Pacific Northwest NATIONAL LABORATORY

PNNL-30492

Open Source Suite for Advanced Synchrophasor Analysis

Final Project Report

September 2020

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Abstract

The report presents the results of the development of the open-source suite of applications for synchrophasor analysis. The suite includes several software tools for oscillation analysis, power plant model validation, and frequency response analysis using synchrophasor measurements. All tools are based on the common framework and data sources. The developed tools have been used by different electrical utilities for synchrophasor analysis. The report includes several use cases based on the actual system PMU data.

Summary

The goal of this research is to develop and advance applications of phasor measurement units (PMUs) and synchrophasor data for power system planning, modeling, and analysis. All applications are based on the common open platform concept, have a common data format structure, and released under an open-source license. This project addresses oscillation detection, frequency response, model validation and calibration, equipment misoperations, and other important power-grid-related issues

Free and open-source applications developed in this project will help the power industry adopt PMU measurements applications for a wider range of tasks (e.g., model validation, model parameter calibration, oscillation analysis, and baselining). Better and more accurate models of power system elements (e.g., synchronous generators, wind plants, and electrical loads, as advanced PMU-based analytical applications) are key factors in enhancing electrical grid reliability and efficiency. The open-source nature of this platform is especially suited for enabling adoption of such PMU-based capabilities at smaller utilities that may not have the resources to fully utilize their PMU investment.

This work expands the feasibility and usefulness of synchrophasor-based applications by leveraging existing work to increase functionality and improve overall technology readiness levels to allow utilities to benefit from their investment in, and deployment of, various synchrophasor technologies. This work also creates a unified application and capabilities suite to consolidate tools and algorithms leveraging synchrophasor data. Because the framework is open source, any developer can contribute to the application set either by modifying existing software or by creating new applications. In addition, third-party organizations and vendors can build commercial products based on the open-source code developed under the proposed project.

Open-source suite of power system analytical tools and software modules is based on the common open platform and data format structures and includes the following applications (Figure 1):

Archive Walker (AW)

The AW is a powerful tool that provides data management, signal processing, and event detection functionalities. It has the capability to read in PMU data from multiple sources (PI database, Open Historian, PDAT, CSV), apply data quality checks, manipulate streams to create custom signals, and apply a variety of signal processing techniques. After the data is prepared, a variety of detectors can be applied to identify out-of-range events (e.g., voltage sag/rise, frequency excursions), search for ringdown-producing events (e.g., line trip or switching operations), detect forced oscillations, and examine characteristics of wind plant ramping and response to disturbances. Events are tracked over time and across the grid to support in-depth analysis by system engineers and reports can be generated automatically.

Oscillation Baselining and Analysis Tool (OBAT)

The oscillation analysis block will be based on algorithms built in the OBAT (e.g., Prony and Matrix Pencil). The OBAT maintains a database of oscillation events, is able to automatically generate oscillation analysis reports, and also has advanced visualization capabilities. One of the most important features of the OBAT is the capability to perform oscillation baselining. Several statistical methods to correlate the output of oscillation analysis algorithms (frequency,

damping ratio) with system condition parameters (e.g., power flows, angle pair difference) have been developed. Statistical analysis can help to extract signatures for different oscillatory conditions. Thus, the OBAT can help to identify system conditions when the power grid can be potentially “at risk” in terms of electromechanical oscillations.

Load Model Data Tool (LMDT)

The LMDT application helps to generate composite load model parameters considering climate zone and seasonal information, operating hour and feeder type. The LMDT reads in the necessary long identifier (LID) information, and supplements that with the base case power flow conditions and supplemental load shape data to generate the composite load dynamics records in GE PSLF and Siemens PTI PSS®E format. LMDT supports a variety of load and distributed energy resources (DER) models.

Power Plant Model Validation Tool (PPMV)

The PPMV tool helps to automate the power plant model validation process based on the disturbance recordings. Validation of power system models for power flow and dynamic studies is very important for ensuring that these models are accurate and up to date. The North American Electric Reliability Corporation (NERC) BAL Modeling, Data, and Analysis (MOD-026-1 & MOD-027-1) standards enforce requirements for power plant modeling, data, and system analysis. The main goal of these standards is to ensure validation and monitoring of model performance. The MOD standards allow generator owners to perform model validation using disturbance event records. The PPMV tool provides a mechanism for doing that evaluation.

Frequency Response Analysis Tool (FRAT)

The FRAT manages the database of under-frequency events and calculates the Frequency Response Measure (FRM) at an interconnection- and BA-level, as defined by the NERC BAL-003-1 standard. In addition to NERC FRM, the application calculates the nadir-based frequency response (FR). The primary users of the FRAT are balancing authorities and reliability coordinators. The individual unit/power plant FR analysis can also be performed. This feature enables comparison of measurement-based vs. model-based frequency response.

Archive Sprinter (AS)

Archive Sprinter was designed to rapidly generate information summarizing large archives of synchrophasor measurements. The tool is intended to generate data for further analysis, rather than detecting periods of interest during processing. The data summaries generated by Archive Sprinter are composed of a user-selected set of signatures, such as the variance and maximum value, that highlight periods of interest in the data. The signatures require little disk space and can be calculated rapidly. Archive Sprinter’s design also allows for parallel processing to make analysis of long record lengths practical.

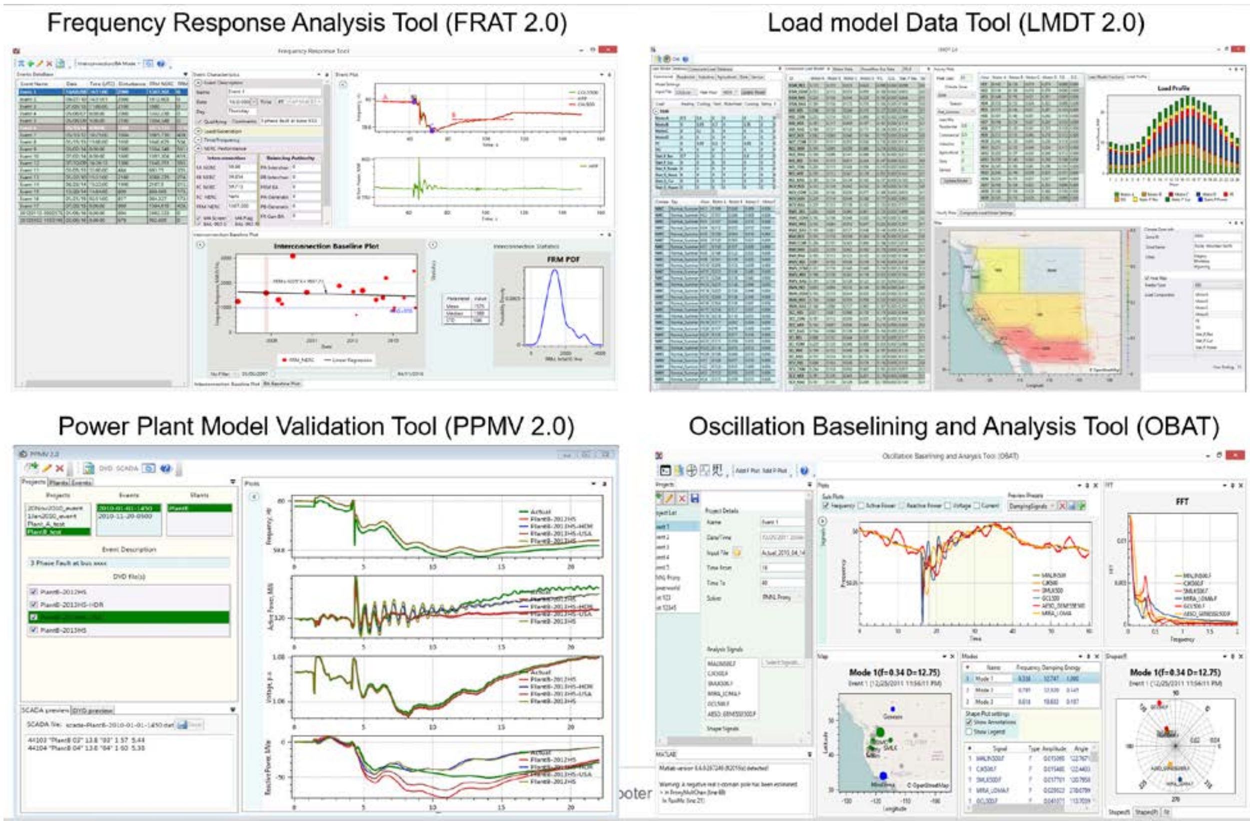

Figure 1. Suite of open source tools for PMU analysis

The software tools are available for downloading on-line at:

- FRAT: https://svn.pnl.gov/FRTool
- PPMV: https://svn.pnl.gov/PPMV
- LMDT: https://svn.pnl.gov/LoadTool
- OBAT: https://svn.pnl.gov/OBAT
- AW: https://github.com/pnnl/archive_walker
- AS: https://github.com/pnnl/archive-sprinter

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Acronyms and Abbreviations

AW	Archive Walker
AS	Archive Sprinter
BPA	Bonneville Power Administration
CSV	Comma Separated Value
DEF	Dissipating Energy Flow
DOE	(U.S.) Department of Energy
EIOC	Electricity Infrastructure Operations Center
EPCL	Engineering Process Control Language
GUI	Graphical User Interface
JSIS	Joint Synchronized Information Subcommittee
FRAT	Frequency Response Analysis Tool
LMDT	Load Modeling Data Tool
MOD	Modeling, Data, and Analysis
ML	Machine Learning
NERC	North American Electric Reliability Corporation
OBAT	Oscillation Baselining Analysis Tool
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Units
PPMV	Power Plant Model Validation
PNNL	Pacific Northwest National Laboratory
RMS	Root mean squared
ROCOF	Rate of change of frequency
SCADA	Supervisory Control and Data Acquisition
WECC	Western Electricity Coordinating Council

Contents

Figures

Tables

1.0 Introduction

Thousands of phasor measurement units (PMUs) have been deployed around the globe and across the U.S. power grid during last decade (Dagle 2011, Madani et al. 2015, Pentayya et al. 2013, Lu et al. 2015). PMUs provide high resolution, accurate, and time-synchronized information about power system state and dynamics. Synchrophasor measurements are used by different power system tools and applications, and PMU information significantly increases the reliability, stability, resiliency, and situational awareness of the electrical grid's operation (Zhang et al. 2011, Zhang et al. 2017, Overholt et al. 2014). All major vendors offer commercial, industry-grade PMU-based solutions for real-time stability assessment, dynamic monitoring, event and oscillation detection, linear state estimation, and many other tasks (Giri et al. 2012, Agarwal et al. 2011, Schweitzer et al. 2010, Vaiman et al. 2010). There are also several open-source projects that aim to facilitate synchrophasor technology deployment (Laverty et al. 2012, Vanfretti et al. 2013, Etingov, Kosterev, and Dai 2014, Carroll 2012). However, there is still a need for high-quality PMU-based power system analytical tools that can be applied to a variety of power system related issues.

This report presents the results of the development of software tools for power system planning, modeling, and analysis using synchrophasor measurements. All software applications are based on a common, open-platform concept, have a common data format structure, and are released under an open-source license. Free and open-source applications developed in this study help the power industry adopt PMU measurements applications for a wider range of tasks (e.g., model validation, model parameter calibration, oscillation analysis, and baselining). Better and more accurate models of power system elements (e.g., synchronous generators, wind plants, and electrical loads, as advanced PMU-based analytical applications) are key factors in enhancing electrical grid reliability and efficiency.

The open-source nature of this platform is especially suited for enabling adoption of such PMU-based capabilities at smaller utilities that may not have the resources to fully utilize their PMU investment.

The framework is built under the Microsoft .NET environment and developed using VB.NET and C# languages. It is based on a common architecture and common data sources, and also uses several popular open-source components, including:

- OxyPlot for visualization (https://github.com/oxyplot)
- Extended WPF toolkit for advanced graphical user interface (GUI) (https://github.com/xceedsoftware/wpftoolkit)
- Math.NET for advanced math operations (https://numerics.mathdotnet.com/)

The suite of tools include (Figure 1-1): Archive Walker (AW)(Follum et al. 2018), Oscillation Baselining and Analysis Tool (OBAT)(Hou, Follum, et al. 2018), Frequency Response Analysis Tool (FRAT) (Etingov, Kosterev, and Dai 2014), Power Plant Model Validation Tool (PPMV)(Etingov et al. 2018a), and Load Modeling Data Tool (LMDT) (Chassin, Zhang, and Etingov 2015).

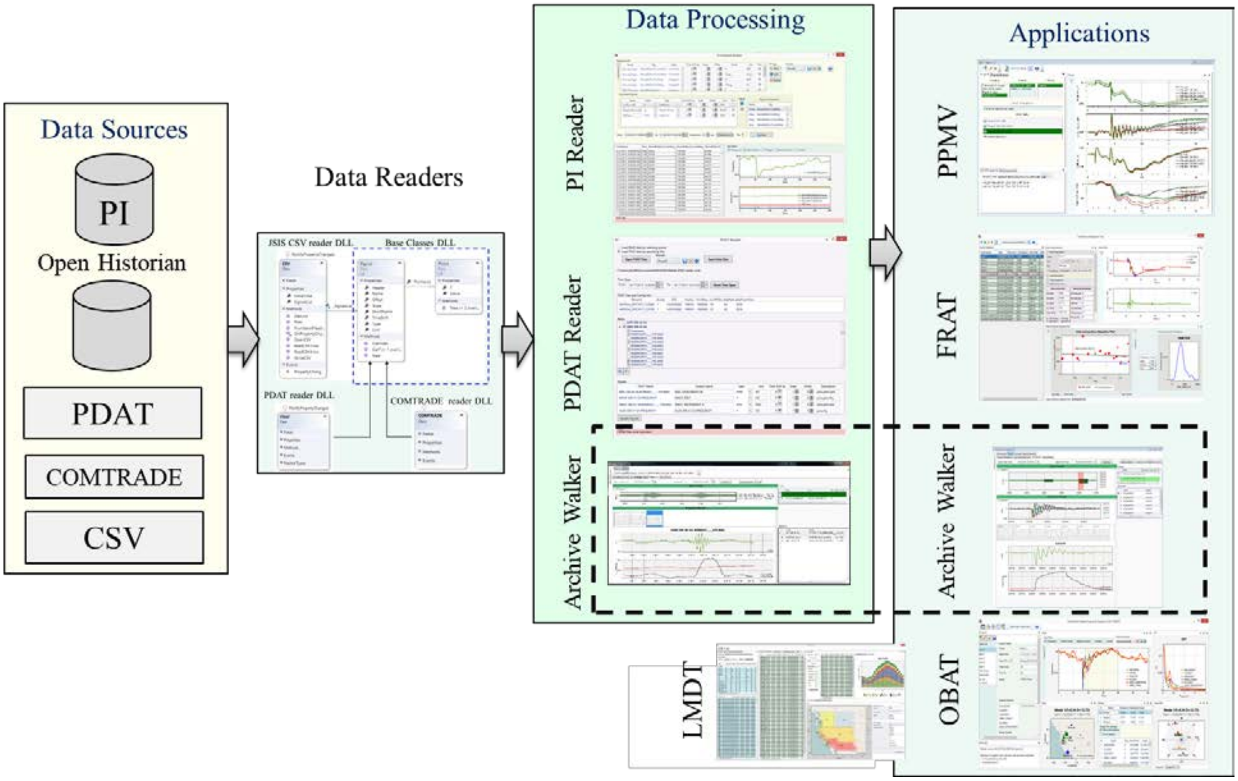


Figure 1-1. Suite of open source tools

2.0 Archive Walker

As PMU networks are extended, archives of synchrophasor measurements stored by utilities continue to grow, often spanning multiple years. Data archives can provide great value in supporting applications such as frequency response analysis, power plant model validation, and stability baselining. The goal of Archive Walker is to identify periods of interest in large archives of PMU data for further analysis with other tools, including those presented in this report. Documentation and downloads of the tool are available at (Follum et al. 2019).

Archive Walker is the most expansive application in the open-source suite of tools. It imports data from a variety of sources, applies data quality checks, enables signal customization and processing, implements several event detectors, and exports created signals and detected events. The tool's design is described in Section 2.1, followed by a discussion of capabilities in Sections 2.2-2.6.

2.1 Design Concepts

Archive Walker was conceived as a research tool with two key characteristics: 1) flexibility to support a wide variety of analyses, and 2) an architecture conducive to rapid prototyping of new methods. The tool was therefore designed in a modular fashion, with separate sections for ingesting data, applying data quality checks, customizing signals, performing signal processing, and detecting events. Rather than passing raw data into a black box analysis engine, users build analyses using the functions available in each module. This provides great flexibility in the analyses that can be performed with Archive Walker. The modular design supports rapid prototyping by allowing new capabilities to be added to one module without requiring significant changes to others. Owing to these design principles, Archive Walker has been modified and deployed to support several research efforts.

Archive Walker is intended for use with large archives of PMU data, making result storage an important consideration. Results must be stored and displayed in a way that is conducive to reviewing long periods, but detailed detector operation provides important insight. Archive Walker addresses both needs by storing results in the hierarchy depicted in Figure 2-1. At the top level, a set of XML files store high-level information about individual events, such as start time, extreme value, and number of channels that the event was detected in. In the tool's user interface, this information is provided in a table, as depicted in highlight A of Figure 2-2. A more detailed view of this table is provided in Figure 2-3. The high-level results require very little disk space, but they contain a very limited amount of information. At the next level of the hierarchy, extrema (maximum and minimum values) of analyzed signals are stored at regular intervals. These intervals are much longer than PMU reporting rates to keep required disk space to a minimum and to allow fast loading into the graphical user interface (GUI). Sudden deviations and long trends in signals can be identified and compared with the high-level event information stored in XMLs. In Figure 2-2, this level of information is plotted in highlight B. At the final level of the hierarchy, information needed to perfectly recreate an analysis is stored at regular intervals. Using this information, detector performance and analyzed signals can be reviewed for specific intervals of time, as in highlight C of Figure 2-2.

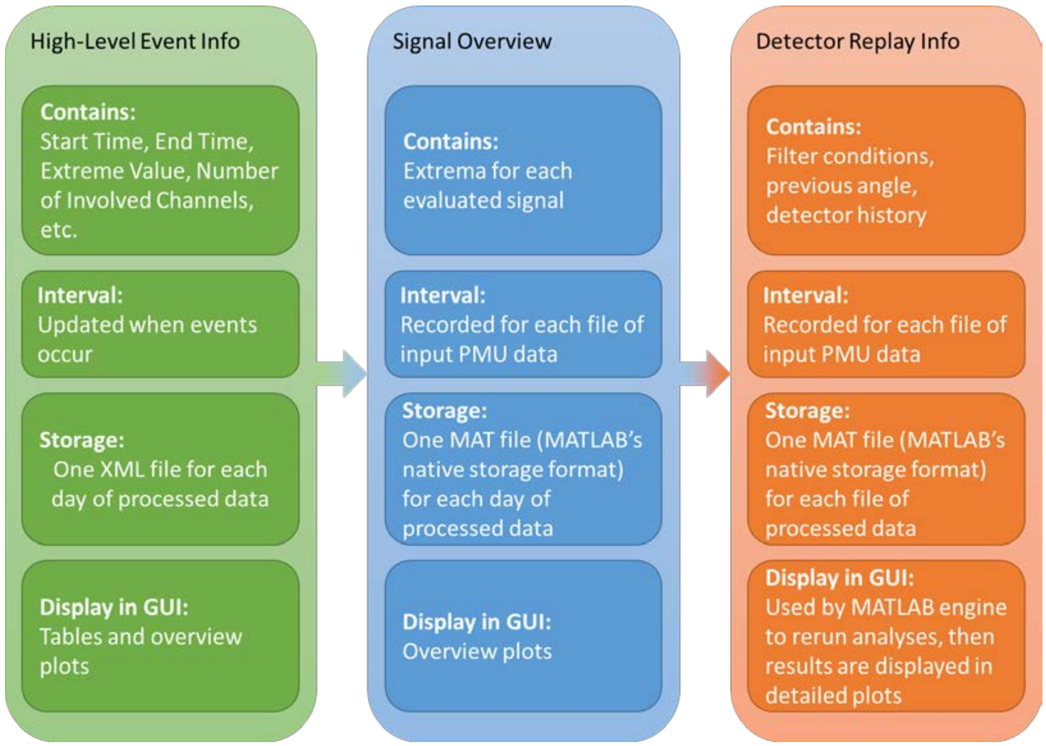


Figure 2-1. Diagram of the results storage hierarchy.

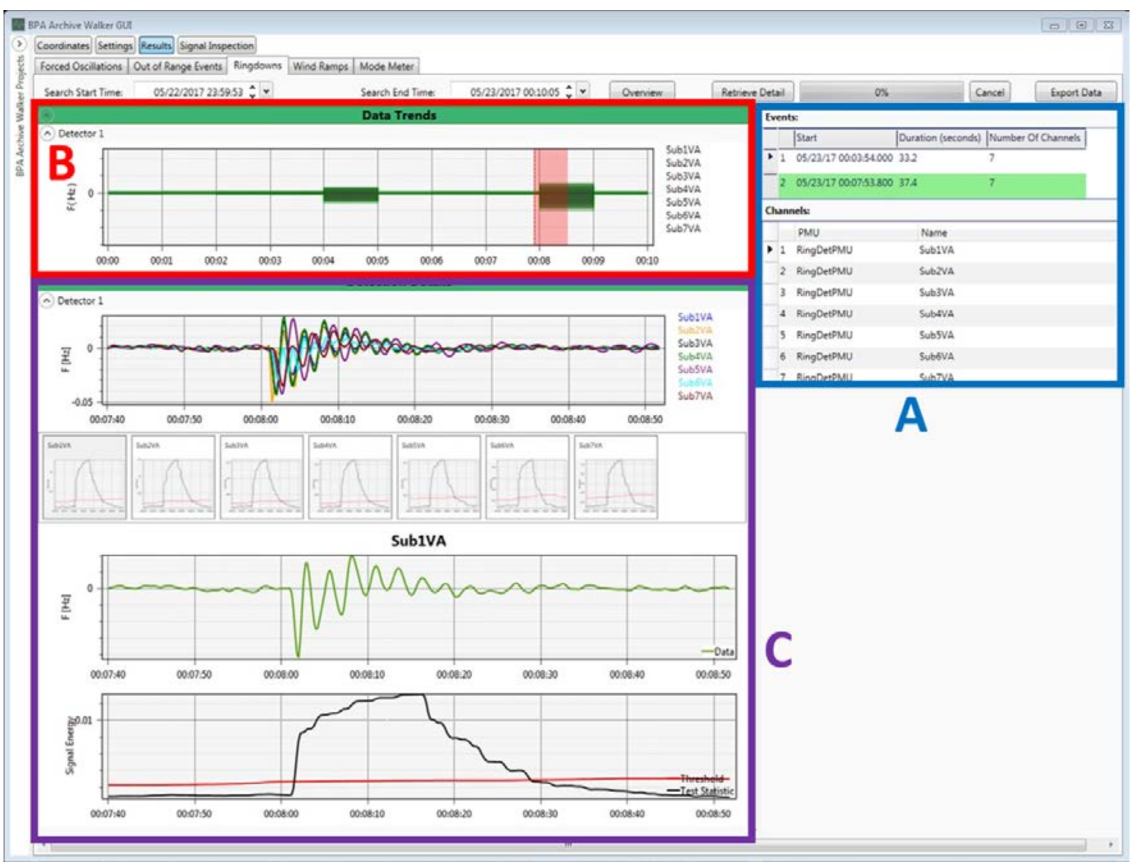


Figure 2-2. Screen capture of Archive Walker with results displayed in (A) a table of events, (B) a plot of the input signals' extrema, and (C) plots detailing the detector's operation.

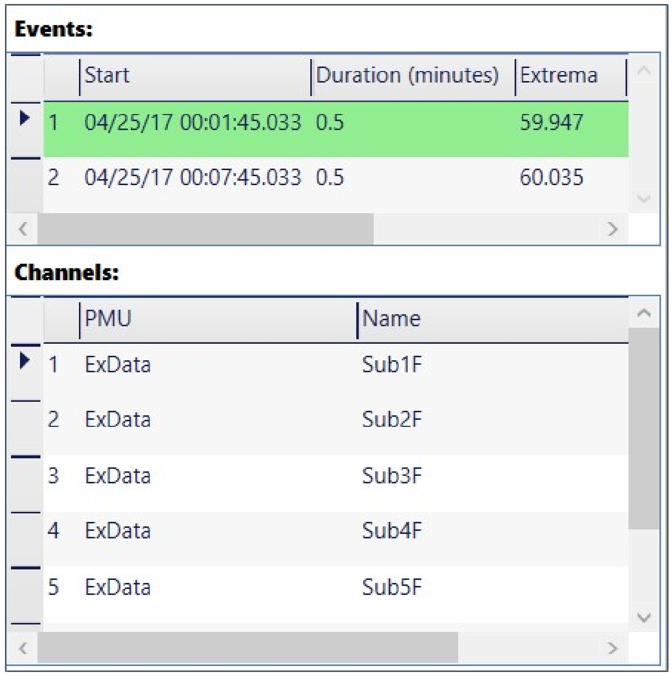


Figure 2-3. Detailed view of the event table in Archive Walker.

2.2 Data Ingestion

Archive Walker was initially designed to process PMU data stored in files. At BPA, PMU data is stored in a custom file format called *PDAT*, an abbreviation for *phasor data*. Each PDAT file captures the binary stream of data in C37.118 format. Additionally, the tool supports a Comma Separated Value (CSV) format proposed by the Joint Synchronized Information Subcommittee (JSIS) under the Western Electricity Coordinating Council (WECC). This format is referred to as *JSIS-CSV*.

While only two file formats were supported initially, Archive Walker was designed to be readily extensible in a variety of ways, including to support additional formats. Recognizing that many utilities store PMU data in databases rather than files, support was added for three database management systems popular among electric utilities: the PI System, openHistorian, and openPDC.

Regardless of the data's format, Archive Walker offers three modes of operation. In *Archive* mode, data is processed from a start time to an end time. Any missing data is skipped under the assumption that the archive is static. In contrast, *Real-Time* mode is used to process measurements shortly after they are collected, so Archive Walker will wait for files to become available. Finally, *Hybrid* mode allows the tool to start at a specified time, catch up to data currently being written, and transition to *Real-Time* mode.

2.3 Data Quality

For reliable operation of Archive Walker's event detectors, the data passed into the detectors must be reliable. However, PMU data often contains missing or unreliable data due to communication dropouts, loss of the Global Positioning System (GPS) clock signal, etc. Thus, a set of data quality filters is included in Archive Walker. Bad data identified by these filters can be replaced through interpolation, as described in Section 2.5.

The first set of data quality filters addresses problems that are clearly indicated in the data. This set includes a filter for missing data where zero was used as a placeholder, missing data that was completely omitted from the data set, and unreliable measurements flagged by the PMU or Phasor Data Concentrator (PDC). These flags are contained in a 16-bit status word that accompanies each frame of measurements from a PMU.

While many data quality problems can be addressed by simply removing missing or previously flagged measurements, other problems require further examination of the data. The second set of data quality filters identifies measurements with unreasonable values. These filters can be tuned to reflect the user's interpretation of “unreasonable” and compromise between sensitivity (identifying bad data) and specificity (ensuring that good data during system disturbances is preserved). This set includes filters for voltage and frequency based on nominal values, outliers (measurements that fall unrealistically far from surrounding measurements), and stale data (measurements that are not being updated).

Data quality problems often occur sporadically, but certain failures, particularly those that persist, lead to the corruption of measurement sets. The final set of filters discards entire data frames, channels, and PMUs if enough measurements from the set are flagged by data quality filters.

2.4 Signal Customization

One of the key advantages of PMU data is that it is synchronized. Because each measurement is time stamped, measurements from the same instant of time can be combined in a variety of ways. Doing so can improve the performance of event detectors. For example, the mode meters described in Section 2.6.4 typically perform best when analyzing signals composed of the difference between voltage angles in different areas of the power system. The signal customizations described in this section allow such combinations to be implemented, along with additional functionality.

Several of the signal customizations are mathematical in nature. Signals can be added, subtracted, multiplied, divided, or raised to an exponent. The sign of a signal can be reversed, or the absolute value can be taken. Complex numbers are also addressed with operations that return the real or imaginary component, calculate the angle associated with a complex number, or return the complex conjugate.

Operations specific to power systems can also be implemented. Real, reactive, apparent, and complex power can be calculated from voltage and current measurements. Voltage or current magnitude-angle pairs can also be used to calculate phasors.

The final set of customizations manipulate the types and units of signals. Though the previously listed customizations assign signal types and units to outputs, the user has the flexibility to reassign any type and unit assigned to a signal. A signal can also be customized by changing the metric prefix of its units. Finally, the units of angle signals can be converted from degrees to radians or vice versa.

2.5 Signal Processing

Appropriate signal processing can be a key to successful PMU data analysis in general, and the same is true for analyses in Archive Walker. The tool makes it simple to correct bad data and prepare signals for further analysis by event detection algorithms.

Data quality problems flagged by the filters described in Section 2.3 and propagated through customization functions can hinder the performance of event detectors. The detectors will not falsely trigger on the flagged measurements, which are treated as if they were missing, but they can keep the detectors from identifying nearby events. This is especially true because signal processing filters will “smear” the flagged measurements so that they have an even greater impact. Thus, it is generally advisable to patch the data through interpolation. The patching offered by Archive Walker is relatively simple and is implemented as linear, quadratic, or cubic interpolation. More advanced techniques could be implemented, but simple interpolation has been found to be sufficient for the current set of detectors.

After interpolation, a set of signal processing filters are available. Rational filters can be specified in terms of their numerator and denominator coefficients, or Archive Walker can design low- or high-pass filters based on user specifications. Three commonly used filters are also available as special cases. The first applies a derivative filter to voltage angles. The output is then scaled to capture the deviation in frequency about nominal. This alternative to the frequency measured by PMUs is often used in applications focused on power system oscillations. The second special filter calculates the running average of a signal. The final special filter calculates the root mean squared (RMS) energy of the input signal within specific frequency bands. As described in(Donnelly et al. 2015), these filters are designed for use in detecting power system oscillations. The oscillation detector can be implemented by passing the RMS-energy signals into the out-of-range detector described in Section 2.6.2.

Along with interpolation and filtering, multirate processing is a major component of Archive Walker's signal processing capabilities. Multirate processing allows the sampling rate of a signal to be adjusted. In most cases, changes in sampling rate should be accompanied by filtering. If specified, Archive Walker will implement this filtering automatically. Reducing the sampling rate can improve the performance of some detectors (mode meters), increase the processing speed of computationally intensive detectors (forced oscillation detection), and reduce the storage space required for results.

2.6 Event Detection

The description in this section is a summary of content previously published in(Follum et al. 2020).

2.6.1 Ringdowns

Ringdowns occur after large system disturbances such as generator trips or transmission line faults that perturb the power system's dynamics. As the system returns to steady state, it “rings down,” as in the top plot of Figure 2-4. This type of oscillation can be modeled as a sum of damped sinusoids. The damping of each sinusoid reflects the damping of an inter-area electromechanical mode of oscillation within the power system. The system's small-signal stability is directly related to the damping of these modes. For reliable power system operation, all modes must be stable. Thus, ringdown analysis is a useful tool for studying the dynamic stability of a power system. Small-signal stability analysis can be carried out on ringdowns detected and exported by Archive Walker using the Oscillation Baselining and Analysis Tool (OBAT) described in Section 4.0.

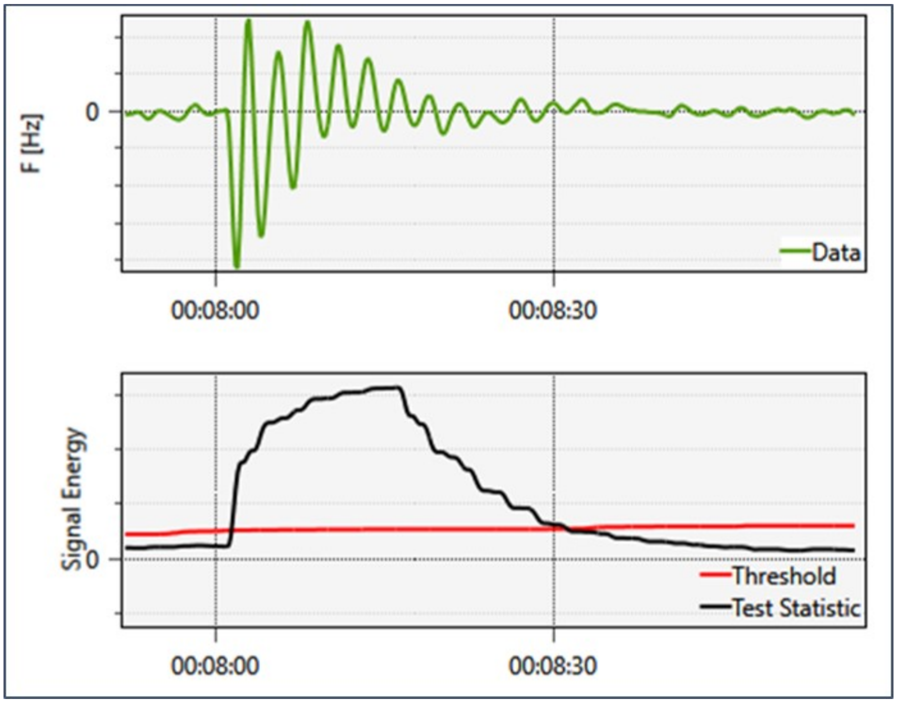


Figure 2-4. Screen capture from Archive Walker showing a ringdown (top) along with the RMS energy and threshold used to detect it (bottom).

The ringdown detector deployed in Archive Walker is a generalization of the oscillation detector proposed in(Donnelly et al. 2015). These detectors operate by monitoring the signal energy of filtered frequency or active power measurements. Applying a filter with a pass band corresponding to the frequency range of electromechanical modes of oscillation, approximately 0.1 to 2 Hz, allows ringdowns to be detected. Ringdowns possess much more energy than the random deviations that are normally observed in PMU data. When the signal energy spikes for a brief period of time, a ringdown is detected. The signal energy is calculated as the RMS-energy of the signal over an analysis window:

$$RMS(n) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} x^2(n)}$$

where $x(n)$ is the signal under analysis and N is the length of the analysis window. To maximize the RMS and ensure good detection performance, N should correspond to the duration of ringdowns, which typically last 10-20 seconds.

To trigger detection, $RMS(n)$ must be compared to a threshold. In Archive Walker, a dynamic threshold is implemented as a scaled running median of the RMS:

$$\gamma(n) = R \times median\{RMS(k)\}$$

where $n - k + 1 \leq k \leq n$. A ringdown is detected when $RMS(n) > \gamma(n)$. Use of the median, which diminishes the influence of extreme values, prevents the threshold from increasing when a ringdown enters the analysis window. Continuously updating the threshold accounts for slowly varying system conditions. An example of the signal energy and threshold is presented in the bottom plot of Figure 2-4.

2.6.2 Out-of-Range Events

The out-of-range event detector is the most general of Archive Walker's detectors. Typical uses include identifying low-voltage conditions or sudden changes in frequency related to generator trips, but it can be used in a variety of ways.

In power systems, deviations from nominal values may occur gradually or suddenly. To capture a wide variety of events, the out-of-range detector operates in two stages. Each stage utilizes a set of upper and lower bounds, which are specified by the user as deviations from a baseline. The baseline can be specified as a nominal value or established using a running average to track slow system changes.

In the first stage, detection occurs if the analyzed signal remains outside of upper and/or lower thresholds for a certain duration. This stage, referred to as the *duration stage*, can detect unusual grid conditions even if they occur gradually. In the second stage, detection occurs if the signal exceeds upper or lower thresholds while simultaneously exceeding a rate-of-change threshold. This stage, referred to as the *rate-of-change stage*, detects events that cause sudden changes in the signal, even if the event's duration is short. In this way, the two stages complement each other. The rate of change is calculated as the slope between adjacent local extrema, as in Figure 2-5. In the top plot, lines connecting extrema in the frequency measurements (black) are indicated in red and green. The absolute values of the slopes of these lines are plotted in the lower portion of the figure. A screenshot of Archive Walker depicting the detector's overall operation is provided in Figure 2-6.

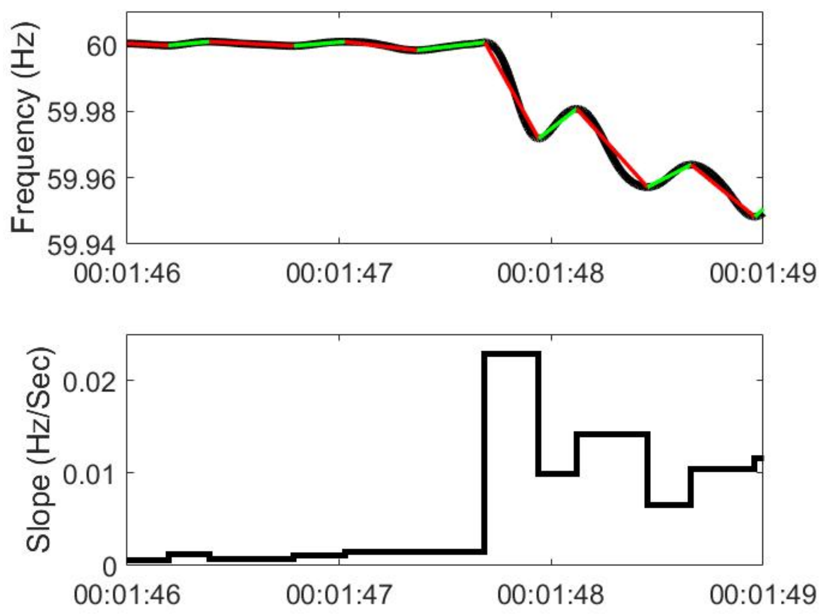


Figure 2-5. Example operation of the out-of-range event detector's rate-of-change stage. The slopes in the bottom plot correspond to the red and green lines connecting extrema of the input signal in the top plot.

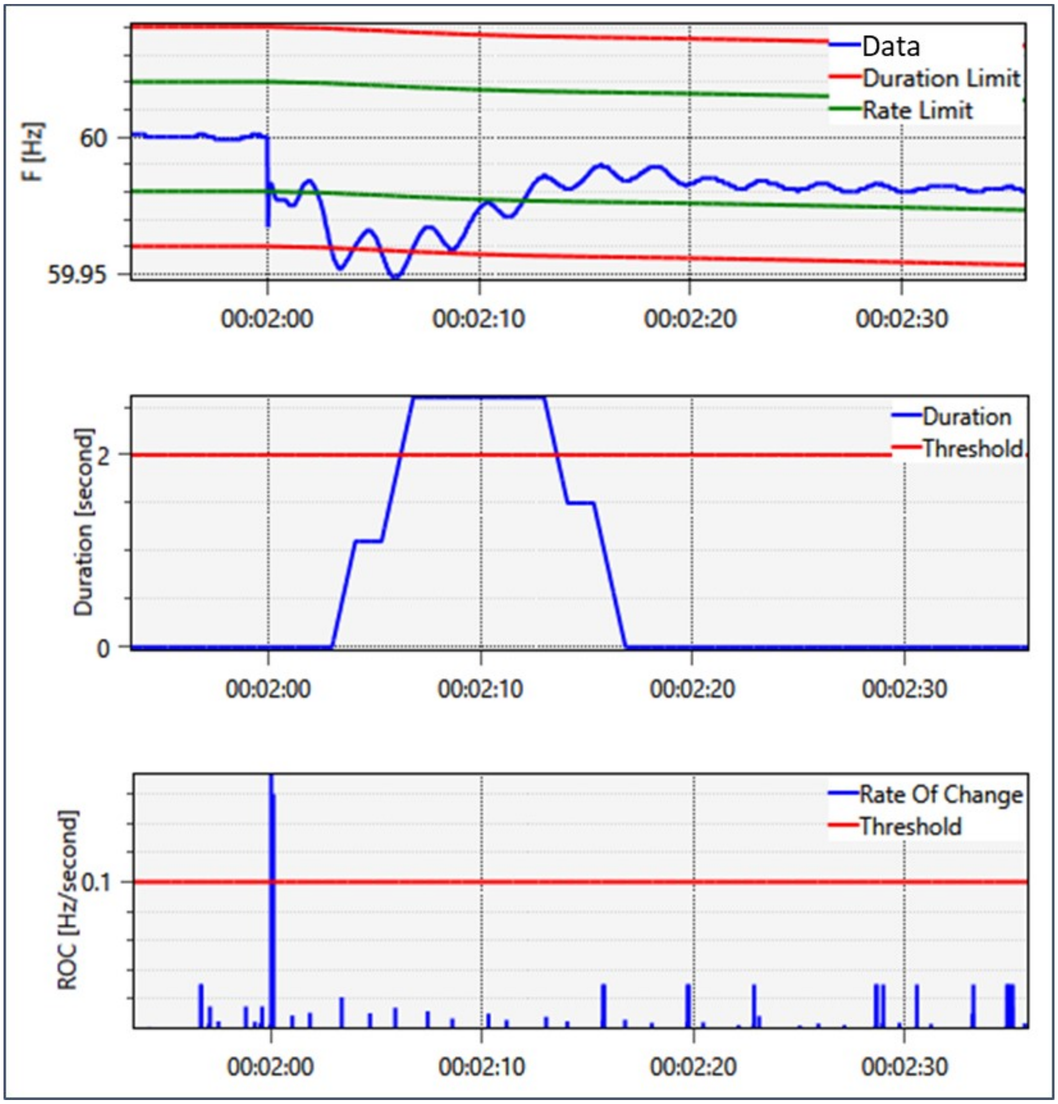


Figure 2-6. Screen capture from Archive Walker showing a frequency event (top) detected by both the duration-based detector (middle) and the detector based on rate-of-change (bottom).

The grid disturbances detected by Archive Walker's out-of-range event detector can be exported for further analysis with other tools in the open-source suite. For example, measurements from a power plant's point of interconnection during a disturbance can be used to validate the plant's model using the Power Plant Model Validation (PPMV) tool discussed in Section 5.0. Additionally, sudden changes in frequency due to generator trips, such as the one depicted in Figures Figure 2-5 and Figure 2-6, can be analyzed using the Frequency Response Analysis Tool (FRAT) described in Section 6.0.

2.6.3 Forced Oscillations

Forced oscillations occur in power systems for a variety of reasons but are most often associated with generating units injecting oscillations into the system due to equipment failure or abnormal operating conditions. Sustained oscillations persist until the source is disabled. Forced oscillations can threaten grid reliability in cases where resonance with a natural system mode of oscillation leads to large oscillation amplitudes across the power system.

Two algorithms designed to detect forced oscillations are available in Archive Walker. The first method is based on the periodogram, which captures the power of a signal as a function of frequency. Forced oscillations appear as narrow peaks in the periodogram, allowing them to be detected. The method is very sensitive and can detect even small forced oscillations, but it requires approximately 10 minutes of data to operate. Detailed derivations of the method and its statistical detection performance are available in(Follum and Pierre 2016), (Follum and Tuffner 2016), and(Follum, Tuffner, and Agrawal 2017).

The second method is based on the coherence among signals. The coherence is a frequency dependent measure of the linear correlation among signals. When a forced oscillation is present, the coherence increases at the oscillation's frequency. This method is less sensitive than the periodogram-based method, but it can detect events faster due to its smaller analysis window. Further details regarding the method and its statistical detection performance can be found in(Ghorbaniparvar and Zhou 2015), (Zhou and Dagle 2015), and(Zhou 2016).

The database of forced oscillation events maintained by Archive Walker can be used in a variety of post-event studies. Often, users are interested in identifying the piece of equipment causing the oscillation. After detecting an oscillation, Archive Walker displays metrics related to the oscillation's amplitude on a map. An example is provided in Figure 2-7. These displays can indicate the region containing the oscillation's source in many cases. However, amplitude is not always the best indicator of an oscillation’s source. Thus, a method of tracing the flow of oscillation energy through the power system network has also been implemented. Technical details for the Dissipating Energy Flow (DEF) method can be found in(Maslennikov, Wang, and Litvinov 2017).

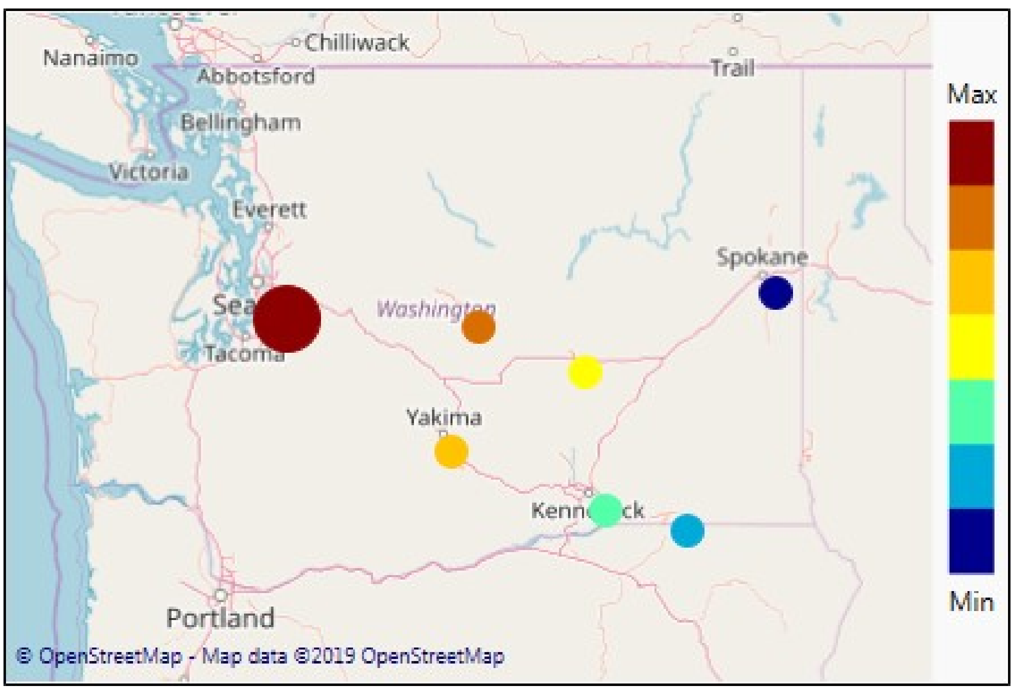


Figure 2-7. Screen capture from Archive Walker displaying a forced oscillation's amplitude at several measurement locations.

2.6.4 Electromechanical Modes of Oscillation

A power system's electromechanical modes dictate natural oscillatory exchanges of energy between generators in different areas of the system. As such, they are directly related to the power system's small-signal stability. Two of the key characteristics of a mode are its frequency and damping ratio. The frequency tends to be fairly consistent and can be used to differentiate between modes. In contrast, the damping ratio can be significantly impacted by changing operating conditions and system topology. Mode damping is directly related to system stability. If a damping ratio falls below zero, the system becomes unstable and oscillations in power and frequency will grow until the system collapses or protective devices successfully return the system to stability. For this reason, monitoring and understanding a system's electromechanical modes can help ensure the system's reliable operation.

A mode meter is a tool that generates estimates of the frequency and damping ratio of a set of modes on a regular interval. The mode meter algorithms available in Archive Walker are recently developed extensions to the classic least-squares and Yule-Walker approaches. These extensions provide reliable mode estimates even during system disturbances. Further details on these algorithms, including statistical evaluation of their estimation performance, can be found in (Follum, Pierre, and Martin 2017) and(Agrawal et al. 2018).

As Archive Walker processes data, mode estimates are recorded in a CSV file alongside user-specified measurements to capture the system's operating conditions. For example, indicators of system stress or generation mix could be recorded. This information can be used in baselining studies that seek to identify how operating conditions influence modes. An initial baselining effort based on application of statistical methods to mode estimates from ringdown analysis is reported in(Hou, Follum, et al. 2018). While ringdowns occur relatively infrequently, continuous analysis with a mode meter provides a larger dataset representing a wider range of system conditions. Baselining studies based on mode meter data could provide a much better understanding of how a system's operation influences its small-signal stability.

2.6.5 Wind Ramping

One of the concerns with the proliferation of variable generation resources, such as wind and photovoltaics, is ramping. While ramping of conventional generators can be controlled, the uncontrolled changes in power production for variable resources can cause reliability concerns. Archive Walker's wind ramp detector is intended to identify ramping by monitoring the power production of wind farms. Periods of interest can then be studied in more detail.

The wind ramp detector operates by tracking low-frequency trends in wind power production. After low-pass filtering the input signal, steady increases or decreases in power are identified. The duration and change in power production for each trend is then recorded. See Figure 2-8 for an example.

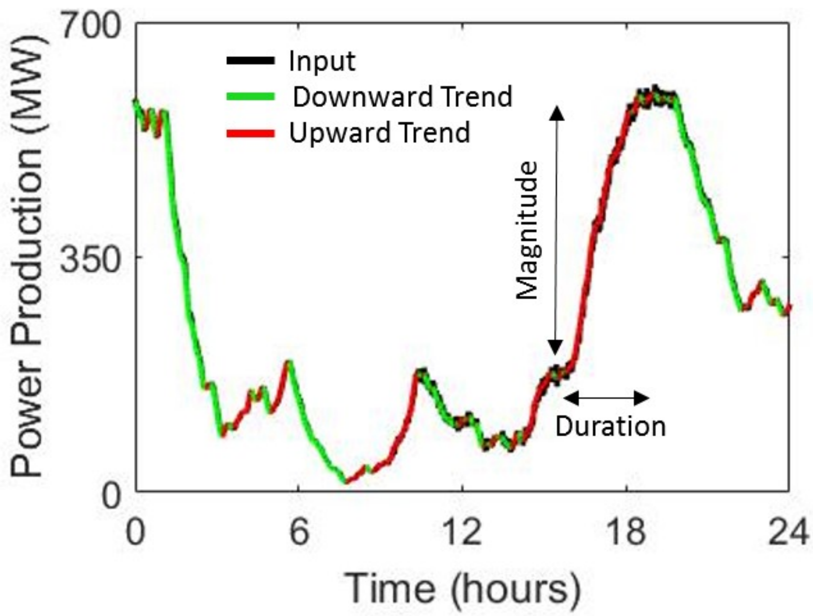


Figure 2-8. Example operation of the trend identifier within the wind ramp detector.

The low-pass filter can be tuned to focus on trends of different lengths, anywhere from several seconds to several hours. For detection, trends are compared to a curve of the form in Figure 2-9. Trends must be of a certain magnitude (change in power production) to be detected. The longer the trend duration, the larger the magnitude must be for the trend to be considered significant. By adjusting the points on the detection curve, different types of events can be targeted for detection.

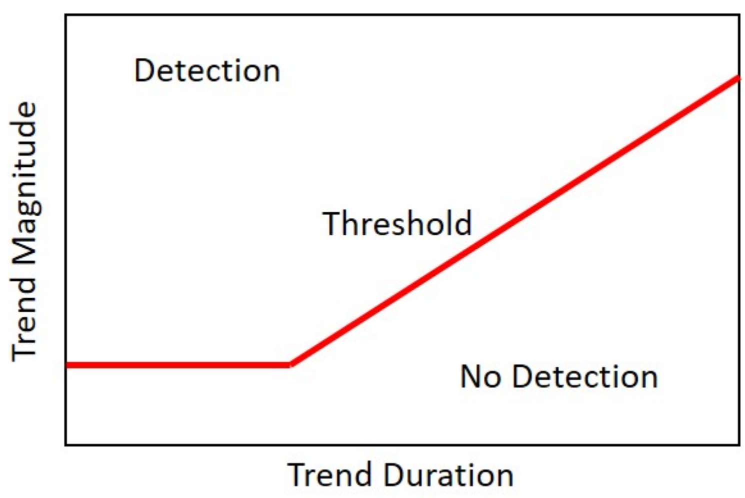


Figure 2-9. Detection threshold utilized in the wind ramp detector.

3.0 Archive Sprinter

Archive Sprinter was designed to rapidly generate information summarizing large archives of synchrophasor measurements. The tool is intended to generate data for further analysis, rather than detecting periods of interest during processing. The data summaries generated by Archive Sprinter are composed of a user-selected set of signatures, such as the variance and maximum value, that highlight periods of interest in the data. The signatures require little disk space and can be calculated rapidly. Archive Sprinter's design also allows for parallel processing to make analysis of long record lengths practical.

Though the tools have similar objectives, Archive Sprinter was specifically designed to provide functionality that would be an ill fit within Archive Walker. The Archive Walker tool excels at producing detailed results from analyses benefiting from signal processing functions such as filtering and multi-rate processing. These capabilities limit Archive Walker's speed because the complex analyses can be computationally intensive and must be performed in serial. In contrast, Archive Sprinter performs relatively simple calculations in parallel, allowing it to summarize a dataset very quickly. These key differences are summarized in Table 3-1.

Table 3-1. Key differences between the Archive Walker and Archive Sprinter tools.

Archive Walker	Archive Sprinter
Processes data in series	Processes data in parallel
Includes signal processing features such as filtering and multi-rate processing	Does not include functions that require serial processing, such as filtering and multi-rate processing
Applies detectors to identify time periods of particular interest	Summarizes all input measurements at a regular interval
Developed in MATLAB and .NET	Developed in .NET
Results reviewed within the tool's GUI	Output signatures serve as input for additional data analytics

Archive Sprinter is currently configured to read data in the PDAT and JSIS-CSV file formats. The tool could be extended to access archives stored in databases such as the PI System, openHistorian, and openPDC with relative ease by leveraging the Archive Walker code. Once data is ingested, it is analyzed within a sliding window. The length of the window and the amount of overlap between calculations is specified by the user. For example, a user may analyze 90-second windows of data, each containing 30 seconds of data from the previous window.

Before calculating signatures, the user may apply the data quality checks and signal customizations described for Archive Walker in Sections 2.3 and 2.4. The signal processing and event detection capabilities described in Sections 2.5 and 2.6 are not available in Archive Sprinter because they require serial processing. Instead, the user selects a set of signatures to calculate from the data. The available signatures are listed in Table 3-2.

Table 3-2. Signatures available in the Archive Sprinter tool.

Signature		Description
Sample Statistics	Mean	Simple average
	Variance	Measure of how dispersed a set of data is from its mean
	Standard Deviation	Square root of the variance
	Kurtosis	Measure of how common extreme values are
	Skewness	Measure of how balanced high and low values are
Order Statistics	Percentile	Value that is greater than a certain percentage of the data
	Quartiles	Correspond to the 25th, 50th, and 75th percentiles
	Median	Value for which half of the data is above and half of the data is below. The 50th percentile
	Maximum	Largest value in the data
	Minimum	Smallest value in the data
	Range	Difference between the maximum and minimum
Correlation Coefficient		Measure of how strongly two signals are related
Covariance		Measure of how much to signals move in tandem
RMS		Root mean squared value of the data
Frequency Band RMS-Energy		Measure of a signal’s energy over a specific frequency range
Histogram		Counts the number of values within a set of ranges
Rise		Difference between the first and final values

The signatures in Table 3-2 were selected to capture a wide range of characteristics that might indicate a period of interest in synchrophasor measurements. For example, consider a researcher seeking to analyze generator trips. Calculating the minimum frequency measured in each minute of data would quickly identify periods for further examination. Calculation of multiple signatures could support more complex analyses based on cluster analysis or machine learning. The signatures available in Archive Sprinter could also be expanded to accommodate specific research needs.

Results from Archive Sprinter are stored in CSV files. An example is provided in Figure 3-1. This format was selected because CSVs are ubiquitous and easily read by data analytics platforms.

	A	B	C	D	E
1	Time	Time	Maximum	Mean	Rise
2	Time	Time	Signal A	Signal A	Signal A
3	Start Time	End Time	Signal A.Freq	Signal A.Freq	Signal A.Freq
4	17:30:00	17:31:00	60.007	59.997	-0.011
5	17:31:00	17:32:00	60.017	59.996	-0.001
6	17:32:00	17:33:00	60.004	59.995	0.001
7	17:33:00	17:34:00	60.008	59.997	0.017
8	17:34:00	17:35:00	60.005	59.985	-0.020
9	17:35:00	17:36:00	60.006	59.988	-0.012
10	17:36:00	17:37:00	59.992	59.981	0.003
11	17:37:00	17:38:00	59.989	59.979	0.001
12	17:38:00	17:39:00	59.992	59.982	0.010
13	17:39:00	17:40:00	59.988	59.979	-0.012
14	17:40:00	17:41:00	60.000	59.984	0.013
15	17:41:00	17:42:00	59.997	59.984	-0.007
16	17:42:00	17:43:00	60.000	59.985	0.008
17	17:43:00	17:44:00	59.999	59.986	-0.024
18	17:44:00	17:45:00	59.982	59.969	0.009
19	17:45:00	17:46:00	59.989	59.971	0.009
20	17:46:00	17:47:00	59.991	59.975	-0.015

Figure 3-1. Example output CSV from Archive Sprinter.

4.0 Oscillation Baselining and Analysis Tool (OBAT)

The Oscillation Baselining and Analysis Tool (OBAT) is a stand-alone software application for ringdown oscillation analysis. It was previously reported in(Etingov et al. 2018b). Ringdowns occur following large disturbances to the power system, such as a generator or transmission line tripping out of service. In the western North American power system, disturbances are also intentionally introduced for testing purposes using the 1400-megawatt Chief Joseph dynamic braking resistor. These disturbances excite the system's dynamics, resulting in decaying oscillations as the system returns to steady state. The oscillations can be analyzed to estimate the system's inter-area electromechanical modes of oscillation (see Section 2.6.4). OBAT was designed to streamline the ringdown analysis process and help users associate the resulting mode estimates with system conditions.

The conceptual design of the tool is shown in Figure 4-1. The OBAT has two built-in oscillation analysis methods: Prony (Trudnowski, Johnson, and Hauer 1999) and Matrix Pencil(Lou, Quintero, and Venkatasubramanian 2007). The tool can also interact with external oscillation analysis solvers. Currently, a MATLAB-based analytical module utilizing the VARPRO method has been integrated into the tool(Borden and Lesieutre 2014).

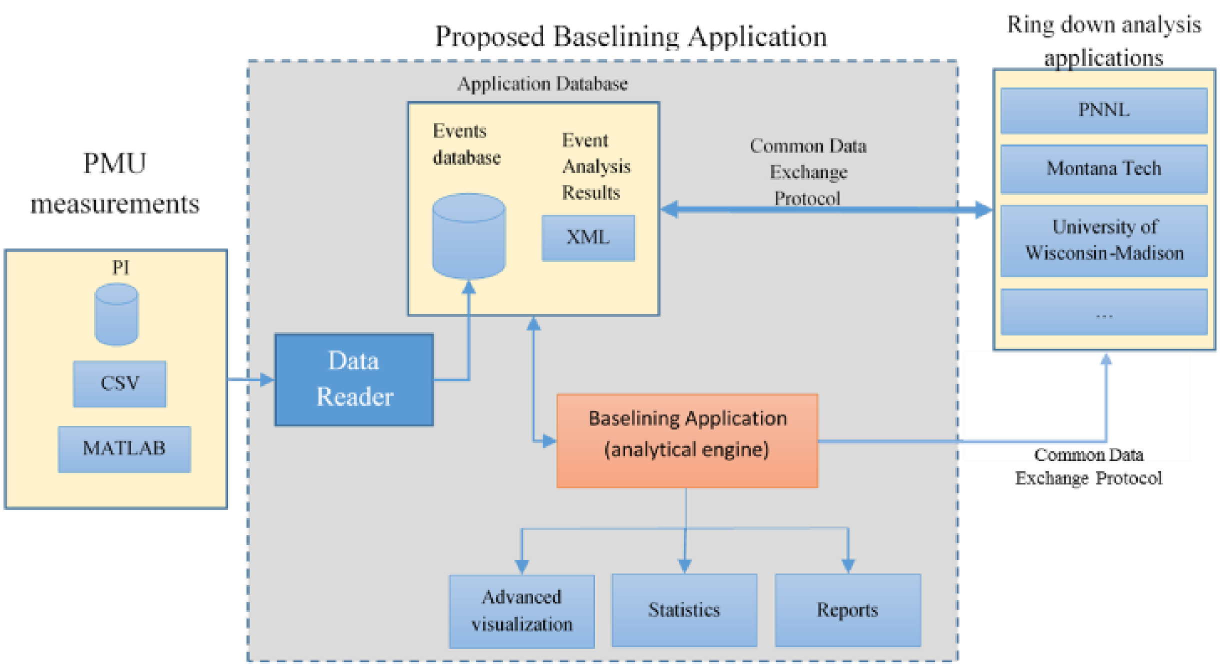


Figure 4-1. OBAT conceptual design.

The OBAT main GUI is shown in Figure 4-2. The tool maintains a database of oscillation events, is able to automatically generate oscillation analysis reports, and also has advanced visualization capabilities. OBAT also records system condition indicators such as power flow. The database of analyzed events can be used to better understand how a system's dynamic performance varies under different operating conditions(Hou, Follum, et al. 2018).

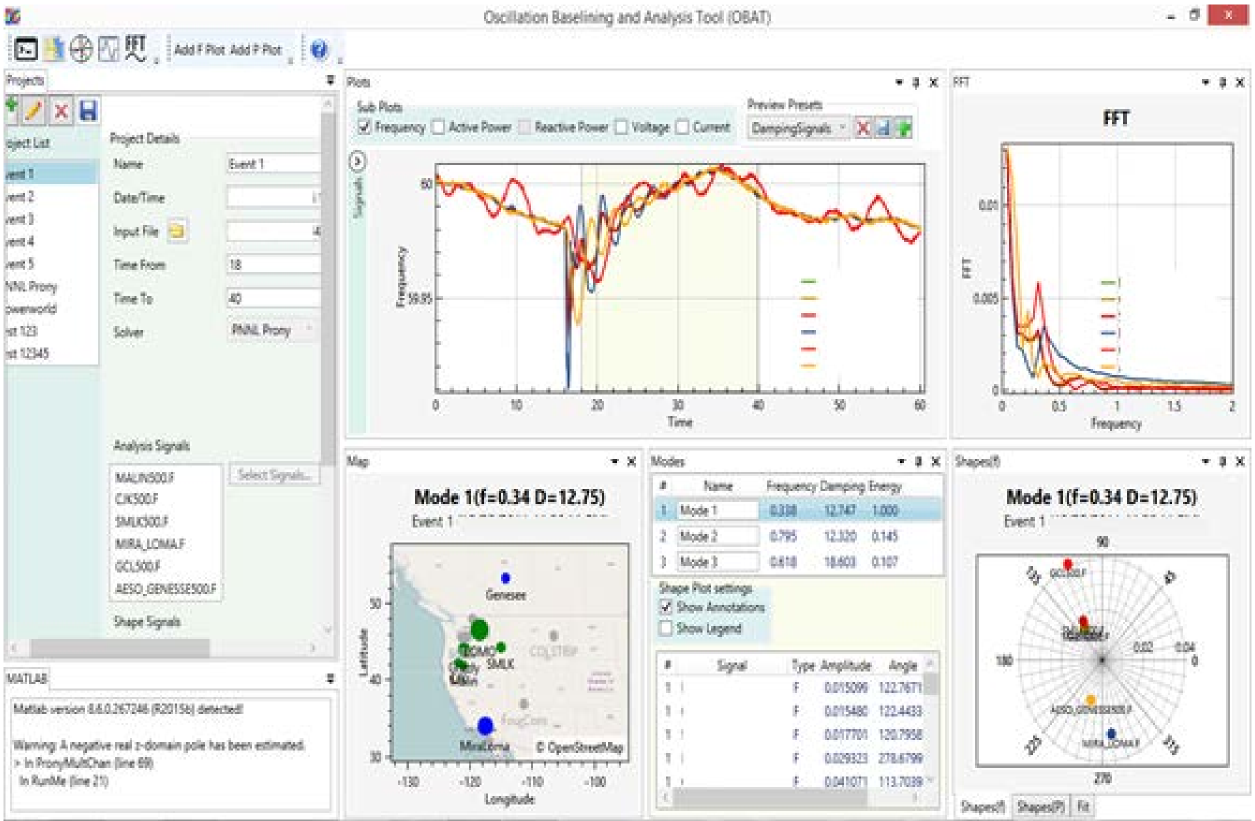


Figure 4-2. OBAT main GUI.

5.0 Power Plant Model Validation (PPMV)

Model validation is a critical component of system-wide model improvements (Overholt et al. 2014). The NERC Modeling, Data, and Analysis (MOD) standards enforce requirements for power plant modeling, data, and system analysis (NERC 2014a, b). The main goal of these standards is to ensure validation and monitoring of model performance. The MOD standards allow generator owners to perform model validation using disturbance event records.

The PPMV is a stand-alone Windows application and it helps to automate the power plant model validation process based on the disturbance recordings. Details on the PPMV approach are given in (Overholt et al. 2014). Figure 5-1 shows the overall PPMV tool structure. The PPMV stores historical disturbance information in the events database. The tool also includes the XML-based database of power plants (mapping power plants with corresponding PMU and SCADA measurement signals), and the database of model validation results.

To perform the model validation, the PPMV tool interacts with an external Play-In module. The current version of PPMV tool supports GE PSLF and Siemens/PTI PSS®E Play-In functions. Interaction between the PPMV application and PSLF is performed through Engineering Process Control Language (EPCL) scripts and with PSS®E through Python scripts. The tool also has built-in advanced visualization and reporting capabilities.

Using the GUI, the user can view existing model validation studies or can create a new model validation project. After the user selects required events and plants, the PPMV tool will interact with PSLF or PSS®E through scripting language to perform the model validation. The validation process consists from three major stages: (1) Mini state estimation to match the initial power flow conditions; (2) Model Validation run using Play-In function; and (3) Information extraction from the PSLF/ PSS®E channel files. The PPMV tool also has capabilities to perform sensitivity studies and interact with external model calibration models. The tool was integrated with a PNNL-developed model calibration solver based on Kalman filter approach (Huang et al. 2018). The PPMV application has been released under an open-source license and can be downloaded at: https://svn.pnl.gov/PPMV.

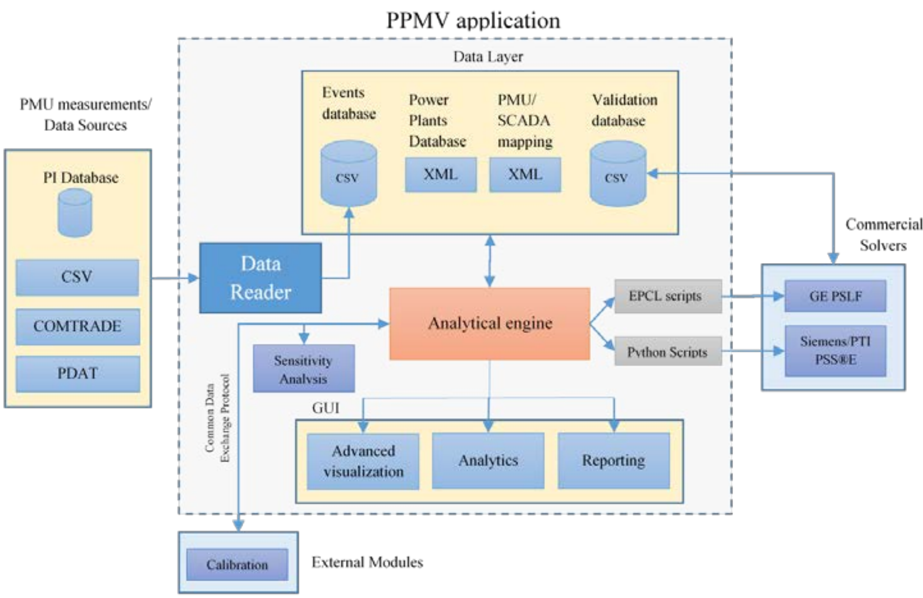


Figure 5-1. PPMV conceptual design

The concept used for power plant model validation using disturbance recordings is illustrated in Figure 5-2.

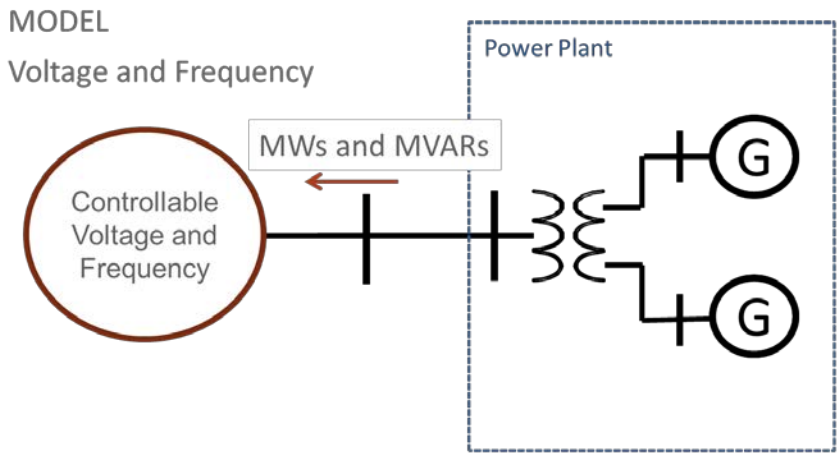


Figure 5-2. Illustration of the disturbance recordings-based power plant model validation

5.1 PPMV tool features

PPMV tool is designed to make the power plant model validation process convenient and user-friendly. For this, several features have been included in the PPMV tool and has advanced visualization techniques. Some of the features of the tool include:

- The database of model validation studies (projects).
- The database of the historic events.
- The database of the power plants.
- A user-friendly graphical user interface (GUI) and advanced visualization capabilities.
- Automatic report generation.
- Connectivity to the OSIsoft PI database.

5.1.1 GUI

Figure 5-3 shows an interactive display of the PPMV tool. The GUI consists of the toolbar and following panels:

- Model validation studies (projects) panel – to show the list of validation studies and their description.
- Power plant panel – to show power plant database and to map a power plant with the corresponding SCADA and PMU measurement signals.
- Events panel – to show event database.
- 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/.dyr files) can be displayed using single a plot.
- DYD/DYR preview/edit panel – to view, modify or create .dyd/.dyr files.

- SCADA preview/edit panel – to view, modify or create SCADA files.

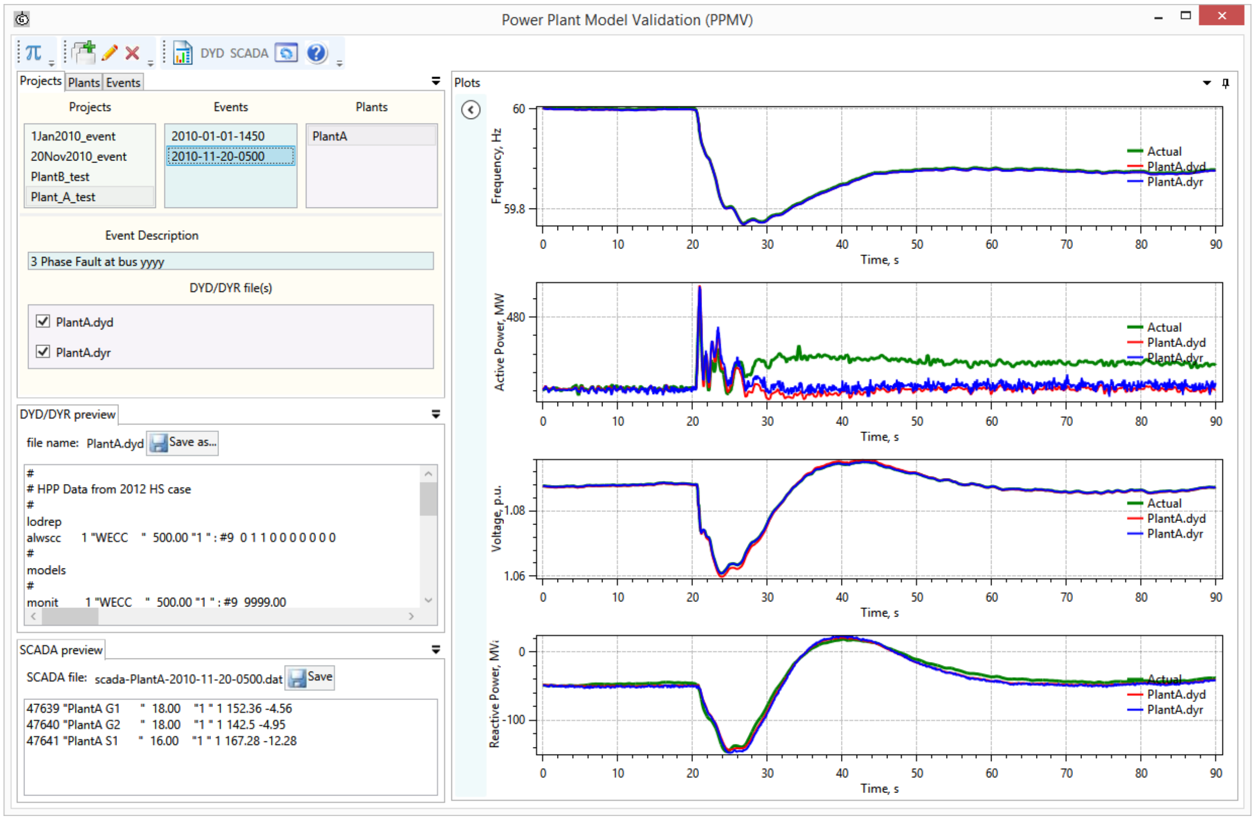


Figure 5-3. GUI of the PPMV tool developed by PNNL and BPA

5.1.1.1 Program settings

This section discusses the program settings available in the PPMV tool for selecting external Play-In modules: GE PSLF and PTI PSS®E as shown in Figure 5-4. These settings can be  assessed by clicking the program settings button and making appropriate selections as discussed in Table 5-1. Program setting options. GE PSLF and/or PTI PSS®E must be preinstalled.

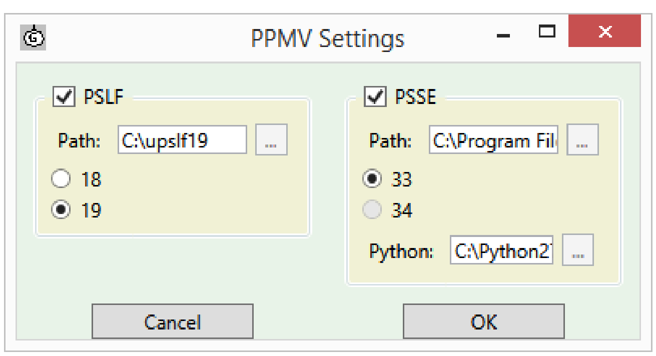
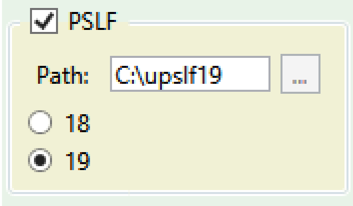
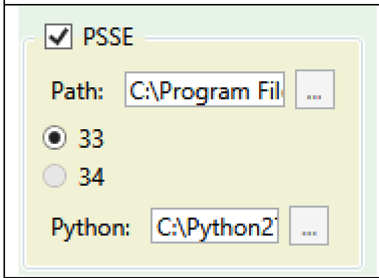


Figure 5-4. Program settings screen.

Table 5-1. Program setting options

	☑ PSLF – select this checkbox to use GE PSLF as a solver Path – path to PSLF PSLF version: 18 or 19
	☑ PSSE – select this checkbox to use PTI PSS®E as a solver Path – path to PSS®E PSS®E version: 33 or 34 Path to python

5.1.1.2 Toolbar

PPMV toolbar is shown in Figure 5-5. The list of toolbar buttons is given in Table 5-2.

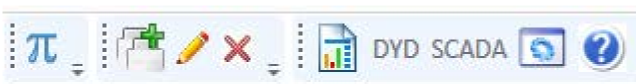
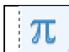


Figure 5-5. PPMV toolbar

Table 5-2. Toolbar buttons

	Open PI database reader
	Create new project
	Edit project
	Delete project
	Open report panel
DYD	Open/close DYD/DYR panel
SCADA	Open/close SCADA panel
	Program settings
	Help/about

5.1.1.3 Project panel (tab)

Project panel, shown in Figure 5-6, lists the available model validation studies. Users can view, edit or create new projects. There are two type of projects:

- By plant: validation of a single plant using multiple events;
- By event: validation of multiple plants using a single event.

As a project database, the xml file is used (*\DB\projects.xml*). User can select a project from the list and see what plants, events and dyd/dyr files are used in the selected model validation study.

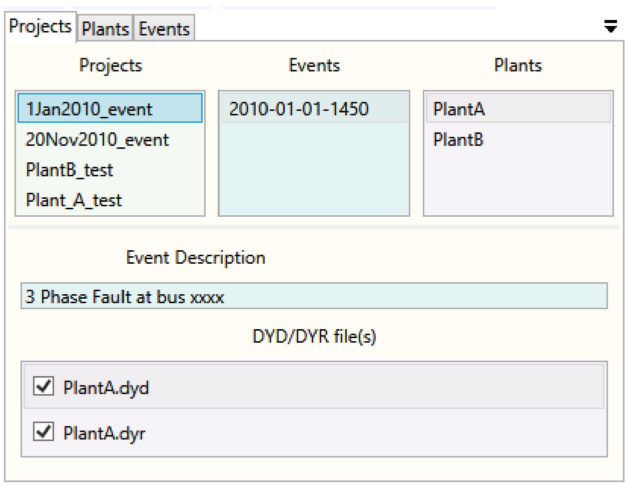


Figure 5-6. Project panel

5.1.1.4 Plant panel (tab)

Power plant database is used to map a power plant with the corresponding SCADA and PMU measurement signals. Power plants information is stored in xml file (\DB\generators.xml). Using the plant panel, shown in Figure 5-7, users can view/modify information on power plants or add new power plant to the database.

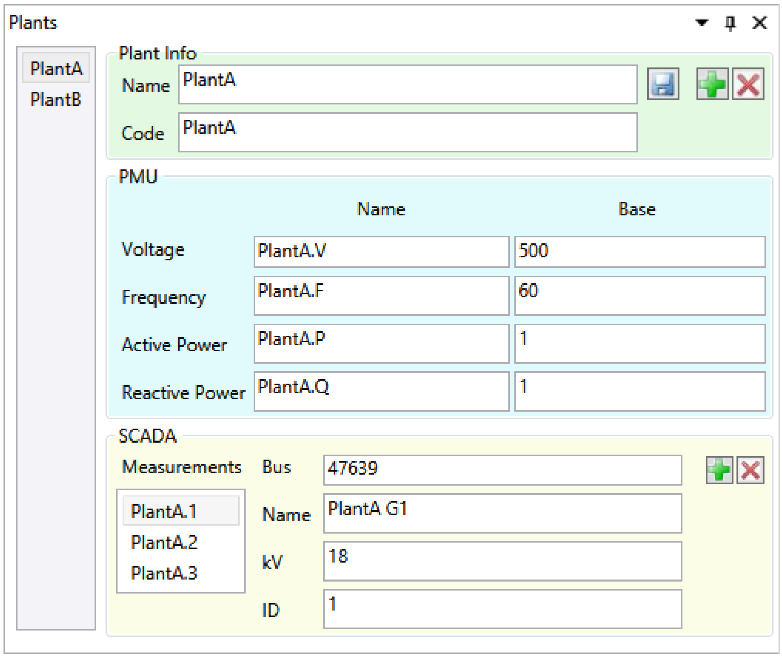


Figure 5-7. Plant panel

5.1.1.5 Events panel (tab)

Events panel, shown in Figure 5-8, displays the list of events in the PPMV event database. User can view available event and also add new events to the database. As an event database a csv file is used (\DB\events.csv).

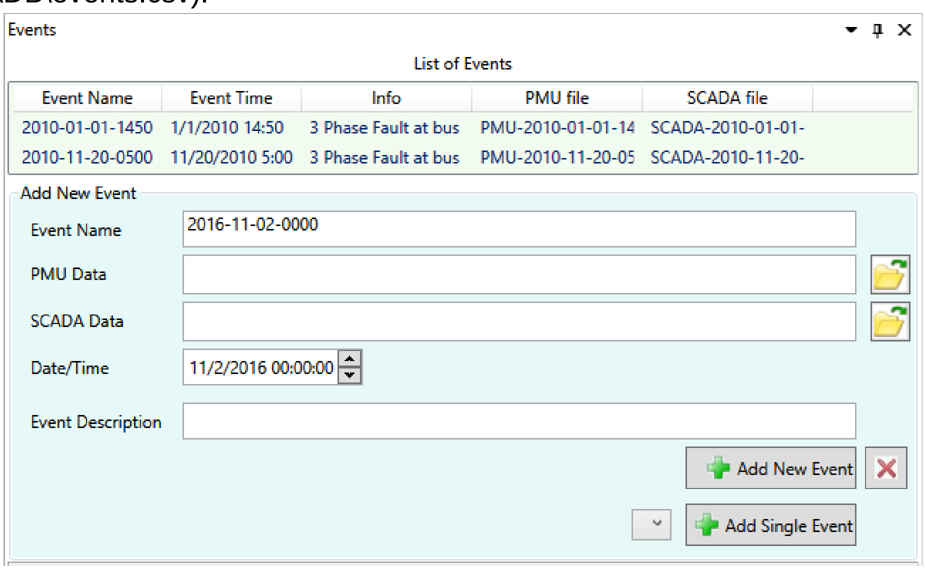


Figure 5-8. Event panel

5.1.1.6 Plot preview panel

Plot panel, shown in Figure 5-9, provides subplots for active and reactive power, voltage and frequency. Both actual and model based active and reactive power response are included in the plots. Some useful hints to control the plots are given in Table 5-3.

Table 5-3. Plot control

Action	Gesture
Pan	Right mouse button
Zoom	Mouse wheel
Zoom by rectangle	Ctrl + Right mouse button
Show 'tracker'	Left mouse button
Reset axes	'A'
Copy bitmap	Ctrl + C

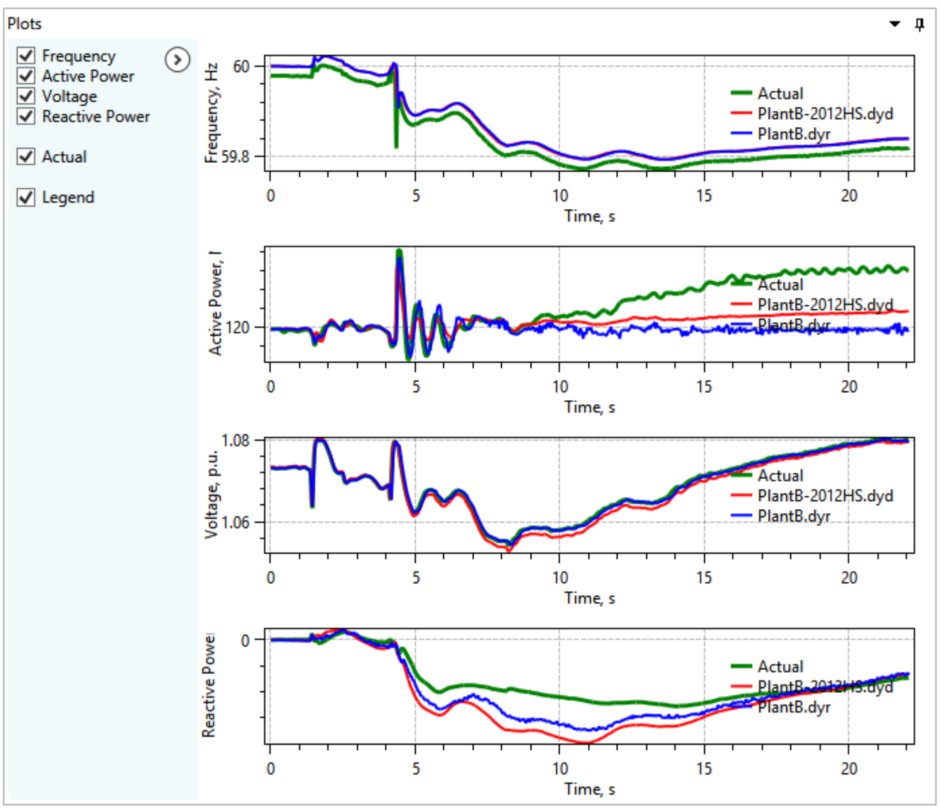


Figure 5-9. Plot preview panel

5.1.1.7 DYD/DYR and SCADA preview panels

In this panel, shown in Figure 5-10, users can view and modify selected (in PPMV edit mode) dynamic data (dyd or dyr) and SCADA files.

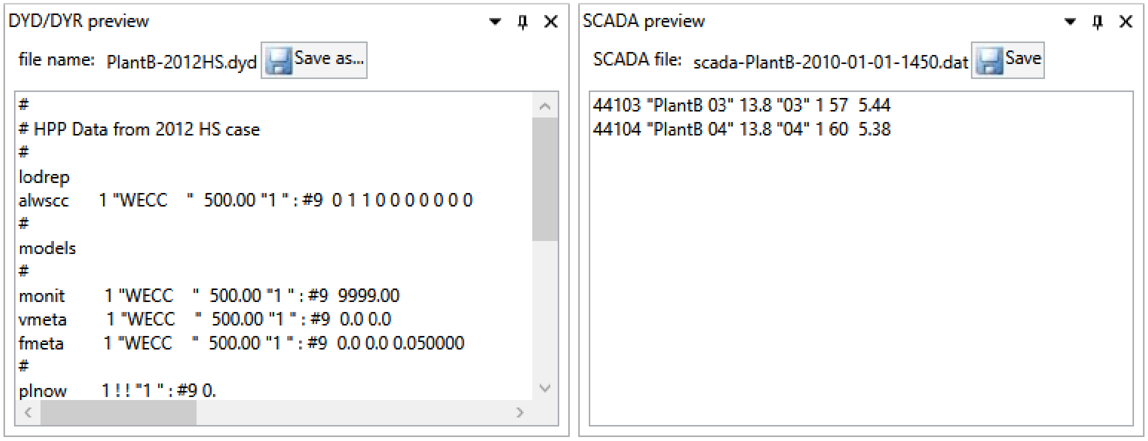


Figure 5-10. Dyd and scada preview panels

5.1.2 Database management

This section discusses the feature of data-base management available in the PPMV tool to store events and power-plants related information.

5.1.2.1 Power plant database

The xml file called *"generators.xml"* is located in "PPMV\DB\" folder. The structure (schema) of this file is shown in Figure 5-11. This file contains information to map power plant to corresponding PMU and SCADA measurements.

```xml
<?xml version="1.0" encoding="utf-8"?>
<plants>
  <plant name="PlantA">
    <code>PlantA</code>
    <SCADA>
      <bus id="PlantA.1">
        <number>47639</number>
        <name>PlantA G1</name>
        <kV>18.0</kV>
        <ID>1</ID>
      </bus>
      <bus id="PlantA.2">
        <number>47640</number>
        <name>PlantA G2</name>
        <kV>18.0</kV>
        <ID>1</ID>
      </bus>
      <bus id="PlantA.3">
        <number>47641</number>
        <name>PlantA G3</name>
        <kV>16.0</kV>
        <ID>1</ID>
      </bus>
    </SCADA>
    <PMU>
      <Voltage name="PlantA.V" base="500"></Voltage>
      <Frequency name="PlantA.F" base="60"></Frequency>
      <Power name="PlantA.P" base="1"></Power>
      <Reactive name="PlantA.Q" base="1"></Reactive>
    </PMU>
  </plant>
</plants>
```

Plant name → corresponds to plant **folder name**

Plant code → corresponds to plant base case **power flow file name**

SCADA information needed to map and extract power plant from the SCADA (state estimation) snapshot. Generator status and initial conditions

PMU information needed to map plant with corresponding columns (measurements) in JSIS csv file

Figure 5-11. Power plant xml schema

5.1.2.2 Event database

CSV file called “events.csv” is used to store event information. It is located in “PPMV\DB” folder.

A sample of the event database file is shown in Figure 5-12. It includes the following columns:

1) Event name – corresponds to the Event subfolder name inside the power plant folder.
2) Event time
3) Info – (optional) addition information about the event
4) PMU file – name of the input .csv file with PMU measurements
5) SCADA file – name of the input .dat file with SCADA measurements

A	B	C	D	E
Event Name	Event Time	Info	PMU file	SCADA file
2010-01-01-1450	1/1/2010 14:50	3 Phase Fault at bus xxxx	PMU-2010-01-01-1450.csv	SCADA-2010-01-01-1450.dat
2010-11-20-0500	11/20/2010 5:00	3 Phase Fault at bus yyyy	PMU-2010-11-20-0500.csv	SCADA-2010-11-20-0500.dat

Figure 5-12. Event database file

PMU measurements input file

Input PMU measurements are located in “PPMV\PMU” folder. The “JSIS” csv format is supported by PMV (Figure 5-13).

First row is signal headers. Headers must have the following structure: “SignalName.SignalType”, where signal type can be:

V- Voltage amplitude;
A – Voltage angle;
F – Frequency
P – Active power
Q – Reactive power

A	B	C	D	E	F	G	H	I	J	K
Time	PlantA.V	PlantA.A	PlantA.F	PlantA.P	PlantA.Q	PlantB.P	PlantB.Q	PlantB.V	PlantB.A	PlantB.F
0	542.9	-153.86	59.998	561.72	-33.208	119.43	2.8131	246.96	-153.57	59.998
0.033333	542.89	-153.88	59.998	561.99	-33.013	119.31	2.8516	246.95	-153.59	59.997
0.066667	542.88	-153.92	59.998	561.9	-33.069	119.22	2.6694	246.96	-153.62	59.998
0.1	542.82	-153.94	59.998	562.16	-33.253	119.19	2.5181	246.97	-153.65	59.997

Figure 5-13. Input PMU file in “JSIS” one row csv format

SCADA input file

Input SCADA files are located in “PPMV\SCADA” folder. The .dat format has the following structure (Figure 5-14).

# Bus Numb	Bus Name	Gen ID	Signal			
47639	PlantA_G1	1	MW	62429	PlantA.XFMF	164.67
47639	PlantA_G1	1	MVAR	62427	PlantA.XFMF	2.23
47640	PlantA_G2	1	MW	62432	PlantA.XFMF	154.74
47640	PlantA_G2	1	MVAR	62430	PlantA.XFMF	4.95
47641	PlantA_S1	1	MW	62435	PlantA.XFMF	236.66
47641	PlantA_S1	1	MVAR	62433	PlantA.XFMF	8.04
#PlantB						
44102	PlantB	2	MW	87005	PlantB.UNIT.	0
44102	PlantB	2	MVAR	103633	PlantB.UNIT.	0

Figure 5-14. Input SCADA file format

5.2 PPMV tool folder structure

Table 5-4 shows the main PPMV folder structure and content. It includes subfolders for input data, program database, power plants, as well as .dll files and scripts. The executable file is PPMV2.exe.

Table 5-4. PPMV tool folders structure and content.

Folder/file	Description
00-DYD	Optional folder for DYD files

01-PMU Data	PMU measurements in JSIS csv format (all plants) folder.
02-SCADA Data	SCADA data (all plants) folder
DB	PPMV database and configuration files folder
INI	Initialization files folder
PI_Reader	PI database reader folder
PLANT-A	Folder for plant “A” (Folder name corresponds to the Plant name in the PPMV tool plant database.)
PSSE	Python PSSE scripts folder
PPMV2.exe	PPMV Executable file
OxyPlot.dll	Required DLL - plots
OxyPlot.Wpf.dll	Required DLL - plots
Xceed.Wpf.AvalonDock.dll	Required DLL - GUI
Xceed.Wpf.Toolkit.dll	Required DLL - GUI
_pslf181epcl_ini.bat	PSLF 18 mini-state estimation batch and EPCL script files (First stage)
_runIni.bat	
_SetBaseCaseBatch.p	
_pslf19epcl_ini.bat	PSLF 19 mini-state estimation batch and EPCL script files (First stage)
_runIni19.bat	
_PPMVa_SetBaseCaseBatch_2014b.p	
_pslf181epcl.bat	PSLF 18 play-in batch and EPCL script files (Second stage)
_runPlayIn.bat	
_RunValidationBatch.p	
_pslf19epcl.bat	PSLF 19 play-in batch and EPCL script files (Second stage)
_runPlayIn19.bat	
_PPMVa_RunValidationBatch_2014b.p	
_plotPSLF18.bat	PSLF 18 batch and EPCL script files to extract data from channel file. (Third stage)
_runPlot.bat	
_chf2csv_ppmv.p	
_plotPSLF19.bat	PSLF 19 batch file to extract data from channel file. (Third stage)

5.2.1 Power plant folder

Each power plant has an individual folder. Power plant folder name corresponds to the power plant name in the PPMV tool plan database. When user adds new plant to the database the power plant folder will be created automatically. Power plant folder content is shown in Table 5-5. It includes subfolders for events and output channel files, dynamic data for the plant in dyd (PSLF) and dyr (PSSE) format, and also base case power flow files in sav (PSLF) and raw (PSSE) format.

Table 5-5. Power Plant folder content

Folder/File		PSLF	PSSE
PlantA			
→	00-CHF	Channel files folder (PSLF output)	-
	00-OUT	-	Channel files folder (PSSE output)

	YYYY-MM-DD-HHmm	Event folder. Folder name corresponds to the event name.	
	PlantA.dyd	Plant DYD file. Plant folder can include multiple .dyd files	-
	PlantA.dyr	-	Plant DYR file. Plant folder can include multiple .dyr files
	PlantA.sav	Base case power flow. File name should correspond to the plant code in the PPMV plant database	-
	PlantA.raw	-	Base case power flow. File name should correspond to the plant code in the PPMV plant database
	Model.dll	Any user-defined model used in .dyr or .dyd file	

5.2.2 Event folder

Event subfolder name corresponds to the event name in the PPMV tool event database. Each event PPMV tool creates a separate folder. Event subfolder content is shown in Table 5-6. It includes PMU measurements in csv (PSLF) and plb(PSSE) format, SCADA information, and also mini-state estimation solution in sav (PSLF) and raw (PSSE) files.

Table 5-6. Event folder content

Folder		Files	PSLF	PSSE
PlantA				
→	YYYY-MM-DD-HHmm			
	→	AN.plb	-	Play-in input file (csv file with PMU measurements). PPMV tool automatically generates this file when new event is added to the tool event database
		pmu-PlantA-YYYY-MM-DD-HHmm.csv	Play-in input file (csv file with PMU measurements). PPMV tool automatically generates this file when new event is added to the tool event database	-
		scada-PlantA-YYYY-MM-DD-HHmm.dat	SCADA input file. SCADA measurements used to identify system initial conditions and generator status.	
		PlantA-YYYY-MM-DD-HHmm.sav	*Output of the mini-state estimation (PPMV stage one)*	-
		PlantA-YYYY-MM-DD-HHmm.raw	-	*Output of the mini-state estimation (PPMV stage one)*

5.2.3 Channel files folder

Power plant folder includes two subfolders for PSSE and PSLF output channel files called 00-OUT and 00-CHF. Subfolder for PSSE channel files include only PSSE output channel files in .out format.
PSLF channel file folder structure is given in Table 5-7. It includes EPCL script files to extract information from .chf file and also .ini file that defines channels that need to be extracted.

Table 5-7. Channel files folder content (PSLF)

Folder		File	Description
PlantA			
→			
	00-CHF		
	→	_plotPSLF18.bat	Scripts for PSLF to extract data from channel file. PPMV tool automatically copies these files from the root folder when new plant is created
		_runPlot.bat	
		_chf2csv_ppmv.p	
		_plotPSLF19.bat	
		PlantA-plot.ini	Initialization file that includes channels that need to be extracted from .chf file. **User must specify this information manually when new plant is added!**
		PlantA-YYYY-MM-DD-HHmm-DYDname.chf	*Output of the play-in run (PPMV stage two)*
		plot-PlantA-YYYY-MM-DD-HHmm-DYDname.csv	*information extracted from the channel file (PPMV stage three)*

5.3 PPMV tool instructions

Several steps need to be followed for creating a project in the folder, such as creating event database, plants data-base and finally creating a project. Each of these steps are described in detail next.

5.3.1 Creating events database

This is a preliminary step that needs to be performed before creating a project in the PPMV tool for validating power plants if the relevant event database does not already exist. All SCADA and PMU data files required for the study must be manually copied in the sub-folders 02-SCADA data and 01-PMU data within the main folder PPMV before adding event to the database. For adding event to the event database:

1. SCADA data-file is selected from files in the folder 02-SCADA Data
2. PMU data-file is selected from files in the folder 01-PMU Data – Users can add a single file for a single event containing PMU data for multiple plants.

Figure 5-15 shows the addition of a single event “Test Event 3” for validating a power plant model.

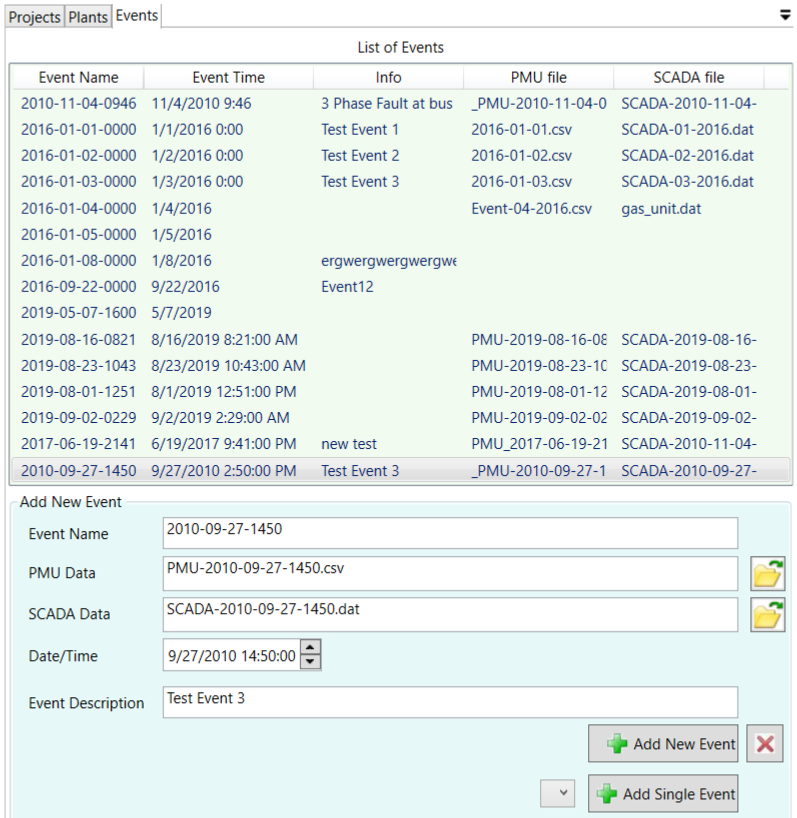


Figure 5-15. Steps for creating event database

5.3.2 Creating plants database

This is second preliminary step that needs to be performed before creating a project in the PPMV tool if the relevant plant database does not already exist.

In this step, users need to add plant database by entering information as shown in Figure 5-16. A new plant folder is created in the PPMV tool folder based on this information. Users also need to manually add .dyd, .dyr, .raw, .sav, .dll files for each plant in the plant folder automatically created in this step.

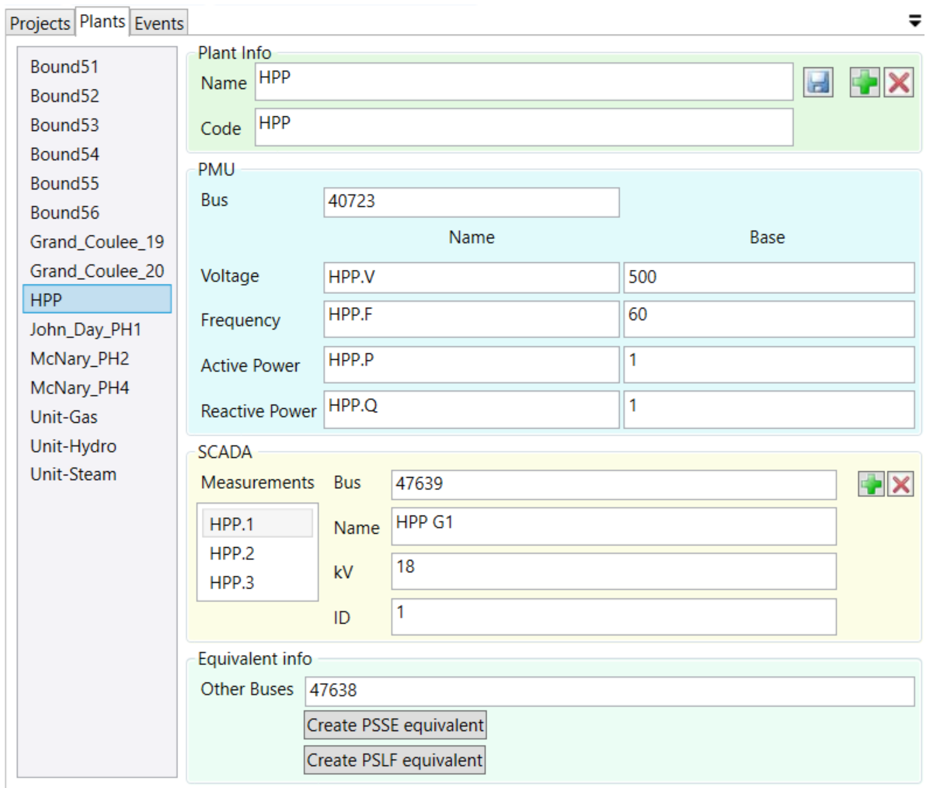


Figure 5-16. Steps for creating plant database

5.3.3 Creating projects

Figure 5-17 shows several steps that need to be performed for creating a project in the PPMV tool for validating power plant models. Each of these steps are:

1. Step 1: Push “Create new project” button
2. Step 2: Enter new project name
3. Step 3: Select project type
   - By Plant (single plant, single/multiple event(s))
   - By Event (single event, single/multiple plant(s))
     - ✓ PMU file must contain data for all plants
4. Step 4: Select the solvers
   - PSLF and/or
   - PSS/E
5. Step 5: Select event(s) and plant(s) from events and power-plants database – if the database for selected event and plant does not exist, create these database following instructions described earlier.
6. Step 6: Run Validation (or Steps 1 to 3 individually)
   - The PPMV tool calls three scripts:
     - ✓ Mini state estimation
     - ✓ Play-in (model validation)
     - ✓ Extracting information from the channel files
7. Step 7: Save Project

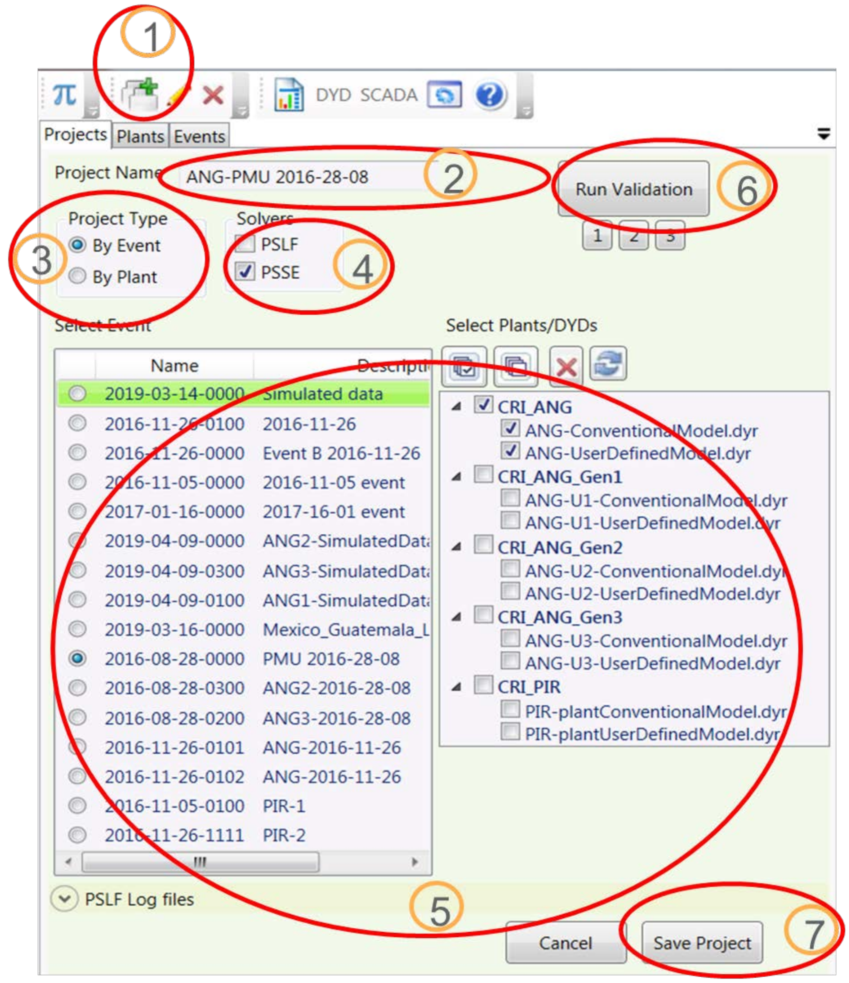


Figure 5-17. Steps for creating a project in the PPMV tool

5.4 Advanced new features added to the PPMV tool

Currently, the model validation results are analyzed by visually comparing actual PMU measurements with the model-based response measurements. In this section, a new methodology is discussed for advanced performance metrics to systematically quantify the generator dynamic model validation results by separately taking into consideration slow governor response and comparatively fast oscillatory response. The performance metrics for governor response is based on the step response characteristics of a system and the metrics for oscillatory response is based on the response of generator to each system mode calculated using modal analysis. These metrics are aimed at providing critical information to help with the selection of parameters to be tuned for model calibration by performing enhanced sensitivity analysis, and also help with rule-based model calibration. Results obtained using simulated measurements and test-case are included in this section.

5.4.1 Methodology

The flowchart showing the methodology for quantifying model validation results is shown in Figure 5-18. Flowchart for the methodology for quantifying model validation results. A detailed description of the methodology is discussed next.

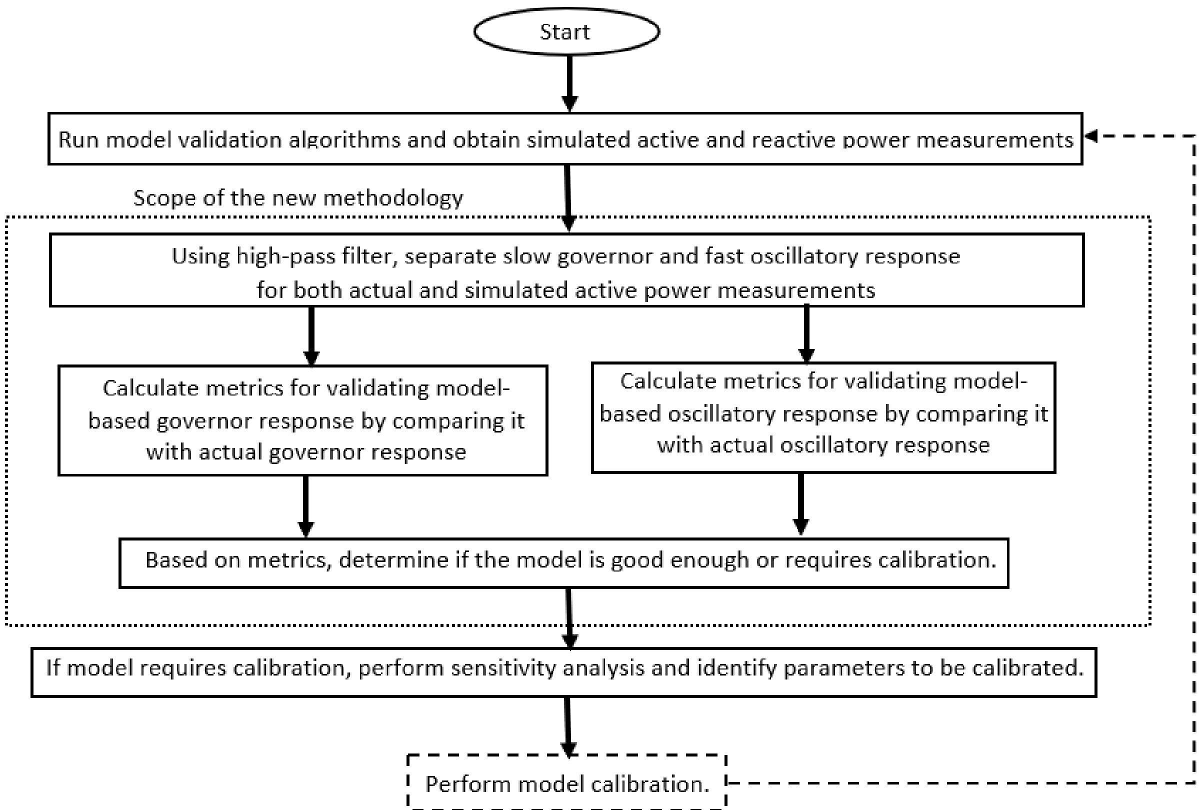


Figure 5-18. Flowchart for the methodology for quantifying model validation results

5.4.1.1 Step 1: Separating governor and oscillatory response

During system faults, generator dynamic response can usually be broken down into two components, one is the slow governor response and the other fast oscillatory response. The generator oscillatory response is determined by system modes and therefore the frequency range of this response lies between 0.1 and 2.0 Hz. Therefore, the slow governor response and the oscillatory response can be separated by passing the generator response through a high-pass filter having a cut-off frequency of less than 0.1 Hz as illustrated in Figure 5-19. The oscillatory response is then obtained by taking the difference of the generator response and the oscillatory response and passing the resultant signal through median filter to smooth out any oscillatory components present in the signal. This is the first and the important step in calculating performance metrics.

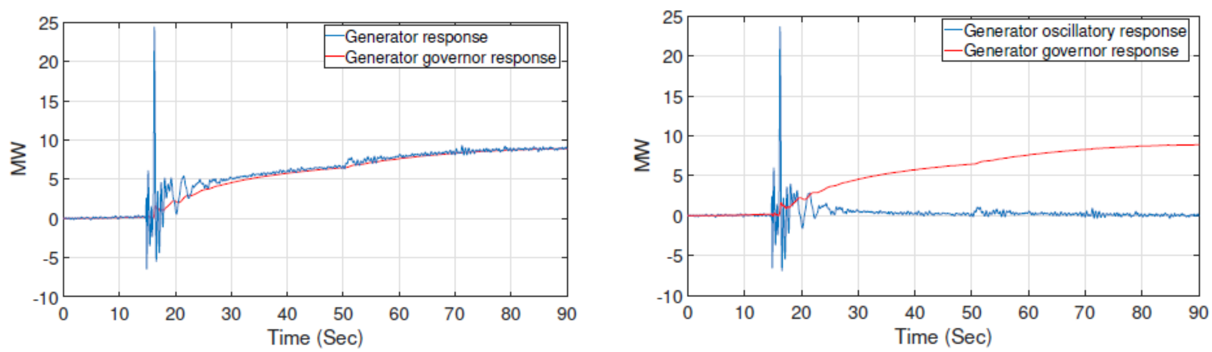


Figure 5-19. Separated governor and oscillatory response using high-pass filter

5.4.1.2 Step 2: Calculation of performance metrics

In the second step, metrics is calculated for the separated governor and oscillatory response corresponding to the active power. Metrics proposed for each of these responses is described next.

Active power - Oscillatory response:
The metric for validating generator oscillatory response is calculated based on the properties of the oscillatory modes observed in the PMU and simulated measurements. The new methodology calculates two metrics for validating generator oscillatory response, one for magnitude component and the other for phase component of oscillatory modes. The metric for magnitude incorporates any discrepancy associated with initial amplitude, damping-ratio and frequency of system modes between the model-based response and actual response. The metric for phase calculates any phase difference between the two signals. The two metrics can either be combined as a weighted average or can be used separately. Here, the two metrics are used separately as this can provide information helpful for calibration, i.e., if the calibration should focus on phase shift or magnitude or both.

For calculating the metric for oscillatory response, the first step is to estimate modes and their mode-shapes observed in both actual and model-based responses. The detail of this can be found in (Agrawal, Etingov, and Huang 2020).

Using the estimates of modes and mode-shapes, the metric for validating the magnitude component of the model-based oscillatory response is given by:

$$Osc_M = 1 - \frac{1}{\sum_{i=1}^{P} \omega_i} \sum_{i=1}^{P} \omega_i \varepsilon_i^m, \qquad \text{..........}(5.1)$$

where, ε_i^m is the error associated with ith mode and given by

$$\varepsilon_i^m = \frac{\|\hat{y}_i^a - \hat{y}_i^s\|}{\|\hat{y}_i^a\|} \quad s.t. \quad 0 \le \varepsilon_i^m \le 1,$$

$\hat{y}_i^*[k] = |\hat{B}_i|\hat{z}_i^k$ is the estimated contribution of the kth sample of the ith mode to the signal,

$\omega_i = \sum_{k=1}^{N} \hat{y}_i[k]^2$ is the weight factor of the i^th mode,

$\hat{y}_i^* = [\,\hat{y}_i^*[1] \quad \cdots \quad \hat{y}_i^*[N]]$ are the N sample of the pre-processed actual and simulated measurements, superscript ‘a' corresponds to estimates using actual response and ‘s' corresponds to estimates using simulated response, ‘P” is the number of dominant modes, $\hat{B}_i$ is the estimate of the mode-shape of the i^th mode and $\hat{B}_i$ is the estimate of the i^th mode in the z-domain as described in (Agrawal, Etingov, and Huang 2020). Here, the reconstructed signal used for calculating this metric is obtained by discarding initial phase of the modes so that the error associated with the initial phase does not impact the magnitude metric. Also, final metric for magnitude component of the oscillatory response is obtained by taking a weighted average of the error for each mode with the weight factor given by mode’s energy.

The metric for validating the phase component of the model-based oscillatory response is given by:

$$Osc_P = 1 - \frac{1}{\sum_{i=1}^{P} \omega_i} \sum_{i=1}^{P} \omega_i \varepsilon_i^p, \qquad \ldots\ldots\ldots (5.2)$$

ε_i^p is the normalized phase error associated with the i^th mode observed in actual and simulated measurements and given by

$$\varepsilon_i^p = \frac{\left|\angle\hat{B}_i^a - \angle\hat{B}_i^s\right|}{180} \quad s.t. \quad 0 \le \varepsilon_i^p \le 1,$$

and $\angle\hat{B}_i^a$ and $\angle\hat{B}_i^s$ are the estimates of the initial phase of the i^th mode obtained using actual and simulated measurements. The metric obtained for each mode is weighted with its energy to obtain a single metric. If any mode observed in the PMU measurement is not observed in the mode estimated using the simulated data, the maximum error of ‘1’ is assigned to both ε_i^m and ε_i^p for that mode.

The stepwise methodology to obtain the proposed metrics for validating model-based oscillatory response is as below:

1. Pre-process PMU and simulated measurements by using signal processing techniques, such as filtering, down-sampling, etc., for modal analysis.
2. Obtain mode estimates and mode-shapes for both pre-processed PMU and model--based measurements using steps described in (Agrawal, Etingov, and Huang 2020). In this step, selection of model order is carried out for both the signals by comparing pre-processed original and reconstructed signal. Also, dominant modes are distinguished from the spurious ones by calculating energy of mode estimates.
3. Calculate the two metrics to validate the model-based oscillatory response by comparing it with the actual oscillatory response -using (5.1) and (5.2).

Active power - Governor response:
Based on the step-response characteristics of a system, as shown in Figure 5-20 (MathWorks 2020), several metrics are defined to validate the model-based governor response by

comparing it with the actual governor response. Each metric looks into a specific aspect of the governor response, which are as follows:

1. Delay (G_d): Obtained by taking the difference of the time taken by the model-based and actual governor response to reach 10% of their respective peak value with respect to a common time--reference.
2. Peak value (G_P): Obtained by taking the difference of the peak value of the model-based and actual governor response.
3. Peak time (G_{PT}): Obtained by taking the difference of the time taken by the model-based and actual governor response to reach peak-value
4. Steady-state error (G_{SS}): Obtained by taking the difference of the final value of the model-based and actual governor response
5. Rise time (G_{RT}): Obtained by taking the difference of the time taken by the model-based and actual governor response to change from 20% to 90% of their respective peak-value.

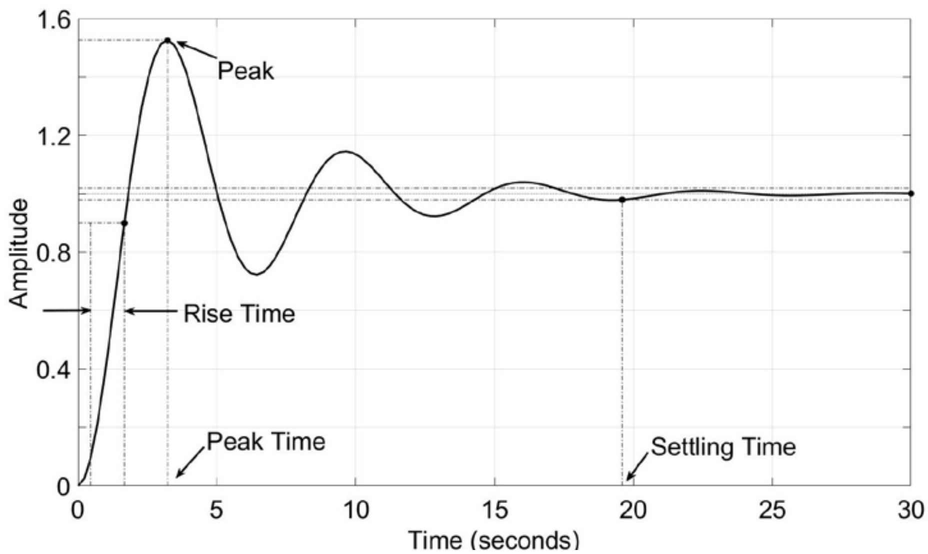


Figure 5-20. Step-response characteristics of a system

A simple root-mean square error can also be used instead of these several metrics to validate generator governor response, however it will not be able to provide any information on errors in specific aspects of the governor response, such as delay in the response, which can be helpful for model calibration.

Ideally, the mismatch observed in the actual and model-based generator response should be equal to zero. However, that is generally not the case. Therefore, certain thresholds need to be determined for each metric to validate the generator model. These thresholds should be determined based on the industry practices and is beyond the scope of the paper.

5.4.2 Results and Discussions

Results were obtained using simulated measurements and test-case to illustrate the effectiveness of the proposed metrics in quantifying model-validation results. This example is taken from the 12 disturbances set prepared by NASPI Engineering Analysis Task Team and NERC synchrophasor measurement subcommittee team for NASPI Technical Workshop on Model Verification Tools in 2016(Quint and Ramasubramanian 2016). Figure 5-21 shows the active power measured at the POI of the generator, and the model-based response of the generator obtained using PPMV tool developed by BPA and PNNL. Figure 5-22 shows governor and oscillatory response obtained from actual and model-based active power response. The results obtained for oscillatory and governor response is presented next.

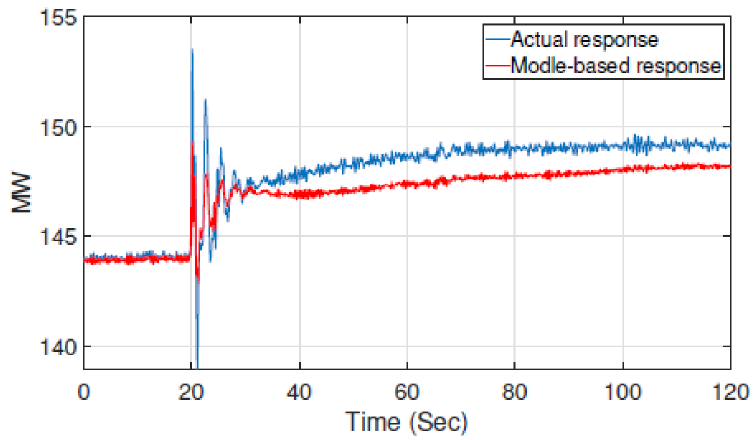


Figure 5-21. PMU measurements recorded at the Point of Interconnection, and model-based response of the generator obtained using PPMV tool

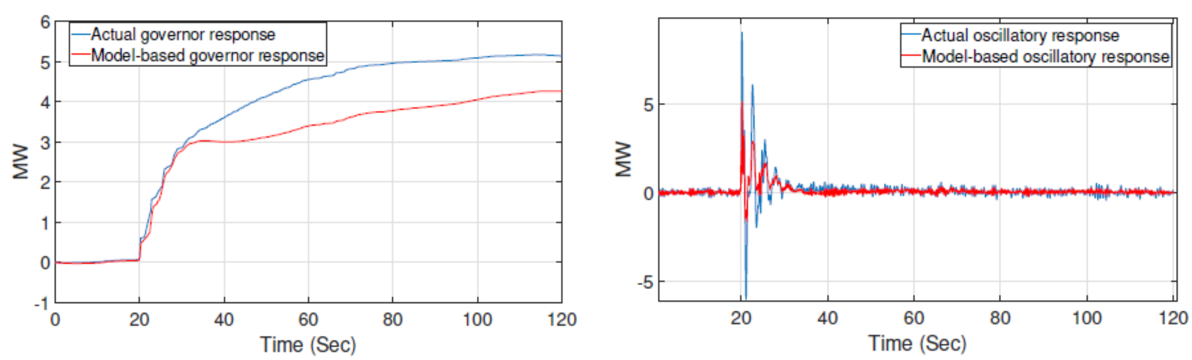


Figure 5-22. Generator governor (left) and oscillatory response (right) calculated using actual and model-based response

5.4.2.1 Metrics for oscillatory response

Using the methodology described in the earlier section, metrics were calculated for validating the model-based oscillatory response of the generator. Before performing modal analysis, the signals were down-sampled to 5 samples/sec and also frequency components lower than 0.1 Hz were removed. Using this pre-processed measurements, system modes and mode shapes were estimated for both actual measurements and model-based response. The model order selection is very critical to the proposed method as it can significantly affect the metrics for quantifying the validation results. For both actual measurements and model-based simulated data, model order of 22 was chosen that gave the best fit between the original and reconstructed data as shown in Figure 5-21.

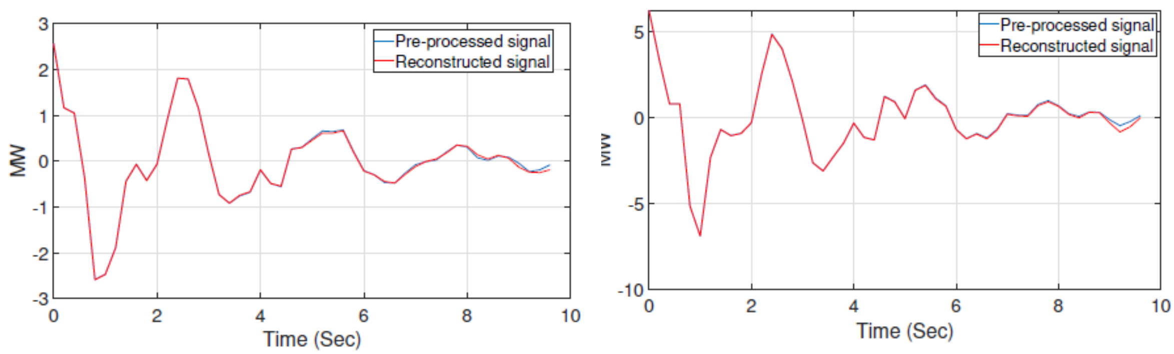


Figure 5-23. Illustration of the model order selection by comparing pre-processed and signal reconstructed by using mode and mode-shape estimates for a. Actual response (model-order = 22 and goodness of fit = 0.96) and b. Model-based response (model-order = 22 and goodness of fit = 0.97)

Table 5-8 and Table 5-9 give the mode estimates for the PMU and model--based simulated measurements. For metric calculations, mode estimates having energy less than 5% of the highest energy were not considered.

Table 5-8. Mode estimates for PMU measurements

Frequency (Hz)	Damping ratio (%)	Initial Amplitude	Initial Phase (Deg)	Normalized Energy
0.362	11.999	3.028	48.384	1.000
0.799	14.678	2.990	-65.998	0.426
0.634	8.873	1.599	161.012	0.272
1.248	2.276	0.503	64.129	0.045
1.737	1.177	0.412	-33.676	0.040

Table 5-9. Mode estimates for model-based simulated data

Frequency (Hz)	Damping ratio (%)	Initial Amplitude	Initial Phase (Deg)	Normalized Energy
0.361	11.759	1.236	41.543	1.000
0.814	12.912	1.177	-76.053	0.399
1.935	4.673	0.545	30.661	0.126
0.634	8.592	0.419	166.861	0.111
2.038	10.432	0.758	151.799	0.101
1.749	4.239	0.351	-1.507	0.059
1.261	1.953	0.112	13.848	0.015

Using (5.1) and (5.2), metrics for validating model-based oscillatory response were calculated and are given in Table 5-10. Based on the metric calculated for magnitude component of the oscillatory response, it can be said that the dynamic model does not accurately represent the model that generated the PMU measurements and requires calibration. This is also illustrated in Figure 5-22 that compares the contribution of two dominant mode estimates to the magnitude component of the PMU measurements and simulated generator oscillatory response. As seen in these figures, the contribution of the two modes to the PMU measurements and generator response do not have a good match. However, the phase component of the oscillatory response matched well based on the metric calculated. By performing sensitivity analysis, model parameters that affect the magnitude of the oscillatory response can be identified for model calibration.

Table 5-10. Metrics calculated for oscillatory response

Original model	Mode-1	Mode-2	Mode-3	Mode-4	Combined Metric
ω_i	1.000	0.426	0.272	0.045	
ε_i^m	0.588	0.593	0.734	0.772	0.3759
ε_i^p	0.038	0.056	-0.032	0.279	0.9342

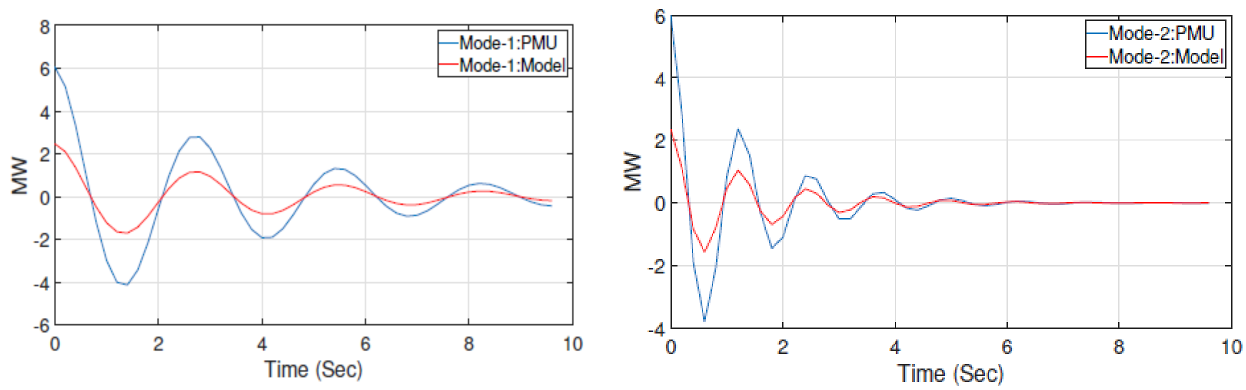


Figure 5-24. Comparison of contribution of selected modes to the magnitude component of oscillatory response of actual and model-based response – a. Mode-1 (left) b. Mode-2 (right)

5.4.2.2 Metrics for governor response

Using governor response extracted from actual and model-based response measurements, metrics were calculated comparing the actual and model-based governor response given in Table 5 11. Based on these metrics, it can be said that model parameters that can increase the peak-value of the governor response needs to be calibrated.

Table 5-11. Metric calculated for governor response

Parameter	G_d	G_P	G_{PT}	G_{RT}	G_{SS}
Error	0	0.9	-4	-18.32	0.88

5.4.2.3 Discussion

These results shown in the previous section validate the effectiveness of these new advanced metrics in distinguishing a good model from the one that requires calibration. These metrics analyze several aspects of generator dynamic response as compared to other existing metrics, and therefore provide more accurate results. Furthermore, generator model parameters that can help improve specific aspect of generator dynamic response, as given by error metrics, can be identified by performing sensitivity analysis using these new metrics.

6.0 Frequency Response Analysis Tool (FRAT)

The FRAT is a standalone Windows application with a user friendly GUI with advanced visualization (Figure 6-1) (Quint et al. 2016). The FRAT manages the database of under-frequency events and calculates the Frequency Response Measure (FRM) at an interconnection- and BA-level, as defined by the North American Electric Reliability Corporation (NERC) BAL-003-1 standard (NERC 2015). The application can use both PMU data, where available, and Supervisory Control and Data Acquisition (SCADA) data.

In addition to NERC FRM, the application calculates the nadir-based frequency response (FR) using Point C. FR metrics are saved in an application database. The primary users of the FRAT are balancing authorities and reliability coordinators. The individual unit FR analysis was also added to the FRAT 2.0 version. The application allows the user to compare measurement-based FR vs. model-based FR response.

The main features of FRAT include (Etingov, Kosterev, and Dai 2014, Quint et al. 2016):

- Automated determination of frequency response parameters (initial frequency, frequency nadir, settling frequency, etc.).
- Visual inspection and adjustment of automatically determined FR parameters.
- Calculation of FRM and nadir-based FRM, as well as additional performance metrics such as FRM at 30 sec, 60 sec, 90 sec, etc.
- Frequency response monitoring for: (1) interconnection-wide, (2) Balancing Authority (BA), and (3) power plant-level
- Archiving historical events into an internal database and baselining system performance.
- Performing statistical analysis and FR event data (linear regression, basic descriptive statistics).
- Visualizing FR performance using different plots based on date, time, day of the week, wind/solar generation, etc.
- Automatically generate reports (including FRS 1 form) in Word format.

Figure 6-2 shows the result of interconnection FR baselining. Historical information of under-frequency events for several years were collected and analyzed using the FRAT. The interconnection baselining helps to identify the interconnection FR trend and also determine basic statistical characteristics (e.g., mean value, median, and standard deviation).

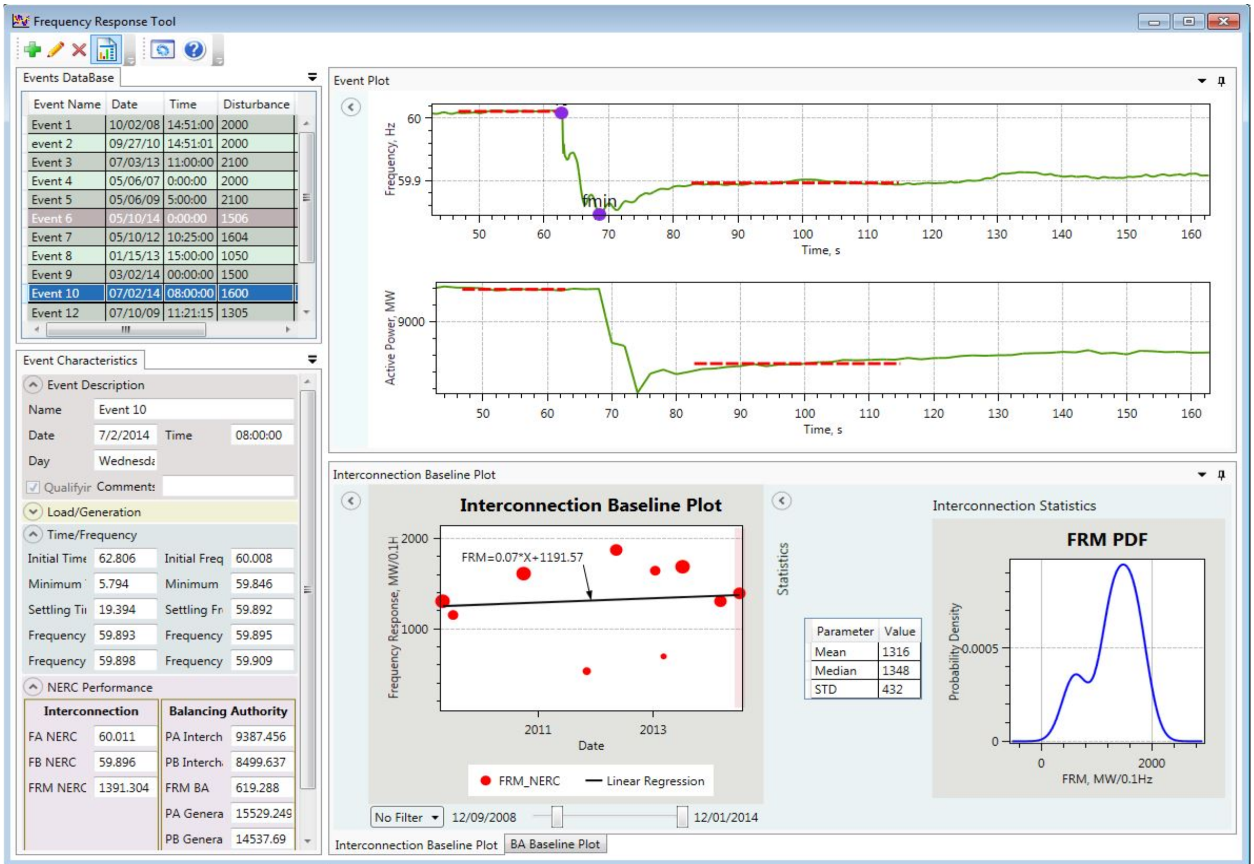


Figure 6-1. FRAT main GUI

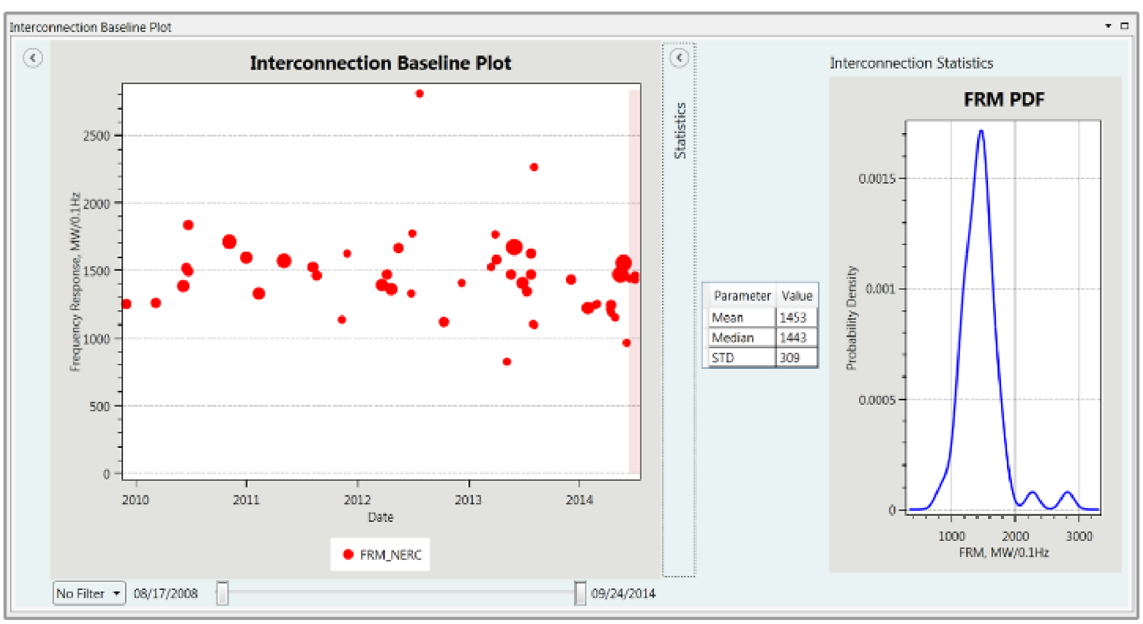


Figure 6-2. Interconnection baselining

The FRAT can also generate an animated heat map that shows the frequency propagation across the electrical grid. An illustration of the event frequency map is presented in Figure 6-3.

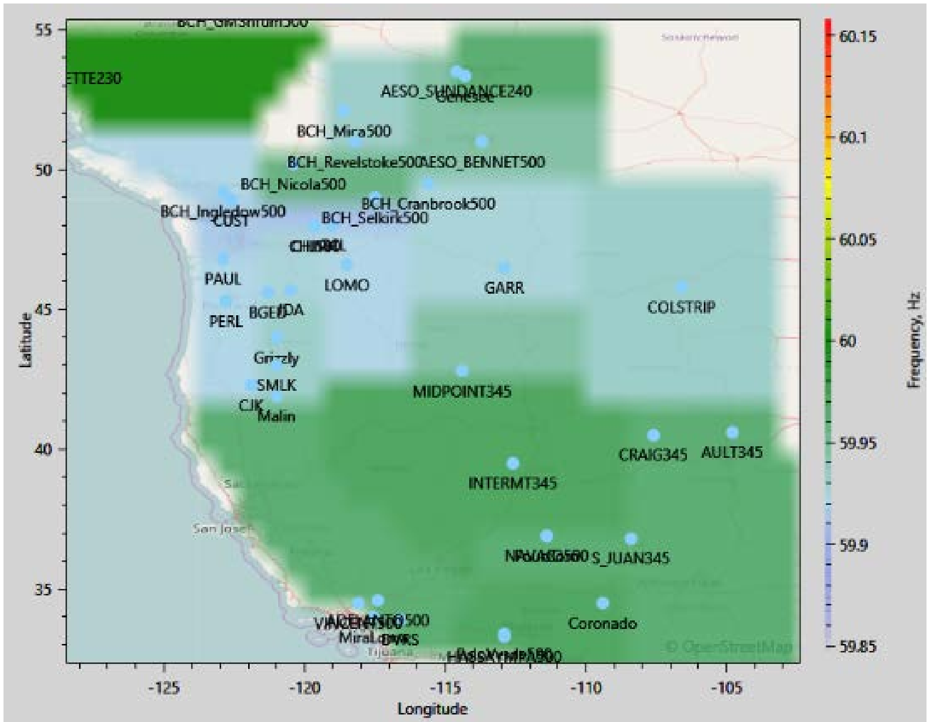


Figure 6-3. Frequency map

7.0 Conclusions

The open-source suite of PMU analysis tools presented in the report expands the feasibility and usefulness of synchrophasor-based applications and allows utilities to benefit from their investment in, and deployment of, various synchrophasor technologies. The software applications presented in the report have been used by BPA and other utilities and received very positive feedback and evaluation. Because the framework is open source, any developer can contribute to the application set either by modifying existing software or by creating new applications. In addition, third-party organizations and vendors can build commercial products based on the open-source code developed under this research.

Open-source power system analytical tools and software modules have been developed. They are based on the common open platform and data format structures and can serve as building blocks and solutions for future and third-party applications:

- Archive Walker (AW)

  The AW is a powerful tool that provides data management, signal processing, and event detection functionalities. It has the capability to read in PMU data from multiple sources (PI database, Open Historian, PDAT, CSV), apply data quality checks, manipulate streams to create custom signals, and apply a variety of signal processing techniques. After the data is prepared, a variety of detectors can be applied to identify out-of-range events (e.g., voltage sag/rise, frequency excursions), search for ringdown-producing events (e.g., line trip or switching operations), detect forced oscillations, and examine characteristics of wind plant ramping and response to disturbances. Events are tracked over time and across the grid to support in-depth analysis by system engineers and reports can be generated automatically.

- Oscillation Baselining and Analysis Tool (OBAT)

  The oscillation analysis block will be based on algorithms built in the OBAT (e.g., Prony and Matrix Pencil). The OBAT maintains a database of oscillation events, is able to automatically generate oscillation analysis reports, and also has advanced visualization capabilities. One of the most important features of the OBAT is the capability to perform oscillation baselining. Several statistical methods to correlate the output of oscillation analysis algorithms (frequency, damping ratio) with system condition parameters (e.g., power flows, angle pair difference) have been developed. Statistical analysis can help to extract signatures for different oscillatory conditions. Thus, the OBAT can help to identify system conditions when the power grid can be potentially "at risk" in terms of electromechanical oscillations.

- Load Model Data Tool (LMDT)

  The LMDT application helps to generate composite load model parameters considering climate zone and seasonal information, operating hour and feeder type. The LMDT reads in the necessary long identifier (LID) information, and supplements that with the base case power flow conditions and supplemental load shape data to generate the composite load dynamics records in GE PSLF and Siemens PTI PSS®E format. LMDT supports a variety of load and distributed energy resources (DER) models.

- Power Plant Model Validation Tool (PPMV)

The PPMV tool helps to automate the power plant model validation process based on the disturbance recordings. Validation of power system models for power flow and dynamic studies is very important for ensuring that these models are accurate and up to date. The NERC Modeling, Data, and Analysis (MOD-026-1 & MOD-027-1) standards enforce requirements for power plant modeling, data, and system analysis. The main goal of these standards is to ensure validation and monitoring of model performance. The MOD standards allow generator owners to perform model validation using disturbance event records. The PPMV tool provides a mechanism for doing that evaluation.

- Frequency Response Analysis Tool (FRAT)

  The FRAT manages the database of under-frequency events and calculates the Frequency Response Measure (FRM) at an interconnection- and BA-level, as defined by the North American Electric Reliability Corporation (NERC) BAL-003-1 standard. In addition to NERC FRM, the application calculates the nadir-based frequency response (FR). The primary users of the FRAT are balancing authorities and reliability coordinators. The individual unit/power plant FR analysis can also be performed. This feature enables comparison of measurement-based vs. model-based frequency response.

- Archive Sprinter (AS)

  Archive Sprinter was designed to rapidly generate information summarizing large archives of synchrophasor measurements. The tool is intended to generate data for further analysis, rather than detecting periods of interest during processing. The data summaries generated by Archive Sprinter are composed of a user-selected set of signatures, such as the variance and maximum value, that highlight periods of interest in the data. The signatures require little disk space and can be calculated rapidly. Archive Sprinter's design also allows for parallel processing to make analysis of long record lengths practical.

The project addressed oscillation analysis, frequency response, model validation and calibration, load modeling, and other important power-grid-related issues. Theoretical outcomes of the project include:

- Improved reliability of oscillation monitoring (mode meter) algorithms that mitigate bias from forced oscillations and grid disturbances.
- Transient oscillation analysis method suitable for online use.
- Methodology for quantifying model validation results for generator governor response, which now completes metrics for quantifying overall generator dynamic response consisting of governor and oscillatory response.
    - These metrics can help identify generator models that do not have accurate dynamic response, and thereby help obtain models that can collectively represent accurate system oscillatory behavior and dynamic response.
    - This method is applicable to ringdown–oscillation type of system response in which modes are observable in the PMU measurements.

The software tools are available on-line for downloading at:

- FRAT: https://svn.pnl.gov/FRTool
- PPMV: https://svn.pnl.gov/PPMV
- LMDT: https://svn.pnl.gov/LoadTool
- OBAT: https://svn.pnl.gov/OBAT
- AW: https://github.com/pnnl/archive_walker
- AS: https://github.com/pnnl/archive-sprinter

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