12/30/07

North American SynchroPhasor Initiative (NASPI)

Performance & Standards Task Team (PSTT)

PMU System Testing and Calibration Guide

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Revision History

Date	Rev. #	Description
12/30/07	1	• Final version of PSTT

i. Disclaimer

The PSTT Guides and Standards are for industry. When a product manufacturer is referenced, it is solely for the purpose of examples, and no endorsement of the product is intended nor implied.

Table of Contents

1 Overview

This section describes the scope, purpose and the limitation of applicability of this document, PMU System Testing and Calibration Guide, hereafter referred to as the Guide.

1.1 Scope

This Guide describes test and calibration procedures for phasor measurement units (PMUs) used in the electric power industry to monitor the condition of the electric power grid. The focus of the Guide is on the performance and interoperability of the PMUs. The performance tests include those specified in IEEE Standard C37.118 [1]. Extended test procedures to address the power system dynamic performance conditions not specified in C37.118 are also considered. This includes performance standards established by the Western Electricity Coordinating Council (WECC) [16]. The test procedures for laboratory and field applications are outlined. Calibration procedures for PMUs and field test sets are also described.

Appendices A and B presents background information on special topics such as WECC monitor standards, signal processing within a PMU, and mathematics relating to modulation of a single phasor. Much of this material is directly extracted from WECC documents [10] through [16].

1.2 Purpose

The purpose of the Guide is to cover those performance parameters that will allow the conforming PMUs to best meet the requirements of the electric utility industry to monitor and control the electric power grid, and for PMU manufacturers to make cost effective instruments. The test descriptions are intended to be detailed enough to allow test laboratories, utilities, and the PMU manufacturers to perform the required tests. Where possible, the test descriptions specify what a test should measure and they suggest proven methods for accomplishing this. Generic descriptions of the test equipment capabilities and test procedure steps are also provided.

The tests include performance tests of the PMUs in a laboratory environment, and in expected utility application environments. This includes tests of the PMU interface with laboratory instruments, field test sets, and typical utility components. It also includes tests to show PMU compatibility with the phasor data concentrators (PDCs) that are used in the system to receive data from the PMUs and to send commands to the PMUs. If PMUs are tested as recommended in this Guide, it should help users with inter-operability and preventing incompatibility among PMUs from various manufacturers.

The Guide should be able to supplement the standards for PMUs for the purpose of procurement specifications and regulatory standards. The Guide should also be able to help users that intend to install PMUs or have already installed them to plan the field test procedures and related test equipment. Users should specify conformance with the Guide to the vendors to help meet their requirements, including PMU inter-operability. Supplemental information on these subjects is provided in WECC documents [10] through [16], and in the references cited therein.

2 References

This standard should be used in conjunction with the publications listed below. Documents [10] through [16] are available at BPA website[1] ftp://ftp.bpa.gov/pub/WAMS_Information/ and other NASPI sources.

[1] IEEE C37.118-2005 (Revision of IEEE Std 1344-1995), IEEE Standard for Synchrophasors for Power Systems.

[2] IEEE Std 1344-1995(R2001), IEEE Standard for Synchrophasors for Power Systems.

[3] IEC 61850-3 - Communication Networks and Systems in Substations - Part 3: General Requirements.

[4] IEEE C37.111-1999, IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems, June 1999. IEC 60255-24:2001, Electrical relays, part 24: Common Format for Transient Data Exchange (COMTRADE) for Power Systems, International Electro technical Commission (On line: www.iec.ch).

[5] IEEE Standard 1588-2002, IEEE Standard for a Precision Clock Synchronization Protocol for Ntworked Measurement and Control Systems.

[6] IRIG Standard 200-04 – IRIG Serial Time Code Formats – September 2004, Timing Committee, Telecommunications and Timing Group, Range Commanders Council, U.S. Army White Sands Missile Range, NM.

[7] NASPI – A Guide for PMU Installation, Commissioning, and Maintenance Part I: PMU Acceptance Test Checklist for Connecting to TVA SuperPDC, Performance and Standards Task Team.

[8] NASPI – A Guide for PMU Installation, Commissioning, and Maintenance Part II: PMU Installation Procedures, Performance and Standards Task Team.

[9] NASPI – SynchroPhasor Accuracy Characterization, Performance and Standards document.

[10] **Evaluating the Dynamic Performance of Phasor Measurement Units: Experience in the Western Power System,** J. F. Hauer, Ken Martin, and Harry Lee. Interim Report of the WECC Disturbance Monitoring Work Group, partial draft of August 5, 2005.

[1] This is the primary website for the WECC WAMS.

[11] **Integrated Dynamic Information for the Western Power System: WAMS Analysis in 2005,** J. F. Hauer, W. A. Mittelstadt, K. E. Martin, J. W. Burns, and Harry Lee in association with the Disturbance Monitoring Work Group of the Western Electricity Coordinating Council. Chapter 14 in the **Power System Stability and Control** volume of **The Electric Power Engineering Handbook**, edition 2, L. L. Grigsby ed., CRC Press, Boca Raton, FL, 2007.

[12] **Blackout Experiences and Lessons, Best Practices for System Dynamic Performance, and the Role of New Technologies.** IEEE Task Force Report, Special Publication 07TP190, July 2007.

[13] **Use of the WECC WAMS in Staged System Tests for Validation of System Performance and Modeling: Summary Report for September 2005–August 2006,** J. F. Hauer, W. A. Mittelstadt, J W. Burns, K. E. Martin, Harry Lee, and D. J. Trudnowski**.** Interim report of the WECC Disturbance Monitoring Work Group, April 25, 2007.

[14] **PMU Testing and Installation Considerations at the Bonneville Power Administration**, K. E. Martin, J. F. Hauer, and T. J. Faris. Presented to the Panel of Performance Characteristics and Evaluation of PMUs at the IEEE/PES 2007 General Meeting, June 24-28, 2007, Tampa, Florida.

[15] **Laboratory Performance Evaluation Report of SEL 421 Phasor Measurement Unit (PMU,** H. Huang et. al. PNNL technical report **PNNL-16852,** November 2007. (Undergoing permission process for general distribution)

[16] **WECC Disturbance/Performance Monitor Equipment: Proposed Standards for WECC Certification and Reimbursement**, Principal Investigator K. E. Martin. Draft report of the WECC Disturbance Monitoring Work Group, March 17, 2004.

[17] **2007 NETA Acceptance Testing Specifications, International Electrical Testing Association, 01-Jan-2007, 254 pages**

[18] **Validation of Phasor Calculation in the Macrodyne PMU for California-Oregon Transmission Project Tests of March 1993**, J. F. Hauer. IEEE Trans. Power Delivery, vol. 11, pp. 1224-1231, July 1996

3 Definitions and Acronyms

This section provides some useful definitions and acronyms pertinent to Global Positioning System (GPS)-synchronized devices, communication protocols, communications media, and signal processing

Absolute Phase Angle – See synchronized phasor definition.

Anti-aliasing – (not defined in IEEE Dictionary). The process of filtering a signal when converting to a sampled form to remove the components of that signal whose frequency is equal to or greater than one half the sample rate. If not removed, these high frequency signal components would appear as a lower frequency component (an alias).

ASCII – American Standard Code for Information Interchange is a character encoding based on the English alphabet used to represent text in computers.

BPA/PDCStream – An extension of IEEE 1344, widely used by the Bonneville Power Administration (BPA) PDC and Human Machine Interface (HMI) software on the West Coast.

COMTRADE-File Format – Common Format for Transient Data Exchange (COMTRADE) file format is a standardized ASCII text or binary file (2 formats), originally designed for exchange of transient data files, and subsequently adopted by Digital Fault Recorders (DFR) vendors as the standard file format for field records made by DFRs. It can be used to transfer locally recorded values from a PMU over to the central data storage. COMTRADE ASCII format is not efficient for long-term data storage but could be used for event file retrieval. Two COMTRADE Standards are in frequent use today: IEEE C37.111-1999 [4] version and IEC 2001 version.

CT – Current Transformer.

DSI Toolbox – Mathematical software package for dynamic system identification. A WECC standard for integrated analsysis of monitor data and/or simulation data from transient stability programs. Available at BPA WAMS website ftp://ftp.bpa.gov/pub/WAMS_Information/ and other NASPI sources.

EIA232 Standard –A telecommunication standard for serial binary data interconnection between a DTE (Data Terminal Equipment) and a DCE (Data Communication Equipment).

EIA485 Standard –An OSI Model physical layer electrical specification of a two-wire, half-duplex, multipoint serial connection.

GPS – Global Positioning System. A satellite based system for providing position and time. The accuracy of GPS based clocks can be better than 1 microsecond.

IED – Intelligent Electronic Device. A general term indicating a multipurpose electronic device typically associated with substation control and protection.

IEEE C37.118 – The new IEEE phasor data protocol that replaced the IEEE 1344 and the BPA/PDCStream protocols. Typically data is streamed in this format over UDP/IP or across a serial link.

IEEE 1344 – Old IEEE standard for synchronized phasor measurement systems in substations. It addresses synchronization of data sampling, data-to-phasor conversions, and formats for timing input and phasor data output from a Phasor Measurement Unit (PMU). It does not specify response time, accuracy, hardware, software, or a process for computing phasors.

IPMU – Integrated Phasor Measurement Unit. Any device that is integrated with
phasor measurement function
_ Phasor measurement is an added function to the primary functions of a device
_ Examples are: relays, meters, fault recorders, etc., which may be denoted as Relay -
IPMU, Meter - IPMU, Fault Recorder - IPMU, etc.

IRIG-B – Time transmission formats developed by the Inter-Range Instrumentation Group (IRIG). The most common version is IRIG-B, which transmits day of year, hour, minute, and second once per second, over a 1 kHz carrier signal.

MATLAB – Commercial numerical computing environment and programming language. (see i. Disclaimer)

Nyquist Rate – A rate that is twice the highest frequency component in the input analog signal. The analog signal must be sampled at a rate greater than the Nyquist rate to be represented accurately in a digital form.

PDC – Phasor Data Concentrator. A logical unit that collects phasor data, and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications. PDCs may buffer data for a short time period but do not store the data.

Phasor – A complex equivalent of a simple cosine wave quantity such that the complex modulus is the cosine wave amplitude and the complex angle (in polar form) is the cosine wave phase angle.

PhasorFile – A binary storage format that is used by PDC for long-term storage of SynchroPhasor data. Currently, this format is not standardized, and may be left in such a state as long as stored data is made available in an industry standard format (e.g. COMTRADE).

POW – Point on wave. Applies or relates to instantaneous signal waveforms, rather than to some average or simplified characterization of them.

PPS – Pulse-Per-Second. A signal consisting of a train of square pulses occurring at a frequency of 1 Hz, with the rising edge synchronized with UTC seconds. This signal is typically generated by GPS receivers.

PMU – Phasor Measurement Unit. A device that samples analog voltage and current data in synchronism with a GPS-clock. The samples are used to compute the corresponding phasors. Phasors are computed based on an absolute time reference (UTC), derived from a built in GPS receiver or time reference signals from an external GPS receiver. (See IPMU)

PT – Potential or voltage transformer

Relay – An electromechanical or electronic device applied to the purpose of power apparatus protection. A relay typically monitors voltages and currents associated with a certain power system device and may trip appropriate breakers when a potentially damaging condition is detected.

Sampling Rate – The number of samples (measurements) per second taken by an analog to digital converter system.

SPM – Synchronized phasor measurements

SPS – samples per second.

SSM – Synchronized system measurements. This extends the concept and technology of synchronized phasor measurements to include devices such as advanced point-on-wave recorders or control system monitors. Many of these are operational in the WECC WAMS.

Synchronism – The state where connected alternating-current systems, machines, or a combination operate at the same frequency and where the phase angle displacements between voltages in them are constant, or vary about a steady and stable average value.

Synchronized Phasor –A phasor calculated with respect to a nominal frequency reference phasor that is synchronized to an absolute time reference. This is also called synchrophasor.

TCP/IP – TCP/IP is a low-level protocol for use mainly on Ethernet or related networks. Most of the higher-level protocols use TCP/IP to transport the data. TCP/IP provides a highly reliable connection over unreliable networks, using checksums, congestion control, and automatic resending of bad or missing data. TCP/IP requires time to handshake new connections and will block if missing data is being resent.

TVE –Total Vector Error – the magnitude of error between the theoretical phasor value of the signal being measured and the phasor estimate, as defined in 5.2

UDP/IP – UDP/IP is a low-level IP protocol that provides low-latency communication across Ethernet or related networks. UDP/IP does not provide any error-control or resending of missing or bad data. The Application will need to check data for correctness. UDP/IP however, does not require time for handshaking and will not block, making it a good choice for *real-time* data communications.

UTC – Coordinated Universal Time (initials order based on French). UTC represents the time-of-day at the Earth's prime meridian (0° longitude).

WAMS – Wide area measurement system. Generally features one or more PMU networks as a "backbone," but may also include local recorders, legacy equipment, or advanced technologies that are GPS synchronized to the PMU networks while recording non-phasor data.

4 Test Equipment

This section describes the performance requirements for the test equipment used to perform the tests of sections 5 and 6. In general the test equipment should be ten times more accurate than the test tolerance, i.e. the uncertainty of the test equipment should be less than one tenth the test tolerance. Under these conditions the error contribution from the test equipment can generally be ignored in the evaluation of units under test.

There should generally be two setups:

Full-featured calibration laboratory – used for testing and calibrating both the PMUs and field test equipment. This setup should be equipped with the best possible clock reference, waveform reconstruction (D/A), measurement (A/D) devices.

Standard test equipment - should be ten times more accurate than the test tolerance. Standard test equipment is calibrated using the full-featured calibration laboratory setup. Different options may fall into this category. It is important to note that some options may be suitable for use in labs, but some may be used in field. Field testing may take place in a substation control house or switchyard depending on which devices are to be tested.

Primary test equipment consists of time reference sources and a multi-phase signal generator. It is suggested that the signal generator be capable of accepting large "playback files" that store point on wave signals that control its output.

Accessory test equipment might include standardized playback files for the signal generator, Matlab (see i. Disclaimer) or equivalent code for constructing additional playback files, PMU modeling codes for test interpretation or test design, and mathematical software for Prony or other curve fitting analysis of PMU response signals. Figure 1 shows a typical layout for PMU tests at BPA and PNNL [10]. This type of test is useful in comparing the performance of PMUs with units that have been well characterized against higher accuracy standards.

Also shown in this figure is another class of accessory test equipment, in the form of a reference PMU. New or revised PMU types are often tested in tandem with other PMU types (or PMU models) that are well understood, and in common use. This provides cross calibration data that may be needed to adjust field measurements to achieve better consistency among different instrument types. Also, by comparing results from the reference units against those of earlier tests, one can readily establish that performance of the present tests is consistent with those of earlier ones.

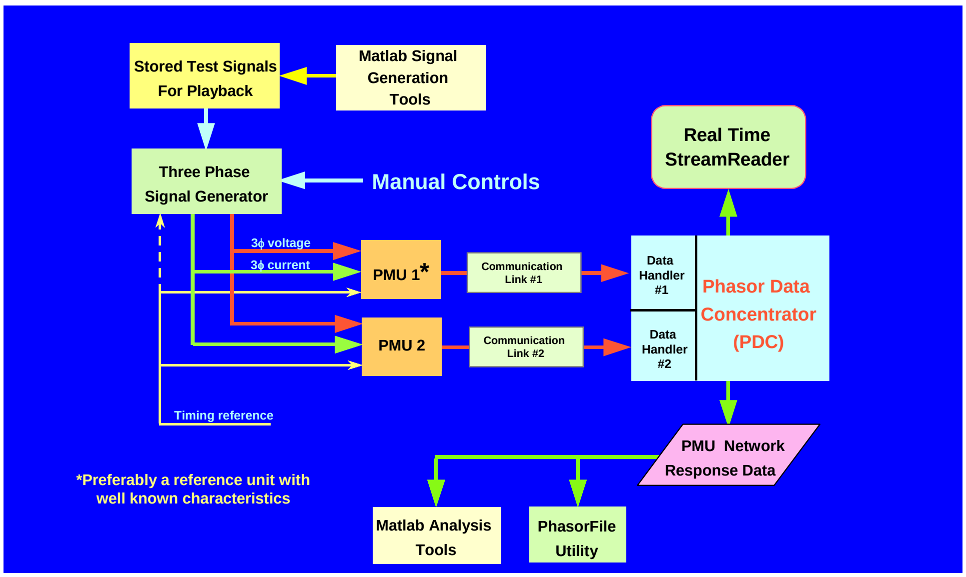


Figure 1. Geometry and Nomenclature for Laboratory Testing of PMU Networks

4.1 Time reference

This section describes the various methods available for time synchronization of the PMU and test systems and the performance requirements for each method.

The current best method for referencing UTC is with a GPS receiver. The GPS system is referenced to atomic clocks maintained by the U.S. military. These clocks are very accurate time and frequency references. However, atmospheric disturbances cause fluctuations in the arrival time of the GPS satellite signals, which result in short term uncertainty of the GPS time reference. By use of a local oscillator these fluctuations can be averaged over time and the result is a lower uncertainty in the time signals. The more stable the oscillator, the more accurate is the time reference.

The GPS receivers require the acquisition of many GPS satellites simultaneously to derive UTC. Depending on the antenna installation and the location's latitude, there may be times when the receiver cannot get enough signals to achieve the highest accuracy. The GPS receiver chosen should give a lock signal to indicate that sufficient signals are being received to deliver the specified uncertainty. This status should be monitored during all tests to assure that the clock reference is accurate. Since this status is being monitored, there will be less concern about "holdover" (time error while GPS time is interrupted for any reason), thus there is less need for the highest-stability free-running oscillators, such as a rubidium (Rb) based one. A good recommended oscillator is a double-ovenized OCXO (oven controlled crystal oscillator), which will perform well for the PMU testing needs without maintenance or tuning issues for many years.

4.1.1 GPS antenna signal

GPS receivers require connection to an antenna to acquire signals from GPS satellites. One should follow manufacturer’s instructions for installing the GPS antenna. Since the test system will require a GPS receiver and some PMUs have built-in GPS receivers, multiple GPS antenna signals may be required. This can be accomplished by using one antenna connected to a GPS splitter. Active splitters are available with two or four outputs. Since most antennas require a dc voltage for power and the polarity and voltage levels can vary from manufacturer to manufacturer, be sure to follow the manufacturer’s instructions for connection of the antenna signals to the splitter and to the various receivers.

In addition to lock status, most GPS receivers indicate the signal level that has been acquired from each of the satellites. This level needs to be checked against the manufacturer’s recommended signal level for the receiver. Signal strength can become a problem if the antenna connection requires a long cable run. So the location of the test facility should consider the manufacturer’s recommendations for the cable length and type. Use of a low attenuation cable can extend the usable cable length as can an antenna signal amplifier.

4.1.2 IRIG-B

PMUs and test sets that do not have a built-in GPS receiver will generally require an IRIG-B [6] connection – a time distribution standard. Other time distribution standards exist, but IRIG-B is one of the most commonly used. The IRIG-B signal transmits the UTC time information including the date and time as well as the second of the year. These signals may be modulated via pulse width modulation or unmodulated via dc level shift. The unmodulated is the most accurate. The modulated versions can be transmitted over longer distances but this is usually not necessary if the GPS receiver is located with the test system. Also, the uncertainty for modulated signals can be as great as 0.1 ms to several ms, which does not meet the PMU test requirements. Care must be taken in distributing the IRIG-B signal to avoid signal reflections that can increase the uncertainty of the time signals. These signals are usually transmitted on 50 Ω cables and require proper termination. Use of multiple drops and unterminated cables should be avoided.

An IRIG-B simulator with control of the leap second and time quality bits can be used to verify proper operation of the PMU for the occurrence of leap seconds and the loss of clock synchronization.

4.1.3 Use for other clock signals

Other clock signals can be used to synchronize the test system with UTC time. 1 pps signal is a common choice. This can be used to synchronize the sampling of a reference PMU (see section 4.4.1 below) with the start of a UTC second. PMUs must transmit phasor measurements that are synchronized to the UTC second and then at the intervals of fractions of a second depending on the data rate. Thus, a PMU transmitting at 30 samples a second will transmit phasor values on the top of each second and at every 0.033333… s in-between. GPS receivers also have other signal frequencies available, such as 1 MHz or 10 MHz. These are useful for synchronizing the test system sampling and signal generation with UTC. Use of signals from one clock to control the operations of the test system, minimizes the jitter that results from the use of several unsynchronized clocks running at slightly different frequencies.

4.2 Steady state signal sources

This section describes the requirements for the voltage and current channels of the multiphase signal generator for steady-state PMU tests. For steady-state tests, the signals have a constant amplitude and frequency during the data collection part of the test.

4.2.1 Steady state magnitude

The voltage and current sources must have an amplitude uncertainty of less than 0.1 % of the specified test level, with total harmonic and noise distortion of less than 0.1 % of the specified test level.

4.2.2 Steady state phase

The voltage and current phases must be known relative to a cosine wave of the test nominal frequency (50 Hz or 60 Hz) synchronized to the on time second of UTC. This phase is referred to as absolute phase angle. The absolute phase angle of the test voltage must be known for each test time, i.e., the times the PMU assigns to its phasor measurements. The absolute voltage phase angle must have an uncertainty of less than 1 mrad (0.057 degrees) relative to the specified test phase or alternatively the absolute phase angle of the voltage signal must be known with an uncertainty of less than 1 mrad (0.057 degrees).

4.2.3 Steady state balance

The three sequence voltages or currents of the source shall be known to better than 0.1 %. For balanced tests the magnitude of the zero sequence and negative sequence shall be less than 0.3 % each.

4.2.4 Steady state frequency and rate of change of frequency

The frequency of the source shall be known with an uncertainty of less than 0.1 mHz. The rate of change of frequency shall be less than 1 mHz per second.

4.3 Dynamic signal sources

This section describes the requirements for the voltage and current channels of the multiphase signal generator for dynamic PMU tests. For dynamic tests, the amplitude or frequency of the signals will vary during the test.

4.3.1 Dynamic magnitude modulation

During the dynamic magnitude modulation test, the magnitude of the fundamental phasor shall have an uncertainty of less than 0.2 % of the nominal magnitude and the phase uncertainty shall be less than 2 mrad (0.12 degrees). The magnitude of the modulation shall have an uncertainty of less than 0.2 % of the nominal magnitude. The phase of the modulation shall have uncertainty less than the equivalent of 1 ms. The frequency of the fundamental shall have an uncertainty of less than 0.5 mHz and the rate of change of the frequency shall have an uncertainty of less than 10 mHz per second.

4.3.2 Dynamic frequency modulation

During the dynamic frequency modulation test, the magnitude of the fundamental phasor shall have an uncertainty of less than 0.2 % of the nominal magnitude and the phase uncertainty shall be less than 2 mrad (0.12 degrees). The magnitude of the modulation shall have an uncertainty of less than 0.2 % of the nominal magnitude. The phase of the modulation shall have uncertainty less than the equivalent of 1 ms. The frequency of the fundamental shall have an uncertainty of less than 0.5 mHz and the rate of change of the frequency shall have an uncertainty of less than 10 mHz per second.

4.3.3 Dynamic frequency ramp

During the dynamic frequency ramp test, the magnitude of the fundamental phasor shall have an uncertainty of less than 0.2 % of the nominal magnitude and the phase uncertainty shall be less than 2 mrad (0.12 degrees). The frequency of the fundamental shall have an uncertainty of less than 0.5 mHz. The rate of change of the frequency shall have an uncertainty of less than 10 mHz per second.

4.3.4 Dynamic magnitude step

During the dynamic magnitude step test, the magnitude of the source shall settle to the new magnitude with less then 0.2% variations within one cycle of the nominal frequency. The phase of the fundamental shall settle to the same phase as before the step within 1 cycle of the nominal frequency within 2 mrad (0.12 degrees). The magnitude of the step shall have uncertainty less than 0.1 % of the nominal magnitude. The time of the step shall be within 1 ms variations.

4.3.5 Dynamic frequency step

During the dynamic frequency step test, the magnitude of the source shall settle to the same magnitude as before the step with less than 0.2% variations within one cycle of the nominal frequency. The frequency of the fundamental shall settle to the new frequency with less than 2 mHz variations within 1 cycle of the nominal frequency. The magnitude of the step shall have uncertainty less than 2 mHz. The time of the step shall be within 1 ms variations.

4.3.6 Dynamic phase step

During the dynamic phase step test, the magnitude of the source shall settle to the same magnitude as before the step with less than 0.2% variations within one cycle of the nominal frequency. The phase of the fundamental shall settle to the new phase with less than 2 mrad (0.12 degrees) variations within 1 cycle of the nominal frequency. The magnitude of the phase step shall have uncertainty less than 2 mrad (0.12 degrees). The time of the step shall be within 1 ms variations.

4.4 Calibration of the test equipment

One method to assure the above accuracy requirements for the signal source is to make use of a stable source and use a reference PMU to determine the actual values of the phasors, frequency, and rate of change of frequency. This reference PMU can be made up of a multichannel sampling system and appropriate software to calculate these quantities. This system must be able to receive clock signals to determine the absolute time of each sample. Use of the 1 pps signal and a 1 MHz or 10 MHz clock signal to synchronize the sampling to UTC is recommended. Also the system must read the IRIG-B or similar timing codes to have a UTC time stamp for the samples and the derived quantities. The following is one procedure to test the phase of the reference PMU.

4.4.1 Phase calibration of reference PMU

Phase calibration of a PMU consists of using a high speed/high resolution oscilloscope to compare the phase of a synchronized oscillator with a 1 pps clock signal. Since the rate of change of a nominal frequency (50 Hz or 60 Hz) signal is not fast enough to easily align with the 1 pps signal, the reference PMU should be capable of measuring the phase angle of signals with frequencies significantly higher than power line frequencies. Care must be taken that the high frequency is within the bandwidth of the reference PMU. This procedure takes advantage of the fact it is easy to synchronize an oscilloscope (or counter) with a 1 PPS signal, and the zero crossing of a sine wave can be more precisely determined than the peak (Figure 2).

As shown in Figure 2, oscilloscope trace triggers at the UTC second mark as signaled by the 1 PPS from GPS. When positive zero crossing of A-phase of the 3-phase signal is aligned with the 1 PPS, the positive sequence phase angle is -90°. At nominal system frequency (50 Hz or 60 Hz), the zero- crossing does not change. Off nominal, the angle changes constantly and may not align at the 1 PPS. However at exact integer frequencies off nominal (e.g. 49, 51, 59, 61) the zero crossing will be aligned with the 1 PPS, making this method of synchronization useable.

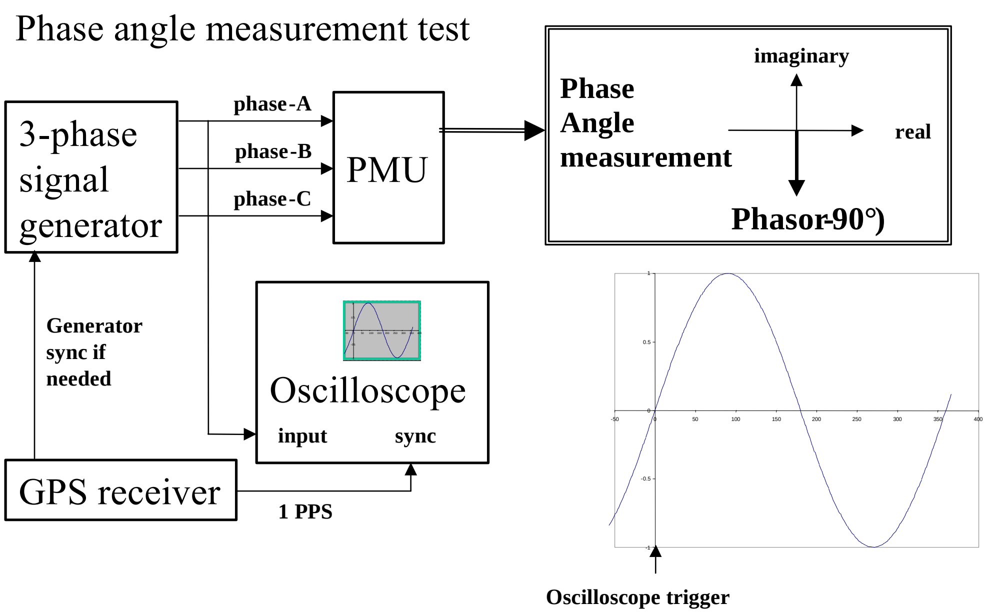


Figure 2. Phase calibration of reference PMU with the 1 PPS clock signal

As an example, let’s assume the bandwidth of the reference PMU is 500 kHz. For each phase of the reference PMU, set the signal generator to 30 kHz, then adjust the phase of the signal so the positive zero crossing of the signal is aligned with the positive edge of the 1 pps signal. The signal phase angle measured by the reference PMU should be –90 degrees. Note the difference in this measurement. Readjust the phase of the signal so the negative zero crossing of the signal is aligned with the positive edge of the 1 pps signal. The signal phase angle measured by the reference PMU should be 90 degrees. The difference in this measurement should be the negative of the first measured difference. The extent to which these differences are not the negative of each other indicates the presence of dc in the signal. Taking half the difference between these two test results, one can convert the angle to a time delay of the 30 kHz signal.

The above time delay determinations should be repeated at 60 kHz, 100 kHz, 200 kHz and 400 kHz. Plot these time delays to see if they fall on a straight line. Fit a line to the lower part of the data that is straight and project the time delay above power line frequencies. Apply this as a correction to the signal phase angles measured. Repeat the above procedure to demonstrate that with this correction the measured time delay at 30 kHz is now approximately 0 second. Use these data to analyze the uncertainty of the phase angles measured by the reference PMU.

Note: Oscilloscopes that have a low-resolution digital front end (7 or 8 bits) do not allow an accurate location of the positive zero crossing. Any DC offset will also change the phase angle based on zero crossing. With 8 bits FS, the zero location could be off by 1 count out of +/-127. This is about to 0.45 degrees (1% TVE = 0.57 deg if magnitude is perfect).

4.5 PMU data communication and analysis

PMU data communication includes transmitting PMU results and receiving PMU commands. Various transmission methods, such as RS 232, RS 485, and Ethernet TBASE 10/100, and various transmission protocols, such as TCP/IP, and UDP/IP, are well-known methods. Details can be readily available from communication documentations.

4.6 Automated features

Test tools including both hardware and software should come with libraries containing standard types of tests. The tools should provide options for performing automated (batch) standard tests described in Chapters 5 and 6. The automation of testing should include applying the signals and measuring the responses. The results need to be stored in a convenient way for later review.

5 Types of Tests

The same as other power system protection and control devices, individual PMUs must undertake various types of tests to ensure its reliable and accurate operation in the installed system. These tests include a thorough factory type test, which typically includes electrical, environmental, mechanical, and performance conformance tests, for each new type of a developed PMU, factory acceptance test for each manufactured product, field acceptance test (commissioning test), and periodical maintenance test. These tests shall follow the requirements and procedures of the relevant international, national and industrial standards and Guidelines where applicable. However, the application of a PMU has some unique requirements:

High accuracy of time synchronization of the measurement results and time tagging

Unified performance of all PMU units across an installed system
Interoperability of PMUs and other PMU system components, such as Phasor Data Concentrators (PDC)

These unique requirements demand a comprehensive set of functional performance conformance and interoperability tests to be conducted employing a well defined test approach to ensure that the performance of an installed PMU system can meet its desired objectives, and allow products from various vendors to be integrated into the PMU system.

The description of different types of tests in this Guide focuses on the conformance and functional performance tests that are unique to PMUs and Synchrophasor measurement devices. The conformance tests are designed to verify whether PMU meets basic specifications provided by the vendor. The functional performance tests are designed to verify whether PMU meets expected functional performance under transient and dynamic power system conditions. For other standard tests, such as electrical, environmental and mechanical tests, please refer to the relevant international, national, and industrial standards and Guidelines as listed in Section 2, References.

5.1 PMU conformance tests

PMU conformance tests shall be included in a comprehensive type test program and performed on each new type of PMU devices. A complete set of conformance tests shall also be performed for PMU devices after firmware/software and hardware revisions. A complete PMU test program should also include electrical, environmental and mechanical tests. Please refer to the relevant international, national, and industrial standards and Guidelines, such as IEC 61850-3 [3], for requirements on these tests.

The description of the PMU conformance tests in this Guide includes the functional performance and the interoperability conformance tests that are unique to PMU and Synchrophasor measurement devices. The conformance tests are performed to verify whether a PMU or a Synchrophasor measurement device meets the requirements of IEEE C37.118-2005 standard and this Guide. The performance tests of this Guide also include tests to document the performance of a PMU under transient and dynamic power system conditions.

5.1.1 PMU protocol conformance test

To ensure the interoperability of different PMU devices, a protocol conformance test shall be performed to confirm all configuration/command/data frame implementations of a PMU are conformed to the C37.118 standard frame definitions.

This test shall be performed prior to the performance conformance test.

The manufacturer/user defined custom control/data frames shall be verified according to agreement between manufacturers and users.

5.1.2 PMU performance conformance test

The IEEE C37.118 standard clearly defined the Total Vector Error (TVE) metric, and established the level 0 and level 1 performance compliance requirements under steady-state conditions for a PMU. However, the standard did not establish the performance compliance requirement under transient and dynamic conditions. In some synchrophasor applications, the consistent dynamic performance among all PMUs in an interconnected system is also of a great importance. For example, a system that measures and records phasors for post-event analysis of system dynamics during a large system disturbance, where system frequencies at different locations could change dynamically, would require the PMUs to be able to follow the frequency change quickly and consistently among all PMUs.

In the following subsections, this Guide will describe the purpose of each performance conformance test and the requirements of the test. The tests are divided into two major categories: steady-state and dynamic tests. In this Guideline the steady-state tests are defined as the tests where the magnitude and frequency of the test signals will not change during the test. Otherwise, a test will be considered as a dynamic test.

The steady-state and dynamic test requirements are defined for test signal injected at the PMU's input terminals.

5.1.2.1 Initial functionality verification

Prior to the full spectrum steady-state tests and/or dynamic tests, a PMU shall pass the following basic functionality tests.

5.1.2.1.1 PMU reporting rate check

The ability of a PMU device to generate specified standard reporting rates as specified in Table 1 of C37.118 standard, shall be verified.

Manufacturer-implemented non-standard reporting rates may be verified according to the manufacturer's own specifications and/or agreement between manufacturer and users.

5.1.2.1.2 Basic functionality test

The basic functionality of a PMU device shall be verified under the following conditions:

Pure sinusoidal input signal (THD < 0.1%)
Input signal frequency at rated 50 Hz and/or 60 Hz system frequency
Balanced three-phase input signal
Single-phase input signals
Input signal is synchronized to produce (1) 0 degree and (2) -90 degree phasor angles at the beginning of each second, i.e. the rising edge of 1 pps reference time frame as per C37.118 section 4.2.

PMU shall report correct phasor values in the above tests with TVE less than 1% as specified in C37.118.

The basic functionality of the PMU time quality flag bits shall be verified under the following conditions:

- PMU with IRIG-B input –
  - Proper leap second operation
  - Proper time quality indication
- PMU with GPS antenna input –
  - Proper time quality indication

5.1.2.2 Steady-state performance conformance test

The steady-state performance conformance tests are conducted to confirm that the accuracy of a PMU is within the specified limits when exposed to specified steady-state operating conditions.

The steady-state performance conformance test shall be performed according to the signal range and test conditions specified in C37.118 Table 3 with the following additional requirements of this Guide:

- Phase unbalance test
- Temperature range: The conformance of PMU steady-state performance shall be verified within its specified operating temperature range

Manufacturer-specified steady-state performance of a PMU in extended signal ranges and test conditions should be verified according to manufacturer's own specifications, or agreement between the manufacturer and users.

5.1.2.3 PMU performance conformance levels

A PMU's performance conformance shall be classified by the highest level that it conforms to. A PMU shall be classified with separate steady-state and dynamic conformance levels. The conformance levels shall be classified for each data reporting rate that a PMU supports.

5.1.3 Performance conformance test of integrated PMU devices

When phasor measurement is one of the functions in a multifunction device, the performance conformance test of such devices shall also verify the followings:

- That operation of other functions will not cause interference, degradation and disruption of the performance of the PMU function under all operating conditions;
- That the PMU function will not cause interference, degradation and disruption to the performance of other functions under all operating conditions;

That the actual range of input signals for an IPMU is determined by (1) the types of transducers dictated by its primary functions, and (2) the C37.118 required signal range for phasor measurement.

5.1.4 Certification of conformance

Certification of conformance shall only be issued to PMUs fully conformed to the requirements of this Guide, accompanied by a detailed test report. Both certification of conformance and the test report shall declare that all tests were conducted in full compliance to the test requirements and test procedures specified in this Guide and that the tests were performed by qualified test labs. The test report shall contain a detailed description of each test conducted, test equipment used, test setup description, test conditions, and test results.

5.2 Performance tests

Performance tests do not have to conform to predefined levels such as conformance tests. Users should assess the performance of a PMU by comparing results of steady-state and dynamic tests to their requirement specifications. Those requirements may depend on applications for which PMUs will be used.

5.2.1.1 Dynamic performance test

IEEE C37.118 standard did not specify the dynamic performance requirements for PMUs under dynamic and transient conditions, but described several dynamic/transient tests in Appendix C of that document. The WECC has a standard for dynamic performance of monitor equipment in general, and this is summarized here as Appendix A of the Guide. Examples of tests against this standard are provided in [10] through [15].

The PMU dynamic conformance under dynamic and transient conditions is important for many PMU applications. The PMU dynamic performance tests shall be performed and the test results shall be documented in the PMU performance conformance test report.

As frequency and change of frequency measurement are an integral part of a PMU's data frame, the dynamic performance of the frequency and change of frequency measurement of a PMU shall also be documented with dynamic performance of phasor measurement results.

5.3 Interoperability test

Interoperability characterizes how different PMUs would be compatible within a wide-area measurement network. A PMU system typically consists of multiple PMUs with one or multiple Phasor Data Concentrators (PDCs) and other system supporting components, such as application servers and application software programs. Those components, which may be from different manufacturers, need to be interoperable. Protocol conformance is the basis for all these system components to be interoperable with each other.

In addition, interoperability may require that components adhere to certain performance requirements. For example, if PMUs from various manufacturers measure different angles at off-frequency conditions, interoperability performance test need to be performed to assure that accuracy requirements for required applications are not jeopardized.

5.4 Factory acceptance test

PMU shall be considered as a protection, control and networking device. Each PMU unit shall pass a proper factory acceptance test program to detect any manufacturing defects. In addition to electrical, environmental and mechanical tests, each PMU shall be verified in the Factory Acceptance Test that it can:

- Correctly receive the synchronized timing signal according to the specifications (e.g., correct reception of GPS signals under specified signal strength);
- Sending/receiving configuration/command/data frames according to protocols defined in C37.118-2005;
- Meet phasor measurement performance requirements at a selected set of test conditions within the specifications of C37.118-2005 and this Guide.

5.5 Field tests

Field tests shall be conducted to verify the proper functionality of a PMU at its installed location after it has been installed. The field tests include field commissioning tests and periodic maintenance tests.

5.5.1 Field commissioning test

Field commissioning test shall be conducted after a PMU is installed.

As with any other digital IEDs installed in the substations, the PMU field commissioning test shall include routine visual inspection, insulation test, wiring check, basic functionality check, etc. as required by the relevant standards, such as “2007 NETA Acceptance Testing Specifications” [17] for protection and control equipment.

In addition, PMU field commissioning test shall verify the following:

- Phase A designation verification and confirmation
- Correct phase sequence verification
- Correct phasor magnitude measurement verification
- Synchronized timing source verification (e.g., GPS signal strength and reception meet the specification)

Data and control frames sending/receiving verification

PMUs are not applied as standalone devices. A typical PMU system typically consists of many PMUs and one or more PDCs. Once a PMU passed the above basic tests and its proper communication with PDCs are established, further system integration tests shall be conducted as a part of the PMU field commissioning tests. The system integration tests shall verify the followings:

Proper sending/receiving data/control frames to/from PDCs
Proper registration of each PMU in the PDC database
Proper logging of PMU activities, such as on-line/off-line time, setting change, and so on
PMU status monitoring and trouble-shooting reporting
Proper handling of communication channel problems and PMU malfunctions.
Communication channel throughput and PDC loading levels

Details of field test procedures are not part of this Guide. Please refer to "Part II – PMU Installation Procedures" of "A Guide for PMU Installation, Commissioning and Maintenance" [10] – a separate NASPI document – for detailed field test procedure descriptions.

5.5.2 Periodic maintenance test

Performance of a PMU shall be checked periodically to ensure it has not been changed and deteriorated. Details of periodic maintenance test procedures are not part of this Guide. Please refer to "A Guide for PMU Installation, Commissioning and Maintenance" – a separate NASPI document – for detailed periodic maintenance test procedure descriptions.

6 Methods for Performing the Tests

Using the equipment specified in Chapter 4 and following the definitions of tests in Chapter 5, this Chapter will describe specifically how the tests are performed. This Chapter starts with methods for determining Total Vector Error (TVE), which is used to assess PMU performance in the various tests. At the end of this Chapter, a testing report outline will be given to specify how the test results should be presented.

6.1 Total Vector Error determination

The Total Vector Error (TVE) definition that IEEE C37.118 -2005 [1] describes can be rewritten as follows:

$$\mathrm{TVE} \equiv \frac{\left|\vec{V}_{\mathrm{Measured}} - \vec{V}_{\mathrm{Ideal}}\right|}{\left|\vec{V}_{\mathrm{Ideal}}\right|}$$

where:

$\vec{V}_{Ideal}$ is the ideal phasor

$\vec{V}_{Measured}$ is the measured phasor

Notice that the measured phasor can be a voltage phasor or a current phasor. Figure 3 shows the graphical representation of the ideal, measured, and error phasors. Figure 3 relates TVE, magnitude error and angle error in the same plot. The plot in this figure shows the expected TVE for angle errors from –0.5° to 0.5° and magnitude errors of 0, 0.1, 0.2 and 0.3 %.

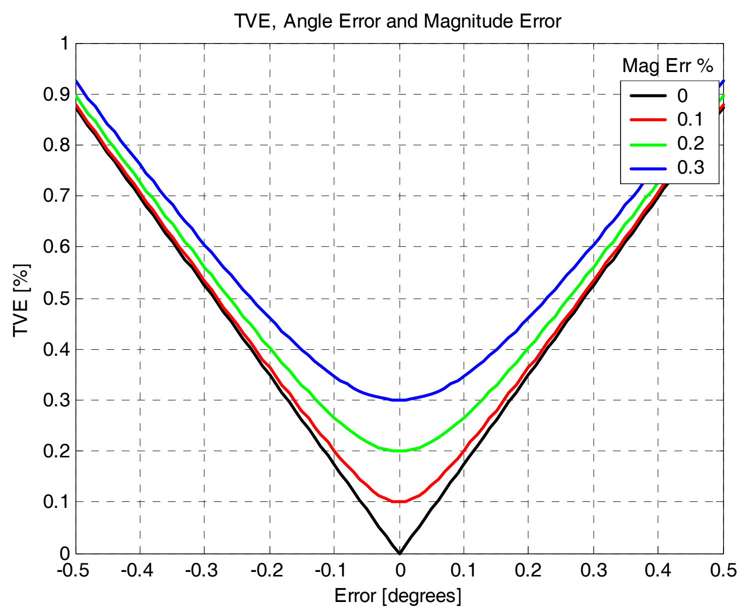


Figure 3 TVE in percentage for angle errors of –0.5° to 0.5° and magnitude errors of 0, 0.1, 0.2 and 0.3.

For a specific test, measurement should be taken from the PMU over a period of time and the TVE should be calculated for each measurement during this time. The error reported for the test shall be the average of these error values. The time period of measurements should generally be from 1 s to 10 s.

6.2 Methods for generating test modules and cases

The tests in this document involve several test signals for characterizing steady-state and dynamic performance of a PMU. The test signals can be generated in two ways, depending on the capability of a test signal generator as specified in Chapter 4. One way is to generate a signal internally by the signal generator. A signal generator is usually capable of generating constant steady-state signals, step change signals, ramping signals, and timing pulses. The other way is to generate a signal (usually point on wave data) using other tools and then use the playback function of the signal generator to create the signal. In this case, the signal generator serves as an amplifier for the constructed signal. (This is especially useful for generating modulated signals.) A collection of playback files and associated software is available from BPA or PNNL.

6.3 Steady-state performance tests

This section describes how to perform tests to assess steady-state performance of a PMU.

6.3.1 Accuracy and time alignment

This section describes how to perform tests to assess accuracy as well as time alignment of a PMU. Accuracy tests include voltage/current magnitude test, voltage/current phase angle test, and frequency test. Rate of change of frequency test is optional. Time alignment test is to determine how accurate time stamps of PMU measurements are as compared with GPS time reference.

6.3.1.1 Magnitude accuracy

For both current and voltage input ranges, apply steady state, nominal frequency (50 Hz or 60 Hz), balanced three phase inputs. Compare accuracy of measurement with input. The test signals must be calibrated or measured to be within 0.1% of reading. Full scale should be somewhat above the nominal input level. Nominal values will be determined by the application, but for test purposes will be 70 or 120 V for voltage, and 5 A for current.

Test Magnitudes: Nominal, +/- 10%, +/- 20%, and 10% of nominal for voltage

Nominal, 150 %, 75%, 50% and 10% of nominal for current.

6.3.1.2 Phase accuracy

For both current and voltage input ranges, apply steady state, nominal frequency (50 Hz or 60 Hz), nominal level, balanced three phase inputs on at least 2 phasor channels simultaneously, and vary the phase angle between. Compare measured angles between channels. The test signals must be calibrated or measured to within 0.1 degree.

Test Angles: +/- 45, +/-90, +/-135, and +/-180 degrees.

6.3.1.3 Frequency accuracy

Apply steady state, balanced three-phase input at the nominal level on a channel that provides a frequency measurement. Vary this frequency from 40 Hz to 70 Hz, making measurements at the intervals shown in table 6.(3.1.3.a) when testing for 50 Hz nominal frequency and at the intervals shown in table 6.(3.1.3.b) when testing for 60 Hz nominal frequency.

Table 6.(3.1.3.a) For devices with 50 Hz nominal frequency

40-45 Hz	45-49 Hz	49-51 Hz	51-55 Hz	55-70 Hz
1 Hz	0.2 Hz	0.1 Hz	0.2 Hz	1 Hz

Table 6.(3.1.3.b) For devices with 60 Hz nominal frequency

40-55 Hz	55-59 Hz	59-61 Hz	61-65 Hz	65-70 Hz
1 Hz	0.2 Hz	0.1 Hz	0.2 Hz	1 Hz

At each frequency, determine the errors in the magnitude, phase angle, and corresponding TVE of each phasor, as well as the error in the frequency reading and the rate of change of frequency.

6.3.1.4 Rate of Change of Frequency accuracy

Apply frequency ramping, balanced three-phase input at the nominal level on a channel that provides a rate of change of frequency measurement. Vary frequency ramp and compare the measured rate of change of frequency with input.

Test Rates of Change: +/- 0.01, +/- 0.05, +/- 0.1, +/- 0.5, and +/- 1 Hz/sec.

Note: Signal generators usually create ramping signals as a series of step changes. The resolution of the steps should be high enough to ensure measurement quality. It is suggested to have at least 100 steps per second.

6.3.1.5 Time Quality Flags

For a PMU with IRIG-B input, the IRIG-B simulator shall be connected to the IRIG-B input connector. Use the simulator to verify that the PMU responds properly to the addition of a leap second and to the deletion of a leap second. Change the time quality bits and verify the PMU properly sends these changes in the synchrophasor message.

For a PMU with only a GPS antenna connection verify that after the GPS signal is removed that the PMU signals that the clock is unlocked in the synchrophasor message..

6.3.2 Reporting rates and reporting times

The PMU shall be configured to operate at each of the required reporting rates as specified by C37.118 Table 1. With near nominal three-phase input voltage and current signals, the TVE of the PMU should be measured. The reporting time stamps shall be examined to see that the fractional second values are given by integer multiples of 1 s/(reporting rate).

6.3.3 Unbalanced three-phase signals

This section describes methods for performing unbalanced three-phase signal test.

6.3.3.1 Response to unbalanced signals, phase and magnitude

For both current and voltage input ranges, apply steady state, nominal frequency input with 2 phases at nominal magnitude and the third being varied as nominal +/- 10%, and nominal +/- 20%. Compare the measurement magnitude and phase angle with that expected, and compute the TVE for each phasor, the magnitude error for each phasor, and the phase error for each phasor. Apply the same test at nominal frequency +/- 1 Hz. Measure the magnitude of any modulation of the TVE, magnitude error, and phase error.

Test imbalances: +/- 10%, and +/-20% on one phase only.

Test frequencies: 49, 50, 51 Hz. (nominal frequency 50 Hz)

Test frequencies: 59, 60, 61 Hz. (nominal frequency 60 Hz)

Test input: Both voltage and Current.

6.3.4 Off-nominal frequency signal

This section describes how to test a PMU with off-nominal frequency signals.

6.3.4.1 Response to off-nominal frequency signals

Apply a steady state, balanced, three-phase signal to both current and voltage inputs, at nominal steady-state magnitude. Adjust the frequency by increments, to cover the range of interest: nominal frequency +/- 0.5 Hz for compliance with Level 0 and nominal frequency +/- 5 Hz for compliance with Level 1. Use enough test frequencies to resolve the variations in magnitude and phase response, if any, across the frequency range of interest. Ten frequencies (plus nominal) are suggested as a starting point for the nominal frequency +/- 0.5 Hz range and 50 frequencies for the nominal frequency +/- 5 Hz range. Compare the measurement magnitude and phase angle with that expected, and compute the Total Vector Error.

Test frequencies: nominal frequency (50 Hz or 60 Hz) +/–0.5 Hz (Level 0) at 0.1 Hz steps or

nominal frequency (50 Hz or 60 Hz) +/–5 Hz (Level 1) at 0.2 Hz steps.

6.3.5 Harmonic distortion

This section describes how to test the PMU response to harmonically distorted input.

6.3.5.1 Response to harmonic frequency signals

Apply a steady state, balanced, three-phase signal to both current and voltage inputs, at nominal steady-state magnitude and nominal system frequency (50 Hz or 60 Hz). Inject into the voltage input a positive-sequence harmonic, from 2^{nd} to 50^{th} individually, at a nominal phase angle of 0 degrees and 90 degrees relative to the fundamental, and with a magnitude of either 1% (for Level 0 compliance) or 10% (for Level 1 compliance). Compare the measurement magnitude and phase angle with that expected, and compute the Total Vector Error. Repeat this test with injection the harmonic into the current inputs. *Optional:* repeat this test for input frequencies other than nominal, within the rated input frequency range of the PMU.

Test harmonics: 2^{nd} through 50^{th}, positive sequence 3-phase.

Test harmonic phase angles: 0 and 90 degrees, relative to fundamental.

Test harmonic levels: 1% (Level 0) or 10% (Level 1) of magnitude.

Test input: Both Voltage and Current.

6.3.6 Out-of-band interference

This section describes how to test the PMU response to out-of-band interference signals. Appendix C is an overview of how out-of-band interference is related to amplitude and phase (or frequency) modulation interference.

6.3.6.1 Response to out-of-band interference

Apply a steady state, balanced, three-phase signal to both current and voltage inputs, at nominal steady-state magnitude and nominal system frequency (50 Hz or 60 Hz). Inject into the voltage input a positive-sequence interharmonic at each frequency as specified in Table 6.(3.6.1.a) or Table 6.(3.6.1.b), and with a magnitude of either 1% (for Level 0 compliance) or 10% (for Level 1 compliance) of the nominal magnitude. Compare the measurement magnitude and phase angle with that expected, and compute the Total Vector Error. Repeat this test with injection of the harmonic into the current inputs. *Optional:* repeat this test for input frequencies other than nominal, within the rated input frequency range of the PMU.

Table 6.(3.6.1.a) Frequency steps of injected interharmonic for devices with 50 Hz nominal frequency, and PMU reporting rate of F_s

25 to 50-F_s/2 Hz	50+F_s/2 to 100 Hz
1 Hz	1 Hz

Table 6.(3.6.1.b) Frequency steps of injected interharmonic for devices with 60 Hz nominal frequency, and PMU reporting rate of F_s

30 to 60-F_s/2 Hz	60+F_s/2 to 120 Hz
1 Hz	1 Hz

Test interharmonic levels: 1% (Level 0) or 10% (Level 1) of magnitude.

Test input: Both Voltage and Current.

6.4 Dynamic performance tests

This section describes how to perform tests to assess the dynamic performance of a PMU. These are tests for signals with time varying magnitudes and/or frequencies.

6.4.1 Amplitude step change response

This section describes methods for determining PMU performance in response to amplitude step changes. Amplitude step changes include voltage/current step changes. Step response can be characterized by rising time, overshoot, and steady state error.

6.4.1.1 Dynamic magnitude response

For both current and voltage input ranges, apply steady state, nominal frequency (50 Hz or 60 Hz), nominal level, balanced three phase inputs. Change the magnitude instantly + 20%, wait a short time, and then change it instantly back to nominal. Allow full settling time at each level. Repeat test for - 20%. Compare accuracy of at both levels and check for overshoot and ringdown. The test signals must be calibrated or measured to within 0.1% of reading. Using some form of synchronization, measure response times at 10% and 90%.

Test Step-changes: +/- 10%, +/-20%, and +/-50% of steady state (may need to omit high value for voltage input).

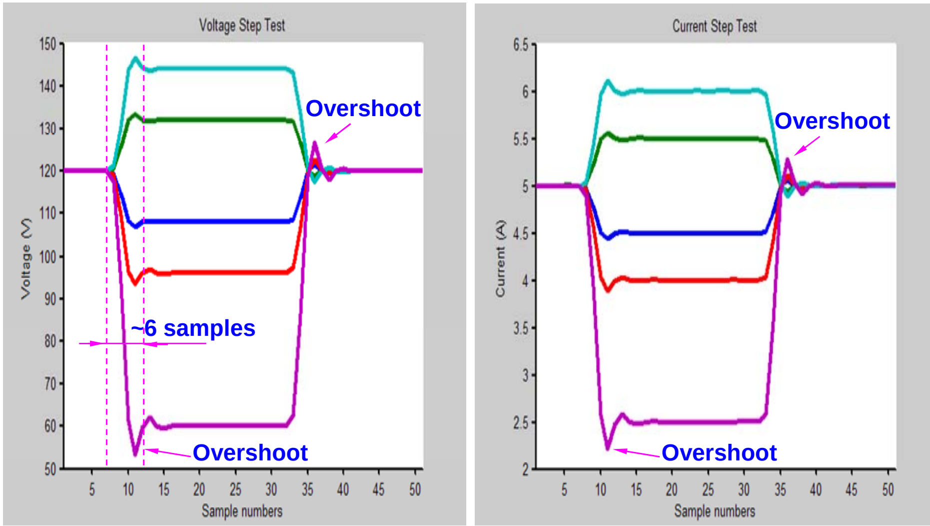


Figure 4 Examples of waveforms from voltages and current magnitude step changes.

6.4.2 Phase step change response

This section describes methods for determining PMU performance in response to phase step changes. Step response can be characterized by rise time, overshoot, and steady state error.

6.4.2.1 Dynamic phase response

For both current and voltage input ranges, apply steady state, nominal frequency (50 Hz or 60 Hz), nominal level, balanced three phase inputs on at least 2 phasor channels simultaneously, and change instantly to + 15 degrees and back to nominal. Allow full settling time at each angle. Compare accuracy of at both angles and check for overshoot and ringdown. The test signals must be calibrated or measured to within 0.1 degree. Using some form of synchronization, measure response times at 10% and 90%.

Test Step-changes: +/- 15, and +/-45 degrees.

6.4.3 Frequency step change response

This section describes methods for determining PMU performance in response to frequency step changes. Step response can be characterized by rise time, overshoot, and steady state error.

6.4.3.1 Dynamic frequency response

Apply steady state, balanced three-phase input on a channel that provides a frequency measurement. Apply nominal (50 Hz or 60 Hz) frequency, then instantly change nominal + 1 Hz and back after settling time. Compare accuracy of at both frequencies and check for overshoot and ringing. The test signals must be calibrated or measured to within 0.1°. Using some form of synchronization, measure response times at 10% and 90%.

Test Step-changes: +/- 1, +/-2, and +/-3 Hz steps.

6.4.4 Amplitude modulation response

Appendix C is an overview of how amplitude modulation is related to phase (or frequency) modulation interference and out-of-band interference.

For both voltage and current three-phase channels apply a sinusoidal magnitude modulated signal. For each modulation frequency measure the TVE of each phasor, the magnitude error for each phasor, the phase error for each phasor, the frequency error, and the rate of change of frequency error for each measurement reading. Record these errors for at least two cycles of the modulation or 1 s whichever is longer. Fit a sine wave to each of the errors. Report the magnitude and time delay of the fit and the residual standard deviation of the fit. Perform the measurements for a modulation index of 0.1 and the modulation frequencies given in Table 6.(4.4.a) for nominal frequency 50 Hz and in Table 6.(4.4.b) for nominal frequency 60 Hz.

Table 6.(4.4.a) Modulation frequencies for devices with 50 Hz nominal signal frequency

0.2 Hz to 2 Hz	2 Hz to 10 Hz	10 Hz to 48 Hz	52 Hz to 130 Hz
Every 0.2 Hz	Every 0.5 Hz	Every 2 Hz	Every 2 Hz

Table 6.(4.4.b) Modulation frequencies for devices with 60 Hz nominal signal frequency

0.2 Hz to 2 Hz	2 Hz to 10 Hz	10 Hz to 58 Hz	62 Hz to 130 Hz
Every 0.2 Hz	Every 0.5 Hz	Every 2 Hz	Every 2 Hz

6.4.5 Frequency modulation response

Appendix C is an overview of how phase (or frequency) modulation is related to amplitude modulation interference and out-of-band interference.

For both voltage and current three-phase channels apply a sinusoidal frequency modulated signal. For each modulation frequency measure the TVE of each phasor, the magnitude error for each phasor, the phase error for each phasor, the frequency error, and the rate of change of frequency error for each measurement reading. Record these errors for at least two cycles of the modulation or 1 s whichever is longer. Fit a sine wave to each of the errors. Report the magnitude and time delay of the fit and the residual standard deviation of the fit. Perform the measurements for a frequency modulation index of 0.1 and the frequencies given in Table 6.(4.4.a) for nominal frequency 50 Hz and in Table 6.(4.4.b) for nominal frequency 60 Hz.

Table 6.(4.4.a) Modulation frequencies for devices with 50 Hz nominal signal frequency

0.2 Hz to 2 Hz	2 Hz to 10 Hz	10 Hz to 48 Hz	52 Hz to 100 Hz
Every 0.2 Hz	Every 0.5 Hz	Every 2 Hz	Every 2 Hz

Table 6.(4.4.b) Modulation frequencies for devices with 60 Hz nominal signal frequency

0.2 Hz to 2 Hz	2 Hz to 10 Hz	10 Hz to 58 Hz	62 Hz to 120 Hz
Every 0.2 Hz	Every 0.5 Hz	Every 2 Hz	Every 2 Hz

6.4.6 Dynamic response scan

This is a multi-purpose test developed at BPA and PNNL. It is based upon a playback file for a sequence of amplitude modulated inputs, for a power system frequency that is somewhat off the nominal 60 or 50 Hz. The methodology is demonstrate here with a playback file called PMU_AMod6006seriesA, for which the power system frequency is 60.06 Hz and the modulation frequencies range from 0.28 Hz to 45 Hz 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. Each of these frequencies represents either a typical power system phenomenon, or is a multiple of the 15 Hz Nyquist frequency for 30 sps operation of a PMU.

Figure 5 shows voltage magnitude signals produced by four different PMUs[2] in response to this test file. Note that all of these PMUs demonstrate at least some response to modulation above the Nyquist frequency, and that this response will necessarily exit the PMU at apparent frequencies that cannot exceed 15 Hz.

Figure 6 shows anomalous cross modulation of the frequency signal for some of the PMUs under test. This is typical of PMUs that are not fully compensated for off nominal operating frequencies, and attempts to reduce the effect through supplemental filtering generally cause the frequency signal to lag the phasors by tens of milliseconds. This effect will increase as the power system frequency deviates farther from its nominal value.

[2] Most of these PMU types have since been upgraded by their vendors.

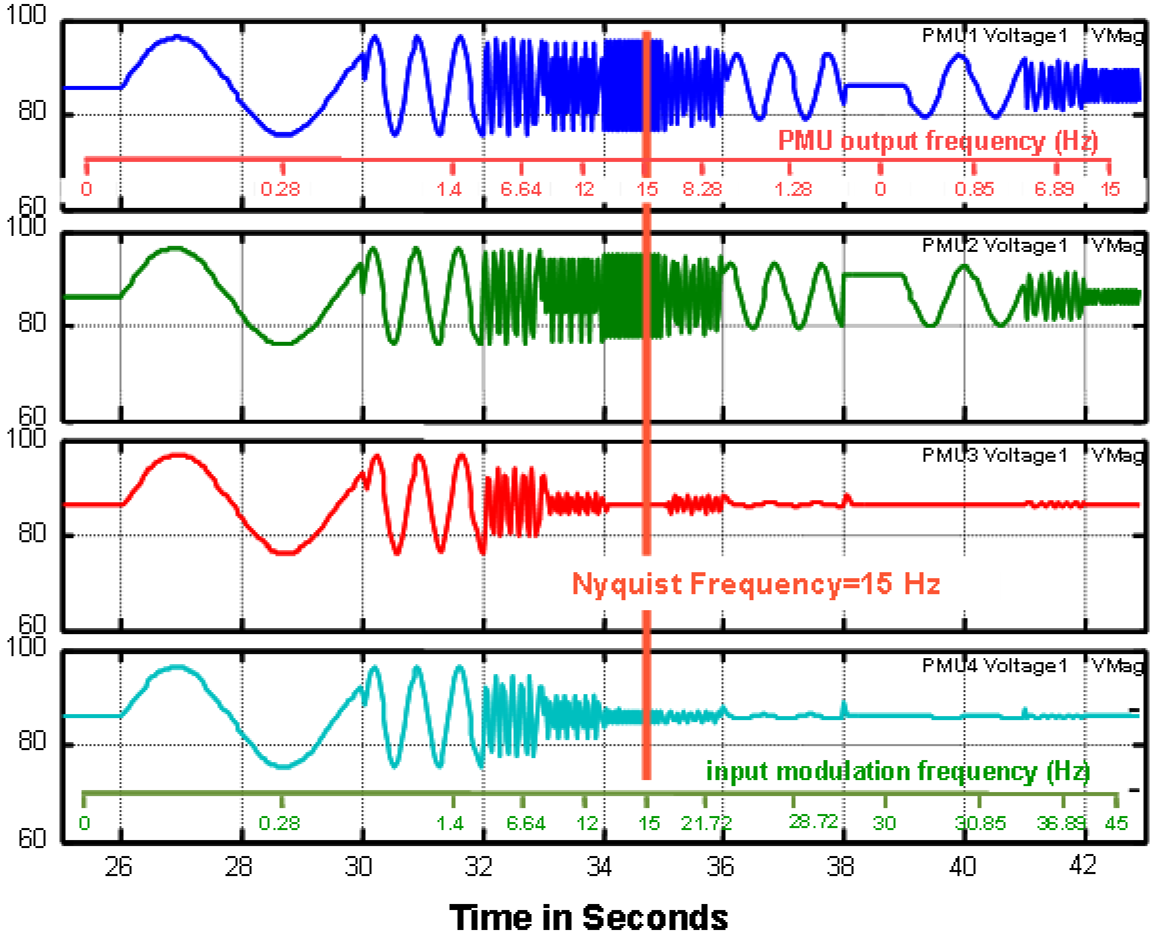


Figure 5. Frequency aliasing in four PMUs

Test file PMU_AMod6006seriesA

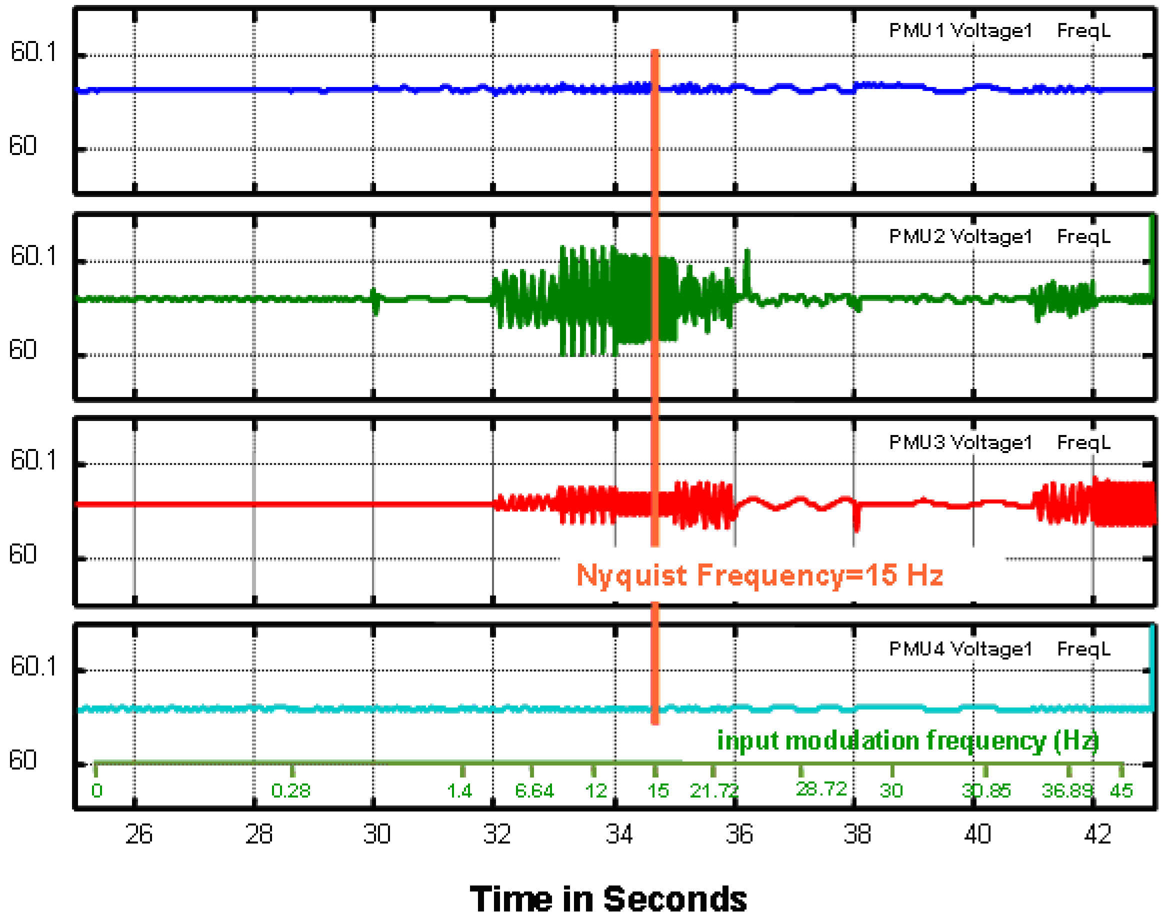


Figure 6. Cross-modulation of frequency signals from four PMUs
Test file PMU_AMod6006seriesA

Comparison of voltage magnitudes or other signals from the PMUs shows substantial timing differences among the units. The results in Figure 7, for modulation at 1.4 Hz, are typical for other modulation frequencies as well.

This is also true for the relative delays shown in Table 1, which shows signal residues obtained through Prony analysis. Such analysis often reveals low levels of distortion in PMU response, and it nearly always reveals appreciable lags between the frequency signal and the phasor outputs [15]. The logic used to calculate the frequency signal seems to differ strongly from one PMU type to the next, and experience to this point indicates that consistent frequency signals require that they be recalculated by applying the same algorithm to the phasors acquired from the entire measurement system.

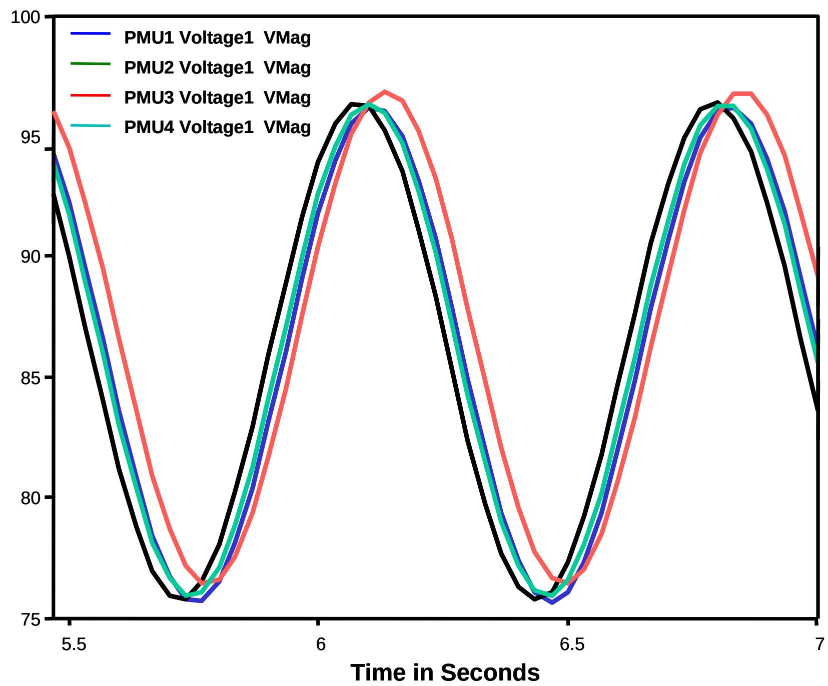


Figure 7. Relative timing of voltage signals from four PMUs

Test file PMU_AMod6006seriesA, 1.4 Hz modulaltion

Table 1. Relative Timing of Four PMUs (playback file Mod6006MseriesB, 1.40 Hz)

Sorted PRS Table for pole1: TRange=[5.4667 7.0]+24.8 seconds

Signal	Freq in Hz	Res Mag	Res Angle	Relative Delay
PMU1 Voltage1 VMag	1.400	10.331	160.562	8.7 msec
PMU2 Voltage1 VMag	1.400	10.340	175.578	-21.1 msec
PMU3 Voltage1 VMag	1.400	10.261	147.745	34.2 msec
PMU4 Voltage1 VMag	1.400	10.263	164.957	0.0 msec

6.5 Interoperability test

PMUs and all other system components that communicate with each other, such as PDCs from different manufacturers, shall conform to the same protocol specified by IEEE C37.118 standard through protocol conformance tests. Protocol conformance is the basis for all these system components to be interoperable with each other. An interoperability test should also be conducted for PMUs, PDCs and other system components with custom-defined protocols if any.

To further confirm the interoperability of PMUs, PDCs and other system components from different manufacturers, an interoperability test, including performance tests, should be conducted in addition to protocol conformance test conducted for individual PMU, PDC or other system component. Those tests should confirm that system components are interoperable and adhere to certain performance requirements, as required by applications.

The interoperability test may be conducted by a qualified independent test lab, or jointly by all manufacturers and user representatives. The tests may be performed in a lab or field environment.

6.6 System test

System test goes beyond single PMU test and aims to characterize performance for the whole measurement channel, including CT/PT, communication channel, etc. Please refer to "SynchroPhasor Accuracy Characterization, Performance and Standards" [9] document – a separate NASPI document – for detailed test procedure descriptions.

6.7 Tests of integrated PMUs

6.7.1 Modified IPMU testing

Devices that have additional functions above those spelled out in IEEE Standard C37.118 shall adjust the above testing of PMU as follows and shall perform the additional testing described below.

6.7.1.1 Range of input signals for IPMU

Actual measurement range of an IPMU is determined by (1) the types of transducers dictated by its primary functions, and (2) the C37.118 required signal range for phasor measurement.

6.7.1.2 Maximum resources loading

The performance of the phasor measurement function of an IPMU shall be tested under the maximum computing and communication resources utilization conditions.

6.7.1.3 Potential interference scenario verification

The performance of the phasor measurement function of an IPMU shall be tested for scenarios that may result in interference between primary functions and the phasor measurement function.

7 Synchrophasor message format

The synchrophasor message formats are given in the IEEE Std. C37.118-2005 Synchrophasor Standard. It was first published as IEEE Std. 1344-1995 and updated with the new standard. This message system is designed for real-time communications between a PMU measuring device and a data collection device, such as a phasor data concentrator (PDC). It can also be used for data sent from a PDC to another PDC. The overall data system is described here along with some implementation considerations. Details on the message format itself can be found in the IEEE standard.

7.1 Message Framework

As defined in IEEE Std. C37.118-2005 standard, there are four types of messages: data, configuration, header, and command. The command message is the only message sent from the receiving device to the PMU. It allows the receiving device to start and stop the data stream, to ask for the configuration message (two types of configuration are allowed in C37.118), or the header message. The command message has allowance for to send extended commands. Since these extensions are manufacturer specific, methods for testing these are not described here.

Each message includes a CRC-CITT check word (2 bytes). The value of this check word should be checked for each message received from the PMU and any deviations should be reported in the test report indicating the conditions under which the deviation was detected.

Whenever any changes are made to the PMU configuration (such as when the PMU reporting rate is changed in tests according to section 6.3.2), the config2 message shall be requested from the PMU. All further interpretations of the data messages shall be in accordance with this new configuration.

The config1 message and the header message shall be requested from the PMU and analyzed for proper format. Finally, the PMU shall be tested to respond properly to the commands to start and to stop sending the data messages.

7.2 Implementation issues

The standard describes a general framework and messages for data reporting. Implementation will depend on the type of medium being used and communication protocols. Most implementations will use IP protocol over Ethernet or other network type protocols. Some additional specifications of unit operation with the protocol layers to be used will simplify interoperability between utilities and within utility systems.

7.2.1 Unit identification

The standard specifies communication between units with a unit ID identifying the source for data or the destination for commands. These IDs are 16-bit integers. In a particular system, the system administrator can easily allocate IDs so they are all unique and make logical sense. When a number of utilities are aggregating their data together, a numbering scheme throughout the phasor network would simplify the identification of the PMUs. This should be handled by a designated coordination entity.

7.2.2 Protocol layers (TCP/UDP)

IEEE C37.118 does not require using specific data transmission methods or protocols. It does specify how data messages are to be encapsulated within a protocol, and gives examples for the IP protocol and RS232 serial. Within the IP protocol, both TCP and UDP can be used. TCP can be a problem with high data rate, continuous data as an error will cause the data stream to be backed up for a period of time while TCP attempts re-transmission of lost data. In the end, more data may be lost than that lost in the first place. UDP is better for high-rate continuous data, particularly when low delay is important. UDP can also be used for commands and configuration, and provides some degree of security from an attack which could tie up connections. However TCP provides assurance of making a connection and guaranteed response for configuration and header messages. Consistent use of these protocols could simplify communication issues. Other issues like message-address mismatch and how to handle multiple PMUs at one address could also benefit from clarification. The problem with over-specifying is there is little freedom for innovation and system improvement. Decisions regarding what will or will not be a requirement should be carefully considered.

7.2.3 Security suffixes

The IEEE standard assigns four bits within the data frame for a security indicator to be added in a future revision. This security is planned to be added as a suffix to the frame. Implementations of the standard should allow for addition of this at a later date. They should also be able to synchronize correctly on SYNC at the beginning of any frame regardless whether there is additional data appended to a frame or extraneous data between frames. Testing thus far has indicated this is not always the case.

7.2.4 Other issues

The above mentioned issues are some that have surfaced with early implementations of the standard. More will come up as development continues, and they need to be added here or in new sections of this Guide.

8 Final comments

Determination of PMU performance is based upon integrated use of laboratory tests, model simulations, and comparative measurements under field operating conditions. This section provides additional comments with regard to PMU evaluation under field conditions.

The laboratory evaluation of PMU dynamic performance has the following immediate objectives:

A. *Determine whether the PMU provides data of acceptable quality across a sufficiently broad frequency range.*

B. *Determine PMU performance in sufficient detail that its behavior can be predicted over a full range of application conditions, many of which cannot be reproduced with laboratory tests.*

There is no one standard that encapsulates the needs of all users, and laboratory tests should be insightful and comprehensive. Implicit in this is the need to develop an approximate model for the signal processing algorithm used in PMUs to help guide the development of appropriate performance testing requirements.

Validation of PMU performance does not end with field installation of the unit. Firmware changes and hardware degradation may produce an instrument that is very different from the one tested in the laboratory. Examining PMU data for evidence of possible discrepancies is a necessary part of WAMS operation, and cross validation of measurement sources is a necessary preface to the analysis of a major test or disturbance on the system.

The basic strategy for field evaluation of PMUs and other measurement sources is to regularly review the data for inconsistencies, and then to resolve such inconsistencies as may be found. The former activity is a normal aspect of WAMS operation. The latter activity may involve such tasks as identifying the cause, upgrading the measurement system, and developing a way to "clean" or repair the data. Success in such matters may require supplemental laboratory tests or modeling studies, and it is rarely immediate.

Sometimes it is possible to compare PMU data against data collected on other devices that share the same inputs, such as a digital fault recorder (DFR) or a PMU of another type. More often, though, one must work solely from PMU data collected at a number of different locations. It can then be difficult to distinguish discrepancies in timing or dynamic response within the measurement system from locational differences in response of the power system itself. WECC experience in these matters is summarized in reports such as [10,11,13].

Appendix A. WECC Requirements for Monitor Equipment

This appendix is for informational purposes only and not part of the requirements of this Guide. It is included as an example of dynamic performance requirements for PMU and point-on-wave monitors. In 2001 the WECC approved its Dynamic Performance and Disturbance Monitoring Plan to address NERC Planning Standard I. F., System Adequacy and Security - Disturbance Monitoring. Within this Plan the WECC established a reimbursement program to assist member utilities with the cost of equipment and maintenance associated with dynamic disturbance monitors at selected system locations. A monitor shall be judged as meeting basic WECC performance requirements if it satisfies the following technical criteria:

- **Frequency response of overall data acquisition:**
  - is -3 dB or greater at 5 Hz.
  - does not exceed -40 dB at frequencies above the Nyquist frequency (a limit of –60 dB is preferred)
  - does not exceed -60 dB at frequencies that are harmonics of the actual power system operating frequency (for design purposes, assume all frequencies in the range of 59 Hz to 61 Hz)
  - does not produce excessive ringing in records for step disturbances
- **Data sampling rate:**
  - Overall frequency response requirements imply a minimum sample rate that is 4 to 5 times the –3 dB bandwidth of overall data acquisition
  - For compatibility with other monitors, the sample rate should be an integer multiple of 20 or 30 samples per second (sps). A multiple of 30 sps is preferred.
- **Numerical resolution and dynamic range:**
  - Resolution of the analog-to-digital (A/D) conversion process must be 16 bits or higher.
  - Scaling of signals entering the A/D conversion should assure that 12-14 bits are actively used to represent them. Signals for which this scaling may overload the A/D during large transients may be recorded on two channels, in which one has less resolution but a greater dynamic range.
- **Measurement noise must be within the normal limits of modern instrument technology**. Noise levels for frequency transducers that are based upon zero-crossing logic tend to be unacceptable.
- **Documentation for the data acquisition process:**
  - must be sufficiently detailed that overall quality of the acquisition system can be assessed
  - must be sufficiently detailed that acquired records can be compensated for attenuation and phase lags introduced by the acquisition system
- **The monitor or monitor system stores data continuously and retains the last 240 hours (10 days) at all times without operator intervention.** A monitor that automatically erases the oldest file and stores the newest file will meet this criterion if the buffer area is 10 days or more. If the monitor requires an operator to remove old data to prevent storage overflow, a 60-day buffer is required to accommodate typical practices with monitor systems.
- **The monitor is able to typically store event data files for 60 days without operator intervention.** Since events are inherently unpredictable, this is only a ‘typical’ value based on operating experience. If the monitor stores continuous data, it does not have to store events.

- **The monitor demonstrates synchronization to Universal Time (UTC) to a 100µs level or better.** Synchronization to GPS based timing with suitable technique is preferred. Other approaches may be acceptable.
- **Data access is by network, leased line, or dial-up with software for transfer, storage, and data archiving.**
- **Data formats are well defined and reasonable**. Preferred formats for real-time data transfer are those equivalent to or meeting IEEE standards IEEE1344 [2] or C37.118 [1] or the PDCstream format for concentrator output. the preferred file format is PhasorFile described in PhasorFileFormat.doc (*.dst) commonly in use in the WECC.

Figure A1 shows a Butterworth filter of order 4, with a 12 Hz bandwidth and the WECC filtering requirements for a PMU output rate of 60 sps. Note that the stop band for each harmonic is proportional to frequency. Figure A2 shows measured and modeled performance for the Macrodyne 1690M (see i. Disclaimer), which does not satisfy the WECC filtering standard.

These minimum requirements are indicated as *sufficient* for meeting WECC needs, but they may not be seen as *necessary* in some cases. They are intended as quantified Guidelines for monitor evaluation, and they are deliberately stated in a simple manner. There are many underlying assumptions, plus considerable room for engineering judgment.

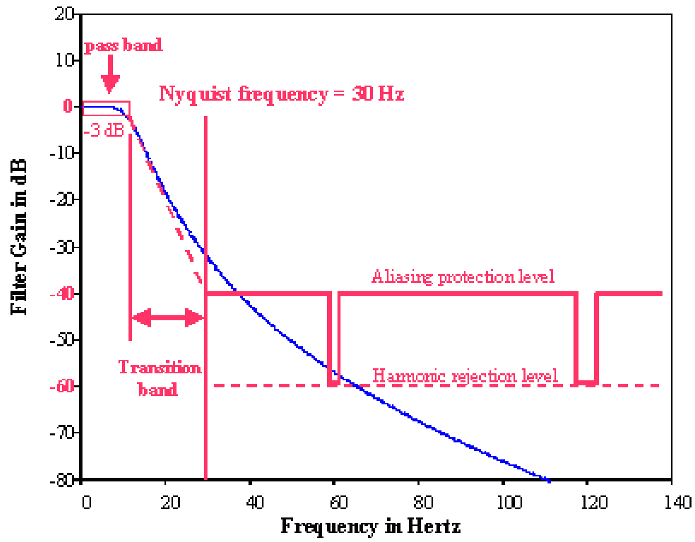


Figure A1. 12 Hz Butterworth filter vs. WECC Filtering Standard

(sample rate = 60 sps)

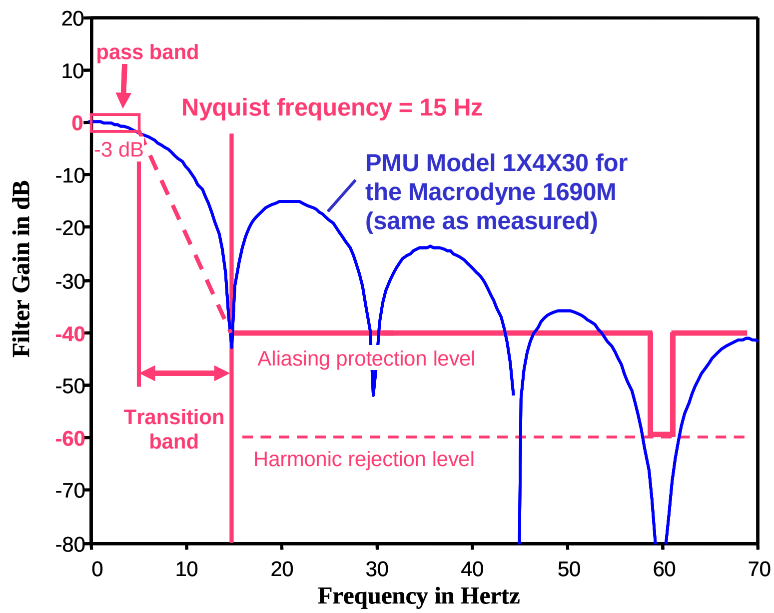


Figure A2. Macrodyne 1690M vs. WECC Filtering Standard (sample rate = 30 sps) (see i. Disclaimer)

Appendix B. Modulation and Demodulation of PMU Inputs

A PMU, like any RMS transducer, provides average measures of point-on-wave (**POW**) input signals that represent local voltages and/or currents in the power system. The pow inputs can be thought of as sets of modulated carriers, containing dynamic information that is impressed through a combination of amplitude modulation and frequency modulation[3]. The carrier frequencies are usually harmonically related to the system operating frequency. This is not necessarily the case, however. Transducer inputs occasionally contain additive components for which the frequencies are essentially arbitrary, and which probably have no direct association with generator activity.

The overall situation is depicted in Figure B1. Signal environment for a power system transducer.. It is useful to think of the carrier levels as *powerflow information*, and the impressed modulation as *dynamic information*. Additive signals, if present, are in a special category and potentially troublesome.

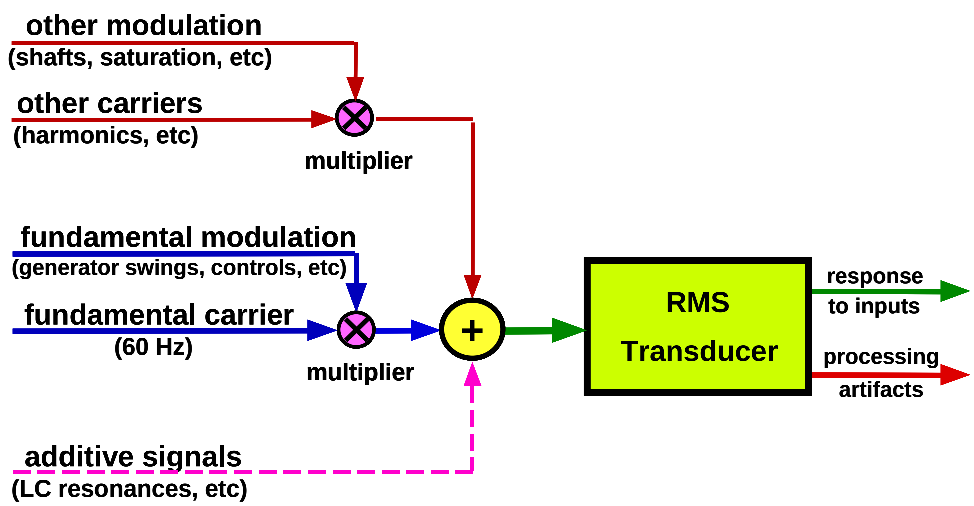


Figure B1. Signal environment for a power system transducer.

Amplitude modulation is the primary means by which dynamic information is impressed upon the POW carriers. Let sin(x) represent the power system "carrier" signal before modulation, and let sin(y) represent the modulating signal. Then the modulation produces sideband pairs according to the (equivalent) relations

$$\sin(x)\sin(y) = \tfrac{1}{2}\left[\cos(x-y) - \cos(x+y)\right] \quad \text{(B1A)}$$

$$\sin(x)\cos(y) = \tfrac{1}{2}\left[\sin(x-y) + \sin(x+y)\right] \quad \text{(B1B)}$$

[3] In this context, frequency modulation is sometimes called angle modulation or phase modulation

So, if x represents a 60 Hz carrier frequency and y represents a 1.2 Hz modulation, there will be a "lower" modulation sideband at 60-1.2=58.8 Hz and a "upper" modulation sideband at 60+1.2=61.2 Hz. Figure B2 provides an example with amplitude modulation sources at 1.05 Hz, 1.46 Hz, and 18.2 Hz. The example also includes an additive signal at 52 Hz; which is representative of a network resonance encountered during operation of the Pacific HVDC.

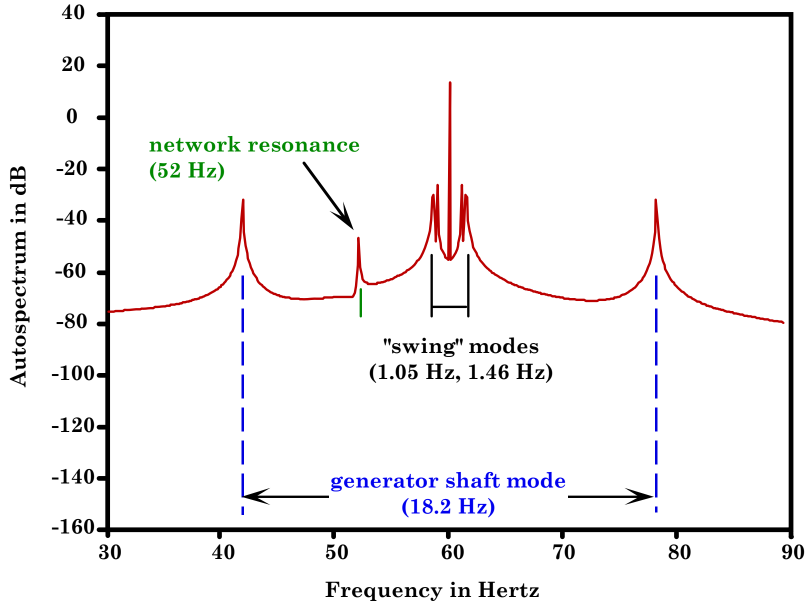
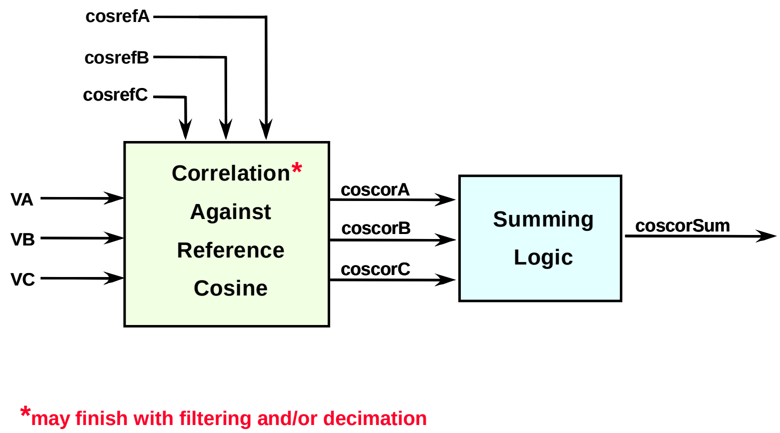


Figure B2. Components of the information spectrum for an RMS transducer

A PMU demodulates each carrier in the same manner as an AM radio receiver. Multiplying the modulated carriers by a reference sine and/or cosine wave of frequency z produces shifted images of the signal spectrum, with each spectral component generated according to equations (B1)[4]. The reference signals will be multiphase quantities dimensioned to match the transducer inputs (see Figure B3).

[4] This demodulation can also be described as a projection onto the reference signal(s), as a correlation process, or as a calculation of the Fourier coefficient at frequency z. The term "complex demodulation" is often used when the projection is onto a sine/cosine pair.



FigureB3. Modeling nomenclature for projection of point-on-wave signals onto reference cosine

Projection onto the cosine reference produces both a lower demodulation spectrum and an upper demodulation spectrum for each pow component (input phase). If the PMU is a three phase unit operating under balanced power system conditions, then the upper demodulation spectrum will usually be eliminated if the three projected signals (shown as coscorA-C in Figure B3) are summed together. Otherwise special filtering may be needed to assure that the upper demodulation spectrum is not "aliased" into some lower range of frequencies when signals internal to the PMU are downsampled for final output. Detailed examples of this are provided in [10], and in PMU modeling codes within the DSI Toolbox [11].

Projection onto the sine reference proceeds in the same manner, and leads to a phasor component that is orthogonal to that for the cosine reference.

There is a final process by which sidebands, or at least signal components that are similar to them. Suppose that the summed cosine projection (shown as coscorSum in Figure B3) contains signal components for more than one amplitude modulation source. This will also be true for the summed sine projection (sincorSum). Then consider calculation of the phasor magnitude. Performing this as the usual square root of squared components added together may well produce spurious components, unless some special relationship exists within the signal structure.

Some tedious trigonometry shows that this special structure does exist for amplitude modulation by a single frequency, and that the phasor magnitude can directly calculated without spurious cross terms. The relationship is destroyed if filtering of the demodulation spectrum is not symmetric, however, and it likely does not exist for the general spectra associated with power system signals [10].

Appendix C: Phasor Aliasing and Interfering Frequencies

This appendix describes issues and methods for testing PMU response to out-of-band signals. These methods and discussions include amplitude and phase (or frequency) modulated signals, which are described as two frequency interference signals, as well as single frequency interference, which is a combined amplitude and phase modulation.

C.1 Scope

The C37.118 compliance requirements specify an interfering signal of certain magnitude and frequency, and require any compliant PMU to suppress such interfering signal. It is beneficial to associate such generic requirement with the actual system events and bring an intuitive way of understanding the intent of the test, any given testing method, and interpretation of test results.

With reference to Figure C.1, two interfering bands are considered in the Standard. They result from a strict mathematical solution of the expression defining the interfering frequency (f_i – interfering frequency, f_s – signal frequency, F_s – reporting frequency):

$$\left| f_i - f_s \right| > \frac{F_s}{2}$$

Solving the above equation leads to:

$$f_i > f_s + \frac{F_s}{2} \quad \text{or} \quad f_i < f_s - \frac{F_s}{2}$$

Assuming no negative frequency is to be applied, i.e. the added component is not rotating in a different direction compared with the signal, the latter condition becomes:

$$0 < f_i < f_s - \frac{F_s}{2}$$

making the two bands not equal.

Several issues arise with respect to the test: purpose of the test (implied Nyquist condition for the phasor reporting process), interpretation of the interfering signal (additive or multiplicative, single component or a pair), range of the lower band (native frequency), DC component in the test signal, overlap between the upper interfering band and the harmonic distortion band.

This section interprets the Standard to arrive at meaningful tests driven by PMU applications. Our interpretation is derived by associating interference with phasor modulation, and further with practical applications of synchrophasors.

A recommendation is made to test for interfering frequencies with a pair of additive signals controlled to test both pure magnitude and pure phase modulation. The issue of a DC component is resolved by setting a rational limit on the fastest meaningful phasor modulation, and by doing so limiting the interfering bands accordingly.

The following subsection explains our approach and derives the test waveforms. The subsequent subsections describe the tests and interpretation of results.

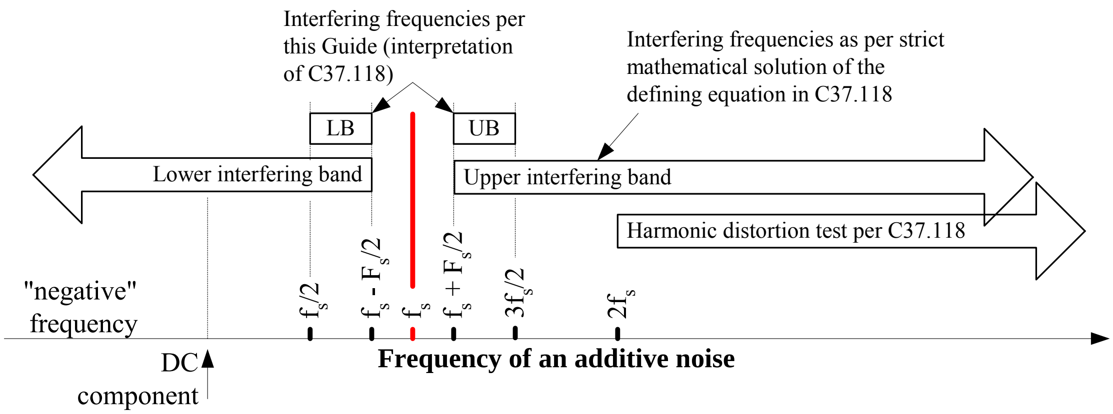


Figure C.1. Comparing the harmonic distortion and interference frequency tests.

C.2 Phasor modulation

C.2.1 Magnitude modulation

With reference to Figure C.2, a phasor rotating at a frequency f_s and magnitude of X_s, is magnitude-modulated with a sine-wave of frequency f_m and magnitude X_m.

Assuming the phasor modulation occurs at frequency above the Nyquist rate as resulting from the applied reporting rate, the phasor – given by the magnitude X_s and angular position as dictated by the frequency f_s – is the information to be passed by a given PMU, and the modulations in the signal is the interference to be suppressed.

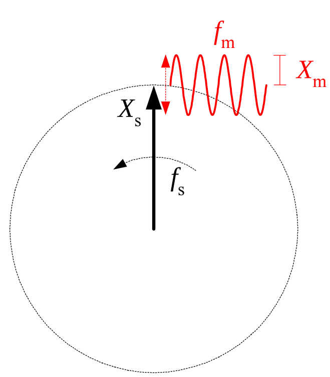


Figure C.2. Magnitude modulation of a phasor.

Mathematically, magnitude modulation can be obtained as follows:

$$x_{(t)} = X_s \cdot \left(1 + X_{m(pu)} \cdot \cos\left(2 \cdot \pi \cdot f_m \cdot t\right)\right) \cdot \cos\left(2 \cdot \pi \cdot f_s \cdot t + \varphi\right) \quad \text{(C1)}$$

In the above equation, the initial angle (φ) is added for generality of our considerations, with no practical effect as shown later. The modulating frequency is practically in the range of a few Hz. Even considering a very fast unstable power swings with a period of a few hundreds of milliseconds, the frequency of effective modulation of system currents and voltages is in the range of a few Hz.

Equation (C1) assumes a multiplicative alternation of the signal magnitude with no variation added to the information contained in the phase of the signal. Basic mathematical identities allow rewriting equation (C1) into an additive noise model more aligned with the interfering frequency test as per the Standard:

$$x_{(t)} = X_s \cdot \cos\left(2 \cdot \pi \cdot f_s \cdot t + \varphi\right) + x_{NOISE(t)} \quad \text{(C2a)}$$

$$x_{NOISE(t)} = \frac{X_s \cdot X_{m(pu)}}{2} \left(\cos\left(2 \cdot \pi \cdot \left(f_s + f_m\right) \cdot t + \varphi\right) + \cos\left(2 \cdot \pi \cdot \left(f_s - f_m\right) \cdot t + \varphi\right)\right) \quad \text{(C2b)}$$

Adding two sine-waves to the signal, one of the frequency being the sum of the signal and modulation frequencies, and the other of frequency being the difference between the signal and modulation frequencies, is effectively equivalent to modulating the signal magnitude without altering its phase.

The synchrophasor standard does not specify whether the interfering signal is of a single frequency, or multiple frequencies can/should be used simultaneously during the compliance test. It simply requires suppressing components of frequencies meeting the key condition:

$$\left| f_i - f_s \right| > \frac{F_s}{2} \quad \text{(C3)}$$

Solving the above yields two bands for the frequency of the interfering signal as per the Standard:

$$f_{i(HIGH)} > f_s + \frac{F_s}{2} \quad \text{(C4a)}$$

$$f_{i(LOW)} < f_s - \frac{F_s}{2} \quad \text{(C4b)}$$

In other words frequencies as close to the signal frequency as half the reporting rate, should be suppressed to claim compliance with the Standard.

If the Standard is interpreted in a way that a pair of interfering signals is applied, one being the mirror image of the other with respect to the signal frequency and equation (C2b) is used to generate the noise component, then the interfering frequency test is equivalent to magnitude modulation, and the following test conditions apply as derived by comparing expressions (C4) with expressions (C2):

$$f_m > \frac{F_s}{2} \quad \text{(C5a)}$$

$$X_{m(pu)} = 0.01 \;\; \text{for level 0 compliance} \quad \text{(C5b)}$$

$$X_{m(pu)} = 0.10 \;\; \text{for level 1 compliance} \quad \text{(C5c)}$$

Expression (C5a) will be further defined later in this section to facilitate practical tests.

Under this interpretation, the interfering frequency test is a modulation of magnitude; the modulation frequency should be above half the reporting frequency; and the test should be performed considering an additive noise per equations (C2).

In equations (C2) an issue may arrive as to the phase relationships between the three sine-waves. In order to achieve pure magnitude modulation the three sine-waves must be in a precise phase relationship as per equations (C2). This is not a problem if the signal and noise components are generated digitally in a single test set. If two sources are used one for the signal and the other for the noise, one can achieve pure magnitude modulation by slow adjustments to the frequency of the modulating signal or the fundamental signal as explained later in this section.

It is worth noticing that only the true phasor component in the signal (equation (C2a)) needs to be either generated with respect to time, or measured synchronously with respect to time for comparison (calibration) purposes. The added noise as per equation (C2b) can be left as not synchronized to time. This can simplify interfering frequency tests as shown later.

Figure C.3 shows a PMU test input amplitude-modulated signal as per our interpretation of the interfering frequency test (top); the actual stationary synchrophasor (equation (C2a), middle); and the added noise (equation (C2b), bottom).

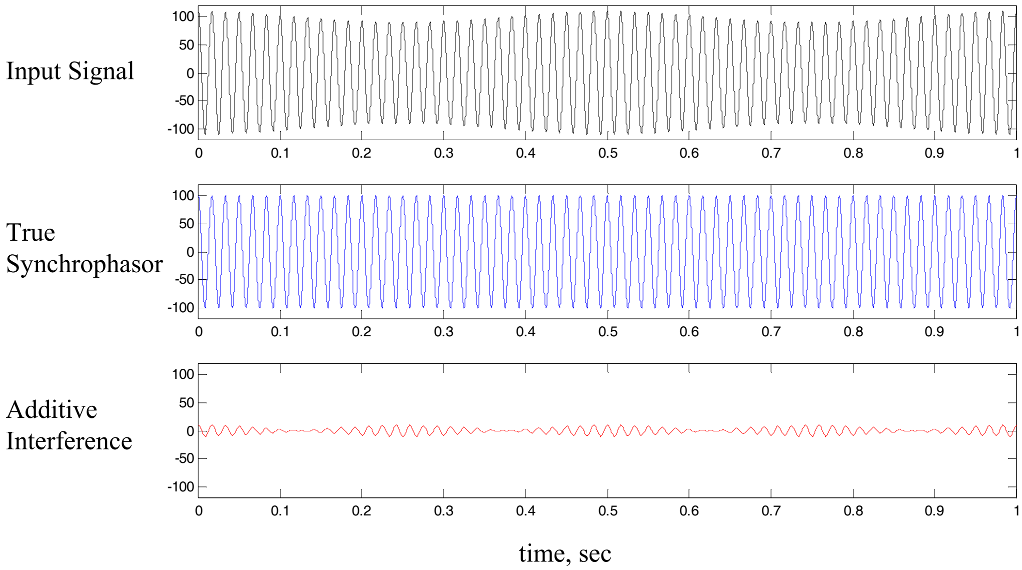


Figure C.3. The input signal being a sum of a stationary synchrophasor and an additive noise as per the "magnitude modulation" interpretation of the interfering frequency test.

Figure C.4 below shows trajectory of a sample magnitude-modulated phasor. Keep in mind that the frequency of modulation is typically much smaller compared with the signal frequency. The following plot will be visible when recording a slightly off-nominal frequency signal being magnitude-modulated.

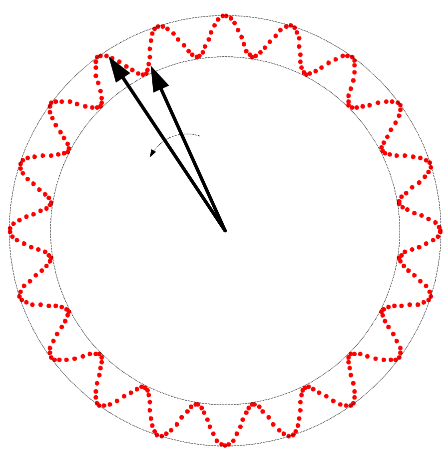


Figure C.4. Trajectory of a magnitude-modulated phasor.

C.2.2 Phase modulation

Magnitude modulation explained in the previous section assumed adding a slowly oscillating component to the magnitude of the signal "in parallel" to the signal, so that the modulation affect the magnitude alone, but not the phase. A complementary test is recommended for modulating the phase of the signal, keeping the magnitude constant or only slightly changing.

For simplicity of the test we will not consider a situation of the magnitude being perfectly constant, but we will allow very minor changes in the magnitude. If so, phase modulation can be easily achieved by adding a "perpendicular" component to a stationary phasor as shown in Figure C.5.

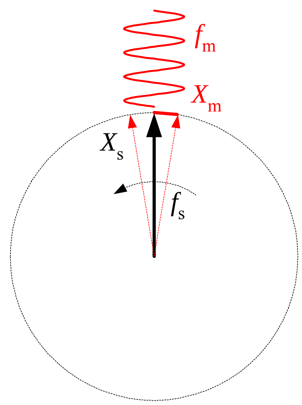


Figure C.5. Phase modulation of a phasor.

Mathematically, the test signal in this case becomes:

$$x_{(t)} = \mathrm{Re}\left(X_s \cdot \left(1 + j \cdot X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot f_m \cdot t)\right) \cdot e^{j(2\cdot\pi\cdot f_s \cdot t + \varphi)}\right) \tag{C6}$$

After basic rearrangements one obtains:

$$x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) - X_s \cdot X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot f_m \cdot t) \cdot \sin(2 \cdot \pi \cdot f_s \cdot t + \varphi) \tag{C7}$$

The above can be further re-arranged in the format of a stationary phasor and an additive noise:

$$x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \tag{C8a}$$

$$x_{NOISE(t)} = \frac{X_s \cdot X_{m(pu)}}{2} \left(\sin(2 \cdot \pi \cdot (f_s + f_m) \cdot t + \varphi) + \sin(2 \cdot \pi \cdot (f_s - f_m) \cdot t + \varphi)\right) \tag{C8b}$$

Equation (C8b) conforms to the same scenario as for the case of pure magnitude modulation: two equal components having frequencies symmetrical with respect to the signal frequency are added. Also, (C8b) is similar to (C2b) except the sine function is used as a base function instead of the cosine. Therefore equations (C2b) and (C8b) can be generalized as follows:

$$x_{NOISE(t)} = \frac{X_s \cdot X_{m(pu)}}{2} \left(\cos\left(2 \cdot \pi \cdot \left(f_s + f_m\right) \cdot t + \varphi + \varphi_{NOISE}\right) + \sin\left(2 \cdot \pi \cdot \left(f_s - f_m\right) \cdot t + \varphi + \varphi_{NOISE}\right)\right) \tag{C9}$$

Equation (C9) is used together with equation (C2a) to perform the interfering frequency test. Two specific alignments between the signal (C2a) and noise (C9) are defined as follows:

$\varphi_{NOISE} = 0$ - magnitude modulation

$\varphi_{NOISE} = \frac{\pi}{2}$ - phase modulation

The generalized test needs to follow conditions (C5) in terms of the magnitude and frequency of the superimposed noise.

Figure C.6 shows the test input signal, true synchrophasor and the additive noise per the phase modulation interpretation of the interfering frequency test.

Figure C.7 presents a trajectory of a phase-modulated phasor. The magnitude remains approximately constant while the "speed of vector rotation" oscillates.

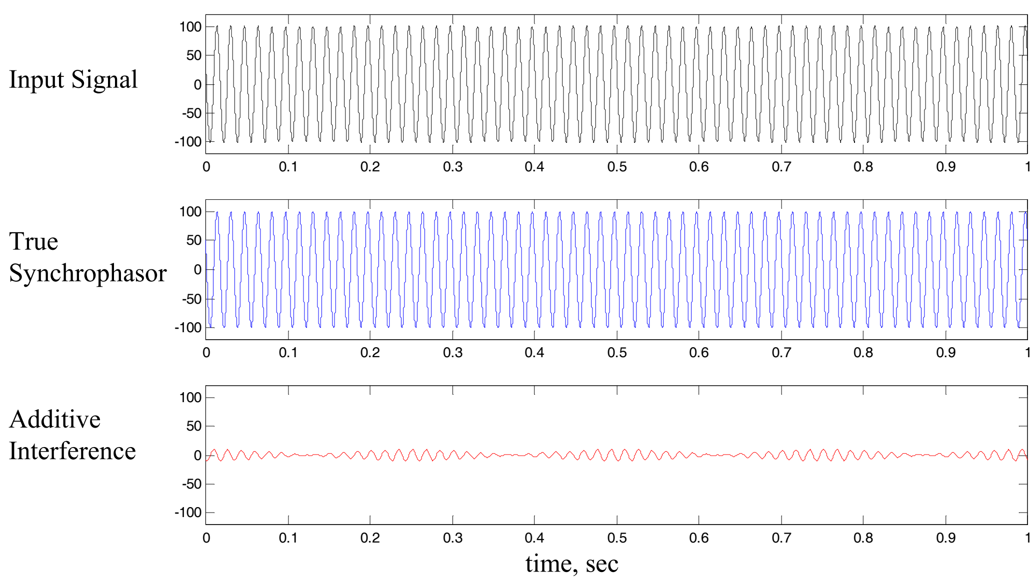


Figure C.6. The input signal being a sum of a stationary synchrophasor and an additive noise as per the "phase modulation" interpretation of the interfering frequency test.

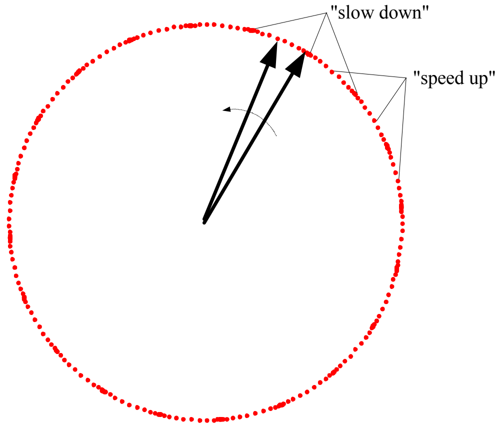


Figure C.7. Trajectory of a phase-modulated phasor.

C.2.3 Single interfering frequency

Let us explore the consequences of adding a single interfering signal component. Consider signal modulation as in Figure C.8. A modulating vector of magnitude X_m rotating at frequency f_m is added to the magnitude of the true phasor, and such modulated magnitude is further assumed to rotate at frequency f_s. The modulating vector in the magnitude rotates in the same direction as the true phasor. The test input signal for such modulation is the real part of the total vector:

$$x_{(t)} = X_s \cdot \mathrm{Re}\left(\left(1 + X_{m(pu)} \cdot e^{j(2\cdot\pi\cdot f_m \cdot t)}\right) \cdot e^{j(2\cdot\pi\cdot f_s\cdot t+\varphi)}\right) \quad \text{(C10)}$$

The above expression is equivalent to:

$$x_{(t)} = X_s \cdot \cos(2\cdot\pi\cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \quad \text{(C11a)}$$

$$x_{NOISE(t)} = X_s \cdot X_{m(pu)} \cdot \cos\left(2\cdot\pi\cdot\left(f_s + f_m\right)\cdot t + \varphi\right) \quad \text{(C11b)}$$

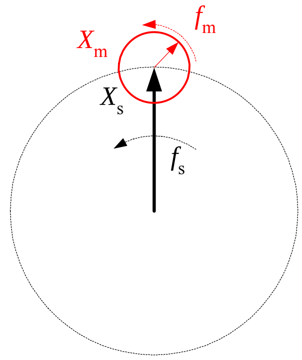


Figure C.8. Modulating a phasor with a single frequency component.

In other words, a single frequency component added to the magnitude of the true phasor and having the frequency above the phasor frequency is equivalent to phasor modulation with a vector rotating in the same direction as the base phasor.

A rotating vector acting as a modulator alters (oscillates) both magnitude and phase position simultaneously as depicted in Figure C.9.

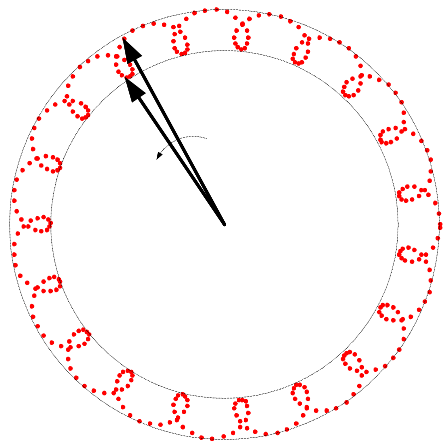


Figure C.9. Trajectory of a phasor modulated with a vector rotating in the same direction as the phasor.

Consider now the same type of modulation but assume the modulating vector rotates in the opposite direction to the base phasor as shown in Figure C.10. Mathematically this scenario is described as:

$$x_{(t)} = X_s \cdot \mathrm{Re}\left(\left(1 + X_{m(pu)} \cdot e^{-j(2\cdot\pi\cdot f_m\cdot t)}\right)\cdot e^{j(2\cdot\pi\cdot f_s\cdot t+\varphi)}\right) \quad \text{(C12)}$$

and is equivalent to:

$$x_{(t)} = X_s \cdot \cos(2\cdot\pi\cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \quad \text{(C13a)}$$

$$x_{NOISE(t)} = X_s \cdot X_{m(pu)} \cdot \cos(2\cdot\pi\cdot(f_s - f_m)\cdot t + \varphi) \quad \text{(C13b)}$$

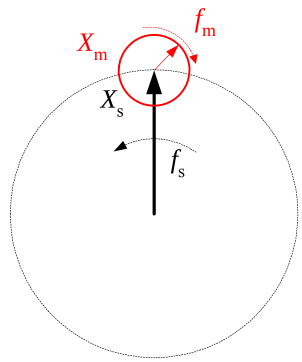


Figure C.10. Modulating a phasor with a single frequency component (opposite directions of the base and modulating vectors).

In other words, a single frequency component added to the true phasor and having the frequency below the phasor frequency is equivalent to phasor modulation with a vector rotating in the opposite direction as the base phasor. Again, adding a single interfering component oscillates both the magnitude and phase of the signal.

Figure C.11 illustrates the single component interfering frequency test signals.

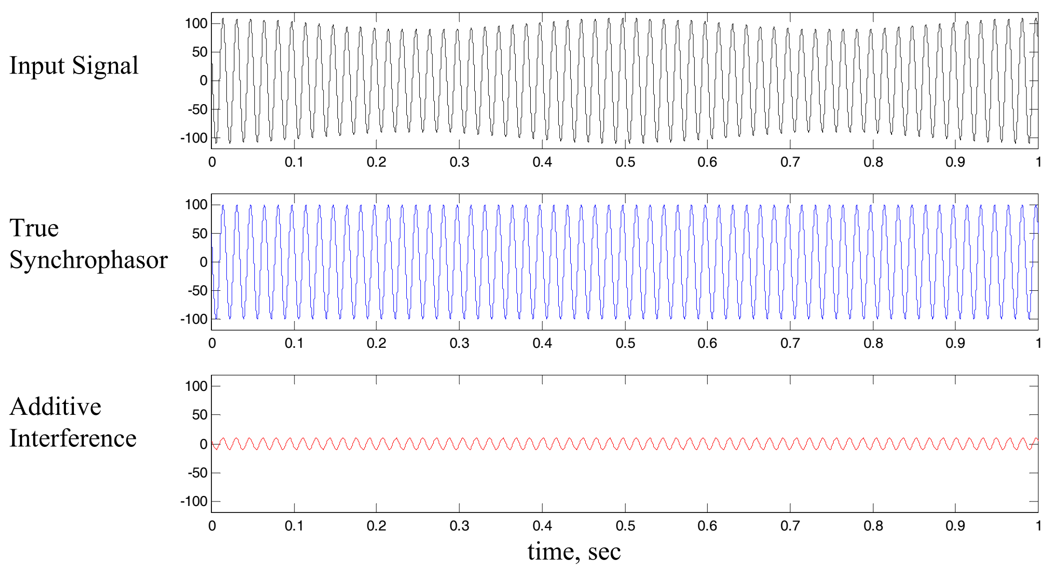


Figure C.11. Single component used as an interfering signal.

Table A.1 summarizes the four modulation methods described in this section and their relation to the interfering frequency tests as specified by the Standard.

Table C.1. Basic modulation methods and their relation to the interfering frequency test.

Modulation	Additive noise	Interfering components	Noise frequency
Oscillating Magnitude	Eq. (C9), $\varphi_{NOISE} = 0$	pair	Above and below the signal, symmetrically
Oscillating Phase	Eq. (C9), $\varphi_{NOISE} = \frac{\pi}{2}$	pair	Above and below the signal, symmetrically
Rotating Vector	Eq. (C11b)	single	Above the signal
Counter-rotating Vector	Eq. (C13b)	single	Below the signal

This section shows that using a symmetrical pair of interfering signals creates intuitively obvious modulation patterns ranging from pure magnitude to pure phase modulation. Adding a single frequency is equivalent to a modulation pattern equivalent to adding a second vector rotating at the modulating frequency, and is not necessarily representative to actual system events.

The Standard does not specify if single-frequency interference is to be tested, or a pair is to be used, or some other combination. However, strictly solving the interfering frequency equation (C3) yields two solutions. This suggests a pair of components symmetrical with respect to the phasor frequency is to be used. Our Guide follows this interpretation. As a result equation (C9) is used to generate the interfering noise signal for the tests. The interfering signal is a pair of sine-waves.

C.2.4 Range of the interfering frequency

As shown in Figure C.1 a compliant PMU should suppresses signal components half the reporting frequency below and above the signal frequency. Two observations can be made in this respect. First, a potentially very low frequency component is allowed as an additive noise challenging implementations that use interposing transformers for galvanic isolation. Second, the lower and upper interfering bands are different, unless one assumes negative frequency that is adding a component rotating in an opposite direction.

Our interpretation of using a pair of interfering frequencies solves both these irregularities.

First consider the two frequency bands: below and above the signal frequency. According to equation (C9) and boundary condition (C5a), the interference component of frequency above half the reporting rate shall be used for testing. The question is how high the frequency defined by (C5a) should become. Naturally, using our signal model (C9), the upper limit for the frequency in the interfering signal is the signal frequency. Going above the signal frequency would make the f_s-f_m expression negative. Negative frequency in one of the interfering signal components can be dealt with for the purpose of testing with appropriate phase adjustment (a steady state sine-wave rolling forward or backward in time is still a sine-wave).

However, going above the signal frequency in terms of modulation would make the interfering frequency test overlap with the harmonic distortion test. We consider it unnecessary and potentially causing test interpretation problems. As a result, the interfering frequency test is to be limited to the signal frequency in terms of the fastest possible frequency of modulation. Therefore, expression (C5a) needs to be further specified as:

$$f_s > f_m > \frac{F_s}{2} \qquad \text{(C14)}$$

This solves the irregularity of the two frequency bands. When using expression (C14) to sweep the two bands, the two bands become as follows:

Below the signal: 0Hz to $f_s - \frac{F_s}{2}$

Above the signal: $f_s + \frac{F_s}{2}$ to $2 \cdot f_s$.

In other words both the bands are equal allowing using a pair of signal with no need to deal with the negative frequency scenario in the lower band. Ability to suppress noise above the second harmonics is now covered by the harmonic distortion test, and not be the interfering frequency test.

The other problem is testing with extremely low frequency components when exercising the band below the signal frequency. This happens when the interfering frequency in equation (C9) approaches the signal frequency. However, question needs to be posted if such a situation is practically meaningful. The question is how fast a carrier of frequency f_s (system frequency) is modulated in practical power systems? WE assume the fastest possible meaningful modulation is in the range of few Hz. Half the signal frequency seems to be satisfying compromise for the fastest possible modulation in practical power systems.

If we agree with the above, expression (C14) needs to be further specified as:

$$\frac{f_2}{2} > f_m > \frac{F_s}{2} \qquad \text{(C15)}$$

Following interpretation (C15) allows avoiding the DC component issue. Now the two bands are:

Below the signal: $\frac{f_s}{2}$ to $f_s - \frac{F_s}{2}$

Above the signal: $f_s + \frac{F_s}{2}$ to $\frac{3}{2} \cdot f_s$.

Interpretation given by equation (C15) is not a part of the Standard, but is practical and meets the intent of the interfering frequency test of satisfying the Nyquist principle as applied to reporting rate.

C.3 Test equipment and setup

With reference to Figure C.12 two approaches can be used to generate the input signal for the interfering frequency tests.

Scenario (C12a) uses separate sources for the true phasor and the interfering signal. In this way the true phasor is available for interdependent verification of the time-synchronized measurement. As a result the source of the true phasor does not have to be synchronized to the clock, or be able to generate the interfering signal. The only requirement for the phasor source is to be stable and provide a clean signal as per the reference condition of the accuracy compliance in the Standard. The second source is used to generate the interfering signal as described in the previous section. The summation node is to be understood as series connection of two voltage outputs from two test sets, or a parallel connection of two current outputs if a current channel is to be tested.

In this method, the test set generating the true phasor can be time synchronized, and when calibrated, it allows avoiding the independent verification of the true phasor. However, it is always prudent to spot check accuracy of the test set. The method of Figure C.12a allows such verification.

The method of Figure C.12b requires a tests set that is both synchronized to the clock, and capable of adding the interfering signal to the pure sine-wave output. In this setup an independent verification of the test set is not straightforward as the output signal is not a pure sine-wave, but a modulated signal.

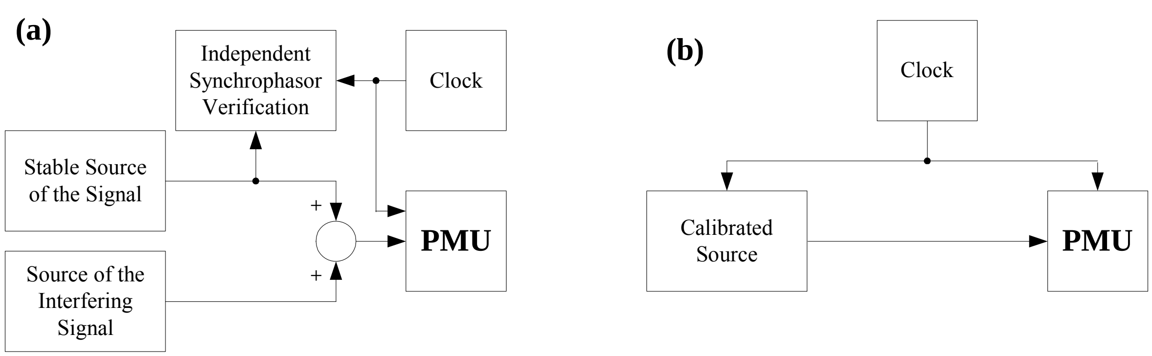


Figure C.12. Simplified setup for the interfering frequency test: true phasor and interference sources separated (a); single source for the true phasor and the interference (b).

The overall requirements for the signal sources and the clock are not different than for other tests outlined in this Guide.

C.4 Test procedure

For illustration purposes we assume interpretation given by equation (C9) of the interfering frequency test; interpretation given by expression (C15) of the out of band frequencies, and test setup of Figure C.12a.

The source of the phasor is configured to generate a stationary phasor as per the reference condition of the Standard. In particular this signal is to be of nominal system frequency ($f_s = f_0$), nominal magnitude and have a THD below 0.2%. Alternatively, the frequency can be varied between tests, preferably in the ±5Hz range; and the magnitude can be varied as required.

The source of the interfering signal is configured to generate a signal as per equation (C9). This signal does not have to be synchronized to the clock, and does not have to be very stable or clean. The f_m frequency in the signal (C9) is to be varied slowly between half the reporting rate and half the phasor signal frequency. The magnitude $X_{m(pu)}$ in equation (C9) needs to be set at 0.1 or 0.01 of the phasor signal magnitude for compliance level 1 and 0, respectively.

At any frequency f_m, the TVE shall remain below 1% for compliance with the Standard. It is likely the error will oscillate slowly at a frequency similar to the modulating frequency. Therefore a time series of synchrophasor shall be captured, and the highest TVE shall be recorded as a test result.

In general, it is difficult to predict the worst-case condition, and therefore, the modulating frequency f_m needs to cover the full range between the half the signal frequency down to half the reporting frequency.

At each frequency point, the frequency f_m can be adjusted very slowly. Small adjustments in this frequency will result in gradual changeover between the pure magnitude modulation and pure phase modulation. Again, it is difficult to predict which type of modulation constitutes the worst-case condition for a given PMU. Therefore, the conceptual angle φ_{NOISE} in equation (C9) shall be swept full range from 0 to 90 degrees. Technically, this is done by very small changes to either the f_m or f_s frequencies. Also, the natural drift in either f_s or f_m frequencies would result in gradual switchover between the pure magnitude and phase modulation.

C.5 Out-of-band frequency rejection vs measuring system oscillations

The C37.118 standard requires a compliant PMU to suppress the modulations that occur too fast compared with the reporting rate as per the Nyquist theorem. As such the test is a steady state test because the phasor to be reported is stationary. It is the noise that changes slowly in time. The TVE definition is unambiguous and one does not venture into the domain of dynamic phasors or testing under dynamic system conditions.

One may however use the interfering frequencies test setup to test the abilities of a given PMU to pass oscillations that occur slowly as compared with the Nyquist frequency of half the reporting rate. Such an approach is meaningful as PMUs are intended to measure system oscillations. This, however, constitutes a dynamic test and is out scope of the C37.118 standard. Such tests can be conducted as informative rather than compliance tests.

Such tests in general are more difficult and call for solving several issues as follows.

First, the rates of modulation of interest need to be established. Typical system events are of frequency well below 10Hz. On the other hand one cannot – per Nyquist – observe modulations occurring faster than half the reporting rate. Therefore the upper limit for phasor modulations to be reported is the lowest number between about 10Hz of interest, and half the reporting rate of Nyquist limit. For example, when reporting at 30 phasors/sec the band of interest is probably from 0 to 10Hz. When reporting at 10 phasors/sec one should not expect a PMU to pass oscillations faster than some 2.5Hz. As a matter of fact a compliant PMU is mandated to stop oscillations faster than 5Hz. It will probably pass phasor oscillations some band down from the 5Hz interfering frequency limit.

Second, the true phasor must be established so that the TVE definition can be applied to the changing phasor. With this respect equations (C1), (C6), (C10) and (C12) can be used.

For example, a magnitude-modulated phasor carried by the signal generated with equation (C1) has a dynamic magnitude of:

$$X_{MAG(t)} = X_s \cdot \left(1 + X_{m(pu)} \cdot \cos\left(2 \cdot \pi \cdot f_m \cdot t\right)\right) \qquad \text{(C16a)}$$

and phase:

$$X_{PHASE(t)} = 2 \cdot \pi \cdot f_s \cdot t + \varphi \qquad \text{(C16b)}$$

Third, the test equipment must be able to generate a modulated signal with all its components being synchronized to time. With this respect a test setup of Figure C.12b is better suited.

Fourth, the magnitude of phasor modulations needs to be established. The interfering frequency test sets a 1% and 10% modulation magnitude. The test to pass phasor oscillations is not bounded by this requirement. Assuming an unstable power swing as an event of interest the magnitude of the modulating component may reach the signal magnitude.

Again, a test confirming ability of a given PMU to pass slow phasor oscillations is outside of the scope of the C37.118 Standard. The Standard mandates compliant PMUs to suppress modulations of relatively high frequencies that could alias given the phasor reporting rate.

When both the interference rejection and modulation tests are done, their results can be summarized as in Figure C.13 below.

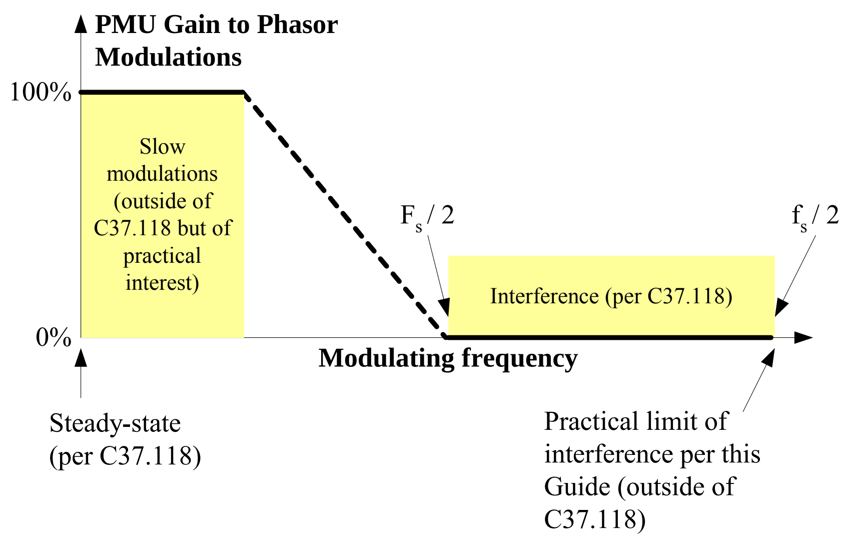


Figure C.13. Comparing the interfering frequency and modulated phasor tests.

C.6 Using the interfering frequency test to check performance for inter-harmonics

The Standard requires rejecting harmonics. Inter-harmonics are not covered explicitly, but in a way capabilities to suppress any high frequency component, not only harmonics, is implied in the interfering frequency tests. Except the latter is meant to address the Nyquist theorem. We propose to add a second interpretation of the interfering frequency test to address the high frequency signal distortions as follows.

A single frequency component is added to a stationary phasor with the magnitude of 1% and 10% for level 0 and level 1 compliance, accordingly. The frequency of such single-frequency additive signal shall be swept as follows:

$$2 \cdot f_s < f_m < 50 \cdot f_s$$

That is between the 2nd and 50th harmonics, but assuming any values not only harmonics. Slow changes in the f_m frequency result it effective change of the angular relationship between the phasor and the distortion and in this way reveal the worst-case situation.

A practical test can be executed by slowly ramping the frequency of the added noise, while keeping the phasor constant, and recording the measurements during the entire test. The expected result is a stationary phasor matching the true phasor in the input. Test setup of Figure C.12a is well suited for this test. One accurate test set is configured to output the phasor of interest, and the other is configured to output a 1% or 10% signal with a frequency ramp.

Overall our interpretation of the interfering frequency test can be summarized as in Figure C.14. Note that the frequency here refers to the frequency of the additive signal component.

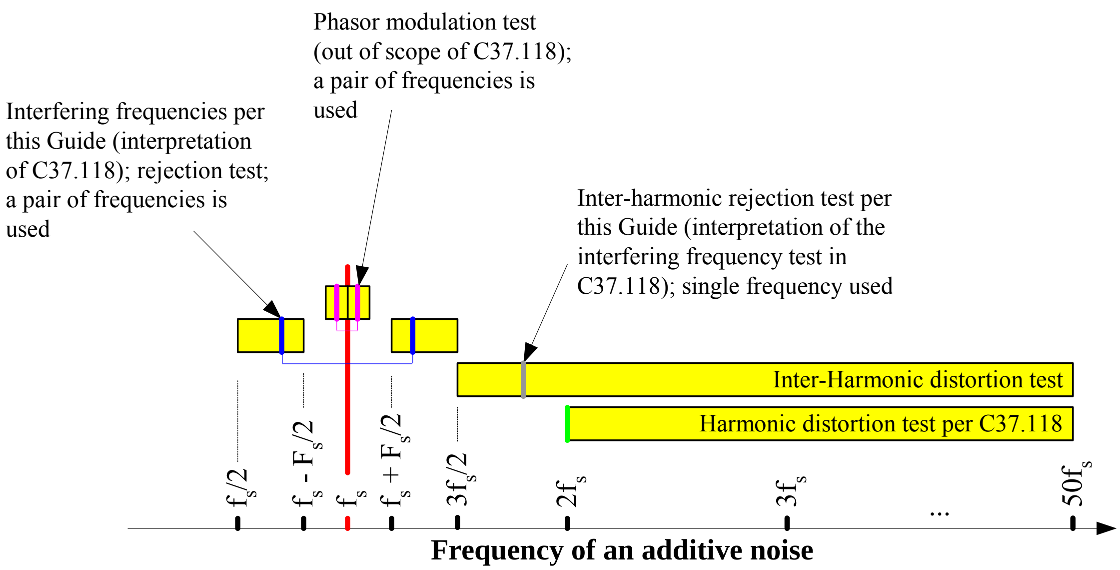


Figure C.14. Overall summary of the interfering frequency test per this Guide.