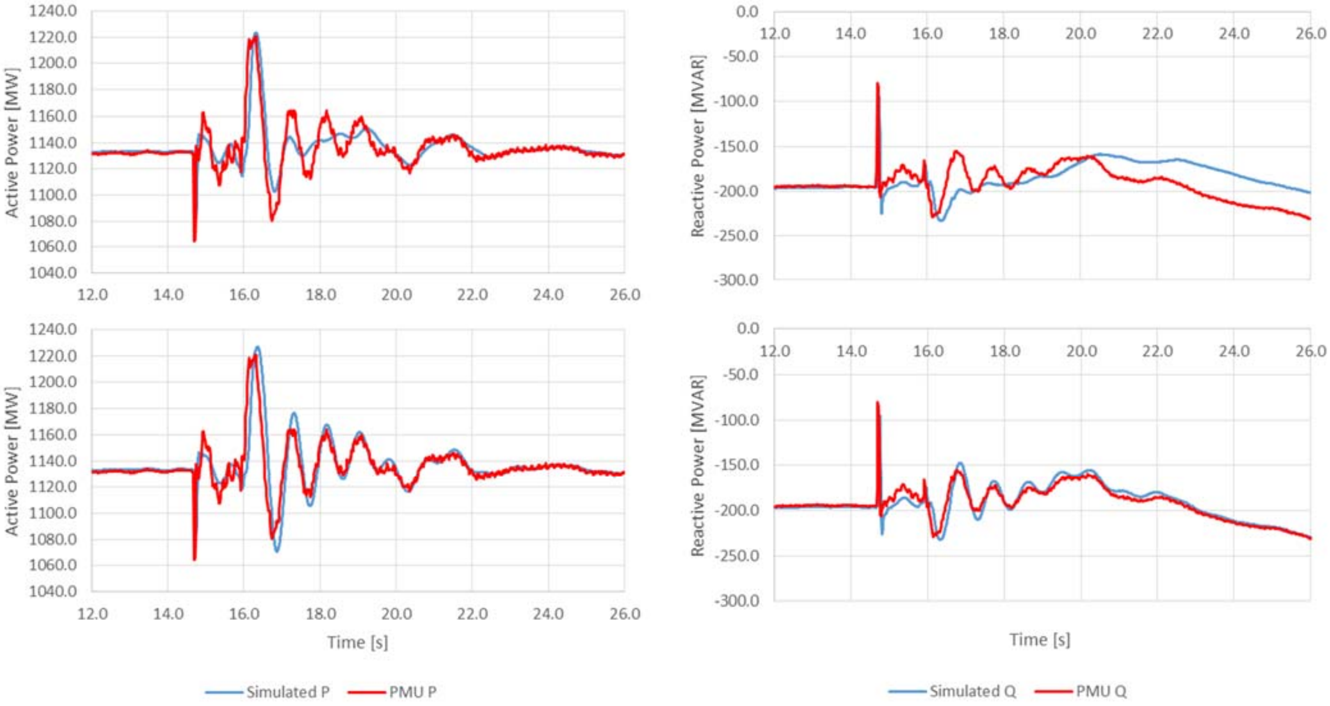


FIGURE 7: Nuclear Plant Calibration Example – Pre (Top) and Post (Bottom) Calibration [Source: Bonneville Power Administration]

Combined Cycle Gas Turbine Governor Modeling

A combined cycle power plant consisting of 3 gas turbines and a steam turbine was tested using PMU data collected at the high side of the generator step-up transformers. For the disturbance analyzed, the gas-fired turbine was not baseloaded so a primary frequency response was expected from the unit gas-fired unit governor. Figure 8 (black) shows the response for the initial model submitted to the Transmission Planner by the Generator Owner when the plant was put into service in 2009. The initial playback simulations showed a large influence of proportional-integral (PI) controller, identified from the lag in response. Initial inspection of the governor model for this gas turbine showed that the GAST model, which is a proportional gain governor model developed in the 1970s, was applied. However, most if not all modern digital governors use at least a proportional-integral gain controller, and the GAST model is not capable of modeling this type of control strategy. A newer, more flexible model, GGOV1, was tested using expected parameters and the results are shown in Figure 8 (red). It is clear that the model needed to be replaced with a different pro forma model to even have the capability to accurately represent the plant's actual response[35].

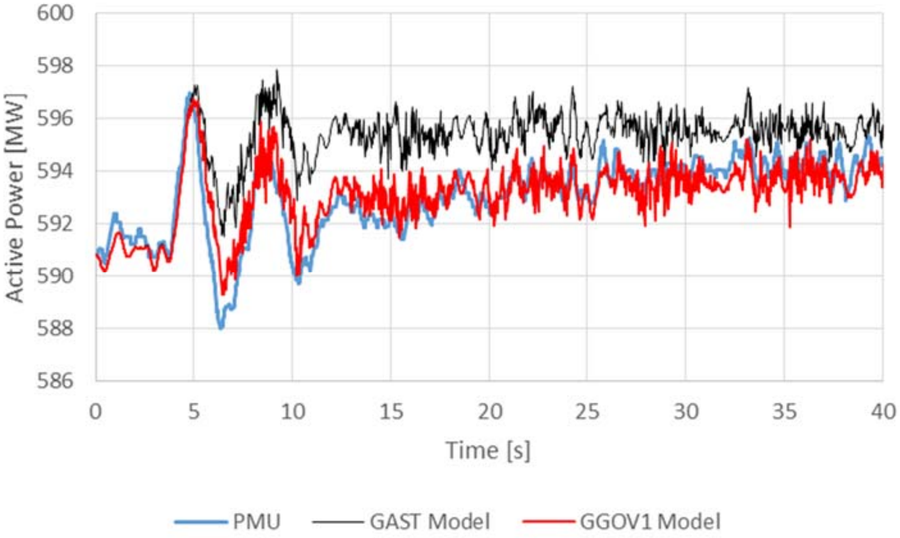


FIGURE 8: Governor Model Improvement – GAST vs. GGOV1

Steam Turbine Generator Mode of Operation

A steam turbine-generator was identified as operating in a control mode not accurately modeled using the submitted models. Figure 9 shows the modeled response versus actual response. It is clear that the unit was non-responsive to the frequency excursion while the modeled response showed a sustained response from the governor. This provided the Transmission Planner with evidence that the unit was not operating as modeled, illustrating that the TP needs to collaborate with the GO to understand the various modes of operation for the plant as well as the governor deadband settings. Furthermore, the TP needs a mechanism to block the governor model for this unit, as appropriate, and account for deadband settings in stability studies.

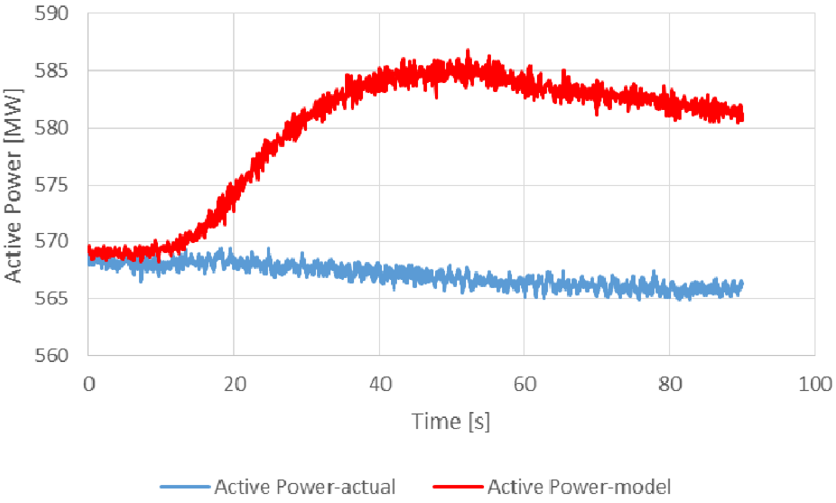


FIGURE 9: Non-Frequency Responsive Mode of Operation

---

[35] This issue is not unique to combined cycle generating resources. It also applies to other gas turbine resources across the system.

For disturbance-based verification, a unit that is not expected to provide any significant response still needs to be verified. For example, a unit loaded to maximum output power can be verified to ensure the model accurately matches this maximum output level in the dynamic simulations. Furthermore, if the unit is expected to operate in a control mode where the governor is not acting on the electrical power output[36], this should be represented in the model (governor limits fixed or governor disabled) such that the simulated response matches actual in-service performance. This applies to all generating resources, not just steam turbine units.

Turbine-Governor Model with Outer-Loop Controller

Figure 10 shows an example of turbine-governor model verification and parameter calibration using disturbance monitoring data. In this case, the generator is also under outer-loop MW control, and the EPRI tool (described in Appendix A) successfully generated a model to estimate the gain of the control loop.

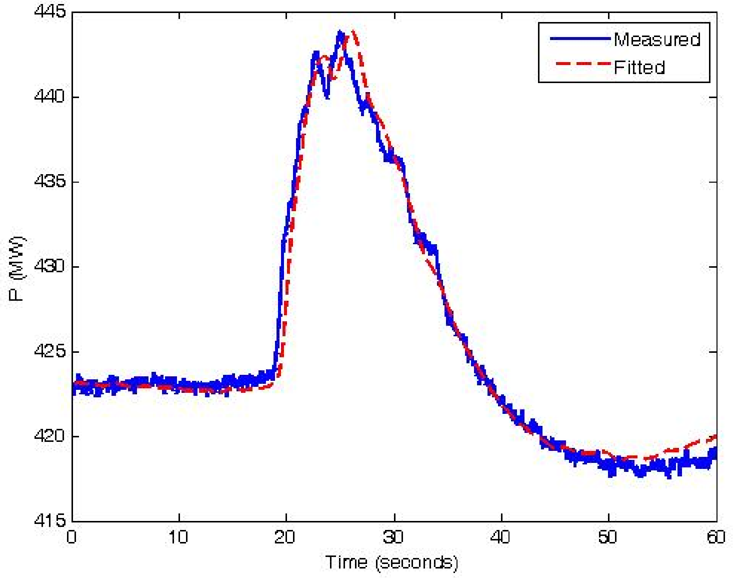


Figure 10: Turbine-Governor Model Verification using EPRI PPPD (©IEEE 2011 reference [A9]).

Wind Power Plants

Disturbance-based power plant dynamic model verification can also be applied to variable energy resources such as wind and solar. Similar techniques apply using the playback model. In particular, model verification of the excitation system controls has proved effective. However, there are considerations that should be made when performing PPMV on variable energy resources:

- **Changing input power**: For conventional plants, available mechanical input power is considered constant during the play-in. However, with changing wind speed (or solar irradiance for solar plants), the input power may vary and should be considered when comparing actual vs. simulated response.
- **Controls time constants:** Point-on-wave data is useful for newer resources with power electronic interfaces that have very fast responding controls. Synchrophasor data rates may not be sufficient for capturing these responses and point-on-wave data may be required.
- **Low MW output:** Situations where not all wind turbines are online must be accounted for by changing the MVA base to represent[37] the number of turbines online during the event.

---

[36] Such as boiler pressure control or other modes where control valves are wide open.

[37] Experience has shown that a reasonable judgment of the number of online turbines can provide a relatively good match.

- **Turbine tripping:** In some situations, some wind turbines may trip offline during the event of nearby faults or very low frequencies. This will not be accounted for automatically using PPMV and must be dealt with manually in the play-in simulations.
- **Low-side substation voltage:** It is important to match the low-side substation voltage if data is available. Generally, the high-side of the plant GSU would have PMU monitoring at the Point of Interconnection; however, availability of the GSU low-side voltage may help improve PPMV efforts for renewables.

Figure 11 shows the active power response to a large frequency excursion event. Notice how the measured active power at the POI fluctuates over the verification timeframe while the simulated response is relatively flat. This is due to the constant wind speed assumption used in the models. Future work will explore playing in wind speed to provide a closer match for verification purposes. Regardless, one can expect that the oscillatory behavior seen in the PMU measured data should be reflected in the simulated response. As in, the general shape and characteristics of the response should match generally close although not perfect. In this example, the model clearly does not reflect the general behavior of the plant during this event.

Figure 12 shows PPMV for a wind farm excitation system. High-side GSU voltage is played in and the low-side GSU substation voltage and reactive power output of the plant are monitored as measures of success. Future work will explore the impact sub-cycle controls in the electronically-coupled resources and renewables plant controllers have on the current injection methods. As illustrated by many examples of successful verification for synchronous machine models, this is a relatively novel consideration for renewable resources, particularly inverter-based resources. Very high resolution measurement data such as point-on-wave three-phase measurement data may be more suitable for electronically-coupled resources along with electromagnetic transient programs which can capture high speed controls, individual phase interactions, and other imbalances.

Similar to conventional units in the selection of events for PPMV, one must consider these sub-cycle interactions within the plant that may not be modeled in the positive sequence models and may not be captured with the measurement data. In particularly, close-in faults near the POI or measurement location can cause issues; however, slower dynamic events or faults away from the generating resource have proved to be effective. Again, engineering judgment must be applied.

The method of playback injection has worked reasonably well for synchronous generating resources, in particular due to the strong short-circuit ratios at the POI and strong network voltage. As such, the injected currents have less influence on the voltages at the POI. Many renewable plants, however, are connected to relatively weak points of the BPS where a weak voltage source may influence the performance of plant compared with the modeled or expected performance of a current source model. In these cases, reference step tests or other methods for verification may be more applicable based on engineering judgment. Future work will consider the electronically-coupled models and weak grid connections on PPMV simulation results.

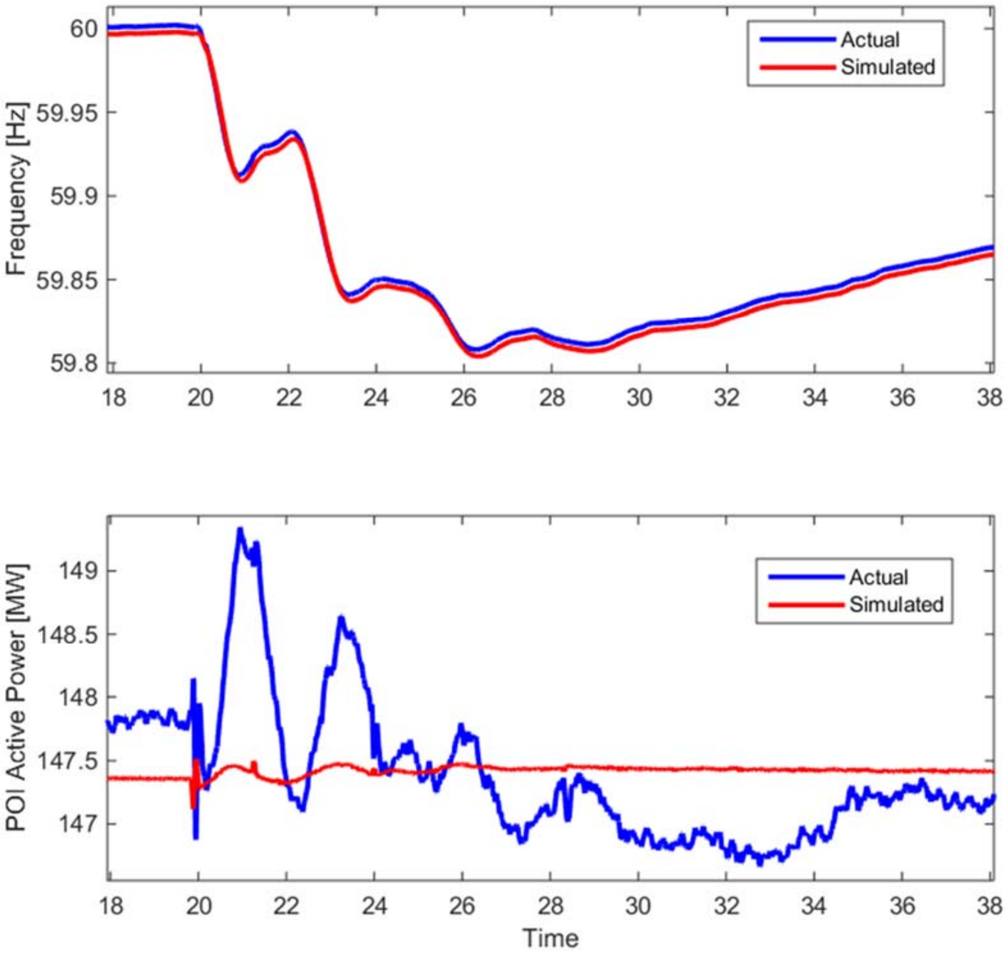


Figure 11: Wind Plant Active Power Response to Frequency Event

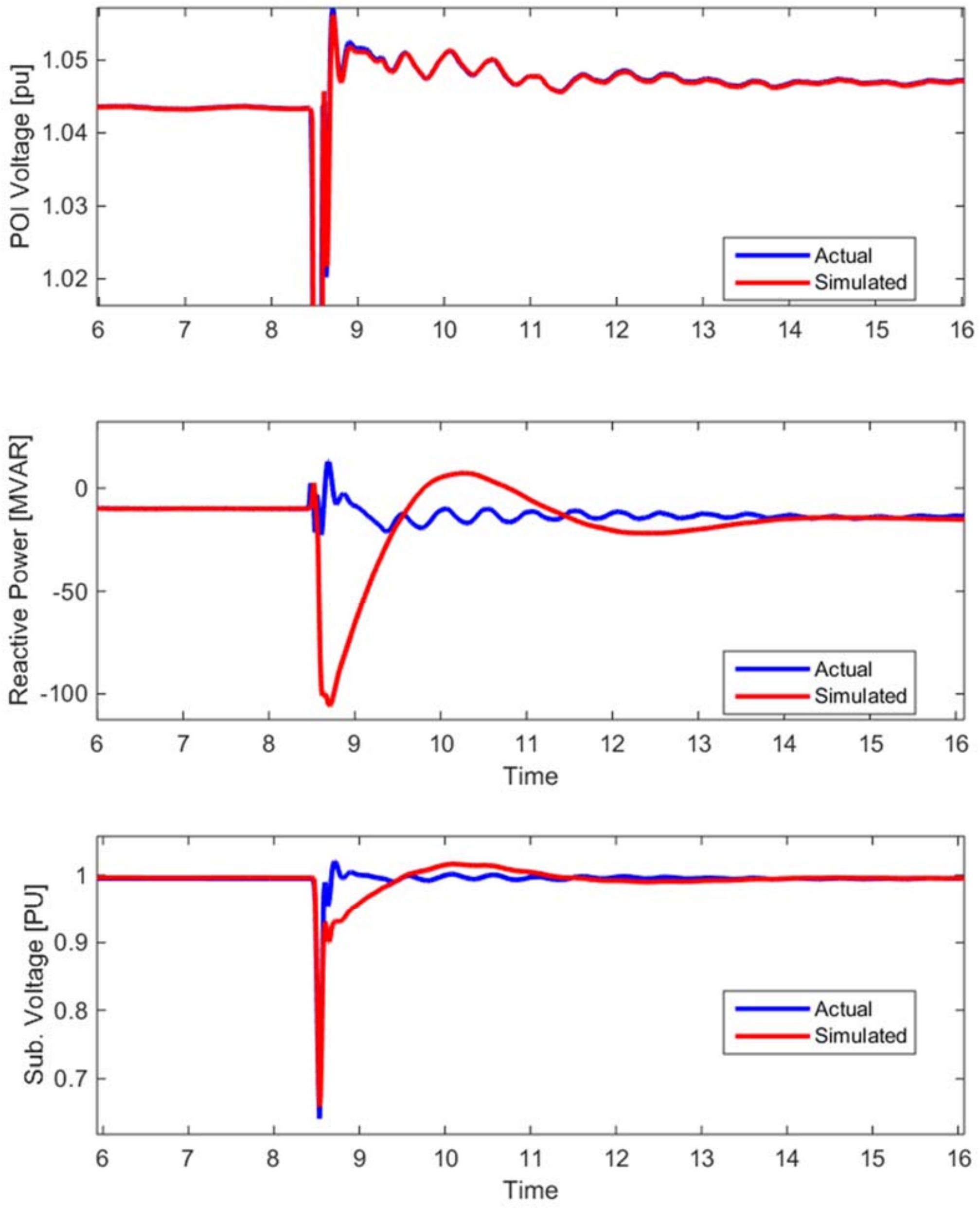


Figure 12: Wind Plant Excitation (Volt-Var Control) Verification

Power Plant Performance Monitoring

Using the tools and processes outlined in the preceding sections, the next step is to move from offline verification to automated or online verification for real-time monitoring purposes. The ability to continuously verify generating fleet performance following major disturbances has numerous benefits from the modeling, planning, and real-time operations aspects. Figure 13 shows the general process for online power plant performance monitoring.

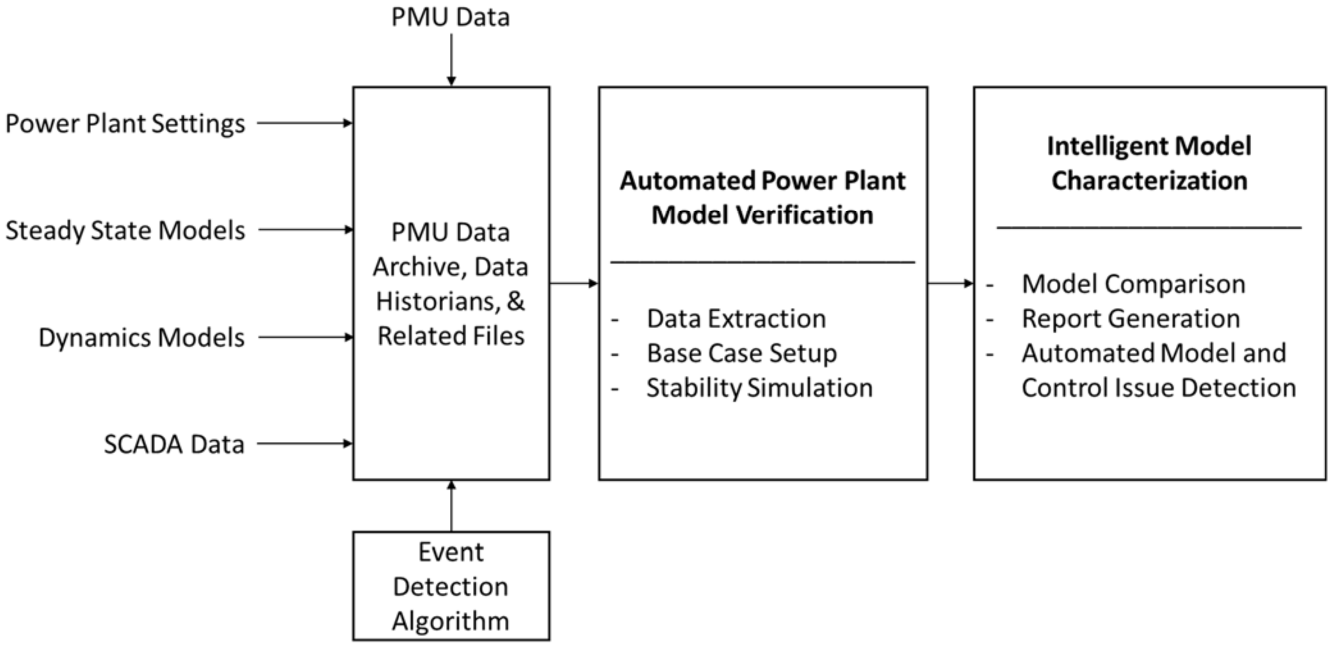


FIGURE 13: Power Plant Performance Monitoring Process

Aside from assuring that the generator models are verified continuously, online power plant performance monitoring unlocks the early detection of failures or control issues within the power plant, mitigating their potential impact on the bulk power system. Industry experience has shown that one of the major benefits of ongoing model verification (offline or online) is the identification of abnormal or unplanned power plant responses or controls. Figure 14 shows some examples of power plant control issues that have been detected and fixed through this process. These examples include failure of a power system stabilizer (PSS), abnormal runback of reactive power output of the unit following a disturbances, and unexpected plant controls. All of these issues result in the grid operating in a state that is not planned, particularly in the transient response timeframe.

Once a verified model is established, that model then becomes the benchmark for performance monitoring. The unit should respond similarly to the modeled behavior, and any abnormalities or discrepancies may be attributed to changes within the plant. Over time, this becomes a recurring process where disturbance events are used to check the equipment performance. The ‘expected’ behavior from the validated model can confirm that the plant is functioning properly by comparing the online response to the modeled response.

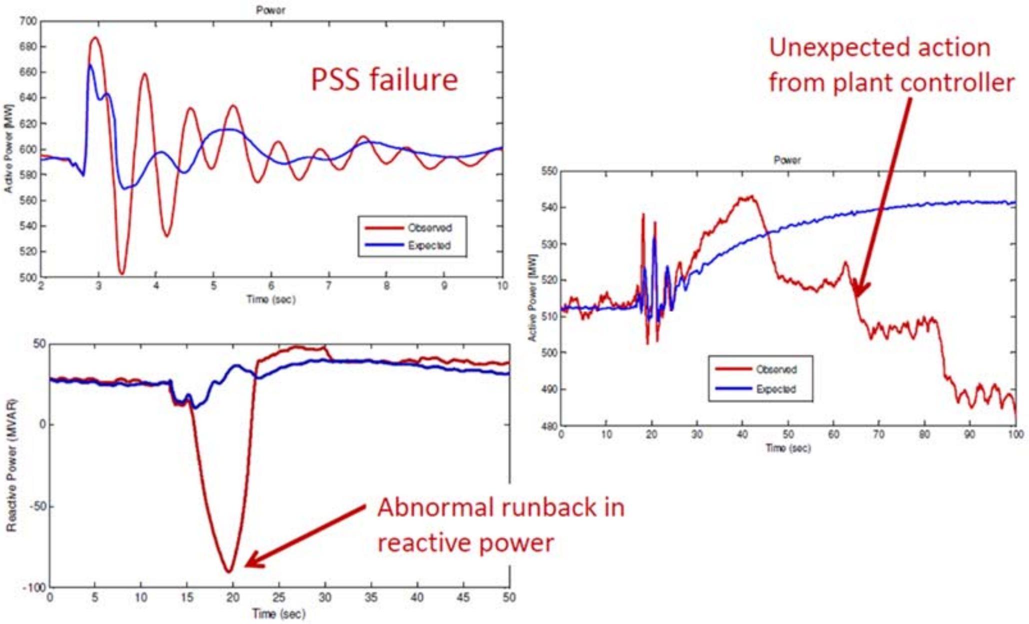


FIGURE 14: Power Plant Control Issues Detected

With respect to frequency response, performance monitoring can help assure that units assumed to be frequency responsive are actually providing that response during over- or under-frequency events. Generally, these units are identified in three major categories:

- **Frequency Responsive:** The governor provides primary frequency response during underfrequency events.
- **Load Control Action:** Plant-level distributed control systems (DCS) act on the turbine-governor to return the power plant or unit output to pre-defined output.
- **Baseloaded:** The plant is operating as a baseloaded unit, with its prime mover (control valves, wicket gates, etc.) providing full output; hence, there is no headroom for the unit to respond to underfrequency conditions.

Verifying the responsiveness of the generation fleet is critical for ensuring that the real-time and offline models used to plan and operate the system match actual operation. Over- or under-estimating frequency response and active power transfers post-contingency can have a substantial impact on the determination of System Operating Limits (SOL) and Interconnection Reliability Operating Limits (IROL).

Power plant performance monitoring using disturbance data from PMUs or other Disturbance Monitoring Equipment (DME) should be an ongoing verification process and can be automated to provide awareness of generation fleet model performance for those units with disturbance monitoring capability. The timelines set forth in NERC Reliability Standards MOD-026 and MOD-027 ensure a 10-year verification, at a minimum. However, it is recommended that the Transmission Planners and Generator Owners that have the capability to perform disturbance-based model verification perform this function much more regularly. Operating conditions and equipment statuses within the power plant change can change over time, sometimes unnoticed, and this process ensures more accurate models and earlier detection of abnormal operating conditions.

Appendix A: Software Tools Guidelines

The following subsections provide guidance (i.e., simplified user's manual) for performing power plant dynamic model verification using high resolution playback data (generally synchrophasor data). NERC does not advocate the use of any one tool, manufacturer, or vendor; this information is provided for helping practitioners execute this functionality within the tools that provide this capability. The commercially available or open-source tools listed below are known to have this capability integrated.

General Electric PSLF

The playback feature in GE PSLF was first introduced in 2001 by Dr. John Undrill in the form of play-in data in the GENCLS model. The first generation of playback models allowed PSLF users to play-in measured voltage and frequency signals from field measurements (PMUs, DFRs, etc.) in the PSLF simulation. In early 2010, Dr. John Undrill introduced the 2nd generation playback models in PSLF, which made it possible for the user to play back various types of field data, as shown in Table A1 and Figure A1.

Table A1: Play-In Quantities and Signals

Field Measurement	Signal
Voltage (bus or internal voltage)	V_{int}
Frequency (bus or internal source)	F_{req}
Generator field voltage	E_{fd}
Turbine mechanical power	P_m
Voltage regulator reference setting for excitation system	V_{ref}
Governor reference setting for turbine controls	ω_{ref}

The figure below summarizes the various types of signals which can be played back in a PSLF simulation.

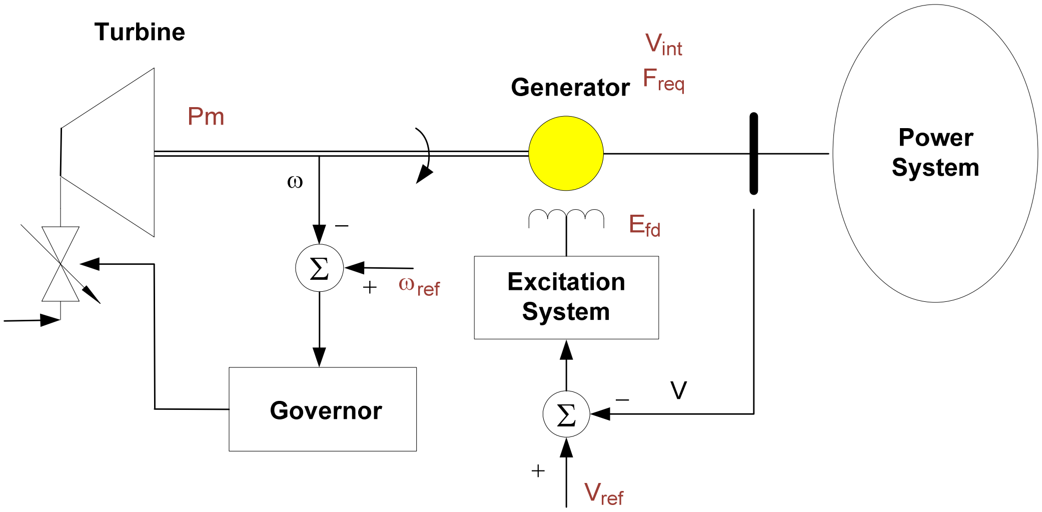


FIGURE A1: 2nd Generation Play-In Signals in PSLF

First generation of playback feature in PSLF

The first generation of playback model was added in the form of GENCLS PSLF dynamic model. The gencls model can be instructed to play back a voltage signal by specifying the name of a file containing sampled data in the PSLF dynamics data file (DYD). The played-back voltage is the Thevenin internal voltage of the generator. Where it is necessary to play back the voltage at a bus where a Thevenin impedance cannot be identified, the MVA base of the generator can be made very large. When used as a playback source, the gencls model must be set up in PSLF exactly as when it is used to represent an actual generator.

The recorded variation of the Thevenin voltage must be described in the playback file as follows:

(maxsamples)
(time_sample0), (voltage_ sample0) , (frequency_ sample0), a2_ sample0, a3_ sample0, a4_ sample0
(time_sample1), (voltage_ sample1) , (frequency_ sample1), a2_ sample1, a3_ sample1, a4_ sample1
.
.
.
end

maxsamples = maximum number of samples to be read from the file
time_samplei = time of ith sample in seconds
voltage_samplei = a0, magnitude of voltage at ith sample instant, per unit
frequency_samplei = a1, frequency of voltage at ith sample instant, per unit
a2,a3,a4 = Associated playback signals, which can be used by the user to compare measured data against the simulated results.

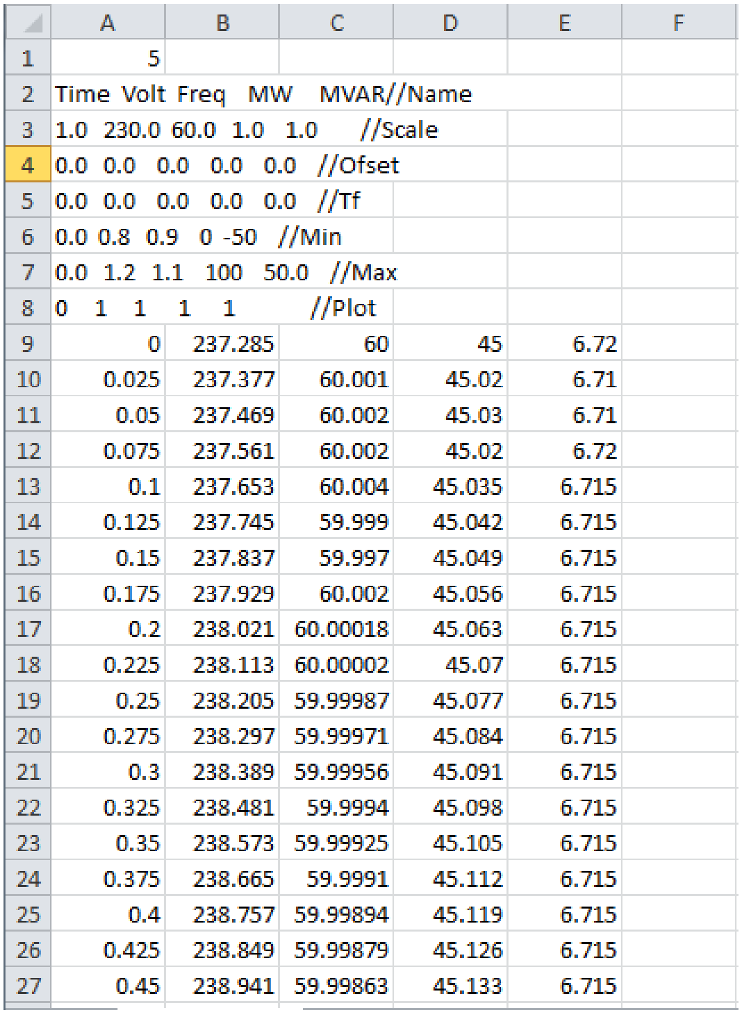
Each sample must be described in a separate record. PSLF reads at most (maxsamples) sample records from the file. The samples need not be equally spaced in time. The samples must appear in the file in increasing time sequence. Entries in the sample records may be separated by spaces or commas. The first value of time must be zero, and all values of time must be stated relative to the time of the first sample.

The playback of the recorded signal starts at time t_0. Prior to t_0 the magnitude and frequency of the Thevenin voltage are held constant at their initial condition values. At time t_0 the initial condition values are replaced by the values of the first sample, offset as noted below. The values of (voltage) and (frequency) in the first sample need not be equal to the initial condition values of the Thevenin voltage and frequency. PSLF allows the user to define bias to reconcile this difference. The model recognizes that the sample times of the recorded signal will not be aligned with time steps of the simulation process. The effective sample value at each simulation time point is obtained by linear interpolation between the sample values immediately preceding and following the present value of time. The sampled signal values can also be smoothed by simple single-pole low pass filters whose time constant is tf. A separate filter time constant can be specified for voltage amplitude and frequency playback channel.

Second Generation Playback Feature in PSLF

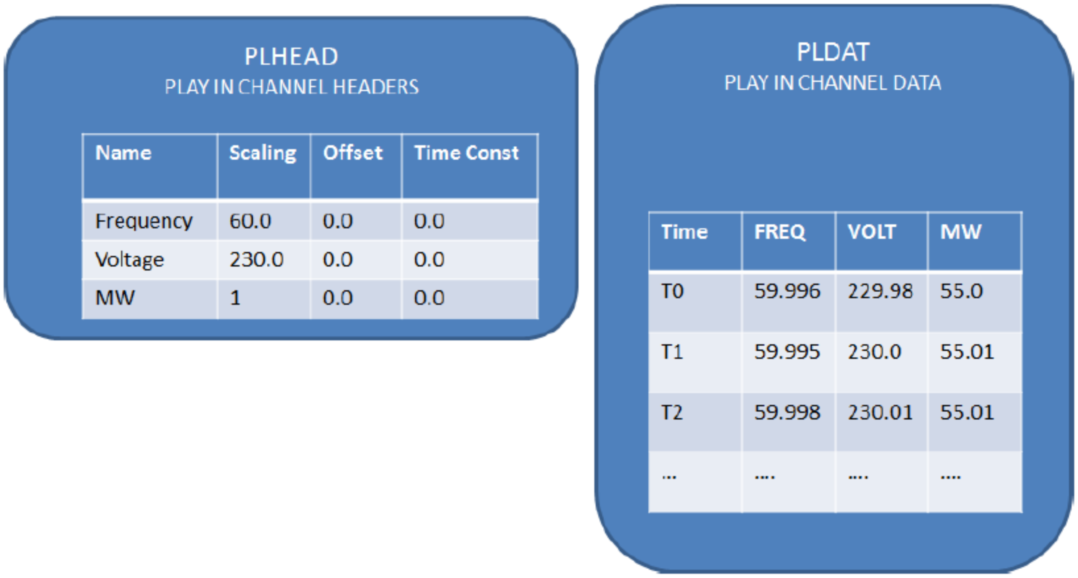
The second generation playback models made it possible to play-in generator field data, turbine mechanical power data, voltage regulator reference voltage data, and governor reference setting data in addition to the generator voltage and frequency.

The playback signals are defined in a .csv or .txt file which can be comma-, space-, or tab-delimited. The play-in signal data can be directly read into PSLF from a .csv file using read play in (rpli) command. This populates the internal PSLF play-in signal data records. The figure below shows the file format of the play-in file read by PSLF. In this example, voltage, frequency, MW and MVAR are defined in the play-in data file.



	A	B	C	D	E	F
1	5					
2	Time Volt Freq MW MVAR//Name					
3	1.0 230.0 60.0 1.0 1.0 //Scale					
4	0.0 0.0 0.0 0.0 0.0 //Ofset					
5	0.0 0.0 0.0 0.0 0.0 //Tf					
6	0.0 0.8 0.9 0 -50 //Min					
7	0.0 1.2 1.1 100 50.0 //Max					
8	0 1 1 1 1 //Plot					
9	0	237.285	60	45	6.72	
10	0.025	237.377	60.001	45.02	6.71	
11	0.05	237.469	60.002	45.03	6.71	
12	0.075	237.561	60.002	45.02	6.72	
13	0.1	237.653	60.004	45.035	6.715	
14	0.125	237.745	59.999	45.042	6.715	
15	0.15	237.837	59.997	45.049	6.715	
16	0.175	237.929	60.002	45.056	6.715	
17	0.2	238.021	60.00018	45.063	6.715	
18	0.225	238.113	60.00002	45.07	6.715	
19	0.25	238.205	59.99987	45.077	6.715	
20	0.275	238.297	59.99971	45.084	6.715	
21	0.3	238.389	59.99956	45.091	6.715	
22	0.325	238.481	59.9994	45.098	6.715	
23	0.35	238.573	59.99925	45.105	6.715	
24	0.375	238.665	59.9991	45.112	6.715	
25	0.4	238.757	59.99894	45.119	6.715	
26	0.425	238.849	59.99879	45.126	6.715	
27	0.45	238.941	59.99863	45.133	6.715	

FIGURE A2: Play-in System Based on Two Tables in PSLF Data System



PLHEAD
PLAY IN CHANNEL HEADERS

Name	Scaling	Offset	Time Const
Frequency	60.0	0.0	0.0
Voltage	230.0	0.0	0.0
MW	1	0.0	0.0

PLDAT
PLAY IN CHANNEL DATA

Time	FREQ	VOLT	MW
T0	59.996	229.98	55.0
T1	59.995	230.0	55.01
T2	59.998	230.01	55.01
…	….	….	….

FIGURE A3: Play In Channel Header and Data

plhead	This table contains header information of the played in signal such as • Signal name • scale factors and offsets that can be used to convert signals from 'raw' engineering values to per unit values suitable for PSLF • Filter time constant to apply time delay to the specified channel.
Pldat	This table contains the recorded signal data to be played in.

It is useful to think of the played-in data as a file of samples of the value of recorded channels. Each set of samples constitutes one record in the file. There are nchan samples per record, including the independent variable channel which is normally the value of time. Time is normally, but not necessarily, contained in channel 0.

The played in data can be scaled, either based upon the scaling and offset specified in the playback file when the play back data is read or it can be scaled at a later time by using the EPCL (PSLF scripting language) command PLSC(). The actual signal value played in to the dynamic models of PSLF is calculated based upon the offset, scale and actual data value. Thus, if a channel contains samples of generator terminal voltage in kV, and if the base value of voltage is 13.8 kV, the per unit voltage can be obtained by setting the scale factor to 13.8. If there is known to be a +0.3 kV zero error in the raw data in that channel, this could be corrected by setting the offset to 0.3.

It is unusual for the sampling of the play-in data to match the numerical integration time step used in PSLF simulation. The models that apply play-in signals to the simulation therefore interpolate between play-in samples to obtain the value to be applied to the simulation at each time step. This interpolation is done by the *plnow* model. At every time step of the simulation *plnow* gets the data samples whose times precede and follow the present simulation time *dypar.time*. *plnow* then gets the value of the play-in signals at the present time by linear interpolation. If a non-zero filter time constant is provided for a channel, the filter is applied to the interpolated signal value.

Second Generation Play-In Dynamic Models in PSLF

Gthev: Dynamic model for playing in voltage amplitude and frequency. The user only needs to reference the play in channel data, which is done by assigning the channel index.

Plefd: Dynamic model for playing in generator field voltage. The user only needs to reference the play-in channel data, which is done by assigning the channel index.

Pltp: This is the dynamic model which can be used to play in turbine power. The user only needs to reference the play in channel data. This is done by assigning the channel index.

Plref: This is the dynamic model which can be used to play in voltage regulator and/or governor reference settings. The user only needs to reference the play in channel data. This is done by assigning the channel index.

Running Playback Simulation using PSLF EPCL Automation Scripts

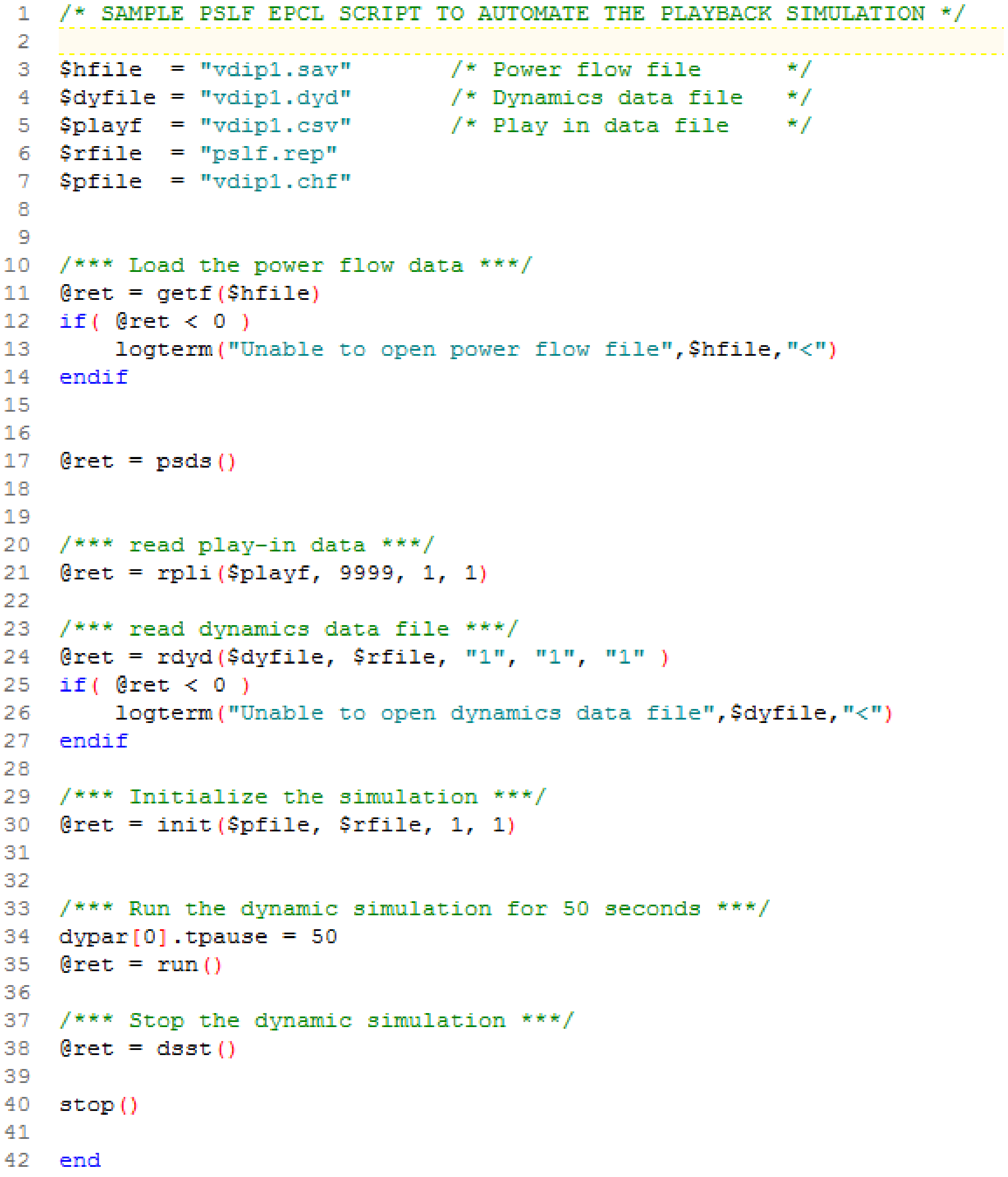
EPCL is the native scripting language of PSLF used to automate various studies or analyses. The play-in signal data can be manipulated via EPCL. The following are the fields in the plhead structure which can be accessed by the user.

The heading of channel nc is	plhead[nc].name
The scale factor for channel nc is	plhead[nc].scale
The offset for channel nc is	plhead[nc].ofset
The filter time constant for channel nc is	plhead[nc].tf

The scale factors and offsets can be changed by simple EPCL statements as shown below. The user can also apply scaling manually to the play-in data by changing the scale or offset and forcing PSLF to recalculate the channel values by using EPCL command plsc().

plhead[7].scale = 13.8
plhead[7].ofset = 0.3

EPCL can be used to automate the entire dynamic simulation using play-in data, as shown in the example script in Figure A4.



```
/* SAMPLE PSLF EPCL SCRIPT TO AUTOMATE THE PLAYBACK SIMULATION */

$hfile  = "vdip1.sav"       /* Power flow file      */
$dyfile = "vdip1.dyd"       /* Dynamics data file   */
$playf  = "vdip1.csv"       /* Play in data file    */
$rfile  = "pslf.rep"
$pfile  = "vdip1.chf"


/*** Load the power flow data ***/
@ret = getf($hfile)
if( @ret < 0 )
    logterm("Unable to open power flow file",$hfile,"<")
endif


@ret = psds()


/*** read play-in data ***/
@ret = rpli($playf, 9999, 1, 1)

/*** read dynamics data file ***/
@ret = rdyd($dyfile, $rfile, "1", "1", "1" )
if( @ret < 0 )
    logterm("Unable to open dynamics data file",$dyfile,"<")
endif

/*** Initialize the simulation ***/
@ret = init($pfile, $rfile, 1, 1)


/*** Run the dynamic simulation for 50 seconds ***/
dypar[0].tpause = 50
@ret = run()

/*** Stop the dynamic simulation ***/
@ret = dsst()

stop()

end
```

FIGURE A4: Example EPCL Script for Playback Model

References/Examples showing use of PSLF playback models in the industry

The playback models in PSLF have been extensively used in the industry for various type of model verification work. In particular, these models have been crucial for:

1. Power plant model verification by the grid code testing team in GE Energy Consulting [A1].
2. EPRI to benchmark the 2nd generation wind turbine models [A2].
3. GE Energy Consulting to validate the GE wind turbine parameters.
4. Generator Model Validation tool developed by Idaho Power [A3].
5. Power Plant Model Validation (PPMV) tool developed by PNNL and BPA [A4].

Figure A5 illustrates how the playback models are used by the GE generator testing team to validate the turbine governor models. The actual system frequency is played back on top of the staged test for speed load reference step changes and active power response is compared for verification.

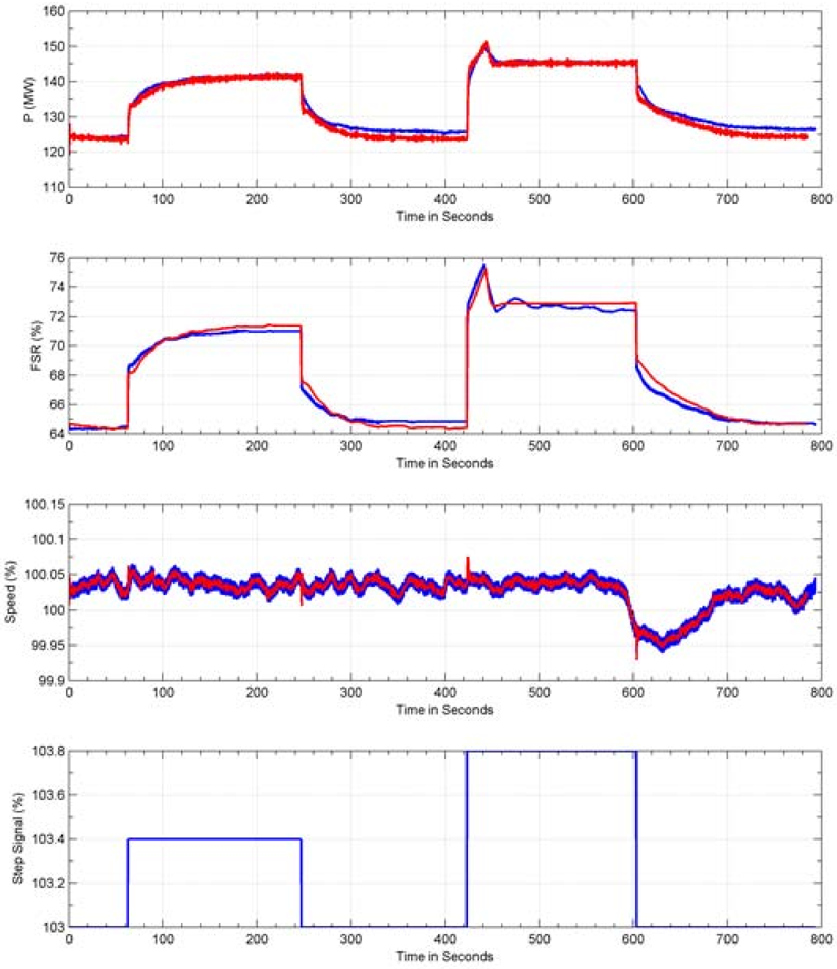


FIGURE A5: GE Generator Testing Team Use of PSLF Playback Model

Siemens PTI PSS®E

The Playback Model in PSS®E is called PLBVFU1, and plays back a known set of voltage and frequency signals. The PLBVFU1 model acts as a generator model, meaning that an excitation system or governor model are not required to represent the playback generator in the model.

To use the playback model PLBVFU1, a new machine has to be created in powerflow at the bus at which the voltage and frequency signals are to be played back. The PLBVFU1 model must be attached to this generator with the following conditions: $V_{scheduled} = V_{initial}$ of the bus, generator $P_{gen} = 0.0$, and generator $Q_{MAX} = Q_{MIN} = 0.0$. When the powerflow is solved under such a condition, the bus voltage angle is expected to be the same as the initial bus voltage angle of that bus.

The played-in voltage and frequency signals must be described in a file as shown below, with each sample described in a separate record and the values in each line separated by spaces or commas:

Time, voltage, frequency

where,

Time:	Relative time of sample [s] (i.e., 0.000, 0.033, and so on)
Voltage:	Bus voltage magnitude at each sampled instant
Frequency:	Bus frequency at each sampled instant

The samples need not be equally spaced in time. However, the value of time must appear in the file in increasing time sequence. The sample values of voltage can be in units of volts or kV or in per unit. If the value of voltage sample is in units of volts or kV, then V_{scale} defined in the .dyr file will be the base voltage value; otherwise, V_{scale} will have a value of 1.0. The sample values of frequency can be in units of Hz or in per unit. If the value of frequency sample is in Hz, then f_{scale} will be the base frequency value (50 or 60 Hz); otherwise, f_{scale} will have a value of 1.0.

The model is supplied as part of PSS®E installation for version 34.1; therefore, use of this model does not require compilation and link. For version 33, a user .dll can be downloaded from the PSS®E user support web page.

The file containing the measurement has to be supplied in a file with an extension ".plb". The file name (without the ".plb" extension) has to be less than or equal to 12 characters long when used with version 34.1 and above, and 2 characters long when used with version 33. The file name is to be input within single quotes in ICON(M+2). This file has to exist in the working folder. If the "plb" file is not found, the PLBVFU1 model will keep the internal voltage and frequency fixed at the initial value (i.e., the playback feature will be ignored).

1. The "plb" file will have to contain the time values in the first column. The 2nd and 3rd columns will contain the voltage and frequency values respectively. To playback both the voltage and frequency signals, the ICON(M) and ICON(M+1) will have values of 1. To playback just the voltage signal but not the frequency signal, set ICON(M) to 1 and ICON(M+1) to -1. In this case, although the ".plb" file will contain the voltage and frequency points, only the voltage signal will be played back. Similarly, to playback just the frequency signal but not the voltage signal, set ICON(M) to -1 and ICON(M+1) to 1.
2. In the traditional GENCLS model, when operated as an infinite bus, the magnitude and phase of the internal voltage are given by the steady state value of E_{fd} (field voltage) and the initial rotor angle (δ). In the play-back model PLVFBU1, the magnitude of the internal voltage is given by Vpu, while the phase (δ) of the internal voltage is obtained as the output of the integrator labeled s2 by integrating the frequency deviation signal.

3. The voltage signal which is played back is the internal (Thevenin) voltage of the playback generator. The ZSORCE of the generator used to represent the PLVFBU1 model should be non-zero. In case the voltage that is played back is a measurement of voltage at the generator terminals (rather than the internal voltage of a source), set the generator MVA to a very large value (e.g. 10,000 MVA) and a low ZSORCE value (e.g. 0.01 pu). This will make the voltage drop across ZSORCE small such that the terminal voltage is the same as the played-in voltage.
4. In the ".plb" file, the first value of time need not necessarily be zero. However all values of time are stated relative to this first value of time, and must be in increasing order. The samples need not be equally spaced in time. The playback of the recorded voltage and frequency signal starts at or after the first time value (Tstart) in the ".plb" file. Prior to Tstart, the magnitude and frequency of the Thevenin voltage are held constant at their initial condition values. Once PSS®E simulation time becomes greater than or equal to the first time sample, the initial condition values are replaced by the values of the sample value. The effective sample value at each simulation time point is obtained by linear interpolation using the sample values immediately preceding and following the value of the present PSS®E simulation time.

   The values of voltage and frequency in the first sample need not be equal to the initial condition values of the Thevenin voltage and frequency. To deal with the difference between the initial sample values and the corresponding initial condition values, an offset (Voffset and foffset) is calculated as the difference between the first sample and the corresponding simulation initial condition value.
5. The sampled voltage and frequency values may be smoothed via a first order block with time constants Tv (for voltage signal) and Tf (for frequency signal).

PLBVFU1

Model to Play-In known voltage and/or frequency signal

This model is located at system bus #______IBUS
Machine identifier #______ID
This model uses CONs starting with #_____J
and STATEs starting with #_____K
and VARs starting with #_____L
and ICONs starting with #_____M

CONs	#	Value	Description
J			Vscale, voltage scaling factor (> 0.0)
J+1			fscale, frequency scaling factor (> 0.0)
J+2			Tv, filtering time constant for voltage signal (s)
J+3			Tf, filtering time constant for frequency signal (s)

STATEs	#	Description
K		Filtered voltage
K+1		Filtered Frequency
K+2		Angle (radians)

ICONs	#	Value	Description
M			Voltage playback flag (1: play voltage signal, else 0)
M+1			Frequency playback flag (1: play frequency signal, else 0)
M+2			Playback file name (in single quotes, without ".plb")

VARs	#	Description
L		V_{offset}
L+1		Input to voltage filter block
L+2		f_{offset}
L+3		Input to frequency filter block
L+4		Scaled value of voltage signal
L+5		Scaled value of frequency signal

DYR format:

IBUS, ‘USRMDL’, ID, ‘PLBVFU1’, 1, 1, 3, 4, 3, 6, ICON(M) to ICON(M+2), CON(J) to CON(J+3) /

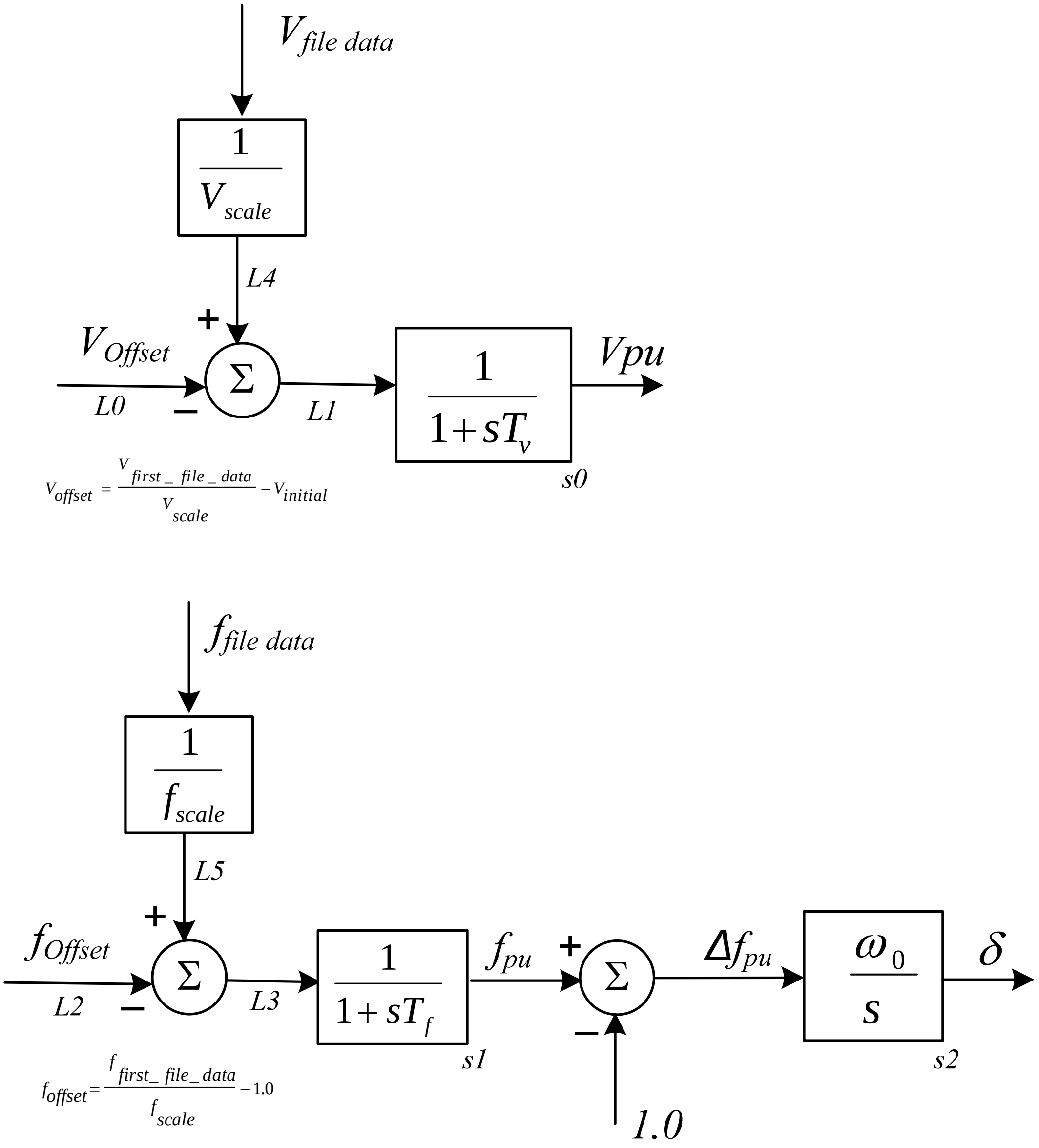
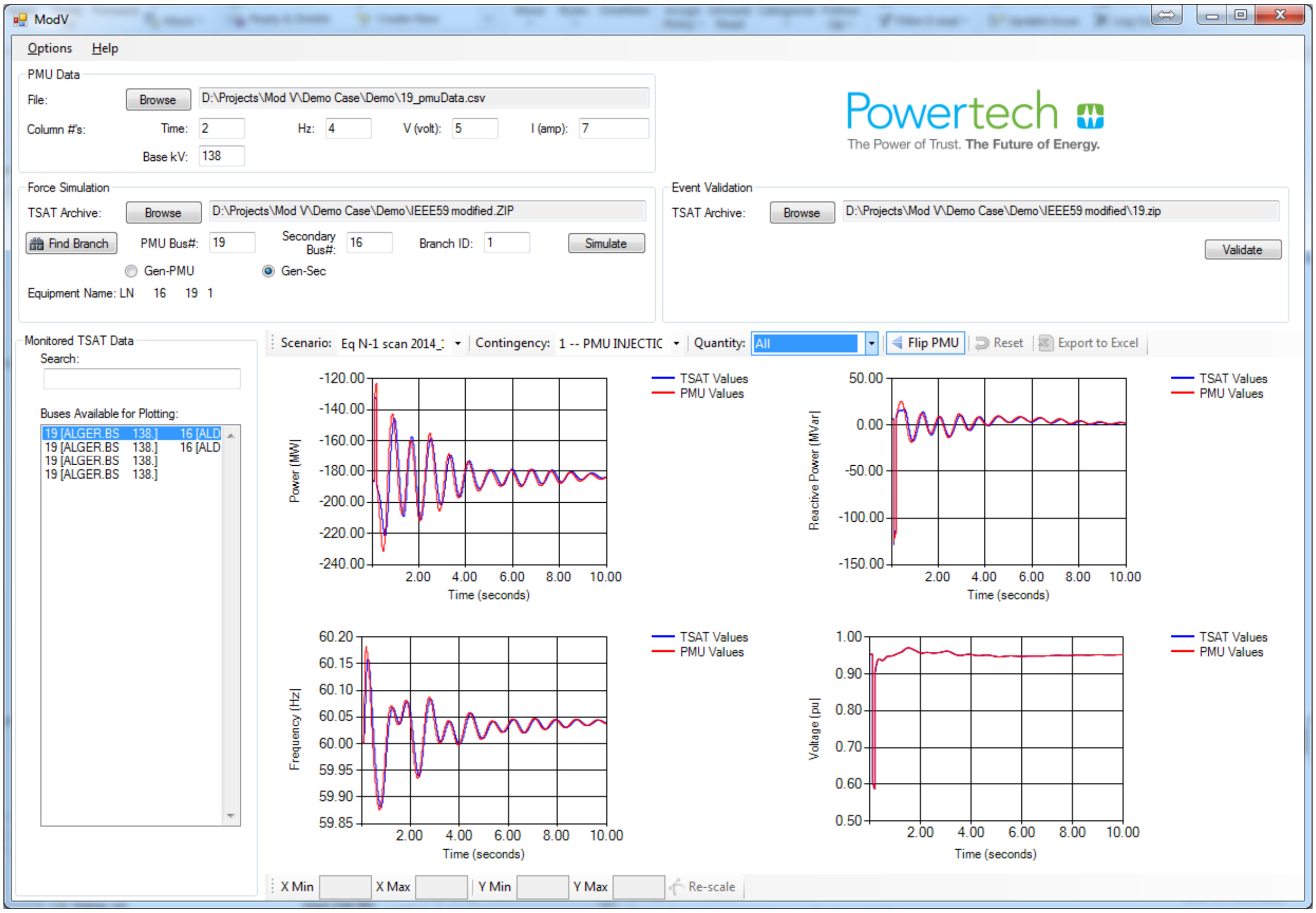


FIGURE A6: Playback Model PLBVFU1 in PSS®E

Powertech Labs Inc.

The **Data Injection** function is available in the *Transient Security Assessment Tool* (TSAT) program, a module in the DSATools® power system analysis package developed by Powertech Labs Inc. Performing detailed time-domain simulation of large and complex power system models is one of the main features of TSAT. Generator models in a power plant together with network models can be simulated in details in TSAT. If high resolution measurements, typically from field measurements such as PMUs, are available to the user, **Data Injection** function enables user to playback those measured data into the simulation system. This function is particularly useful for dynamic model calibration as the actual measured data can be incorporated into the dynamic simulation. Comparing simulation results, such as power output from generators, with measured data facilitates the dynamic model calibration. The injection data can be time varying voltage and frequency/angle measurements and is specified as part of a dynamic data files in TSAT. For each given bus, one set of injection data can be specified. Multiple data files may be specified at different buses. For model calibration purpose, TSAT supports a wide range of models, from conventional generators and their controls, to renewables (wind, solar, etc.) and FACTS/HVDC/SPS. For tuning control systems, a very flexible user-defined modeling approach can be used to adjust control system structures and parameters. Data (both powerflow and dynamics) can be provided in TSAT native format as well as third party formats, such as PSS®E and PSLF®.

In addition to the **Data Injection** function in TSAT, a dedicated program, called “Model Validation tool”, in short “**ModV”,** is also available to users with a consolidated workspace where selecting PMU data, matching dynamic models with simulation case, performing time domain simulations, and comparing simulation results with measurements can be done in one place. **ModV** is a standalone, highly intuitive, user-friendly application that aims to enhance power system modelling and analysis by tuning the model parameters of generating units according to PMU measured data. Voltage and frequency/angle, available from PMU data, is injected at the PMU bus to monitor the reaction of the generators under study. The simulated MW and MVar power flow from the generators on the PMU branch is compared against the PMU data as illustrated in the figure below.



PMU Data

File: D:\Projects\Mod V\Demo Case\Demo\19_pmuData.csv

Column #'s: Time: 2 Hz: 4 V (volt): 5 I (amp): 7

Base kV: 138

Force Simulation

TSAT Archive: D:\Projects\Mod V\Demo Case\Demo\IEEE59 modified.ZIP

PMU Bus#: 19 Secondary Bus#: 16 Branch ID: 1

○ Gen-PMU ● Gen-Sec

Equipment Name: LN 16 19 1

Event Validation

TSAT Archive: D:\Projects\Mod V\Demo Case\Demo\IEEE59 modified\19.zip

Monitored TSAT Data

Search:

Buses Available for Plotting:

19 [ALGER.BS 138.] 16 [ALD
19 [ALGER.BS 138.] 16 [ALD
19 [ALGER.BS 138.]
19 [ALGER.BS 138.]

Scenario: Eq N-1 scan 2014_ Contingency: 1 -- PMU INJECTIC Quantity: All

X Min X Max Y Min Y Max

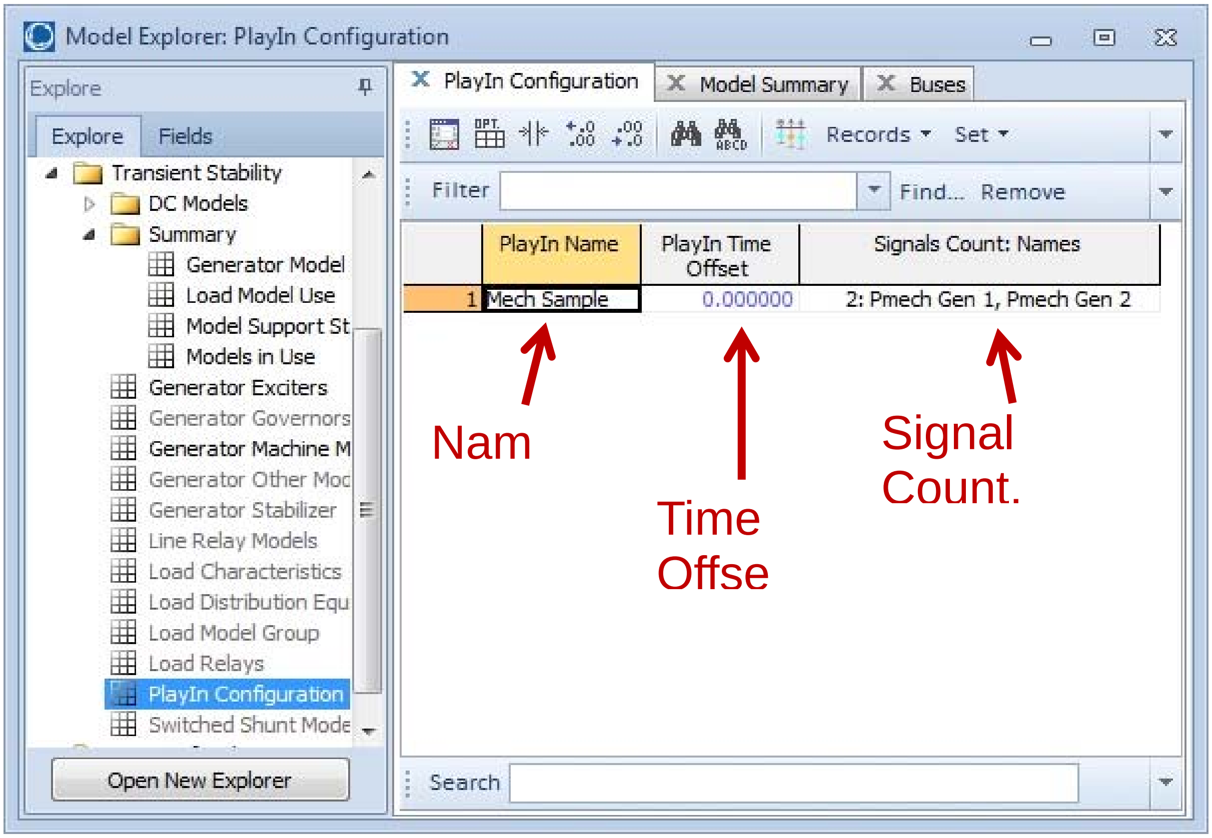
Figure A7: Comparison of model simulation with PMU data in ModV

ModV comes with a suite of features like zooming, panning, setting axis, and exporting data to Excel that allows easy graphical analysis of the results in detail.

PowerWorld Corporation

PlayIn models are used to play input data into the transient stability tool at a specified time. The models are set to be used as a generator, a reference signal, governor or a exciter. Respectively, there are three types of PlayIn models available: PlayInGen, PlayInRef, PlayInGov and PlayInEx. The data for the models can be set manually using the **PlayIn Configuration** model type inside the Transient Stability folder on the [Model Explorer](#).

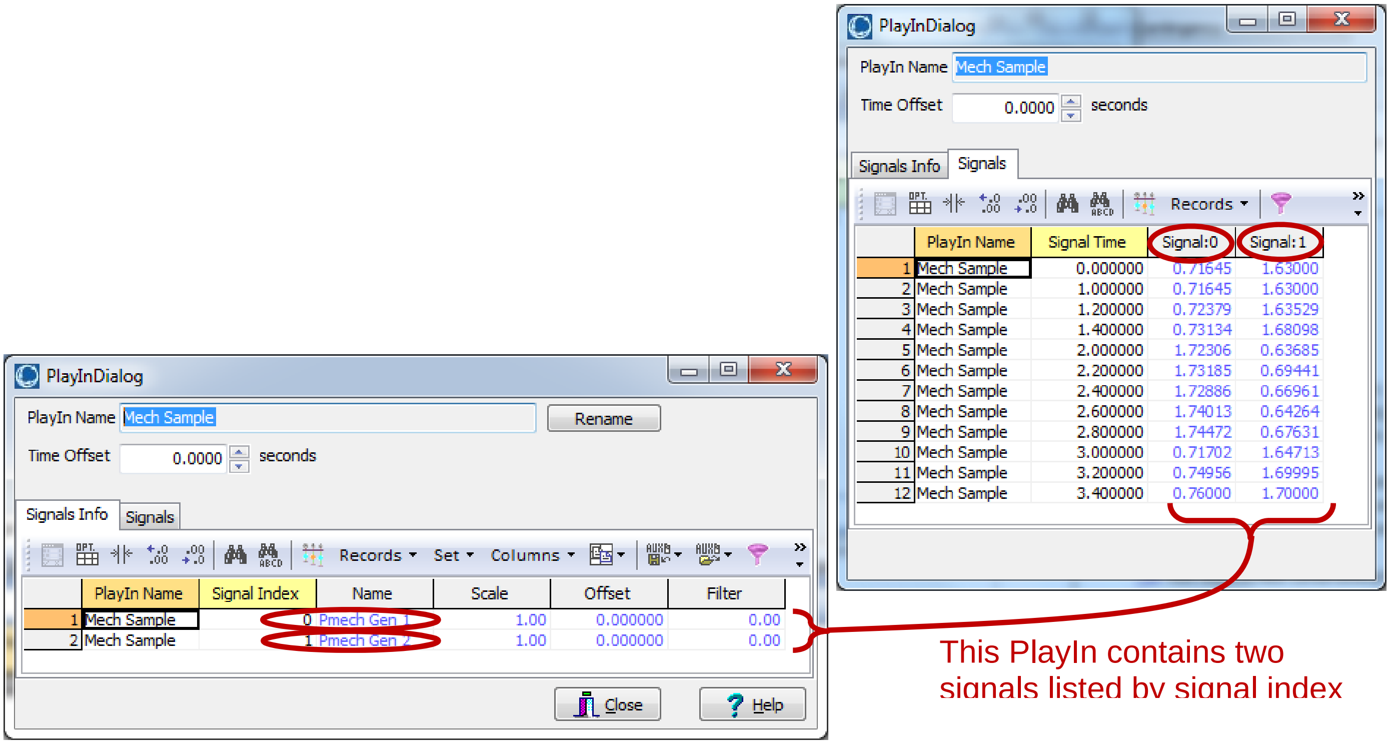
Playin Configuration



	PlayIn Name	PlayIn Time Offset	Signals Count: Names
1	Mech Sample	0.000000	2: Pmech Gen 1, Pmech Gen 2

Figure A8: Playin configuration tab in Model Explorer

In the PlayIn Configuration model (Figure A8) type you can insert a PlayIn model signal by its name and specified Offset to be applied when play in that particular model. To insert a new PlayIn model, right click on the PlayIn entry and choose Insert. This will open a dialog to enter the PlayIn model Name. Then after pressing OK the PlayIn Time offset can be specified. To insert data to a particular PlayIn Model right click on the entry and choose Show Dialog. This will open another dialog with a case information display to enter the data for the PlayIn Model. The Dialog have the PayInName which can be rename and also the Time Offset can be changed. Below there are two tabs: Signals Info and Signals (Figure A9).



PlayIn Name: Mech Sample

Time Offset: 0.0000 seconds

	PlayIn Name	Signal Index	Name	Scale	Offset	Filter
1	Mech Sample	0	Pmech Gen 1	1.00	0.000000	0.00
2	Mech Sample	1	Pmech Gen 2	1.00	0.000000	0.00

PlayIn Name: Mech Sample

Time Offset: 0.0000 seconds

	PlayIn Name	Signal Time	Signal:0	Signal:1
1	Mech Sample	0.000000	0.71645	1.63000
2	Mech Sample	1.000000	0.71645	1.63000
3	Mech Sample	1.200000	0.72379	1.63529
4	Mech Sample	1.400000	0.73134	1.68098
5	Mech Sample	2.000000	1.72306	0.63685
6	Mech Sample	2.200000	1.73185	0.69441
7	Mech Sample	2.400000	1.72886	0.66961
8	Mech Sample	2.600000	1.74013	0.64264
9	Mech Sample	2.800000	1.74472	0.67631
10	Mech Sample	3.000000	0.71702	1.64713
11	Mech Sample	3.200000	0.74956	1.69995
12	Mech Sample	3.400000	0.76000	1.70000

This PlayIn contains two signals listed by signal index

Figure A9: Elements of a Playin – Signal Info and Signals

In the Signal Info tab you specified the Signal Index as well as a respective name, scale, offset and filter. These signals are the signals that the PlayIn Model will have. For example, a PlayIn generator will need a signal for the amplitude of the Thevenin source and the frequency of the generator. The scale is used to scale the signal to a particular value. The offset will be applied to the signal to match the initial condition of the particular signal established in the initialization of the model. The filter values is a time constant, such as for a filter block [1/(1+sT)], used to filter the signal.

In the Signal Tab (Figure A9) the signal value can be specified for the particular signal index. To insert a new signal time right click in an entry and choose insert. This will open a dialog to specify a time for the signals.

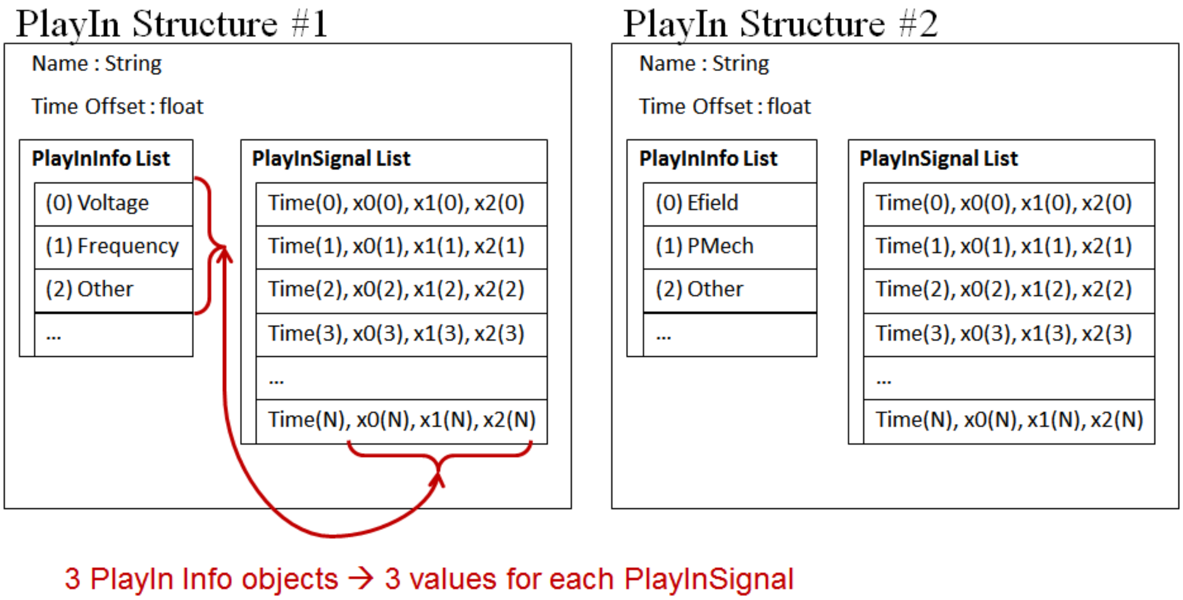


Figure A10: Graphical Representation of Playin Structures

The playin signals are stored/interpreted based on the structure shown in Figure A10.

PlayIn structure

Time Offset : shifts signal in time axis to match simulation

PlayInInfo

Offset : shifts the signal in y-axis

Scale : multiplies the signal

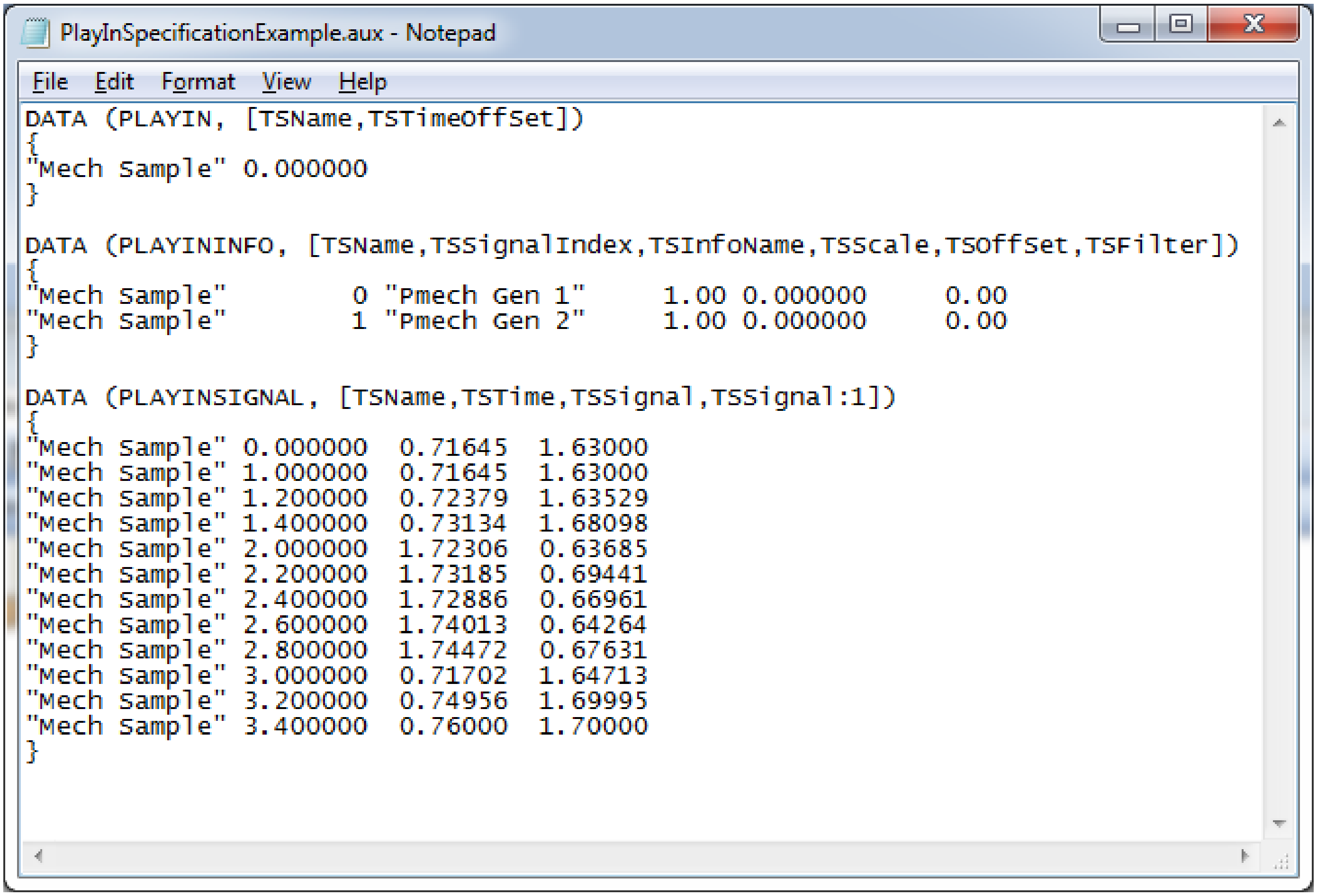
Filter Time : runs the signal through an additional [1/(1+Ts)] delay block during the simulation

*General note about time

*All signals in a **PlayIn** structure use the same time axis

*For all signals, a value must be specified at every time

Use multiple PlayIn structures if your signals do not have the same time points. The other easy way to enter PlayIn signals and new PlayIn models is to use an auxiliary file (Figure A11) with the desired signals and the desired data values, offset, scale and filter values.



```
DATA (PLAYIN, [TSName,TSTimeOffSet])
{
"Mech Sample" 0.000000
}

DATA (PLAYININFO, [TSName,TSSignalIndex,TSInfoName,TSScale,TSOffSet,TSFilter])
{
"Mech Sample"         0 "Pmech Gen 1"     1.00 0.000000     0.00
"Mech Sample"         1 "Pmech Gen 2"     1.00 0.000000     0.00
}

DATA (PLAYINSIGNAL, [TSName,TSTime,TSSignal,TSSignal:1])
{
"Mech Sample" 0.000000  0.71645  1.63000
"Mech Sample" 1.000000  0.71645  1.63000
"Mech Sample" 1.200000  0.72379  1.63529
"Mech Sample" 1.400000  0.73134  1.68098
"Mech Sample" 2.000000  1.72306  0.63685
"Mech Sample" 2.200000  1.73185  0.69441
"Mech Sample" 2.400000  1.72886  0.66961
"Mech Sample" 2.600000  1.74013  0.64264
"Mech Sample" 2.800000  1.74472  0.67631
"Mech Sample" 3.000000  0.71702  1.64713
"Mech Sample" 3.200000  0.74956  1.69995
"Mech Sample" 3.400000  0.76000  1.70000
}
```

Figure A11: Playin Specification as an AUX File

Each signal defined in the playin configuration can be associalted with playin models available in Simulator. The following is a description about them:

PlayInGen Model

The PlayIn Gen model is a generator model to play in data to the transient stability tool. The PlayIn Gen models a generator Thevenin voltage amplitude source in p.u. and the frequency amplitude in p.u.

The model can be entered in the generator dialog Machine Models Stability Tab and requires the following:

- PlayIn Model Signal applied for the particular generator
- VIndex: Index of the Thevenin Voltage amplitude signal
- FIndex: Index of the frequency amplitude signal
- Rth: The Thevenin resistance of the generator in p.u.
- Xth: The Thevenin reactance of the generator in p.u.

PlayInRef Model

The PlayIn Gen model is a voltage regulator and governor reference model to play in data to the transient stability tool. The PlayInRef models a voltage regulator reference voltage in p.u. and the governor reference Pref (Speed-load reference) in p.u.

The model can be entered in the generator dialog Other Models Stability Tab and requires the following:

- PlayIn Model Signal applied for the particular generator
- VIndex: Index of the voltage regulator reference signal
- FIndex: Index of the governor reference signal

PlayInGov Model

The PlayIn Gov model is a governor model to play in data to the transient stability tool. The PlayInGov models a governor mechanical power (Pmech) in p.u.

The model can be entered in the generator dialog Governors Stability Tab and requires the following:

- PlayIn Model Signal applied for the particular generator
- FIndex: Index of the governor Pmech reference signal

PlayInEx Model

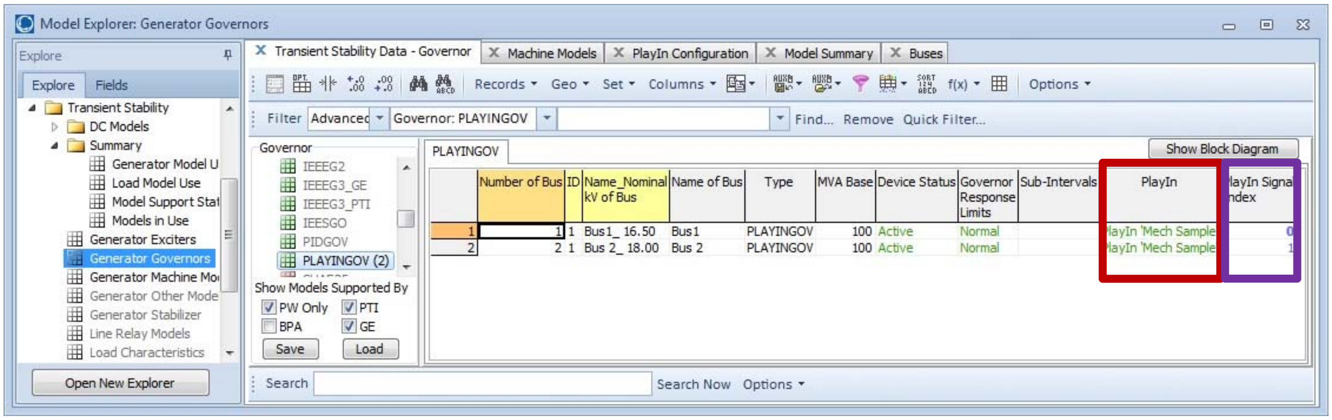
The PlayIn Gov model is a n exciter model to play in data to the transient stability tool. The PlayInEx models an exciter field voltage in p.u.

The model can be entered in the generator dialog Exciters Stability Tab and requires the following:

- PlayIn Model Signal applied for the particular generator
- FIndex: Index of the exciter field voltage signal

Example

Using the two signals defined in the earlier section, this section provides an example of utilizing the playin signals for the PlayinGov model in a transient simulation. In Model Explorer, the 'Trasient Stability Data – Governor' tab is where these signals are defined. The models behave similar to other transient models, and transient simulation can be carried out as per the regular procedure used for other transient simulations. Figure A13 shows the use of two mechanical power playin signals that perturb the intial operating point of an example system.



	Number of Bus	ID	Name_Nominal kV of Bus	Name of Bus	Type	MVA Base	Device Status	Governor Response Limits	Sub-Intervals	PlayIn	layIn Signa ndex
1	1	1	Bus1_ 16.50	Bus1	PLAYINGOV	100	Active	Normal		layIn 'Mech Sample	0
2	2	1	Bus 2_ 18.00	Bus 2	PLAYINGOV	100	Active	Normal		layIn 'Mech Sample	1

Figure A12: PlayinGov Example

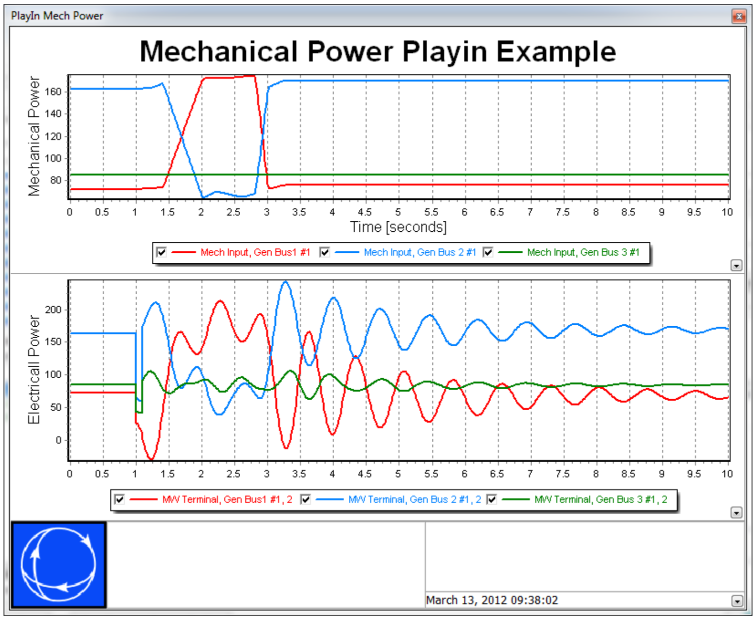
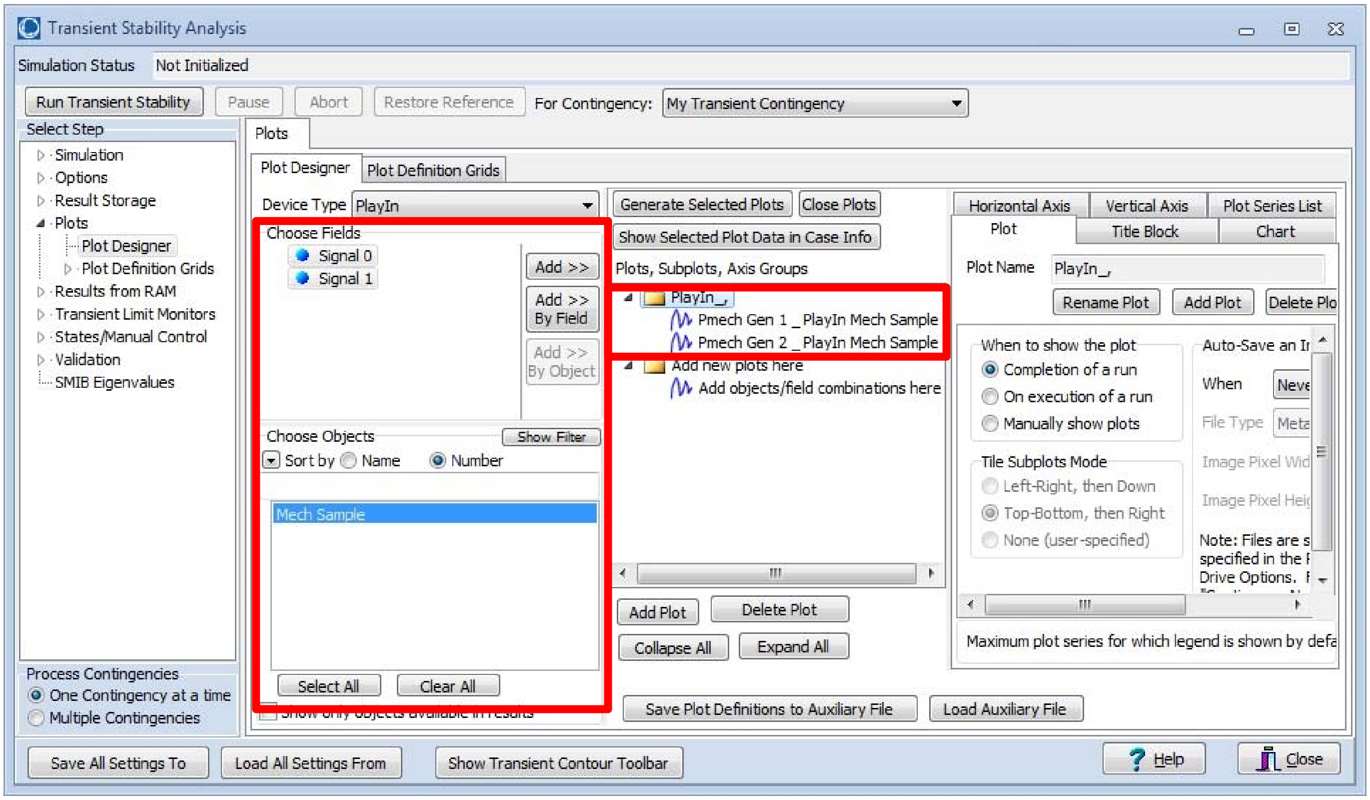


Figure A13: Example Transient Simulation with Playin Mechanical Power

In addition to using playin signals in transient simulation, they can also be plotted just like any other signal obtained in PowerWorld Simulator. The screenshot below shows the user interface in the Transient Stability Analysis window, and the Playin Device type is where the playin signals are found for plotting purposes.



Simulation Status: Not Initialized

For Contingency: My Transient Contingency

Device Type: PlayIn

Sort by ○ Name ● Number

Mech Sample

PlayIn_
Pmech Gen 1 _PlayIn Mech Sample
Pmech Gen 2 _PlayIn Mech Sample

Plot Name: PlayIn_

When to show the plot
● Completion of a run
○ On execution of a run
○ Manually show plots

Tile Subplots Mode
○ Left-Right, then Down
● Top-Bottom, then Right
○ None (user-specified)

Note: Files are s specified in the f Drive Options.

Maximum plot series for which legend is shown by defa

● One Contingency at a time
○ Multiple Contingencies

Figure A14: Playin for Plotting

EPRI PPPD

EPRI has developed a number of tools for performing model verification of power system components using on-line disturbance monitoring by either PMUs or DFRs. These tools can be used to verify the models of shunt FACTS devices, wind and PV power plants, and synchronous generator based conventional power plants [A5-A11]. A brief description of the Power Plant Parameter Derivation (PPPD) tool developed by EPRI is provided[38].

Presently, PPPD is used by 23 entities internationally, and the tool has been used to validate more than one-hundred generators and exciters and more than fifteen turbine-governor models. PPPD can be used for power plant dynamic model verification (generator, exciter, PSS and turbine-governor) with measured data coming from either off-line staged-tests, on-line step tests of the voltage regulator and/or turbine-governor speed reference (for digital controls) or using disturbance monitoring of on-line power plant response. In the case of disturbance monitoring, the monitoring equipment may be either a PMU or DFR, and can be set-up to monitor the generator at either the terminals of the generator (low-side of the generator step-up transformer) or on the high-voltage side of the generator step-up transformer (GSU). For generator owner/operators, monitoring on the generator terminals, typically with a DFR, is most common and has many more benefits above and beyond model verification, such as troubleshooting and diagnostics. Furthermore, by being installed at the generator terminals addition variables (such as the unit's field voltage and current) may be monitored for increased fidelity and flexibility in parameter optimization during the verification process. For Planning Coordinators such as ISOs, PMUs installed at the high-side of the GSU tends to be a more common approach. Either source of data is usable with PPPD.

With reference to the subject of this report, the approach to model verification and calibration using PPPD with on-line disturbance data is as follows:

1. The engineer should first understand the power plant to be modeled and validated, and thus selected the appropriate model structures for the plant. That is, the correct model for the generator, excitation system, PSS (if any) and turbine-governor.
2. Then the user can import or enter the base-line parameters for each of the models. By base-line parameters we mean the data that was originally supplied by the equipment vendor (e.g. generator data sheets) or provided in the testing reports for the model validation testing of the power plant upon commissioning. In general, it is recommended that model verification testing be done when first commissioning a new power plant or retrofitting new equipment (e.g. new excitation systems, etc.) for the purpose of collecting good base-line data. Also, commissioning of new power plant equipment is always a good opportunity for installing monitoring equipment such as DFRs or PMUs.
3. Then disturbance data is extracted from the PMU or DFR records, and ideally for multiple events. The events of interest are typically significant system wide frequency events (e.g. loss of a major or largest unit on an interconnection that results in a significant frequency dip, and at least of the amounts shown in Table 3 in the main report) or nearby transmission faults. Verification over several events always yields greater confidence in the models [A9].
4. Then the collected disturbance data is read into the PPPD tool. In the latest version to be released in 2015, a feature in the tool will, with appropriate base values entered by the user, per unitize the raw data.
5. At the last stage the user has the option to set upper and lower bounds on an appropriate selection of parameters, in order to have the tool automatically apply an optimization algorithm to achieve a best fit between the simulated and measured respond of the generator and its applicable controls.

---

[38] The Renewable Energy Model Validation (REMV) tool is a similar tool, but used for model validation of wind and PV power plants.

In general, experience has shown that the electrical parameters of the generator provided by the original equipment manufacturer (OEM) are typically quite reliable. Some exceptions exist in rare cases, particular where the OEM data is decades old or missing certain quantities. So typically, the process is to first accept the generator parameters, then validate the excitation system model and apply optimization, with engineering judgment, as needed to validate and calibrate the model of the excitation system (the PSS is included in this process, if it exists, see e.g. [A8]) and then finally to validate/calibrate the turbine-governor model. The entire process can be summarized by Figure A15.

Finally, as reported in [A8], [A9] and [A10], PPPD uses the play-back approach for model verification. That is, certain measured quantities are played into the model to simulate the response of the generating unit. Then the output of the simulation is compared to the remaining measured quantities to determine verification. For this reason there is no need on the part of the user to know the exact nature of the disturbance or to have a detailed model of the power system – the focus is entirely on the model of the power plant.

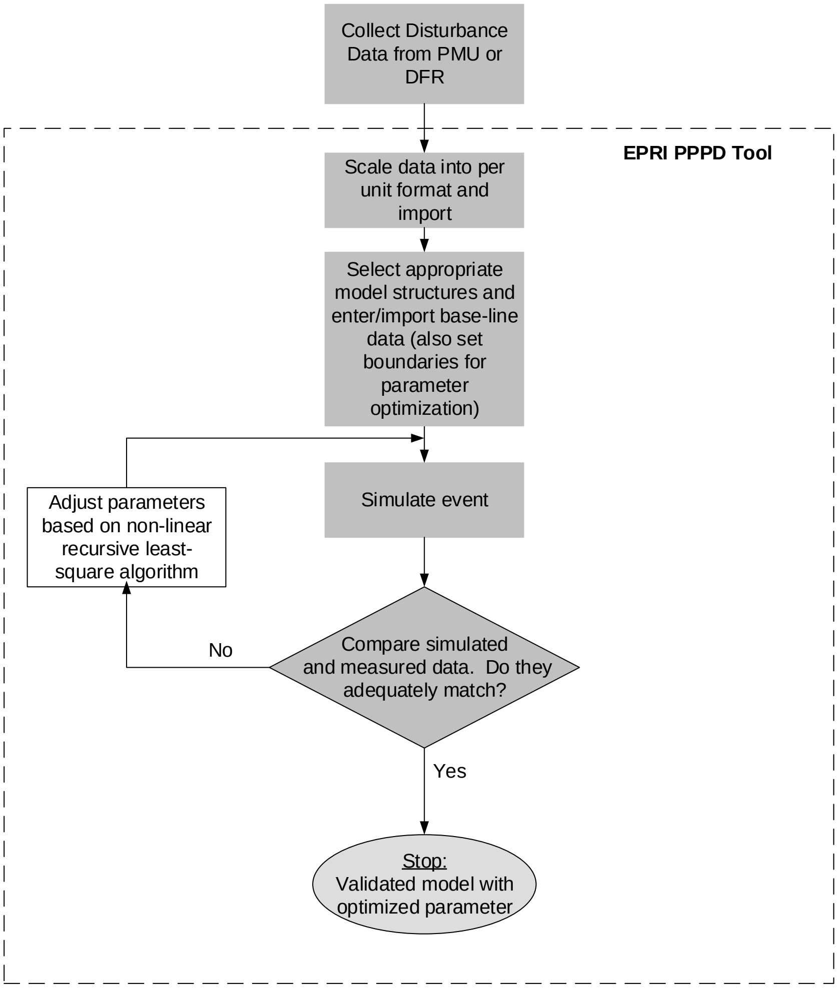


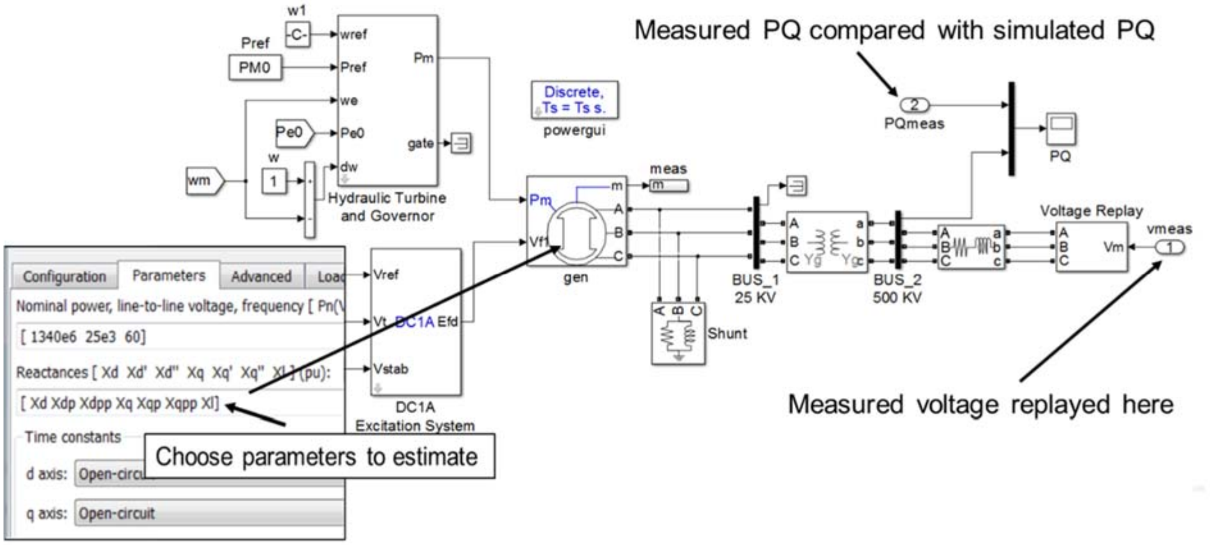
Figure A15: EPRI PPPD Model Verification Process

MATLAB® and Simulink®

The MATLAB and Simulink product family from MathWorks provides tools that support automation and scaling of power system model verification tasks. Visit this link to access on-line tutorials. Workflows for model verification that use both offline generator testing and online performance monitoring are established through the following capabilities,

1. Access data from data historians, field instruments, SQL databases, text files, binary files and other APIs.
2. Model the system using standard representations of generation equipment and/or build your own from base components.
3. Replay offline or online data from digital fault recorders and/or PMUs through the simulation model.
4. Estimate model parameters of generation and control equipment using formal optimization techniques.
5. Scale the model verification task for multiple generation assets through automated scripting.
6. Continuously verify models by including new events and historical events in the model verification task.
7. Share the outcome of the model verification task through automated reporting and transfer of parameter values to other simulation platforms.

The figures below highlight key aspects of power plant model verification using PMUs for an example grid event.



Nominal power, line-to-line voltage, frequency [Pn(V

[1340e6 25e3 60]

Reactances [Xd Xd' Xd'' Xq Xq' Xq'' Xl] (pu):

[Xd Xdp Xdpp Xq Xqp Xqpp Xl]

Time constants

d axis: Open-circu

q axis: Open-circuit

Measured PQ compared with simulated PQ

Choose parameters to estimate

Measured voltage replayed here

Figure A16. Example Model in Simulink Connected to Measured Data

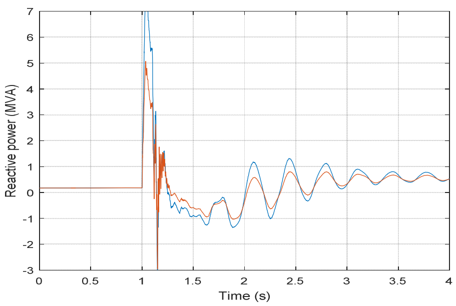


Figure A17a. Reactive Power at POC before Estimation

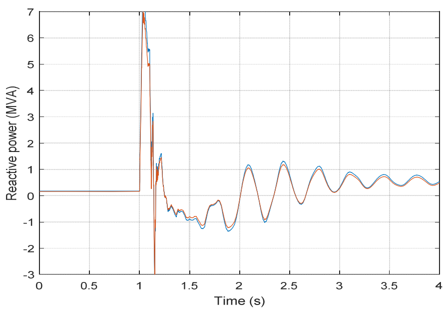


Figure A17b. Reactive Power at POC after Estimation

PNNL-BPA PPMV Tool

The Power Plant Model Validation (PPMV) Tool has been developed by PNNL in cooperation with Bonneville Power Administration (BPA). The PPMV Tool is a standalone Windows application which automates the disturbance-based power plant dynamic model verification process. To perform model verification, the PPMV Tool interacts with an external Play-In module. The current version of PPMV tool supports GE PSLF Play-In functions. Interaction between the PPMV application and GE PSLF is performed through EPCL language scripts. Implementation of Siemens/PTI PSS®E support by the PPMV tool is under development and will be added in the future release. The tool also manages the database of historical events and power plants. The PPMV application has been released under an open-source license[39], and the main features include:

- The tool uses GE PSLF Play-In function for generator model verification.
- Support of Siemens/PTI PSS®E Play-In function is under development and will be added in a future release.
- The tool maintains the database of model verification studies (projects).
- The tool maintains the database of the historic events.
- The tool maintains the database of the power plants.
- The tool has a user friendly graphical user interface (GUI) and advanced visualization capabilities.
- The tool automatically generates reports.
- The tool supports connectivity to the OSIsoft PI database.

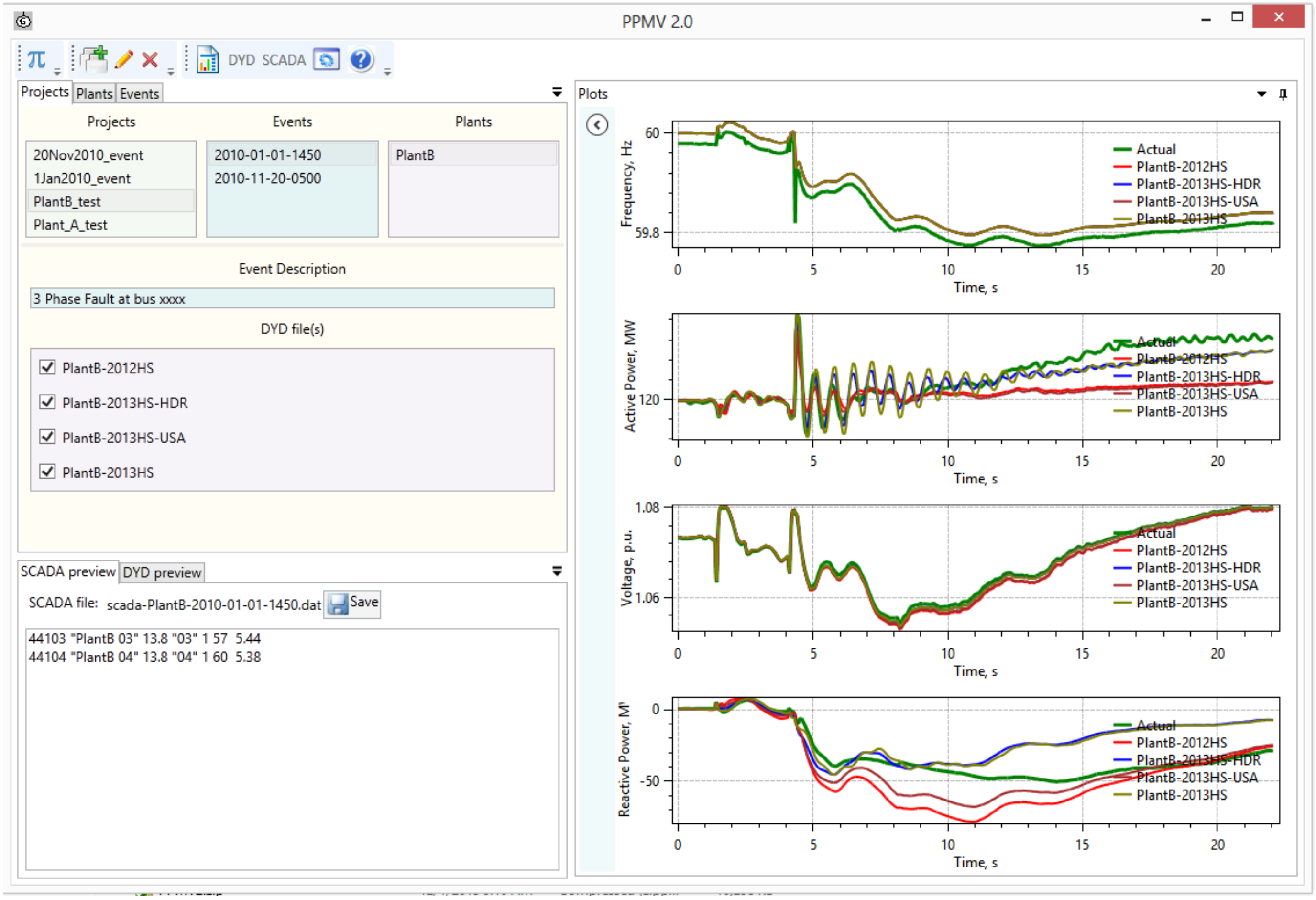
PPMV Tool requires a Windows XP operating system, or higher, as well as Microsoft .Net 4.0 Framework, PI SDK (required for OSIsoft PI database connectivity only), and GE PSLF version 18 or higher. The PPMV tool uses a comma-separated value (.csv) format file as an input. To automatically recognize the type of measurement, the input file format should follow WECC JSIS CSV requirements [A11]. The one row and four rows header .csv files are supported by the PPMV.

Figure A18 shows an interactive display of the PPMV Tool. The GUI consists of a toolbar and several panels:

- Model verification studies (projects) panel – to show the list of verification studies and their description.
- Event plots panel – to graphically display the power plant response. The user can compare measurement based response vs. model based response. Model based response based on different power plant parameters (.dyd files) can be displayed using single a plot.
- DYD and SCADA preview/edit panel – to view, modify or create .dyd and SCADA files.

---

[39] PPMV Tool can be downloaded at: https://svn.pnl.gov/PPMV.



Projects: 20Nov2010_event, 1Jan2010_event, PlantB_test, Plant_A_test

Events: 2010-01-01-1450, 2010-11-20-0500

Plants: PlantB

Event Description: 3 Phase Fault at bus xxxx

DYD file(s):

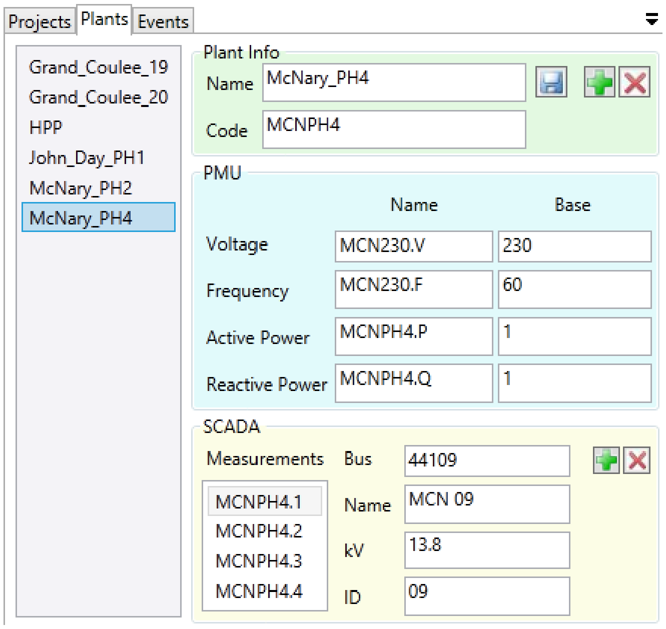
- ☑ PlantB-2012HS
- ☑ PlantB-2013HS-HDR
- ☑ PlantB-2013HS-USA
- ☑ PlantB-2013HS

SCADA file: scada-PlantB-2010-01-01-1450.dat

```
44103 "PlantB 03" 13.8 "03" 1 57  5.44
44104 "PlantB 04" 13.8 "04" 1 60  5.38
```

Figure A18. PPMV Tool Graphical User Interface

A power plant database is used to map a power plant with the corresponding SCADA and PMU measurement signals. Power plants’ information is stored in an .xml file. In the PPMV Tool power plants panel (Figure A19), the user can view/modify information on power plants or add a new power plant to the database.



Grand_Coulee_19
Grand_Coulee_20
HPP
John_Day_PH1
McNary_PH2
McNary_PH4

Plant Info
Name: McNary_PH4
Code: MCNPH4

PMU

	Name	Base
Voltage	MCN230.V	230
Frequency	MCN230.F	60
Active Power	MCNPH4.P	1
Reactive Power	MCNPH4.Q	1

SCADA
Measurements
MCNPH4.1
MCNPH4.2
MCNPH4.3
MCNPH4.4

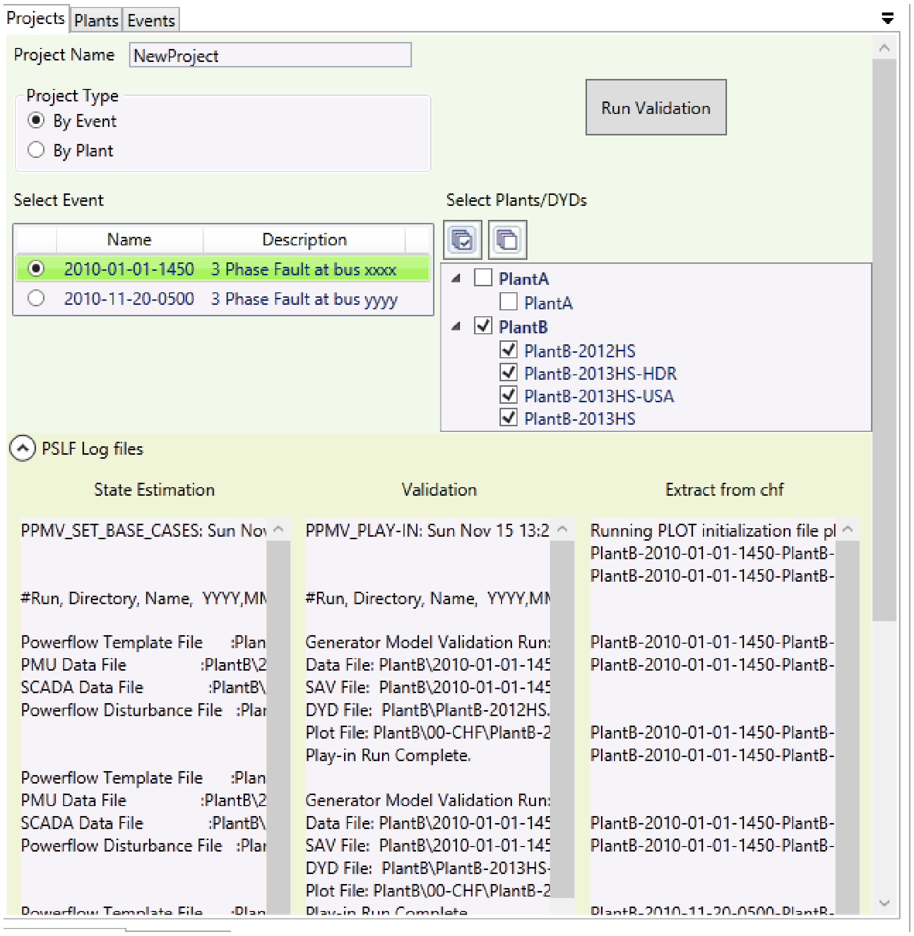
Bus: 44109
Name: MCN 09
kV: 13.8
ID: 09

Figure A19. Power Plant Database Screen

The *New Model Validation Project* screen is shown in Figure A20. The user specifies the project type (plant study or event study) and then selects the corresponding power plants/DYDs and events to be used in the new model validation project. To run the simulation, press the *Run Validation* button. The PPMV tool will interact with GE PSLF through EPCL language scripts to perform the model verification for selected power plant using disturbance records for selected events. The verification process consists from three major stages:

1. Mini state estimation to match the initial power flow conditions;
2. Model verification simulation using the Play-In function; and
3. Information extraction from the channel files.

After completion of the model validation process, the PSLF simulation error logs will be also displayed and new project will be added to the project database.



Project Name: NewProject

Project Type
● By Event
○ By Plant

Select Event

	Name	Description
●	2010-01-01-1450	3 Phase Fault at bus xxxx
○	2010-11-20-0500	3 Phase Fault at bus yyyy

Select Plants/DYDs

- ☐ PlantA
  - ☐ PlantA
- ☑ PlantB
  - ☑ PlantB-2012HS
  - ☑ PlantB-2013HS-HDR
  - ☑ PlantB-2013HS-USA
  - ☑ PlantB-2013HS

State Estimation

```
PPMV_SET_BASE_CASES: Sun Nov

#Run, Directory, Name,  YYYY,MM

Powerflow Template File     :Plan
PMU Data File              :PlantB\2
SCADA Data File            :PlantB\
Powerflow Disturbance File  :Plan


Powerflow Template File     :Plan
PMU Data File              :PlantB\2
SCADA Data File            :PlantB\
Powerflow Disturbance File  :Plan


Powerflow Template File     :Plan
```

Validation

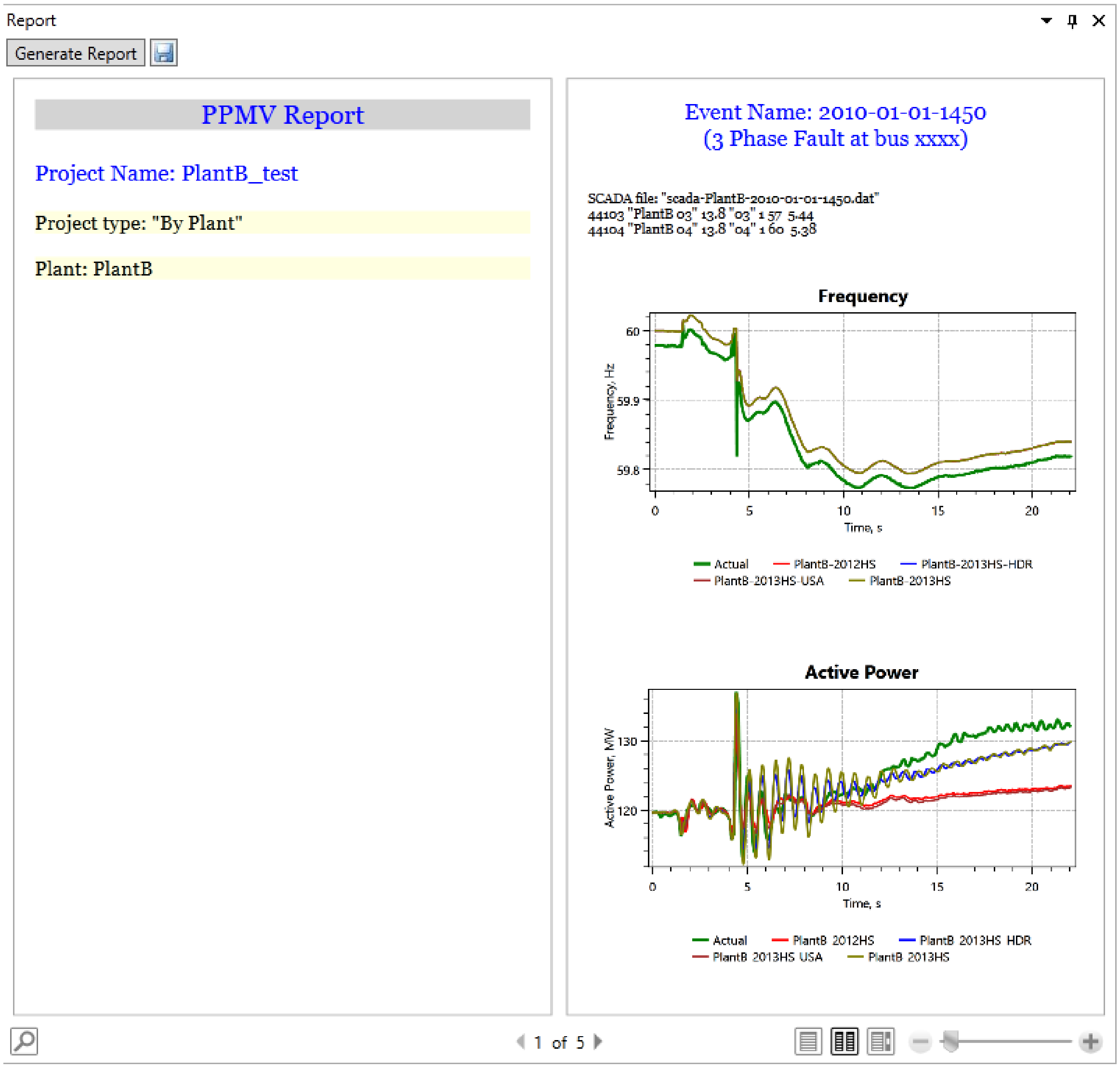
```
PPMV_PLAY-IN: Sun Nov 15 13:2

#Run, Directory, Name,  YYYY,MM

Generator Model Validation Run:
Data File: PlantB\2010-01-01-145
SAV File:  PlantB\2010-01-01-145
DYD File:  PlantB\PlantB-2012HS.
Plot File: PlantB\00-CHF\PlantB-2
Play-in Run Complete.

Generator Model Validation Run:
Data File: PlantB\2010-01-01-145
SAV File:  PlantB\2010-01-01-145
DYD File:  PlantB\PlantB-2013HS-
Plot File: PlantB\00-CHF\PlantB-2
Play-in Run Complete
```

Extract from chf

```
Running PLOT initialization file pl
PlantB-2010-01-01-1450-PlantB-
PlantB-2010-01-01-1450-PlantB-


PlantB-2010-01-01-1450-PlantB-
PlantB-2010-01-01-1450-PlantB-


PlantB-2010-01-01-1450-PlantB-
PlantB-2010-01-01-1450-PlantB-


PlantB-2010-01-01-1450-PlantB-
PlantB-2010-01-01-1450-PlantB-


PlantB-2010-11-20-0500-PlantB-
```

Figure A20. New Model Validation Project Screen

The *Report* screen is shown in Figure A21. To generate the model validation report, the required project needs to be selected and then the *Generate Report* button should be pressed. The automatically generated report includes information on all plants and events used in the project and also all corresponding plots. The report can be copied to the clipboard or saved to a file in MS Word format.



PPMV Report

Project Name: PlantB_test

Project type: "By Plant"

Plant: PlantB

Event Name: 2010-01-01-1450
(3 Phase Fault at bus xxxx)

SCADA file: "scada-PlantB-2010-01-01-1450.dat"
44103 "PlantB 03" 13.8 "03" 1 57 5.44
44104 "PlantB 04" 13.8 "04" 1 60 5.38

Figure A21. Model Validation Report Screen

Electric Power Group Generator Parameter Validation (GPV)

GPV uses recorded disturbance data at the terminals of a generator or the Point of Interconnection (POI) of a power plant to verify generator model parameters. The types of models that can be verified are generators, governors, exciters and stabilizers. The GPV tool uses PSS®E and is based on the research conducted by Dr. Wei-Jen Lee et al. from the University of Texas at Arlington.

The steps involved in the verification process are shown in Figure A22.

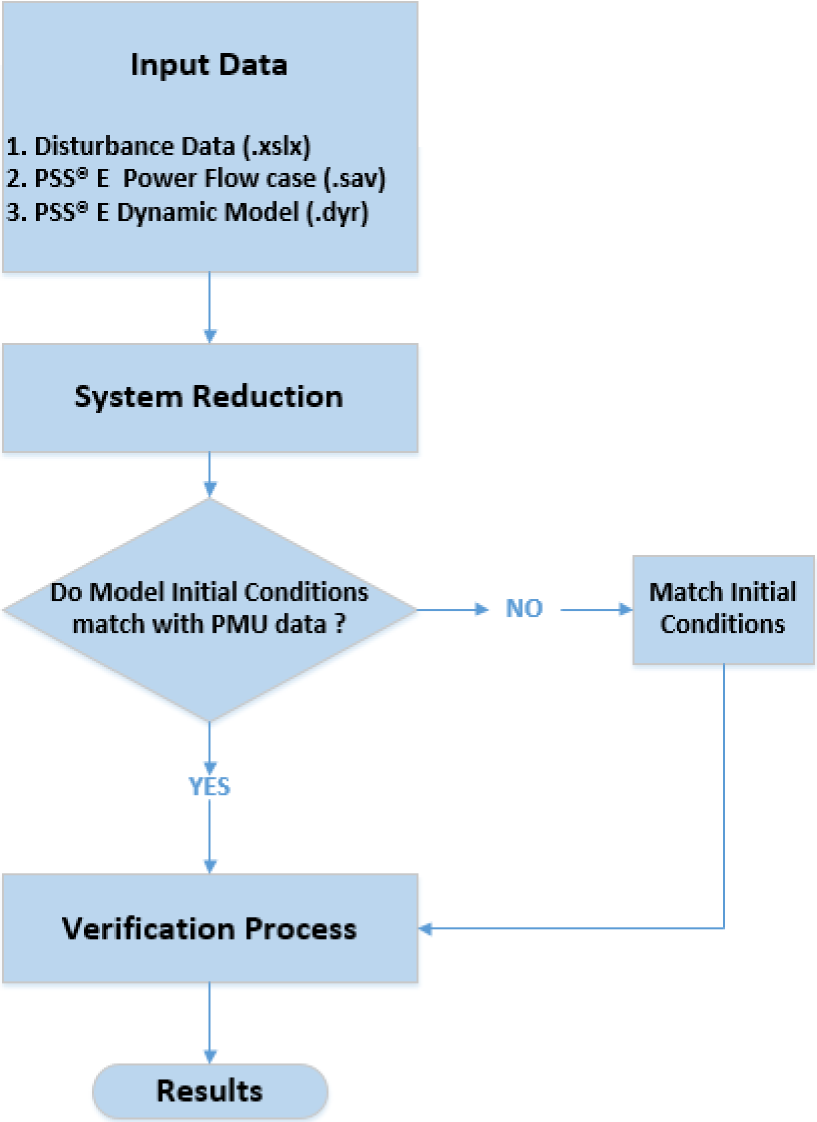


Figure A22. GPV Process Flowchart

Three input files are required to run GPV:

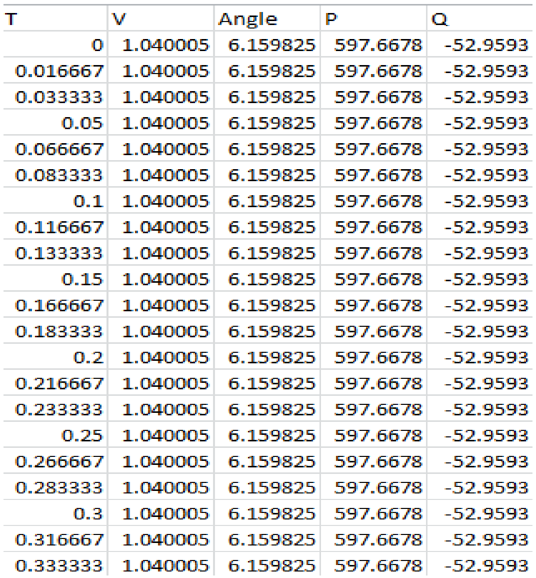
1. High resolution PMU data for selected grid disturbances (.xlsx);
2. Steady-state network model in PSS®E saved case format (.sav); and
3. Dynamic model of power plant in PSS®E dynamics data format (.dyr)

The GPV methodology uses a system reduction approach. The entire power system is reduced to a smaller system at the terminals of the generator and dynamic simulations are performed using both, the measured data as well as the simulation model. The active and reactive power output of the generator (and hence at the PMU boundary bus) in the .sav saved case file should match the operating conditions corresponding to the PMU measurements (excel file). If the mismatch in P and Q at the PMU boundary bus is greater than 2 MW/MVar, the tool does perform an initial condition match. However, it is recommended to have the initial conditions matched before running the tool. Mismatch in the initial conditions may lead to a dc offset in the plots.

Guideline to Run GPV

Prepare an Excel file with the PMU data in the required format and order (i.e., columns) as shown below (T, V, Angle, P, and Q) in Figure A23.

Column 1: Time stamps – The time tag should start from 0
Column 2: Line to Line voltage in per unit (p.u.)
Column 3: Voltage Angle in degrees
Column 4: Active Power in MW
Column 5: Reactive Power in MVar



T	V	Angle	P	Q
0	1.040005	6.159825	597.6678	-52.9593
0.016667	1.040005	6.159825	597.6678	-52.9593
0.033333	1.040005	6.159825	597.6678	-52.9593
0.05	1.040005	6.159825	597.6678	-52.9593
0.066667	1.040005	6.159825	597.6678	-52.9593
0.083333	1.040005	6.159825	597.6678	-52.9593
0.1	1.040005	6.159825	597.6678	-52.9593
0.116667	1.040005	6.159825	597.6678	-52.9593
0.133333	1.040005	6.159825	597.6678	-52.9593
0.15	1.040005	6.159825	597.6678	-52.9593
0.166667	1.040005	6.159825	597.6678	-52.9593
0.183333	1.040005	6.159825	597.6678	-52.9593
0.2	1.040005	6.159825	597.6678	-52.9593
0.216667	1.040005	6.159825	597.6678	-52.9593
0.233333	1.040005	6.159825	597.6678	-52.9593
0.25	1.040005	6.159825	597.6678	-52.9593
0.266667	1.040005	6.159825	597.6678	-52.9593
0.283333	1.040005	6.159825	597.6678	-52.9593
0.3	1.040005	6.159825	597.6678	-52.9593
0.316667	1.040005	6.159825	597.6678	-52.9593
0.333333	1.040005	6.159825	597.6678	-52.9593

Figure A23. GPV PMU Input File Format

Note: Sign Convention for Power Flow in the input file: Power flow from the Boundary (PMU bus) bus to the Target bus (In to the generator) is Negative and from Target Bus to Boundary bus (Out of the generator) is Positive as shown in the figure below. Ensure that this sign convention is used when preparing Input data file.

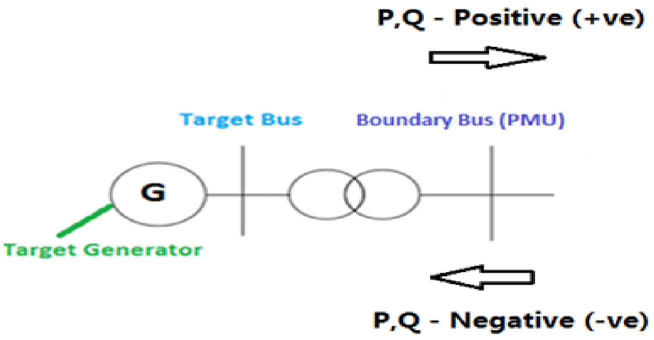
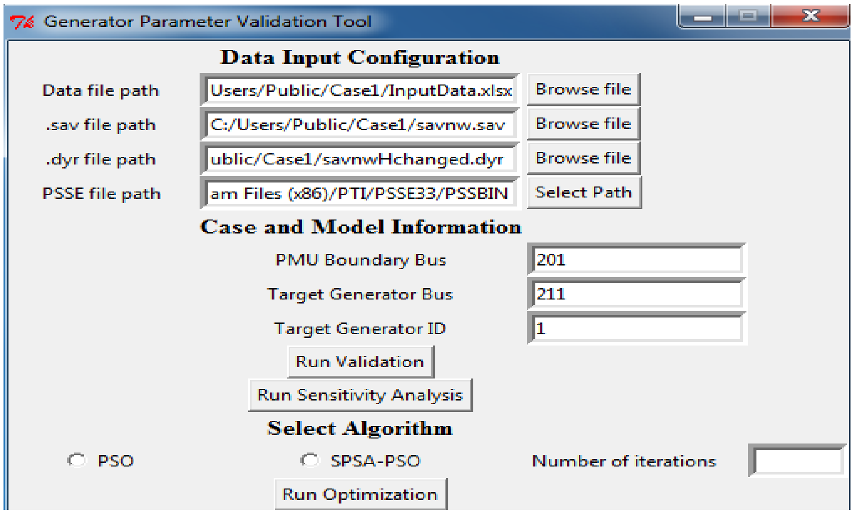


Figure A24. GPV Sign Convention

Input Data and Model Information



Data Input Configuration

Data file path: Users/Public/Case1/InputData.xlsx

.sav file path: C:/Users/Public/Case1/savnw.sav

.dyr file path: ublic/Case1/savnwHchanged.dyr

PSSE file path: am Files (x86)/PTI/PSSE33/PSSBIN

Case and Model Information

PMU Boundary Bus: 201

Target Generator Bus: 211

Target Generator ID: 1

Select Algorithm

○ PSO ○ SPSA-PSO Number of iterations:

Figure A25. GPV Tool GUI

Once, the GUI is loaded, enter the input data on the GUI shown in Figure A25 as follows:

1. Select the data file (.xslx)
2. Select the .sav case file
3. Select the .dyr file
4. Enter the path to the PSSBIN folder, Select the PSSBIN directory using the browser button
5. Enter the PMU boundary bus number, target bus number, and target generator ID (Figure A26)

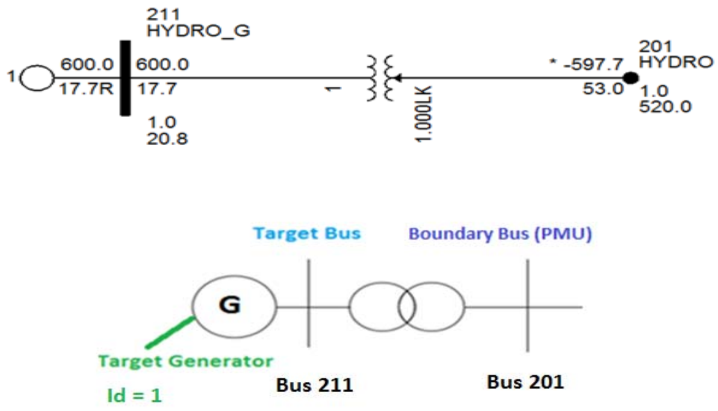


Figure A26. Powerflow Buses Used

Note: The boundary bus is the bus at which PMU measurements are obtained and the target bus is the bus at which the generator to be verified is connected.

Verification Process

1. Click on run Validation to perform the verification process and compare the simulation results with the input measured response.
2. The results show 4 plots comparing measured versus simulated quantities: Active Power (P), Reactive Power (Q), Voltage (V), and Bus Phase Angle.

Sample output plots for P and Q are shown in figures below. The dynamic simulation method injects the measured voltage and voltage angle values at the PMU boundary bus and hence the simulated voltage and voltage angle values are likely to match the input values. The verification process mainly involves the verification of the P and Q response. Example plots for are shown below in Figure A27.

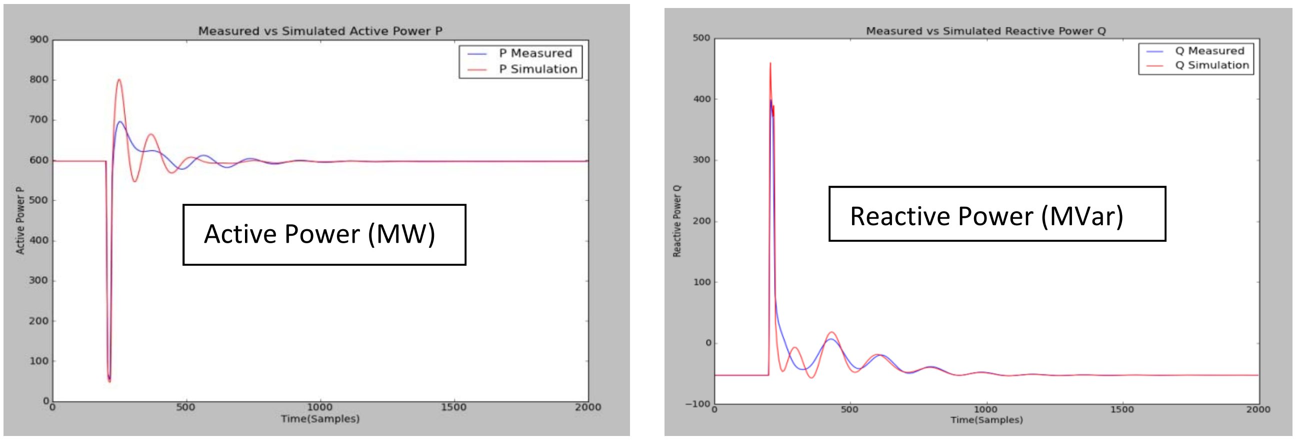


Figure A27. Active and Reactive Power Plots for Verification

Appendix B: References

North American Synchrophasor Initiative Reports and Workshops

1. North American Synchrophasor Initiative, "Model Validation Using Phasor Measurement Unit Data: NASPI Technical Report," March 2015. [Online]. Available: https://www.naspi.org/documents.
2. North American Synchrophasor Initiative, "NASPI Technical Workshop on Model Validation using Synchrophasor Data," Rosemont, IL, 2013. [Online]. Available: https://www.naspi.org/techworkshops.

Related NERC Reliability Standards

1. NERC. 2014. Standard MOD-026-1 – Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions. North American Electric Reliability Corporation: Atlanta, GA.
2. NERC. 2014. Standard MOD-027-1 – Verification of Models and Data for Turbine/Governor and Load Control or Active Power/Frequency. North American Electric Reliability Corporation: Atlanta, GA.

GE PSLF References

[A1] Grid Code testing work performed by GE Energy Consulting, http://www.geenergyconsulting.com/practice-area/global-power-projects

[A2] P. Pourbeik, "Model Validation on Wind Turbine Generators using the 2nd Generation Wind Turbine Generator Models", WECC Renewable Energy System Models Webcast, July 2015.

[A3] Eric Bakie, "Generator Model Validation Using PI Data using PSLF Play-In Function", WECC MVWG Workshop, Nov 2013.

[A4] D. Kosterev, S. Yang, P. Etingov, "PMU-based application for power plant model validation", North American SynchroPhasor Initiative Working Group Meeting, March, 2015.

EPRI PPPD References

[A5] P. Pourbeik and G. Stefopoulos, "Validation of Generic Models for Stability Analysis of two Large Static Var Systems in New York using PMU Data", Proceedings of the IEEE T&D Show and Exposition, April 2014.

[A6] Renewable Energy Model Validation (REMV) Version 2.0, EPRI, 2014.

[A7] P. Pourbeik, R. Rhinier, S-M. Hsu, B. Agrawal and R. Bisbee, "Semi-Automated Model Validation of Power Plant Equipment Using On-Line Measurements", IEEE Transactions on Energy Conversion, June 2013, pages 308 - 316.

[A8] P. Pourbeik, C. Pink and R. Bisbee, "Power Plant Model Validation for Achieving Reliability Standard Requirements Based on Recorded On-Line Disturbance Data", Proceedings of the IEEE PSCE, March 2011.

[A9] P. Pourbeik, "Automated Parameter Derivation for Power Plant Models From System Disturbance Data", Proceedings of the IEEE PES General Meeting, Calgary, Canada, July 2009.

[A10] P. Pourbeik, "Automated Parameter Derivation for Power Plant Models Based on Staged Tests", Proceedings of the IEEE PES Power Systems Conference & Exposition, Seattle, WA, March 2009.

PPMV Tool Reference

[A11] Western Electricity Coordinating Council. 2013. "WECC Guideline for Data Format Used in Engineering Analysis Applications of Disturbance and Simulated Data.," Salt Lake City UT, August 2013.