Standardized Testing of Phasor Measurement Units

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Abstract

This paper describes a set of tests used to determine Phasor Measurement Unit (PMU) measurement characteristics under steady state and dynamic conditions. The methodology is repeatable, comparable among test facilities, and can be performed at any facility with commonly available relay and standard test equipment. The methodology is based upon using test signals that are mathematically generated from a signal model and played into the PMU with precise GPS synchronization. Timing flags included with the test signal provide correlate the test signals and the PMU output. This allows accurate comparison of the phasor model with the value estimated by the PMU for accurate performance analysis. The timing flags also facilitate programmed plot and report generation.

I. Introduction

A Phasor Measurement Unit (PMU) is an intelligent electric device (IED) whose principal function is estimating the phasor equivalent for power system voltage and current signals [1]. It also measures system frequency, digital status indications, and in some cases, other point-on-wave analog quantities [2]. A PMU is distinguished from other transducers by using precise timing to determine phase angles relative to a universal timing reference and by the potential quality of its data output.

PMUs provide best value when organized into synchronized phasor measurement (SPM) networks to obtain an integrated profile of network conditions across a wide area of the power system. The SPM networks provide a technology base for more general synchronized system measurement networks that incorporate data from critical facilities, such as HVDC and high performance generator controls, with links into SCADA and other EMS resources.

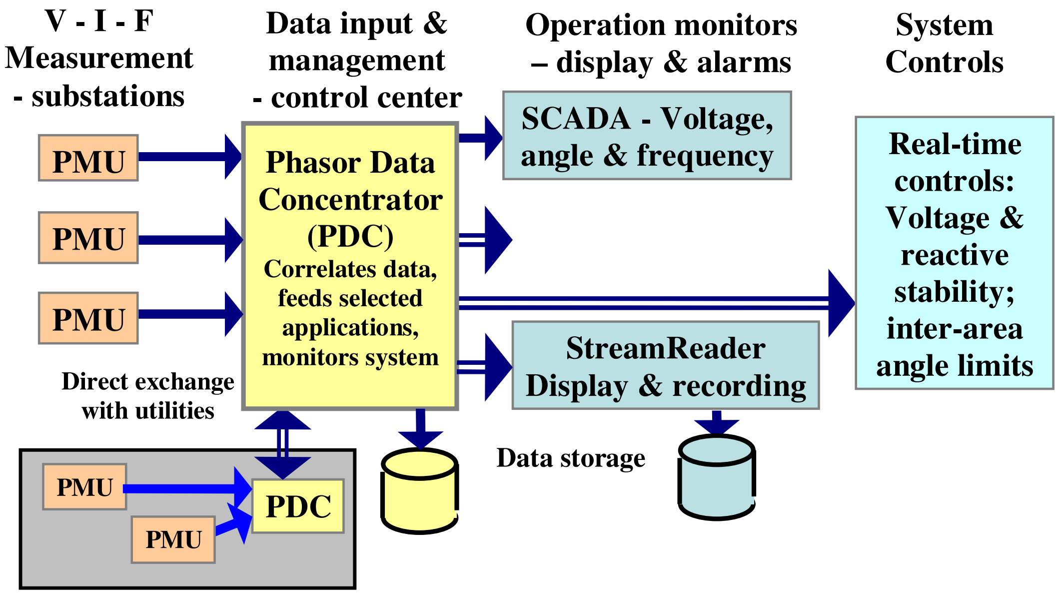


Figure 1. Real-time phasor measurement system used at the Bonneville Power Administration, typical of many real-time systems used by many utilities.

Most utilities install PMUs at their key substations and use dedicated communications to send the data to their control center in real time. A data concentrator (PDC) at the control center collects the data, sending it to local applications and recording it. These systems may be further linked to other utilities to provide a true wide area view of the power system. Data reporting rates for these systems range from 6 to 60 samples per second (sps). Figure 1 illustrates the phasor measurement system used at BPA, which is typical of many utility systems. Phasor systems in the WECC generally use one measurement every two cycles (30 sps). This data rate can capture most wide area dynamic behavior of the AC transmission system. Data from other monitor systems that operate at lower or higher data rates can be integrated into the SPM data set with appropriate up or down sampling.

Phasor measurement systems provide essential power system information for a variety of applications. These measurements have been used extensively to observe and analyze power system operation, both in real time and in post event analysis [3,4,5] using displays showing power flow, system frequency, and system wide phase angle. State estimation is the process of estimating system bus voltages, both phase angle and magnitude, from line flows and using that to solve all line flows. Phasor measurement estimates these voltages directly from the waveform, offering a significant improvement in the process. Several utilities are in the process of adding phasor data into the state estimation process. Some utilities are sampling phasor data into their EMS (SCADA) system. This data can then be included in operator and dispatcher reporting and operating screens. BPA uses selected phase angles reported to SCADA to alert dispatchers to possible cut-plane violations. At the other end of the spectrum, the high-speed and high accuracy capability make phasor data ideal for measurements in response based controls. BPA is developing a Wide Area Control System (WACS) which uses both the voltage and power measurement capability of phasors to detect a large disturbance that will require control action to prevent a system failure [6,7]. Many other utilities are also using or developing applications that use phasor measurements.

Early deployments of PMUs demonstrated they can make accurate, high-speed measurements of power system quantities [8]. However, comparisons with field data from analog systems, SCADA, and DFR snapshots were not sufficient to fully characterize and validate phasor measurements. At BPA, we subsequently performed detailed tests using a digital simulator. In 1991 we tested the original PMUs from Virginia Tech [9] and found the basic measurements very accurate and the dynamic response fast and predictable. Those tests focused on the high-speed estimates used internally in the PMU rather than the slower data being sent to the concentrator. In 1993 the first commercial PMU, the Macrodyne 1690M, was examined under field conditions. This identified filtering needs beyond those of a simple Fourier conversion [1] and it initiated a program of PMU model development at BPA [10,11]. In 1995 BPA performed a more extensive set of tests on this PMU [12]. Results were similar to the first set of tests in terms of accuracy and speed, but we found that the PMU introduced anomalies when it decimated data from the 720/sec internal speed to the 30/sed reporting speed. In 2001 BPA purchased second generation PMUs and designed a set of tests designed to verify specification compliance. Related tests were performed at British Columbia Hydro (BCH) and at the Pacific Northwest National Laboratory (PNNL), to evaluate PMU types that BPA did not possess at that time [13]. These tests, supplemented by model studies and by evaluation under field conditions, have been steadily improved to better characterize PMU performance in all aspects of measurement. The results have provided useful guidance in vendor development of PMU technology, and they have sometimes been necessary for operational use of data from evolving PMU types.

Other organizations have also developed tests to characterize PMUs and qualify them for service. American Electric Power has developed a testing standard for PMUs. Like BPA, their test results are used for qualification of devices to be deployed in their system. Virginia Tech comparison tested four different PMUs at both nominal and off-nominal frequencies [14]. They found these PMUs responded differently in all situations, particularly in special conditions, like off-nominal frequency. This emphasized the need to characterize PMU performance in all conditions under which the PMU will be expected to operate. Related issues, based on PMU simulations, are raised in [15].

II. PMU Technology

A phasor is an equivalent representation of a pure sine wave. A pure sine wave is fully characterized by frequency, magnitude, and phase angle. For a given frequency, representation only requires magnitude and phase angle, two values that can be represented by a complex number. This number can be viewed as a vector in the s-plane (Fig 2).

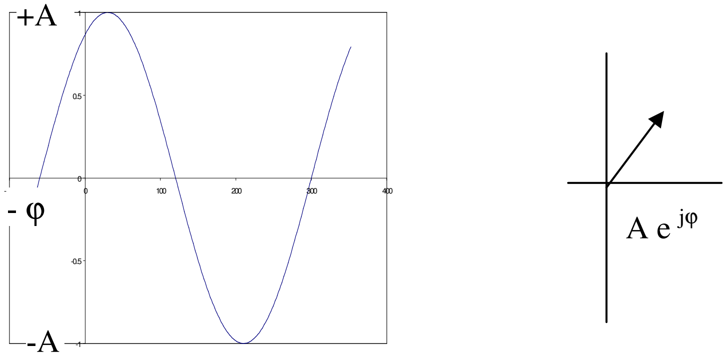


Figure 2. Sine wave with equivalent phasor representation on the complex plane.

While this signal model can represent a fixed sinusoid exactly, actual power system signals are far more complex than that. PMU inputs may contain many sinusoidal components, even under normal conditions; mathematically, they contain infinitely many sinusoidal components during a sharp transient. Furthermore, the parameters for each of these signal components are continually varying. For these reasons the design of an instrument for phasor measurements must consider the frequency range of signal components to enter and exit the instrument, and how to present appropriate average values for varying phasor parameters.

A. Phasor Measurement Units

There are a variety of methods for estimating phasor equivalents of voltage and current waveforms. The most common method uses time synchronized sampling and a Discrete Fourier Transform (DFT) to estimate a phasor equivalent. Typically, a PMU estimates the phasor value for all three phases and derives a positive sequence equivalent using the symmetrical component transform. Some special applications use single phase phasors, and others use negative or zero sequence. Most applications use phasor values as a measure of power system operation, of which positive sequence is the most useful. Figure 3 is a block diagram of the overall process.

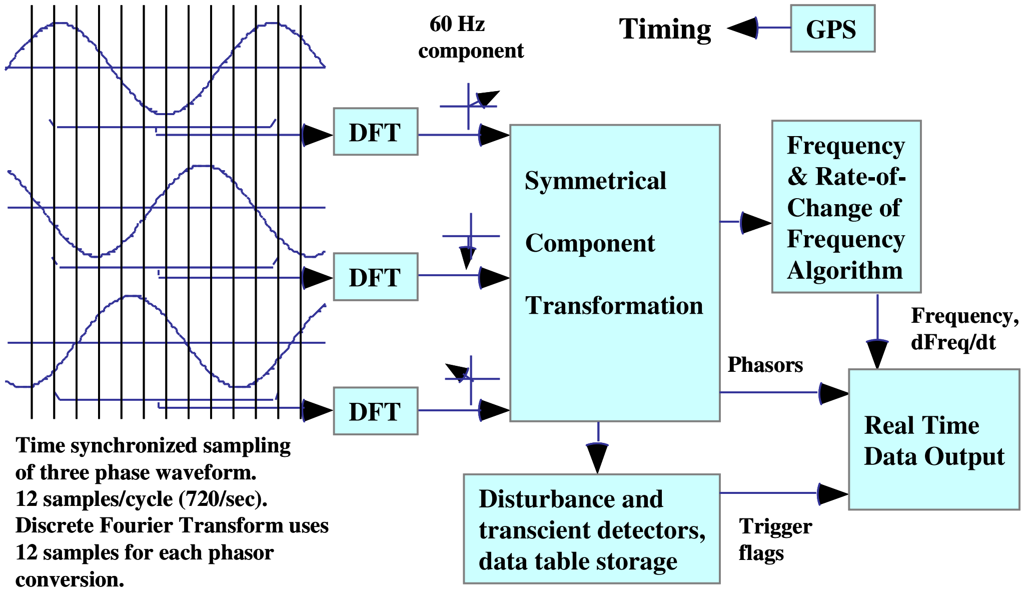


Figure 3. Typical PMU measurement process

B. Measurement Issues

Proper performance of a phasor network requires that the data from all PMUs be *valid*, *consistent*, and sufficiently *detailed* for the intended range of applications. Application issues are out of the scope of this document, but can be found in other references [4,11,13].

PMU testing can be broken into two categories: comparing the measurement with a known standard or reference to see if it meets specific criteria, and characterizing the measurement for comparison with similar or complimentary measurements. The first category includes simple measurements like magnitude or phase angle with a constant input. We also associate measurement errors with this category, which are caused by hardware problems, algorithm errors, and other design shortcomings. The second category includes characteristics of the measurement that result from tailoring to the application (response time, data rate, etc) and occur in special situations, such as varying system frequency or modulated signals.

Many measurement errors have been discovered during testing. Problems have also been discovered during analysis of power system events by careful comparisons from multiple sources [13,14]. In some cases, the equipment vendor has corrected the problems. In others, we have been able to compensate the data to correct it. It is certainly a goal of careful testing to determine and resolve all these issues before deployment. But in reality, one can not fully predict the performance of a PMU in actual operation. We continually bring operational experience back to testing to improve the process.

To calculate a phasor equivalent, a waveform must be observed over an interval long enough to measure its characteristics, typically at least a cycle. With the power system, the waveform is not a pure sine wave over any interval. It will have changes in amplitude, phase angle, and frequency as well as other artifacts such as random noise, modulated signals, and harmonics. The interval must be the right length to allow the estimation process to produce a good estimate, which will be a kind of ‘average’ equivalent over the interval. Different interval lengths as well as different conversion algorithms, filtering, measurement rate, synchronization, and equipment resolution will effect the measurement. These differences will produce different results under various power system conditions. Many of these differences reflect design trade-offs that favor different applications, and no one implementation will best serve all of them.

The second goal of testing is to characterize performance well enough that the user can choose the device that best meets the application needs. It should be complete enough to compensate measurement differences between PMUs for combined analysis.

III. PMU Testing

The basic test process requires generation of a test signal with specific characteristics, application to the PMU, and comparison of the resulting PMU output with the expected result. It is relatively easy to calculate a sine wave equivalent for a given phasor. However it can be difficult to generate a three-phase signal of voltage and current at power system levels with precise time synchronization to UTC. Fortunately, several relay test sets are available now which will do that, and they greatly simplify the task. Ultimately the goal is to create a signal using phasor representation, convert that into a test signal, input the test signal into the PMU, and then compare the PMU estimate with the original phasor representation (figure 4). If any of the measured parameters vary in time, the test signal generator will require precise timing of the signal output. At 60 Hz, 0.1 electrical degree is 4.6 microseconds; testing to that accuracy requires generating signals with time synchronization 2.3 microseconds or better.

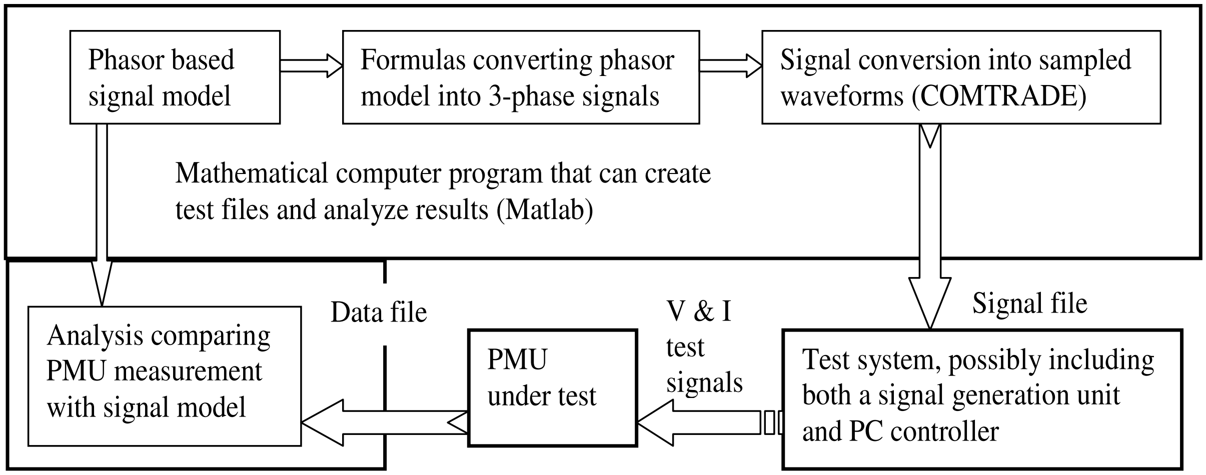


Figure 4. Block diagram of idealized test procedure

A. Testing goals

Regardless of how testing is designed or implemented, it should cover all aspects needed to assure the equipment will perform as expected. Some important tests are not covered here, including performance over a temperature range, input isolation (SWC), and mechanical construction. This document covers only the measurement performance. The ultimate goals of measurement performance tests are:

- Compare certain performance characteristics against standards
- Reveal errors in measurement
- Provide sufficient information that measurements from different PMU devices can be used together accurately

The tests developed to meet these goals can be categorized into 3 groups: steady-state, step, and structured signal. In steady-state tests, the measured parameter is constant during test. These include basic tests like magnitude, phase angle, and frequency. Step tests are a simple dynamic test where the measured parameter undergoes a step change. It provides a simple method to compare dynamic response that is relatively easy to implement. Structured signal tests are all those that could not be implemented with standard test-set methods, and include modulated and harmonic signal combinations. These tests are detailed in the following sections.

B. Steady-state tests

Steady-state tests form the backbone of all testing. A PMU device should provide an accurate measurement of the power system at standard signal levels in non-changing conditions. Failure of this indicates inadequate design or device capability. Accuracy limits depend on requirements for a specific test. Generally we find magnitude accuracy better than 1%, phase angle accuracy about 0.2 degrees, and frequency measurement within .002 Hz. Steady-state tests include the following:

1. Phasor magnitude – balanced, three-phase voltage and current.
2. Relative phasor angle – angle between two balanced, three-phase voltage and/or current signals.
3. Absolute phasor angle – absolute phase angle relative to UTC time with balanced, three-phase voltage or current.
4. Phasor magnitude vs. frequency – balanced, three-phase voltage and current with constant magnitude and phase angle, and frequency from 10 to 300 Hz. Frequency measurement 55-65 Hz should be with small increments to assess measurement accuracy; wider bandwidth can be larger increments as purpose is to assess filtering.
5. Phasor angle vs. frequency – balanced, three-phase voltage or current with constant phase angle and magnitude and frequency varied from 55 to 65 Hz.
6. Phasor magnitude with unbalanced signals – three-phase voltage and current with one phase varied in magnitude. Perform at 59, 60 and 61 Hz.

7. Frequency measurement – balanced, three-phase voltage or current into channel in which the PMU measures frequency. Test 28 to 92 Hz (limit of measurement by IEEE standard data), or narrower depending on need or PMU capability.
8. Measurement noise – examine a number of records where magnitude, phase angle, or frequency are constant and compute the point to point deviation. This is not an exact measurement; the maximum peak-to-peak deviation is probably the easiest to measure and the best indicator of the usability of a measurement.

Figure 5 illustrates test 5, one of the more complex of these tests to perform. The test signal is set at -90 degrees since it is much easier to compare the sine wave with GPS at a zero crossing than a maximum at 0 degrees. The result should be a constant -90 degrees. One PMU has not been compensated for internal delays and is 16 degrees off at 60 Hz. None of them (in this test) are compensated for frequency, and errors range from +1.8 to -15.2 degrees/Hz. Under stressed conditions, the power system could easily have an excursion to 60.2 Hz which could result in errors of up to 3.4 degrees between PMUs, even if corrected at 60 Hz. This kind of error is not immediately obvious, nor would it be noticed in most measurements. An important result of this testing is to bring out latent issues like this so they will not lead to incorrect analysis conclusions, or ill-advised operating decisions at a critical moment.

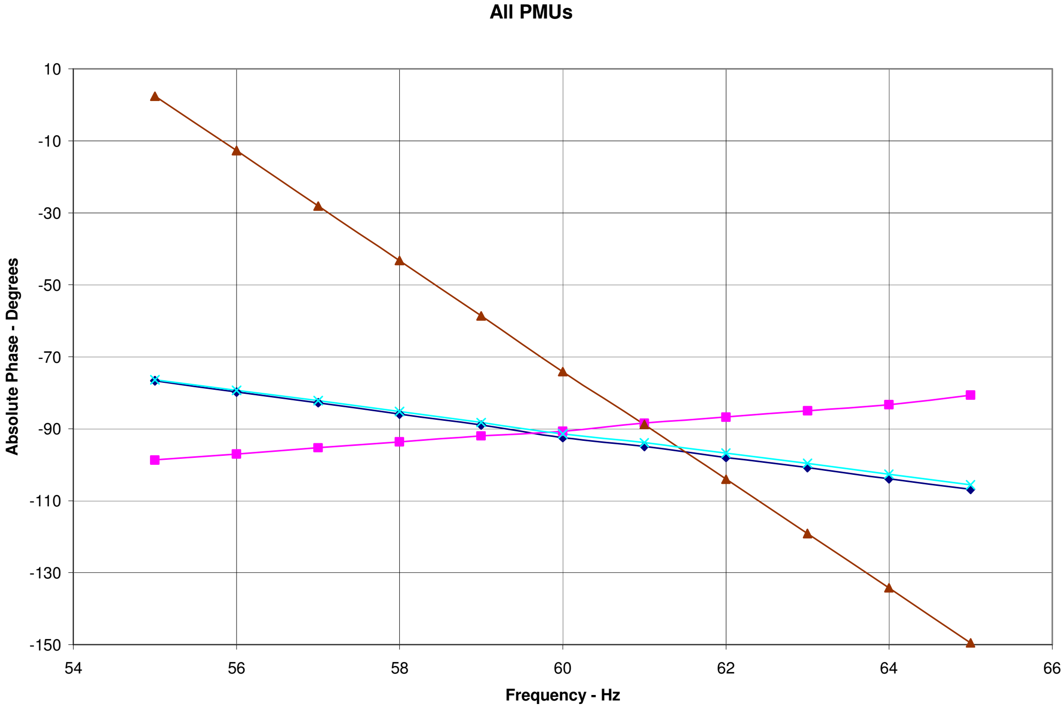


Figure 5. Measured phase angle over frequency. 4 different PMUs with the test signal set at a constant -90 degree phase angle.

C. Step tests

Step tests characterize the measurement with a step change. An impulse function is the best way to characterize a linear system since the response describes the transfer function. However, most physical devices become non-linear with true impulse functions, so a step function is a suitable second choice. A step function provides a well defined time and transition between two states, is easy to model and generate, and shows the response speed and characteristics such as overshoot and settling. Most important events in a power system include faults and switching, which are step functions. It is important to be able to characterize PMU measurement in these conditions. These tests are used to categorize the PMU response and compare PMUs.

Useful step response tests include the following:

1. Phasor magnitude step – balanced, three-phase voltage or current with 10% to 50% steps in magnitude, both positive and negative.
2. Phasor angle step – balanced, three-phase voltage or current, constant magnitude, with positive and negative steps, 10 to 90 degrees.
3. Frequency step – balanced, three-phase voltage and current, constant magnitude and phase angle, frequency stepped from 60 to other values between 0.1 and 5 Hz.

Originally, a technique was used that would introduce the step at a known instant of time showing the actual time delay. That technique did not work universally, so the usual procedure is to introduce steps randomly, compare across many responses, and use a typical response as representative. A typical test with 4 PMUs is shown in Figure 6. This shows the substantial difference in responses which may be important for some analyses. Since the exact point the step occurs is unknown, it is not possible to quantify response time. However they all complete their response within 4 sample points (.133 sec) which is close enough for many data uses.

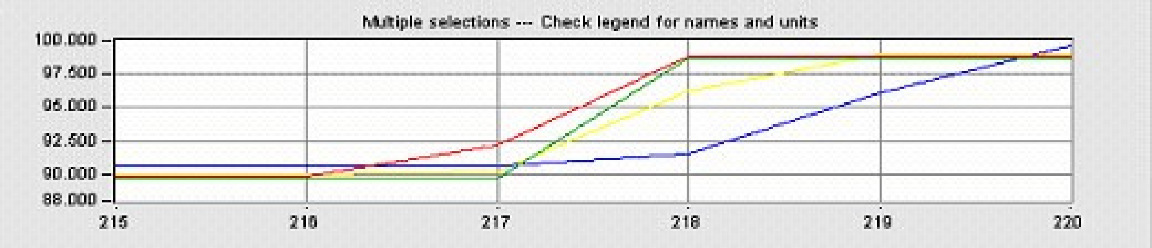


Figure 6. Positive 10% step in magnitude, 4 different PMUs show similar but significantly different responses.

D. Structured signal tests

This category includes steady state and dynamic test signals that are not standard features in relay test sets. They include modulated and combined multiple signals. These tests have always been performed using files of signals, and can be used to categorize group delay, filter effects, distortion, and relative response of modulated signals. Such tests include:

1. Modulation scan This test examines PMU response to several kinds of modulation of the 60 Hz power signal. These include modulating with a sine wave with varying amplitude, angle, or frequency with appropriate ranges of variation. Several frequencies of the fundamental can be used (typically 59 Hz to 61 Hz), and with various unbalanced inputs.
2. Single frequency response scan This is the same test as steady state test #4 but using a set of frequencies recorded in a test file.
3. Harmonic rejection test This test examines PMU response to harmonics of the operating frequency. Rather than using lower frequencies modulated on a carrier as in test 1, this one adds harmonics to test the PMU ability to reject harmonics.

Figures 7 through 9 illustrate some of the information produced. The amplitude modulation scan shown in Figure 7 is a useful first test under laboratory conditions. The assumed operating frequency is 60.06 Hz, and the amplitude modulation frequencies are in the sequence [0 0.28 1.4 6.64 12.0 15.0 21.72 28.7 30.0 30.85 36.89 45.0] Hz.

The output rate for these instruments is 30 sps, which can support no output frequency higher than the Nyquist frequency of 30/2=15 Hz. Response to inputs higher than this will necessarily be "aliased" to a lower frequency – e.g., a generator shaft oscillation at 21.72 Hz would produce an output at 1.28 Hz, and mimic a generator swing mode. The secondary axes in Figure 7 show the relationship for this, and the overall figure shows that none of these instruments is fully protected against aliasing. This same information is implicit in the single frequency response scans of Figure 8.

Another class of problems is shown in Figure 9, where amplitude modulation of some PMUs has produced spurious cross modulation of their frequency output signals. This appears to be a result of asymmetric filtering in PMUs that do not compensate for off nominal system operating frequencies.

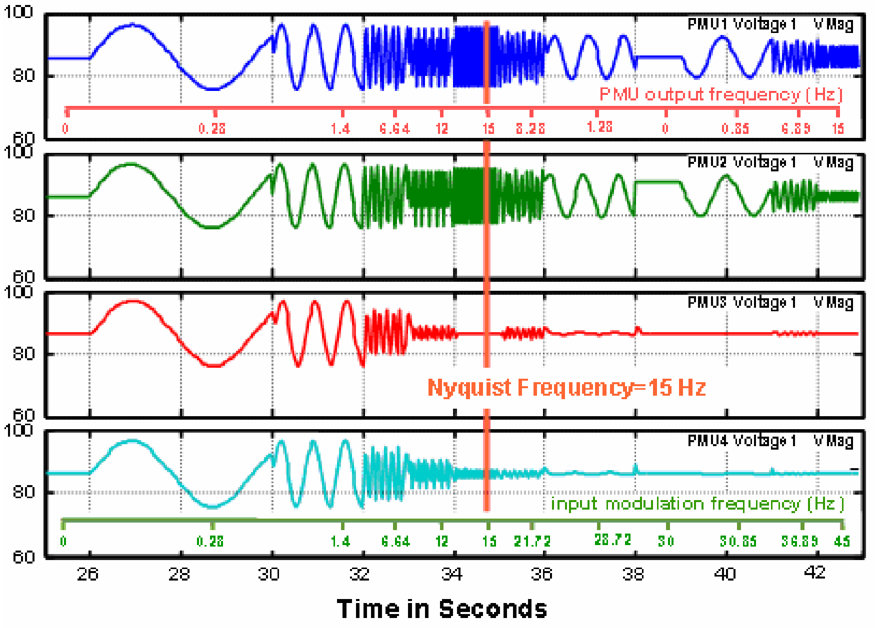


Figure 7. Amplitude modulation scan of four PMUs.

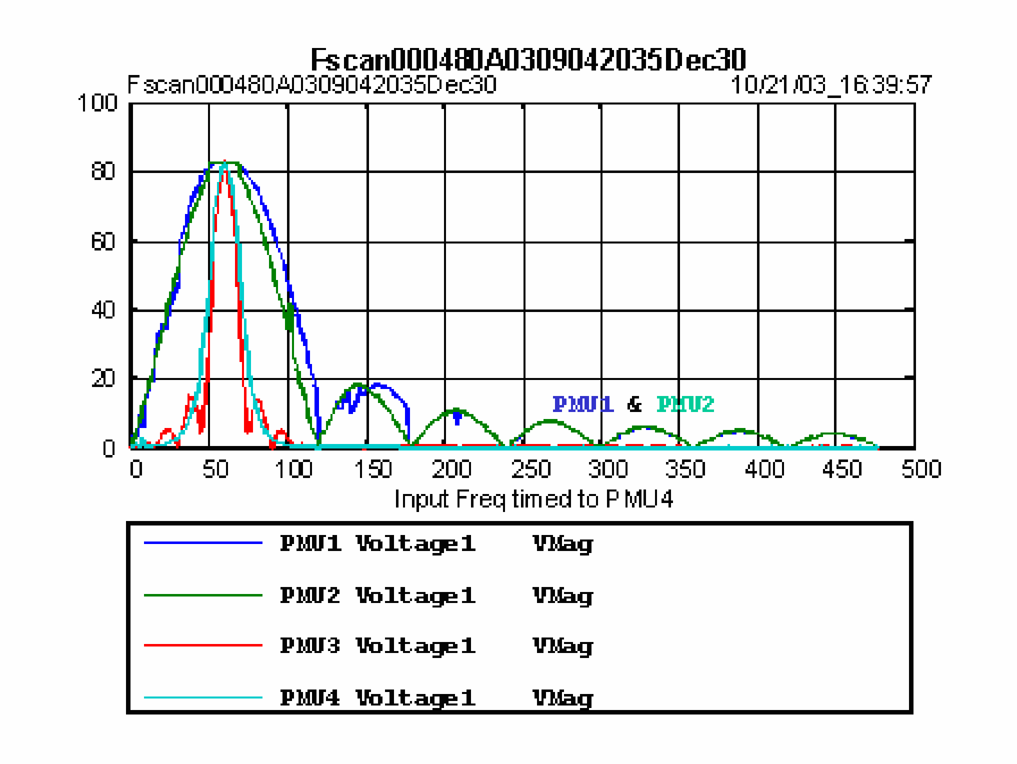


Figure 8. Single frequency response scan of four PMUs.

Several other kinds of information can be extracted from the amplitude modulation scan. Examining PMU outputs across a time interval of zero modulation provides general indications of their relative accuracy, offsets, and noise characteristics. Relative timing, gain, and waveform distortion can be determined very accurately through Prony analysis of PMU response to the lower modulation frequencies (e.g., up to perhaps half the Nyquist frequency) [13].

Table 1 indicates that the voltage output from PMU3 is about 34 msec later than that from PMU4, and some 55 msec later than that from PMU2. Mode shape analysis, if based upon this collection of PMUs, would have an uncertainty of ±14 degrees for a 1.4 Hz local mode oscillation. These output discrepancies exist even though the instruments, nominally at least, are synchronized within a few microseconds at their inputs.

Table 1. Relative Timing of Four PMUs (playback file AMod6006MseriesA, 1.40 Hz)

Signal	Res Mag	Res Angle	Rel Delay (msec)
PMU1 VMag	10.3309	160.562	8.7
PMU2 VMag	10.3400	175.578	-21.1
PMU3 VMag	10.2610	147.745	34.2
PMU4 VMag	10.2632	164.957	0.0

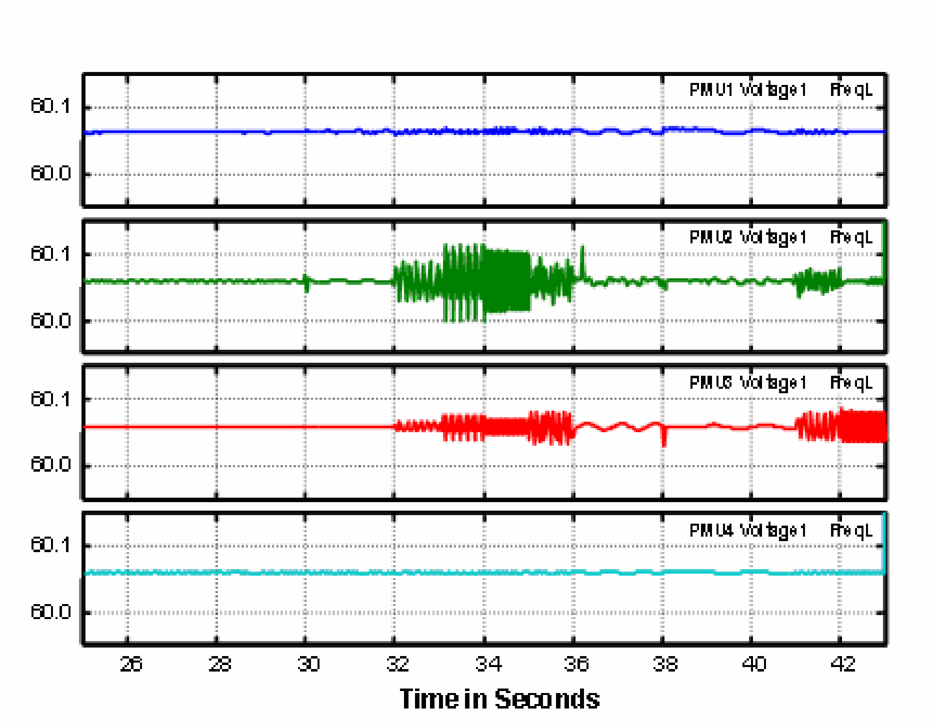


Figure 9. Spurious cross modulation of PMU frequency outputs.

E. Measurement noise, latency, and environmental tests

Measurement noise in this context is the small point-to-point variations in a constant measured signal (fuzziness on a line). It may be caused by noise in the signal being measured, limitations in the sampling and processing, or errors in the signal processing. It limits the resolution of the measurement and if significant, necessitates some kind of reprocessing to reduce noise. Considerable variation was observed in the PMUs under test, so noise in magnitude and phase angle is assessed by observing a few seconds of the signal under constant input conditions, and recording the peak-to-peak values.

There are a number of aspects to latency (or delay) that won't be delved into here. Generally, latency is the time from when an event occurs in the power system until the corresponding data can be available at a data receiving unit. This is only important for real-time applications, from controllers to system operations. The first aspect is the length of time between the occurrence of an event and the processed data representation. This can be estimated with an accurate step test. The second aspect is how long it takes the PMU to compute the data and output it. This requires the ability to apply absolute arrival time to data at a receiving device. Together these show overall latency. BPA has made a number of these measurements using specialized GPS based measurement timers in a PDC. In all cases, measured latency—excluding external data communications—was less than 200 ms, quite fast enough for operators but too slow for some controls.

Environmental tests include operation under standard temperature and humidity ranges. They also include power supply variation and ability to withstand damage from all inputs (SWC). The unit also has to be mechanically sound and be installable in a standard rack or panel.

F. Testing requirements for IEEE standard 37.118, 'Synchrophasors for Power Systems'

IEEE standard C37.118, Standard for Synchrophasors for Power Systems [2], defines a Synchrophasor, sets out performance requirements, and describes a communication protocol for real-time phasor measurement systems. Section 5 of the standard defines minimum reporting rates, response time, and in particular, performance requirements. Performance is measured as the difference between the ideal phasor value for the given AC waveform and that measured by the PMU device. For a waveform described by the phasor value $\boldsymbol{P} = X_r + jX_i$ where X_r is the real component and X_i is the imaginary component at instant t_0 and $\boldsymbol{P}(t_0) = X_r(t_0) + j\, X_i(t_0)$ is the estimated phasor value for that same instant, the total vector error is:

$$TVE = \sqrt{\frac{(\mathrm{X_r}(t_0) - X_r)^2 + (\mathrm{X_i}(\mathrm{t_0}) - \mathrm{X_i})^2}{\mathrm{X_r}^2 + X_i^2}} \qquad (1)$$

The phasor equivalent is one complex number and this evaluation method treats it as one value, simplifying the specification of requirements. It may make evaluation more complicated where users evaluate the magnitude and angle measurement accuracy separately. The tests described in the previous sections separate magnitude and angle, since it is easier to set up standard test equipment using magnitude and angle. The standard allows evaluating characteristics independently, so results of the tests above can be evaluated in the TVE model. Annexes G and H of the standard provide examples.

Table 3 in Section 5.3 of the Standard gives the actual measurement requirements for a PMU. To claim full compliance with the standard, a PMU needs to meet the requirements of level 0 or level 1 compliance, and state which level was met. Level 0 is the least restrictive set and is particularly for devices that are intended for real-time systems that only need to observe large system changes. It only requires compliance over narrow frequency and magnitude ranges with little filtering of interfering signals. Level 1 tightens these requirements, which will probably slow the measurement response because of added filtering needs. The standard does not restrict the vendor from providing additional ranges or accuracy levels. Additional compliance and TVE levels may be added in future revisions.

The tests outlined in the sections above cover all the requirements of the IEEE standard. All that is needed is to find a way to put the phasor value that defines the test signal together with the measured response into the TVE equation. This is precisely what has been done with the development of automated testing described in the next section.

IV. Semi-automated testing

A. Need for improved test methodology

The tests described in Section III reveal most of the important characteristics of a PMU. They can be can be performed by an experienced engineer in a reasonable amount of time. Most of them can be done with commonly available test equipment.

Performing these tests is time consuming. With today's tight budgets, it is unlikely that most utilities will do complete testing or extensive comparison among devices. While some of the tests, such as amplitude or frequency scans, are just tedious, the phase angle tests are difficult to execute. A separate GPS reference is needed as well as a phase comparison device to determine absolute phase. A method that could simplify and speed these processes would be a benefit, particularly if most of the testing could be done by less costly personnel.

Another aspect is quantifying results. Many of the tests described previously do not result in a simple set of numbers or figures that could easily be compared between test facilities, or even among different devices. Test methods that produce the same type of results at any facility would simplify comparison between units, both between models of the same type over time as well as among manufacturers.

While step tests provide useful comparison between PMUs, they do not provide quantifiable results. This is due to the step occurring at an undefined time and having too few data points output to truly observe the response. In general, step change responses are defined by the delay in initial response, the rise time to some point on the waveform, the overshoot past the final value, and the time to settle to within a percentage of the final value. Most PMUs will fully respond to a step change within a few data points, which is not enough to characterize the response (Figure 6).

B. Test technique improvement

The previous section illustrated some of the difficulties in carrying out the test schedule of section III. With time and effort, we have achieved useful results. Some tests still have not produced the results we would like. We still have not achieved full comparability among PMU units. The IEEE standard calls for the full input to output comparability illustrated in Figure 4. This calls for the ability to generate tests from phasor models, apply those tests with precise time synchronization, and compare the results with the original phasor models. In addition, we would like tests that can:

- easily be shared among testing facilities
- be applied by technicians with standard relay equipment test training
- be easily modified as needed
- be used with similar standard test equipment

The techniques we developed to achieve these goals are described in the following sections. These techniques provide comparability with the phasor model as well as the goals of applicability, repeatability, and accuracy. These tests build on the basic concept of using playback files that has been used in structured signal tests.

Two techniques have been added: the capability of a test set to synchronize a test in absolute time and a digital marker in the test file that will be recorded in the PMU file. Test sets will start a recorded test file on an exact instant of time (capability for end-to-end relay testing). The playback clock is accurate enough that all signals stay time synchronized within a few microseconds throughout the test. This allows making precise measurements throughout the duration of a test file by using test signals exactly synchronized to the start of the file. The test signals are defined by the phasor model from which they came. A digital signal is imbedded in the test file to identify each section of the test. This digital signal is fed into a PMU digital input. For analysis, the test characteristics (phasor model) and digital identification track are taken from the file that creates signals. The analysis program uses the digital signal to match sections of the test file with the PMU recorded data for analysis. Note that for tests that require exact timing, this precision is built into the test signal file and is produced by the test set; the digital signal only matches sections between test and measurement. Once the data is loaded and correlated, the analysis program produces plots and statistics that characterize the PMU.

C. General Test methodology

All tests are performed by playing back a signal file into a PMU using a test set. The overall automated testing process follows the four steps shown in Figure 10.

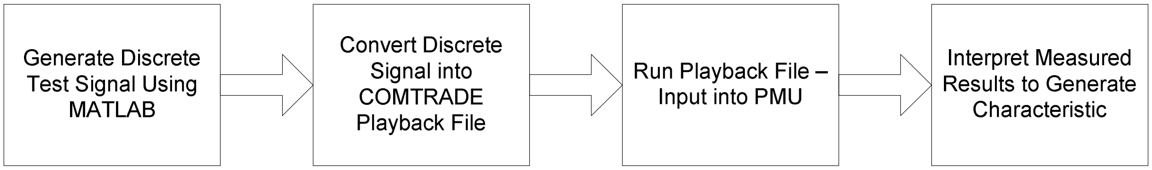


Figure 10. Automated Testing Process

These signals are generated using MATLAB programs written by BPA and PNNL. For each test, the phasor model of the test is determined by the test requirements. The formulas for the signals follow from the phasor model. The formulas create test signals in digital sample form. A basic sine wave, for example, is represented by samples of a continuous wave at a predefined interval, translating the continuous-time signal into a discrete-time signal, as shown in Figure 11. Increasing the sampling rate also increases the precision of the test signal and may produce more precise test results.

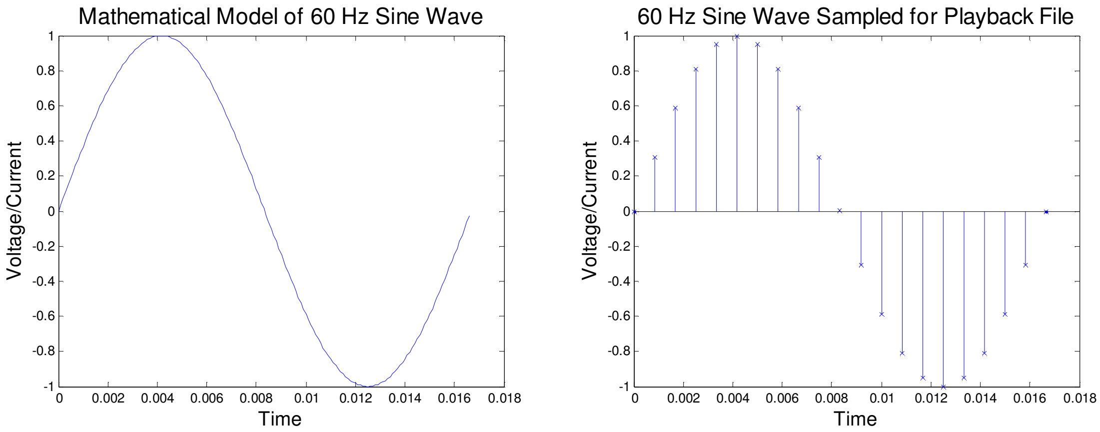
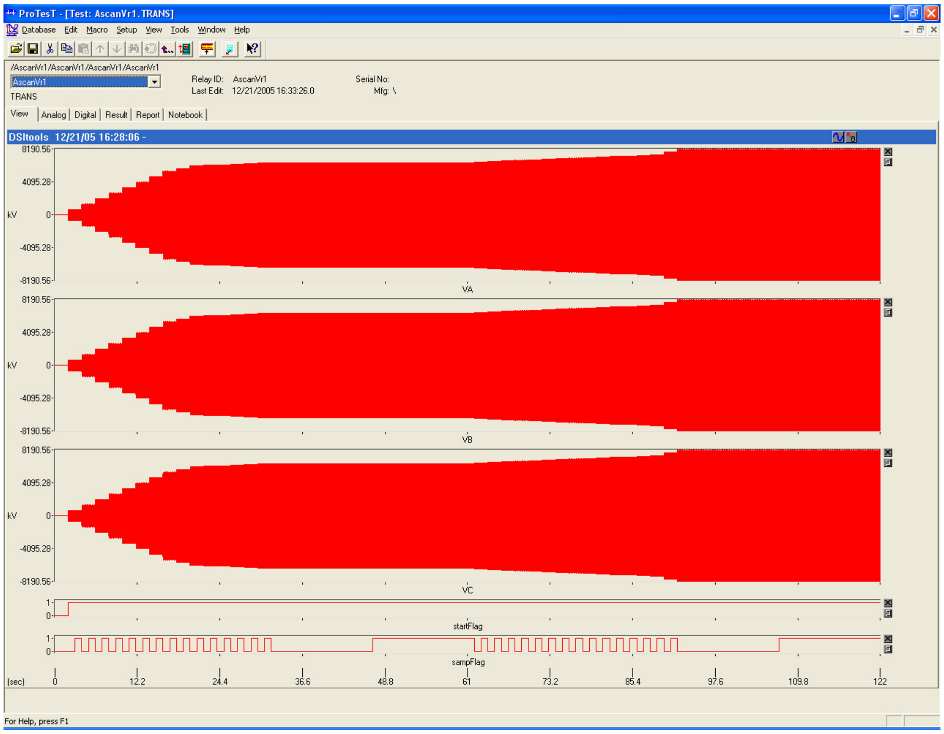


Figure 11. Continuous and Discrete Models of Sine Wave

This discrete-time representation of the signal is then translated to a text file in COMTRADE format, which includes the time and magnitude of every data point in the signal. The COMTRADE data file is read by a test set, which will interpolate the discrete signal and generate an analog voltage or current that is sent into the PMU. Data from the PMU is recorded in a file. This file is read and compared with the original test file characteristics using MATLAB-based analysis tools to interpret the test results. Though the playback files and specific analysis techniques are different for each test, this overall method is consistent throughout this testing process.

Tests are set up with a number of test points in one file. The test file will separate each test point with a small delay, allowing PMU measurements to settle. This "dwell" is either the time when a signal will be at a constant value to be measured, or a delay between dynamic measurements. Two digital signals are used: SG1 indicates the start of a test file, and SG2 each measurement point. For steady-state tests, SG2 indicates the center of a dwell, where the dwell is the length of time that the input remains at a constant value. This assures the measurement is made after all transients have settled. For step tests, SG2 indicates the location of the input step. The specific methodology of both kinds of tests is discussed below. Figure 12 shows the display provided by the test set, including a three phase signal and two digital signals for an amplitude scan. All three phases change in amplitude simultaneously at various points throughout the duration of the test. A rising edge of the first digital signal (SG1) indicates the beginning of the test. A rising edge on the second (SG2) indicates the center of a dwell where the measurement should be taken. Note the extra long dwells in the middle and end of the test signals; these are provided to allow manual measurement of the signal to check the test set.

As described in Section B, the signal timing precision is based on the test set output and the points stored in the signal file. The test set starts the signal output at the first point in the data file at a precise GPS time and outputs each successive sample at a precise rate. Every test element is at a precise interval from the start of the file, so all signal timing is determined. Since the PMU recording is at a much slower rate than the test signals, the digital signal with the PMU data cannot indicate precise timing in the test signal. The digital signals are provided to simplify comparison of the test signals and the recorded data from the PMU. However, most test data can be analyzed manually using the start time and the interval times.



Relay ID: AscanVr1
Last Edit: 12/21/2005 16:33:26.0
Serial No:
Mfg: \

Figure 12. Test Set Display showing a 3 phase sweep of varying amplitudes and the digital indicators at the bottom.

D. Steady state Tests

Three sweep tests aid in the general characterization of the steady-state behavior of a PMU: amplitude, frequency, and phase angle scans.

Amplitude Scan

An amplitude scan uses a test signal varying over a wide range of amplitudes. By using a playback file, the full scan is performed in a single test, with digital signals monitoring the location of each change in amplitude. In this way, the input amplitude is compared to the output amplitude in the middle of each dwell where the transients have settled out. The interpretation program plots both the response and error, and provides a simple statistical summary. Sample plots are shown in Figure 13.

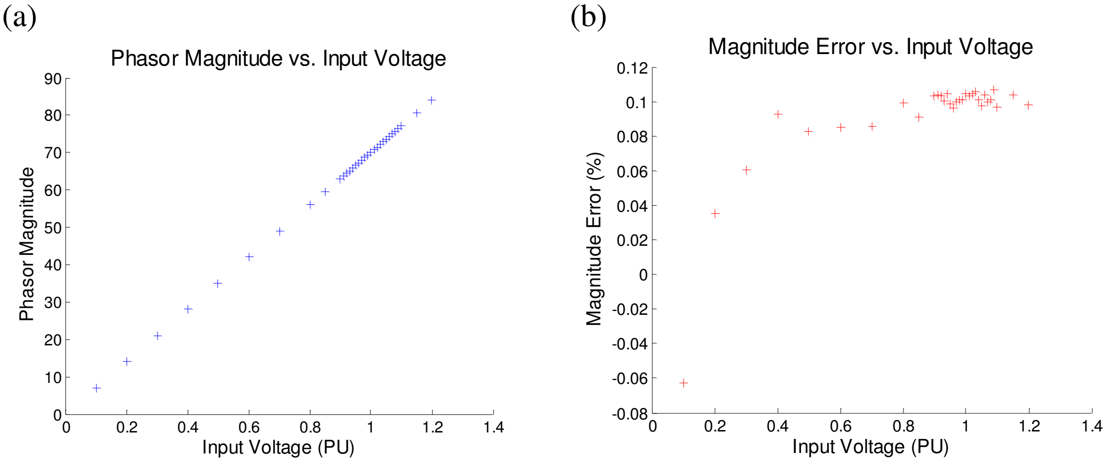


Figure 13. Sample Results of Amplitude Scan.

Phase Angle Scan

Phase angle scans are performed similar to amplitude scans, with a sweep of angles from 0 to 360 degrees on both a voltage and current channel, with an offset angle between the two channels. The playback file accurately generates the sweep as demonstrated by the measured absolute phase characteristic (Figure 14) and the relative phase characteristic (Figure 15). As in the amplitude scan, the digital signal indicates the center of a dwell and is used to generate points which are linearly interpolated to create the characteristic shown. In both sample cases, the input phase is scanned in five-degree intervals, with a 30 degree offset between voltage and current, which is observable in the relative phase scan results.

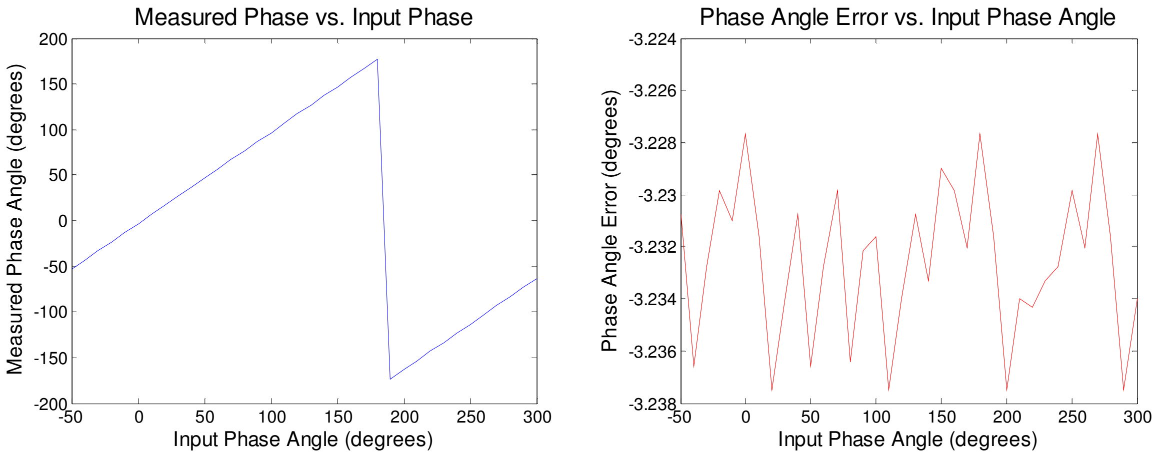


Figure 14. Sample results of phase angle scan. Left figure shows whole 360 degree scan and right shows measurement error. Test set had a -3.2 degree error, so actual PMU error is .028 to .038 degrees.

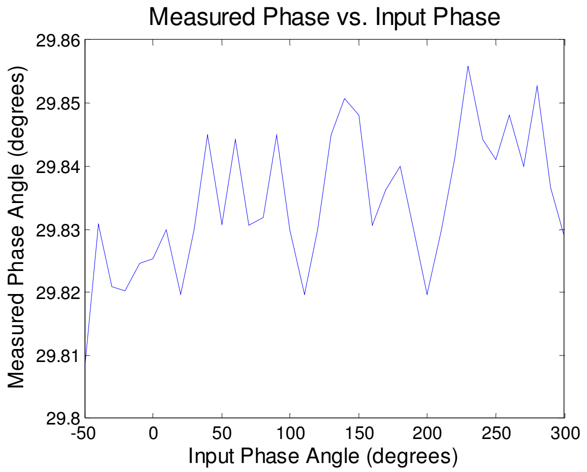


Figure 15. Relative phase angle scan. Angle difference between two phasor inputs to the same PMU which should be exactly 30 degrees in this case.

Frequency Scan

Wideband frequency response can provide a good deal of information about the filtering and frequency tracking algorithms of a PMU. The narrowband frequency response near nominal (60 Hz) shows the magnitude measurement frequency response. Three phase signal frequency is varied and held with digital signal SG2 marking the middle of each dwell, as in the previous two scans. Smaller frequency steps are used near nominal to more accurately characterize the passband. An ideal frequency response is unity within the passband and zero elsewhere. The passband is centered on nominal frequency with a bandwidth equal to the Nyquist frequency (±15 Hz for a 30 sample/sec rate). Figure 16 shows the response of 4 PMUs with different filtering and has the ideal response superimposed. Two responses show the typical sin(x)/x characteristic of a uniform Fourier conversion (filter). In addition, there is a response of a narrowband post filter without and with frequency tracking (55-65 Hz). Any response outside of the passband can result in aliasing unwanted signals into the passband. Figure 17 shows these same curves in a narrowband plot which allows determining the measurement frequency response. The wideband and tracking responses are much more accurate within the passband. Since power system frequency usually deviates very little from nominal, accuracy over much more than 59 to 61 Hz may be academic.

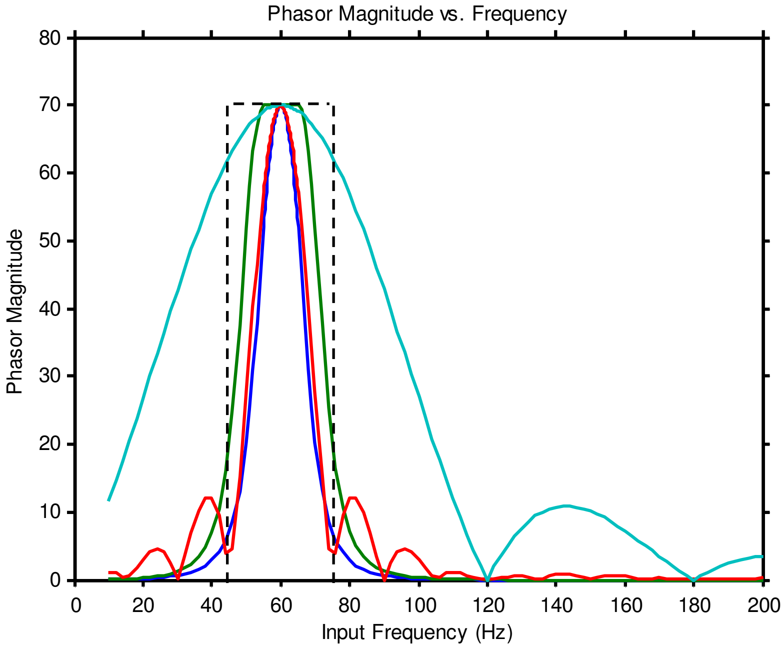


Figure 16. Wideband Frequency Response – 1 cycle Fourier (lt blue), 4 cycle Fourier (red), narrow band (blue), narrowband with frequency tracking (green). Ideal filter is shown by dashed lines. 70V RMS input.

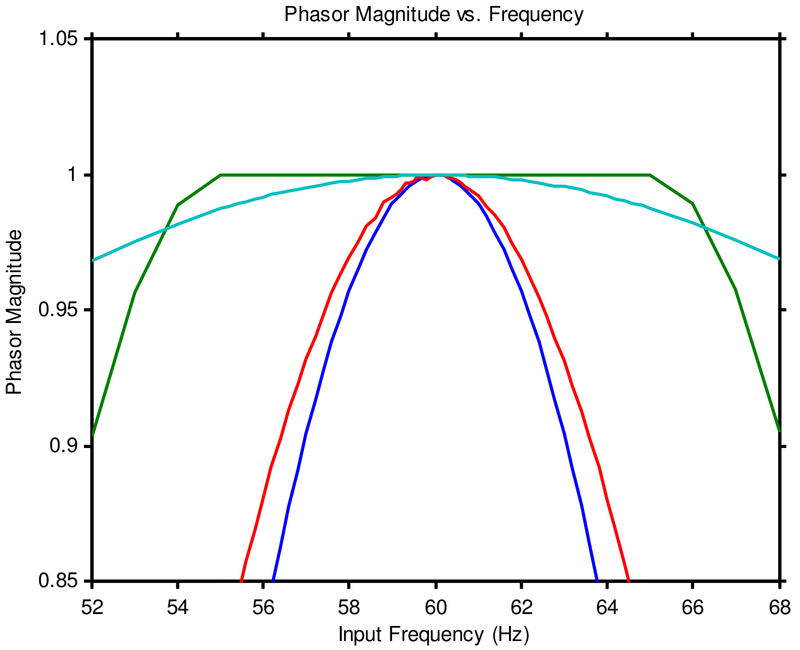


Figure 17. Narrowband Frequency Response, plotted in per unit at nominal. Same PMUs as in Fig. 16.

Phase-Frequency Scan

Using the same methodology as the standard frequency scan, variations in phase angle measurement are tested over a range of frequencies. If the input phase angle is not altered during the scan, the phase angle measurement ideally does not change. These playback files are generated using a sine wave, which crosses 0 V at the one second rollover. This is easier to check against a reference 1 PPS signal from GPS than a cosine waveform. A standard sine wave will have a phase angle of -90 degrees, which is the ideal response across all frequencies. The sample results in Figure 18 show an error that slopes .6 degrees across the test. Monitoring the test instrumentation showed the test set signal was delayed 120 to 140 microseconds across the test. The measurement was corrected at 60 Hz, but the slope due to the test set and PMU are indistinguishable. As good as test sets are, there are still errors that much be cross checked and removed. These instrumentation problems are being investigated to improve the tests so manual corrections are not required.

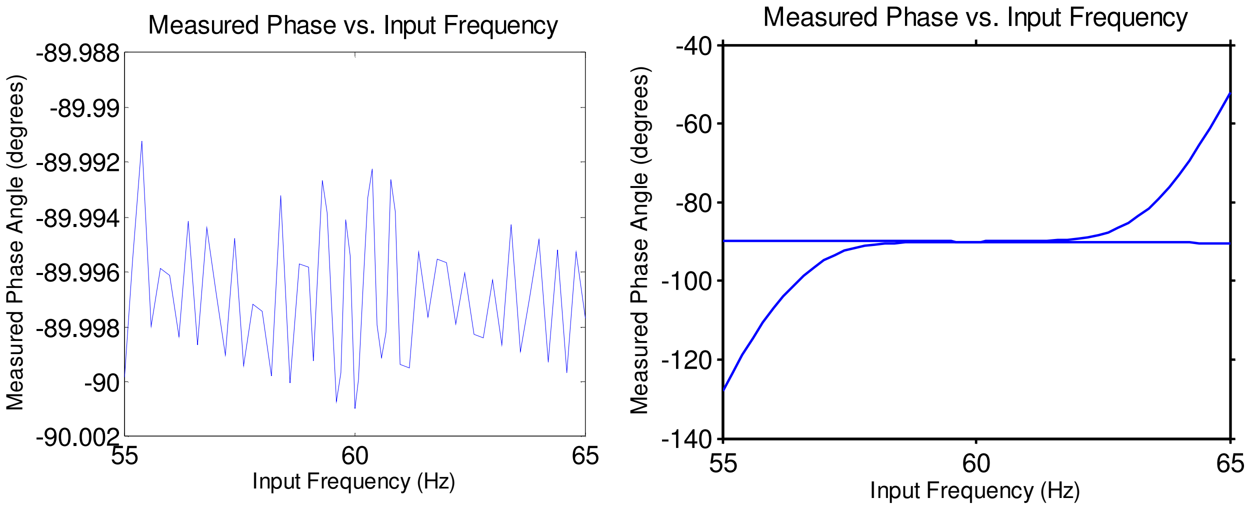


Figure 18. Phase-frequency Scan with test signal at -90 degrees. PMU on left used wideband filter with frequency tracking, and is very close to ideal -90 degrees. PMU on right uses a narrowband filter, with frequency tracking (the flat line) in one test and without tracking (large deviation due to the sharp filter cutoff) in another.

E. Step Tests

PMU response to an input step in magnitude, phase, or frequency is dependant on several factors, including the filtering, the measurement window, and measurement decimation for data output. By definition, data output from a PMU is at evenly spaced intervals that are the inverse of the sample rate and with one sample on the second rollover. Thus samples are at fixed times relative to UTC. For example, with a 30 sample/second (2-cycle) data rate, data will be output at the second rollover and every 33.3 ms between rollovers. The apparent PMU step response must be interpreted using data at these intervals. PMU internal measurement is generally much faster than this output data rate, so it is difficult to characterize the response with a simple step. There may be curves in the response, overshoot, or settling oscillations that may not show up in the measured response due to the small number of data points. The concept used here assumes internal PMU processing is constant in time relative to the window for data output. That is, an output data sample will reflect the input over a certain window relative to the time of that sample. By putting a step into the PMU at varying time relative to the data output time, we can observe the PMU at more points on the response curve and achieve a more complete characterization of the PMU response.

All three step tests follow the same general methodology. A playback file is generated with a series of steps, each delayed by a short interval within the data output interval. Each step is the same except for the relative timing. The file has an interval of constant signal, a step to the new value at a defined time, an interval at the new value, and then a return to the pre-step signal. There will be enough time before and after the step to allow the PMU to stabilize at that value. For example, given a 30/second (2-cycle) data rate, the 33.3 ms sample interval may be divided into four equal intervals so the file will include a step precisely at the beginning of a data interval, one delayed by 8.3 milliseconds, a third delayed by 16.6 milliseconds, and a final step delayed by 24.4 milliseconds. The stabilizing interval will be ½-1 second (this can be altered depending on the PMU and test type). A digital signal is used to mark the location of each step. However, since the digital signal is only reported at the same rate as the phasor data, it is not precise enough to determine the measurement. It essentially identifies the time interval where the step is made. The step time is set in time by the file (and the test set start) and the delay lengths (in this case, 8.3, 16.6, and 24.4 milliseconds) are stored in a separate file for interpretation by the Matlab-based plotting program. In this way, the full PMU response can be plotted as described below.

To establish the full response curve, these individual responses need to be combined into a single curve. For the example above using a 10% magnitude step, all four step responses are superimposed on a single plot, as shown in Figure 19(a). The step that occurs exactly at sample 0 is represented by the blue curve (+). At sample 0 there is only pre-step input and the value remains at 1.0. It achieves full response at sample 3, but may actually achieve full response at some point between 2 and 3; there just aren't samples to tell. The delayed steps are shifted back by a time corresponding to the delay in the step to fill in the curve. Figure 19(b) shows a plot following the first of such shifts. The data points that result from a 1.5 cycle delay (3/4 of a data point interval) are shifted to the left by ¾ of a data point. The new curve is generated from the points that are not delayed and those that have just been shifted. The same process is repeated for the step delayed by ½ of a window (Figure 19(c)) and ¼ of a window (Figure 19(d)). After all shifts have been completed, a final plot is the linear interpolation of the all data points. The resolution of this final plot is based on the number of delayed steps that are used, with more steps yielding a more detailed curve. In Figure 19, using any one of the 4 curves by itself would have given a misleading figure, but using all 4 together gives an accurate picture.

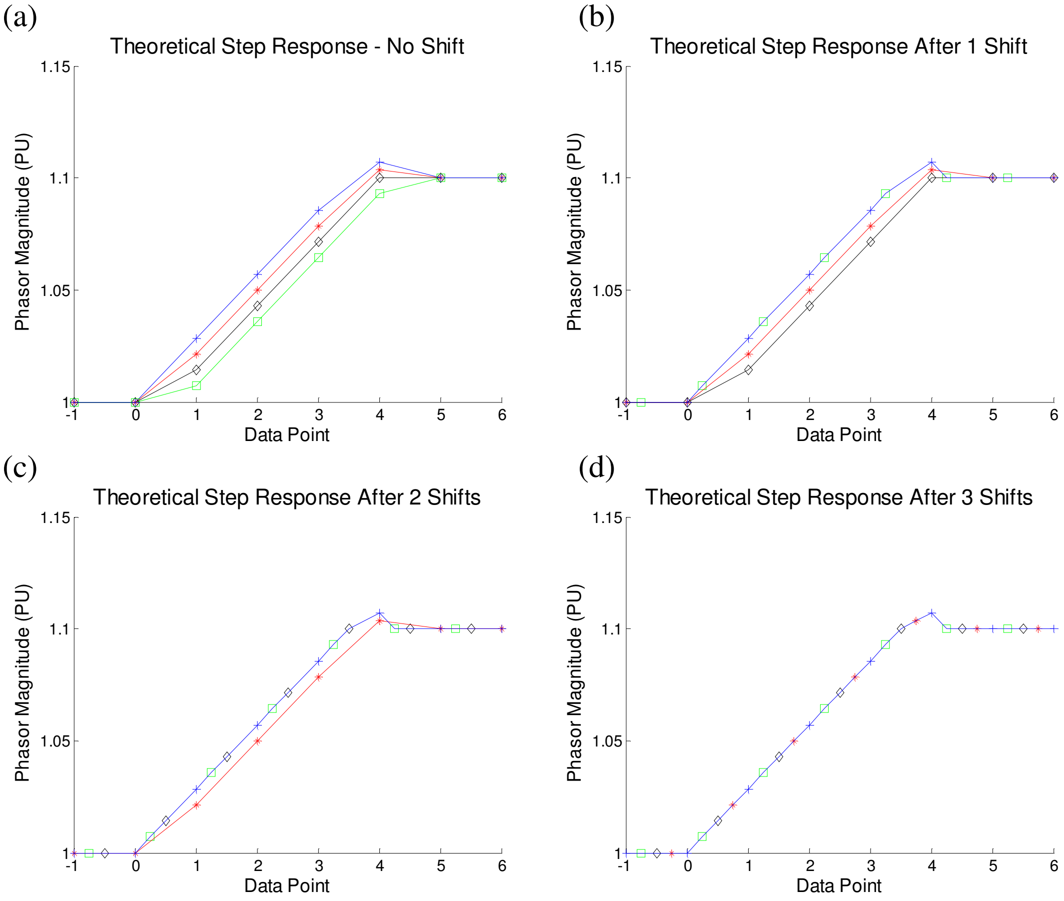


Figure 19. Theoretical Step Response after Each Shift

Magnitude Step

As an example of this technique, the plots in Figure 20 show a 10% step in magnitude. The red vertical trace at time=0 is where the step occurs. The PMU response is the blue trace obtained by the shifted sample technique described above. The dashed line represents the response curve using only the points at the normal output rate. In Plot (a), the timetag is set to the beginning of the phasor estimation window making the response appear to occur before the input. In (b) the timetag is in the middle of the window so the response appears about half way through the input. It is clear this technique gives a much more detailed and accurate picture of the response. Responses from phase angle and frequency steps yield similar results.

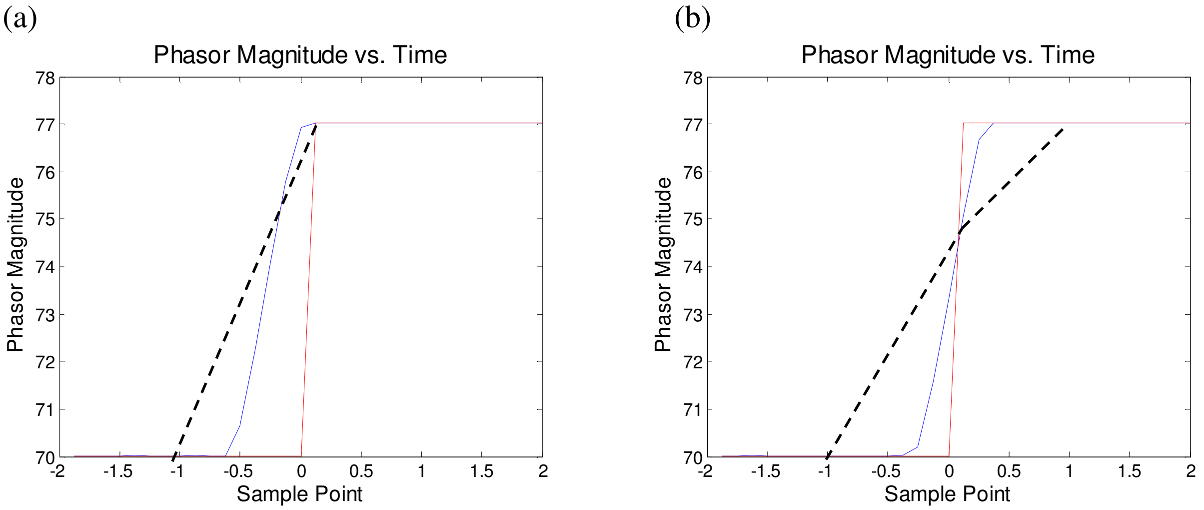


Figure 20. Magnitude step responses showing the step input (at 0 in red) and the measurement filled in with shifted inputs (blue curve). The response represented by the normal sample rate is shown by the dashed lines.

F. Structured Signal Tests

Structured signal test processing can also be facilitated with the digital signal identification. These tests include a number of different test points that need to be related back to the test signal. An example of amplitude modulation is shown in Figure 21. The modulation starts at .1 Hz and proceeds in .1 Hz increments up to 5 Hz and continues in larger increments to 60 Hz. The falling edge of SG2 indicates a change in test frequency and the rising edge indicates the center of the dwell. Here the data rate is 30/sec so the passband is 0 to 15 Hz and the rejection band is 15 to 60 Hz. The PMUs shown in this are similar to those in Figures 16 & 17. In the passband, the 1 cycle filter is the flattest and the 4 cycle filter falls off the quickest. However, the middle filter with tracking and no tracking gives the same middle response. Tracking only follows the center frequency, which in this case is the same. Flattening the center response has no effect on the ability to measure oscillations. The rejection curve shows the flattest filter has little rejection of out of band signals, and the other units will still have a excessive leakage of out-of-band signals into the passband.

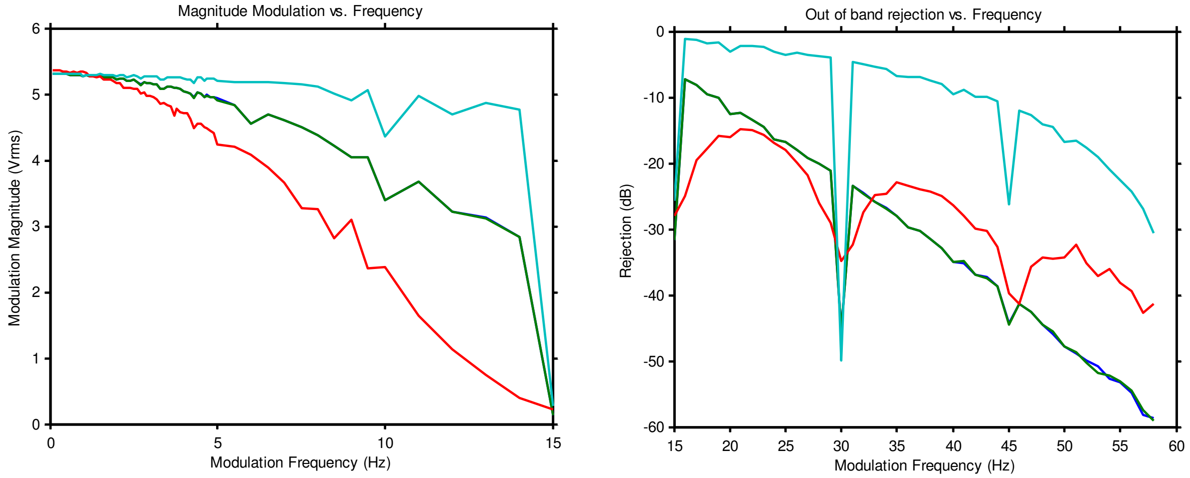


Figure 21. PMU response to modulated signals. The 1-cycle Fourier filter (lt blue) shows the flattest response but the least rejection. The bandpass filter (blue-grn together) shows middle rejection and is the same in tracking and non-tracking. The 4-cycle Fourier rolls off more quickly but does not stay low at higher frequencies.

V. Conclusions

PMU testing at BPA has undergone many changes and advancements since the first testing was performed in 1990. It has been very successful in both proving the validity of the measurements and in revealing implementation problems. The overall effort has expanded to include British Columbia Hydro (BCH) and PNNL and has benefited from the support of other utilities using PMUs. Through testing, WECC users have achieved sufficient PMU characterization to integrate the data from several different PMU models. Steady state measurements are well enough characterized that data can be compensated for use in most real-time systems.

The advances in testing detailed in this paper mark a significant advancement in testing technique. It has always been difficult to create signals from phasor models that match precisely in waveform and absolute time. Since PMU measurements relate to absolute time, this is necessary to provide the kind of phasor model to phasor measurement (estimation) that is needed to fully characterize a PMU. The test file methodology described here coupled with synchronization capability of modern test sets make this possible, and with a reasonable effort. We can now test dynamic as well as steady-state capability with high accuracy. In addition, using a digital signal track to provide matching between the test results and the test input allows programmed analysis and automation of many tedious procedures. It opens the way to much easier evaluation which will benefit PMU users and vendors alike.

On the negative side, we have found the PMU to be more precise than the test set output in some cases. Even with modern test sets, it necessary to measure the tests signals at certain points for assurance or corrections in signal processing. These assurance tests are exacting and time consuming. Currently we are trying to derive correction formulas to minimize these tests. Despite our efforts to make testing quick and painless, it continues to require careful observation and thorough methods.

Characterizing transient response is still a work in progress. Most dynamic measurement problems have been discovered during data analysis from system events. Testing for most of these problems has been incorporated into the test procedures. For example, we have found the frequency measurement sometimes does not match the phasor measurement. So we will add a test for synchronization of measurements within the PMU, including the phasors, frequency, analogs, and digitals. We also are still developing better analysis of current tests such as determining group delay of modulated signals. We also will be finding better ways to catalog results from present tests, such as step tests, that improve PMU comparisons. Even with the advances in testing detailed in this paper, we are steadily discovering areas for improvement.

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Many of these or related documents are available at **ftp.bpa.gov/pub/WAMS%20Information/.**

VII. About the authors

Ken Martin is a Principal Engineer at the Bonneville Power Administration. His primary responsibility is the development of Wide Area Measurement Systems (WAMS), particularly phasor measurement systems for high-speed dynamics measurements. Duties include system development, operation oversight, and coordination with other utilities. He is also responsible for the development of precise timing systems at BPA. He has worked primarily with instrumentation, communication, and power system protection systems at BPA. Mr. Martin holds a BSEE from Colorado State University and an MA from the University of Washington. Mr. Martin is a Senior Member of IEEE, a member of the Power System Relay Committee and the Relay Communications Sub-committee. He is the chair of the Synchrophasor Standard working group. He is a registered Professional Engineer in Washington State.

Tony Faris began working with phasor measurement systems in 2004 at the Bonneville Power Administration. He holds a BSEE from the University of Portland and is currently pursuing an MSEE from the University of Washington in VLSI and embedded systems. He is currently employed at UW as a teaching assistant, providing assistance in courses on Devices and Circuits and Digital Systems. He is a member of IEEE and Tau Beta Pi.

John Hauer (F'90) started his engineering career with the General Electric Company in 1961. This was followed by industrial work at Boeing Aerospace, a Ph.D. at the University of Washington, and a faculty position at the University of Alberta. In 1975 he joined the Bonneville Power Administration and began a long involvement with identification, analysis, and control of power system dynamics. In 1994 he stepped down as BPA Principal Engineer for power system dynamics, and assumed technical leadership of the power systems group at the DOE's Pacific Northwest National Laboratory in Richland, Washington. He is a Laboratory Fellow at PNNL, and a Life Fellow of the IEEE.