

1 **IEEE PC37.242™/D3.1**
2 **Draft Guide for Synchronization,**
3 **Calibration, Testing, and Installation**
4 **of Phasor Measurement Units (PMU)**
5 **for Power System Protection and**
6 **Control**

7 Sponsor

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1. Overview

1.1 Scope

The document provides guidance for synchronization, calibration, testing, and installation of Phasor Measurement Units (PMU) applied in power system protection and control. The following are addressed in this guide:

- a) Considerations for the installation of PMU devices based on application requirements and typical bus configurations.
- b) Techniques focusing on the overall accuracy and availability of the time synchronization system.
- c) Test and calibration procedures for PMUs for laboratory and field applications.
- d) Communication testing for connecting PMUs to other devices including Phasor Data Concentrators (PDC).

1.2 Purpose

This guide is intended to be used by power system protection professionals for PMU installation and covers the requirements for synchronization of field devices and connection to other devices including PDCs.

1 2. Normative References

2 The following referenced documents are indispensable for the application of this document. For dated
3 references, only the edition cited applies. For undated references, the latest edition of the referenced
4 document (including any amendments or corrigenda) applies.

5 IEC¹ 60255-24:2001, Electrical relays, part 24: Common Format for Transient Data Exchange
6 (COMTRADE) for Power Systems, International Electro Technical Commission.

Deleted: Available online at
www.iec.ch.

7 IEC 60870, Telecontrol Equipment and Systems, Transmission Protocols.

8 IEC 61850-3, Communication Networks and Systems in Substations – Part 3: General Requirements.

9 IEEE² Standard 1344-1995 (R2001), IEEE Standard for Synchrophasors for Power Systems.

10 IEEE Standard 1588-2008, IEEE Standard for a Precision Clock Synchronization Protocol for Networked
11 Measurement and Control Systems.

12 IEEE Standard C37.111-2011, IEEE Standard Common Format for Transient Data Exchange
13 (COMTRADE) for Power Systems, June 1999.

14 IEEE Standard C37.118-2005 (Revision of IEEE Std 1344-1995), IEEE Standard for Synchrophasors for
15 Power Systems.

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16 IEEE Standard PC37.118.1 and IECPC37.118.2 (Revision of IEEE Std C37.118-2005), IEEE Standard for
17 Synchrophasors for Power Systems.

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18 IEEE Standard C37.2 – 1991, IEEE Standard Electrical Power System Device Function Numbers and
19 Contact Designations.

20 IEEE C37.233 – 2009 Guide for Power System Protection Testing

21 IEEE C37.238 – 2011 Standard for Use of IEEE Std. 1588 Precision Time Protocol in Power System
22 Applications.

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

26 IRIG Standard 200-98, IRIG Serial Time Code Formats, May 1998, Telecommunications Group, Range
27 Commanders Council, US Army White Sands Missile Range, NM, USA.

28 NASPI – Performance and Standards Task Team - A Guide for PMU Installation, Commissioning, and
29 Maintenance Part I: PMU Acceptance Test Checklist

30 NASPI – Performance and Standards Task Team - A Guide for PMU Installation, Commissioning, and
31 Maintenance Part II: PMU Installation Procedures, Performance and Standards Task Team.

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- 1 NASPI – Performance and Standards Task Team - SynchroPhasor Accuracy Characterization, Performance
- 2 and Standards document.

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For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions* shall be referenced for terms not defined in this clause.³

These definitions, acronyms and abbreviations are especially pertinent to GPS-synchronized devices, communication protocols and communications media.

3.1.1 Definitions

Absolute Phase Angle: See *Synchronized Phasor*, below.

Common Format for Transient Data Exchange (COMTRADE): A file format in standardized ASCII text or binary file (two 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 version and IEC 2001 version.

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

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

IEEE 1344: An old, highly efficient IEEE protocol 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). Typically data is streamed in this format over UDP/IP or across a serial link. It does not specify response time, accuracy, hardware, software, or a process for computing phasors.

IEEE C37.118-2005: Related to IEEE 1344, but adds much needed capability. This protocol and its associated standard are intended to replace IEEE 1344 and the BPA/PDCStream protocols. Typically data is streamed in this format over UDP/IP or across a serial link.

Integrated Phasor Measurement Unit (IPMU): Any device that is integrated with phasor measurement function. Phasor measurement is an added function to the primary functions of a device (e.g., relays, meters and fault recorders, which may be denoted as Relay-IPMU, Meter-IPMU, and Fault Recorder-IPMU).

IRIG-X: 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.

Navigation: The mode in which a GPS receiver locks onto signals from three or more satellites, thus providing accurate time and position.

Open Process Control Alarms and Events (OPC AE): an offshoot of OPC DA, which allows clients to be notified on alarm conditions. As with OPC HAD, this is a separate protocol, and different servers/clients must be developed.

Open Process Control Data Access (OPC DA): Created for industrial automation (e.g., for use within a factory), OPC DA shares simple data between computers running only Microsoft Windows®. There are

³ The *IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

1 three revisions that are commonly used, but each is not compatible with the others. This protocol is useful
2 for simple data sharing between computers in a small LAN, but has serious security and performance issues
3 when deployed across a WAN. OPC uses TCP/IP the underlying link.

4 **Open Process Control Historical Data Access (OPC HAD):** An offshoot of OPC DA which allows a
5 client to request stored data. This is a separate protocol, and different servers/clients must be developed.

6 **Open Process Control XML Data Access (OPC XML DA):** An OPC DA protocol designed for use
7 across a WAN. This protocol uses the standard Web Services structure, using SOAP and XML. This
8 protocol is simple to work with and will allow PMU devices that don't run Windows as an operating
9 system, to be an OPC server for providing data to any client. The OPC Foundation is creating a 'Unified
10 Architecture' using the XML-based structure as the foundation for future development.

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

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

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

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

23 **Point on Wave (POW):** Applies or relates to instantaneous signal waveforms, rather than to some average
24 or simplified characterization of them.

25 **Pulses Per Second (PPS):** A signal consisting of a train of square pulses occurring at a frequency of 1 Hz,
26 with the rising edge synchronized with UTC seconds. This signal is typically generated by GPS receivers.

27 **Synchronized System Measurements (SSM):** This extends the concept and technology of synchronized
28 phasor measurements to include devices such as advanced point-on-wave recorders or control system
29 monitors. Many of these are operational in the WECC WAMS.

30 **Virtual Private Network (VPN):** A communication network constructed by using public wires to connect
31 nodes with procedures to ensure that only authorized users can access the network and that the data cannot
32 be intercepted. These procedures typically use encryption and other security mechanisms.

33 **Wide Area Measurement System (WAMS):** Generally features one or more PMU networks as a
34 "backbone," but may also include local recorders, legacy equipment, or advanced technologies that are
35 GPS-synchronized to the PMU networks while recording non-phasor data.

36 3.1.2 Acronyms and abbreviations

37 **CT** - Current Transformer.

38 **DFR** - Digital Fault Recorder.

39 **PT** - Potential Transformer or Voltage Transformer.

1 SPS - Samples per Second.

2 GNSS - Global navigation satellite system

3 **4. Guidelines for synchronization techniques, accuracy and availability**

4 **4.1 Introduction**

5 This section presents a review of the main technologies available to synchronize Phasor Measurement
6 Units (PMU), the basic principles of clock synchronization, and time referencing for geographically
7 distributed PMUs and their impact on the phasor measurement accuracy. The document also analyses the
8 main synchronization sources for time referencing, including both satellite (e.g., GPS, GLONASS, Galileo)
9 and terrestrial (e.g., LORAN, Network Time Protocol, Precision Time Protocol) based technologies. The
10 main advantages (e.g., timing accuracy) and potential vulnerabilities (e.g., susceptibility to intentional and
11 unintentional interference) of these techniques are also reported.

12 This section also presents testing procedures (e.g., periodic Timing Signals Measurement, measurement of
13 Two Consecutive Timing Signals) aimed at assessing the main performance characteristics of
14 synchronization sources (e.g., short term stability, “bad” data management, handoff algorithm).

15 Lastly, the synchronization distribution infrastructure is also discussed within this section.

16 **4.2 The role of synchronization techniques in PMU**

17 Electronic clocks in PMUs keep inaccurate time. Their accuracy vary over time due to manufacturing
18 defects, changes in temperature, electric and magnetic interference, oscillator age, and even computer load.
19 Additionally, even small errors in timekeeping can add up significantly over a long period.

20 Careful work and analysis is required to describe and quantify performance of timing in PMU systems, to
21 meet the accuracy requirements of the C37.118.1-2012 standard. Some clock variations are random, caused
22 by environmental or electronic variations; others are systematic, caused by a miscalibrated clock.

23 Correct operation of a PMU requires a common and accurate timing reference. The timing reference is
24 described in IEEE Standard C37.118, which establishes the relationship between the UTC time scale and
25 the phase of the reference cosine wave. The required performance could be realized by synchronizing the
26 samples directly to the timing reference (e.g., 1 PPS signal through the hardware) or by software-based post
27 processing of the acquired samples. To achieve a common timing reference for the PMU acquisition
28 process, it is essential to achieve accurate synchronization of the sampling pulses. This requires a source of
29 accurate timing signals (i.e., synchronizing source) that may be internal or external to the PMU. In the first
30 case the synchronization source is integrated (built-in) into the PMU. In the latter case, the timing signals
31 are provided to the PMU by means of an external source, which may be local or global, and a distribution
32 infrastructure (based on broadcast or direct connections).

33 The timing signal generated by the synchronizing source shall be referenced to Coordinated Universal
34 Time (UTC), and shall provide enough time information to determine time in agreement with UTC. It must
35 also be available without interruption at all measurement locations throughout the interconnected grid. The
36 timing signal shall provide the availability, reliability, and accuracy suitable for power system
37 requirements.

38 The timing signal shall be accurate enough to allow the PMUs to maintain synchronism with an accuracy
39 sufficient to keep the Total Vector Error (TVE) (i.e., the magnitude of the vector difference between the
40 theoretical phasor and its estimate computed by the PMU, expressed as a fraction of the magnitude of the
41 theoretical phasor) within the limits defined in IEEE Standard C37.118.

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1 It is useful to note that an uncertainty of 1 microsecond in the synchronization signal leads to a phase error
 2 of 0.022/0.018 degrees for a 60/50 Hz system. Thus a synchronization uncertainty of 26/31 microseconds
 3 for a 60/50 Hz system (corresponding to a phase error of 0.57 degree) will cause a 1% TVE (assuming that
 4 the magnitude of the signal is 100% accurate). Refer to IEEE C37.118.1-2012 for details related to TVE.
 5 Actual PMU implementations require timing accuracy better than this, since there are other errors that also
 6 contribute to the TVE of a PMU.

7 The PMU shall detect a loss of time synchronization that would cause the TVE to exceed the allowable
 8 limit, or within 1 minute of an actual loss of synchronization, whichever is less [IEEE Std C.37.118-2005].
 9 In this case a flag in the PMU data output (STAT word Bit 13) shall be asserted until the data acquisition is
 10 resynchronized to the required accuracy level.

11 In addition to the STAT word Bit 13, the standard specifies further signals intended to describe the time
 12 quality of the synchronization source. Each of the four PMU output messages defined (Configurations 1
 13 and 2, Header, and Data) have a time quality field of 4 bits. This field allows the PMU to state the
 14 uncertainty of the time source from clock locked, 1 ns to 10 s, or clock failure. Also, the Data message
 15 STAT has two bits to indicate the length of time the clock has been unlocked. This varies from locked, to
 16 unlocked for more than 10 s, 100 s, or more then 1000 s.

17 The C37.118.2 adds a 3-bit PMU Time quality field to the stat word in place of a previously unused
 18 security bit field. This field indicates continuous time uncertainty when the PMU is either locked to UTC
 19 or unlocked.

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20 4.3 Synchronizing sources

21 This section summarizes the main technologies that could be adopted for PMU synchronization.

22 The following figures of merit have been considered in assessing the performances of the synchronization
 23 source technologies [Lilley, Church and Harrison 2006]:

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- 24 • Accuracy: The degree of conformance between the measured synchronization signal and its true
 25 value.
- 26 • Availability: The capability of the synchronization system to provide usable timing services within
 27 the specified coverage area.
- 28 • Continuity: The probability that the synchronization system will be available for the duration of a
 29 phase of operation, presuming that the system was available at the beginning of that phase of
 30 operation. The factors that affect availability also affect continuity.
- 31 • Reliability: A function of the frequency with which failures occur within the synchronization
 32 system. It is the probability that a synchronization system will perform its function within defined
 33 performance limits for a specified period of time under given operating conditions.
- 34 • Integrity: The ability of the synchronization system to detect the timing signals' degradation and
 35 provide timely warnings to users.
- 36 • Coverage: The geographical area in which the application-specific synchronization system
 37 requirements for accuracy, availability, continuity, reliability, integrity and coverage parameters
 38 are satisfied at the same time. System geometry, signal power levels, receiver sensitivity,
 39 atmospheric noise conditions, and other factors that affect signal availability influence coverage.

4.3.1 Satellite navigation systems

The carrier signals transmitted by Global Navigation Satellite Systems (GNSS) disseminate precise time, time intervals, and frequency on wide geographic areas.

Satellite based timing signals are particularly suitable, since they make possible accurate PMU synchronization without requiring the deployment of primary time and time dissemination systems. At the same time, GNSS systems provide intrinsic advantages such as wide area coverage, easy access to remote sites and adaptability to changing network patterns. The only user cost is for the receiver equipment, although fees may be levied in future satellite systems.

Global Positioning System (GPS) is a U.S. Department of Defense satellite-based radio navigation system. It consists of 24 satellites arrayed to provide a minimum worldwide visibility of four satellites at all times. GPS is steered by a ground-based cesium clock ensemble that itself is referenced to UTC. Each satellite provides a correction to UTC time that the receiver automatically applies to the outputs. The GPS satellites broadcast on two carrier frequencies: the L1 at 1575.42 MHz, and the L2 at 1227.6 MHz. Each satellite broadcasts a spread-spectrum waveform called a pseudorandom noise (PRN) code on L1 and L2, and each satellite is identified by the PRN code it transmits [Lombardi et al. 2001].

With this continuous adjustment, timing accuracy is limited only by short-term signal reception whose basic accuracy is 0.2 microseconds. This baseline accuracy can be improved by advanced decoding and processing techniques, giving actual performance of approximately 10 to 20 ns rms. The inherent availability, redundancy, reliability, and accuracy make it a system well suited for synchronized phasor measurement systems [IEEE Std C37.118-2005; Holbert et al. 2005].

The new INMARSAT system satellites will carry a GPS-like transponder. The signal will be similar to existing GPS transmissions, so it can be used with slightly modified GPS receivers. INMARSAT satellites are geostationary, which may make reception difficult at some locations.

The Russian Global Navigation Satellite System (GLONASS) provides similar capabilities to GPS. Sporadic funding, and the resulting inconsistent satellite coverage, have hampered widespread acceptance of the GLONASS system, although it is in some ways superior to GPS with respect to accuracy [Dickerson 2007].

The European Space Agency's (ESA) Galileo system is the third global satellite time and navigation system to come online. It comprises a constellation of 30 satellites divided among three circular orbits at an altitude of 23222 km to cover the Earth's entire surface. Galileo will have an integrity signal to ensure the quality of the signals received, and to inform the user immediately of any error. The Galileo time precision in terms of time errors (95% confidence) for different signals range from 0.7 to 8.1 ns [Mack et al. 2007].

China is also developing its own GNSS, called Beidou.

These systems provide timing accuracy that easily exceeds the needs of the power industry. Future development in receiver technology is expected to provide the ability to receive signals from two or more GNSS systems, though existing receivers generally are limited to a single system. Specifically, international cooperation efforts have led to new GPS and GLONASS signals, for new satellite deployments, which are compatible with the Galileo and Beidou signals.

4.3.2 Timing errors

Timing errors in satellite based synchronization systems are caused by various sources, including uncompensated antenna cable delays and distribution delays (delay of clock output signals going to PMUs). Uncorrected delays cause errors in the received timing signals at the PMU. The magnitude of the errors can be estimated by dividing the electrical length of the cable with the propagation velocity of the signal

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1 | along the cable (approximately 5 ns per meter). ~~The errors may need to~~ be compensated in power-system
 2 | applications if they introduce uncertainties not consistent for the desired level of performance.

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3 | 4.3.3 Systems vulnerabilities

4 | Satellite based synchronization systems rely on information transfer over the airwaves. The wireless nature
 5 | of satellite communications links and the weak power levels of received GNSS signals make them
 6 | vulnerable to radio-frequency interference. Any electromagnetic radiation source can act as an interference
 7 | source, if it can potentially emit radio signals in the GNSS frequency bands.

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8 | The disruption mechanisms that could limit the GNSS performance can be classified as:

- 9 | a) Ionospheric effects: Sunspot activity causes an increase in the solar flux—charged particles and
 10 | electromagnetic rays emitted from the Sun. This solar flux affects the ionosphere and influences the
 11 | transit time of satellite signals through the ionosphere. Consequently the receiver equipment may
 12 | experience degraded performance in tracking of the satellites due to scintillations, rapidly varying
 13 | amplitude and phase of the satellite signal. The equatorial and high latitude regions are most
 14 | severely affected by this increased ionospheric activity [Orpen and Zwaan 2001; Volpe 2001].
- 15 | b) Unintentional interference: Satellite signals travel through the upper reaches of Earth’s atmosphere
 16 | and can be affected by solar disturbances. Moreover, when there will be restricted lines of sight to
 17 | satellites (e.g., in urban areas, near or under foliage), the synchronization signal quality could
 18 | deteriorate for short or long periods of time. It is important to have realistic expectations of GNSS
 19 | availability under conditions where there is not a clear view of the sky.
- 20 | c) Radio Frequency Interference (RFI): This is caused by electronic equipment radiating in the GNSS
 21 | frequency band (e.g., television/radio broadcast transmitters, mobile phones). Although
 22 | transmission is designed to not interfere with GNSS signals, it can radiate at the same frequency as
 23 | the GNSS signals if it is faulty or badly operated. This interference, if powerful enough, can lead to
 24 | degradation of the GNSS signal received.
- 25 | d) Intentional interference: Received GNSS signals are extremely weak and can therefore be
 26 | deliberately jammed by radio interference. The levels of interference needed to jam a typical
 27 | consumer GNSS receiver are quite low, and jamming equipment can be small. Further intentional
 28 | interference could be induced by:
- 29 | 1) Spoofing – counterfeit signals
 - 30 | 2) Meaconing – Delay, interception and / or rebroadcast of navigational signals
 - 31 | 3) System damage

32 | 4.3.4 Countermeasures

33 | The main strategies that could be adopted to protect GNSS receivers from RFI attacks are based on the
 34 | principle of raising the power levels required by the jammers to disrupt the receivers. This makes attacks
 35 | too expensive, unsustainable in terms of the power required to run, or easily detectable and therefore
 36 | readily intercepted.

37 | As per the Australian Global Navigation Satellite Systems (GNSS) Coordination Committee 2006, the
 38 | main mitigation techniques that could be adopted are as follows:

- 39 | a) A Controlled Reception Pattern Antenna (CRPA) that has the capability of determining the
 40 | direction of the jamming source and modifying its antenna reception pattern to ignore signals from
 41 | that direction.
- 42 | b) Narrowband interference processing that attempts to measure the frequency of the jamming signal
 43 | and then ignore it. This technique only works well when the frequency band of the jamming signal
 44 | is much narrower than that of the GNSS satellite signal.

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1 c) A jamming signal to thermal noise (J/N) ‘powermeter’ that measure the total amount of power
 2 received by the antenna, and knowing the amount of power expected from thermal noise, it
 3 estimates the amount of received jamming power. In this way, the receiver can monitor the
 4 likelihood it is being jammed, and inform the user of this condition.

5 Other mitigation strategies, such as physically shielding the GNSS receiver’s antenna from interference
 6 sources, rely on prior knowledge of the location of the interference but may be useful under some
 7 circumstances.

8 Intentional spoofing is much harder to mitigate. There are methods to test and mitigate spoofing which are
 9 telecommunication technology related and are not addressed in this guide.

Deleted: However, since a very high level of technical expertise is required to successfully deploy a spoofing attack and the equipment to successfully conduct an attack is relatively expensive. The risk associated with encountering such a threat is very low.

10 Further countermeasures that can be applied to effectively address both intentional and unintentional
 11 interference are based on redundancy of the synchronization source.

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12 For example, the employment of local oscillators (e.g., quartz or rubidium oscillators) and/or multiple
 13 (complementary) timing signals have been proposed as possible solution strategies [Jacoby et al. 1999;
 14 Celano et al. 2003]. These “backup systems” come into effect in the case of a GNSS failure, thereby
 15 providing a more reliable timing source. If one signal is degraded or unavailable, the receiver could still
 16 operate within overall system constraints.

17 One possible solution is ensemble time base generation. In this approach, various weighting factors based
 18 upon the predicted or measured accuracy and stability of different time sources (e.g., Loran and GPS [Celo
 19 et al. 2003] or Galileo and GPS [Deeths and Brunette 2001]) are taken into account, to provide a
 20 disciplined time scale generator.

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21 The employment of modular and flexible synchronization systems, including multiple external timing
 22 signals and local oscillators, can provide a high degree of redundancy to ensure reliability and accuracy of
 23 the overall synchronization system.

24 4.3.5 Performance testing

25 The performance of commercially available GNSS receivers vary depending on the receiver hardware and
 26 software architecture. For example:

27 • Satellite selection: Receivers could adopt different algorithms to automatically select the satellites
 28 used in the timing solution (e.g., the satellites providing the best geometric dilution [Mills 2006]).
 29 Moreover, each algorithm could be characterized by a different set of thresholds defining the
 30 condition for keeping, dropping or acquiring a satellite. Therefore, different receivers can obtain
 31 different results even when connected to the same antenna in the same location.

32 • Short term stability: This is influenced by the hardware architecture of the receiver. In particular,
 33 receivers integrating a satellite disciplined oscillator (e.g., an oven controlled quartz oscillator or a
 34 rubidium oscillator) exhibit improved short-term stability. To avoid perfect lineup between
 35 sampling frequency and satellite spreading code, an alternative technique currently adopted in
 36 commercial receivers is based on the employment of a temperature controlled crystal oscillator for
 37 down-sampling of the satellite signals. This type of receiver accumulates time errors until the total
 38 error reaches a maximum value (i.e., a multiple of the half period of the oscillator), and then
 39 generates a phase step that reduces the time error to a minimum. Some receivers step phase in
 40 increments of 100 ns (or less) or 1 microsecond (or larger) [Lombardi et al. 2001; Mills 2006].
 41 Consequently, the short-term stability of these receivers could vary significantly (although their
 42 long term performance may be equivalent to models integrating a disciplined oscillator).

43 • Handoff algorithm: Since the satellite position within the range of the GPS receiver changes with
 44 time as the satellite movements changes the position, various handoff strategies may be

implemented in the receivers. The application will determine the level of knowledge and testing needed by the user.

- “Bad” data management: Receivers manage satellite broadcast errors in different ways. Although some receivers are equipped by specific software routines able to remove "bad" data, they might fail under certain critical conditions [Lombardi et al. 2001; Mills 2006].

Therefore in order to assess the performances of GNS receivers applied in PMU time synchronization, detailed experimental testing is necessary.

4.3.6 Experimental Tests

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Experimental testing aimed at assessing the GNSS receiver performance may comprise of the following analysis:

- Periodic timing signals measurement
- Measurement of two consecutive timing signals
- Short-term stability test
- Long-term stability test

The minimum set of measures may include tests of the receiver sensitivity, Time to First Fix (TTFF) and position accuracy/repeatability. Some of the tests may be more suited in laboratory environment.

Sensitivity is one of the most important measurements of a NSGPS receiver’s capability. It defines the lowest satellite power level at which a receiver is still able to track and achieve a position fix on satellites overhead. As the RF power levels of a GPS signal decrease, SNR decreases and eventually the receiver will no longer be able to track the satellite. To amplify the received signal to the appropriate power level, NSGPS receivers integrate several cascaded Low Noise Amplifiers (LNA). This improves the received signal power but it also degrades SNR.

Sensitivity can be assessed by measuring the receiver’s carrier-to-noise (C/N) ratio at a known satellite power level.

The typical test system adopted for single-satellite sensitivity measurement employs a simulated L1 single-satellite carrier feeding the RF port through a direct connection. To report the C/N ratio, the GPS clock can be configured to communicate via the NMEA-183 protocol. According to the GPS specification documents, the power of a single L1 satellite shall be no less than -130 dBm at the Earth’s surface.

The first step in developing this measurement is to perform a basic system calibration process aimed to assess the RF power level accuracy of the adopted laboratory equipment. This process is oriented to determine the exact power of the test stimulus. System calibration can be carried out by connecting the simulated L1 single-satellite carrier to an RF vector signal analyzer by using the exact same cable adopted to test the DUT. In particular, since receivers report C/N to within 0 digits (no fraction of digit) of precision (e.g., 34 dB-Hz), sensitivity measurements in production testing are made with ± 0.5 dB of resolution. Thus, it is important to ensure that the instrumentation used has adequate performance (output level accuracy) to make the application measurement.

After the measurement system has been calibrated, it is possible to measure the sensitivity by programming the RF generator to the power level at which the receiver is expected to return the minimum C/N. The C/N ratio that can be achieved at a given power level is determined by the noise figure of the entire receiver.

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1 To measure sensitivity, several strategies can be adopted. Since RF power is directly correlated with
 2 sensitivity, it is possible to measure the receiver's C/N ratio at the given sensitivity power level, or derive
 3 sensitivity based on RF power at a different power level. Once the C/N ratio has been measured, it is
 4 possible to calculate the noise figure of the receiver or chipset which is directly proportional to the RF
 5 power level and the C/N ratio.

6 To measure the other properties of the receiver's accuracy (e.g., TTFF, position accuracy, and dilution of
 7 precision), it is necessary to employ a test stimulus that simulates multiple satellites. This happens because
 8 these measurements require the receiver to obtain a position fix and, consequently, it shall acquire at least
 9 four satellites.

10 TTFF and position accuracy measurements are most important in the design validation stage of a NSGPS
 11 receiver.

12 The most common TTFF conditions are:

- 13 • Cold start: The receiver must download almanac ephemeris information to achieve a position fix.
- 14 • Warm start: The receiver has some almanac information that is less than one week old, but does
 15 not have any ephemeris information.
- 16 • Hot Start: The receiver has up-to-date almanac and ephemeris information. In this scenario, the
 17 receiver only needs to obtain timing information from each satellite to return its position fix
 18 location.

19 In most cases, TTFF and position accuracy are specified at a specific power level. It is worth noting that it
 20 is valuable to verify the accuracy of both of these specifications under a variety of circumstances.

21 To perform both TTFF and position accuracy measurements, three different sources of data could be
 22 adopted:

- 23 a) Live data where the receiver is set up in its deployment environment with an antenna.
- 24 b) Recorded data where a receiver is tested with an RF signal that was recorded off of the air.
- 25 c) Simulated data where an RF generator is used to simulate the exact time-of-week when live data
 26 was recorded. When testing a receiver with three different sources of data, it is necessary to verify
 27 that the measurements from each source are both repeatable and correlated with other data sources.

28 4.4 Terrestrial systems

29 Synchronizing signals may also be disseminated using terrestrial systems (e.g., radio broadcasts,
 30 microwave, and fiber-optic systems).

31 ~~Network Time Protocol (NTP) is a robust and mature technology for synchronizing a set of network clocks~~
 32 ~~using a set of distributed clients and servers over packet-switched, variable-latency data networks [Mills~~
 33 ~~2006]. It is built on the User Datagram Protocol, which provides a connectionless transport mechanism. It~~
 34 ~~is evolved from the Time Protocol and the ICMP Timestamp message.~~

35 ~~NTP hierarchy uses one or more precision clocks synchronized to a common time reference, each one using~~
 36 ~~methods outside the scope of NTP (i.e., GPS signals, radio signals, or extremely accurate frequency~~
 37 ~~control). Reference clocks are verified for accuracy, with proper losses for antenna accounted for. The~~
 38 ~~accuracy of other clocks is compared against the reference clock, the network latency to the clock, and the~~
 39 ~~claimed accuracy of the clock. It not only corrects the current time, but it can also keep track of consistent~~
 40 ~~time variations and automatically adjust for time drift on the client. Flexibility of the client/server~~

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Reference [1]

~~Deleted: LORAN is a terrestrial radio navigation system based on low frequency radio transmitters. LORAN uses ground based transmitters that only cover certain regions. Coverage is quite good in North America, Europe, and the Pacific Rim. The current version of LORAN in common use is LORAN-C, which operates in the low frequency portion of the EM spectrum from 90 to 110 kHz. LORAN suffers from electronic effects of weather and the ionospheric effects of sunrise and sunset. Substation environments suffer from extreme levels of radio-frequency noise in this frequency band. Magnetic storms also have serious effects as with any radio based system [Carroll and Celano 2003; Behrendt and Fodero 2006]. Furthermore, the United States and Canada discontinued transmitting LORAN-C signals in 2010.~~

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1 relationship and security methods allow NTP to work well in many environments and on a wide variety of
 2 platforms [Deeths and Brunette 2001].

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3 Version 4 of the NTP can usually maintain time to within 10 milliseconds (1/100 s) over the public
 4 Internet, and can achieve accuracies of 200 microseconds (1/5000 s) or better in Local Area Networks
 5 (LAN) under ideal conditions. This performance is not generally adequate for PMU applications, which
 6 require accuracy substantially better than 25 microseconds as described in earlier sections under the role of
 7 synchronization techniques in PMU.

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8 In environments that need more accurate time than an Internet link will allow (due to latency or other
 9 concerns), or environments that cannot rely on Internet time sources due to security implications, a radio
 10 time clock, NSGPS system or cesium clock can be used to keep the primary NTP servers aligned with
 11 UTC.

12 It shall be noted that Simple Network Time Protocol (SNTP), which supports a subset of NTP
 13 functionality, is often used in place of NTP. The above considerations for time distribution hierarchy and
 14 achievable time accuracy apply to SNTP as well. In fact often terms NTP and SNTP are used
 15 interchangeably.

16 A new time distribution protocol called Precision Time Protocol (PTP) is now also available. PTP
 17 Version 2 is specified in IEEE Std 1588 -2008, and its profile for power system applications is specified in
 18 IEEE C37.238 Standard.

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19 The C37.238 specifies time distribution over Ethernet networks that could achieve +/- 1 microsecond time
 20 accuracy over 16 network hops. At the top of time distribution chain, there shall be a clock with the best
 21 capabilities that is traceable to UTC (called grandmaster clock). Each device in the time distribution chain
 22 (including Ethernet switches) need to support C37.238 to achieve 1 microsecond time accuracy. Ethernet
 23 switches supporting C37.238 shall perform measurements and corrections for cable delay and residence
 24 time (e.g., variable time in which a synchronization message spends inside an Ethernet switch due to
 25 queuing and other processing delays).

26 ~~The IEEE C37.238/1588 do not operate over wireless network at this time.~~

28 ~~C37.238 distribution technology offers time accuracy that is adequate for PMU applications (1
 29 microsecond), the use of the same communication infrastructure (Ethernet) for PMU/PDC data and time
 30 distribution, and reduced use of GPS connectivity whenever possible. Due to these benefits a rapid
 31 adoption of this technology is expected.~~

Deleted: Ethernet use. ; however, NTP is about 3 orders of magnitude less precise than the requirements of C37.238/1588 Accordingly, use of IEEE One-step sync messages are more suitable for wired systems. C37.238 uses one-step for highly technical reasons involving redundancy.

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32 **4.5 Synchronization distribution Methods**

33 IEEE Standard C37.118 requires a PMU to be synchronized to UTC time. UTC time synchronization may
 34 be delivered to the PMU by using, for example:

- 35 • IRIG-B: The IRIG-B time code is fully described in IRIG STANDARD 200-04. It repeats each
 36 second, and has a total of 100 bits per second. Some of these are framing (sync) bits, some are
 37 assigned for time, and some are available for control functions. IRIG-B code may be used in either
 38 logic-level (unmodulated) format or as an amplitude-modulated signal with a 1 kHz carrier
 39 [Dickerson 2007]. The modulated IRIG signal is generally capable of accuracy exceeding 1
 40 millisecond (one period of 1 kHz), but not usually better than 10 microseconds. The unmodulated
 41 IRIG-B code can deliver accuracy limited only by the slew rate of the digital signal, much better
 42 than 1 microsecond.

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1 • IEEE Standard C37.118 defines use of the control bits in the IRIG message to provide extensions
 2 for real-time applications: leap second and daylight savings or summer time status; year of
 3 century; and time quality. These extensions are generally required to meet the requirements of
 4 IEEE C37.118.1 PPS: a one pulse per second positive pulse with the rising edge on time with the
 5 second change provides precise time synchronization [IEEE Std C37.118-2005]. However, since
 6 each pulse is identical there is no way of knowing which second a pulse is associated with.
 7 Resolving this ambiguity requires a simultaneous data channel.

8 • IEEE 1588: IEEE 1588 Standard specifies a Precision Time Protocol and C37.238 Standard
 9 specifies IEEE 1588 profile for power system applications, such as PMU. PTP distributes precise
 10 time over Ethernet-based networks over multiple network hops and requires special hardware
 11 support at each Ethernet port to achieve high time accuracy. Messages containing precise actual
 12 time are transmitted once per second. By adding dedicated timing hardware to each port in a data
 13 network, the time of transmission and reception of certain messages can be determined with
 14 accuracy sufficient to transfer time with performance comparable to that of an IRIG-B or 1 PPS
 15 signal. The protocol supports corrections for variable cable and processing delays in intermediate
 16 devices (e.g., Ethernet switches). The protocol needs to be supported by all devices in time
 17 distribution chain to achieve 1 microsecond time accuracy.

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18 • ~~IEEE C37.238 specifies extensions for real-time applications: leap second and daylight savings,~~
 19 ~~local time (if needed) and time quality. In addition a flag that indicates if provided time is~~
 20 ~~traceable to UTC is supported. These extensions are generally required to meet the requirements~~
 21 ~~of IEEE C37.118.~~

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1 5. Synchrophasor measurement accuracy characterization

2 5.1 Introduction

3 The overall objective of this section is to provide a method by which users can assess the overall accuracy
 4 of their selected instrument transformers and ~~GPS-synchronized equipment~~. To do this, users shall define
 5 accuracy characterization tests to be performed on GPS-synchronized equipment, which will provide the
 6 necessary information to make informed decisions as to the quality of data obtained with these units. Users
 7 shall also determine the level of inaccuracy injected into the measurements from instrumentation channels,
 8 and to provide methodologies to quantify this inaccuracy. This section will also discuss methodologies by
 9 which the overall accuracy can be improved.

Comment [ARG9]: “GPS-synchronized equipment” is used throughout section 5 and should be replaced with “PMUs” since the equipment may be synchronized by something other than GPS.

Comment [v10]: Discuss ARG 31 Comment at the September meeting. There are other equipment such as various PDC that may also be required to be synchronized -

10 Sources of error are:

- 11 • Instrumentation channel characteristics
- 12 • GPS-equipment characteristics
- 13 • System asymmetries.

14 The characterization process is separated into two parts:

- 15 • Accuracy for power frequency data (fundamental frequency phasors)
- 16 • Accuracy during transients

17 5.2 Data accuracy characterization

18 An important issue is the knowledge of the data accuracy. Synchrophasor data represents the power level
 19 voltages and currents that are obtained by first transforming the power level voltages and currents to
 20 instrumentation level, and then having the GPS-synchronized equipment digitize the reduced level voltages
 21 and currents. Assuming an ideal transfer function of the overall instrumentation channel, the power level
 22 voltages and currents are obtained. Unfortunately, the instrumentation channel does not have ideal
 23 characteristics.

24 The chain of measurement starts from the high voltage or current measurement point and ends at the digital
 25 signal generated by the A/D converter. The devices in between are referred to as the instrumentation
 26 channel. ~~Figure A-1~~ illustrates the devices forming voltage and current channels typically found in electric
 27 power generating stations and substations.

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28 The purpose of the instrumentation channel is to provide isolation from the high voltage power system and
 29 to reduce the voltages and currents to standard instrumentation level. Ideally, it is expected that the
 30 instrumentation channel will produce at the output a waveform that will be an exact replica of the high
 31 voltage or current and scaled by a constant factor. In reality, the instrumentation channel introduces an
 32 error. Specifically, each device in this chain, namely, Instrument Transformers, Control Cables, Burdens,
 33 Filters, and A/D converters, may contribute to some degree to signal degradation. Furthermore, the error
 34 introduced by one device may be affected by interactions with other devices of the channel. It is thus
 35 important to characterize the overall channel error.

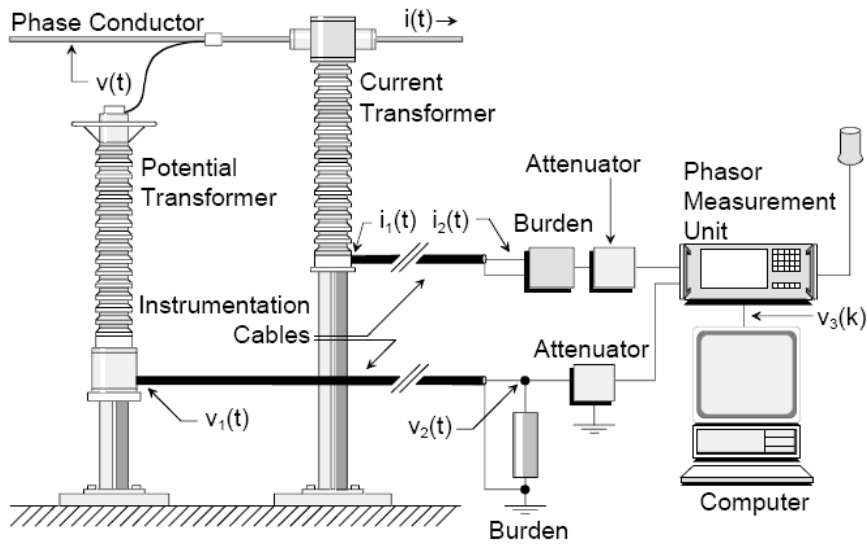


Figure A-1—Typical potential and current instrumentation channels

The first link in the instrumentation channel equipment chain consists of voltage and current transformers, collectively called instrument transformers. These devices transform power system voltages and currents to levels appropriate for driving relays, fault recorders and other monitoring equipment. Several instrument transformer technologies are presently in use. The most common traditional technology devices are voltage transformers (PT) and current transformers (CT), which are based on magnetic core transformer technology. Another type of commonly used voltage transducers are Coupling Capacitor Voltage Transformers (CCVT). These are based on a combination of capacitive voltage dividers and magnetic core transformers. Recently, voltage and current instrument transformers have been constructed based on the electro-optical and magneto-optical phenomena. These devices are known as Electro-Optical Voltage Transformers (EOVT) and Magneto-Optical Current Transformers (MOCT). While reference is made to these new types of instrument transformers, this report mainly focuses on PT, CT and CCVT devices.

5.3 Data accuracy

GPS-synchronized equipment has the capability to provide a data acquisition system with the following accuracy:

- a) Time tagging with accuracy better than 1 microsecond (or equivalently 0.02 degrees of phase at 60 Hz).
- b) Magnitude accuracy of 0.1% or better.

This accuracy is not available in all GPS-synchronized equipment. Even for the equipment that conforms to [IEEE C 37.118-1](#), this accuracy cannot be achieved for the overall system in any practical application (e.g., in the substation environment). In addition, depending on the implementation approach and equipment used, the accuracy of the collected data and the reliability of the data availability may differ. Typical GPS-synchronized equipment (PMU) are very accurate devices. However, the inputs to this equipment are scaled down voltages and current via instrument transformers, control cables, attenuators, etc., collectively referred to as the instrumentation channel. The instrumentation channel components are typically less accurate. Specifically, potential and current instrument transformers may introduce magnitude and phase errors that can be magnitudes of order higher than the typical PMU accuracy.

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1 Although high accuracy laboratory grade instrument transformers are available, their application in
2 substation environment is practically and economically infeasible.

3 Note that for most of the CT, VT, CCVT, etc. in substations, the associated secondary circuit wiring
4 (significant component of the instrumentation channel) is not normally “instrumentation class” wiring. In
5 many cases, this wiring is control type cabling (non-twisted pairs) and is often unshielded. Often changes
6 are made to these secondary circuits that affect the overall secondary circuit burden (e.g., adding or
7 replacing relays or other devices when electromechanical or static equipment is used, which has a high
8 burden), without a detailed engineering analysis of the impact on high accuracy applications such as the
9 PMU installation. This problem does not exist when the modern microprocessor relays are used because
10 they have a very low burden. The use of isolating switches, the application of grounds on these secondary
11 circuits, and the presence of non-linear burdens are a few of the items that can have a significant impact on
12 the accuracy of the instrumentation channel.

13 In some jurisdictions, utility regulators have mandated the use of dedicated instrument transformers for
14 revenue or tie line metering (including those located in HV substations) as well as the application of
15 specific design and testing criteria for the associated secondary circuit wiring. In at least one jurisdiction,
16 this secondary wiring is “secured” to help ensure that other devices (burdens) are not inadvertently
17 connected, either permanently or temporarily. In other words, the instrument transformer secondary circuit
18 is carefully designed and tested (measuring actual burdens), and, then, access is controlled to ensure the
19 ongoing accuracy of the overall revenue metering installation.

20 With most utilities in the long term, there is a high probability that the presence of PMUs will be
21 overlooked when changes are made to the secondary circuits of “shared use” instrument transformers. If
22 this happens, it will have a negative impact on the long term accuracy of individual PMU installations.

23 The above described issues ~~are some of the commonly practiced~~ consideration for the purpose of assessing
24 the quality of data from PMUs.

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25 Instrumentation channels can be classified into five distinct categories, depending on the instrument
26 transformer used. These are:

- 27 a) CT based instrumentation channel
- 28 b) Wound type VT based instrumentation channel
- 29 c) CCVT based instrumentation channel
- 30 d) EOVT based instrumentation channel
- 31 e) MOCT based instrumentation channel

32 The five categories are pictorially illustrated in ~~Figure A-2, Figure A-3, Figure A-4, Figure A-5 and Figure~~
33 ~~A-6~~. In each one of these cases, the error is defined as follows.

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34 Voltage Error:

$$35 \quad v_{measured}(t) = k_{ideal} v_{out}(t)$$

$$36 \quad v_{error}(t) = v_{measured}(t) - v_{ps}(t)$$

37 Current Error:

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$$i_{measured}(t) = k_{ideal} i_{out}(t)$$

$$i_{error}(t) = i_{measured}(t) - i_{ps}(t)$$

Comment [ARG11]: Define "k"

Where:

- Subscript "out" refers to the actual output of the instrumentation channel
- Subscript "measured" refers to the quantity reported by the equipment
- Subscript "ps" refers to the actual power level quantity.

The error waveform can be analyzed to provide the rms value of the error, the phase error, etc.

Although we characterize the error for each one of the five generic categories listed above, it is important to realize that each of these categories may have additional options (e.g., CT based instrumentation channel may be implemented with different accuracy class CTs).

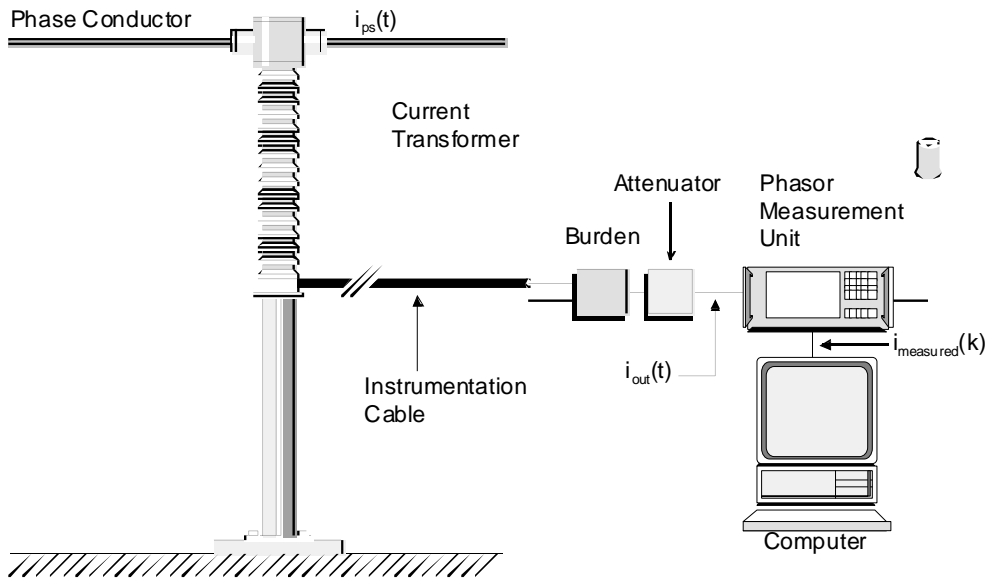


Figure A-2—CT based instrumentation channel

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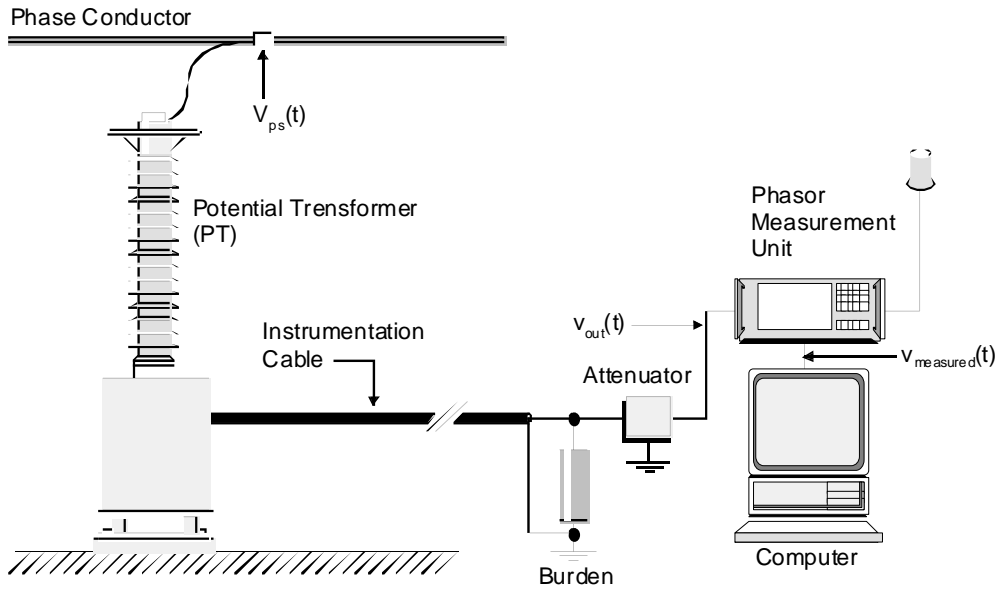


Figure A-3—Wound type VT based instrumentation channel

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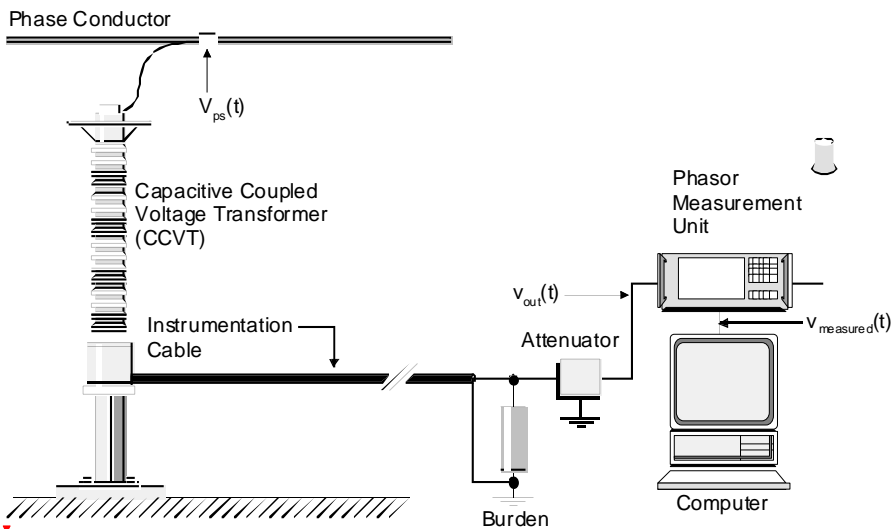


Figure A-4—CCVT based instrumentation channel

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[AD: The burden symbol in Fig. 4 appears to have missing lines and ground connection.]

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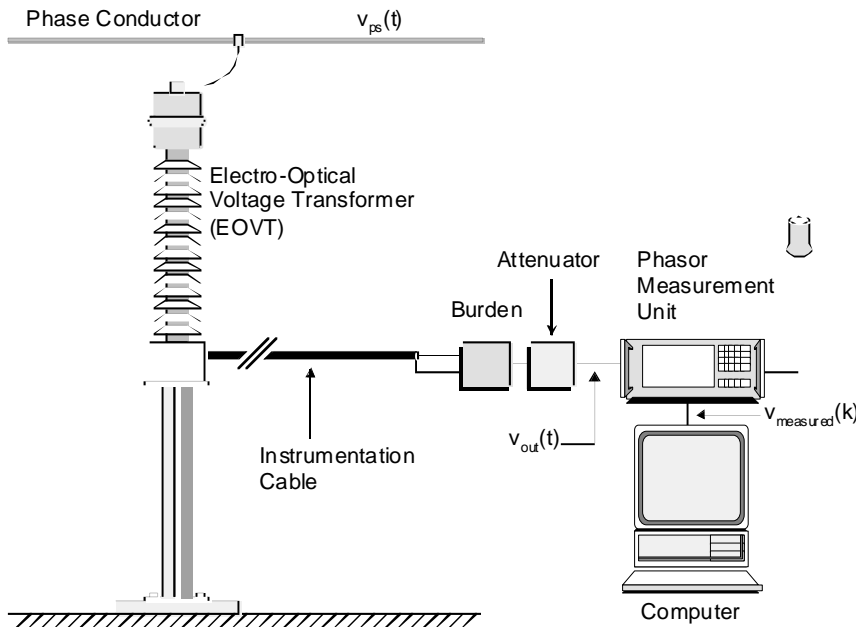


Figure A-5—Optical VT based instrumentation channel

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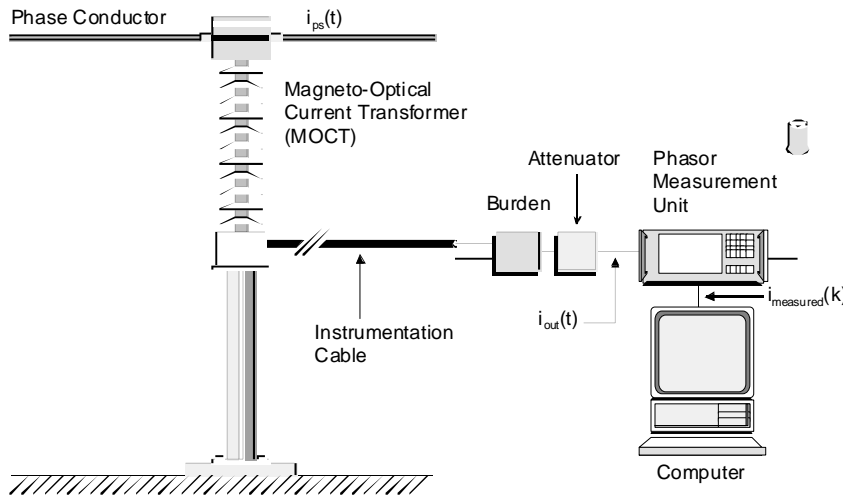


Figure A-6—Optical CT based instrumentation channel

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5.4 Characterization of GPS-synchronized measurement devices

This section highlights the importance of conformance and compliance to standards. Equipment for synchronized measurements from various vendors may have different designs and, therefore, different ways of data acquisition and processing and different accuracy characteristics. As an example, in a recent characterization of devices from different manufacturers, a difference of 1 degree at 60 Hz has been

Comment [v13]: [AD: Shall they comply with the C37.118 Standard? Is it OK if the different designs have different accuracy?]

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1 identified – This angle difference is equivalent to 47 microseconds error which can not be ignored for many
 2 applications. When all PMUs are manufactured by the same facility, similar hardware, and technology
 3 the systematic errors are irrelevant. However, in a multi-vendor environment, and as more manufacturers
 4 start offering GPS synchronization, It is expected that devices conforming to the IEEE C 37.118-1 will
 5 have have matching characteristics and perform similarly. It is also possible for the user to identify their
 6 application requirements and coordinate expected performance with manufacturers.

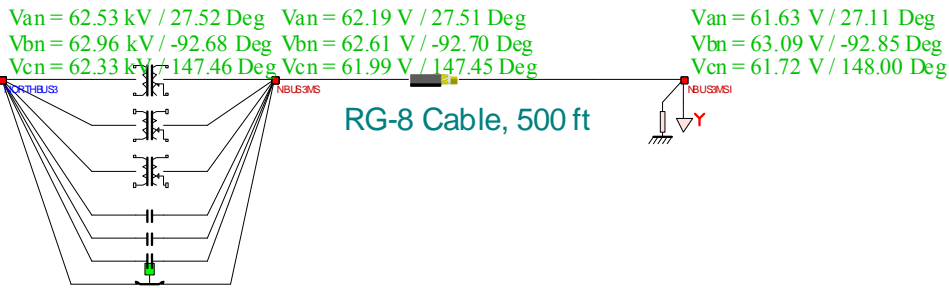
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7 Full characterization of a GPS-synchronized device shall include error analysis of both timing accuracy and
 8 magnitude accuracy over a generally accepted range of operating conditions defined in terms of frequency,
 9 frequency rate of change, voltage magnitudes, current magnitudes, harmonics and imbalances. IEEE
 10 C37.118.1, defines the standard and testing ranges and limits.

11 **5.5 Characterization of instrumentation channels**

12 High voltage instrumentation channels introduce errors to phasor measurements. The level of error is
 13 dependent upon the type of instrument transformers, control cable type and length and protection circuitry
 14 at the input of the A/D converters. For example, Figure A-7 illustrates the errors for a specific
 15 instrumentation channel. Note that the VT introduces a very small error (0.01 degrees), while the 500 ft
 16 cable introduces an error of 0.4 degrees. The overall error is more than an order of magnitude higher than
 17 the error of a typical PMU.

**Voltage Measurement IC
Substation A, 115 kV Bus**



18 **69kV:69V Wound Type VT**

19 **Figure A-7—Illustration of instrumentation channel errors for a typical case**

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20 Depending on the instrumentation channel, the characterization of these errors may be possible.
 21 Meliopoulos and Cokkinides 2002 provide some additional information. In most cases these errors can be
 22 accounted for and corrected via software. Two approaches are very promising:

- 23 a) Modeling the instrumentation channel and providing model based correction algorithms.
- 24 b) Using state estimation methods to correct the error.

25 A combination of these two approaches will be ideal. Addressing this issue is very important to assure
 26 accuracy.

27 Annex C provides examples of instrumentation channel characterization and the effects on the overall
 28 accuracy of the GPS-synchronized measurements. Further work is recommended to develop

1 methodologies for characterizing the instrumentation channel errors and algorithms to correct for these
 2 errors

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3 It shall be recognized that GPS-synchronized equipment may be also connected to existing instrumentation in substations that may be for other purposes (e.g., metering). Often, the instrument transformers are
 4 connected in an arrangement that generates a phase shift (e.g., delta connection). The resulting phase shift
 5 must be accounted for.
 6

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7 Optical CTs and VTs present a special case. Although these devices can be quite accurate, the analog
 8 interface device, or the electronic equipment associated with converting the optical CT / VT measurements
 9 to analog parameters, need to be qualified for PMU related applications. Refer to C37.233 for information
 10 related optical sensor characterization and testing. The interface device introduces latency, typically in the
 11 order of few tens of microseconds which is greater time error from typical PMUs. There are methods to
 12 compensate for delays associated with Optical Sensors, in the interface device. Another alternative maybe
 13 use of time tagging at the PMU. From PMU characterization perspective, there is no need to use interface
 14 (analog output). The data from the optical CTs and VTs are typically digital and could be used directly
 15 without the analog output. The user may need to consider other critical aspects of the Optical CT and VT
 16 as well as integration with other standards such as data communications with phasor data concentrator
 17 (PDC), or between PDCs.

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18 Optical sensors providing digital output according to IEC 61850-9-2, from their merging units, may be
 19 more suited for PMU applications. The merging unit provides digital time-tagged measurements of voltage
 20 and signal waveforms with the signal processing delays already accounted for. Refer to C37.233 for details
 21 associated with merging unit and methods for testing.

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23 **5.6 GPS-synchronized equipment reliability**

24 GPS-synchronized equipment has not been in marketing operation for a long period of time and reliability
 25 data are scarce. In addition the few available data may not be representative of the present technology as
 26 they have been collected on first generation equipment. Table A-1 provides reliability data of the PMUs on
 27 the western system over a two-month period in 2002. Note that the available data indicate that the
 28 technology is quite reliable, and most unreliability is due to the GPS signal availability.

29 **5.6.1 Synchrophasor system performance**

30 The synchrophasor system performance analysis typically includes recording of data loss, signal loss, and
 31 PMU time-synchronization failures. Table A-1 summarizes typical system performance during a randomly
 32 chosen two-month period in 2002. In Table C-1, Signal Reliability is the percent of time the system
 33 continuously received data from the PMU. Sync Reliability is the percent of time the PMU is synchronized
 34 with a GPS

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Table A-1—Synchrophasor system performance for a random two-month period in 2002

Station	Reliability (%)		Notes
	Signal	Sync	
GCoul	97.52	99.974	PMU fail 2 days
JDay	99.929	99.996	Normal, modem
Malin	99.997	93.74	PMU clock failure
Colstrip	99.82	100	Comm sys problems
BigEddy	99.99	99.988	Normal, fiber, digital
MValley	99.983	99.74	PMU clock problems
Keeler	99.996	99.95	Normal, modem

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 GPS-synchronized equipment is very accurate as compared to standard power system instrumentation. However, application of this equipment to a practical power system is prone to errors that are introduced by the standard instrumentation channels utilized in power systems. ¶
 The most accurate instrumentation channels are current instrumentation channels that use CTs. The length of the control cable is very important in determining the level of errors. ¶
 The next most accurate instrumentation channels are voltage instrumentation channels that use wound type VTs. The length of the control cable is very important in determining the level of errors. ¶
 CCVT based instrumentation channels are relatively accurate when they are well calibrated. They perform well when the frequency is near nominal. A main drawback is that the parameters of the components shift with time and subsequently introduce large errors. In addition, during transients the error is very large because their characteristics deteriorate at frequencies other than the fundamental. On the other hand, due to economic factors, CCVTs are commonly used in high voltage applications. ¶
 The optical VTs and CTs are high accuracy devices for magnitude measurement but very poor for phase angle measurement. Specifically, they exhibit a time delay in the order of few tens of microseconds that translates to phase angle error in the degree range.
 [AD: These two statements completely duplicate page 17, lines 18-20. Better fits in the previous section.] ¶
 How errors introduced by instrumentation channels will affect applications using GPS-synchronized data depends on specific application requirements. Characterizing those errors and addressing their effect on applications

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 In any case, as improving accuracy is important for variety of applications, it is recommended to further develop algorithms to correct for these errors. ¶
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1 **6. A guide for PMU installation, commissioning and maintenance**

2 **6.1 Preface**

3 This section discusses recommendations for PMU installation, and is based on general installation
 4 requirements for PMUs and typical substation configurations. The summary of a PMU installation survey
 5 can be found in [Annex J](#). The information found in this section are only considered a starting point, and is
 6 expected to be expanded and modified as applications are expanded.

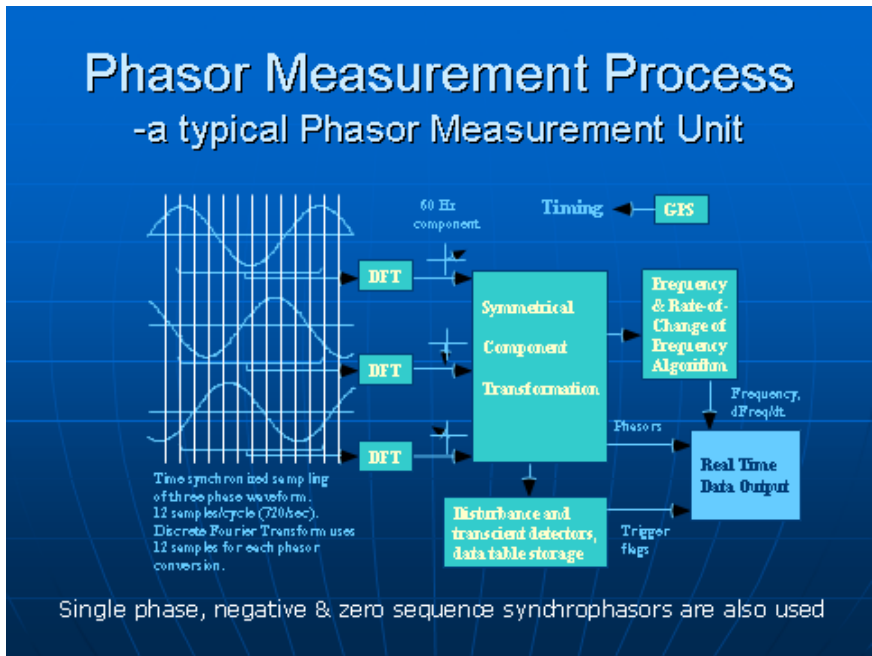
Comment [ARG16]: IRIG 200-98 has a summary of PMU Installation?

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7 **6.2 Overview**

8 PMU installation requires access to measured power system parameters, a timing signal to synchronize the
 9 measurements, and data communications to transmit the measurement. These items are discussed in the
 10 pre-installation procedures below. A PMU primarily monitors AC voltage and current signals and
 11 estimates a phasor equivalent based on a time signal.

12 There are different techniques for computing the synchronized measurements such as frequency tracking or
 13 synchronous sampling. It estimates a phasor as referenced to absolute time. Power system phase and
 14 sequence quantities are computed and are available to the user for recording and/or reporting purposes.
 15 Different sampling options are offered by different manufacturers. [Figure A-8](#) is an example of the phasor
 16 measurement process (synchronized sampling) for steady state conditions.



17 **Figure A-8—Typical PMU measurement process reflecting synchronized sampling**

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18 [Figure A-9 is a synchrophasor data from frequency tracking sampling.](#)

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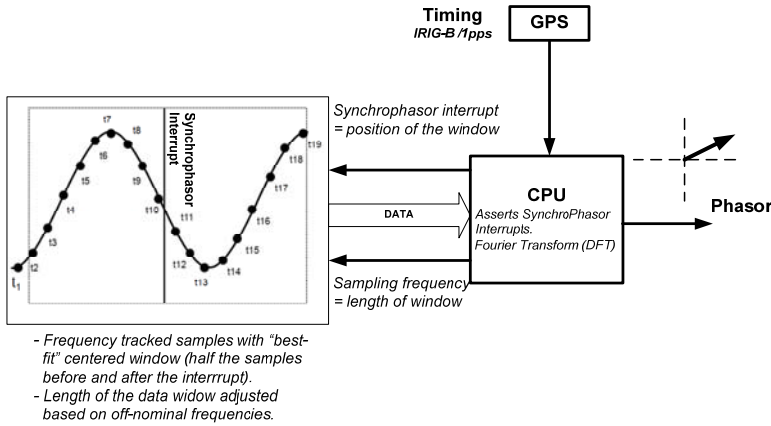


Figure A-9—Synchronized phasor with frequency tracking sampling

When a PMU is designed to support multiple three-phase voltages and currents, the phasor quantities for each of the three-phase systems connected to the device can be independently computed, recorded locally and/or streamed to a remote location in real time. A PMU needs access to a communication system that can transmit data at the PMU reporting rate and one that matches the format and interface. These requirements are detailed below.

In some cases, the PMU will have status inputs (Boolean 1 or 0) or other measured value (“analog”) inputs such as temperature or wind speed. The PMU communication provides support for analog and digital data as well as phasor, frequency, and rate of change of frequency data. Access to these signals will depend on the situation, but need to be considered at the planning and specification stages.

6.3 Pre-installation procedures

6.3.1 Installation design

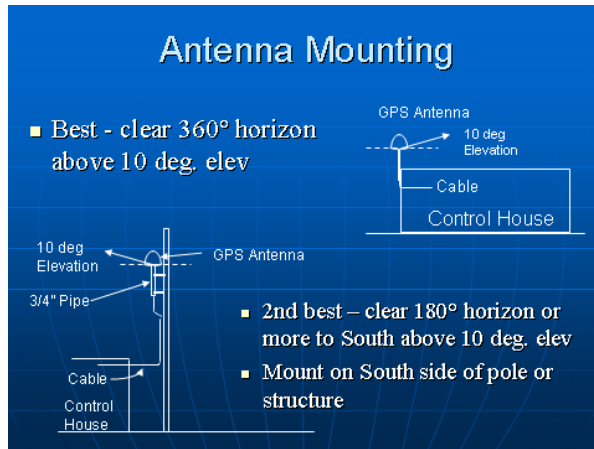
In most cases, a PMU installation is considered a permanent installation and requires a complete design. Below are only supplementary guidelines to help scope a project and proceed with the design. Typical design includes selection of power system sources, inputs, outputs including alarms, absolute time source and communication interfaces. Some of the key components of a typical PMU are described in the sections below.

6.3.2 Timing input

The choice of GPS or other time source hardware, antenna location, cabling and routing of the cable are critical in the overall design of the PMU system. When input time from GPS is directly connected to the PMU, antenna open to GPS signals and cable to the PMU are critical factors in design and installation. Antennas ideally have a clear sky view (free from obstructions) above a 15 degree elevation. In cases where this is difficult to achieve, compromise factors need to be followed. Precision of the internal clock determines the ride through variance during complete or intermittent loss of GPS synchronization. Figure A-10 shows recommended antenna mounting design. In the example of antenna installation, most of the signals will come from the south (in the Northern hemisphere) from the horizon to about 15 degrees north of vertical (see Figure A-11).

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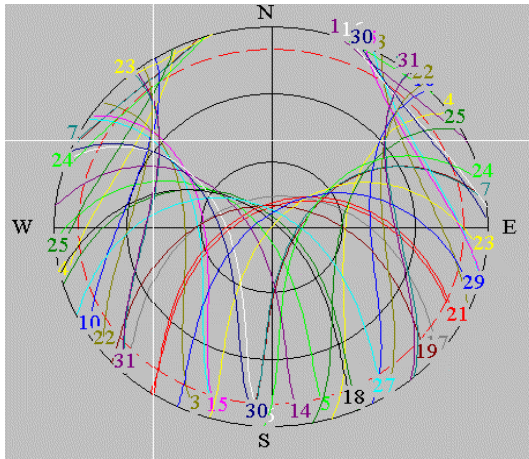


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Figure A-10—Recommended antenna mounting locations on pole or roof. Plot of GPS satellite trajectories for 45° North latitude shows that best coverage is to the south.

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Figure A-11—GPS signal visibility pattern reflecting the orbit for various satellite

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The antenna should be mounted with a clear view towards the equator with 10 degrees elevation from horizontal axis. Small obstructions more than half a meter away from the antenna will not cause a problem, but a large flat obstruction within a few hundred meters could act as a reflector and cause multi-path problems. Check around the mounting location for a structure, such as a flat metal roof, that is oriented so it can reflect a satellite signal to the antenna (keeping in mind satellites will traverse most points in the sky). Also check for obstructions that can block the signal, and high power signal sources that can saturate the GPS input. Some GPS receivers have been operated successfully with the antenna mounted inside a building, receiving signals through the roof. In other situations, mounting the antenna by an equatorial facing window has been successful. Many less than optimal installations will experience some signal outage which degrades the clock signal measurement. The most reliable antenna mounting option is an open air sky-view installation.

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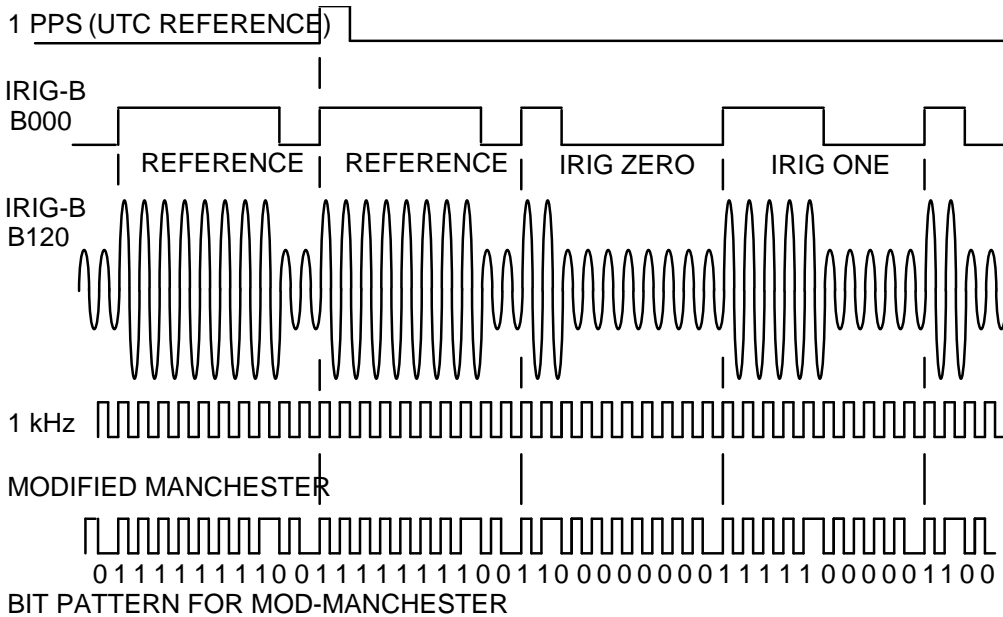
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1 The satellite synchronization signal (center frequency) is transmitted at 1.5 GHZ. The 1.5 GHz signal
 2 attenuates rapidly in a cable, and most vendors recommend limiting cable runs to less than 150 ft. There are
 3 alternatives for longer cable distances, such as high power antenna or in-line amplifiers and low loss cable.
 4 It is common practice to compensate the time signal to address delays and latency associated with the
 5 length of the antenna cable. The cable length could be a straight run between the antenna to the clock
 6 receiver and/or the distance within the control room to distribute the clock signal. Cable delay
 7 compensation and/or clock offset are also available in some clocks.

8 For an externally mounted antenna, it is advisable to incorporate a lightning arrester into the design.

9 It is common practice to use a signal source that will provide the required signals at the accuracy the PMU
 10 requires for meeting timing requirements. Some PMUs input time from a local source, such as a GPS
 11 receiver or clock server, using a local signal type such as IRIG-B, 1 PPS, or IEEE 1588. Some of these
 12 signals degrade rapidly. Delays are associated with the dielectric constants (i.e., capacitance of cable) and
 13 the length of the transmission medium. Therefore, excessive cable runs should be avoided. When using
 14 this type of PMU, consult the vendor as to what signals they require and whether the delays are
 15 compensated. For example, IRIG-B may be specified and can be used in any of its modulated forms, but
 16 the DC level-shift or the Modified-Manchester coding forms will allow the highest accuracy. The example
 17 shown in [Figure A-12](#) uses Manchester time coding.

18



19

20 **Figure A-12—Example showing forms of IRIG-B comparing the un-modulated (level shift)**
 21 **B000, 1 kHz modulated B120, and modified Manchester B200.**

22 A GPS fed clock can potentially serve a number of devices using one IRIG-B output port. The number of
 23 clients (users) that a clock can serve depends on both the drive capacity of its IRIG-B port as well as the
 24 amount of load (both capacitive and resistive) that the devices connected to the clock represent. The
 25 cabling, associated routing, and termination methods also affect the clock loading. To design a highly
 26 reliable timing circuit, product specifications should be studied and respective manufacturers may be
 27 consulted. Some of the key factors to consider are:

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- 1 • Load and capacitance of the wire/cable – use ultra low capacitance cables. For example, twisted-
2 pair usually has lower capacitance than coaxial cable;
- 3 • Cumulative sum of the loads represented by input impedances of all clock clients (PMU and non-
4 PMU) and the associated cabling should not be larger than the clock’s output port (IRIG-B port)
5 output serving capacity with some safety margin (e.g., more than 30% margin).
- 6 • Impact or presence of redundant clock architecture should be considered. For example, if the
7 application has primary and alternate clock provisions into the respective device input, both clocks
8 need to have similar port output ratings.

9 Signal propagation in cabling should be considered and corrected for longer cables (typically 1 ns/ft or 3
10 ns/m of delay). Also, longer cable length (and the associated effective impedance/capacitance) will result
11 in slowing down the rise-time of the clock pulse edge received by the PMU. Accordingly, minimizing
12 cable lengths will be beneficial. When daisy chaining of the clock signal is considered, the user should
13 carefully examine to make sure the receiving device does not process the clock and then pass to other
14 devices part of the daisy chaining. Processing time by the first device will introduce delays for the other
15 subsequent devices that are part of the daisy chain.

16 The type of connector, e.g., screw-terminal vs. BNC, usually has negligible impact – all other factors being
17 equal.

18 Table 32 shows results of connecting multiple devices to one port of a clock for both modulated and un-
19 modulated outputs in a lab environment. Notice, lab environment typically is controlled and devices are in
20 close proximity of one another. In this example, four IEDs were used with signal through BNC type
21 connector. A variable resistance source (decade box) was placed between the IRIG-B signal and ground.
22 The resistance was varied until the IRIG-B valid LED in front of the device indicated the device is no
23 longer receiving valid signal (unlocked from IRIG-B). The actual signal was measured with a calibrated
24 voltmeter (given in the table below as voltage (p-p)).

Comment [FR20]: Table number and cross-reference to be edited by IEEE.

25 Table 32A – Test results for four devices with IRIG-B input signal through BNC connector – signal type:
26 Modulated

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Resistance ohms (decade box)	Voltage Level (p-p)-V	Results
500	3.56	Locked
50	2.40	Locked
15	1.42	Locked
10	1.16	Locked
9	1.08	Unlocked Momentarily
6	0.784	Unlocked Momentarily
3	0.472	Unlocked
2	0.368	Unlocked

27 Table 32B – Test results for four devices with IRIG-B input signal through BNC connector – signal type:
28 Un-Modulated
29

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Resistance ohms (decade box)	Voltage Level (p-p)-V	Results
500	3.88	Locked
50	2.88	Locked
30	2.68	Locked
20	2.00	Unlocked Momentarily
10	1.36	Unlocked Momentarily
9	1.26	Unlocked
8	1.18	Unlocked

30

1 When designing the timing circuit, the substation environment and routing of the cable should also be
 2 considered. In larger substations, it may be more practical and economical to use two or more clocks and
 3 GPS antennas to serve devices in different parts of the substation as opposed to running long cables to all
 4 devices from one clock. This approach also helps with distribution of the load on a given clock.

5 Some PMUs (and other devices) have options to accept clock signals (through IRIG-B, 1-PPS, etc.) and/or
 6 to use an internal GPS clock to provide internal timing information if connected to a GPS antenna. The
 7 choice of timing circuit depends on various factors. Generally, sharing GPS antenna signals can become
 8 complicated, especially when active antennas (antenna requiring power from the clock) are used.
 9 Accordingly, use of a PMU's internal GPS clock connected to the GPS antenna is more practical when the
 10 PMU is the only device (or one of very few devices) using the time information. In cases where absolute
 11 timing information is necessary for several devices, use of external clock connected via IRIG-B interface
 12 (or 1-PPS signal) is more practical. Use of external clock may also facilitate on-site trouble-shooting
 13 processes.

14 It should also be noted that the naming convention (clock identifier) when using 1-pps signal is not
 15 standardized (is product specific). Consequently, use of IRIG-B protocol may be more appropriate as
 16 opposed to using 1-pps signal for sharing clock signals.

17

18 6.3.3 Voltage and current input

19 Most PMUs convert voltage and current signals by use of A/D converters (Analog-to-Digital converter
 20 electronic chips). When possible, the PMU shall be installed with test access to the PT and CT inputs so
 21 test signals can be injected for performance tests and calibration. When multiple PMU devices are installed,
 22 test procedures need to account for the various sources of current and voltages signals.

23 Good measurements require consideration of the signal sources. Accurate frequency tracked sampling or
 24 synchronized sampling are important features of a PMU. The measurement speed within the PMU needs to
 25 be fast enough to capture required frequency contents. Similarly, the range needs to be high enough to
 26 capture required maximums and low resolution signals. The PMU will need to have adequate sample rates
 27 and filtering for accurate signal representation. The PMU specification will reflect the maximum input
 28 range and resolution. Also, IEEE C 37.118-1 provides additional performance parameters.

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Comment [ARG23]: This paragraph does not give any useful information. If the PMU is not standards compliant, it should not be used.

29 User defined scaling factors will impact resolution and dynamic range for measurement/monitoring phasor
 30 quantities. Scaling factors are application driven. For example, under steady state conditions, when voltages
 31 up to 200% of nominal voltage are of interest, the scaling factor of 50% would be desirable, and prevent the
 32 secondary voltage measurements without being clipped. This threshold set point gives some overhead for
 33 large swings, but good resolution for nominal input. On the other hand, current values will need a much
 34 larger dynamic range. It is very important to consider references to "nominal current" with respect to
 35 normal currents on the primary system. When connecting current measurement inputs of the PMU to the
 36 CTs, the rating and ratio of the CTs relative to nominal primary current levels shall be considered. For
 37 example, at a wind farm with certain energy generation capability, the rated primary current may be 400
 38 amperes while the short circuit duties near the station may be much higher than the rated nominal primary.
 39 In order to have adequate resolution (and accuracy) at 10% of nominal current (40 A primary), the
 40 protection CT output (operating near 1% of its 3000 A rated value) may not be appropriate.

41 Fault recording and relaying requires a scale that will accommodate very high currents; phasor
 42 measurements are concerned with normal operational and system swing currents which range from
 43 somewhat over nominal to light load (10% of nominal). Setting the maximum at about 2X nominal will
 44 give good measurements at light load and normally cover swings. However, it may be considered more
 45 important to capture all swings and overloads at the expense of lighter loads. Sometimes the PMU is a part
 46 of another device, such as a relay or DFR and the calibration will be dictated by another requirement. This
 47 is a user consideration where the user needs to be aware of the tradeoffs.

1 The choice of appropriate CT and PMU current range depends on many factors, including application
 2 (functions) being deployed and system cost. The user shall consider the entire instrumentation channel,
 3 the available standards, and whether the standards meet the application requirements (in particular, if a PMU is
 4 expected to perform outside of nominal rating, or dynamic range). (For example, for TVE of 1% and the
 5 PMU calibrated for 10% and 120% of rated CT.) If the range of performance interest is outside of the
 6 example, it is common practice for the user to ask for the desired range and validate the performance as
 7 part of the certification process.

8 The PMU will also derive frequency from one of the AC input signals. These are fully user selectable in
 9 some PMUs and fixed in others. Some PMUs will allow selecting a backup channel when the primary one
 10 has a low signal. To assure a good frequency measurement, it is best to select a voltage input channel which
 11 has good signal strength, since these don't vary as much as currents.

12 6.4 Analog and digital input

13 Some PMUs allow connecting other measurements such as a MW transducers for measuring temperature or
 14 wind speed. These values will be reported along with phasor values in the time synchronized data packet,
 15 which opens up the use of phasor data for many real-time and analysis applications. Generally these data
 16 signals are easier to transmit than high-current CT circuits, but they need to be considered. When a PMU
 17 provides "status" inputs such a breaker status, these parameters are represented as a Boolean logic ("0" or
 18 "1") single bit in a digital word. Access to these signals is usually not difficult, but again needs
 19 consideration during installation.

20 6.5 Power input

21 Since PMUs need to operate continuously, and without interruption during disturbances, most applications
 22 are designed to connect the PMU to the station DC power. When using station DC, the impact of the DC
 23 ripple to the power supply shall also be considered to make sure quality or accuracy of the measurements
 24 are not impacted. PMU Manufacturers should specify DC ripple immunity and stations should characterize
 25 ripple on station DC.

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26 6.6 Communications

27 Communication interfaces are critical parts of phasor measurement systems. It is important to carefully
 28 plan the system and be sure all aspects are addressed. The first part will be cabling from the PMU to the
 29 communication interface device. Next will be the interface medium. The third component is the interface
 30 with the PMU. The overall system including the application end (PDC or other devices) requires complete
 31 planning, but that is beyond the scope of this document. Station architecture must be considered in the
 32 design of the communication interfaces. For example, when an application includes an interface with
 33 station bus, the PMU communicates with the station bus processor. Likewise, in process bus applications,
 34 the PMU merging unit interfaces perhaps through a unit to the local data processor.

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35 Cabling is required between the PMU and the communication interface (e.g., modem, router, etc). Most
 36 cabling is small and rather easy to route and install, and the principal issues are interference and cable
 37 length. An additional consideration is the impact of the secondary voltage during a nearby fault. When
 38 possible, use Fiber Optic (FO) cable for all signals that travel outside of a single rack (grounding unit). A
 39 signal within a building can run in metallic cable as long as the length does not exceed maximum specified
 40 distances. If the signal is to run between buildings (e.g., between a control building and a communication
 41 interface building), it is best to use FO cables. In some cases, this requires signal converters at each end, but
 42 many vendors have FO I/O built into their equipment.

43 When metallic cables are use, considerations shall be given to minimize the most likely sources of
 44 interference. Coaxial cable has good electrostatic shielding but is subject to electromagnetic interference,
 45 particularly where ground differences can occur (conduction through the ground). Shielded twisted pair

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(CAT5) has good rejection for both electrostatic and electromagnetic interference, but all shielding has limitations. High magnetic fields can penetrate most kinds of shielding, and are best treated with appropriate grounding and bonding practices. It is best to route cables with some thought as to what is in close proximity. Also note that many substation cables are large and heavy, so they may pinch a poorly routed communication cable which may result in loss of shielding and transmission properties. Table A-II summarizes the signal types, the recommended and practical length, and some comments. Refer to NASPI SynchroPhasor Accuracy Characterization for more considerations regarding cable selection.

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Table A-II—Recommended cable lengths for signal transmission

Signal type	Cable type	Recommend max length	Interference/comments
Asynchronous serial (RS-232)	Twisted pairs	15 m @ 20K BPS	Actual length depends on cable & rate.
V.35	Twisted pairs	600 m @ 100K BPS 90 m @ 10M BPS	Standard well specified and followed. Widely used outside of US.
Synchronous serial (RS-422)	Twisted pairs	1200 m @ 100K BPS	Bipolar low level signal has good transmission characteristics
Ethernet thin-net	Co-ax		Good static shielding, use tri-ax where there are grounding issues
Ethernet 10BaseT	CAT4	100 m	Good shielding, move up to Cat5 for better signal
Ethernet 10/100BaseT	CAT5	150 m	Good shielding, use ruggedized version for better mechanical protection*
Ethernet 100BaseFX	FO	2 km	Best for interference rejection & avoiding grounding problems

* Std CAT5 is Unshielded Twisted Pair (UTP). This shall be Shielded Twisted Pair (STP).

In addition to the physical installation considerations, the communication types need to match in type and rates. PMUs are required to support all data rates up to 50/60 reports per second. Some, but not all PMUs can report at higher rates if required by the application. PMUs generally will have asynchronous serial (RS-232) or Ethernet communications. Both will handle data at the rate and block size used in most measurement systems. An interface device between the PMU and the communication system is required. The user must identify the communication medium, interface, and technology required for the particular application (e.g., whether multi-case communication is needed). Generally, a modem translates between a digital data system and an analog communication system, and a CSU/DSU (Service Unit) or router or bridge translates between a digital data system and a digital communication system. In either case, the PMU output is a digital data type and needs one of these devices to interface to the communication system. Most importantly, the appropriate sides of the interface have to match the PMU and communication system, and must handle the required data rate. If the PMU output is asynchronous serial, the interface must handle asynchronous serial at the given rate.

Comment [ARG25]: PMUs are required to support all data rates except those above 50/60 reports per second.
Deleted: The basic consideration is the PMU itself and data rates required by the measurement system. The PMU shall be chosen so that it will output measurements at the rate required by the measurement system. For example, if the application requires 30 samples per second, the PMU needs to measure and stream data at 30 samples per second.
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Table A-III—Examples of required data rates using C37.118 data format and protocol

30 frames/sec	All Integer format	All floating point format
5 phasors, no analog/digital	1260 bytes/sec	1980 bytes/sec
10 phasors, no analog/digital	1860 bytes/sec	3180 bytes/sec
5 phasors, 2 analog/ 1 digital	1440 bytes/sec	2280 bytes/sec
10 phasors, 2 analog/ 1 digital	2040 bytes/sec	3480 bytes/sec

Notes:

- Asynchronous serial requires 10 bits/byte, so required BPS rates are 10X the above figures.
- UDP/IP over Ethernet has a fixed size overhead of 54 bytes per packet, so actual required rate is higher than the requirement above. It ranges from 23,040 BPS for phasor/integer to 41,120 BPS for the 10 phasor-2 analog-1 digital/floating point shown above.

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1 • Since data is sent continuously at the rates shown in the table, the communication channel must have a
2 capacity at least that large, and must be at least 10% higher than the required data rate to accommodate error
3 correction and short dropouts. The PMU port speed will likewise have to be equal or higher than the actual
4 data rate. In many cases this requires high serial data rates, such as 38.4 or 57.6 KBPS.

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5 PMU communications by Ethernet match directly with digital systems and interface well with digital
6 communications such as SONET. Ethernet based digital systems are well developed and supported, so
7 building these systems is generally very straightforward. Care needs to be exercised when connecting the
8 local Ethernet system through a digital communication system (e.g., SONET), usually called the Wide Area
9 Network (WAN) connection. The WAN needs to support the minimum data rate with some room for
10 overhead, and the interface needs to have sufficient buffering to match WAN and Ethernet speed
11 differences. Most of these systems currently use Internet Protocol (IP) for data communication. Building
12 and managing these systems is centered on setting up IP hosts, subnets, and routing. Additional
13 considerations for communication interface include data exchange with neighboring systems, neighboring
14 countries, local ISO, or at the Regional levels. Depending on the application, data reliability and accuracy
15 may be critical factors. Cyber security requirements are also important considerations when application is
16 considered critical.

Comment [ARG26]: Probably an unneeded paragraph.

Deleted: Generally speaking, asynchronous serial ports interface better with analog modems than digital type interfaces. Analog modems are also easy to interface with analog communications. The problems with analog modems include limited bandwidth and data loss due to communication impairment. Also, as digital communication becomes more prevalent, there is decreasing availability and support for this equipment.

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17 **6.6.1 Communication over serial port**

18 The synchrophasor Standard C37.118 defines the concept of “frames” for transmitting data from a PMU to
19 a PDC. The standard does not impose any restriction on the communication media itself. Basically a
20 Configuration frame, Data frame, Header frame and a Command frame are specified. These frames have a
21 particular structure and data type associated with them. Configuration frame, Data frame, and Command
22 frame are binary types, while Header frame is a ASCII type. The Data frame is the most frequently
23 transmitted message based on the PMU sample rate, and the typical size is of the order of few hundreds of
24 bytes. The variable size in the Data frame is the number of phasors and analog and digital signals
25 transmitted depending on the PMU capability. For example, if a serial communication is chosen to transmit
26 the PMU data, the data transfer capability depends on the baud rate of the communication port. Table A-IV,
27 shows the typical data transfer capabilities, assuming that the PMU supports up to 12 phasor channels.

Comment [v27]: Verify reference number

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28 **Table A-IV—Estimated number of phasor channels that can be transmitted at various baud**
29 **rates and PMU reporting rates over serial port**

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Baud rate, (bps)	Reporting rate (frames / second)								
	10	12	15	20	25	30	50	60	
9,600	12	12*	10*	6*	4*	2	0	0	
19,200	12	12	12	12	12	10	4*	2	
38,400	12	12	12	12	12	12	12	10	
56,700	12	12	12	12	12	12	12	12	
115,200	12	12	12	12	12	12	12	12	

30 *Calculated required bandwidth is very close to the actual baud rate. Actual number of phasors may be less than the
31 estimate. The above estimates were calculated for 1 start bit, 1 stop bit, 8 data bits and no parity bit, or a total of 10 bits
32 to transmit each byte.

33 **6.6.2 Summary**

34 Table A-V, summarizes basic design considerations in the order of importance. Since many factors impact
35 the application, it is important to scope the entire project before deciding on equipment and design. For the
36 overall project consideration, spare parts, training, overall cost, and company policies are equally important
37 factors.

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Comment [v29]: Verify Figure number as consolidating the entire document

38 **Table A-V—Summary of design considerations for PMU installation**

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Question	Answers	Additional Comments
Primary source of current and voltages?	Number of available voltage sources, location of the voltage source (bus side or line side). When line voltages are used, contingency considerations are commonly considered in case a line is out of service.	Number of feeder currents needed for important power flow calculations?
Does PMU require direct GPS input?	The choice of IRIG vs. GPS is user consideration based on the device specification. Both options work as long as accuracy is not impacted. When GPS is provided within the device, the clock is internal to the device. The location for the antenna <u>must</u> provide for best reception of the signal. Several receivers can be connected to one antenna. When using IRIG-B input, the clock is external to the device. It is recommended to use un-modulated IRIG-B signal. Some clocks provide a means to determine signal strength.	IRIG-B/1PPS signals are generally easier to route, but check wiring availability. <u>Long cable runs or serial line drivers may cause unacceptable delays in IRIG B/1PPS signals.</u> <u>A suitable GPS antenna splitter is required when connecting more than one GPS receiver to a single antenna. Some antennas require preamplifier power so the receiver and splitter must be capable of routing appropriate power to the antenna.</u>
Does the PMU output match the communication system interface?	If system is digital and PMU is RS232, be sure interface is available in type and speed (see Table A-IV).	
What types of communications are established within the substation?	If Fiber Optic (FO), will it match the PMU interface? If not FO, is the distance short enough for galvanic (see Table A-II)?	Other factors include grounding and shielding when metallic mediums are used. Design considerations shall include methods of grounding the shield and whether the cable is shielded on both ends or one end.
Impact if including a PMU into an existing CT and PT circuits, and the additional burden impacting PMU performance?	Most PMU devices have a very low burden.	A good design with engineering calculations for the overall burden will prevent installing a PMU in a circuit that would impact performance of the PMU. When impact of the burden is high, separation of the PMU sources from other devices will help with improving inputs to the PMU and therefore the PMU performance.
Does the application have particular filtering needs (P & M classes as defined per standard)?	Yes, be sure the PMU has settings that match or use alterable settings to satisfy the application requirements.	Filter in this context is in reference to "P" and "M" class. In general, microprocessor based devices have filtering beyond the intent of the reference to the "P and "M" classes.

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Comment [v30]: Sakis will provide narrative regarding clock monitoring satellite location and signal attenuation.

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Comment [v31]: Make sure table is provided, or remove reference to the table.

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Comment [ARG32]: This is a gross over-simplification. Generating an input signal is only part of the problem, analyzing the response of the PMU in comparison to the signal generator output can be quite difficult.

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1 **6.7 Pre-installation tests**

2 The extent of pre-installation testing depends on power company practices. At a minimum, some quality
 3 assurance testing shall be done to ensure units work in the planned system and are reasonably calibrated.
 4 Many of the tests can be performed using conventional test equipment or signal generators, as long as the
 5 test equipment is calibrated in accordance to the IEEE C 37.118-1 Standard.

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1 A complete set of test and performance results for each PMU type must be acquired to make sure the
 2 product meets the user specification. This testing is referred to as “Type Test,” [see IEEE Standard C37.233
 3 for additional information regarding different types of tests].

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4 As part of the pre-installation testing, wiring checks are performed to verify that the PMU connectivity
 5 meets the customer specification. Performing some basic tests will confirm proper wiring, terminations and
 6 grounding of the equipment mounted. Pre-installation tests for the communication components, such as
 7 cabling, will be the next step in the pre-installation test sequence. Typically, the biggest problem is data
 8 communications, so minimizing other problems ahead of time is worth the effort.

9 A risk assessment is needed to investigate worst-case problem scenarios that may occur while
 10 commissioning the PMU installation. This risk would include information from an equivalent to
 11 Transmission Services with respect to power system conditions allowed during commissioning.

12 Cyber security issues have to be resolved beforehand with information services. Each utility will have its
 13 own recommendations, but the use of a Virtual Private Network (VPN) form of communication not
 14 connected to the internal LAN is one option for providing isolation and security. Communication links
 15 shall be in place prior to the day of commissioning the PMU.

16 6.8 Verification of calibration part of installation

17 Full calibration and characterization of the PMU and measurement system are generally performed in a lab
 18 environment where the input values can be precisely controlled.

19 For installation, it is important to assure measurement calibration continuity from instrumentation to the
 20 end application. The verification will be based on the actual system signals. When the PMU installation
 21 includes test switches supervising the current and voltage inputs to the PMU, the inputs can be accurately
 22 measured, but since the real system is constantly changing, it is difficult to achieve precision. Calibrated
 23 test equipment can be used to provide test signal sources for validating the field installations and PMU
 24 calibrations. Application considerations may affect the type of installation testing. Other factors impacting
 25 the testing include the type of installation (e.g., Y or Delta transformer connectivity), the PMU filtering,
 26 and any instrument transformer compensation (phase or magnitude) to offset for current and voltage
 27 transformer inaccuracies.

28 The principal points covered include:

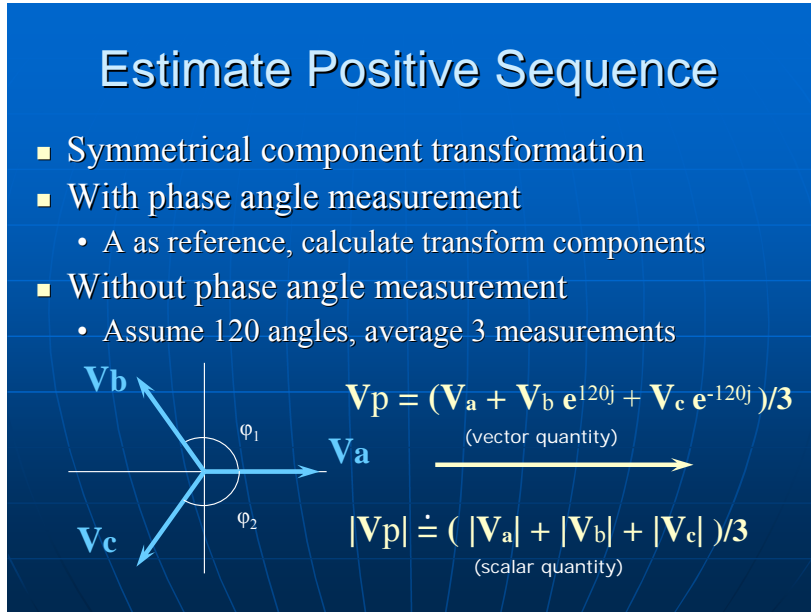
- 29 • GPS connectivity is accurate, clock is locked in, and the device is set for unmodulated signal.
- 30 • Accuracy of the measured quantities, and whether the values are reasonably correct.
- 31 • Whether the measured values are in reasonable agreement with other measurements.
- 32 • Whether the phase angle is consistent with other local devices for basic connectivity verification.
- 33 • Whether the phasing is in agreement with other devices capable of producing PMU type values.
- 34 • Whether communication with other devices, or data streaming, is working properly.

35 6.9 Correctness of measured value

36 The most reliable method of checking the measured values is comparison with the input. This is easiest to
 37 do if the PMU has a local readout or tool that provides a local readout. One way is to measure the input V
 38 & I with a calibrated meter. The positive sequence phasor magnitude is approximately the average RMS of
 39 all three phases (see [Figure A-13](#)). For a PMU with three-phase voltage and current inputs, it is best to

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1 confirm the input values when the system is in steady state condition and large value swings are not
 2 anticipated. All three-phase voltage magnitudes are measured, with a calibrated RMS meter in quick
 3 succession, and are then averaged. The averaged values are then compared against PMU secondary positive
 4 sequence values displayed by the device software or local display. The same process is generally repeated
 5 for three-phase currents. For current and voltages, the compared input and displayed values are anticipated
 6 to be within 1 to 2%. If the currents are very steady and midrange, the comparison shall also be within 2%.
 7 It is a good practice to also verify the phase angle relative to a known reference and anticipate less than 2%
 8 deviation between measured and displayed values. When the phase imbalance is significant (> 2%), it is
 9 advisable to use phase angle as well as magnitude readings to come up with the estimated value of the
 10 device telemetry output, since this also affects the positive sequence equivalent.



11

12 **Figure A-13—Estimate positive sequence from individual readings if power system is**
 13 **reasonably well phase balanced**

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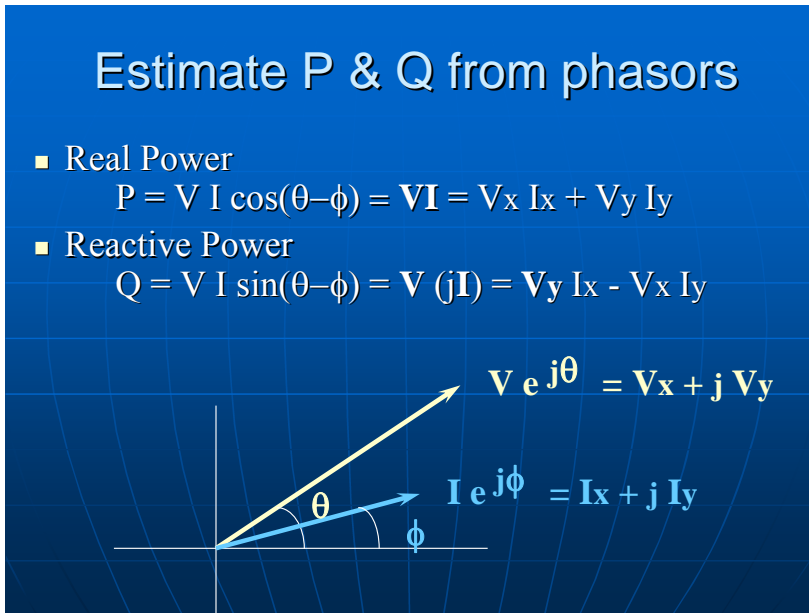
14 6.10 Comparison with other measured values

15 It is good practice to verify wiring before starting to take measurements to validate accuracy of
 16 measurements. For a dedicated and newly installed PMU, the measurements can be compared with panel
 17 meters and transducer measurements such as through the SCADA system where available. For angular
 18 measurements, State Estimator snapshot can be used as an alternative. Keep in mind that the EMS
 19 measurement may be a single-phase measurement. Due to variances in technology, manufacturing,
 20 calibration of existing equipment to be used for telemetry comparison, or modeling inaccuracies, these
 21 telemetry values may not agree very closely, but the comparison provides indication about any wiring
 22 related problems. It is best to take the measurements when there is sufficient amount of current flowing
 23 through the portion of the system where the PMU values are monitored and wiring is being confirmed.

24 When single-phase voltage or current measurements are available, single phase metering is used similar to
 25 the three-phase without averaging. It is possible that the single-phase measured values can be further off
 26 than expected. When only power measurements are available, the user can either combine the phasor
 27 current with the appropriate bus voltage and compare power, or divide the power measurement by (1.732 *
 28 voltage) to determine the current (see [Figure A-14](#)).

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1 It pays to check the phasor measurements to account for differences and the accuracy of the PMU
2 calibration.



3

4 **Figure A-14—Estimate real and reactive power from complex phasor values. Be sure to**
5 **use the phasor scaling values as well as PT/CT ratios.**

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6 Comparison with another certified PMU can provide a good check of measured phase angles. It is
7 important that the comparisons are made at the same time, since loading and angles constantly change.

8 6.11 Phasing of local signals

9 This guide is focused on the application and installation of PMU devices and makes little references to the
10 general prudent practices of verifying polarity connections and phase sequence verifications by the user.

11 Once the phasor measurements can be confirmed as correct and defensible, the phasing of the signals
12 relative to one another shall be checked. In a case when PMU is measuring line parameters, and the line is
13 open ended, the impacts of distributed capacitance influencing the phase angle measurements (or
14 displayed) shall be considered.

15 It is usually instructive to convert the phasor values into MW and MVAR and compare with other
16 measurements. At low values, various measurement systems may differ significantly, but anything near full
17 scale may provide useful comparison within a few percent.

18 6.12 System signal phasing

19 In general within a single power company, phase naming convention is consistent throughout the system.
20 For example, phase-A is well defined and shall be the same at all substations. One way to validate that
21 phase-A at a new PMU installation agrees with other installations, is by comparing the phase angle with the
22 nearest installed PMU.

1 When the PMU Installations are at two adjacent stations, then, the angle between them can be
2 approximately calculated by:

$$3 \quad \phi = \arcsin\left(\frac{PX}{V_1V_2}\right)$$

4 Where:

- 5 • P = power flow on the line
- 6 • X = line reactance
- 7 • V1 and V2 are the bus voltages.

8 Power always flows from a leading angle to a lagging one. The measured angle will be reasonably close to
9 the value calculated from the power flow above.

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10 Even if the stations are not adjacent, or the parameters are not well known, the measurement phasing can be
11 confirmed using a heuristic approach and applying the following rules:

- 12 • Power flows from buses with leading angles to those with lagging angles. By noting the power
13 flow in the area between the stations being compared, and if it is notably flowing from one to the
14 other, the angle definitely will match in polarity.
- 15 • If there is little power flow, the distance is short, or the impedance is low, the angle will be small.
16 Higher voltage systems have lower impedance. Multiple lines or a meshed grid have lower
17 impedance.
- 18 • If the stations are fairly close (within 200 miles), expect an angle of 30 degrees or less. If they are
19 more distant, it could be higher (possibly more than 90 degrees in a meshed grid).
- 20 • If the power flow between stations is not clearly one direction or the other, the angle could go
21 either way but the total will be smaller, perhaps in the area of 15 degrees.
- 22 • Large errors of 30 degrees can usually be detected if the PMU is assumed to be connected for line-
23 to-neutral measurements but is actually line-to-line (or vice-versa).

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24 Since the main objective here is to detect phasing errors and phase selection errors resulting in a 120 degree
25 phase shift, such a large discrepancy will be distinguishable from the angles estimated by power flow using
26 the rules mentioned above. However, certain factors such as Y-Δ and phase shifting transformers, as well as
27 series capacitors, can produce results that make phase checking difficult to determine.

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28 A similar approach is recommended when the PMU data is compared with a neighboring system. The first
29 step is to confirm the phase naming convention and determine the relative phase angle relation between
30 comparable power system phases.

31 With these large errors removed, comparison to SCADA load flows can be expected to be within a couple
32 of degrees.

33 6.13 Communications operation

34 Deployment of appropriate communication technology with well defined monitoring and maintained
35 system is important in meeting life cycle requirements when installing PMU and associated interface
36 equipment and a data concentrator.

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1 Communications from the PMU to the data concentrator is a critical link and often the most troublesome.
2 Initial checkout details depend on the particular system. A few general observations are offered here.

3 Data are sent at the selected reporting rate from the PMU in packets that are precisely time tagged, and
4 terminated with a CRC or checksum. In many cases, the communication medium provides its own
5 packetizing with a check word. The receiving device (e.g., PDC) shall use the check word to detect
6 corrupted data, and timetags to keep track of missing data. This information is essential for initial system
7 checkout as well as ongoing maintenance and repair.

8 After installation, corrupt and missing data must be monitored closely for a few days. For example, the
9 communication system may not lose more than 3 packets per hour at a data rate of 30 samples per second,
10 and may vary based on application, design and tolerance requirements amongst factors influencing
11 communication requirements. At the receiving end, it is not possible to differentiate between data that has
12 been lost in communication and data that was never sent. Pre-installation testing must include enough
13 monitoring to prove that the PMU outputs data reliably to meet the application requirements. Overall
14 performance is also impacted by levels of redundancy in the application.

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Comment [v33]: Do we want to include additional information, a table, or references regarding "Good" / "Acceptable" communication system performance?

15 Patterns of data loss indicate different problems depending on the type of communication. For example,
16 alarms are commonly set to identify/measure acceptable lost packets over a given time period.

17 For example, with RS-232 serial systems using audio-tone (analog) or digital communications, the user
18 may set parameters for monitoring lost packets after a few check word errors and a few lost packets per
19 hour. Lost packets may have increased activities—particularly longer periods of outage—at certain times of
20 day if affected by fading (temperature related). Occasional to frequent outage blocks can indicate
21 communication system synchronization problems or modem re-synchronization due to low signal levels.
22 Any more than a few lost samples per hour usually indicates a communication problem that can be
23 resolved.

24 Network based systems over audio-tone communications will behave somewhat like the RS-232. Network
25 over digital communications can be divided into connected types like Transmission Control Protocol
26 (TCP/IP) and non-connected types like User Datagram Protocol (UDP/IP). TCP/IP provides packet
27 ordering and re-transmission in the case of missing or corrupted packets. With a good communication
28 system, data will be delayed occasionally, but otherwise there will be no data loss apparent to the user.
29 With a degraded or overloaded system, data delay may become significant enough that TCP cannot recover
30 lost packets, which would result in longer outages while the system holds data waiting for recovery, and
31 perhaps re-synchronizes the data stream.

32 With UDP, data is sent to a destination, but there is no built-in ordering or recovery. Sometimes ordering
33 and re-transmission can be built into the application. UDP is used commonly with phasor measurement
34 systems since UDP is a one-way communication to the receiver(s), and therefore it is un-delayed and
35 simple.

36 With a good communication system, data will rarely be delayed and data loss will be less than 1 packet per
37 hour (in practical experience, these systems have been observed to run weeks without any data loss). The
38 overall performance is application-dependant, and the user will need to define acceptable levels of lost data
39 packets (i.e., occasional packet loss may be tolerated based on the application). If a general purpose
40 network is being used, there may be greater loss during periods of heavy use. Router or switch mis-
41 configuration problems can cause unresolved collisions resulting in high loss. A good commission or
42 maintenance testing will often identify key sources of configuration or data errors. A sound engineered
43 system with detailed engineering and design records provides means for guidance of the maintenance staff
44 to troubleshoot and expedite repairs, and helps in maintaining the system to meet overall performance
45 requirements.

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1 6.14 Record keeping

2 A permanent record of installation details and initial tests is important. The installation will normally have
3 formal drawings that include wiring and physical layout, but not necessarily details of scaling, ratios, and
4 settings. A clear record of settings is essential for checkout, verification, and ongoing maintenance. This
5 record must include all PT/CT scaling, method of synchronization and GPS clock accuracy, PMU
6 calibration factors, communication settings, triggers, limits, and recording parameters. It will be used and
7 confirmed during the checkout outlined above. Additional information such as cable type and length (signal
8 attenuation and delays), CT/PT/CCVT details, line or bus voltage source, etc., can help with ease in
9 troubleshooting. The record of initial tests can be used as a baseline during ongoing maintenance and
10 provides a baseline for problem resolution. Installation test records have also been used to identify whether
11 a particular issue/feature was tested initially, or if a problem is introduced as the result of a change in the
12 system, or some kind of component failure.

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 Comment [ARG34]: This should be an Annex.
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7. Example of commissioning tests

7.1 Introduction

Figure A-15 shows test set-up for performance testing by a user. The test setup uses 1 PPS signal from GPS to synchronize the 3-phase signal generator and produce -90 positive sequence angle when the positive zero crossing of A-phase is aligned with this 1 PPS. At nominal frequency of 60 Hz this zero crossing does not change (nor does it change for exact integer off-nominal frequencies of 61 Hz or 59 Hz etc.).

Deleted: Manitoba Hydro performed field tests on its Dorsey PMU on March 9, 2007. The results are shown here.
 Deleted: The test setup used for the PMU Performance tests is shown in Figure 15.

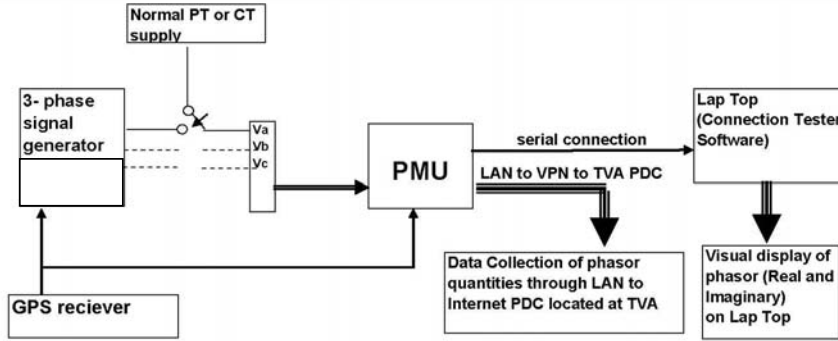


Figure A-15—PMU performance test setup

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The connection tester software shown acted like a local PDC and was used to confirm correct expected magnitudes and angles. Final results were taken from the PDC located at Tennessee Valley Authority (TVA) in order to include all delays, including any delays within the network. The results of the tests are described in the following section.

Deleted: The test setup uses 1 PPS signal from GPS to synchronize Doble Test Set software and produce -90 positive sequence angle when the positive zero crossing of A-phase is aligned with this 1 PPS. At nominal frequency of 60 Hz this zero crossing does not change (nor does it change for exact integer off-nominal frequencies of 61 Hz or 59 Hz etc.).

7.2 Steady-state tests

The results are for a 230 KV bus voltage, and the positive sequence angle is taken for various initial angles of Va.

Deleted: the MBHydro PMU located at the Dorsey station on their

For Va = 0 degrees the pos sequence angle is -90.36782837 (expected -90 degrees according to the defined phasor in C37.118) as shown in Figure A-16. The error is 0.36782837 degrees.

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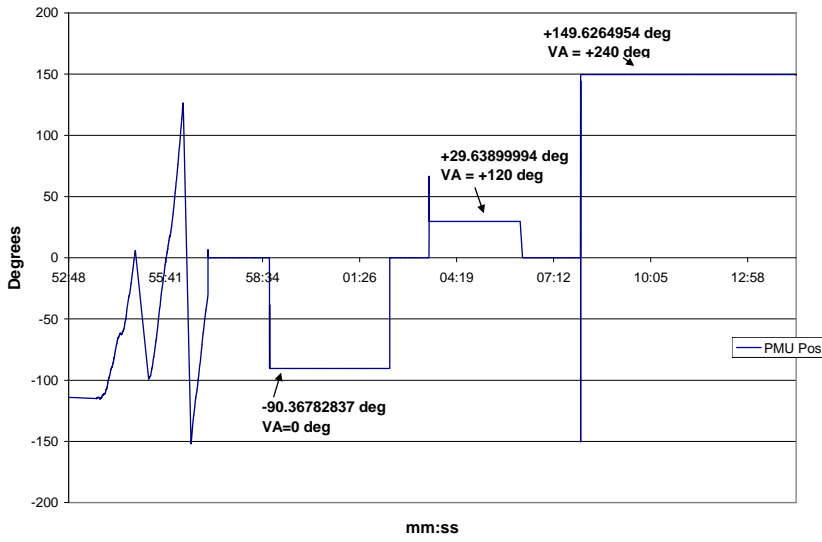
Similarly for Va = 120 degrees the angle is +29.63899994 degrees (expected 30) and for Va=240 degrees the angle is 149.6264954 degrees (expected 150). A close-up of the angle for Va=0 is shown in Figure A-17.

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PMU Positive sequence

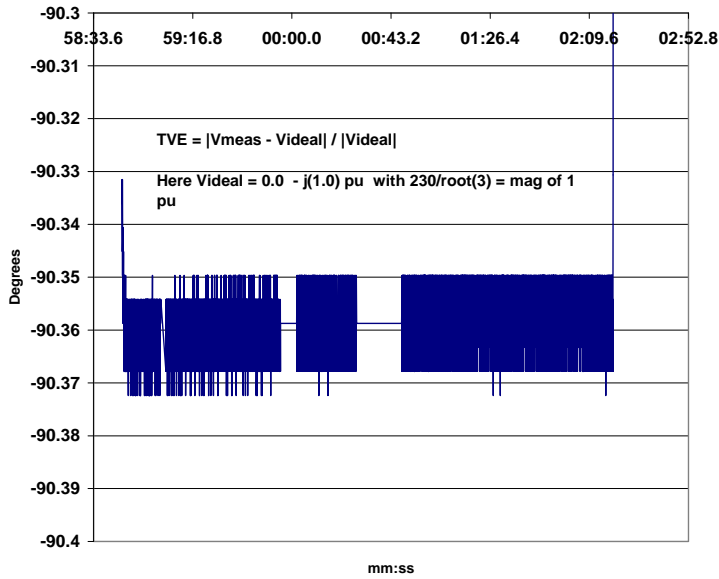


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Figure A-16—Phasor outputs positive sequence angle as VA is rotated

Positive Sequence angle with VA = 0 Degrees,

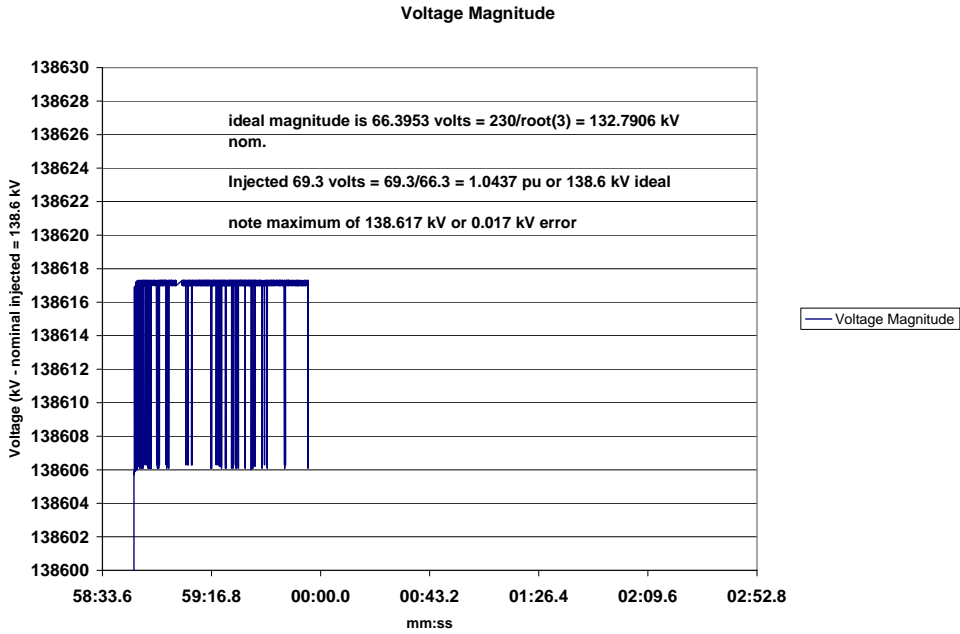


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Figure A-17—Phasor output angle closeup for VA=0 degrees

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Figure A-18—Phasor output magnitude closeup

The voltage magnitude for the injected voltage of 69.3 V was expected to be 138.6 kV and was found to be a maximum of 138.617 or an error of 0.017kV.

The maximum error in the vector for positive sequence is 138.617 kV and an angle of -90.37 degrees or 0.006486545700177 - 1.004450070277750j compared to an ideal = 0.00-1.00j or 138.6 kV and an angle of -90.0 degrees.

This compares well to the C37.118 Standard. Note that the standard does not include errors in the field which are outside of PMU device itself (i.e., these field result errors are what is termed full-scale tests that do not separate the time tagging error and the angle accuracy), which sets a maximum error on angle of 0.57 degrees and a voltage error of less than 1.0%.

$$TVE = \sqrt{\left[\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^2 + X_i^2} \right]} = 0.007866282514468 \text{ or } 0.8\%$$

This measurement can be averaged over the number of times the test was performed by:

$$TVE = (1/N) \sum_n \left[\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^2 + X_i^2} \right] n = 1, 2, \dots, N$$

Here TVE based on the three measurements of positive sequence voltage and angle (i.e., Va=0 deg., Va=120 deg., and Va=240 deg.) is 1/3(0.7866%+0.772300%+0.7866%) = 0.781852% or approx. 0.8%

7.3 Dynamic tests

The same setup as in [Figure A-15](#), was used for dynamic tests, but synchronizing the start of the test was more difficult. It was attempted to record the GPS time in an effort to retrieve the data for the start of the step changes. By examining the frequency and magnitude test results, it was possible to see when the tests

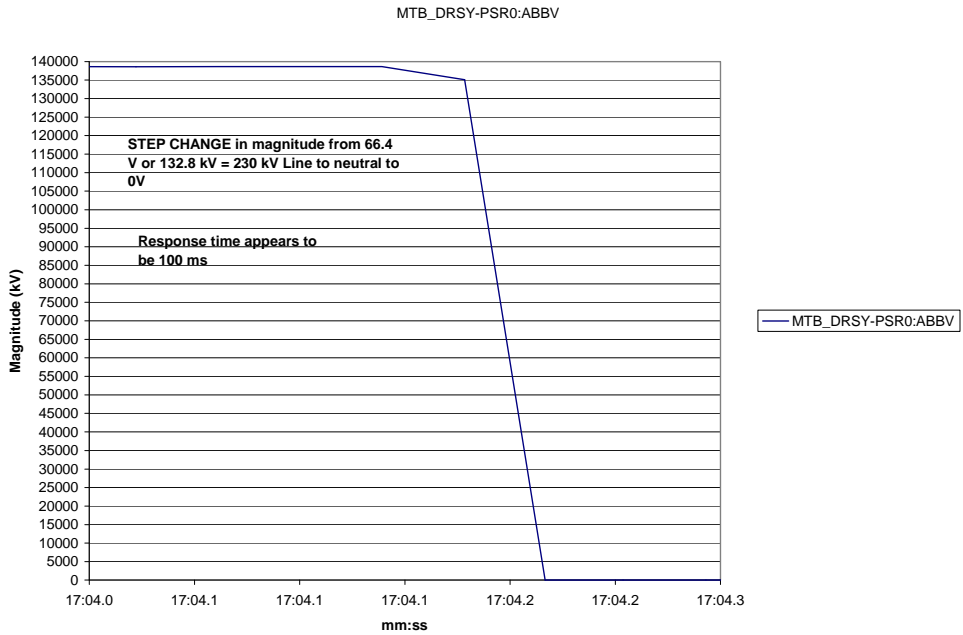
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1 occurred, but their time values did not exactly match our recorded GPS times. The tests were able to be
 2 aligned and produce the valuable information shown in [Figure A-19](#).



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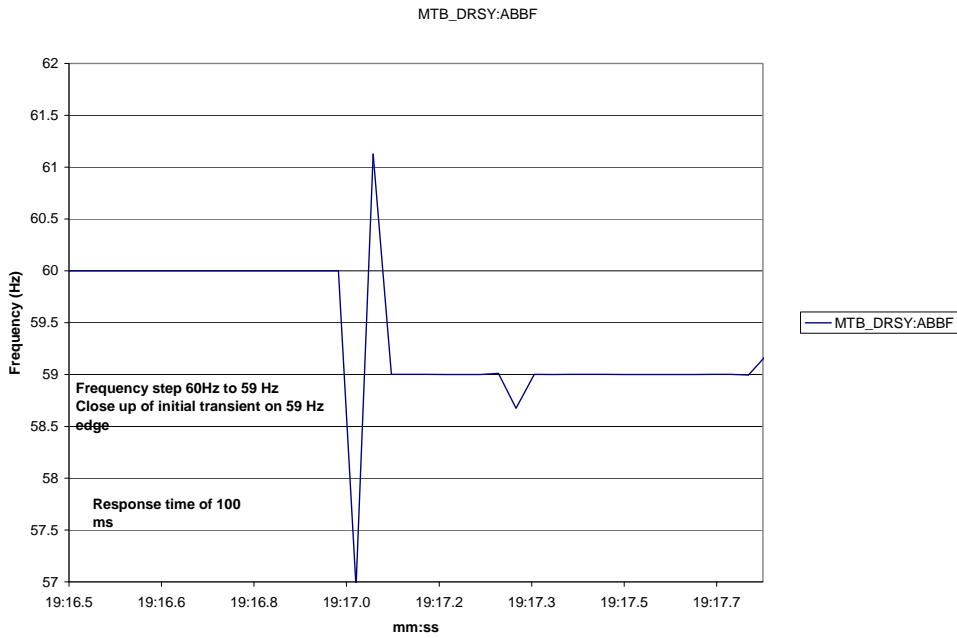
4 **Figure A-19—Step change in magnitude on all three phases from 230 kV L-L nominal (66.4**
 5 **V L-N injected) to 0kV (0V injected)**

6 In [Figure A-19](#), the response time appears to be about 100 ms. The recorded GPS time of the test was
 7 15:17:15 and the chart shows the test at 15:17:04, so it is not clear why the mismatch. There could be an
 8 additional delay before the signal begins to ramp down (inherent to network). Once the signal begins to
 9 ramp, though, it is possible to determine that the response time is 100 ms. A positive step exhibited a
 10 similar response.

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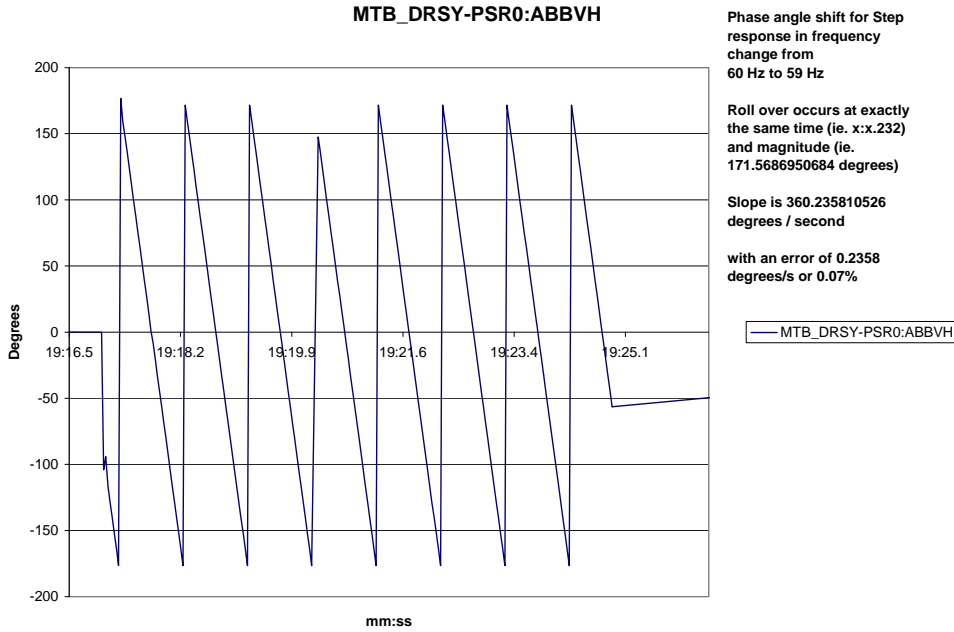
Figure A-20—Step change if frequency on all three phases from 60 Hz to 59 Hz

If frequency on all three phases from 60 Hz to 59 Hz, [Figure A-20](#), shows evidence of some initial overshoot, and then a quickly damped oscillation to the final value of 59 Hz. The response time to get to with 99% of 59 Hz is about 100 ms.

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Figure A-21—Absolute phase angle in degrees is plotting while at 59 Hz

Figure A-21 shows absolute phase angle in degrees is plotting while at 59 Hz. The rollover can be seen to occur at exactly the same time xx:xx.x.232 seconds and the magnitude of the phase angle after each roll over is the same at 171.5686950684 degrees. This shows good accuracy of the PMU. Also the slope is 360.235810526 degrees/second with an error of only 0.07%.

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7.4 Conclusion

The PMU installed is meets the criteria of C37.118 even with any extra delays inherent from network or field. The TVE is about 0.8% and the dynamic response appears to be within 100 ms. PT and CT error would add to the error shown here and has not been evaluated.

1 **8. PMU system testing and calibration guide**

2 **8.1 Overview**

3 This section describes test and calibration procedures for Phasor Measurement Units (PMU) used in the
4 electric power industry to monitor the condition of the electric power grid. The performance tests include
5 those specified in IEEE Standard C37.118-2005 and the extensions being developed in the 2012 revisions
6 C37.118.1 and C37.118.2. References to the IEEE C37.118-2005 are referred to as the Standard.
7 References to the proposed IEEE C37.118.1-2012 and the IEEE C37.118.2-2012 revisions are referred to
8 as the Proposed Standards.

9 The purpose of this section is to provide a basis for comprehensive testing of PMUs. The testing shall
10 provide characterization of PMU measurements under a wide variety of conditions suitable for most
11 deployments. There may be some specialized deployments that will require specialized tests which are not
12 covered by this section. This section covers all tests required for conformance to the standards and
13 proposed standards, and some tests which are not required but are useful during PMU algorithm design.

14 **8.2 Objective of testing**

15 **8.2.1 Compliance**

16 Specific testing is required to claim conformance to C37.118-2005, PC37.37.118.1 and PC37.118.2 as
17 specified by the standards:

18 Documentation shall be provided by any vendor claiming compliance with C37.118.1 Standard that shall include
19 the following information:

- 20 1) Performance class
- 21 2) Measurements that meet this class of performance
- 22 3) Test results demonstrating performance
- 23 4) Equipment settings that were used in testing
- 24 5) Environmental conditions during the testing
- 25 6) Error analysis if the verification system is based on an error analysis as called for above

26 Compliance certification is by PMU and class of performance. All signals supplied under a particular class of
27 service must meet the compliance requirements under the specified class of service to qualify the PMU as
28 compliant.

29 **8.2.2 Manufacturing**

30 When a PMU is manufactured, functional testing of the PMU is conducted to ensure that no manufacturing
31 defects have caused the device to deviate from the intended design.

32 **8.2.3 Installation and commissioning**

33 Testing a PMU following installation is needed to ensure that the PMU is configured as intended and has
34 been installed correctly.

35 **8.2.4 Periodic maintenance**

36 Installed PMUs are periodically tested to ensure that the PMU performance has not deviated beyond
37 required performance limits over the course of its service history. Periodic maintenance also verifies that
38 the PMU configuration has not changed from the intended and documented configuration.

1 8.3 Types of tests

2 As with other power system protection and control devices, PMUs must undertake various types of tests to
 3 ensure reliable and suitably accurate operation in the installed system. These tests include a thorough
 4 conformance test, which typically includes electrical, environmental, mechanical, and performance
 5 conformance tests for each new model of PMU. Factory acceptance tests ensure a manufactured product
 6 performs as designed. Field acceptance tests (commissioning tests), and periodic maintenance tests ensure
 7 PMUs are configured and perform as desired in the particular installation. These tests shall follow the
 8 requirements and procedures of the relevant international, national and industrial standards and guidelines
 9 where applicable. The application of a PMU has some unique requirements:

- 10 • High accuracy of time synchronization of the measurement results and time tagging.
- 11 • Unified performance of all PMU units across an installed system.
- 12 • Interoperability of PMUs and other PMU system components, such as Phasor Data
 13 Concentrators (PDC).

14 These unique requirements demand a comprehensive set of functional performance, conformance and
 15 interoperability tests to be conducted, employing a well defined test approach to ensure that the
 16 performance of an installed PMU system can meet its desired objectives and allow products from various
 17 vendors to be integrated into the PMU system. The descriptions of different types of tests in this document
 18 focus on the conformance and functional performance tests that are unique to PMUs and Synchrophasor
 19 measurement devices. The conformance tests are designed to verify whether the PMU meets the
 20 requirements of C37.118 (-2005, .1 and/or .2) under steady-state and transient and dynamic power system
 21 conditions. For other standard tests, such as electrical, environmental and mechanical tests, please refer to
 22 the relevant international, national, and industrial standards and guidelines as listed in the references.

23 8.4 PMU conformance tests

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

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29 The description of the PMU conformance tests in this guide includes performance and interoperability
 30 conformance tests that are unique to PMU and Synchrophasor measurement devices. The conformance
 31 tests are performed to verify whether a PMU or a Synchrophasor measurement device meets the
 32 requirements of IEEE C37.118-2005 Standard and/or PC37.118.1 and PC37.118.2.

33 8.4.1 PMU message protocol conformance test

34 To ensure the interoperability of different PMU models, a message protocol conformance test will be
 35 performed to confirm all configuration/command/data frame implementations of a PMU conform to the
 36 C37.118 and/or PC37.118.2 Standard message frame definitions.

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37 If manufacturer/user custom control/data message frames are defined, they shall be verified according to
 38 agreements between manufacturers and users.

39 8.4.2 PMU performance conformance test

40 The IEEE C37.118 Standard defines the TVE metric, and establishes the level 0 and level 1 performance
 41 compliance requirements under steady-state conditions. PC37.118.1 establishes M-class and P-class

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1 performance compliance requirements under steady-state as well as transient and dynamic conditions.
 2 Consistent performance among all PMUs in an interconnected system is of great importance for
 3 interoperability.

4 This document describes the purpose of each performance conformance test and the requirements of the
 5 test. Performance tests are divided into steady-state and dynamic tests, latency and time quality tests.
 6 Steady-state tests are defined as tests where the magnitude and frequency of the test signals do not change
 7 during an individual subtest. Otherwise, a test will be considered as a dynamic test.

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

10 **8.4.2.1 Initial functionality verification**

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

13 **8.4.2.2 Basic functionality test**

14 The basic functionality of a PMU device must be verified at all reporting rates under the following
 15 conditions:

- 16 • Pure sinusoidal input signal (THD < 0.1%).
- 17 • Input signal frequency at rated 50 Hz and/or 60 Hz system frequency.
- 18 • Balanced three-phase input signal.
- 19 • Single-phase input signals.
- 20 • Input signal is synchronized to produce known phase angles for each reported phasor.
- 21 • PMU must report correct phasor values in the above tests with TVE less than 1% as specified in
 22 C37.118. Additionally, the out-of-band interference test shall be run to verify the filters at each
 23 Standard required reporting rate.

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

26 **8.4.2.3 Steady-state performance conformance test**

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

29 The steady-state performance conformance test shall be performed according to the signal range and test
 30 conditions specified in C37.118 Table 3. Additionally this guide presents a test plan for a Phase or
 31 Magnitude Unbalance test.

32 It is common practice to verify manufacturer-specified steady-state performance of a PMU in extended
 33 signal ranges and test conditions according to manufacturer's own specifications, or agreement between the
 34 manufacturer and users.

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1 **8.4.2.4 PMU performance conformance levels**

2 In order for a PMU to conformance to IEEE C37.118:1-2012, it must be classified by performance class (M
3 or P). The P or M performance level is to be specified for each data reporting rate that a PMU supports.

4 **8.4.3 Integrated PMU (IPMU) device performance test**

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

- 7 • That operation of other functions will not cause interference, degradation and disruption of the
8 performance of the PMU function under all operating conditions.
- 9 • That the PMU function will not cause interference, degradation and disruption to the performance
10 of other functions under all operating conditions.
- 11 • That the actual range of input signals for an IPMU is determined by (1) the types of transducers
12 dictated by its primary functions, and (2) the C37.118 required signal range for phasor
13 measurement.

14 **8.4.4 Certification of conformance**

15 Certification of conformance will only be issued to PMUs fully conformed to the requirements of the
16 Standard, C37.118-2005, or the proposed standards, C37.118.1-~~2012~~ and ~~2-2012~~, accompanied by a
17 detailed test report. Both certification of conformance and the test report will declare that all tests were
18 conducted in full compliance with the test requirements and test procedures specified in the standard or
19 proposed standard, and that the tests were performed by qualified test laboratories. The test report must
20 contain a detailed description of each test conducted, test equipment used, test setup description, test
21 conditions, and test results.

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22 **8.5 Interoperability test**

23 PMUs and all other system components that communicate with each other, such as PDCs from different
24 manufacturers, must conform to the same protocol specified by IEEE C37.118.2-~~2012~~ standard through
25 protocol conformance tests. Protocol conformance is the basis for all system components to be
26 interoperable with each other. An interoperability test shall also be conducted for PMUs, PDCs and other
27 system components with custom-defined protocols, if any.

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

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

35 **8.6 Factory acceptance test**

36 PMUs are considered as protection, control, and networking devices. Each PMU unit passes a proper
37 factory acceptance test program to detect any manufacturing defects. In addition to electrical,
38 environmental and mechanical tests, each PMU must be verified in the Factory Acceptance Test that it can:

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- 1 • Correctly receive the synchronized timing signal according to the specifications (e.g., correct
- 2 reception of GPS signals under specified signal strength).
- 3 • Sending/receiving configuration/command/data frames according to protocols defined in
- 4 C37.118.2-~~2012~~.
- 5 • Meet phasor measurement performance requirements at a selected set of test conditions within the
- 6 specifications of C37.118.1-~~2012~~.

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7 **8.7 Field tests**

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

10 **8.7.1 Field commissioning test**

11 Field commissioning test will be conducted after a PMU is installed.

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12 As with any other digital IEDs installed in the substations, the PMU field commissioning test must include
 13 routine visual inspection, insulation test, wiring check, basic functionality check, etc., as required by the
 14 relevant standards, such as 2003 NETA Acceptance Testing Specifications for protection and control
 15 equipment.

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16 In addition, PMU field commissioning test will verify the following:

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- 17 • Phase A designation verification and confirmation.
- 18 • Correct phase sequence verification.
- 19 • Correct phasor magnitude measurement verification.
- 20 • Synchronized timing source verification (e.g., GPS signal strength and reception meet the
- 21 specification).
- 22 • Data and control frames sending/receiving verification.

23 PMUs are not usually deployed as independent measurement devices. A typical PMU system typically
 24 consists of many PMUs and one or more PDCs. Once a PMU passes the above basic tests and its proper
 25 communication with PDCs are established, further system integration tests are conducted as a part of the
 26 PMU field commissioning tests. The system integration tests verify the following:

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

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1 8.7.2 Periodic maintenance test

2 Performance of a PMU must be checked periodically to ensure it has not been changed and deteriorated.

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3 8.8 Test equipment

4 This section describes the test equipment used to perform the tests. Test equipment will generally be in one
5 of the following categories:

- 6 • Full-featured calibration laboratory equipment: Specialized test instruments developed and
7 adapted specifically for PMU testing. These will be systems made from general or specially
8 developed hardware, hand-tuned and controlled for testing. This setup will be equipped with the
9 best possible clock reference and precise time synchronized waveform generation devices.
10 Design and documentation of the collective test system must demonstrate traceability to National
11 Standards. Synchrophasor standards require uncertainty less than 25% of the allowed error.
12 However, it is generally recommended that uncertainty of test equipment shall be less than 10% of
13 the allowed error (e.g., if a TVE of 1% is allowed for a PMU, the test setup used to examine the
14 accuracy of that PMU should have traceable uncertainty of better than 0.1%).
- 15 • Standard test equipment: General purpose laboratory and test equipment that can be used to test
16 PMU functions. It should be 4 to 10 times more accurate than the test tolerance, but this will vary
17 depending on the circumstance. These test setups may be used in a laboratory or field location.
18 They must be calibrated against a standards laboratory, which will have the full-featured test
19 equipment and calibration method well defined and repeatable.

20 8.8.1 Time reference

21 Test equipment needs to be accurately synchronized to UTC. PMUs make measurements relative to UTC,
22 and the test equipment needs to use that same reference to confirm measurements. Description of the time
23 reference can be found in other sections of this document.

24 8.8.2 Steady state signal sources

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

28 8.8.2.1 Steady state magnitude

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

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31 8.8.2.2 Steady state phase

32 The voltage and current phases must be known relative to a cosine wave of the nominal frequency (50 Hz
33 or 60 Hz) synchronized to the on time second of UTC. This phase is referred to as absolute phase angle.
34 The absolute phase angle of the test voltage must be known for each report time (i.e., the times the PMU
35 assigns to its phasor measurements). The absolute phase angle must have an uncertainty of less than 1 mrad
36 (0.057 degrees) relative to the specified test phase, or alternatively the absolute phase angle of the test
37 signal must be known with an uncertainty of less than 1 mrad (0.057 degrees).

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1 **8.8.2.3 Steady state balance**

2 The three-phase voltages and currents of the test signal source should be known to better than 0.1%. For
3 balanced tests, the magnitude of the zero sequence and negative sequence should each be less than 0.3%.

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4 **8.8.2.4 Steady state frequency and rate of change of frequency**

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

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7 **8.8.2.5 Steady state harmonics**

8 The test signal generator must be capable of generating multiple harmonics from the 2nd though the 50th
9 harmonic of the nominal frequency. The magnitude of the harmonics must be at least 10% of the magnitude
10 of the nominal input magnitude. These signals must be generated in conjunction with a signal at nominal
11 magnitude and frequency.

12 **8.8.2.6 Steady state out-of-band interfering signals**

13 The test signal generator must generate out-of-band interfering signals (interharmonics) with frequency
14 from 0.1 Hz up to the Nyquist frequency of the highest reporting rate to be tested. The magnitude of the
15 interharmonics must be up to 10% of the magnitude of the nominal input frequency. These signals must be
16 generated in conjunction with a signal at nominal magnitude and frequency.

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17 **8.8.3 Dynamic signal sources**

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

21 **8.8.3.1 Amplitude and phase modulation**

22 During the dynamic compliance measurement bandwidth test, the magnitude of the fundamental phasor
23 should have an uncertainty of less than 0.2% of the nominal magnitude and the phase uncertainty should be
24 less than 2 mrad (0.12 degrees). The magnitude of the modulation should have an uncertainty of less than
25 0.2% of the nominal magnitude. The phase of the modulation should have an uncertainty less than the
26 equivalent of 1 ms. The frequency of the fundamental should have an uncertainty of less than 0.5 mHz and
27 the rate of change of the frequency should have an uncertainty of less than 10 mHz per second.

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28 **8.8.3.2 Frequency ramp**

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

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33 **8.8.3.3 Magnitude step**

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

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1 8.8.3.4 Phase step

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

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7 8.8.4 Equipment calibration

8 Test equipment needs to be calibrated to reference standards. Established worldwide standards are
 9 maintained as a statistical reduction between first level physical standards maintained by designated
 10 standards laboratories worldwide. First level standards are compared with each other using a suitable
 11 device that can be exchanged between laboratories. Each laboratory makes measurements before and after
 12 exchanging the device and compares measurements with the other laboratories. Analyses of results show
 13 how close the reference at each laboratory is to the other. A statistical reduction of the measurements
 14 provides a true standard and an offset that each laboratory can use to correct their measurement to the
 15 standard.

16 PMU calibration has not reached the point of developing a worldwide standard or even recognized first
 17 level laboratories to maintain such a standard. Further, there is not yet consistent agreement on the
 18 measurements and tests that need to be performed to assure these measurements. However, many of the
 19 measurements are straightforward within the realm of current standard measurement. For assurance of the
 20 measurements particular to PMU technology, it is necessary to depend on a reference system suitably
 21 linked to first principles for which an estimate of accuracy has been determined by a suitable suite of tests.
 22 This then needs to be confirmed by comparison with tests done by other laboratories using the same or
 23 other methods. Once an acceptable reference has been developed, it can be used for calibration of other test
 24 systems using the transfer PMU as described above.

25 The National Institute of Standards and Technology in Gaithersburg, MD, USA, and several other
 26 laboratories have developed special tests for many of the PMU tests described in this guide. This is the start
 27 of a test verification process for a worldwide standard compliance for PMUs.

28 8.8.4.1 Steady-state signal calibration

29 The test system output can be calibrated under steady-state output conditions using standard reference
 30 instruments. Under steady state the test system must be capable of generating three-phase voltages and
 31 currents with set amount of balance and at varying frequency and amplitude. Voltage and current
 32 magnitude and frequency are well established measurements. Test system output shall be calibrated at
 33 suitable amplitude and frequency points using certified test instrumentation. Phasor Measurement Unit
 34 testing requires determining the voltage and current signal phase angles with respect to a UTC time
 35 reference which is unique to this technology. The following paragraphs describe two methods to assure this
 36 calibration.

37 Both calibration methods use a high speed/high resolution oscilloscope to compare the phase of a
 38 synchronized oscillator with a UTC synchronized clock signal, typically a 1 PPS signal. Since the rate of
 39 change of a nominal frequency (50 Hz or 60 Hz) signal is not fast enough to easily align with the 1 PPS
 40 signal, this first method uses a reference PMU that is capable of measuring the phase angle of signals with
 41 frequencies significantly higher than power line frequencies. It also requires that the signal generator will
 42 put out synchronized waveforms at much higher frequencies than the normal power signal. The second
 43 method is not as precise, but does not require a reference high frequency PMU nor a specialized multi-
 44 frequency signal source. These procedures take advantage of the fact it is easy to synchronize an
 45 oscilloscope (or counter) with a 1 PPS signal, and the time of a zero crossing of a sine wave can be more
 46 precisely determined than the time of a peak.

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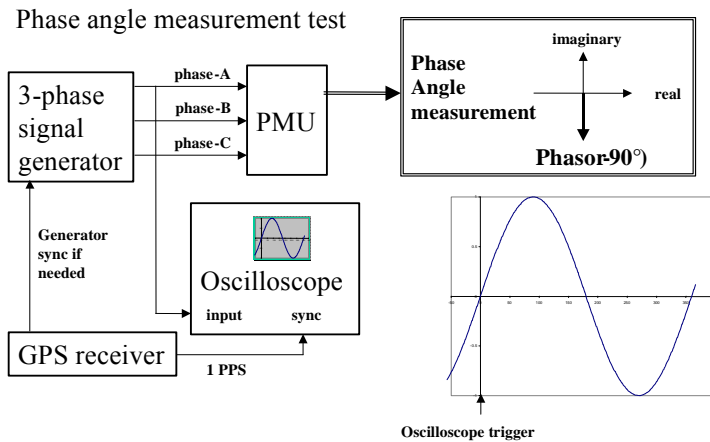
1 For the first method, assume the bandwidth of the reference PMU is 500 kHz. For each phase of the
 2 reference PMU, set the signal generator to 30 kHz, then adjust the phase of the signal so the positive zero
 3 crossing of the signal is aligned with the positive edge of the 1 pps signal. The signal phase angle measured
 4 by the reference PMU shall be -90 degrees. Note the difference in this measurement. Readjust the phase of
 5 the signal so the negative zero crossing of the signal is aligned with the positive edge of the 1 pps signal.
 6 The signal phase angle measured by the reference PMU shall be 90 degrees. The difference in this
 7 measurement shall be the negative of the first measured difference. The extent to which these differences
 8 are not the negative of each other indicates the presence of DC in the signal. Taking half the difference
 9 between these two test results, one can convert the angle to a time delay of the 30 kHz signal.

10 Repeat the above time delay determinations at 10 kHz, 3 kHz, 1 kHz and 500 Hz. Plot these time delays to
 11 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
 12 delay above power line frequencies. Apply this as a correction to the signal phase angles measured. Repeat
 13 the above procedure to demonstrate that with this correction the measured time delay at 30 kHz is now
 14 approximately 0 second. Use this data to analyze the uncertainty of the phase angles measured by the
 15 reference PMU. Note: the uncertainty in the time delay estimates for 10 kHz and 30 kHz will be the
 16 smallest. The lower frequency measurements will show more scatter, but look to see that there is no
 17 significant slope to this data.

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18 The second method is shown in Figure A-22. The test signal output is set to a $\pm 90^\circ$ phase angle output at
 19 the nominal system frequency. By the Synchrophasor standard, A-phase will have a positive zero crossing
 20 at a -90° phase angle and will have a negative zero crossing at a $+90^\circ$ phase angle. Use the synchronized 1
 21 PPS signal from a GPS source to trigger the trace on the oscilloscope. The signal source shall cross 0 V at
 22 the trigger point. At nominal system frequency (50 Hz or 60 Hz), the zero-crossing does not change. For off
 23 nominal frequencies, the angle changes constantly and may not align at the 1 PPS. However at exact integer
 24 frequencies off nominal (e.g., 49, 51, 59, 61) the zero crossing will be aligned with the 1 PPS, making this
 25 method of synchronization useable for checking phase over a band of frequencies. Use positive and
 26 negative zero crossings to average out DC offset as described above to improve accuracy.

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28 **Figure A-22—Phase calibration of reference PMU with the 1 PPS clock signal**

29 The principal problem with this method is that the zero crossing needs to be measured within a
 30 microsecond, and the slope of a 100 V_{peak} 60 Hz wave is 37.700 V/s or .037 V/ μ s. With the input set to
 31 input a 100 V signal, determining a zero crossing to within 1 μ s is not possible. If the oscilloscope limits
 32 input overload without distortion, the input can be amplified to show the waveform at a millivolt level so
 33 that the zero crossing can be clearly determined. Alternatively, a diode limiter can be used to reduce the

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1 voltage signal to a low level so that the 0 crossings can be seen clearly without overdriving the front end.
2 For observing the 0 crossings of the current signals, use a low resistance non-inductive shunt. In all cases,
3 care is required to prevent ground loops from distorting the signal.

4 It is important to note that oscilloscopes that have a low-resolution digital front end (7 or 8 bits) do not
5 allow an accurate location of the positive zero crossing. Any DC offset will also change the phase angle
6 based on zero crossing. With 8 bits full scale, the zero location could be off by 1 count out of +/-127. If the
7 full scale is +/- 100 V, this is about a .79 V error that is equivalent to about 10 μ s or about 0.22 degrees at
8 60 Hz. (1% TVE = 0.57 deg if magnitude is perfect). However, if the full scale is reduced to +/- 1 V, this is
9 about a .0079 V error that is equivalent to about 0.1 μ s or about 0.0022 degrees, which is insignificant.

10 **8.8.4.2 Dynamic signal calibration**

11 A stable and accurate signal source is required for dynamic signal production. It may not be possible to
12 measure the signal with standard calibration instruments during dynamic signal production. It is necessary
13 to rely on other confirmation methods such as analysis of the signal production equipment or a reference
14 PMU with known analysis capability.

15 The first method relies on analysis of the test equipment being used and the test methodology. In most
16 cases, dynamic signals will be produced by a test set that converts signals stored in a digital file to analog
17 signals using D/A converters. In this case, the accuracy of these reproduced signals can be assured by:

- 18 • Calibration of the D/A converters at magnitudes that cover the range that will be required.
- 19 • Calibration of the D/A output clock relative to time and frequency references.
- 20 • Characterization of the output frequency response allowed by D/A output filters.
- 21 • Accounting for loading effects such as cabling and test unit burdens.

22 This method depends on careful analysis of all these effects, and shall provide sufficient accuracy for
23 performing dynamic tests. Test equipment designed for performing dynamic test signals shall have
24 established performance characteristics and is a good choice for these measurements. A secondary method
25 of monitoring the test signals shall also be used, such as by recording the waveforms or comparing
26 measurement results with a PMU with previously established performance.

27 A second method of dynamic signal calibration uses both a stable signals source and a reference PMU to
28 determine the actual values of the phasors, frequency, and rate of change of frequency. This reference PMU
29 can be made up of a multichannel sampling system and appropriate software to calculate these quantities.
30 This system must be able to receive clock signals to determine the absolute time of each sample. Use of the
31 1 PPS signal and a 1 MHz or 10 MHz clock signal to synchronize the sampling to UTC is recommended.
32 Alternatively the system could read IRIG-B or similar timing codes to synchronize to UTC. The reference
33 PMU has to be itself confirmed using analytical methods to be sure it accurately determines the correct
34 phasor value from the analog signals, both for steady state and dynamically changing signals.

35 Modulated waveforms can be confirmed to be accurate by fitting synchronized samples of the signals to an
36 appropriate model. Stenbakken et al. 2008 describe two analysis models that fit the data. The first is the
37 Taylor expansion model that fits modulation frequencies from 0.1 Hz to over 1 Hz. The second is the three
38 waveform model that fits modulation frequencies from 1 Hz to over 70 Hz.

39 **8.8.5 PMU data communication and analysis**

40 PMU data communication includes transmitting PMU measurements and receiving PMU commands.
41 Various transmission methods, such as RS 232, RS 485, and Ethernet 10/100BaseT, and various
42 transmission protocols, such as TCP/IP and UDP/IP, are well-known methods. The test system needs to

1 have various communication capabilities available to communicate with different PMUs. At a minimum,
2 the test system shall be able to send commands and receive data using:

- 3 • RS232, BPS 19.2K to 57.6K, commanded or spontaneous
- 4 • 10/100BaseT using—TCP, TCP/UDP, or UDP (multicast, unicast), or spontaneous UDP
5 (multicast, unicast).

6 PMUs do not necessarily support all communication modes, so the test system must be able to be set up for
7 the particular DUT.

8 PMU latency testing requires determining the difference between the timestamp in a PMU message and the
9 time when the PMU outputs that message. To measure this time difference the test equipment receiving the
10 PMU messages must be able to timestamp the arrival of the PMU message relative to UTC. The time
11 uncertainty of the message receipt timestamp shall be less than 100 μ s.

12 8.8.6 Automated features

13 Test time can be substantially reduced if testing is automated. Test equipment could provide options for
14 performing automated testing (batch mode). The automation of testing shall include applying the signals,
15 waiting for the PMU measurement to settle, and measuring the responses. The results need to be stored in a
16 convenient way for later review.

17 8.9 Methods for performing the tests

18 This section provides recommendations for how the tests can be performed. This section is ordered
19 similarly to Section 5 of C37.118.1:2012, which specifies methods for determining Total Vector Error
20 (TVE), Frequency Measurement Error (FE), and Rate of Change of Frequency Measurement Error (RFE)
21 used to assess PMU performance in the various tests. This section goes on to present recommended test
22 procedures for steady state compliance, dynamic compliance, and reporting latency.

23 8.9.1 Total Vector Error, Frequency Error and Rate of Change of Frequency Error

24 8.9.1.1 Total Vector Error

25 The Total Vector Error (TVE) definition that IEEE C37.118.1:2012 describes can be rewritten as follows:

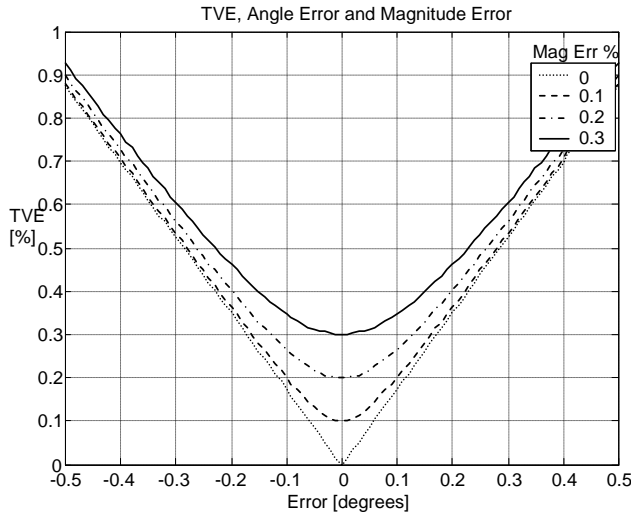
$$26 \quad TVE \equiv \frac{|\vec{V}_{Measured} - \vec{V}_{true}|}{|\vec{V}_{true}|}$$

27 Where:

28 \vec{V}_{true} is the true phasor

29 $\vec{V}_{Measured}$ is the PMU measured phasor

30 Notice that the measured phasor can be a voltage phasor or a current phasor. [Figure A-23](#), shows the
31 graphical representation of the true, measured, and error phasors, and relates TVE, magnitude error and
32 angle error in the same plot. The plot in this figure shows the expected TVE for angle errors from -0.5 to
33 0.5 degrees and magnitude errors of 0, 0.1, 0.2 and 0.3%.



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Figure A-23—TVE in percentage for angle errors of –0.5 to 0.5 degrees and magnitude errors of 0, 0.1, 0.2 and 0.3%.

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C37.118.1 specifies the minimum amount of time to take measurements: 5 seconds unless otherwise noted in the individual test. TVE shall be calculated for each measurement during this time. The error reported for the test shall be the maximum of these error values.

7

8.9.1.2 Frequency Error and Rate of Change of Frequency Error

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Frequency Error and Rate of Change of Frequency Error measurements are tested for accuracy using the following error definitions:

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13

$$FE = \text{Frequency Measurement Error} = |f_{\text{true}} - f_{\text{measured}}| = |\Delta f_{\text{true}} - \Delta f_{\text{measured}}|$$

$$RFE = \text{Rate of change of Frequency Measurement Error} = |(df/dt)_{\text{true}} - (df/dt)_{\text{measured}}|$$

Where:

14
15
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18

- The measured and true values are taken at the same instant of time
- Δf_{true} is the deviation of the true frequency from the nominal frequency
- $\Delta f_{\text{measured}}$ is the deviation of the PMU measured frequency from the nominal frequency
- $(df/dt)_{\text{true}}$ is the true rate of change of the frequency
- $(df/dt)_{\text{measured}}$ is the PMU measured rate of change of frequency

19

8.9.1.3 Reporting rates and reporting times

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

1 8.9.2 Test settling time

2 During PMU testing, the PMU may be subjected to non-system like changes in the input signals. This will
 3 require some settling time before test data is taken. This settling time will vary from PMU to PMU, ~~for~~
 4 ~~different~~ PMU settings, and on the type of signal presented by the test system. For some test systems the
 5 nominal test signal will be applied to the PMU before each test. Changes to the new parameter will be a
 6 change in signal magnitude, frequency, distortion, etc. For other test systems the signals may be set to zero
 7 before each test and the new signals applied as a step. For each such test condition transition the settling
 8 time of the PMU must be estimated.

9 This settling time can be provided by the manufacturer. Otherwise it can be determined by selective
 10 transition measurements on the PMU. The PMU settling time could be up to 2 to 4 seconds or as little as a
 11 few reports.

12 8.9.3 Steady-state compliance test plans

13 This section describes how to perform tests to assess steady-state compliance of a PMU. Suggestions for
 14 step-by-step methods to perform the tests (“Test Plans”) are below.

15 8.9.3.1 Steady state compliance

16 According to C37.118.1-~~2012~~, steady state compliance shall be confirmed by comparing the phasor,
 17 frequency, and ROCOF estimates obtained under steady-state conditions to the corresponding input values
 18 and calculating TVE, FE, and RFE as defined above. *Steady-state conditions* are where X_m , ω , and ϕ of the
 19 test signal, and all other influence quantities, other than the quantity being tested, are fixed for the period of
 20 the measurement. Note that for off-nominal frequencies, the measured phase angle will change at a rate
 21 proportional to the difference in frequency between the applied signal and the nominal frequency, 50 Hz or
 22 60 Hz.

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23
 24 The steady state compliance tests are specified by C37.118.1-~~2012~~. Influence quantities, minimum range of
 25 influence quantities, and limits for performance of P and M class PMUs are found in the standard and will
 26 not be repeated in this guide. Testers must refer to the Standard for the latest required limits.

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27
 28 The influence quantities are:

- 29 • Signal frequency (range)
- 30 • Signal magnitude: voltage
- 31 • Signal magnitude: current
- 32 • Phase angle
- 33 • Harmonic distortion
- 34 • Out of band interfering signals

35 For each parameter of an influence quantity (e.g., frequency tested in frequency variation tests) determine
 36 the magnitude error, phase error, FE, and RFE at each timestamp. Calculate the TVE at each timestamp.
 37 Over the time specified for the test, calculate the maximum, minimum, mean, and standard deviation of
 38 these errors. These statistics can be plotted versus the parameter values tested. Use the largest maximum
 39 error for the range of parameters to compare with the test requirements.

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1 **8.9.3.1.1 Frequency variation compliance**

2 For certification of compliance, C37.118-1 requires that the signal frequency compliance tests be
 3 performed over the given ranges and meet the given requirements at three temperatures: T = nominal (~23°
 4 C), T = 0° C, and T = 50° C.

5 This is a series of subtests where magnitudes are held at nominal and frequency is changed by 0.1 Hz
 6 between each test. The first subtest is at nominal frequency minus the bandwidth range limit, and the last
 7 test is at nominal frequency plus the bandwidth range limit. These bandwidths are listed in Table A-VII in
 8 the column bandwidth for each reporting rate, Fs.

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9 See C37.118.1 Tables 3 and 4 for the required TVE, FE, and RFE limits for the given Fs, where Fs
 10 is the reporting rate.

- 11 a) Begin at the frequency range: nominal minus the range limit.
- 12 b) Wait for the system to settle.
- 13 c) Capture the PMU output for 5 seconds.
- 14 d) Calculate the Max TVE, FE and RFE.
- 15 e) Increase the frequency by 0.1Hz.
- 16 f) Repeat steps b through e until the upper frequency range limit is reached.
- 17 g) Compare the results to the class limits in C37.118.1.
- 18 h) Place the PMU into a temperature chamber set to 0°C. Allow PMU to reach temperature
 19 equilibrium within 1°C.
- 20 i) Repeat steps a through g.
- 21 j) Set temperature chamber to 50°C. Allow PMU to reach temperature equilibrium within 1°C.
- 22 k) Repeat steps a through g.

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23 **8.9.3.1.2 Steady state magnitude compliance: voltage and current**

24 For both current and voltage input ranges, apply steady state, nominal frequency (50 Hz or 60 Hz),
 25 balanced three-phase inputs. Compare accuracy of measurement with input. The test signals must be
 26 calibrated or measured to be within 0.1% of reading. Full scale shall be somewhat above the nominal input
 27 level. Nominal values will be determined by the application, but for test purposes will be 70 V rms or 120
 28 V rms for voltage, and 5 A rms for current unless other values are specified. Depending on the level or
 29 class the PMU must operate over a range of voltages and currents relative to the nominal values. See
 30 C37.118.1 Tables 3 and 4 for magnitude values and test limits.

31 Test Magnitudes: Nominal, Vmin % to Vmax % of nominal for voltage
 32 Nominal, Imin % to Imax % of nominal for current.

- 33 a) Begin at the low magnitude limits (Vmin % of nominal voltage or Imin % of nominal
 34 current).
- 35 b) Wait for the system to settle (see PMU Settling Time).
- 36 c) Capture the PMU output for 5 seconds.
- 37 d) Calculate the Max TVE, FE and RFE.
- 38 e) Increase the input magnitudes by 10%.
- 39 f) Repeat steps b through e until the upper magnitude limits are reached.
- 40 g) Compare the results to the class limits in C37.118-1.

41

1 8.9.3.1.3 Phase angle compliance

2 For both current and voltage input ranges, apply steady state, nominal frequency (50 Hz or 60 Hz), at
3 nominal levels. The test signals must be calibrated or measured to within 0.057 degree.

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

- 5 a) Begin at nominal levels for all influence quantities.
- 6 b) Wait for the system to settle (see PMU Settling Time).
- 7 c) Capture the PMU output for 5 seconds.
- 8 d) Calculate the Max TVE, FE and RFE.
- 9 e) Increase absolute phase angle of all phases by 45 degrees.
- 10 f) Repeat steps b through e until 0 degrees has been reached.
- 11 g) Compare the results to the class limits in C37.118-1.

12 Alternatively, the phase test can be performed with f_{in} (input frequency) offset and $|f_{in} - f_0| < 0.25$ Hz to
13 provide a slowly varying phase. The phase errors of the phasors can be determined over several cycles of
14 the absolute phase angle. For example, the frequency can be set to 0.12 Hz above the nominal frequency
15 (50.12 Hz or 60.12 Hz) and measurements taken over 50 s. This data will cover six cycles of the absolute
16 angle. If the phase errors are plotted versus the true phase-A phase angles, the plot will show the angle
17 errors versus the true phase angle of $\pm 180^\circ$. During this test the maximum TVE, FE, and RFE must remain
18 within the required limit.

19 8.9.3.1.4 Response to harmonic distortion signals

20 Response to harmonic distortion is specified for 2nd harmonic to 50th harmonic. Testing reach harmonic
21 individually could be quite time-consuming, but response to harmonic distortion can be tested with both
22 individual and combined harmonics. Recommended practice is to test some harmonics at the bottom,
23 middle and top of the frequency range individually, and also to test all even harmonics and all odd
24 harmonics in combination.

25 **Table A-VI—Recommended harmonics for response to harmonic distortion testing**

2 nd	3 rd	4 th	5 th	15 th	16 th	31 st	32 nd	49 th	50 th	2 nd – 50 th combined	3 rd -50 th , odd only
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26

- 27 a) Begin at nominal levels for all influence quantities.
- 28 b) Inject into the voltage and current inputs a positive-sequence harmonic from the table above [with](#)
29 [the magnitude of each harmonic component set to the](#) level specified by C37.118:2012 for Class P
30 or M PMUs.
- 31 c) Wait for the system to settle (see PMU Settling Time).
- 32 d) Capture the PMU output for 5 seconds.
- 33 e) Calculate the Max TVE, FE and RFE.
- 34 f) Change to injecting the next harmonic or group of harmonics from [Table A-VI](#).
- 35 g) Repeat steps b through f until all harmonics and harmonic groups have been tested.
- 36 h) Compare the results to the class limits in C37.118-1.

37 *Optional:* repeat this test for input frequencies other than nominal such as $f_0 \pm 1$ Hz, within the rated input
38 frequency range of the PMU.

39 Test input: Both Voltage and Current.

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1 **8.9.3.1.5 Response to out-of-band interfering signals**

2 There are no requirements for Class P response to out-of-band interfering signals. This test is for Class M
 3 compliance only.

4 Out-of-band compliance (M class only) is to be checked with the frequency of the dominating signal
 5 components within the nominal system frequency $\pm (2/3)$ of the signal frequency range or bandwidth. See
 6 Table A-VII. The In band is defined as the frequency range from the nominal frequency minus half the
 7 reporting rate, $f_0 - F_s/2$, to the nominal frequency plus half the reporting rate, $f_0 + F_s/2$.

Comment [gns36]: This definition is needed so that the In band can be determined for reporting rates not specified in Table 7, such as 100 per second and 120 per second.

8 Out-of-band compliance can be confirmed by adding a single frequency sinusoid to the fundamental power
 9 signal at the required amplitude level and varying the frequency of this signal over the out-of-band range
 10 from below the In band (at least down to 10 Hz) to the second harmonic ($2 \times f_0$) for reporting rates up to 50
 11 per second or 60 per second. For higher reporting rates, such as 100 per second or 120 per second, start at
 12 the upper end of the In-band and inject frequencies up to f_0 higher. Thus, for reporting rates of 100 per
 13 second and 120 per second the testing will go from $2 \times f_0$ to $3 \times f_0$. If the positive sequence measurement is
 14 being tested, the interfering signal must be positive sequence. This test needs to be repeated three times
 15 with input signal (f_{in}) frequency at nominal (f_0), at $f_{in} = f_0 + 2/3$ the signal frequency bandwidth and at $f_{in} = f_0 - 2/3$ the signal frequency bandwidth. Table A-VII shows the bandwidth and the in-band range for each
 16 reporting rate, and nominal frequency. The in-band range is the range in which interfering signals will not
 17 be injected.
 18

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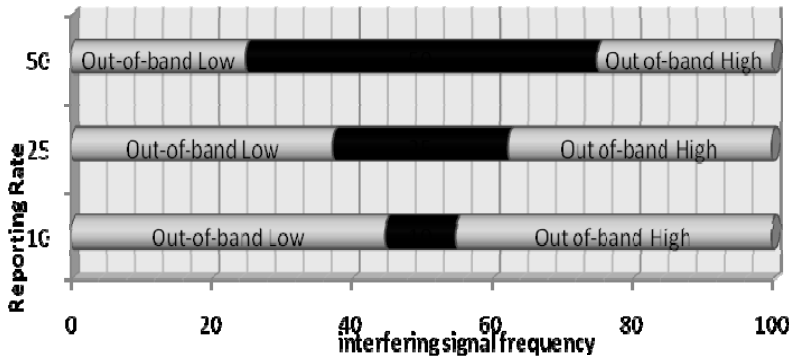
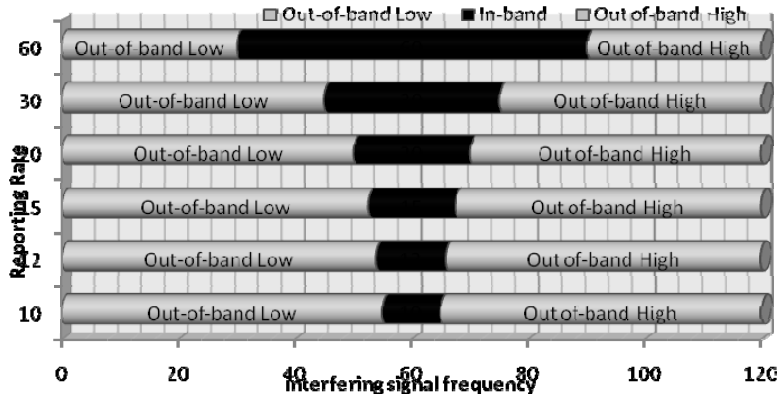
19 **Table A-VII—Out-of-band interference test with C37.118.1-2012**

60 Hz nominal				In band
F _s	Bandwidth	2/3 BW	F _s /2	F _{nom} = 60
10 or less	±2 Hz	±1½ Hz	5 Hz	55-65 Hz
12	±2.4 Hz	±1.6 Hz	6 Hz	54-66 Hz
15	±3 Hz	±2 Hz	7.5 Hz	52.5-67.5 Hz
20	±4 Hz	±2⅔ Hz	10 Hz	50-70 Hz
30	±5 Hz	±3⅓ Hz	15 Hz	45-75 Hz
60	±5 Hz	±3⅓ Hz	30 Hz	30-90 Hz
50 Hz nominal				In band
F _s	Bandwidth	2/3 FrqRng	F _s /2	F _{nom} = 50
10 or less	±2 Hz	±1½ Hz	5 Hz	45-55 Hz
25	±5 Hz	±3⅓ Hz	12.5 Hz	37.5-62.5 Hz
50	±5 Hz	±3⅓ Hz	25 Hz	25-75 Hz

20
 21 Interfering signals are not injected at the in-band frequencies above.

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3 Apply a steady state, balanced, three-phase signal to both current and voltage inputs, at nominal steady-
 4 state magnitude and nominal system frequency (50 Hz or 60 Hz). Inject into the voltage and current inputs
 5 a positive-sequence interharmonic at:

6 Frequency f_i where $|f_i - f_0| \geq F_s/2$

7 Where:

9 F_s is the reporting rate.

10 f_0 is the nominal frequency.

11 (f_i = finterharmonic is the frequency of the interfering signal frequency)

- 13 a) Add a 10 Hz interharmonic signal at 10% nominal magnitude to the nominal input signal.
- 14 b) Wait for the system to settle.
- 15 c) Capture the PMU output for 5 seconds.
- 16 d) Calculate the Max TVE, FE and RFE.
- 17 e) Increase the interharmonic frequency by 1Hz.
- 18 f) Repeat steps b through e until $f_i = f_0 - F_s/2$.
- 19 g) set $f_i = f_0 + F_s/2$.
- 20 h) Repeat steps b through e until $f_i = 2 \times f_0$.
- 21 i) Compare the results to the class limits in C37.118-1.

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- 1 j) Run the test two more times with input signal frequency at nominal frequency plus and minus 2/3
2 of the bandwidth.
- 3 k) Odd reporting rates (15 and 25 Hz) will not have been tested with interharmonics at the bandwidth
4 corner frequencies. For those reporting rates, test two more times with interharmonics at the corner
5 frequencies. See [Table A-VII](#) for the corner frequencies. [For example, at a nominal frequency of 50](#)
6 [Hz and a reporting rate of 25 per second, the corner frequencies are 37.5 Hz and 62.5 Hz.](#)
- 7 Test input: Both Voltage and Current.

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8 8.9.3.2 Unbalanced three-phase signals

9 Unbalanced tests are not required by C37.118:2012 draft. Since unbalance only applies to sequence
10 components of a polyphase system, it is not included in the standard where the requirements apply to both
11 single phase and sequence components. It is generally agreed that unbalanced testing is good to do but is
12 not required for certification. This section describes methods for performing unbalanced three-phase signal
13 test.

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14 8.9.3.2.1 Response to unbalanced signals, phase and magnitude

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

21	Test imbalances:	magnitude +/- 10%, and +/-20% on one phase only, and
22		phase $\pm 60^\circ$, $\pm 40^\circ$, and $\pm 20^\circ$ on one phase only.
23	Test frequencies:	49, 50 Hz. (nominal frequency 50 Hz)
24	Test frequencies:	59, 60 Hz. (nominal frequency 60 Hz)
25	Test input:	Both voltage and Current.

26 8.9.4 Dynamic compliance tests

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

29 8.9.4.1 Dynamic compliance – measurement bandwidth

30 The measurement bandwidth shall be determined by applying sinusoidal amplitude and phase modulated
31 signals to the PMU. This shall be done by applying the modulation applied to balanced three-phase input
32 signals (voltages and currents) with simultaneous modulation applied to signal amplitudes and phase
33 angles. Mathematically the input signals may be represented by:

$$34 \quad X_a = X_m [1+k_x \cos(\omega t)] \times \cos [\omega_0 t + k_a \cos(\omega t - \pi)]$$

$$35 \quad X_b = X_m [1+k_x \cos(\omega t)] \times \cos [\omega_0 t - 2\pi/3 + k_a \cos(\omega t - \pi)]$$

$$36 \quad X_c = X_m [1+k_x \cos(\omega t)] \times \cos [\omega_0 t + 2\pi/3 + k_a \cos(\omega t - \pi)]$$

37
38 where:

39 X_m is the peak amplitude of the input signal
40 ω_0 is the nominal power system frequency in radians per s ($2 * \text{Pi} * f_0$)
41 ω is the modulation frequency in radians per s

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1 $f_m = \omega/2\pi$ is the modulation frequency in Hz
 2 k_x is the amplitude modulation factor
 3 k_a is the phase angle modulation factor
 4 t is time

6 $k_x = 0.1$ and $k_a = 0.1$ for combined phase and amplitude modulation tests
 7 $k_x = 0.0$ and $k_a = 0.1$ for phase modulation tests

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8 For class P and M, the modulation frequency shall range as specified in C37.118.1-2012.

- 9 a) Begin with combined phase and amplitude modulated input at $\omega = 0.1$ Hz.
- 10 b) Wait for the system to settle (see PMU Settling Time).
- 11 c) Capture the PMU output for at least 2 full cycles of modulation.
- 12 d) Calculate the Max TVE, FE and RFE.
- 13 e) Increase the modulation frequency ω by 0.2Hz
- 14 f) Repeat steps b through e until the upper frequency range limit is reached.
- 15 g) Compare the results to the class limits in C37.118.1.
- 16 h) Repeat the entire test for phase modulation only.

17 The IEEE Standard only prescribes these combined amplitude-phase and phase only tests. However, an
 18 amplitude only test may be useful to observe if there is an effect on the frequency measurement due to
 19 processing issues in the PMU. Adding this test is an option to consider.

20 **8.9.4.2 Dynamic compliance – performance during ramp of system frequency**

21 PMU performance during system frequency change is tested with a ramp of frequency applied to balanced
 22 three-phase input signals (voltages and currents). ~~Optionally, a~~ harmonic ~~can be~~ added to a second ramp
 23 test.

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- 24 • The ramp rate shall be as specified by C37.118.1-2012.
- 25 • The ramp range for class P and M class shall be as specified by C37.118.1-2012.

26 For $F_s = 12$ FPS, Ramp range shall be $\pm 2 \frac{1}{3}$ (two and one-third) Hz to allow for an integer number of
 27 samples in the result.

28 Note that the allowed TVE may be exceeded during a “transition time” when a change is made to the
 29 applied rate-of-change-of-frequency, ROCOF. A time period of two sample periods after any change in the
 30 test ROCOF shall not be included in the TVE calculation for the test. An example of this transition time is
 31 when the ROCOF is changed from a 0 Hz/s value to a ramp at 1 Hz/s. The test shall not include frequency
 32 discontinuities (frequency steps or rate of change of frequency steps).

33 Mathematically, the input signals may be represented by:

34 $X_a = X_m \cos [\omega_0 t + \pi R_f t^2]$
 35 $X_b = X_m \cos [\omega_0 t - 2\pi/3 + \pi R_f t^2]$
 36 $X_c = X_m \cos [\omega_0 t + 2\pi/3 + \pi R_f t^2]$

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37 Where:

38 X_m is the amplitude of the input signal
 39 ω_0 is the nominal power system frequency

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- 1 $R_f (= df/dt)$ is the frequency ramp rate (fixed value in this equation)
- 2 a) Begin with input at nominal magnitude and lower frequency range.
- 3 b) Wait for the system to settle (see PMU Settling Time).
- 4 c) Begin ramping the frequency with a positive ramp rate specified by C37.118:2005.
- 5 d) Calculate the Max TVE, FE and RFE excluding data from the first 2 sample periods following the
- 6 change in ramp rate.
- 7 e) Hold the frequency constant for at least two sample periods then begin ramping the frequency at the
- 8 negative ramp rate.
- 9 f) Calculate the Max TVE, FE and RFE excluding data from the first two sample periods following
- 10 the change in ramp rate.
- 11 g) Compare the results to the class limits in C37.118.1.
- 12 h) ~~Optionally repeat the above tests adding a specified amount of a harmonic to the fundamental~~
- 13 ~~signal. This test is not required by the standard.~~

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14 8.9.4.3 Dynamic compliance – performance during step changes in amplitude or phase

15 A recommended practice for measuring a PMU's response to step changes in input is to run a series of step

16 tests displaced in time and then recombine them to trace a complete response curve. For each test in the

17 series, the step is applied a fraction of the reporting period later in time relative to the beginning of a

18 reporting cycle, than the previous step. In each test, the influence quantity (amplitude or phase) is stepped,

19 the response data is gathered, and the influence quantity is returned to nominal in preparation for the next

20 test in the series. At the end of the series of tests, the data from all tests is indexed and overlaid to create a

21 smooth curve approximating the step response of the PMU. From the curve, response delay and response

22 time are calculated.

23 A total number N tests shall be run where $N \geq 8$. The first step shall occur at the beginning of a reporting

24 cycle, (for example at the same time as the 1 Pulse Per Second timing signal). PMU Data is gathered then

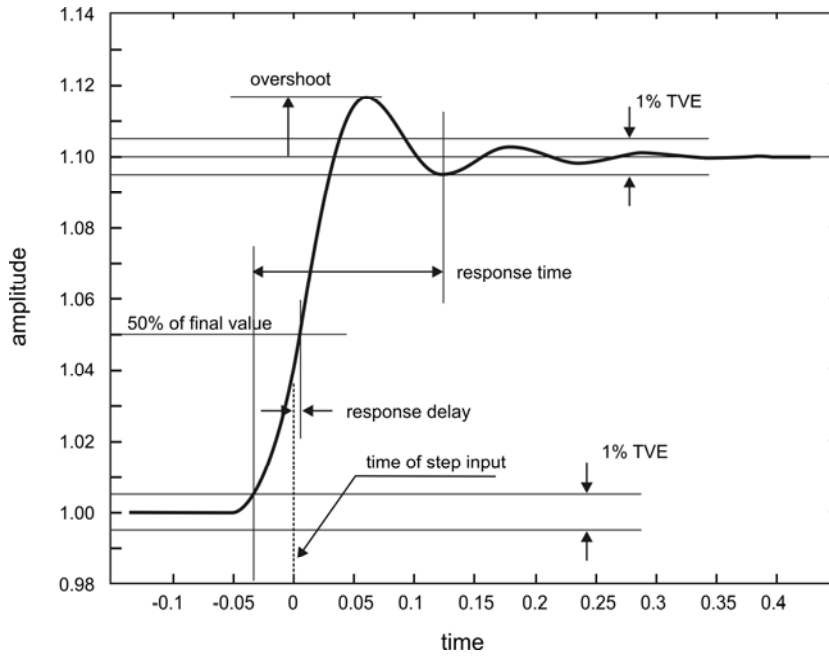
25 the input returned to nominal. The next step shall occur $1/N$ times the reporting period after the beginning

26 of a reporting cycle, the subsequent test $2/N$, then $3/N$, etc., until all N tests are complete.

27 When the PMU data is indexed and overlaid, the result shall be a curve similar to ~~Figure A-24~~:

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Figure A-24—Sample of step change at $t = 0$, illustrating response time, response delay, and overshoot measurements. Note that maximum overshoot may be over or under the final value, and the response delay may be positive (response after step) or negative (response before step).

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3

4

a) For the first test, let $n = 0$.

5

b) Begin with three-phase balanced input at nominal amplitude and frequency.

6

c) At the beginning of a reporting cycle plus $n \cdot \frac{1}{N} \cdot (N \cdot F_s)$ (i.e., $n \cdot \frac{1}{N}$ reporting period / N) step the influence quantity (amplitude or phase) by the amount specified in C37.118.1:2012.

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d) Gather the PMU data, return the influence quantity to nominal and wait for the PMU to settle.

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e) Increment n by one ($n = n + 1$), then repeat steps c through d until $n = N-1$.

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f) Index and overlay the PMU data to obtain a smooth response curve.

10

The Measurement Delay time is the time from the step in influence quantity until the point at which the response curve exceeds 50% of the difference between the nominal value and the value after the step. Note that delay can be positive (after the step, as shown in Figure A-24) or negative (before the step) depending on how the PMU applies the time stamp.

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The Response Times are the times between TVE, FE, and RFE exceeding the limits and the time where TVE, FE, and RFE reaches and remains within the limits as specified in C37.118.1:2012.

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Compare the Measurement Delay and Response Times to the limits in C37.118.1:2012.

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13

8.9.4.4 Measurement reporting latency compliance testing

14

Design of real time systems such as control loops rely on measured latency information. The total latency for a PMU is the time between the occurrence of an event at the PMU input and the time the event is reported at the output port of the PMU. The time between an event and the time stamp in a report is the

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1 Measurement Delay measured in the step response test above. Adding ~~the Measurement Delay~~ to the
 2 difference in time between the time stamp in the report and the time the time the report arrives at the device
 3 output, and ~~gives~~ the total ~~measurement~~ latency ~~of the PMU~~. It is this second latency, the Measurement
 4 Reporting latency which will be measured by the following recommended practice.

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5 Since a PMU may rely on a microprocessor running a real-time operating system, the reporting latency may
 6 not be consistent from report to report. C37.118.1 ~~2012~~ requires measurement of the reporting latency over
 7 at least 1000 consecutive reports. The latency is the maximum of these values.

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8 Recommended practice for the accuracy of the reporting latency measurement is 100 microseconds.

- 9 a) No special input is required.
- 10 b) Within 100 microseconds of the report arriving at the output port of the PMU, capture the time.
- 11 c) Subtract the time captured above to the time in the timestamp of the report.
- 12 d) Repeat steps b and c for 1000 consecutive reports.
- 13 e) The maximum of these 1000 time differences is the Measurement Reporting Latency. Compare this
 14 latency to the limits in C37.118.1 ~~2012~~.

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15 8.9.4.5 Time quality tests

16 C37.118-2005 defines a time quality indication field in the FRACSEC portion of all messages. This time
 17 quality is 0 when the PMU is locked to a traceable source of UTC time and indicates a maximum time error
 18 when the PMU is not locked to its time source.

19 PC37.118.2 renames the above time quality indication the “message time quality indication” and adds a
 20 second “PMU time quality indication” which is zero only when it is not implemented (as for pre-C37.118.2
 21 devices) and indicates time quality whether the PMU is locked to a traceable time source or not. This time
 22 quality field has also been added to the IRIG-B time code extensions of C37.118.2 Annex F and to the
 23 Synchrophasor profile for IEEE-1588.

24 This guide does not provide a test plan for the PMU time quality indication. At the time of writing of this
 25 guide, this indication is preliminary. Time sources and PMUs implementing this indication have not been
 26 designed and there has been no field experience with such devices. Test plans ~~have not been discussed nor~~
 27 devised.

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28 8.9.4.5.1 Message time quality test

29 Testing the message time quality involves measuring the steady state phase error while the device is locked
 30 to its time source (this will be the “baseline” phase error), removing the time source from the PMU,
 31 measuring the phase error and comparing it to the message time quality over a period of no less than 1000
 32 seconds. The phase error minus the baseline phase error is assumed to be caused by the PMU’s timing
 33 inaccuracy. If the phase error “drifts” beyond the phase error which would be caused by the message time
 34 error, the PMU fails the Message Time Quality test.

35 8.9.5 Tests of integrated PMUs

36 8.9.5.1 Modified IPMU testing

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

1 **8.9.5.1.1 Range of input signals for IPMU**

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

4 **8.9.5.1.2 Maximum resources loading**

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

7 **8.9.5.1.3 Potential interference scenario verification**

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

10 **8.10 Synchrophasor message format**

11 The Synchrophasor message formats are given in the IEEE Std. C37.118-2005 Synchrophasor Standard and
12 are extended in C37.118.2-2012 with a new Config3 message and a Continuous Time Quality (CTQ) field
13 in the SYNC word. This message system is designed for real-time communications between a PMU
14 measuring device and a data collection device such as a phasor data concentrator (PDC). It can also be used
15 for data sent from a PDC to another PDC. The overall data system is described here along with some
16 implementation considerations. Details on the message format itself can be found in the IEEE Standard.

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17 **8.10.1 Message framework**

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

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

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

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

33 **8.10.2 Implementation issues**

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

1 8.10.3 Unit identification

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

7 8.10.3.1 Protocol layers (TCP/UDP)

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

21 8.10.3.2 Security suffixes

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

27 8.11 Final comments

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

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

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

41 Sometimes it is possible to compare PMU data against data collected on other devices that share the same
42 inputs, such as a digital fault recorder (DFR) or a PMU of another type. More often, though, one must work
43 solely from PMU data collected at a number of different locations. It can then be difficult to distinguish
44 discrepancies in timing or dynamic response within the measurement system from locational differences in

1 response of the power system itself. Consequently PMU characterization through laboratory tests is
2 essential and may be the only reference for power system analysis.

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1 **Annex B**

2 (informative)

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3 **Responses of the reference signal processing model to test signals**

4 **B.1 General**

5 This annex provides sample typical responses of the Reference Signal Processing Model presented in
6 Appendix C of C37.118.1:2012. Typical responses are informative only and do not construe specifications
7 or limits. PMUs being tested may respond in a similar or quite different manner but would still be in
8 compliance if they meet or exceed the limits of C37.118.1:2012.

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9 **B.2 Introduction to the graphs**

10 The graphs below were made using a mathematical model of the PMU Reference signal processing model
11 of C37.118.1 Annex C. The graphs are made at the full system sampling rates of 960 samples/second for
12 M-Class and 900 samples per second for P-Class. this is done before the decimation to the output reporting
13 rate in order to show the actual internal response to the PMU filters which were used to verify the
14 performance limits of the standard.

15 **B.3 Response of the model to steady state test signals**

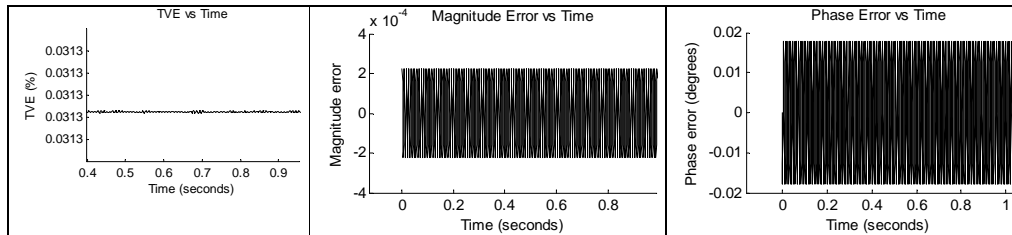
16 **B.3.1 Steady state – signal frequency range**

17 **B.3.1.1 M-Class Signal Frequency Range**

18 The TVE of the M-Class reference model at nominal frequency is dominated by the attenuation of the filter
19 following the complex multiplication of the input signal with the Nominal frequency carrier. The output of
20 this multiplication is both the difference of the signals and the sum of the signals. The M-class filter passes
21 the difference signal and attenuates 20 dB of the sum signal.

22 Below are plots of TVE, magnitude error, and phase error for Nominal Frequency input at a PMU reporting
23 rate (Fs) of 60 Frames per Second. These plots are taken at the internal sampling rate of the PMU model at
24 960 samples per second and the sum signal can clearly be seen:

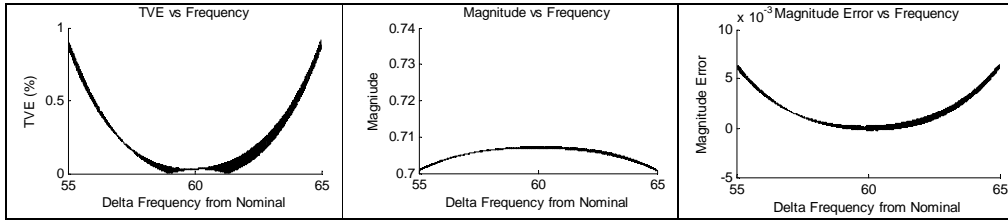
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26 **Figure B-1 —TVE, magnitude and phase error for nominal input at 60 FPS reporting rate**

1 **B.3.1.1.1 TVE at bandwidth limits**

2 TVE as the input frequency changes is dominated by the magnitude roll off of the PMU filter. This can be
 3 observed by looking at plots of TVE, magnitude and magnitude error as the frequency ramps from the low
 4 bandwidth limit to the high bandwidth limit:



5 **Figure B-2 —TVE, magnitude and magnitude error for Fs = 60fps as frequency ramps**
 6 **between the bandwidth limits (M-class)**

7 More on frequency ramping later...

8

9 **Table B.1—TVE, FE and RFE at the bandwidth limits (M-Class)**

Reporting Rate (Fs) Upper Frequency (Fu) Lower Frequency (Fl)	Upper Bandwidth Frequency (Fu)	Lower Bandwidth Frequency (Ll)
Fs = 120 Fu=65Hz Fl=55Hz	Max TVE(%) = 1.0371 Max FE = 3.7925e-013 Max RFE = 1.1767e-010	Max TVE(%) = 0.82995 Max FE = 4.4675e-013 Max RFE = 1.4325e-010
Fs = 60 Fu=65Hz Fl=55Hz	Max TVE(%) = 0.92123 Max FE = 1.6875e-013 Max RFE = 9.1234e-011	Max TVE(%) = 0.92361 Max FE = 2.1316e-013 Max RFE = 1.3642e-010
Fs = 30 Fu=65Hz Fl=55Hz	Max TVE(%) = 0.99538 Max FE = 1.4211e-013 Max RFE = 1.3216e-010	Max TVE(%) = 1.0207 Max FE = 1.3145e-013 Max RFE = 1.1426e-010
Fs = 20 Fu=64Hz Fl=56Hz	Max TVE(%) = 0.89033 Max FE = 1.1058e-013 Max RFE = 1.2406e-010	Max TVE(%) = 0.87659 Max FE = 1.0836e-013 Max RFE = 1.4282e-010
Fs = 15 Fu=63Hz Fl=57Hz	Max TVE(%) = 0.88493 Max FE = 9.5923e-014 Max RFE = 1.4325e-010	Max TVE(%) = 0.89083 Max FE = 1.168e-013 Max RFE = 1.4325e-010
Fs = 12 Fu=62.4Hz Fl=57.6Hz	Max TVE(%) = 0.8861 Max FE = 1.1946e-013 Max RFE = 1.6925e-010	Max TVE(%) = 0.87822 Max FE = 1.0303e-013 Max RFE = 1.6286e-010
Fs = 10 Fu=62Hz Fl=58Hz	Max TVE(%) = 0.85292 Max FE = 1.128e-013 Max RFE = 1.4325e-010	Max TVE(%) = 0.85727 Max FE = 1.0636e-013 Max RFE = 1.6946e-010

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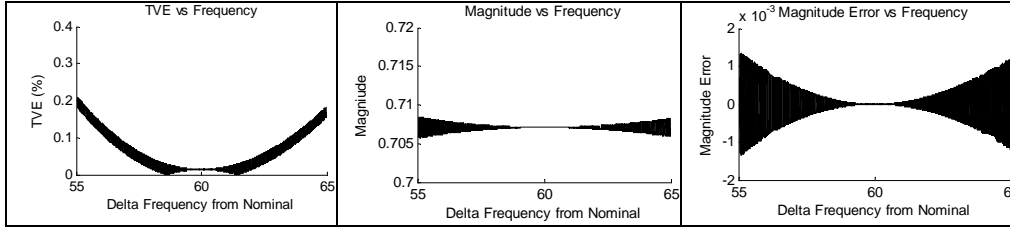
1 **B.3.1.2 P class signal frequency range**

2 For steady state input at the nominal frequency, the P class reference model filter has extremely good
3 attenuation of all harmonics. This means that the effect of the sum output of the complex multiplication is
4 insignificant and TVE for nominal signals is effectively 0.

5 The P-Class PMU model also uses magnitude compensation for off-nominal signals which improves
6 performance; however the attenuation for off-nominal sum signal can be as little as 25dB.

7 Below are plots of TVE, magnitude, and magnitude error for a frequency ramp from 5 Hz below to 5 Hz
8 above the nominal frequency:

9



10 **Figure B-3 —TVE, magnitude and magnitude error for P-Class**

11 In the above figures, the effect of the sum signal at off-nominal frequencies is apparent. The effect of the
12 frequency compensation for magnitude is also apparent when compared to the M-Class magnitude plot.

13

14 **Table B.2—TVE, FE and RFE at the bandwidth limits (P-Class)**

Reporting Rate (Fs) Upper Frequency (Fu) Lower Frequency (Fl)	Upper Bandwidth Frequency (Fu)	Lower Bandwidth Frequency (LI)
Fs = 60 Fu=62Hz Fl=58Hz	%TVE =0.030166 Fe =2.0939e-013 RFe =1.3169e-010	%TVE =0.032015 Fe =3.5016e-013 RFe =7.474e-011

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16 Note that the P-Class reference model filter is the same at all reporting rates so the performance will be the
17 same for all reporting rates.

18 **B.3.2 Steady state signal magnitude range**

19 The PMU reference model performs the same under any steady state signal magnitude. The results of this
20 test for the limits of the magnitude range are trivial and are not shown here. The results will not be trivial
21 for real-world PMUs.

22 **B.3.3 Steady state phase angle range**

23 The PMU reference model performs the same under any steady state phase angle. The results of this test for
24 the limits of the magnitude range are trivial and so are not shown here. The results will not be trivial for
25 real-world PMUs.

1 **B.3.4 Steady state worst case harmonic distortion**

2 The PMU reference model is most susceptible to interference from lower harmonics. This is due to filter
 3 design tradeoffs between reporting latency, relation of frequency and ROCOF measurements and the
 4 timestamp of the phasor, and applications need for out-of-band noise immunity.

5 **B.3.4.1 M-Class response to harmonic distortion**

6 **Table B.3—M Class response to 10% 2nd through 8th harmonics**

	2 nd	3 rd *	4 th	5 th	6 th *	7 th	8 th
F _s =120	%TVE =1.1194 Fe =0.018391 RFe =19.5273	%TVE =0.1283 Fe =4.4997e-014 Rfe =2.2649e-011	%TVE =0.13558 Fe =0.018391 Rfe =19.5273	%TVE =0.1273 Fe =0.0014782 RFe =6.5583	%TVE =0.13246 Fe =5.1613e-014 RFe =2.5303e-011	%TVE =0.12675 Fe =0.0014782 RFe =6.5583	%TVE =0.13169 Fe =0.0028583 RFe =5.3684
F _s =60	%TVE =0.038135 Fe =0.0023167 RFe =2.4598	%TVE =0.036179 Fe =2.5095e-014 RFe =2.4258e-011	%TVE =0.034976 Fe =0.0023167 Rfe =2.4598	%TVE =0.034496 Fe =0.00018343 RFe =0.81381	%TVE =0.034273 Fe =3.5194e-014 RFe =3.4845e-011	%TVE =0.034169 Fe =0.00018343 RFe =0.81381	%TVE =0.034169 Fe =0.00018343 RFe =0.81381
F _s =30	%TVE =0.01227 Fe =0.0015596 RFe =1.656	%TVE =0.019548 Fe =1.2947e-014 RFe =2.6071e-011	%TVE =0.013835 Fe =0.0015596 RFe =1.656	%TVE =0.019175 Fe =0.00016231 RFe =0.72009	%TVE =0.013981 Fe =3.1176e-014 RFe =4.5498e-011	%TVE =0.019109 Fe =0.00016231 RFe =0.72009	%TVE =0.014008 Fe =0.0015061 RFe =2.8286
F _s =20	%TVE =0.013071 Fe =0.0013213 RFe =1.4029	%TVE =0.017928 Fe =2.8953e-014 RFe =4.9502e-011	%TVE =0.014281 Fe =0.0013213 RFe =1.4029	%TVE =0.016093 Fe =3.3924e-005 RFe =0.1505	%TVE =0.016052 Fe =1.651e-014 RFe =3.1529e-011	%TVE =0.014721 Fe =3.3924e-005 RFe =0.1505	%TVE =0.016797 Fe =0.00067122 RFe =1.2606
F _s =15	%TVE =0.0044539 Fe =0.00058532 RFe =0.62147	%TVE =0.0069564 Fe =6.6417e-014 RFe =9.6832e-011	%TVE =0.0048171 Fe =0.00058532 RFe =0.62147	%TVE =0.0068731 Fe =6.358e-005 RFe =0.28207	%TVE =0.0048495 Fe =5.5129e-014 RFe =6.9487e-011	%TVE =0.0068584 Fe =6.358e-005 RFe =0.28207	%TVE =0.0048556 Fe =0.00059173 RFe =1.1113
F _s =12	%TVE =0.007429 Fe =0.00012616 RFe =0.13395	%TVE =0.0099091 Fe =5.0538e-014 RFe =9.2945e-011	%TVE =0.0097307 Fe =0.00012616 RFe =0.13395	%TVE =0.0088105 Fe =2.0347e-005 RFe =0.090268	%TVE =0.0096188 Fe =4.4539e-014 RFe =8.3954e-011	%TVE =0.0096188 Fe =4.4539e-014 RFe =8.3954e-011	%TVE =0.0096149 Fe =2.0347e-005 RFe =0.090268

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	2 nd	3 rd *	4 th	5 th	6 th *	7 th	8 th
F _s =10	%TVE =0.0099453	%TVE =0.0089413	%TVE =0.0081662	%TVE =0.0079532	%TVE =0.008222	%TVE =0.0086324	%TVE =0.0088204
	Fe =0.00015078	Fe =5.0404e-014	Fe =0.00015078	Fe =1.8305e-005	Fe =5.5168e-014	Fe =1.8305e-005	Fe =0.00022834
	RFe =0.1601	Rfe =6.2694e-011	RFe =0.1601	RFe =0.081212	RFe =1.0362e-010	RFe =0.081212	RFe =0.42885

1 * Harmonic numbers with multiples of 3 are zero sequence and have no effect on the Frequency and
2 ROCOF measurements.

3 ROCOF is most sensitive to harmonic distortion. The higher the reporting rate, the more susceptible the
4 ROCOF measurement is.

5 **B.3.4.2 P-class response to harmonic distortion**

6 Since the P-Class reference model filter has excellent harmonic rejection, the TVE, Fe, and RFe for
7 harmonics are very small.

8 **Table B.4—P-Class response to 1% 2nd through 8th harmonics**

	2 nd	3 rd *	4 th	5 th	6 th *	7 th
F _s =Any	%TVE =1.8067e-012	%TVE =1.7883e-012	%TVE =1.4525e-012	%TVE =2.2045e-012	%TVE =2.6668e-012	%TVE =2.0764e-012
	Fe =1.1403e-013	Fe =1.0398e-013	Fe =8.7776e-014	Fe =1.5191e-013	Fe =2.4231e-013	Fe =1.1715e-013
	RFe =3.0598e-011	Rfe =2.6287e-011	RFe =2.1018e-011	RFe =3.9081e-011	RFe =4.245e-011	RFe =3.9666e-011

9 * Harmonic numbers with multiples of 3 are zero sequence and have no effect on the Frequency and
10 ROCOF measurements.

11 **B.3.5 Steady state worst case out of band interfering signal**

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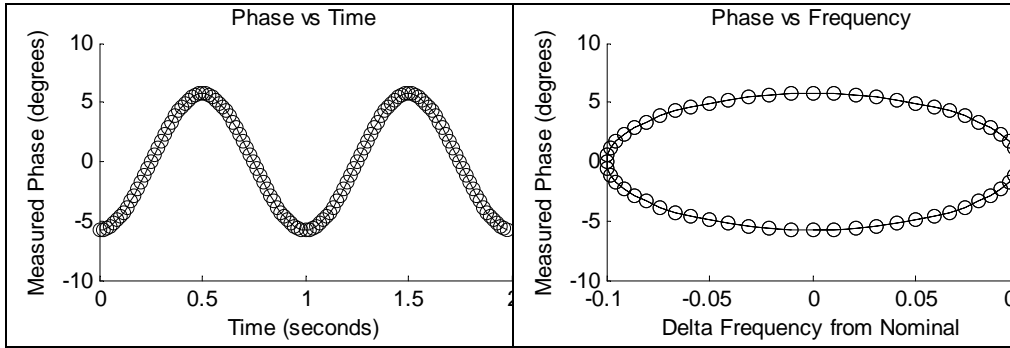
1 **B.4 Response to dynamic input signal tests**

2 **B.4.1 Dynamic measurement bandwidth tests response**

3 To understand how the PMU reference model responds to modulated input, it is helpful to look at the
4 response to Phase Modulation and Amplitude Modulation separately.

5 Plots of PMU response with respect to input signal frequency can be quite informative, especially when
6 troubleshooting. Figure B-1 shows plots for measured phase at reporting rate of 60 fps versus both time
7 and frequency for a $\omega_a = \omega_x = 1$ Hz phase modulation at $K_a = K_x = 0.1$ Hz modulation index:

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9 **Figure B-4 —Phase versus Time and frequency for 1Hz modulation at 0.1 index**

10 The phase modulation is specified to be $K_a \times \cos(\omega_m t - \pi)$ so the measured phase begins at -5 degrees at 0
11 Hz delta frequency and increases to 0 degrees at 0.1 Hz delta frequency. 0.1 Hz delta frequency is where
12 the modulation is crossing 0 (going positive) so the phase continues to increase towards 5 degrees while the
13 frequency decreases back to 0. Frequency crosses 0 at the positive peak of the modulation signal so phase
14 begins to decrease as the frequency decreases and phase reaches 0 at -0.1Hz which is the negative going
15 zero crossing of the modulation signal. Frequency begins to increase and phase continues to decrease as the
16 modulation continues towards the negative peak where it began.

17 Note that for a modulated phase, the input frequency is at its maximum and minimum at the zero crossings
18 of the modulation; this is where the ROCOF is at its maximum.

19 Dynamic measurement bandwidth uses combined amplitude and phase modulated input signals to test
20 PMU response. For all tests, amplitude and phase modulations indices are fixed at 0.10 (10%). Modulation
21 frequency (Fmod) is varied from 0.1Hz up to the reporting rate divided by 5 (Fs/5).

22 The worst case response for the reference PMU at any reporting rate is at the maximum modulation
23 frequency of Fs/5. Table B.5 shows Max TVE, Frequency error and ROCOF error for the worst-case
24 modulation frequencies:

25 **Table B.5—Response to combined amplitude and phase modulated input, 10% index**

	M-class	P-class
Fs=120Hz	Fmod = 24Hz %TVE =3.0111 Fe =1.1552 RFe =215.0233	Fmod=12Hz %TVE =1.9802 Fe =0.3349 RFe =30.4745

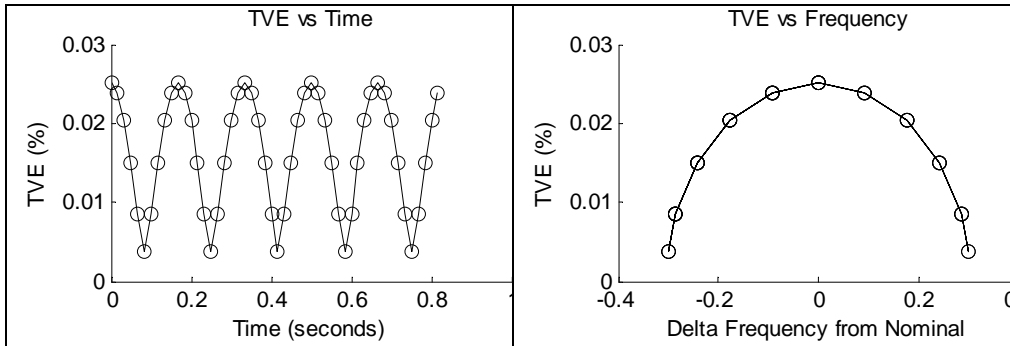
Fs= 60Hz	Fmod = 12Hz %TVE =1.7499 Fe =0.3414 RFe =33.4533	Fmod=6Hz %TVE =0.52044 Fe =0.078166 RFe =3.6154
Fs=30Hz	Fmod=6Hz %TVE =0.56378 Fe =0.094607 RFe =5.5946	Fmod=3Hz %TVE =0.13162 Fe =0.019039 RFe =0.43362
Fs=20Hz	Fmod=4Hz %TVE =0.35362 Fe =0.04679 RFe =2.0388	Fmod=2Hz %TVE =0.058623 Fe =0.0084155 RFe =0.12657
Fs= 15Hz	Fmod=3Hz %TVE =0.73533 Fe =0.037678 RFe =1.2016	Fmod=1.5Hz %TVE =0.033 Fe =0.0047245 RFe =0.052994
Fs=12Hz	Fmod=2.4Hz %TVE =0.34896 Fe =0.022204 RFe =0.65003	Fmod=1.2Hz %TVE =0.021127 Fe =0.0030209 RFe =0.027011
Fs=10Hz	Fmod=2 %TVE =0.75658 Fe =0.022918 RFe =0.48083	Fmod=1Hz %TVE =0.014674 Fe =0.0020968 RFe =0.015584

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2

3 **B.4.1.1 Effect of phase modulation on TVE**

4 The effect of phase modulation on TVE is also quite informative, especially what happens as the
5 modulation frequency increases. The next few plots show TVE for low modulation frequencies increasing to
6 higher modulation frequencies.

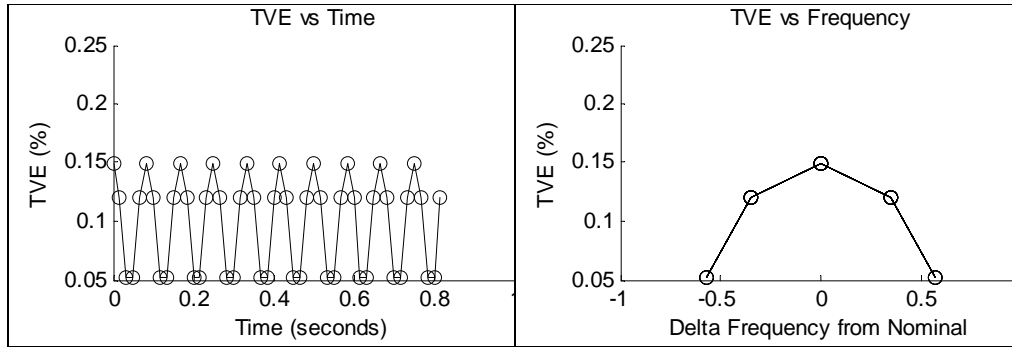
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8 **Figure B-5 —TVE versus time and frequency for Fs=60, 3Hz phase modulation at 0.1 index**

9 Figure B-5 shows TVE versus time and frequency for 60 FPS reporting rate, 3 Hz modulation frequency and
10 0.1 modulation index. The max TVE is well within the limits but is maximum at 0 Hz delta frequency.

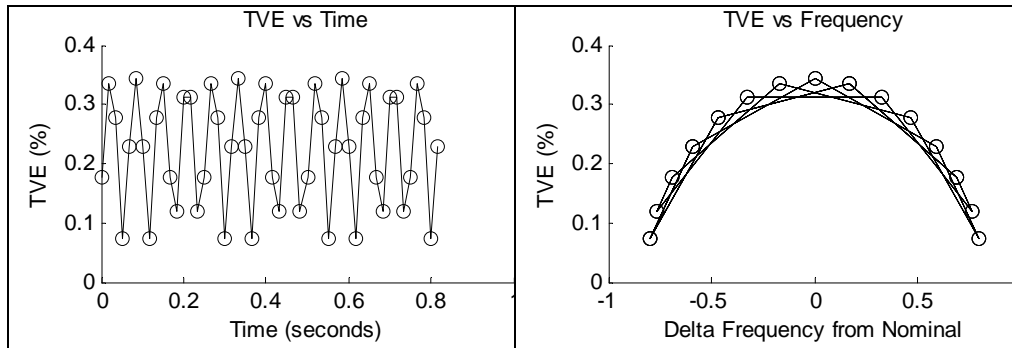
- 1 This is where the modulation is crossing 0 and the ROCOF is at its highest. At either end of the delta
- 2 frequency (0.1 index x 3 Hz modulation frequency = 0.3Hz delta frequency) the TVE is at its lowest.
- 3 As the modulation frequency increases, so does the max TVE:



4 **Figure B-6 TVE versus time and frequency for $F_s=60$, 6Hz phase modulation at 0.1 index**

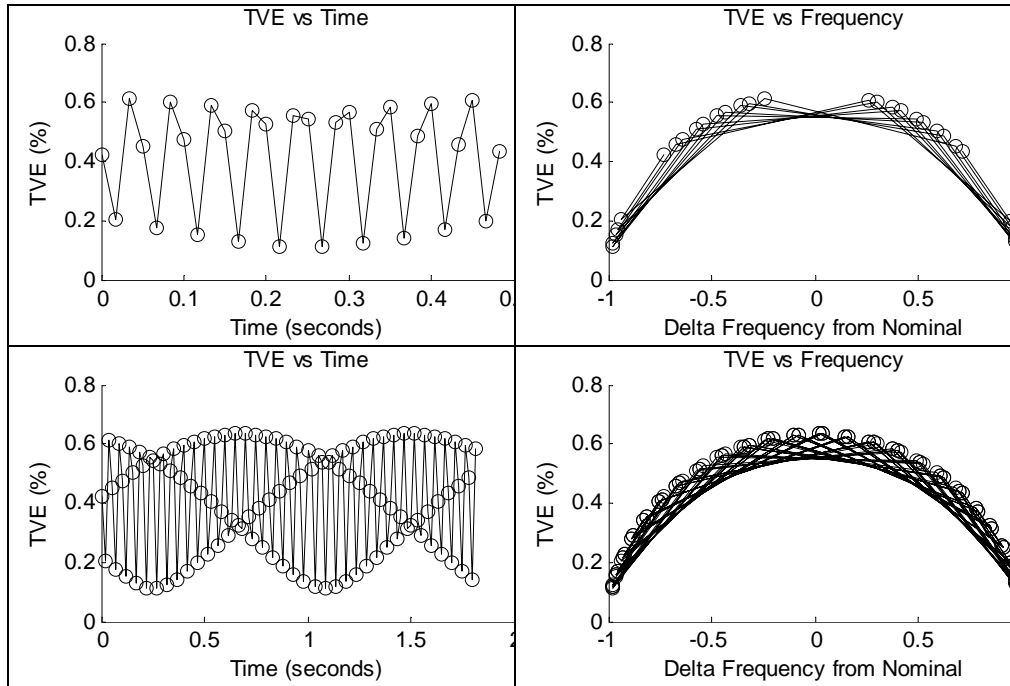
- 5 The plots in Figure B-6 were made at 6Hz modulation frequency, 0.1; the max TVE is about 0.15% and the
- 6 minimum TVE is about 0.05. Notice that the TVE samples are symmetrical on either side of 0 delta
- 7 frequency. This is an effect of the relation between the modulation frequency and the sample rate.

- 8 An interesting and important effect occurs then the TVE samples are not symmetrical about 0 delta
- 9 frequency, as shown in the plots of 8Hz modulation frequency in Figure B-7 **Error! Reference source not**
- 10 **found.**



12 **Figure B-7 —TVE versus time and frequency for $F_s=60$, 8Hz phase modulation at 0.1 index**

- 13 Notice on the plot of TVE versus time the lines between the TVE sample points. This effect could be a
- 14 problem an insufficient number of samples is taken. The Max TVE may not be found, as illustrated by the
- 15 following set of plots taken at 9.8z modulation frequency.

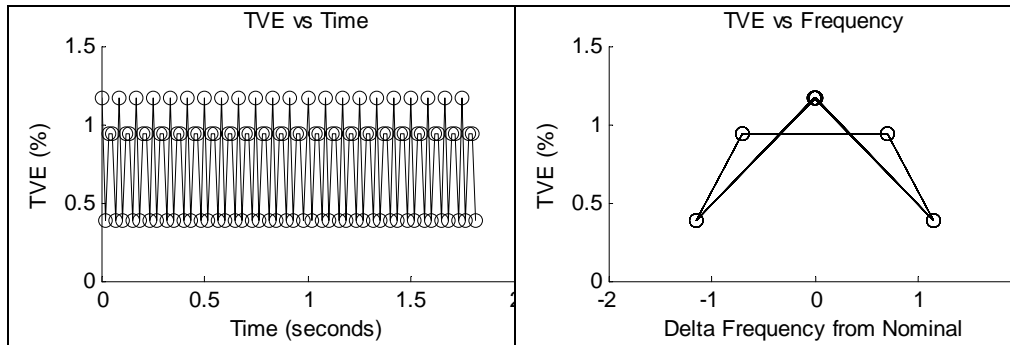


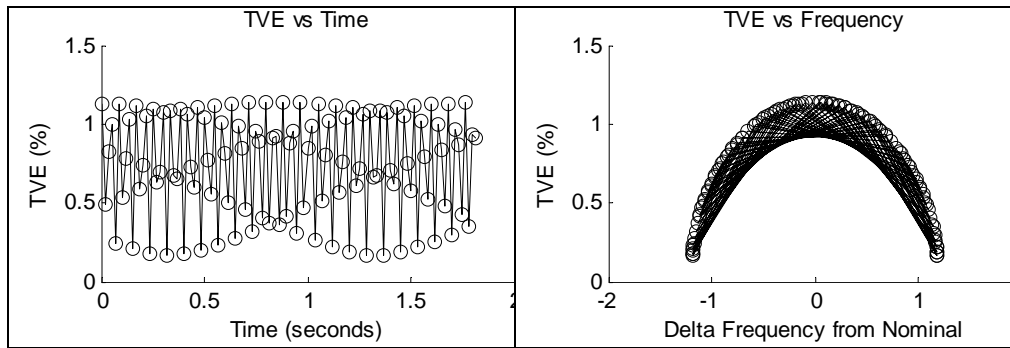
1 **Figure B-8 —TVE vs. time and frequency for $F_s=60$, 9.8Hz phase modulation at 0.1 index**

2 In the plots in Figure B-8, it is clear that an insufficient number of samples were taken to determine the
 3 maximum TVE. The pair of plots took a sufficient number of samples.

4 Finally, the plots in Figure B-9 show what happens at the upper limit of the measurement bandwidth test.
 5 The upper set of plots was taken at modulation frequency of 12Hz (still at 60 fps reporting rate) and the
 6 lower set taken at modulation frequency of 11.9Hz. Both show max TVE at about 1.15%.

7

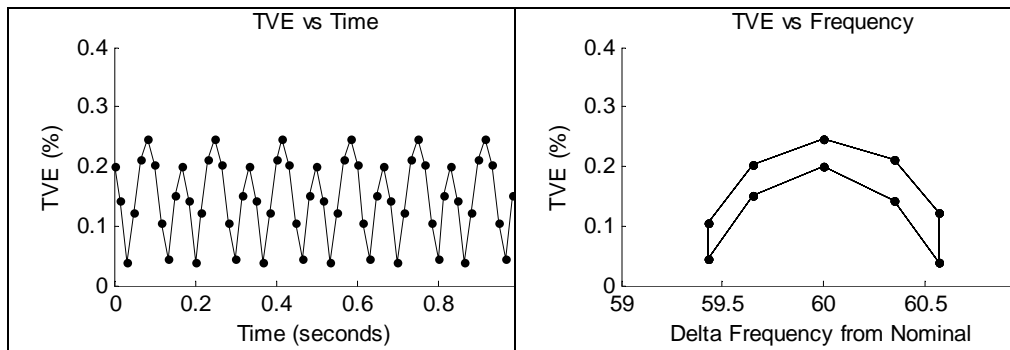




1 **Figure B-9 —TVE vs. time and frequency for 12Hz and 11.8Hz modulation at 0.1 index**

2 **B.4.1.1.1 Combined amplitude and phase modulation**

3 An interesting thing happens to TVE when phase and amplitude modulation is combined (see Figure B-10).



4 **Figure B-10 —TVE vs time and frequency for AM and PM at 6Hz, 0.1 index**

5 TVE as frequency is increasing is lower than TVE as frequency is decreasing. The maximum TVE is where
 6 the frequency crosses zero which is also the maximum ROCOF because this where the phase error is at its
 7 maximum. The main contributor to TVE at the frequency endpoints (where the ROCOF is 0) is magnitude
 8 error due to the filter rolloff described in the section on signal frequency range.

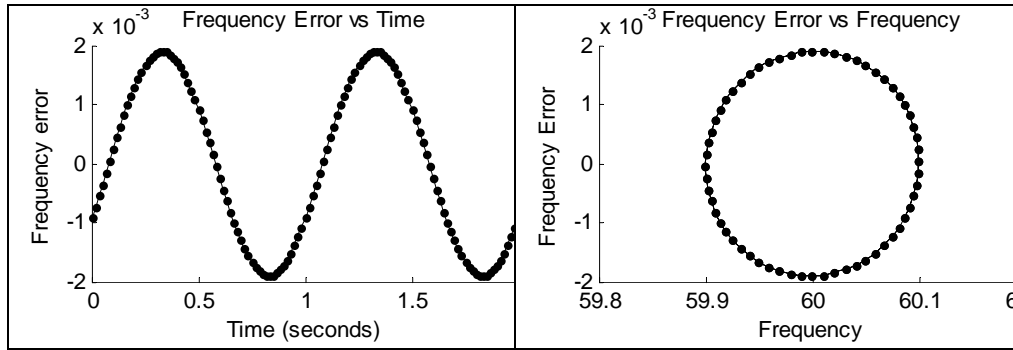
9 The reason that the TVE versus frequency is different for increasing and decreasing frequency is because
 10 the amplitude modulation is 180 degrees out of phase with the frequency modulation. When the frequency
 11 is increasing, the amplitude is decreasing and its contribution to TVE is reduced compared to when the
 12 frequency is decreasing and the amplitude is increasing.

13 **B.4.1.2 Effect of phase modulation on Frequency Error and Rate of Change Frequency**
 14 **Error**

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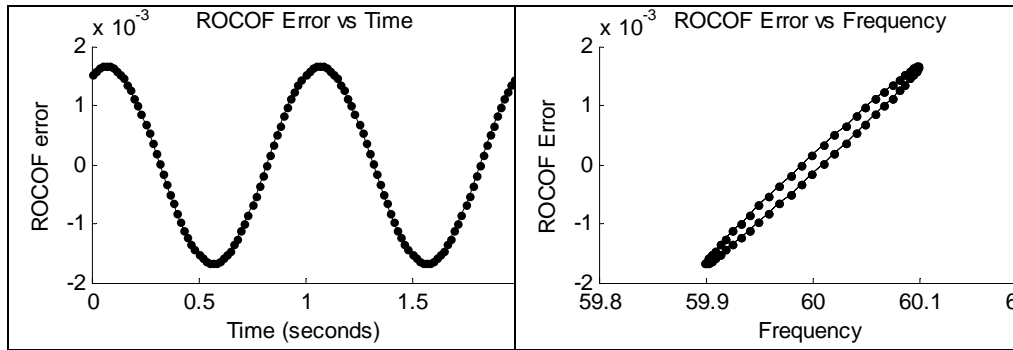
16 **B.4.1.3 Effect of modulation on Frequency Error and Rate of Change Frequency Error**

17 The plots in Figure B-11 illustrate Frequency Error (FE) and Rate of Change of Frequency Error (RFE)
 18 under 1 Hz phase modulation with 0.1 modulation index:



1 **Figure B-11 —Frequency Error vs. time and frequency for 1Hz phase modulation at 0.1**
2 **index**

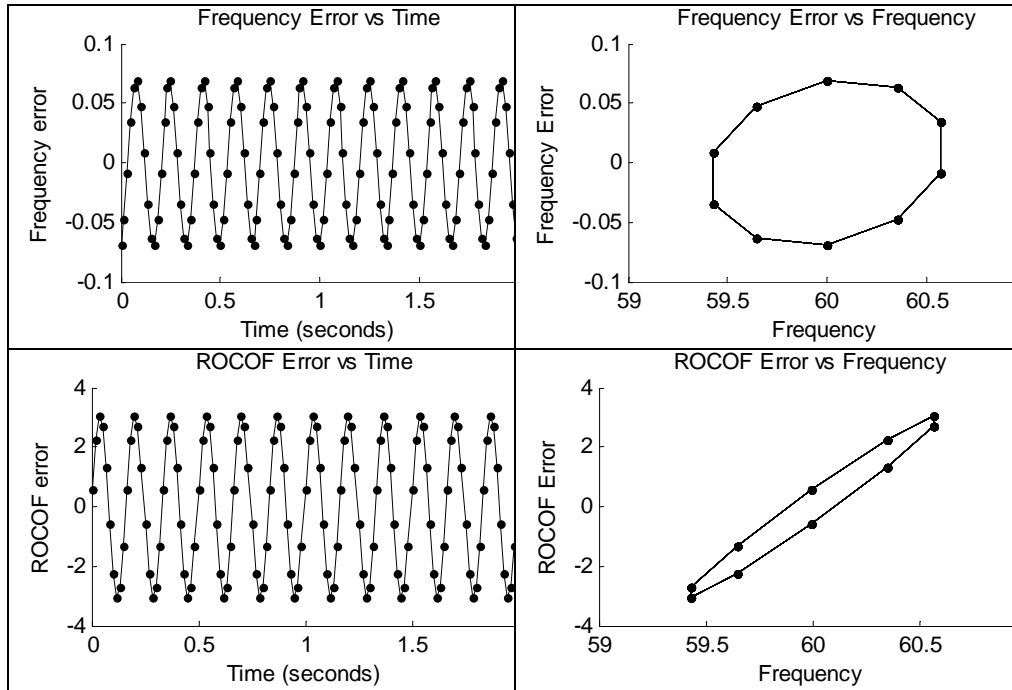
3 The frequency error is greatest when the delta frequency is crossing zero. This is because the rate of change of
4 of frequency is at its greatest at this point, and the effect of the very small difference between the phasor
5 timestamp and the actual time of the frequency measurement has its greatest effect. The sign of the
6 frequency error changes and is positive while the frequency is increasing and negative when it is
7 decreasing.



8 **Figure B-12 —FE vs time and frequency for 1Hz phase modulation at 0.1 index**

9 RFE is greatest where the delta frequencies are greatest and least where the frequency crosses 0. The reason
10 for this is that ROCOF itself is zero when the modulation signal is at its positive and negative peaks and
11 maximum where the modulation signal is crossing 0.

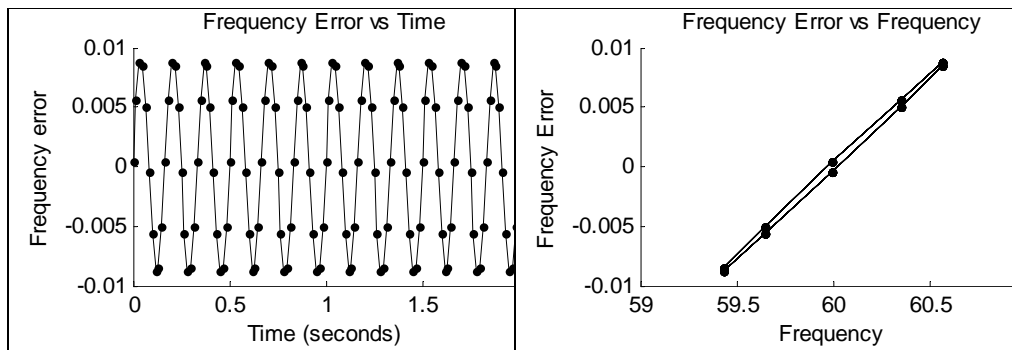
12 As the phase modulation frequency increases, so does the error due to the effect of the small time offset
13 from the phasor estimate:



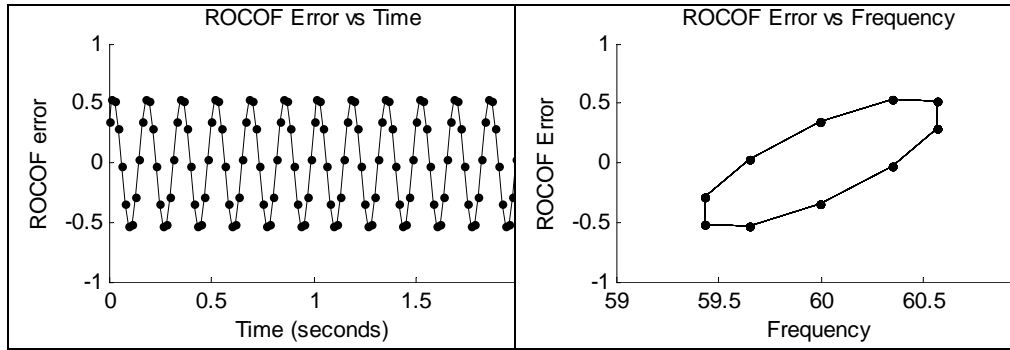
1 **Figure B-13 —FE and RFE vs time and frequency for 6Hz phase modulation at 0.1 index**

2 An improvement can be made to the frequency and ROCOF estimation by centering the estimate over the
 3 timestamp. This is made at the cost of one or two internal PMU sample periods of additional latency.

4 Figure B-14 shows plots at the same modulation as above using a three-sample estimate of frequency
 5 centered on the phasor being reported at the time of the timestamp. Max Fe is improved from 0.069 Hz to
 6 0.024Hz and RFe is improved from 3.08Hz/Sec to 1.37Hz/Sec.



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1 **Figure B-14** — Similar plots using a three sample estimate of frequency centered on the
2 **phasor being reported at the time of the timestamp**

3

4

Table B.6—Response to combined amplitude and phase modulated input, 10% index

	M-class	P-class
F _s =120Hz	F _{mod} = 24Hz %TVE =0.83591 Fe =0.27736 RFe =26.5284	F _{mod} =12Hz %TVE =1.7926 Fe =0.33256 RFe =29.3964
F _s = 60Hz	F _{mod} = 12Hz %TVE =1.6047 Fe =0.28701 RFe =26.3259	F _{mod} =6Hz %TVE =0.47497 Fe =0.077737 RFe =3.613
F _s =30Hz	F _{mod} =6Hz %TVE =0.55538 Fe =0.076642 RFe =3.9116	F _{mod} =3Hz %TVE =0.11953 Fe =0.018748 RFe =0.42714
F _s =20Hz	F _{mod} =4Hz %TVE =0.35362 Fe =0.04679 RFe =2.0388	F _{mod} =2Hz %TVE =0.058623 Fe =0.0084155 RFe =0.12657
F _s = 15Hz	F _{mod} =3Hz %TVE =0.33952 Fe =0.02962 RFe =0.74913	F _{mod} =1.5Hz %TVE =0.029933 Fe =0.0047061 RFe =0.05144
F _s =12Hz	F _{mod} =2.4Hz %TVE =0.33891 Fe =0.021474 RFe =0.44169	F _{mod} =1.2Hz %TVE =0.019161 Fe =0.0030134 RFe =0.026124
F _s =10Hz	F _{mod} =2 %TVE =0.34094 Fe =0.016693	F _{mod} =1Hz %TVE =0.013307 Fe =0.0020932

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	M-class	P-class
	RFe =0.28953	RFe =0.015034

B.4.1.4 Response to amplitude modulation only

Though C37.118.1 does not specify AM only testing, the graphs of the PMU response shall be useful to the practitioner.

Note that there are no plots versus frequency. That is because there is no frequency shift to AM only.

It is interesting to note that the maximum modulation frequency may expose the worst-case TVE. Figure B-15 shows a plot of TVE at $F_s = 60\text{fps}$ with a 12 Hz modulation frequency:

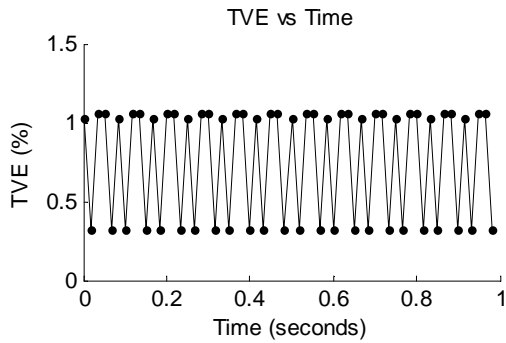


Figure B-15 —TVE for AM at 12Hz, index 0.1 at $F_s=60\text{fps}$

However at 11.9Hz, it is apparent that the TVE goes above where it was at 12Hz:

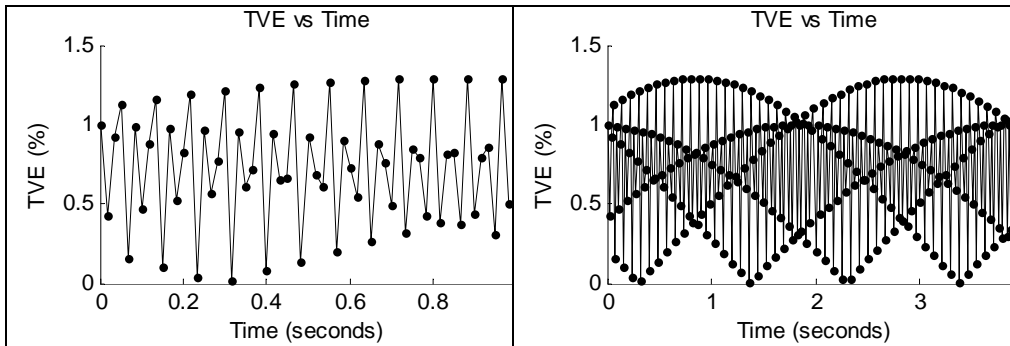


Figure B-16 —TVE for AM at 11.9Hz, 0.1 index at $F_s=60\text{fps}$

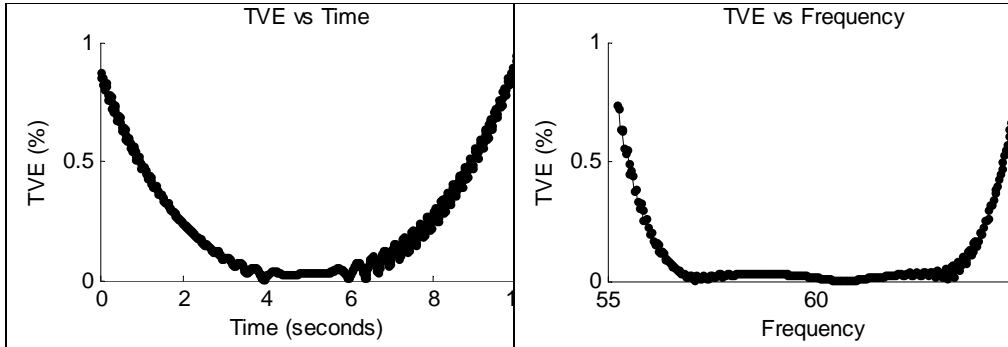
The second plot shows once again why it is important to make sure enough samples are gathered to ensure that Max TVE is reached.

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1 **B.4.2 Dynamic response to linear frequency ramp test signals**

2 **B.4.2.1 M-class TVE response to frequency ramps**

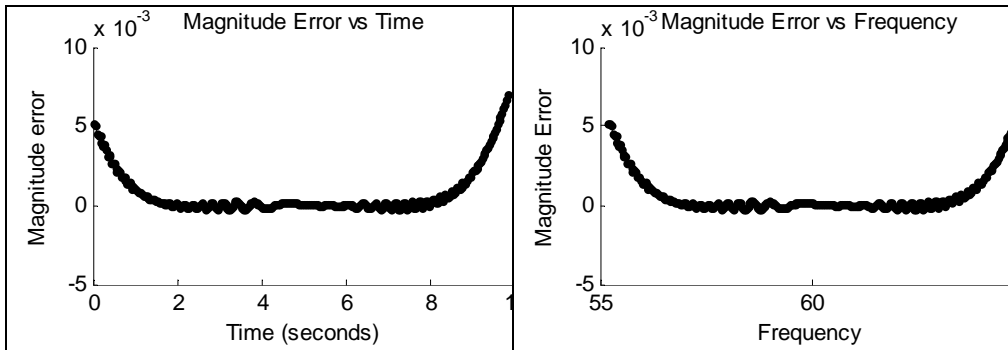
3 In Section B.3, a plot from a frequency ramp was used to illustrate the impact of magnitude roll off of the
 4 M-Class reference model's filter on TVE. For reporting rates of F_s below 30fps, the TVE is above 1% until
 5 the input frequency reaches reporting rate divided by 5 ($F_s/5$). This is the basis for the M-Class limits of
 6 C37.118.1.



7 **Figure B-17 —TVE vs. time and frequency for 1Hz frequency ramp from -5Hz to +5Hz at F_s**
 8 **= 30 FPS**

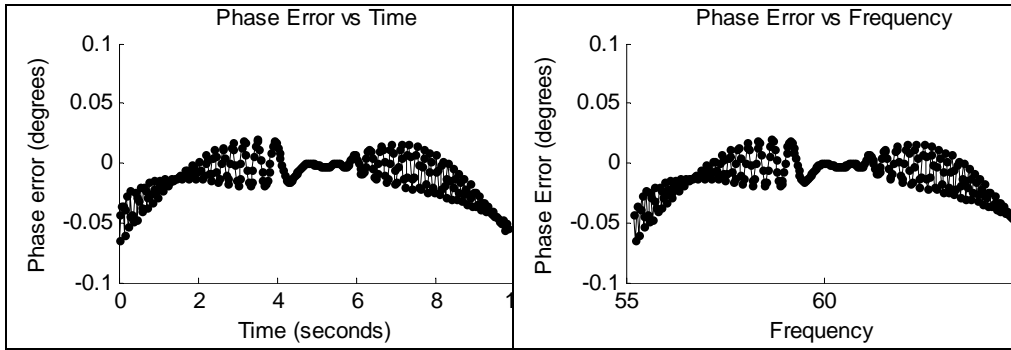
9 The primary contributor to the M-Class TVE is the magnitude rolloff of the M-Class reference model's
 10 filter which is not required to be frequency compensated. **Error! Reference source not found,** shows
 11 graphs of magnitude and phase error over the ramp:

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12 **Figure B-18 —Magnitude error vs. time and frequency for 1 Hz frequency ramp from -5Hz**
 13 **to +5Hz at F_s = 30 FPS**

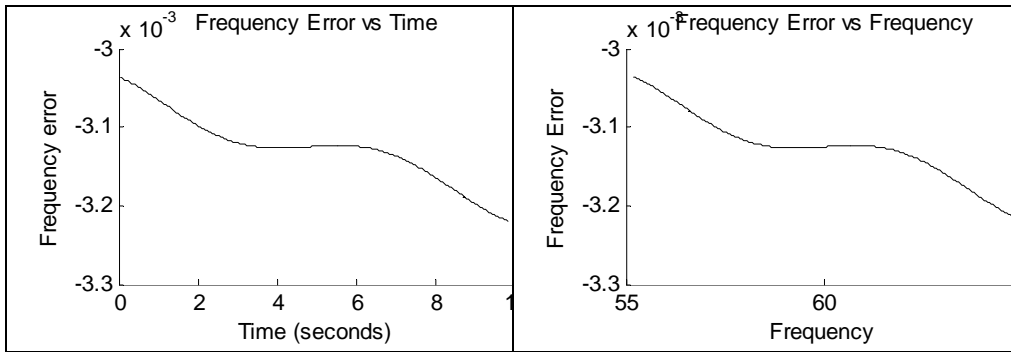
14



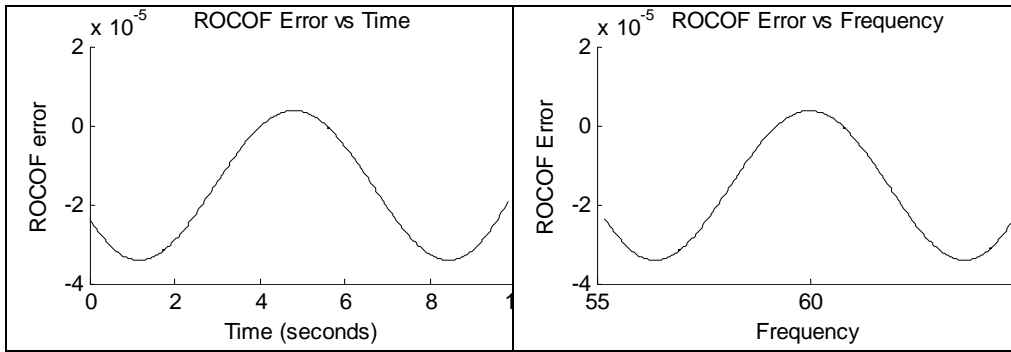
1 **Figure B-19 —Phase error vs time and frequency for 1 Hz frequency ramp from -5Hz to**
2 **+5Hz at $F_s = 30$ FPS**

3 **B.4.2.2 M-class Frequency and RFE response to frequency ramps**

4 The primary contributor to PMU reference model frequency and ROCOF error under ramp test is the small
5 offset of the frequency measurement from the timestamp.



6 **Figure B-20 —Frequency error vs. time and frequency**



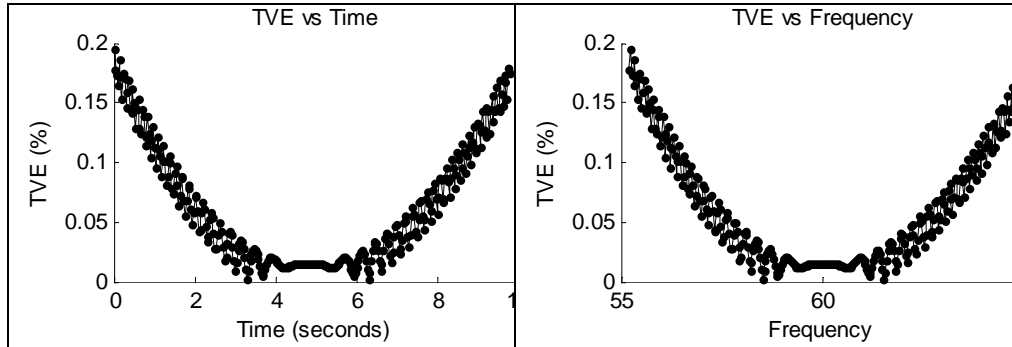
7 **Figure B-21 —ROCOF error vs. time and frequency**

8 The ROCOF error for frequency ramp tests is very low.

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1 **B.4.2.3 P-class TVE response to frequency ramps**

2 The P-Class reference PMU model requires magnitude compensation for the frequency roll off of the filter.
3 Since magnitude roll off is the main contributor to TVE in the M-Class model, the P-Class model responds to
4 frequency ramps with lower TVE:



5 **Figure B-22 —TVE versus time and frequency for P-Class Frequency Ramp**

6 Despite the improved TVE performance of the P-Class PMU, the bandwidth is limited to $\pm 2\text{Hz}$ for the
7 ramp test. This gives even better TVE.

8 **Table B.7—Response to frequency ramp rate = 1Hz/second, Ramp Range = +/- BW**

	M-class	P-class Same for all Fs. BW = +/- 2Hz
Fs=120Hz BW=5Hz	%TVE =1.0203 Fe =0.0031251 RFe =2.9604e-008	%TVE =0.043057 Fe =0.0033335 RFe =5.8997e-008
Fs= 60Hz BW=5Hz	%TVE =0.92373 Fe =0.0031314 RFe =1.6385e-006	
Fs=30Hz BW=5Hz	%TVE =0.96836 Fe =0.0032185 RFe =3.4113e-005	
Fs=20Hz BW=4Hz	%TVE =0.92993 Fe =0.0035742 RFe =0.00026776	
Fs= 15Hz BW=3Hz	%TVE =1.0495 Fe =0.0041837 RFe =0.00084565	
Fs=12Hz BW=2.4Hz	%TVE =0.96192 Fe =0.0051353 RFe =0.0020545	
Fs=10Hz BW=2Hz	%TVE =1.1278 Fe =0.0066097 RFe =0.0042228	

Comment [AG40]: TO DO: Step tests have been implemented in the simulator. I will add these two sections during the next round of comments.

9 **B.4.3 Dynamic response to step changes in amplitude**

10 **Need content here.**

1 **B.4.4 Dynamic response to step changes in phase**

2 **Need content here.**

3

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Comment [ARG41]: The annex topics should flow in the same order as the document. This should be moved to Annex B. The figure numbers need to be updated.

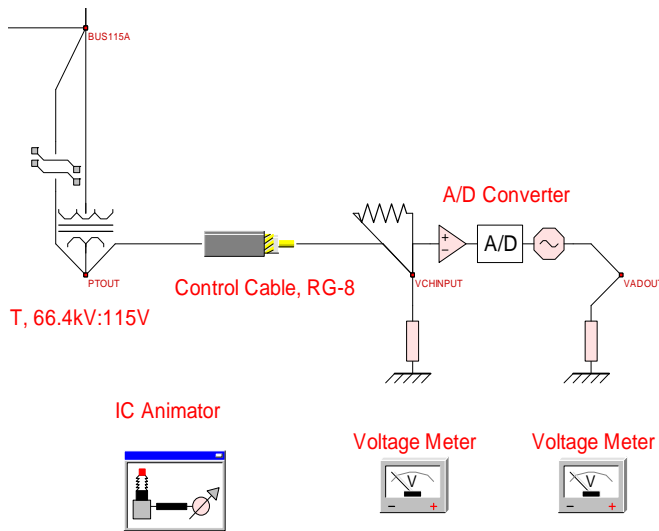
1 **Annex C**
 2 (informative)

3 **Instrumentation channel characterization**

4 This section provides characterization of errors resulting from instrumentation channel wiring, attenuators,
 5 and A/D converters.

6 The error resulting from these components of the instrumentation channel is complex. The approach taken
 7 here is to define a general instrumentation channel model and study the variations parametrically. Two
 8 generic instrumentation channels have been defined: one for voltage measurement (see Figure E.1) and
 9 another for current measurement (see Figure E.2). The important parameters are: 1) cable type and length,
 10 2) burdens, 3) A/D conversion type, accuracy and filtering. In this section, results of measurement accuracy
 11 in a parametric manner are presented.

12 Note that the cable types used for VT and CT secondary circuit wiring would not normally be type RG-8
 13 cable and may often be unshielded multi-conductor control type cables (i.e., non-twisted pairs).
 14 Additionally, there will normally only be one ground in the VT or CT secondary circuit (to avoid
 15 circulating currents, etc.).

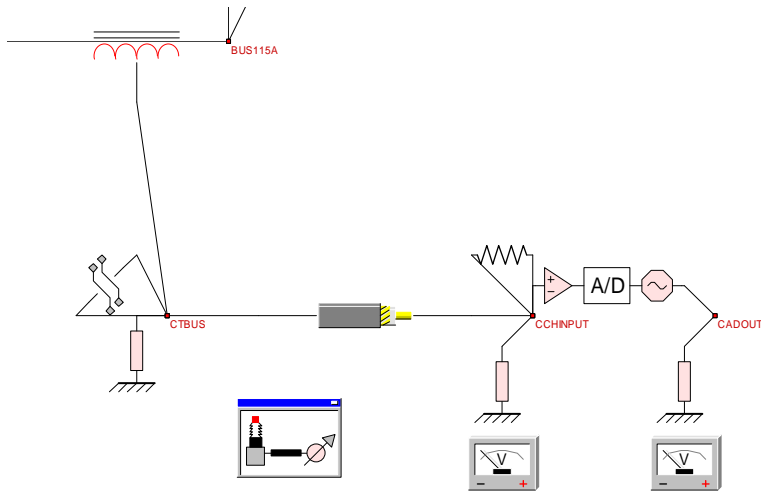


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Figure E.1—Computer model of a voltage instrumentation channel

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Figure E.2—Computer model of a current instrumentation channel

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1 **Annex D**
2 (informative)

3 **Instrument transformer characterization – steady state**

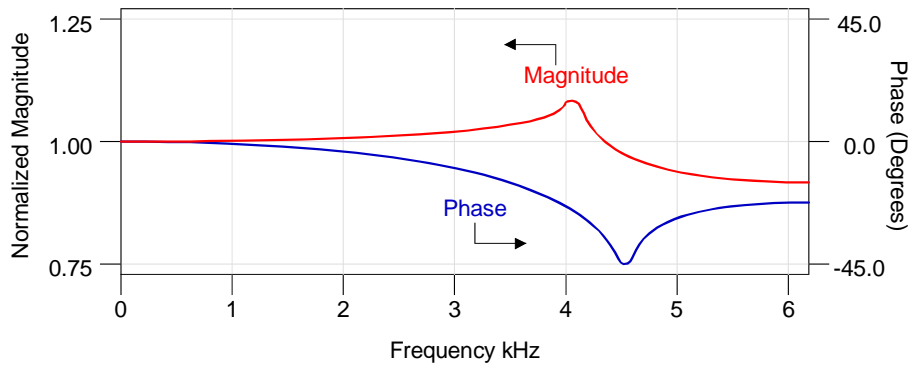
Comment [ARG42]: I'm confused about the relation between this Annex and the previous Annex. Annex C seems incomplete. Should this be a part of Annex C?

4 **D.1 General**

5 This section provides characterization of errors resulting from instrument transformers. The instrument
6 transformers that are considered are: current transformers, wound type voltage transformers or CCVTs.

7 **D.2 CT steady state response**

8 The conventional CT steady state response is very accurate. The steady state response can be extracted
9 from the frequency response of the device. Figure F.1 provides a typical frequency response of a CT. Note
10 that the response is flat in the frequency range of interest. It is important to note that errors may be present
11 due to inaccurate determination of the transformation ratio. These errors are typically small.



12 **Figure F.1—Typical 600 V metering class CT frequency response**

14 **D.3 VT steady state response**

15 Wound type VTs are in general less accurate than CTs. Again the steady state response can be obtained
16 from the frequency response of the device. Figure F.2 provides a typical frequency response of a wound
17 type VT. Note that the response is flat in a small frequency range around the nominal frequency. Our work
18 has shown that the higher the transformation ratio of the VT, the higher the errors will be.

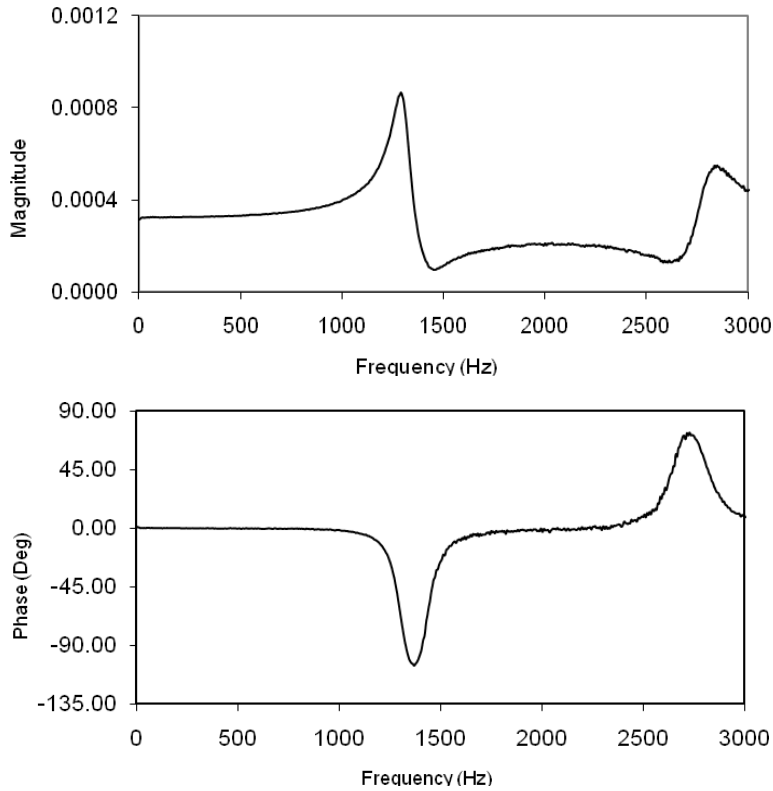


Figure F.2—200kV/115V potential transformer frequency response

D.4 CCVT steady state response

By appropriate selection of the circuit components, a CCVT can be designed to generate an output voltage with any desirable transformation ratio, and most importantly with zero phase shift between input and output voltage waveforms. In this section the possible deviations from this ideal behavior due to various causes by means of a parametric analysis are examined, namely:

- Power frequency drift
- Circuit component parameter drift
- Burden impedance

The parametric analysis was performed using the CCVT equivalent circuit model illustrated in Figure F.3.

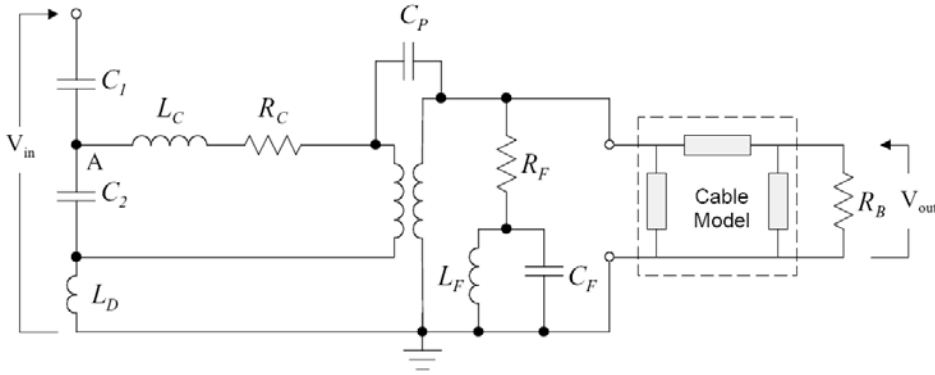


Figure F.3—CCVT equivalent model

The model parameters are given in Table F.1.

Table F.1—CCVT equivalent circuit parameters

Parameter Description	Schematic Reference	Value
CCVT Capacitance Class		Normal
Input Voltage		288 kV
Output Voltage		120 V
Upper Capacitor Size	C1	1.407 nF
Lower Capacitor Size	C2	99.9 nF
Drain Inductor	LD	2.65 mH
Compensating Reactor Inductance	LC	68.74 H
Compensating Reactor Resistance	RC	3000 Ohms
Burden Resistance	RB	200 Ohms
Ferroresonance Suppression Damping Resistor	RF	70 Ohms
Ferroresonance Suppression Circuit Inductor	LF	0.398 H
Ferroresonance Suppression Circuit Capacitor	CF	17.7 uF
Cable Type		RG-8
Cable Length		100 Feet
Transformer Power Rating		300 VA
Transformer Voltage Rating		4kV/120V
Leakage Reactance		3%
Parasitic Capacitance	CP	500 pF

Figure F.4 shows the results of a frequency scan. Note that over the frequency range of 0 to 500 Hz the response varies substantially both in magnitude and phase. Near 60 Hz (55 to 65 Hz) the response magnitude is practically constant but the phase varies at the rate of 0.25 degrees per Hz.

1 Table F.2 shows the results of a parametric analysis with respect to burden resistance and instrumentation
 2 cable length. Note that the system is tuned for zero phase error for a short instrumentation cable and with a
 3 200 Ohm Burden.

4 Table F.3 shows the results of a parametric analysis with respect to CCVT component parameter
 5 inaccuracies. Specifically the varied parameters were the compensating reactor inductance and the
 6 capacitive divider capacitance.

7 **Table F.2—Phase error (in degrees) vs burden resistance and cable length**

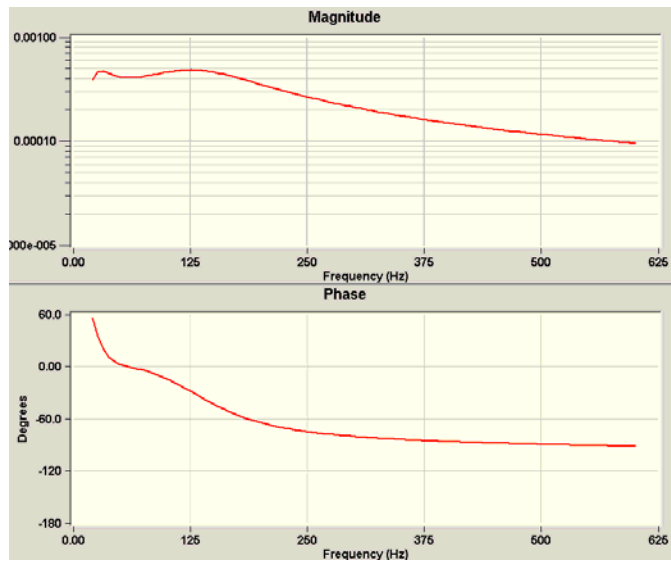
Burden Resistance (Ohms)	Cable length (feet)		
	10	1000	2000
50	0.077	-0.155	-0.365
100	0.026	-0.096	-0.213
200	0.000	-0.063	-0.127
400	-0.013	-0.047	-0.080
1000	-0.022	-0.036	-0.052

8

9 **Table F.3—Phase error (in degrees) vs capacitance and inductance**

Capacitance Error(%)	Inductance Error (%)		
	0	1	5
0	0.000	-0.066	-0.331
-1	-0.066	-0.132	-0.397
-5	-0.330	-0.396	-0.661

10



11

12

Figure F.4—CCVT Computed Frequency Response over 10-600 Hz

1 **D.5 MOCT steady state response**

2 MOCTs are relatively very accurate devices for magnitude (typical accuracy 0.1%) but relatively
3 inaccurate in time (phase). Typical time latencies are in the order of 30 to 50 microseconds. This translates
4 to 0.648 degrees to 1.08 degrees phase error at 60 Hz.

5 **D.6 EOVT steady state response**

6 EOVTs are relatively very accurate devices for magnitude (typical accuracy 0.1% to 1%) but relatively
7 inaccurate in time (phase). Typical time latencies are in the order of 30 to 50 microseconds. This translates
8 to 0.648 degrees to 1.08 degrees phase error at 60 Hz.

1 Annex E

2 (informative)

3 Instrument transformer characterization – transients

4 E.1 General

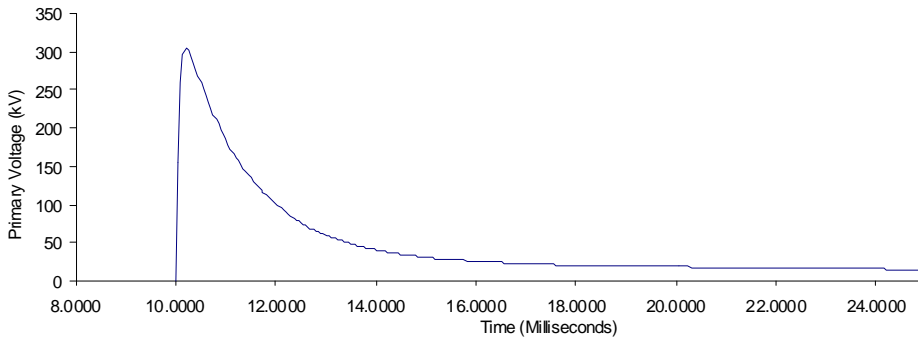
5 This section provides characterization of errors resulting from instrument transformers during transients.
6 The instrument transformers that are considered are: current transformers, wound type voltage
7 transformers, CCVTs, MOCTs and EOVTs.

8 E.2 CT transient response

9 The conventional CT transient response depends on the frequency content.

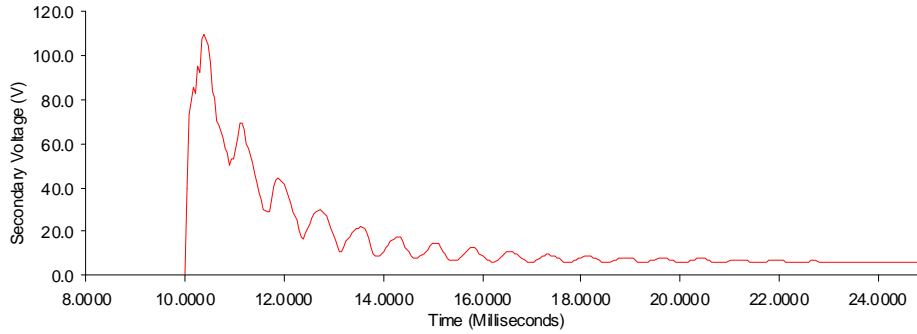
10 E.3 Wound VT transient response

11 The transient response of potential transformers can be determined from frequency response tests, using
12 Fourier transformation techniques, or by direct time domain test. Figure G.1 and Figure G.2 illustrate the
13 measurement data from a direct time domain test, performed on the same VT for which the frequency
14 response was given. A double exponential waveform was applied across the primary winding, while both
15 primary (Figure G.1) and secondary (Figure G.2) voltage waveforms are recorded. Note the 1250 Hz
16 oscillation on the secondary voltage due to resonance.



17

18 **Figure G.1—C(x) Transient response of a 200kV / 65V VT open circuit secondary. Primary**
19 **voltage waveform.**



(b)

Figure G.2—C(x) Transient response of a 200kV / 65V VT open circuit secondary.
Secondary voltage waveform.

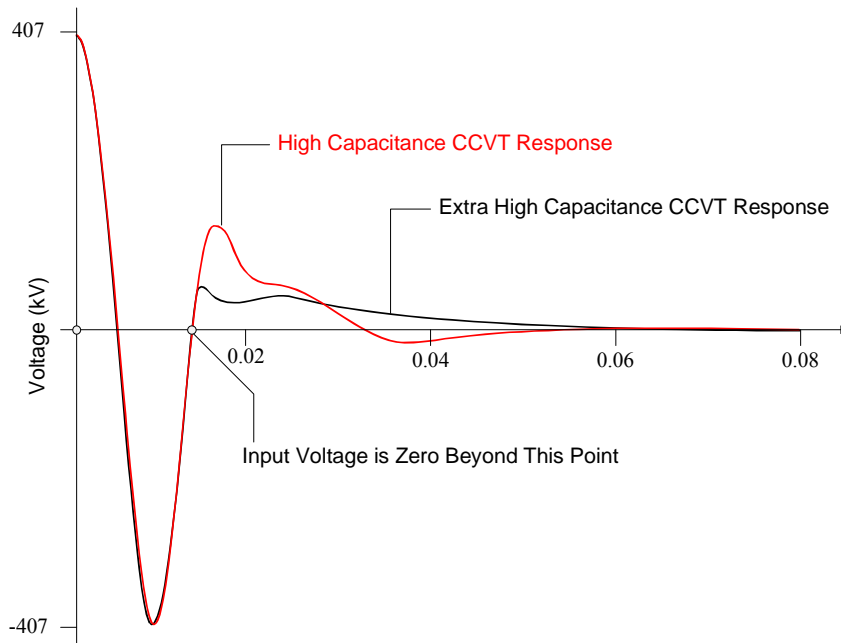
E.4 CCVT transient response

The transient response of CCVTs is quite complex. Early CCVT's suffered from poor transient response, typically lasting up to two power frequency cycles. The main reason for this is the resonance between the divider capacitance and the compensating reactor inductance. The main factors affecting the CCVT transient response duration and magnitude of the resulting measurement errors are:

- Divider capacitance value
- Burden resistance
- Ferroresonance circuit type (active versus passive)
- Input waveform characteristics

In general, the higher capacitance CCVTs have better transient response. This is illustrated in [Figure G.3](#), which shows typical transient response for two CCVT classes: 1) High capacitance, and 2) Extra high capacitance. The input waveform is sinusoidal up to the zero crossing at 0.012 seconds, and remains at zero beyond this time. The both transient response outputs last for about 0.04 seconds, however the transient amplitude of the extra high capacitance CCVT is substantially lower [IEEE Standard 1344-1995; IEEE Standard C37.118].

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Figure G.3—CCVT Transient Response

E.5 MOCT transient response

At present data of transient response of MOCTs are not available. Test data from manufacturers will continue to be sought.

E.6 EOVT transient response

At present data of transient response of EOVTs are not available. Test data from manufacturers will continue to be sought.

1 Annex F

2 (informative)

3 System errors

4 This section provides characterization of errors resulting from system asymmetries and imbalances.

5 The imbalances affect the computation of the positive sequence phasors. In the case that an application uses
6 the individual phase phasors directly, the imbalance will be treated within the application. This section
7 provides characterization of the error performed when there is certain imbalance and neutral voltage shift.

8 First, it is important to recognize the following fact: the computation of the positive sequence phasors is
9 independent of whether the inputs to the GPS-synchronized device is line-to-line voltages or phase to
10 neutral voltages. However, the results will be shifted by a specific phase angle. Specifically the following
11 relationships hold:

$$V_{LL}^+ = \frac{1}{3}(\tilde{V}_{ab} + a\tilde{V}_{bc} + a^2\tilde{V}_{ca}) = \frac{a^2(a-1)}{3}[\tilde{V}_a + a\tilde{V}_b + a^2\tilde{V}_c] = \sqrt{3}e^{j30^\circ}\tilde{V}_{LN}^+$$

12
13 In other words for computation of the positive sequence phasors, using the line-to-line voltages or the phase
14 voltages (phase to neutral) will yield the same answer with the exception of a constant factor.

15 Here parametric analysis of the positive sequence phasor errors as a function of 1) Percent negative
16 sequence (0, 1, 2 and 4%), 2) Percent zero sequence (0, 1, 2 and 4%), and 3) Percent neutral voltage shift
17 (0, 0.1, 0.2, 0.5%) is provided. In all of these analyses it is assumed that the phase A phasor is 1.0 pu and at
18 zero phase angle.

1 **Annex G**
2 (informative)

3 **Instrumentation nominal accuracy/standards**

4 This section provides typical data for CTs and VTs utilized in a measurement circuit for GPS-synchronized
5 measurements. The emphasis is on standard instrumentation characteristics.

6 The 0.02 degree accuracy given to the PMU by the GPS signals is usually not achievable in practice, due
7 mostly to the magnitude and phase errors caused by the instrument transformers used to obtain the signal
8 from the power system. The magnetizing current drawn by the transformer's core and the current drawn by
9 the burden produce an impedance drop across the instrument transformers that results in a magnitude and
10 phase error in the secondary signal compared to that of an ideal transformer. Industry standards set classes
11 for instrument transformers based on the allowed limits in the phase and magnitude errors of the secondary
12 signal.

13 Testing of the instrument transformers prior to installation can be performed to determine a more accurate
14 phase and magnitude error of each individual transformer that will allow the use of correction factors to
15 reduce the error in the measurements. Unfortunately for installed transformers, testing is not possible and
16 the only error information available is obtained from the transformer class limits as set by the existing IEEE
17 and IEC standards. The magnitude and phase errors required by the different standards are presented in
18 tables at the end of this document. Tests have been proposed that will allow field determination of the
19 transformer and instrumentation error using state estimation techniques [Hamrita, Heck and Meliopoulos
20 2001].

21 The following tables show the maximum limits on the transformers for the different standards with the
22 magnitude of errors expressed in per unit and the phase errors expressed in degrees and microseconds for
23 60Hz signals. Phase errors shall be doubled when referenced phasor are being used. Actual devices under
24 normal operating conditions (no faults) exhibit much lower errors. Optical PTs and CTs (EOVT and
25 MOCTs) present a special case as these devices are internally quite accurate but the final output exhibits
26 time latencies in the order of 40 to 70 microseconds which translates to a substantial phase error.

27 **Table I.1—Maximum magnitude and phase error for ANSI class type CTs**

ANSI CT Type	Load Current (%)	Max. Magnitude Error pu	Max. Phase Error (degrees)	Max. Phase Error (μseconds)
Relaying	10 to 2000	0.10	Not tested	Not tested
Metering 1.2	10	0.024	2.08	96
	100	0.012	1.04	48
Metering 0.6	10	0.012	1.04	48
	100	0.006	0.52	24
Metering 0.3	10	0.006	0.52	24
	100	0.003	0.26	12

28

29 **Table I.2—Maximum magnitude and phase error for ANSI class VTs**

ANSI VT Type	Max. Magnitude ± Error P.U.	Max. Phase Error (± degrees)	Max. Phase Error (± μseconds)
--------------	-----------------------------	------------------------------	-------------------------------

Relaying	0.1	Not tested	Not tested
Metering 1.2	0.012	2.08	96
Metering 0.6	0.006	1.04	48
Metering 0.3	0.003	0.52	24

1

2

Table I.3—Maximum magnitude and phase errors of IEC class CTs

IEC CT Type	Load	Max. Magnitude Error \pm P.U.	Max. Phase Error \pm degrees	Max. Phase error \pm μ seconds
Relay Type 10P	100%	0.1	Not tested	Not tested
	max. limit	0.5	Not tested	Not tested
Relay Type 5P	100%	0.3000	2.000	92.6
	max. limit	1.0000	2.000	92.6
Metering Type 1.0 Accuracy	5%	0.0300	6.000	277.8
	20%	0.0150	3.000	138.9
	100%	0.0100	2.000	92.6
	120%	0.0100	2.000	92.6
Metering Type 0.5 Accuracy	5%	0.0150	3.000	138.9
	20%	0.0075	2.000	92.6
	100%	0.0050	1.000	46.3
	120%	0.0050	1.000	46.3
Metering Type 0.2 accuracy	5%	0.0075	1.000	46.3
	20%	0.0035	0.500	23.1
	100%	0.0020	0.167	7.7
	120%	0.0020	0.167	7.7
Metering Type 0.1 Accuracy	5%	0.0040	0.500	23.1
	20%	0.0020	0.333	15.4
	100%	0.0010	0.167	7.7
	120%	0.0010	0.167	7.7

3

1 **Annex H**

2 (informative)

3 **Description of typical instrumentation channels**

4 **H.1 General**

5 This section provides a set of typical instrumentation channels. In selecting the instrumentation channels
6 the following have been considered.

7 Voltage Transformer technologies include:

- 8 • Wound type Potential Transformers (PT)
- 9 • Capacitive Coupled Voltage Transformers (CCVT)
- 10 • Capacitive Voltage Dividers (CVD)
- 11 • Resistive Voltage Dividers (RVD)

12 Generally voltage dividers provide accurate wide bandwidth measurements with flat frequency response;
13 however, these technologies are limited to laboratory grade instrumentation. In high voltage power system
14 applications (outdoor relaying and metering units), PTs and CCVTs are commonly used.

15 Current transformers are typically core type transformers with current output. The ratings depend on the
16 maximum permissible voltage that can be developed on the secondary before saturation occurs. For PMU
17 type applications, saturation is not a concern as the current through the CT is typically much lower than the
18 capability of the CT.

19 A number of instrumentation channels have been defined. The parameters of these instrumentation
20 channels have been selected to represent near actual systems. They have been constructed by considering
21 combinations of the following important instrumentation channel parameters: CT types, VT types, CCVT
22 types, communication cable (type, shielded/unshielded, length). Other instrumentation channels based on
23 optical CTs and VTs have not considered.

24 The typical instrumentation channels listed here have been constructed from data provided by Entergy and
25 TVA. Additional input from other utilities is solicited. Using this typical instrumentation channels, the
26 errors introduced are evaluated and tabulated.

27 **H.2 Description of the typical instrumentation channels**

28 The instrumentation channels are defined in terms of the following:

- 29 • Instrument transformer (ratio, impedance, parasitic capacitance)
- 30 • Cable type, size and length
- 31 • Attenuators, if present
- 32 • Burden

- Intelligent Electronic Device (in this case PMU)

Table J.1—Lists of test instrumentation channel models

I-Channel # & Type	I-XFMR	Cable	Attenuators	Burden	IED
1 – V (PT)	69kV:69V, 2.5%, 25nF	RG-8, 200 feet	1.0	10,000	16 bit, 2V, Sigma/delta
2 – V (PT)	199kV:115V, 2.5%, 50nF	RG-8, 200 feet	0.1, 300 ohm	10,000	16 bit, 2V, Sigma/delta
3 – C (CT)	600A:5A, 1%, negligible	RG-8, 200 feet	1.0	0.14	12 bit, 10V, multpx
4 – C (CT)	3000A:5A, 1%, negligible	RG-8, 200 feet	1.0	0.14	16 bit, 2V, Sigma/delta
5 – V (CCVT)	288kV:120V, 1.5%, 100nF	RG-8, 200 feet	0.1, 300 ohm	10,000	12 bit, 10V, multpx

The error characterization for each one of these channels is as follows.

- VT Instrumentation Channels: The voltage magnitude error is defined as the percentage difference between the primary voltage of the PT and voltage seen by the relay scaled by a nominal factor $k_{nominal}$. That is:

$$\%Error_{V,magnitude} = \left| \frac{V_{primary} - k_{nominal} \cdot V_{relay}}{V_{primary}} \right| \times 100\%$$

$$\text{where: } k_{nominal} = \frac{V_{primary,nominal}}{V_{relay,nominal}}$$

In addition, the phase error is defined as the phase angle difference between the reading at the primary side of the PT and voltage reading seen by the relay.

- CT Instrumentation Channels: The current magnitude error is defined as the percentage difference between the primary current of the CT and voltage seen by the relay scaled by a nominal factor $k_{nominal}$. That is:

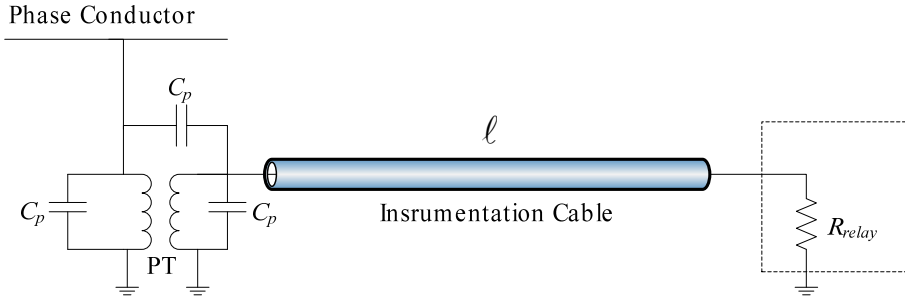
$$\%Error_{I,magnitude} = \left| \frac{I_{primary} - k \cdot I_{relay}}{I_{primary}} \right| \times 100\%$$

In addition, the phase error is defined as the phase angle difference between the current reading at the primary side of the PT and current reading seen by the relay.

H.3 Potential transformer instrumentation channel error

Each potential transformer instrumentation channel defined above (cases 1 and 2) have been analyzed and the error introduced from each component of the channel has been tabulated. Therefore, these results provide a quantitative analysis of the impact of the potential transformer instrumentation channel on the quality and accuracy of the data from PMUs.

The PT instrumentation channel model is shown in Figure J.1. The model includes the effect of parasitic capacitances and instrumentation cable. The relay burden is also model by a large resistance (typically in the order of few thousand ohms).



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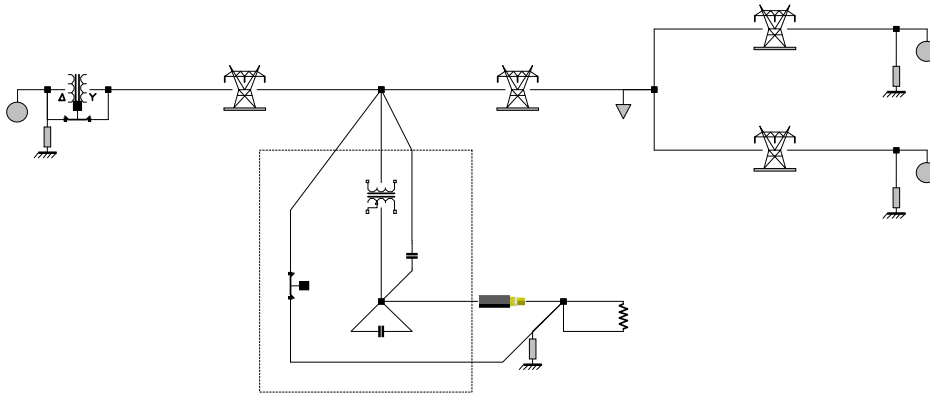
Figure J.1—PT instrumentation channel model parameters

3

The system that is used to perform this parametric analysis is shown in Figure J.2. The simulation is performed for different values of the model parameters. The error is quantified in terms of magnitude and phase error.

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Figure J.2—System model used for PT instrumentation channel error characterization

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H.3.1 Case 1: 69kV/69V PT

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The base case model parameters are shown in Table J.2. The error results are shown in Table J.3, Table J.4, Table J.5 and Table J.6.

10

11

Table J.2—Base-case parameters for 69kV/69V PT instrumentation channel model simulation

12

13

Parameter Description	Value
Nominal Ratio	69kV/69
PT VA rating	30 kVA
PT Resistance	0.01 pu
PT leakage reactance X_l	0.06 pu

PT Nominal Core Loss	0.005 pu
PT Nominal Magnetization Current	0.005 pu
PT parasitic capacitance C_p	25 nF
Instrumentation cable type	#10 Copper Pair
Instrumentation cable length ℓ	200 ft
Relay burden resistance R_B	10 k Ω

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Table J.3—69kV/69V PT instrumentation channel voltage magnitude error in % for different burden resistances

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	500	800
5k	0.007	0.009	0.012	0.015
10k	0.008	0.010	0.012	0.015
20k	0.008	0.010	0.012	0.015

4

5

6

Table J.4—69kV/69V PT instrumentation channel voltage phase error in degrees for different burden resistances

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	500	800
5k	0.07	0.10	0.15	0.23
10k	0.05	0.08	0.12	0.18
20k	0.05	0.08	0.12	0.18

7

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Table J.5—69kV/69V PT instrumentation channel voltage magnitude error in % for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	500	800
10	0.004	0.006	0.016	0.025
25	0.010	0.015	0.030	0.045
50	0.020	0.037	0.090	0.158

10

11

12

Table J.6—69kV/69V PT instrumentation channel voltage phase error in degrees for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	500	800
10	0.06	0.12	0.26	0.49
25	0.14	0.27	0.67	1.07
50	0.28	0.59	1.30	2.21

13

H.3.2 Case 2: 199kV/69V PT

The base case model parameters are shown in Table J.7. The error results are shown in Table J.8, Table J.9, Table J.10 and Table J.11.

Table J.7—Base-case parameters for 69kV/69V PT instrumentation channel model simulation

Parameter Description	Value
Nominal Ratio	199kV/69
PT VA rating	30 kVA
PT Resistance	0.01 pu
PT leakage reactance X_ℓ	0.025 pu
PT Nominal Core Loss	0.005 pu
PT Nominal Magnetization Current	0.005 pu
PT parasitic capacitance C_p	50 nF
Instrumentation cable type	#10 Copper Pair
Instrumentation cable length ℓ	200 ft
Relay burden resistance R_B	10 k Ω

Table J.8—199kV/69V PT instrumentation channel voltage magnitude error in % for different burden resistances

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
5k	0.009	0.016	0.22	0.52
10k	0.009	0.015	0.19	0.48
20k	0.009	0.014	0.18	0.41

Table J.9—199kV/69V PT instrumentation channel voltage phase error in degrees for different burden resistances

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
5k	0.121	0.212	0.425	0.638
10k	0.115	0.198	0.411	0.614
20k	0.115	0.196	0.399	0.589

Table J.10—199kV/69V PT instrumentation channel voltage magnitude error in % for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
25	0.008	0.012	0.17	0.41
50	0.009	0.015	0.19	0.48
75	0.015	0.026	0.22	0.61

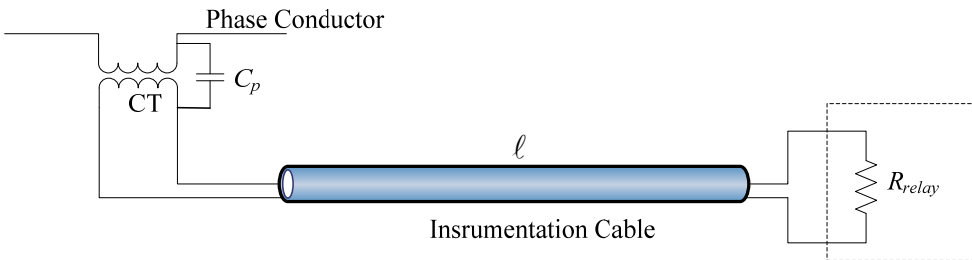
1 **Table J.11—199kV/69V PT instrumentation channel voltage phase error in degrees for**
 2 **different parasitic capacitances**

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
25	0.090	0.185	0.382	0.538
50	0.115	0.198	0.411	0.614
75	0.196	0.235	0.479	0.779

3
4
5 **H.4 Current transformer instrumentation channel error**

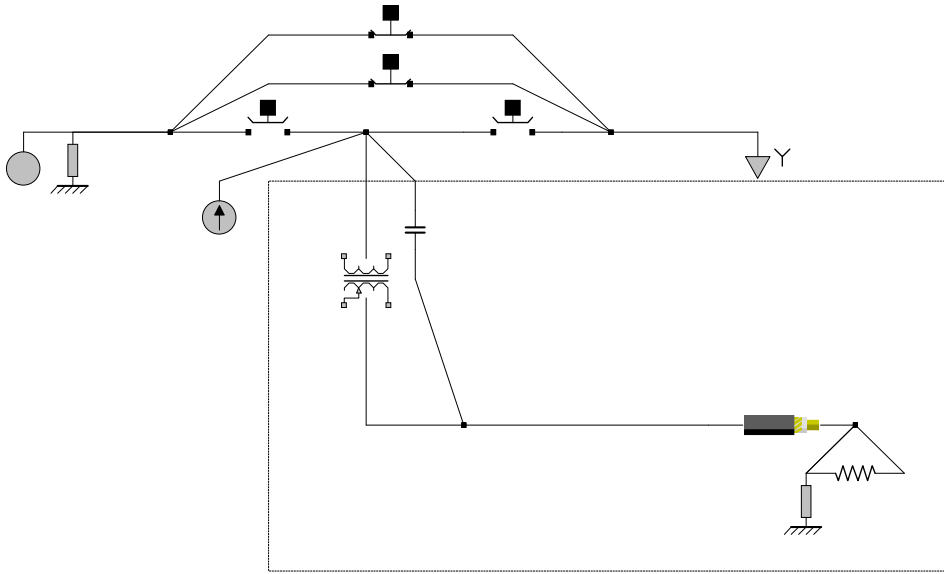
6 Each current transformer instrumentation channel defined above (cases 3 and 4) has been analyzed and the
 7 error introduced from each component of the channel has been tabulated. Therefore, these results provide a
 8 quantitative analysis of the impact of the current transformer instrumentation channel on the quality and
 9 accuracy of the data from PMUs.

10 The CT instrumentation channel model is shown in Figure J.3. The model includes the parasitic
 11 capacitances and instrumentation cable. The relay burden is also modeled (usually 0.1 or 0.14 ohms).



12
13 **Figure J.3—CT instrumentation channel model parameters**

14 The system that is used to perform this parametric analysis is shown in Figure J.4. The simulation is
 15 performed for different values of the model parameters. The error is quantified in terms of magnitude and
 16 phase error.



1

2 **Figure J.4—System model used for CT instrumentation channel error characterization**

3 **H.4.1 Case 3: 600/5A CT**

4 The base case model parameters are shown in Table J.12. The error results are shown in Table J.13, Table
5 J.14, Table J.15 and Table J.16.

6 **Table J.12—Base-case parameters for 600/5A CT instrumentation channel model**
7 **simulation**

Parameter Description	Value
Nominal Ratio	600/5A
CT VA rating	300 VA
CT Resistance	0.001 pu
CT leakage reactance X_l	0.003 pu
CT Nominal Core Loss	0.004 pu
CT Nominal Magnetization Current	0.005 pu
CT parasitic capacitance C_p	5 nF
Instrumentation cable type	#10 Pair
Instrumentation cable length ℓ	200 ft
Relay burden resistance R_B	0.05Ω

8

9 **Table J.13—600/5A CT instrumentation channel voltage magnitude error in % for different**
10 **burden resistances**

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
0.1	0.066%	0.066%	0.066%	0.066%

0.14	0.066%	0.066%	0.066%	0.066%
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Table J.14—600/5A CT instrumentation channel voltage phase error in degrees for different burden resistances

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
0.1	0.03°	0.04°	0.09°	0.23°
0.14	0.03°	0.04°	0.09°	0.23°

Table J.15—600/5A CT instrumentation channel voltage magnitude error in % for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
1	0.06656%	0.06656%	0.06656%	0.06656%
5	0.06656%	0.06656%	0.06656%	0.06656%
10	0.06656%	0.06656%	0.06656%	0.06656%

Table J.16—600/5A CT instrumentation channel voltage phase error in degrees for different parasitic capacitances

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
1	0.02°	0.03°	0.08°	0.20°
5	0.03°	0.04°	0.09°	0.23°
10	0.05°	0.08°	0.14°	0.32°

H.4.2 Case 4: 3000/5A CT

The base case model parameters are shown in Table J.17. The error results are shown in Table J.18, Table J.19, Table J.20 and Table J.21.

Table J.17—Base-case parameters for 3000/5A CT instrumentation channel model simulation

Parameter Description	Value
Nominal Ratio	3000/5A
CT VA rating	500 VA
CT Resistance	0.001 pu
CT leakage reactance X_l	0.003 pu
CT Nominal Core Loss	0.004 pu
CT Nominal Magnetization Current	0.005 pu
CT parasitic capacitance C_p	5 nF
Instrumentation cable type	#10 Pair
Instrumentation cable length ℓ	200 ft
Relay burden resistance R_B	0.1 Ω

1
2 **Table J.18—3000/5A CT instrumentation channel voltage magnitude error in % for different**
3 **burden resistances**

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
0.1	0.066%	0.066%	0.066%	0.066%
0.14	0.066%	0.066%	0.066%	0.066%

4
5 **Table J.19—3000/5A CT instrumentation channel voltage phase error in degrees for**
6 **different burden resistances**

Burden Resistance R_B (Ω)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
0.1	0.03°	0.04°	0.09°	0.23°
0.14	0.03°	0.04°	0.09°	0.23°

7
8 **Table J.20—3000/5A CT instrumentation channel voltage magnitude error in % for different**
9 **parasitic capacitances**

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
1	0.066%	0.066%	0.066%	0.066%
5	0.066%	0.066%	0.066%	0.066%
10	0.066%	0.066%	0.066%	0.066%

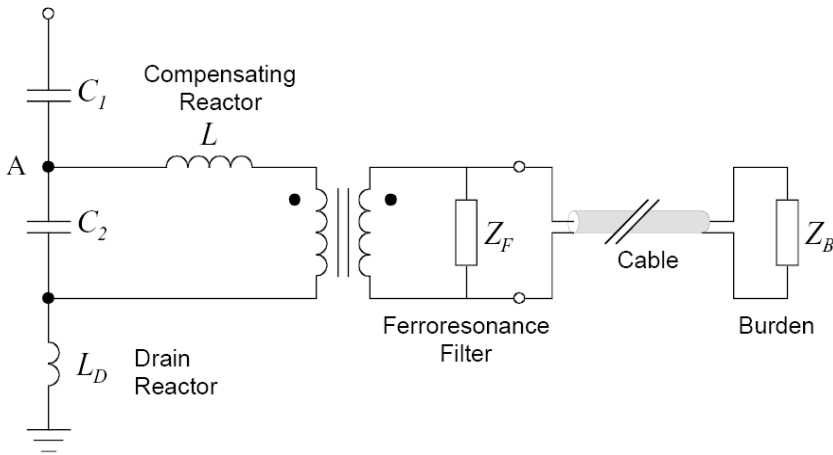
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11 **Table J.21—3000/5A CT instrumentation channel voltage phase error in degrees for**
12 **different parasitic capacitances**

Parasitic Capacitance C_p (nF)	Instrumentation Cable length ℓ (ft)			
	100	200	400	800
1	0.02°	0.03°	0.08°	0.20°
5	0.03°	0.04°	0.09°	0.23°
10	0.05°	0.08°	0.14°	0.32°

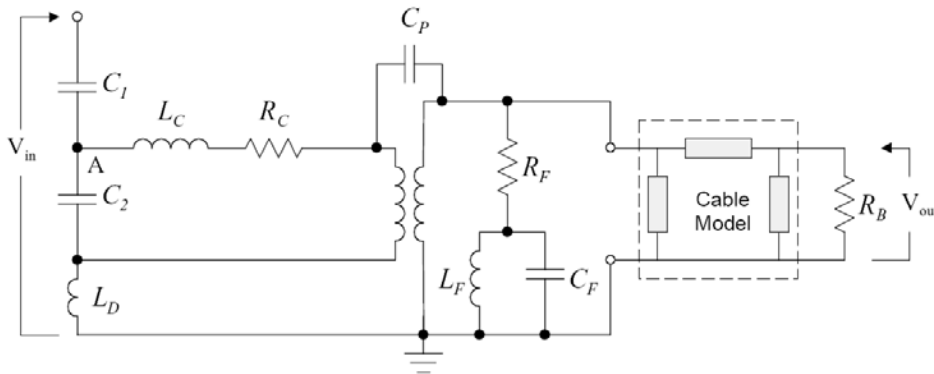
1 **H.5 CCCVT instrumentation channel error**

2 Each CCVT instrumentation channel defined above (case 5) has been analyzed and the error introduced
 3 from each component of the channel has been tabulated. Therefore, these results provide a quantitative
 4 analysis of the impact of the CCVT instrumentation channel on the quality and accuracy of the data from
 5 PMUs.

6 The basic CCVT configuration is illustrated in Figure J.5. The capacitive divider is formed by capacitors
 7 C1 and C2. In typical high voltage CCVTs (115-500kV), the capacitor values are selected so that the
 8 voltage at the tap point A is in the order of 4 to 10 kV. The transformer scales this voltage to standard
 9 instrumentation voltage level (e.g., 69V or 120V). The output of the transformer is connected to a burden
 10 via instrumentation cable (usually a coaxial cable). The burden represents the relay input impedance, which
 11 is typically resistive. Since the interaction of the capacitive divider and the resistive burden introduces
 12 considerable phase shift, a series inductor L is added to compensate the divider output capacitance. The
 13 CCVT equivalent model is shown in Figure J.6. Table J.22 summarizes the parameters of the CCVT model.



14
15 **Figure J.5—CCVT physical circuit**



16
17 **Figure J.6—CCVT equivalent model**

16
17
18

Table J.22—CCVT parameters summary

Parameter Description	Schematic Reference
Upper Capacitor Size	C_1
Lower Capacitor Size	C_2
Drain Inductor	L_D
Compensating Reactor Inductance	L_C
Compensating Reactor Resistance	R_C
Burden Resistance	R_B
Ferroresonance Suppression Damping Resistor	R_F
Ferroresonance Suppression Circuit Inductor	L_F
Ferroresonance Suppression Circuit Capacitor	C_F
Parasitic Capacitance	C_P

The inductor L is selected by setting the sum of the equivalent capacitive reactance and the inductive reactance to zero at the power frequency. Note that the Thevenin equivalent capacitive reactance at point A is the sum of the upper and lower leg capacitances, C_1+C_2 , thus:

$$j\omega L + \frac{1}{j\omega(C_1 + C_2)} = 0$$

or equivalently:

$$L = \frac{1}{\omega^2(C_1 + C_2)}$$

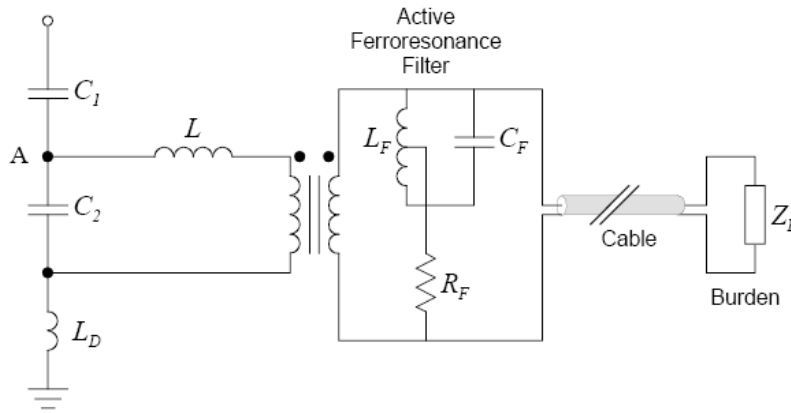
The Reactor L_D , known as the drain reactor, is for the purpose of power line carrier filtering and may be optionally shorted by a manual switch. For the purpose of low frequency analysis (0-1kHz) this reactor has negligible effect and is ignored.

In standard CCVT designs, typical values of capacitor dividers are selected so that the sum of the capacitances C_1+C_2 is in the order of 100 nF. The corresponding compensating reactor inductance for 60 Hz power frequency is in the order of 70 Henries. A reactor of such large inductance must have a magnetic core, and will also have a substantial resistance. As a result, the compensating reactor is also subject to saturation. Furthermore, its resistance makes the CCVT transformation ratio dependent on the burden resistance. Recently, CCVTs with larger capacitance values and smaller compensating reactors have become available. These devices exhibit improved transient response, as well as less sensitivity to burden resistance.

Some manufacturers classify CCVTs as 1) Normal Capacitance, 2) High Capacitance, 3) Extra High Capacitance, although the threshold values separating these classes are vague. CCVTs of total capacitance value (C_1+C_2) as high as 400 nF are presently commercially available.

The interaction of the transformer saturation characteristics with the divider capacitance makes this circuit subject to ferroresonance. Specifically, during transients, a resonance may occur at the frequency determined by the transformer magnetizing reactance and the circuit equivalent capacitance. This results in

1 overvoltages developing across the transformer which drive the core into saturation. This nonlinear high
 2 amplitude oscillation causes severe measurement errors and can damage the circuit components. For this
 3 reason, CCVTs include a ferroresonance suppression circuit, usually located across the transformer
 4 secondary winding (Z_F in Figure J.5). Several ferroresonance suppression circuit topologies are presently in
 5 use. These circuits are considered proprietary by some manufacturers, and thus the circuit details are not
 6 readily available. However, two generic circuit models capture the basic behavior of these filters: The
 7 “active” suppression circuit illustrated in Figure J.7, and the “passive” suppression circuit illustrated in
 8 Figure J.8.

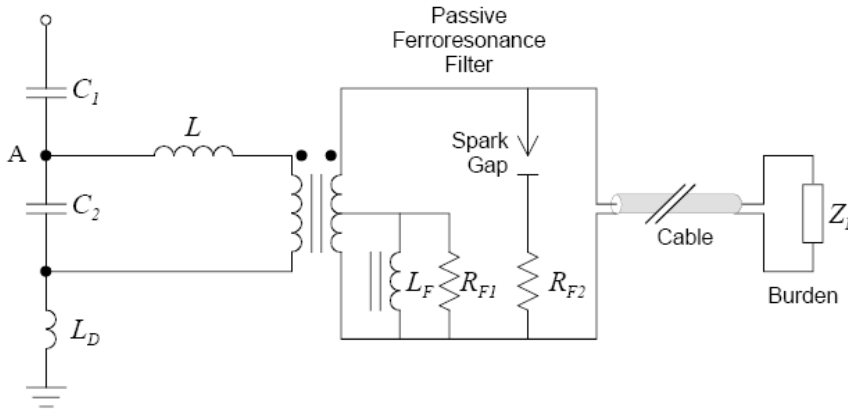


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10 **Figure J.7—Equivalent circuit of a CCVT with active ferroresonance suppression circuit**

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14 **Figure J.8—Equivalent circuit of a CCVT with passive ferroresonance suppression circuit**

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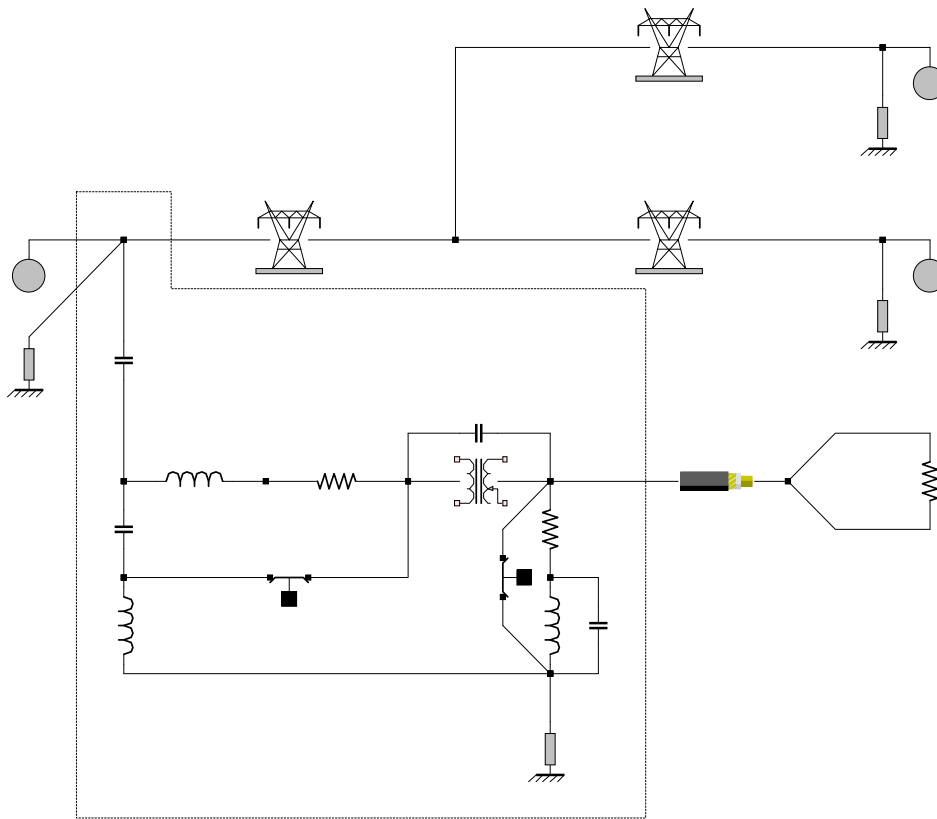
1 The active suppression circuit inductor L_F and capacitor C_F are tuned to the power frequency. Thus during
 2 normal steady state operation, the impedance of the L_F/C_F branch is very large and the suppression circuit
 3 draws negligible current. During transients, the impedance of L_F/C_F branch is lower and thus the resonating
 4 energy is dissipated through the filter resistor R_F .

5 The passive suppression circuit (see Figure J.8) consists of a saturable core reactor L_F and a damping
 6 resistor R_{F1} connected at the center tap of the transformer secondary, plus a spark gap in series with a
 7 second damping resistor R_{F2} .

8 During steady state 60 Hz operation, both of these filter circuits have negligible effect on the CCVT
 9 response. However during transients they generally prolong the CCVT transient response. It has been
 10 shown that CCVTs with passive ferroresonance suppression circuits have better transient response
 11 characteristics (error decays to negligible levels faster). They are also more expensive than active circuits.

12 The CCVT simulation model is shown in [Figure J.9](#). The model explicitly represents the upper and lower
 13 capacitors, the drain inductor, the compensating reactor inductance and resistance, ferroresonance
 14 suppression damping, the parasitic capacitance and the burden resistance. In addition, the control cable is
 15 modeled with an RG-8 copper cable model.

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Figure J.9—CCVT simulation model

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1 H.6 Case 5: 288kV:120V CCVT

2 The base case parameter values for this CCVT are given in Table J.23. The simulation is repeated for
3 different instrumentation cable lengths. In addition, different values of burden resistance, and different
4 inductance and capacitance values are used to generate the rest of the phase error results.

5 Table J.24 and Table J.25 summarize the voltage phase error results.

6 **Table J.23—Base-case CCVT instrumentation channel simulation parameters**

Parameter Description	Schematic Reference	Value
CCVT Capacitance Class		Normal
Input Voltage		288 kV
Output Voltage		120 V
Upper Capacitor Size	C_1	1.407 nF
Lower Capacitor Size	C_2	99.9 nF
Drain Inductor	L_D	2.65 mH
Compensating Reactor Inductance	L_C	68.74 H
Compensating Reactor Resistance	R_C	3000 Ohms
Burden Resistance	R_B	200 Ohms
Ferroresonance Suppression Damping Resistor	R_F	70 Ohms
Ferroresonance Suppression Circuit Inductor	L_F	0.398 H
Ferroresonance Suppression Circuit Capacitor	C_F	17.7 uF
Cable Type		RG-8
Cable Length		100 Feet
Transformer Power Rating		300 VA
Transformer Voltage Rating		4kV/120V
Leakage Reactance		3%
Parasitic Capacitance	C_P	500 pF

7

8 **Table J.24—Phase error (in degrees) versus burden resistance and cable length**

Burden Resistance (Ohms)	Cable Length (feet)		
	10	1000	2000
50	0.077	-0.155	-0.365
100	0.026	-0.096	-0.213
200	0.028	-0.063	-0.127
400	-0.013	-0.047	-0.800
1000	-0.022	-0.036	-0.520

1

2 **Table J.25—Phase error (in degrees) versus capacitance and inductance**

Capacitance Error (%)	Inductance Error (%)		
	0%	1%	5%
0	0.020	-0.066	-0.331
-1	-0.066	-0.132	-0.397
-5	-0.330	-0.396	-0.661

3

1 Annex I

2 (informative)

3 Control cables of typical instrumentation channels

4 This section provides a set of typical instrumentation channels. In selecting the instrumentation channels
5 the following have been considered.

6 LOW VOLTAGE POWER AND CONTROL CABLES IN SUBSTATIONS

7 600 and 1000 Volts SHIELDED

8 CROSS-LINKED POLYETHYLENE (XLPE) INSULATED

9 CHLORINATED POLYETHYLENE (CPE)

10 MULTIPLE CONDUCTOR CONTROL CABLES

- 11 a) The cables described in this document are 600 and 100 Volt, multiple conductor shielded control
12 cables.
- 13 b) The control cables supplied are suitable for installation in high-voltage (60-500 kV) substation
14 environments. The cables are suitable for installation indoors or outdoors (wet or dry); in raceway
15 of surface trench, duct, conduit, or cable tray.
- 16 c) The cables may not be suitable for installation in corrosive environments. Cables described in this
17 report, however, are suitable for installation in either grounded (100%) or ungrounded (133%)
18 electrical systems.
- 19 d) Some systems may be using 1000 Volt shielded multiple conductor XLPE-CPE cables – Samples
20 of the 1000 Volt Shielded conductor specification are covered in Table IA for PMU accuracy
21 considerations.

22 Notes: Over the course of history, the users may have:

- 23 • Interchangeably applied either the 1000 V or the 600 Volts XLPE based on market factors at the
24 time of application.
- 25 • Also, in some installations (power companies) cable splicing may be OK, and some users do not
26 permit splicing and require one continuous cable.
- 27 • Other factors such as availability of supply may require alternate cable of equal ratings to be used.
28 Therefore, a non-homogeneous low voltage cable environment may provide a more conservative
29 approach for voltage circuits.

30 Minimum 3000 feet (or 80% length of cable needed) continuous cables and increments of 500 feet
31 thereafter are common practice.

32 a) General

- 33 • Cables applicable requirements include.
- 34 • ICEA publications S-95-658 (NEMA WC 70) and S-73-532 (NEMA WC 57).
- 35 • Cable operating temperature range:

- 1 o Maximum conductor temperature of 90° C for normal operation, 130° C for emergency
2 overload conditions, and 250° C for short-circuit conditions.
- 3 o Suitable for operation in either wet or dry environments, indoors and outdoors.
- 4 b) Conductors
- 5 • Conductor Metal: Bare annealed copper.
- 6 o Requirements described in ASTM B 3.
- 7 • Some companies may use tinned copper conductor in place of bare conductor.
- 8 o Requirements described in ASTM B 33.
- 9 • Conductor Stranding:
- 10 o Class B concentric-lay-stranded in accordance with ASTM B-8 for copper conductors.
- 11 c) Insulation
- 12 • Flame retardant, heat and moisture resistant, thermosetting cross-linked polyethylene (XLPE)
13 or ethylene propylene rubber (EPR) compound.
- 14 • Minimum average insulation thickness are shown in Table K.1 and Table K.2. The minimum
15 thickness at any point not less than 90% of the specified minimum average thickness.

16 The tables below show typical specifications for 1000V (Table K.1) and 600V (Table K.2) low voltage
17 cables.

18 **Table K.1—1000 volt, shielded, XLPE insulated, CPE jacketed, multiple conductor control**
19 **cables**

Size AWG	Number of Conductors	Insulation Thickness (mils)	Shield Thickness (mils)	Jacket Thickness (mil)	Nominal OD (in)
#12	7	45	5	60	0.7500
#12	4	45	5	60	0.5500
#10	7	45	5	80	0.8500
#10	4	45	5	60	0.6500
#8	7	55	5	80	1.1000
#8	4	55	5	80	0.9000
#6	4	55	5	80	1.0000
#4	4	55	5	80	1.2500

20

21 **Table K.2—600 volt, shielded, XLPE or EPR insulated, CPE or CSPE jacketed, multiple**
22 **conductor control cables**

Size AWG	Number of Conductors	Insulation Thickness (mils)	Shield Thickness (mils)	Jacket Thickness (mil)	Nominal OD (in)
#12	7	30	5	60	0.5970
#12	4	30	5	45	0.4773

#10	7	30	5	60	0.6690
#10	4	30	5	60	0.5651
#8	7	45	5	80	0.8890
#8	4	45	5	60	0.7097
#6	4	45	5	60	0.8013
#4	4	45	5	80	0.9570

1
2**Table K.3—Insulation properties**

Property	Requirement (max/Min)
Original Physicals	
Tensile Strength, psi	1800 (min) for XLPE, 700 (min) for EPR
Elongation, %	250 (min)
Air-Oven Aging, after 7 days @ 121 degrees C	
Tensile Strength, % retained	75 (min)
Elongation, % retained	75 (min)
Hot Creep @ 150 degrees C	
Elongation, %	100 (max)
Set, %	5 (max)
Accelerated Water Absorption	
Dielectric Constant (SIC) 24 Hours	4.0 (max) *
Increase in capacitance, %	
1 to 14 days	3.0 (max) for XLPE, 3.5 (max) for EPR
7 to 14 days	1.5 (max)
Stability Factor, after 14 days	1.0 (max)
Alternate to Stability Factor	0.5 (max)

3 * Requirement is more stringent than ICEA S-95-658 & ICEA S-73-532

1 **Annex J**

2 (informative)

3 **Responses summary to questionnaire on PMU installation**4 **J.1 Introduction**

Comment [ARG43]: What was the date of this survey? Readers will need to know how current these results are.

5 The Performance and Standards Task Team (PSTT) of the Eastern Interconnection Phasor Project (EIPP) in
6 the process of creating a guideline for installation and maintenance of Phasor Measurement Units (PMUs)
7 sent a survey to PMU users participating in the EIPP. The intent of the survey was to collect data to reduce
8 some of the possible installation problems, provide some reference for PMU maintenance, and create a
9 general and practical guideline to future users.

10 Where applicable, multiple choice answers were provided, but users were encouraged to add any
11 comments, explanations or questions. It is worth mentioning that some responses were received from
12 companies that do not possess PMUs but are planning to install them and/or use them in the near future.

13 The following sections of this document provide a summary of the responses of the 17 companies that
14 answer the survey. The comments received from the different companies for some of the question are also
15 listed. After reviewing the responses to the questioner, the PSTT realized the limitations of the multiple
16 choice options, and recommends that numerical answer be requested in future questioners.

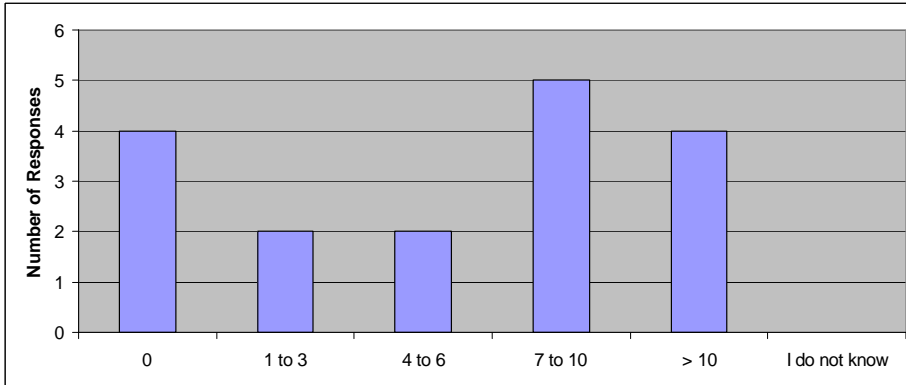
17 **Table L.1—List of responding companies**

Company	Contact
American Electric Power	Sanjoy K Sarawgi
Alberta Electric System Operator	Darren McCrank
Ameren	Rajesh Pudhota
Arizona Public Service Co.	Douglas Selin
BC Hydro	Harry Lee
Bonneville Power Administration	Ken Martin
Entergy	Floyd Galvan
Florida Power and Light	Don Mcinnis
Hydro Quebec	Danielle McNabb
Michigan Electric Transmission Company	Paul Myrda
MidAmerican	Mark Albright
New York ISO	Dean Ellis
New York Power Authority	Bruce Fardanesh
PG&E	Fred Henderson
PJM	Jon Ponder
Southern Company	Lee Taylor
Tennessee Valley Authority	Ory Shannon

18

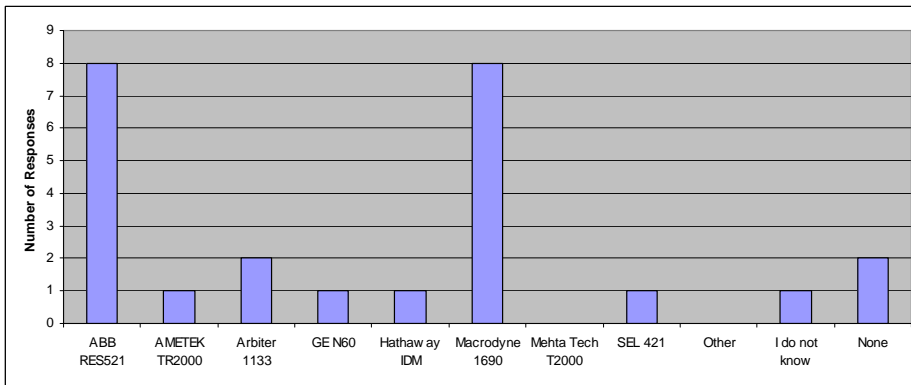
1 **J.2 General Information**

2 **J.2.1 How many PMUs does your company currently own?**



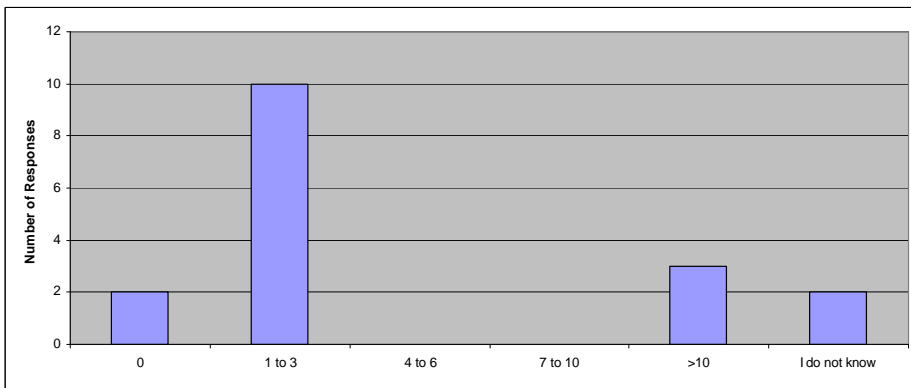
3

4 **J.2.2 What are the models of the PMUs your company currently owns?**



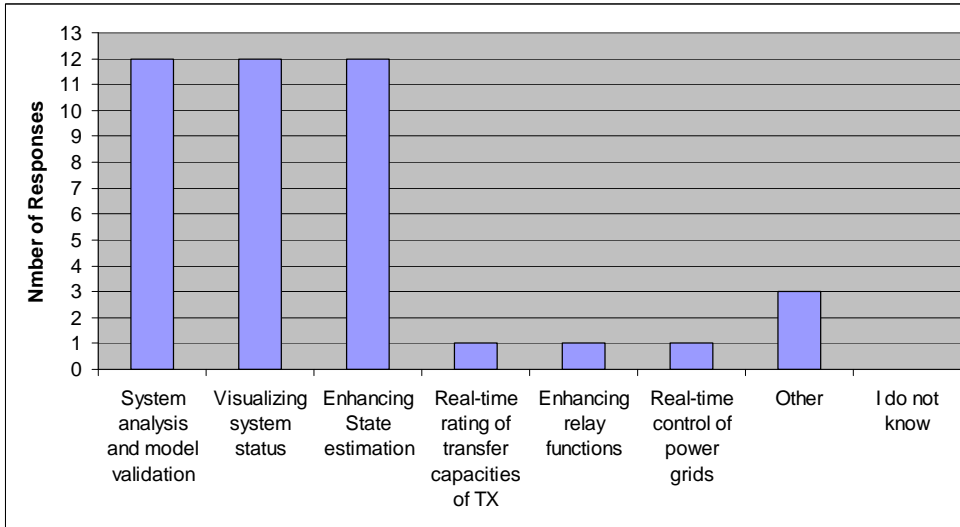
5

6 **J.2.3 How many PMUs is your company planning to install over the next year?**



7

1 **J.2.4 What applications are you using, or do you plan to use, the PMUs for**

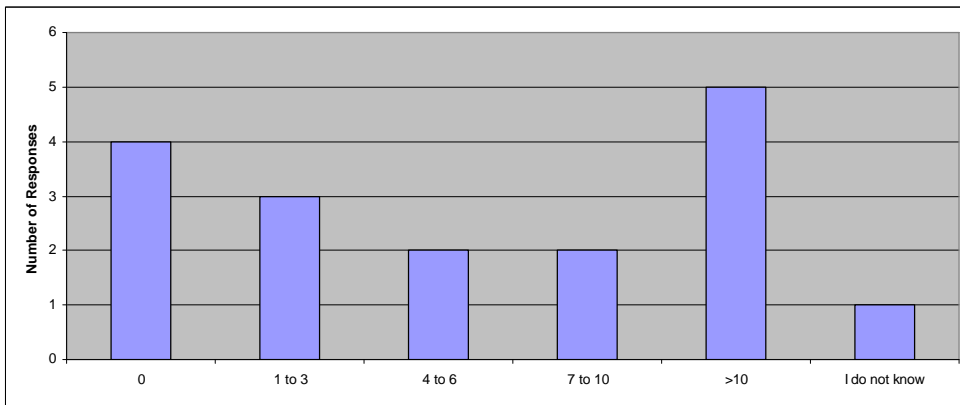


2

3 Other:

- 4 • Detection of geomagnetic activity. High accuracy frequency monitoring. Accumulated time error monitoring (Hydro Quebec).
- 5
- 6 • Potential subsynchronous resonance condition near a critical power plant but suspect that the relay sample rates, processing, and memory are inadequate (MidAmerican).
- 7
- 8 • Monitoring the units (Ameren).

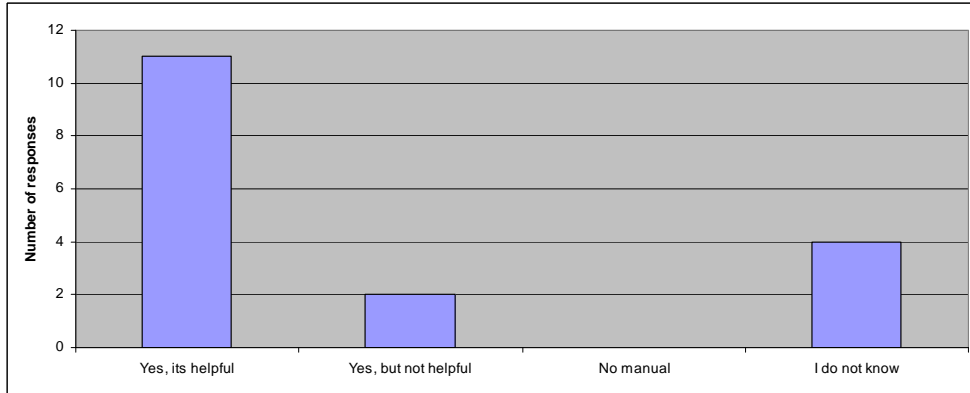
9 **J.2.5 How many years since the first PMU was installed in your company?**



10

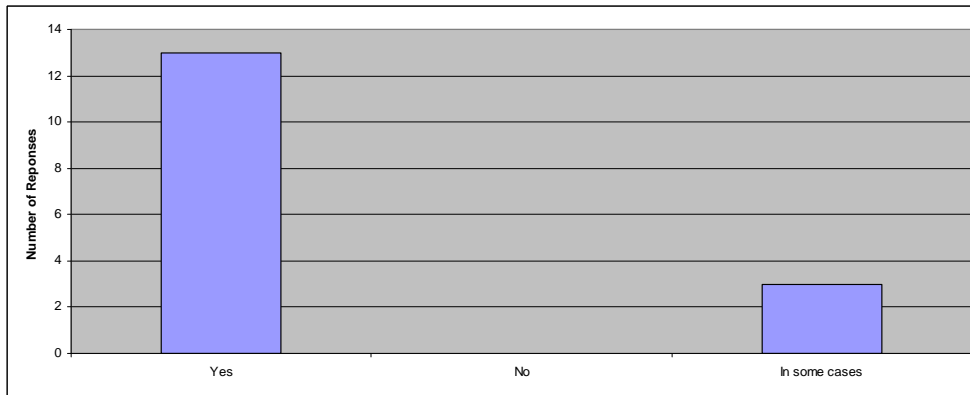
1 **J.3 PMU installation**

2 **J.3.1 Is the installation manual coming with your PMU helpful?**



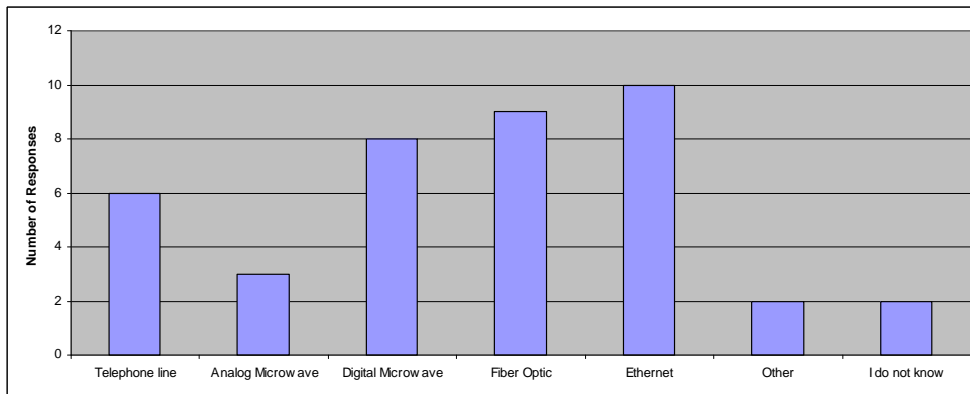
3

4 **J.3.2 Were there existing CTs/PTs available for your PMU installation?**



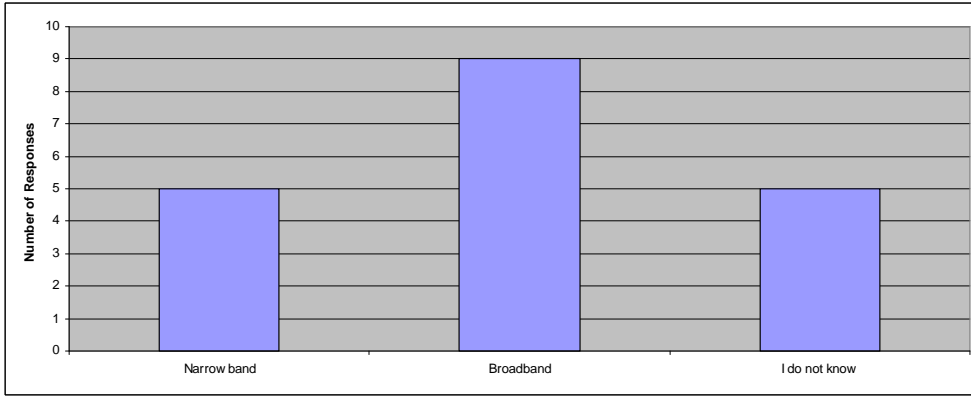
5

6 **J.3.3 What type of data networks available for your PMU installation?**



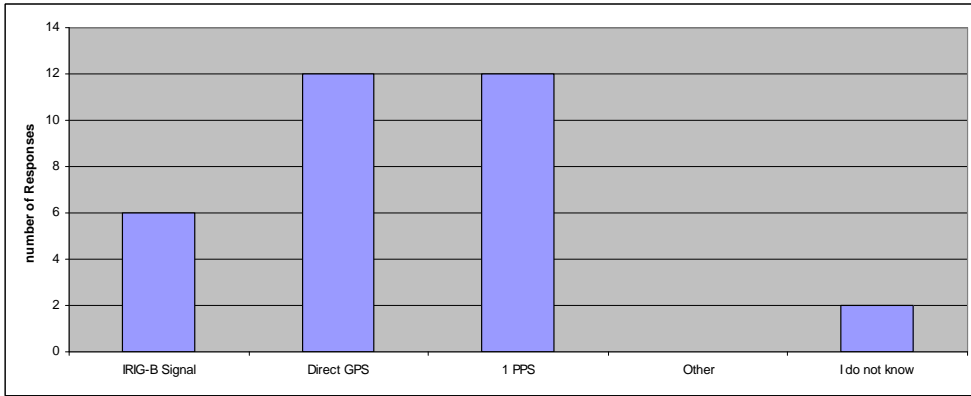
7

1 **J.3.4 Are your data networks narrowband channels (voice channels) or broadband**
2 **channels?**



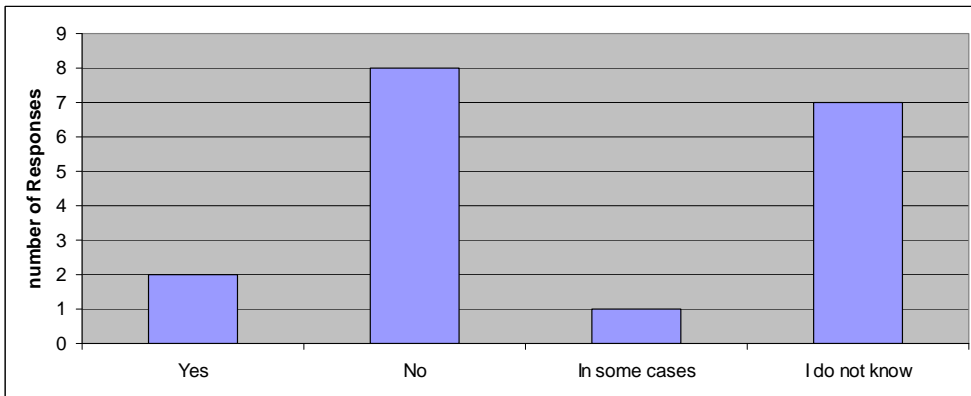
3

4 **J.3.5 What time synchronizing signals are available for your PMU installation?**



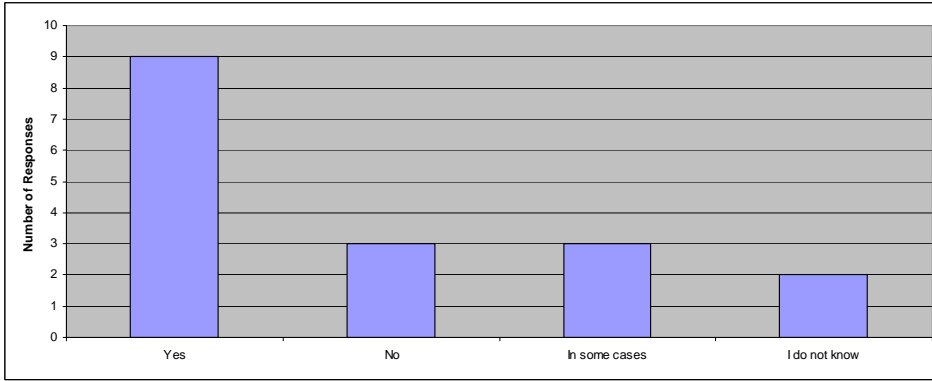
5

6 **J.3.6 Does the engineer or technician installing the PMU have remote angle information**
7 **from the utility selected reference phasor?**



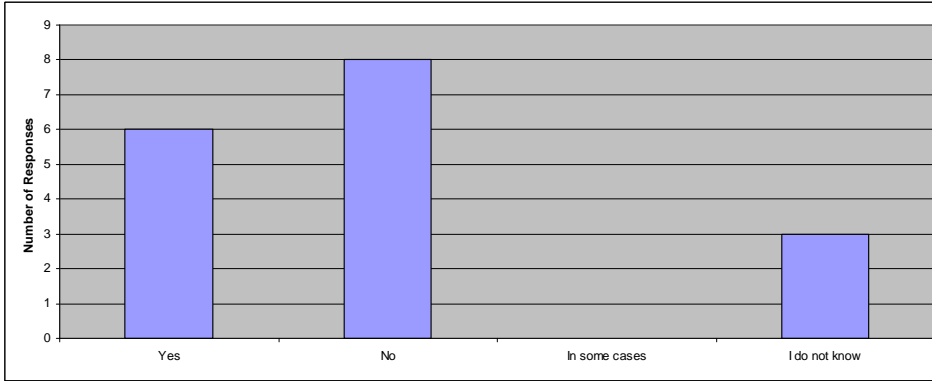
8

1 **J.3.7 Does the engineer or technician installing the PMU have access to real and reactive**
 2 **power flow information from a separate device?**



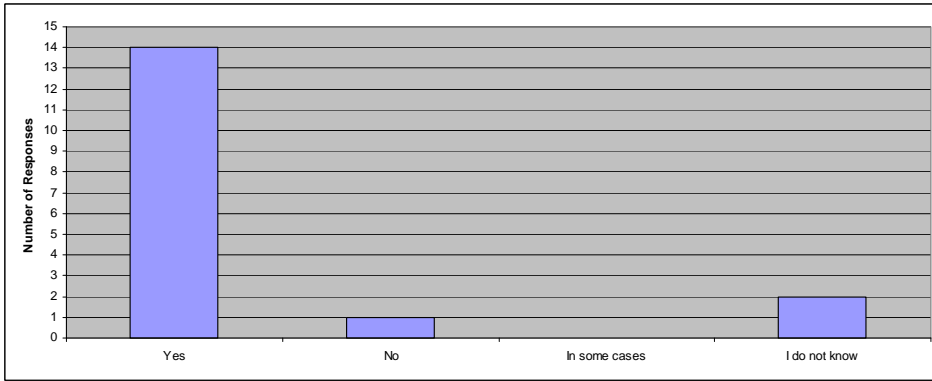
3

4 **J.3.8 Does the engineer or technician installing the PMU have access to phasor data**
 5 **concentrator (PDC) information?**



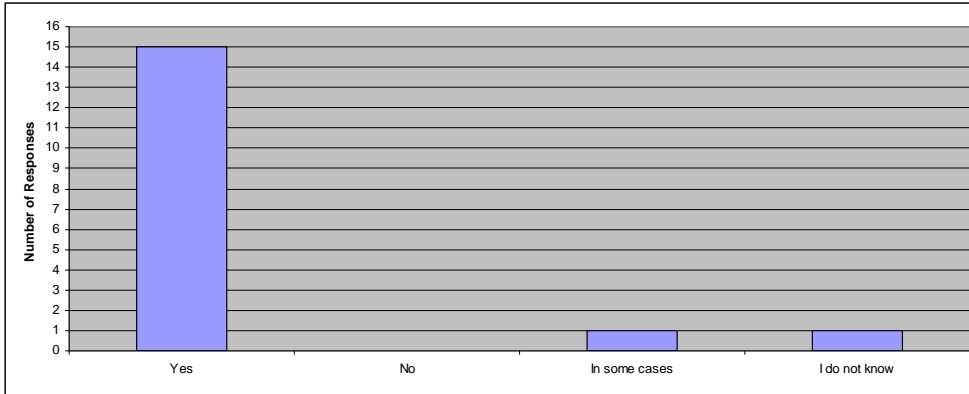
6

7 **J.3.9 Does the engineer or technician installing the PMU have communication with the**
 8 **control center that collects PMU information?**



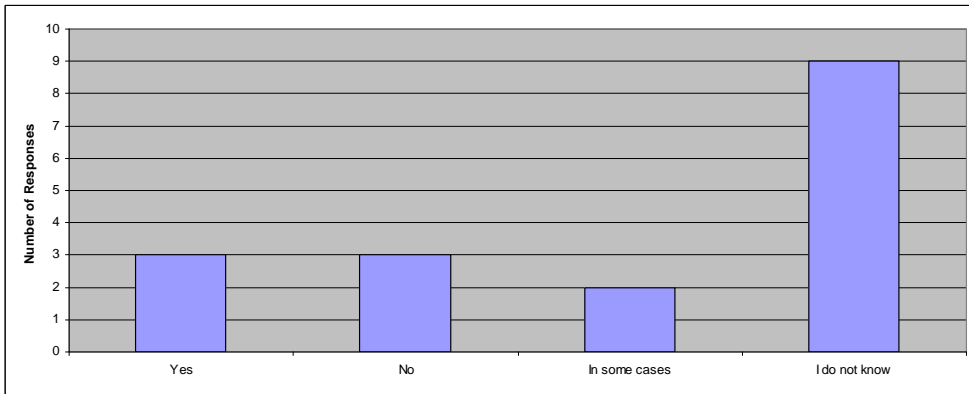
9

1 **J.3.10 Is it generally assumed that utilities can consistently identify phases ‘a’, ‘b’, and ‘c’**
 2 **voltage and current signals at their substations?**



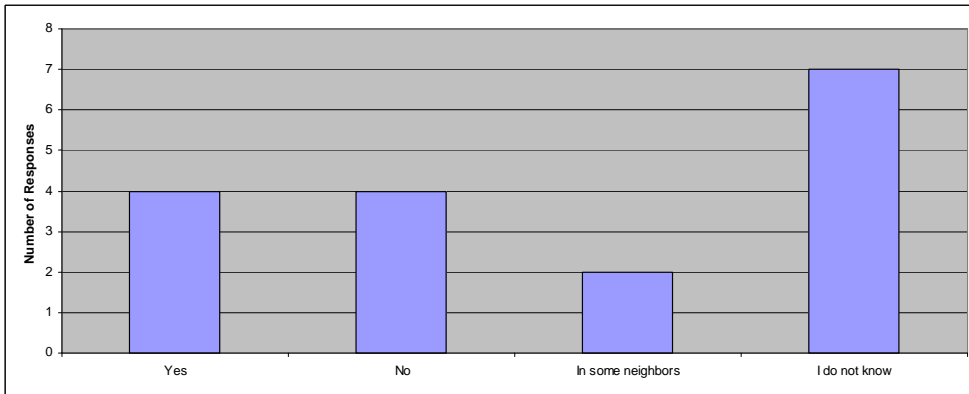
3

4 **J.3.11 To your knowledge, is there any agreement among utilities on which phase is called**
 5 **phase ‘a’?**



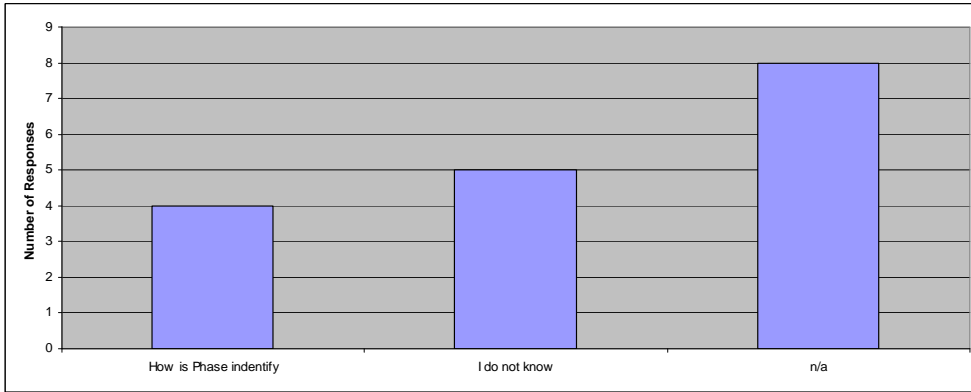
6

7 **J.3.12 Do you know the phase ‘a’ convention of your neighboring utility companies?**



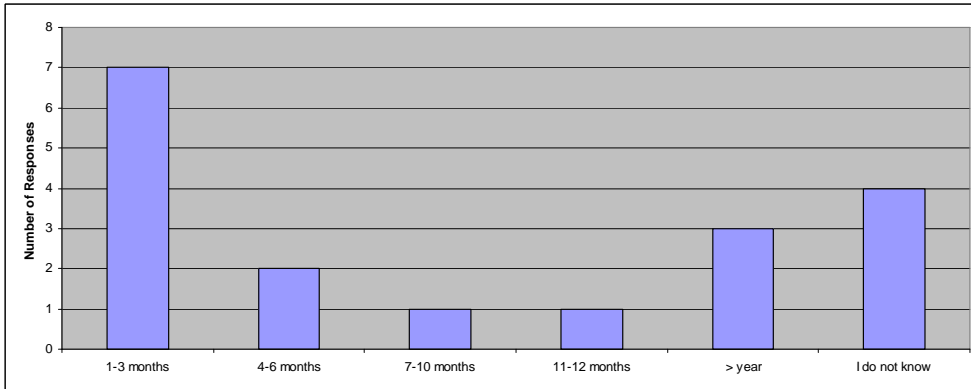
8

1 **J.3.13 How is the phase 'a' identified when you install your PMUs?**



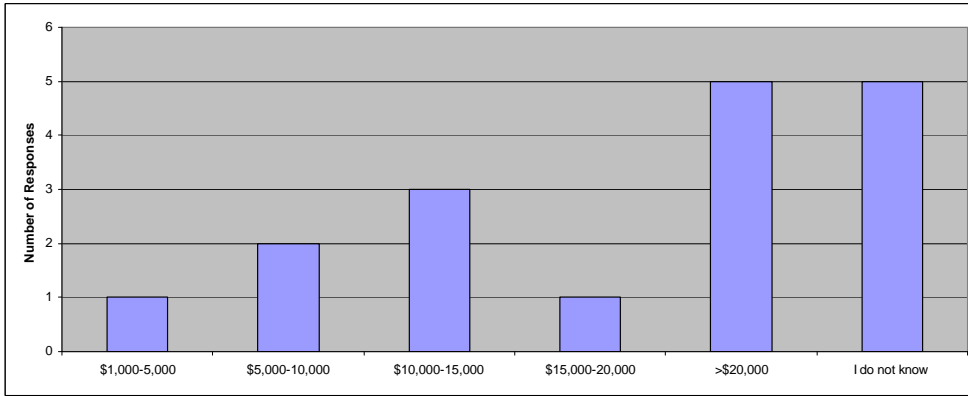
- 2
3
4
5
6
7
8
9
- a) Phase A is always identified within the substation. It is originally identified when hooking up with other substations, but by convention is the N. or S. or E. or W. bus in the sustaiton. That is, it is the bus on the same side relating to direction in every station, but I don't know which it is (BPA).
 - b) By looking at the detailed protection wiring schematics of the substation where each PMU is installed (Hydro QB).
 - c) From the prints, markings, and labels (NYPA).
 - d) Phase ID's are labeled on substation structures and represented on 3-line diagrams (TVA).

10 **J.3.14 How long did it take you to complete the installation of one PMU?**



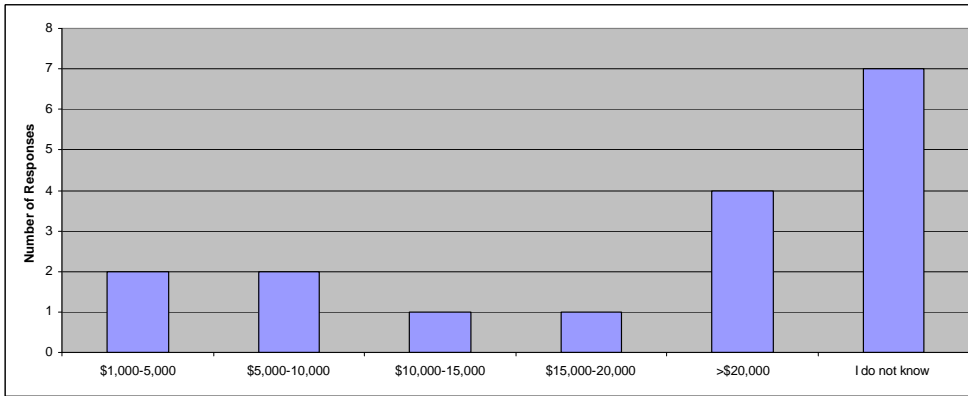
11

1 **J.3.15 What is the average cost of hardware, including PMU, for one installation?**



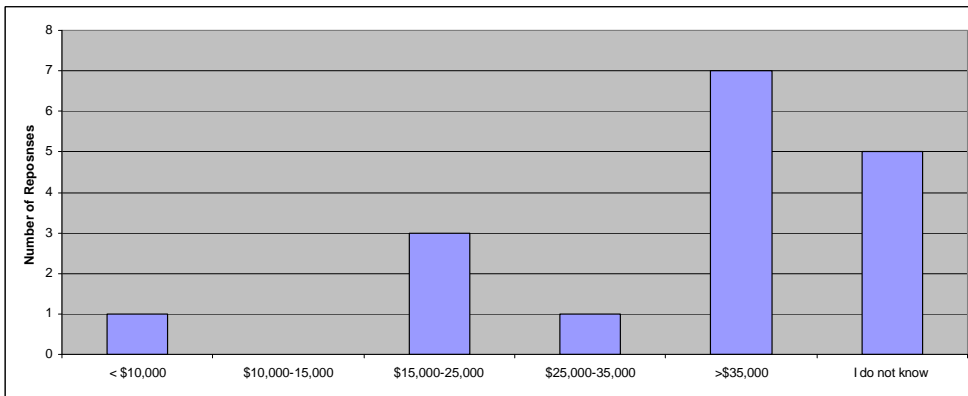
2

3 **J.3.16 What is the average cost of labor for one PMU installation?**



4

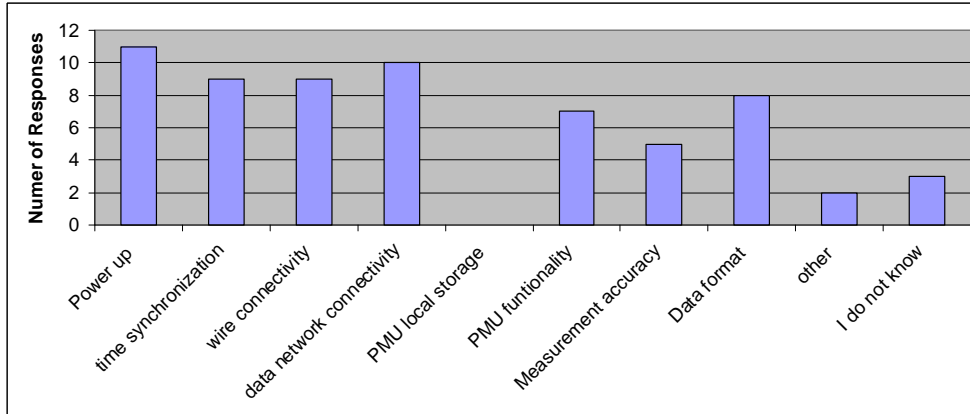
5 **J.3.17 What is the average total cost for one PMU installation?**



6

1 **J.4 PMU commissioning**

2 **J.4.1 What test did you perform before commissioning the installed PMUs?**



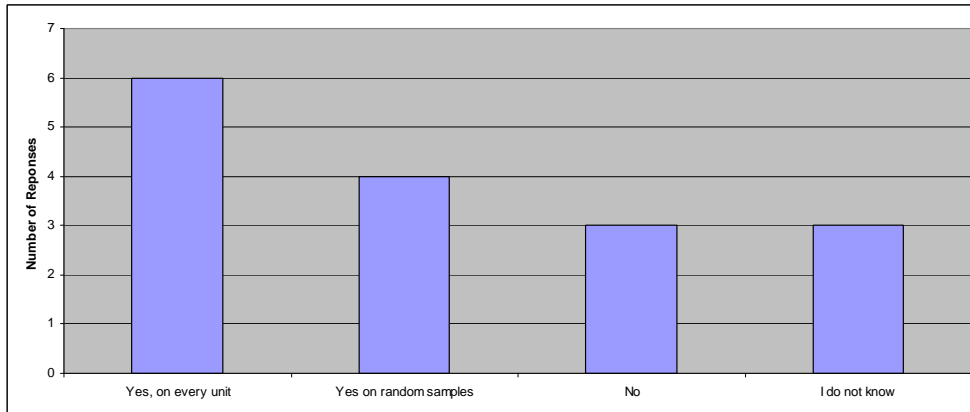
3

4 Other:

5 a) It varies depending on who does the installation (BPA).

6 b) We plan to perform the above tests when the first single test PMU installation is completed
7 (MidAmerican).

8 **J.4.2 Do you check PMU accuracy on every unit? On random measurement samples,
9 None?**



10

11 **J.4.3 What else do you do to initially calibrate PMU measurements?**

12 a) Verify PT and CT ratios with System Protection (PG&E).

13 b) We have no way to calibrating the unit as we have no other PMU to compare it with (PJM).

14 c) Compare to SCADA (Alberta Electric).

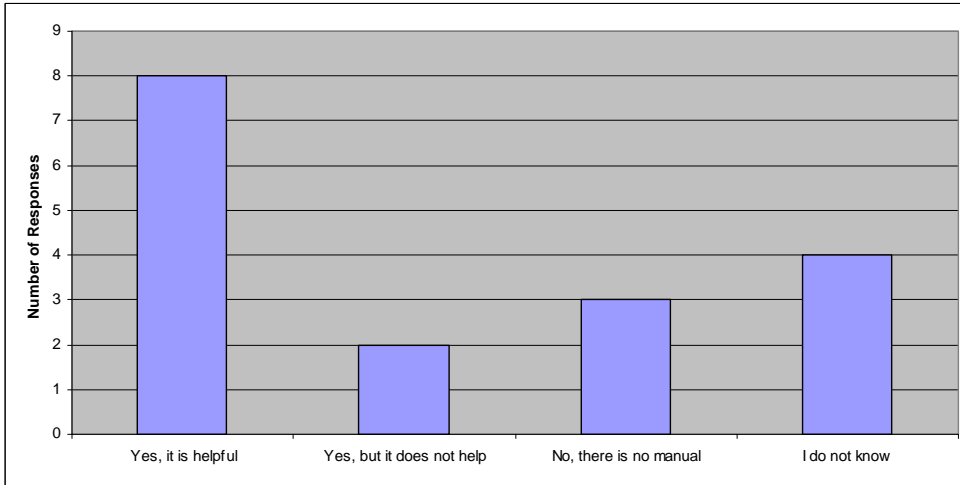
15 d) No calibration is done on the PMUs (AEP).

16 e) Meter is calibrated by manufacturer and they deliver a calibrated meter (Entergy).

- 1 f) Each unit is calibrated in the lab, all the settings are entered and tested except final PT/CT ratios,
- 2 and the operation is confirmed. Calibration is done using accurate test instruments and meters
- 3 calibrated against traceable standards (BPA).
- 4 g) Each PMU has been tested for accuracy in lab before installation. Once installed, the measured
- 5 voltage phase angle is checked to make sure that the phasing is correct (Hydro QB).
- 6 h) Look at data from the state estimator in the EMS and local meters.

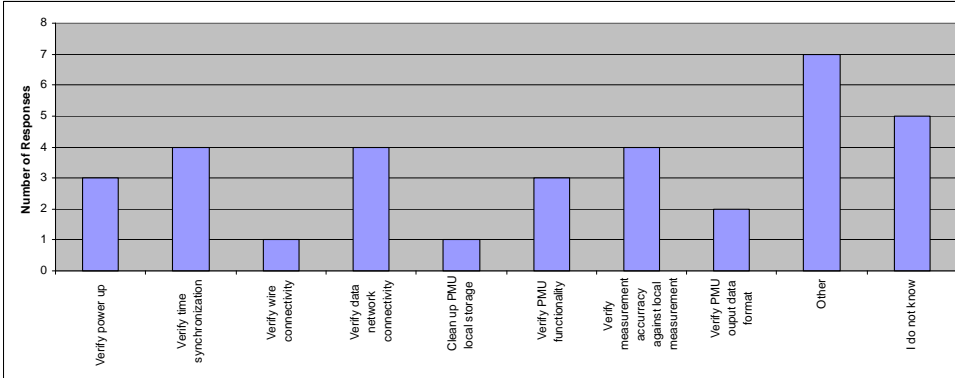
7 **J.5 PMU maintenance**

8 **J.5.1 Is there a maintenance manual coming with your PMU products? If yes, is it helpful?**



9

10 **J.5.2 What kind of maintenance is performed on your PMUs?**



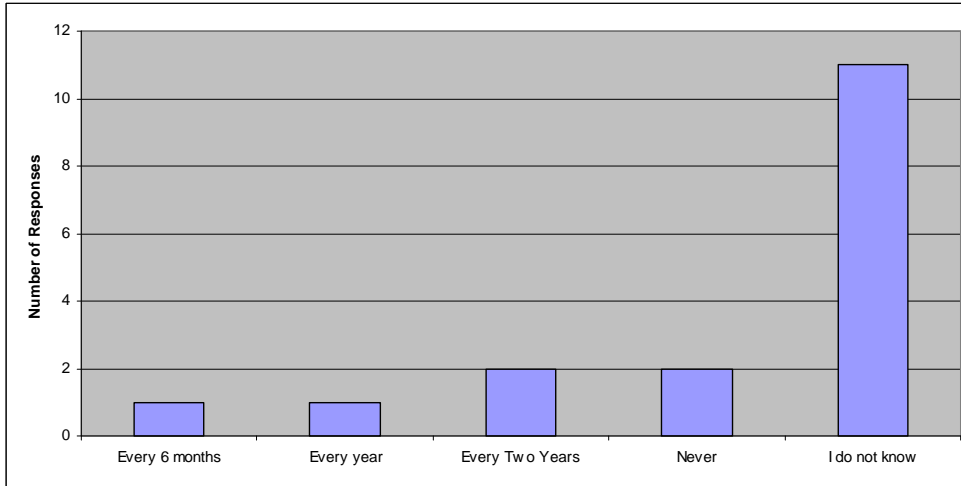
11

12 Other:

- 13 a) Cleaning fans. Replace backup batteries (Hydro QB).
- 14 b) The Maintenance program has not been specified (MidAmerican).
- 15 c) Meter is pulled and send back to manufacturer for calibration (Entergy).
- 16 d) Not yet determined (METC).

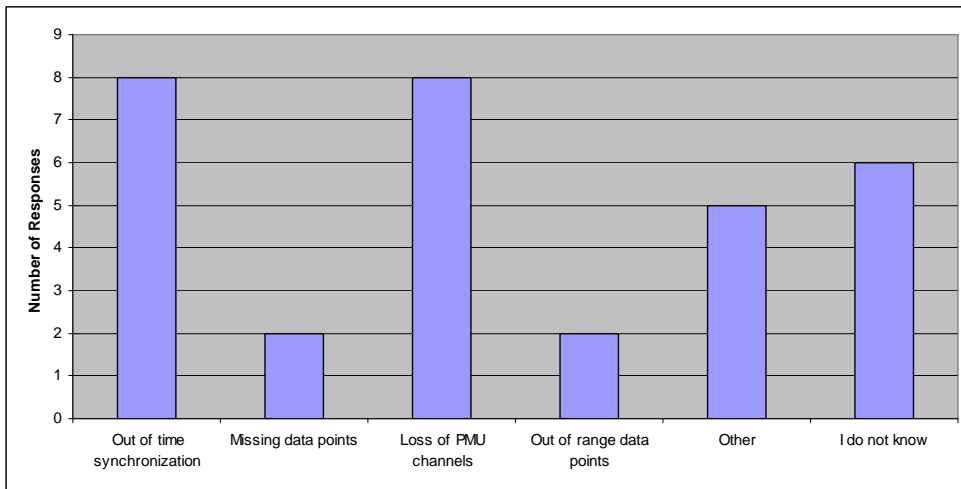
- 1 e) No online monitoring of PDC anyway (BC Hydro).
- 2 f) Will do whatever is required. Maintenance is expected to be minimal (PJM).
- 3 g) Maintenance is an on-line operation, and re-calibration and repair when there is an obvious
- 4 problem or failure. We have no routine maintenance (BPA).

5 **J.5.3 How often do you perform maintenance on your PMUs?**



6

7 **J.5.4 What alarms do you have to alert you to problems?**

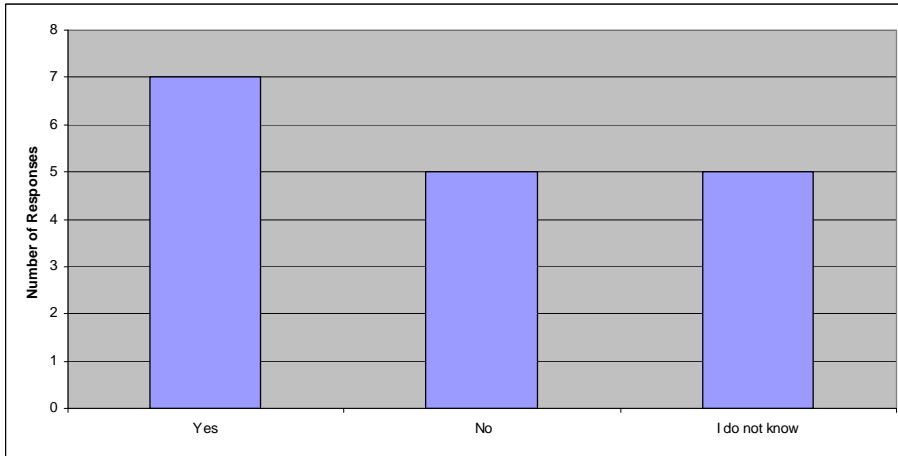


8

1 Other:

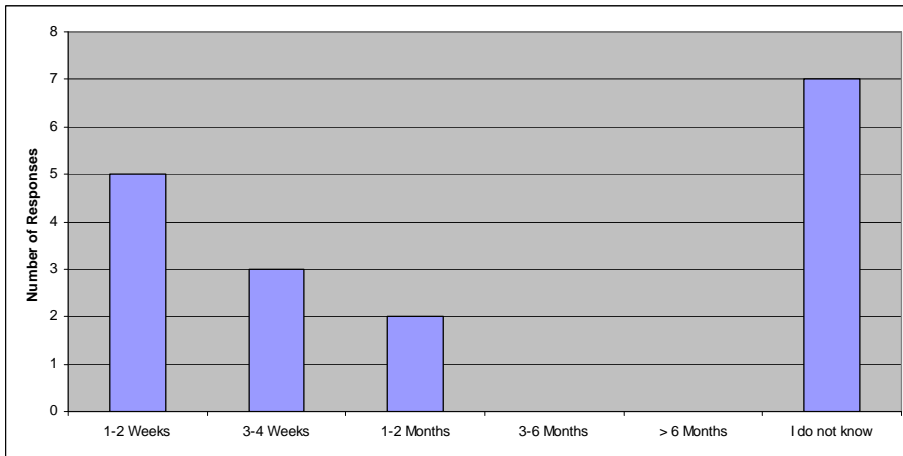
- 2 a) Our PMUs are on-line all the time. Synchronization & outage problems are tracked and reported by
- 3 the concentrator. Calibration problems must be reported by users. If reported, we will investigate
- 4 and resolve the issue (BPA).
- 5 b) Email indicating loss of communication (Alerta Electric SO).
- 6 c) No planning on using alarms (PJM).
- 7 d) There are other indications on the PDC but there are no alarms (PG&E).
- 8 e) Alarm capability exist in PMUs but it is not used (AEP).
- 9 f) Utility to talk to the PMU (NYPA).

10 **J.5.5 Do you monitor the performance of your overall measurement system other than just**
 11 **PMUs?**

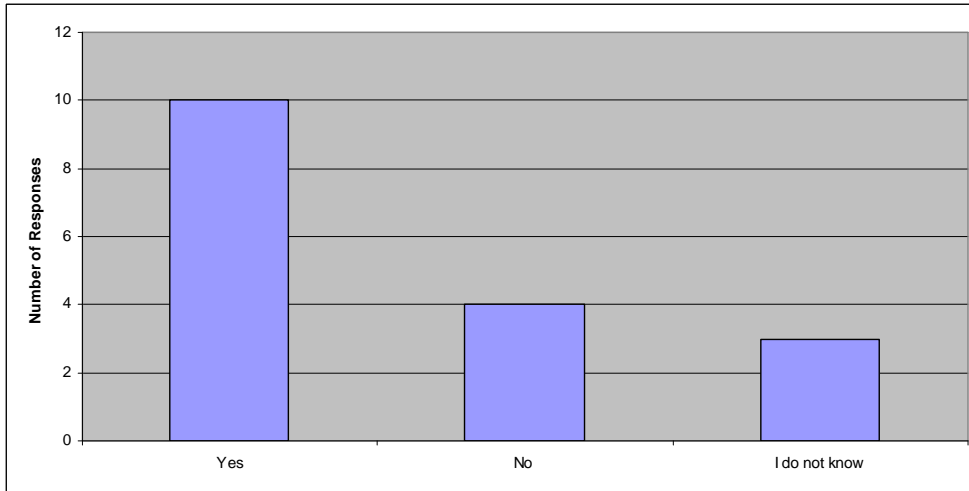


12

13 **J.5.6 What is the average time from problem appearance to correction?**



14

1 **J.6 Other information**2 **J.6.1 Do you think an installation/commissioning /maintenance guide would help your job?**

3

4 **J.6.2 Did you have any other problems during PMU installation/commissioning/**
5 **maintenance?**

- 6 a) The field needs to be educated in these new instruments. We plan on hosting a two day meter
7 workshop for our field personnel. (ENTERGY).
- 8 b) The biggest problems seem to be getting the data communications to work right with the PMU and
9 data concentrator. This is when there is a mismatch, such as synchronous to asynchronous or
10 network to channel. Standard interfacing is sometimes difficult to specify and install (BPA).
- 11 c) Sometimes there is an issue with the GPS antenna where the cable is pinched or broken. In one case
12 the antenna was close to a UHV line and induced voltage zapped it. Since then if there is any
13 possibility of that, I have instructions for grounding during installation and hook-up (BPA).
- 14 d) The biggest maintenance problem is getting people to notice sync or data promptly, and notify the
15 right personnel to fix the problem. It is often difficult to diagnose the root cause from the symptom,
16 so a lot of issues go un-resolved for a long time (BPA).
- 17 e) Firmware did not comply to specifications (took about one year to correct, Hydro QB).
- 18 f) Early hardware failure on one unit after installation (Hydro QB).
- 19 g) Inability to get up to date communication front ends for the PMU. Slow upgrade of the vendor.
- 20

1 **Annex K**

2 (informative)

3 **Examples of commissioning tests – Bonneville Power Administration**4 **K.1 Introduction**

5 This commissioning test example is from a PMU installed at the Big Eddy substation in January, 1998.
 6 This was long before the Standard C37.118 was available, so there was no criteria for comparison. The
 7 focus of this test was to establish that the PMU was properly installed, measured the correct signals, and
 8 compared reasonably accurately with other measurements.

9 **K.2 In-service readings for Big Eddy 230 Phasor Measurement Unit**

10 All quantities are referenced to “A” phase Bus section #3 1V-0V. Measurements made on January 6, 1998,
 11 from 1:00pm to 2:30pm. Board meters and board meter racks were read on all lines, then Rack 67 was
 12 read for all lines. After that Scada reading were entered. Due to the time lag, magnitudes may be off some.
 13 The power house lines were fluctuating a lot due to some generator control problems.

14 **Table M.1—In-service readings for Big Eddy 230 Phasor Measurement Unit**

Quantity	Rack 67			PTR / CTR	Board Meter Racks			Board Meters	Scada
	Mag.	Angle	Primary		Mag.	Angle	Primary		
Bus Sect. 3 VA	69.3	ref.	240.1	2000/1	69.4	ref.	240.4	240 kv	240.2 kv
Bus Sect. 3 VB	69.1	-120	239.4		69.6	-120	241.1		
Bus Sect. 3 VC	69.0	120	239.0		69.1	120	239.4		
Bus Sect. 1 VA	69.1	ref.	239.4	2000/1	69.6	ref.	241.1	240 kv	239.9 kv
Bus Sect. 1 VB	69.0	-120	239.0		69.7	-121	241.4		
Bus Sect. 1 VC	68.9	120	238.7		69.5	120	240.8		
Celilo #3 IA	1.07	48	642	3000/5	1.06	48	636	180 mw out	177 mw out
Celilo #3 IB	1.08	-71	648		1.06	-71	636	190 mv in	196 mv in
Celilo #3 IC	1.07	167	642		1.05	167	630	550 amps	634 amps
Celilo #4 IA	1.19	48	714	3000/5	1.20	47	720	200 mw out	197 mw out
Celilo #4 IB	1.19	-72	714		1.21	-72	726	220 mv in	225 mv in
Celilo #4 IC	1.23	169	738		1.24	168	744	700 amps	719 amps
Power Hs #3 IA	2.57	-149	771	1500/5	1.82	-150	546	200 mw in	239 mw in
Power Hs #3 IB	2.60	91	780		1.83	90	549	110 mv out	171 mv out
Power Hs #3 IC	2.60	-31	780		1.83	-31	549	550 amps	815 amps

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Quantity	Rack 67			PTR / CTR	Board Meter Racks			Board Meters	Scada
	Mag.	Angle	Primary		Mag.	Angle	Primary		
Power Hs #4 IA	2.46	-148	590	1200/5	2.51	-154	602	220 mw in	221 mw in
Power Hs #4 IB	2.46	92	590		2.52	86	605	110 mv out	124 mv out
Power Hs #4 IC	2.46	-30	590		2.52	-35	605	600 amps	609 amps
Power Hs #5 IA	3.49	-148	838	1200/5	3.67	-148	881	320 mw in	307 mw in
Power Hs #5 IB	3.55	92	852		3.73	92	895	190 mv out	180 mv out
Power Hs #5 IC	3.53	-28	847		3.69	-28	886	880 amps	854 amps
Power Hs #6 IA	1.52	-149	608	2000/5	1.67	-149	668	240 mw in	246 mw in
Power Hs #6 IB	1.60	90	640		1.75	90	700	150 mv out	134 mv out
Power Hs #6 IC	1.58	-29	632		1.74	-29	696	700 amps	673 amps
XFMR #2 IA	0.52	5	312	3000/5	0.54	6	324	120 mw out	120 mw out
XFMR #2 IB	0.55	-117	330		0.55	-117	330	10 mv in	15 mv in
XFMR #2 IC	0.53	122	318		0.54	122	324	300 amps	
XFMR #5 IA	0.49	0	392	4000/5	0.49	1	392	180 mw out	189 mw out
XFMR #5 IB	0.51	-122	408	See Note	0.52	-121	416	10 mv in	6 mv in
XFMR #5 IC	0.51	116	408	Below	0.51	118	408	400 amps	
XFMR 2&5 IA				XFMR 5 CTR was later changed to 3000/5 so that XFMR 2&5 could be one PMU channel.					
XFMR 2&5 IB									
XFMR 2&5 IC									
XFMR #1 IA	1.16	-120	232	1000/5	1.24	-107	248	40 mw in	54 mw in
XFMR #1 IB	1.21	134	242		1.28	130	256	40 mv out	122 mv out
XFMR #1 IC	1.11	10	222		1.19	9	238	280 amps	
Bus Tie #1 IA	0.33	90	99	1500/5	0.33	90	99	0	1 mw in
Bus Tie #1 IB	0.33	-30	99		0.33	-30	99	40 mv in	81 mv in
Bus Tie #1 IC	0.33	-150	99		0.32	-150	96	100 amps	195 amps
Bus Tie #2 IA				1500/5					
Bus Tie #2 IB									
Bus Tie #2 IC									
Bus Tie #3 IA	0.00	92	0	1500/5					
Bus Tie #3 IB	0.00	-29	0						

Deleted: June
Deleted: 0

Quantity	Rack 67			PTR / CTR	Board Meter Racks			Board Meters	Scada
	Mag.	Angle	Primary		Mag.	Angle	Primary		
IB									
Bus Tie #3 IC	0.00	-152	0						
Midway IA	1.31	-175	314	1200/5	1.33	-175	319	140 mw in	119 mw in
Midway IB	1.31	66	314		1.33	67	319	10 mv in	4 mv out
Midway IC	1.27	-56	305		1.29	-56	310	320 amps	286 amps
Troutdale IA	1.53	3	367	1200/5	1.47	3	353	150 mw out	151 mw out
Troutdale IB	1.56	-114	374		1.51	-113	362	10 mv in	8 mv in
Troutdale IC	1.52	122	365		1.47	122	353	370 amps	365 amps
Redmond IA	1.35	7	324	1200/5	1.36	7	326	140 mw out	141 mw out
Redmond IB	1.38	-112	331		1.38	-112	331	20 mv in	17 mv in
Redmond IC	1.38	127	331		1.38	127	331	340 amps	340 amps
Chemawa IA	out			800/5					
Chemawa IB	of								
Chemawa IC	service								
Mcloughlin IA	1.69	4	507	1500/5	1.68	3	504	220 mw out	217 mw out
Mcloughlin IB	1.81	-118	543		1.80	-118	540	5 mv in	12 mv in
Mcloughlin IC	1.76	121	528		1.74	120	522	530 amps	521 amps
Harvalum IA	1.03	-11	247	1200/5	1.07	-15	257	100 mw out	105 mw out
Harvalum IB	1.01	-127	242		1.05	-131	252	50 mv out	14 mv out
Harvalum IC	1.07	113	257		1.10	109	264	260 amps	254 amps

1

2 **K.3 PMU accuracy check**

3 All quantities are referenced to "A" phase Bus section #3 1V-0V. Measurements made on January 7, 1998,
4 from 7:30am to 8:30am.

5 **Table M.2—In-service readings for Big Eddy 230 Phasor Measurement Unit**

Channel & Quantity	Rack 67 Input (Secondary)	Rack 67 Input Angle	Phasor Quantity (As Read in Labview)	Phasor Angle (As Read in Labview)	Error (%)
1 - Bus Sect. #3 VA	68.817	ref.			
1 - Bus Sect. #3 VB	69.101	-120.10			
1 - Bus Sect. #3 VC	68.749	119.78			
1 - Positive Sequence	68.889	ref.	68.62	ref.	0.39

Channel & Quantity	Rack 67 Input (Secondary)	Rack 67 Input Angle	Phasor Quantity (As Read in Labview)	Phasor Angle (As Read in Labview)	Error (%)
2 - Celilo #3 IA	1.7913	ref.			
2 - Celilo #3 IB	1.7933	-120.10			
2 - Celilo #3 IC	1.7675	119.80			
2 - Positive Sequence	1.7840	10.93	0.1807	11.12	1.29
3 - Celilo #4 IA	1.9895	9.80			
3 - Celilo #4 IB	1.9920	-110.59			
3 - Celilo #4 IC	2.0198	130.42			
3 - Positive Sequence	2.0004	9.88	0.2013	9.78	0.63
4 - Power House #3 IA	1.5096	-162.31			
4 - Power House #3 IB	1.5239	78-07			
4 - Power House #3 IC	1.5447	-43.44			
4 - Positive Sequence	1.5260	-162.56	0.1532	-162.56	0.39
5 - Power House #4 IA	1.1888	-163.96			
5 - Power House #4 IB	1.1851	76.82			
5 - Power House #4 IC	1.2023	-45.21			
5 - Positive Sequence	1.1920	-164.12	0.1202	-164.02	0.84
6 - Power House #5 IA	2.1375	-162.09			
6 - Power House #5 IB	2.1794	78.39			
6 - Power House #5 IC	2.1877	-42.32			
6 - Positive Sequence	2.1682	-162.00	0.2187	-161.52	0.87
7 - Power House #6 IA	1.2933	-164.01			
7 - Power House #6 IB	1.3590	76.19			
7 - Power House #6 IC	1.3511	-42.66			
7 - Positive Sequence	1.3344	-163.48	0.1344	-163.72	0.72
8 - XFMR #2 IA	0.7961	-168.11			
8 - XFMR #2 IB	0.7859	72.39			
8 - XFMR #2 IC	0.7812	-48.47			
8 - Positive Sequence	0.7877	-168.06	0.0797	-167.96	1.18
9 - Midway IA	2.2009	-169.55			
9 - Midway IB	2.2099	72.31			
9 - Midway IC	2.1572	-49.61			
9 - Positive Sequence	2.1891	-168.95	0.2157	-168.46	1.47
10 - Troutdale IA	1.0949	2.14			
10 - Troutdale IB	1.1366	-114.00			
10 - Troutdale IC	1.0987	121.29			
10 - Positive Sequence	1.1094	3.18	0.1128	3.33	1.68

1

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1 **Annex L**

2 (informative)

Comment [ARG44]: This Annex may be completely obsolete considering C37.118.1. I did not delete it but we should consider removing it entirely.

3 **WECC requirements for monitor equipment**

4 This section is for informational purposes only and is included as an example of dynamic performance
 5 requirements for PMU and point-on-wave monitors. In 2001 the WECC approved its Dynamic
 6 Performance and Disturbance Monitoring Plan to address NERC Planning Standard I. F., System Adequacy
 7 and Security – Disturbance Monitoring. Within this Plan the WECC established a reimbursement program
 8 to assist member utilities with the cost of equipment and maintenance associated with dynamic disturbance
 9 monitors at selected system locations. A monitor shall be judged as meeting basic WECC performance
 10 requirements if it satisfies the following technical criteria:

Comment [ARG45]: This document has no requirements.

Deleted: not part of the requirements of this document

11 • **Frequency response of overall data acquisition:**

- 12 ○ Is -3 dB or greater at 5 Hz.
- 13 ○ Does not exceed -40 dB at frequencies above the Nyquist frequency (a limit of -60 dB is
14 preferred).
- 15 ○ Does not exceed -60 dB at frequencies that are harmonics of the actual power system
16 operating frequency (for design purposes, assume all frequencies in the range of 59 Hz to 61
17 Hz).
- 18 ○ Does not produce excessive ringing in records for step disturbances.

19 • **Data sampling rate:**

- 20 ○ Overall frequency response requirements imply a minimum sample rate that is 4 to 5 times the
21 -3 dB bandwidth of overall data acquisition.
- 22 ○ For compatibility with other monitors, the sample rate shall be an integer multiple of 20 or 30
23 samples per second (sps). A multiple of 30 sps is preferred.

24 • **Numerical resolution and dynamic range:**

- 25 ○ Resolution of the analog-to-digital (A/D) conversion process must be 16 bits or higher.
- 26 ○ Scaling of signals entering the A/D conversion shall assure that 12-14 bits are actively used to
27 represent them. Signals for which this scaling may overload the A/D during large transients
28 may be recorded on two channels, in which one has less resolution but a greater dynamic
29 range.

30 • **Measurement noise must be within the normal limits of modern instrument technology.**
 31 Noise levels for frequency transducers that are based upon zero-crossing logic tend to be
 32 unacceptable.33 • **Documentation for the data acquisition process:**

- 34 ○ Must be sufficiently detailed that overall quality of the acquisition system can be assessed.

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- 1 o Must be sufficiently detailed that acquired records can be compensated for attenuation and
- 2 phase lags introduced by the acquisition system.

- 3 • **The monitor or monitor system stores data continuously and retains the last 240 hours (10**
- 4 **days) at all times without operator intervention.** A monitor that automatically erases the oldest
- 5 file and stores the newest file will meet this criterion if the buffer area is 10 days or more. If the
- 6 monitor requires an operator to remove old data to prevent storage overflow, a 60-day buffer is
- 7 required to accommodate typical practices with monitor systems.

- 8 • **The monitor is able to typically store event data files for 60 days without operator**
- 9 **intervention.** Since events are inherently unpredictable, this is only a ‘typical’ value based on
- 10 operating experience. If the monitor stores continuous data, it does not have to store events.

- 11 • **The monitor demonstrates synchronization to Universal Time (UTC) to a 100µs level or**
- 12 **better.** Synchronization to GPS based timing with suitable technique is preferred. Other
- 13 approaches may be acceptable.

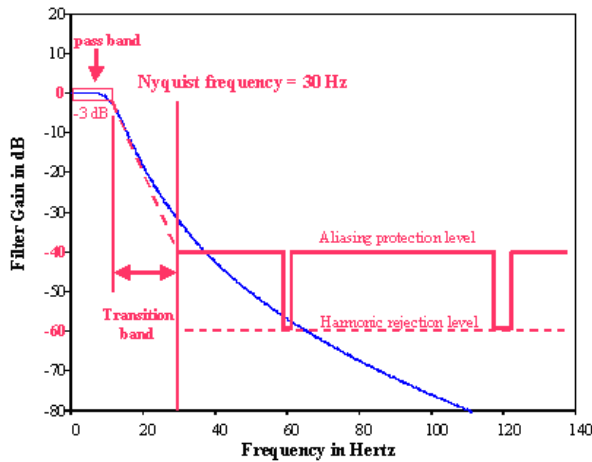
- 14 • **Data access is by network, leased line, or dial-up with software for transfer, storage, and**
- 15 **data archiving.**

- 16 • **Data formats are well defined and reasonable.** Preferred formats for real-time data transfer are
- 17 those equivalent to or meeting IEEE Standards IEEE1344 or C37.118 or the PDCstream format
- 18 for concentrator output. the preferred file format is PhasorFile described in PhasorFileFormat.doc
- 19 (*.dst) commonly in use in the WECC.

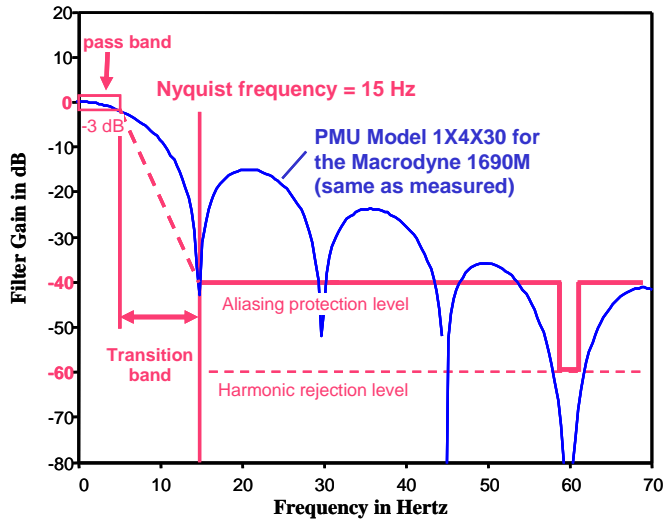
20 | **Error! Reference source not found.** A1 shows a Butterworth filter of order 4, with a 12 Hz bandwidth and
 21 the WECC filtering requirements for a PMU output rate of 60 sps. Note that the stop band for each
 22 harmonic is proportional to frequency. Figure N.2 shows measured and modeled performance for the
 23 Macrodyne 1690M, which does not satisfy the WECC filtering standard.

Deleted: —12 Hz Butterworth filter vs. WECC Filtering Standard (sample rate = 60 sps)

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



28
 29 **Figure N.1—12 Hz Butterworth filter vs. WECC filtering standard (sample rate = 60 sps)**



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Figure N.2—Macrodyne 1690M vs. WECC filtering standard (sample rate = 30 sps)

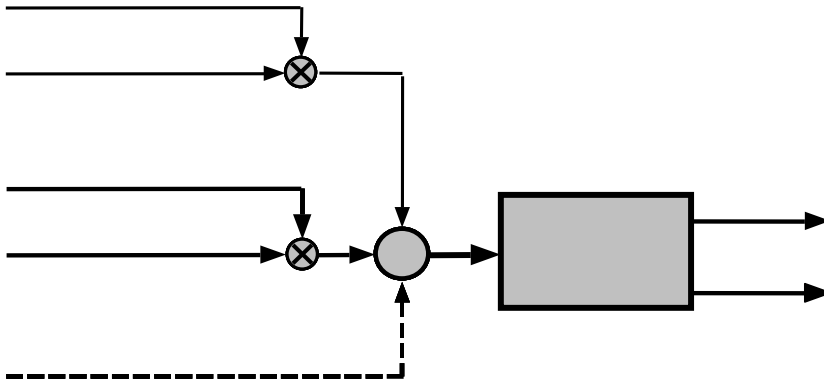
1 Annex M

2 (informative)

3 Modulation and demodulation of PMU inputs

4 A PMU, like any RMS transducer, provides average measures of point-on-wave (POW) input signals that
 5 represent local voltages and/or currents in the power system. The POW inputs can be thought of as sets of
 6 modulated carriers, containing dynamic information that is impressed through a combination of amplitude
 7 modulation and frequency modulation⁴. The carrier frequencies are usually harmonically related to the
 8 system operating frequency. This is not necessarily the case, however. Transducer inputs occasionally
 9 contain additive components for which the frequencies are essentially arbitrary, and which probably have
 10 no direct association with generator activity.

11 The overall situation is depicted in Figure O.1. It is useful to think of the carrier levels as powerflow
 12 information, and the impressed modulation as dynamic information. Additive signals, if present, are in a
 13 special category and potentially troublesome.



14

15

Figure O.1—Signal environment for a power system transducer

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

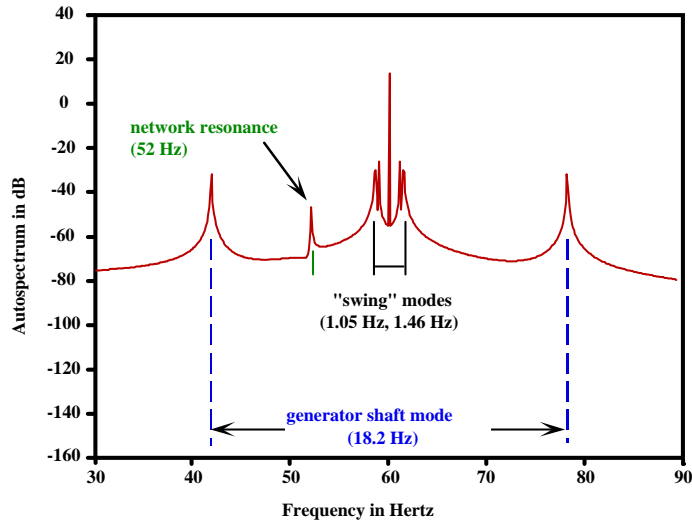
$$19 \quad \sin(x) \sin(y) = \frac{1}{2} [\cos(x - y) - \cos(x + y)] \quad (1A)$$

$$20 \quad \sin(x) \cos(y) = \frac{1}{2} [\sin(x - y) + \sin(x + y)] \quad (1B)$$

21 So, if x represents a 60 Hz carrier frequency and y represents a 1.2 Hz modulation, there will be a "lower"
 22 modulation sideband at $60 - 1.2 = 58.8$ Hz and a "upper" modulation sideband at $60 + 1.2 = 61.2$ Hz. Figure O.2
 23 provides an example with amplitude modulation sources at 1.05 Hz, 1.46 Hz, and 18.2 Hz. The example

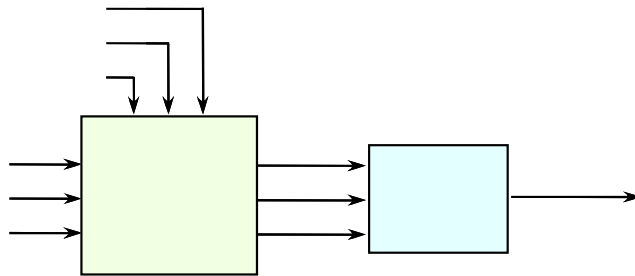
⁴ In this context, frequency modulation is sometimes called angle modulation or phase modulation

1 also includes an additive signal at 52 Hz; which is representative of a network resonance encountered
 2 during operation of the Pacific HVDC.



3
 4 **Figure O.2—Components of the information spectrum for an RMS transducer**

5 A PMU demodulates each carrier in the same manner as an AM radio receiver. Multiplying the modulated
 6 carriers by a reference sine and/or cosine wave of frequency z produces shifted images of the signal
 7 spectrum, with each spectral component generated according to equations 1A and 1B, above⁵. The
 8 reference signals will be multiphase quantities dimensioned to match the transducer inputs.



9
 10 **Figure O.3—Modeling nomenclature for projection of point-on-wave signals onto reference**
 11 **cosine**

⁵ 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.

1 Projection onto the cosine reference produces both a lower demodulation spectrum and an upper
2 demodulation spectrum for each pow component (input phase). If the PMU is a three-phase unit operating
3 under balanced power system conditions, then the upper demodulation spectrum will usually be eliminated
4 if the three projected signals are summed together. Otherwise special filtering may be needed to assure that
5 the upper demodulation spectrum is not “aliased” into some lower range of frequencies when signals
6 internal to the PMU are downsampled for final output. Detailed examples of this are provided in Hauer,
7 Martin and Lee 2005, and in PMU modeling codes within the DSI Toolbox [Hauer et al. 2005].

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

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

15 Some tedious trigonometry shows that this special structure does exist for amplitude modulation by a single
16 frequency, and that the phasor magnitude can be directly calculated without spurious cross terms. The
17 relationship is destroyed if filtering of the demodulation spectrum is not symmetric, however, and it likely
18 does not exist for the general spectra associated with power system signals [Hauer, Martin and Lee 2005].

1 Annex N

2 (informative)

3 Phasor aliasing and interfering frequencies

4 N.1 General

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

9 N.2 Scope

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

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

$$17 \quad |f_i - f_s| > \frac{F_s}{2}$$

18 Solving the above equation leads to:

$$19 \quad f_i > f_s + \frac{F_s}{2} \text{ or } f_i < f_s - \frac{F_s}{2}$$

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

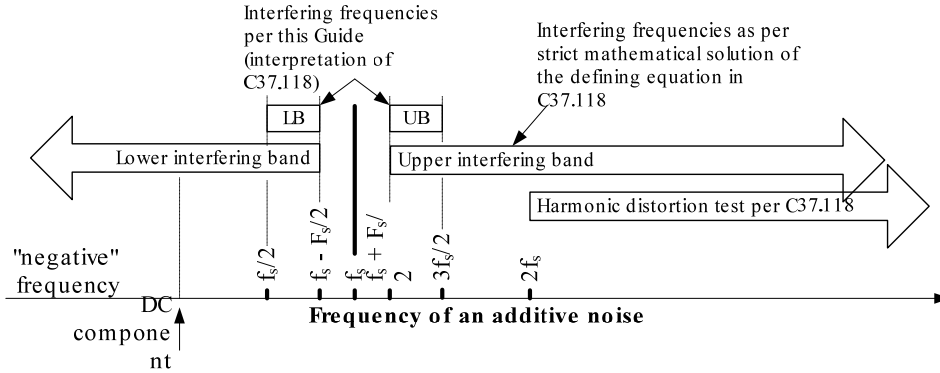
$$22 \quad 0 < f_i < f_s - \frac{F_s}{2}$$

23 making the two bands not equal.

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

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

1 A recommendation is made to test for interfering frequencies with a pair of additive signals controlled to
 2 test both pure magnitude and pure phase modulation. The issue of a DC component is resolved by setting a
 3 rational limit on the fastest meaningful phasor modulation, and by doing so limiting the interfering bands
 4 accordingly.
 5 The following subsection explains our approach and derives the test waveforms. The subsequent
 6 subsections describe the tests and interpretation of results.



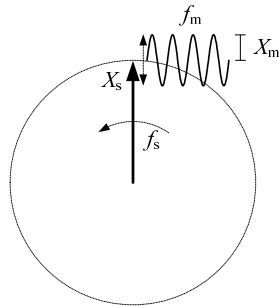
7
8 **Figure P.1—Comparing the harmonic distortion and interference frequency tests**

9 **N.3 Phasor modulation**

10 **N.3.1 Magnitude modulation**

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

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



17
18 **Figure P.2—Magnitude modulation of a phasor**

19 Mathematically, magnitude modulation can be obtained as follows:

20
$$x_{(t)} = X_s \cdot (1 + X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot f_m \cdot t)) \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) \quad (1)$$

1 In Equation 1 above, the initial angle (φ) is added for generality of our considerations, with no practical
 2 effect as shown later. The modulating frequency is practically in the range of a few Hz. Even considering a
 3 very fast unstable power swings with a period of a few hundreds of milliseconds, the frequency of effective
 4 modulation of system currents and voltages is in the range of a few Hz.

5 Equation 1 assumes a multiplicative alternation of the signal magnitude with no variation added to the
 6 information contained in the phase of the signal. Basic mathematical identities allow rewriting Equation 1
 7 into an additive noise model more aligned with the interfering frequency test as per the standard:

$$8 \quad x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \quad (2)$$

$$9 \quad x_{NOISE(t)} = \frac{X_s \cdot X_{m(pu)}}{2} (\cos(2 \cdot \pi \cdot (f_s + f_m) \cdot t + \varphi) + \cos(2 \cdot \pi \cdot (f_s - f_m) \cdot t + \varphi)) \quad (3)$$

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

13 The Synchrophasor Standard does not specify whether the interfering signal is of a single frequency, or
 14 multiple frequencies can/shall be used simultaneously during the compliance test. It simply requires
 15 suppressing components of frequencies meeting the key condition:

$$16 \quad |f_i - f_s| > \frac{F_s}{2} \quad (4)$$

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

$$18 \quad f_{i(HIGH)} > f_s + \frac{F_s}{2} \quad (5)$$

$$19 \quad f_{i(LOW)} < f_s - \frac{F_s}{2} \quad (6)$$

20 In other words frequencies as close to the signal frequency as half the reporting rate, shall be suppressed to
 21 claim compliance with the standard.

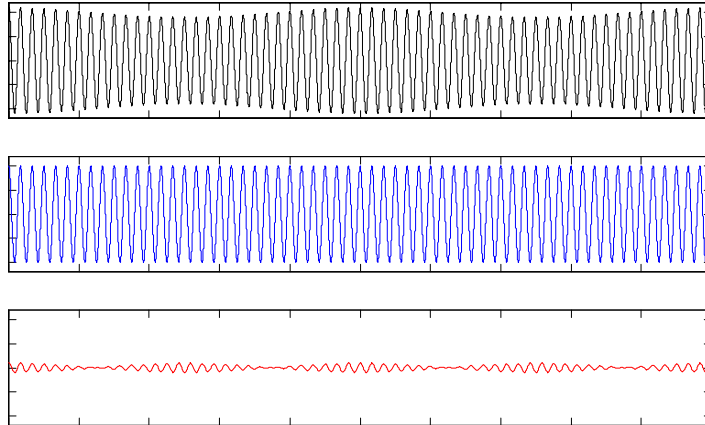
22 If the standard is interpreted in a way that a pair of interfering signals is applied, one being the mirror
 23 image of the other with respect to the signal frequency and Equation 3 is used to generate the noise
 24 component, then the interfering frequency test is equivalent to magnitude modulation, and the following
 25 test conditions apply as derived by comparing Expression 5 and Expression 6 with Equation 2 and Equation
 26 3:

$$27 \quad f_m > \frac{F_s}{2} \quad (7)$$

$$28 \quad X_{m(pu)} = 0.01 \text{ for level 0 compliance} \quad (8)$$

$$29 \quad X_{m(pu)} = 0.10 \text{ for level 1 compliance} \quad (9)$$

- 1 Expression 7 will be further defined later in this section to facilitate practical tests.
- 2 Under this interpretation, the interfering frequency test is a modulation of magnitude; the modulation
3 frequency shall be above half the reporting frequency; and the test shall be performed considering an
4 additive noise per Equation 2 and Equation 3.
- 5 In Equation 2 and Equation 3, an issue may arrive as to the phase relationships between the three sine-
6 waves. In order to achieve pure magnitude modulation the three sine-waves must be in a precise phase
7 relationship as per Equation 2 and Equation 3. This is not a problem if the signal and noise components are
8 generated digitally in a single test set. If two sources are used, one for the signal and the other for the noise,
9 one can achieve pure magnitude modulation by slow adjustments to the frequency of the modulating signal
10 or the fundamental signal as explained later in this section.
- 11 It is worth noting that only the true phasor component in the signal (Equation 2) needs to be either
12 generated with respect to time, or measured synchronously with respect to time for comparison
13 (calibration) purposes. The added noise as per Equation 3 can be left as not synchronized to time. This can
14 simplify interfering frequency tests as shown later.
- 15 Figure P.3 shows a PMU test input amplitude-modulated signal as per our interpretation of the interfering
16 frequency test (top); the actual stationary Synchronphasor (Equation 2, middle); and the added noise
17 (Equation 3, bottom).



- 18
- 19 **Figure P.3—The input signal being a sum of a stationary synchronphasor and an additive**
20 **noise as per the “magnitude modulation” interpretation of the interfering frequency test**

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

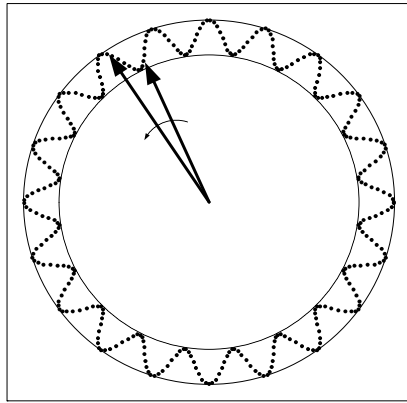


Figure P.4—Trajectory of a magnitude-modulated phasor.

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N.3.2 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, a situation of the magnitude being perfectly constant is not considered, but very minor changes in the magnitude are allowed. If so, phase modulation can be easily achieved by adding a “perpendicular” component to a stationary phasor as shown in Figure P.5.

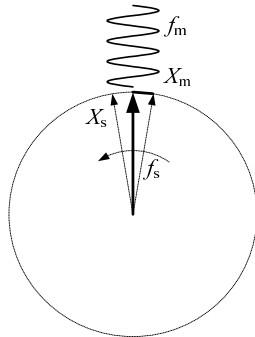


Figure P.5—Phase modulation of a phasor

12
13

Mathematically, the test signal in this case becomes:

$$x_{(t)} = \text{Re}\left(X_s \cdot \left(1 + j \cdot X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot f_m \cdot t)\right) \cdot e^{j(2\pi \cdot f_s \cdot t + \varphi)}\right) \tag{10}$$

After basic rearrangements one obtains:

$$1 \quad x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) - X_s \cdot X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot f_m \cdot t) \cdot \sin(2 \cdot \pi \cdot f_s \cdot t + \varphi) \quad (11)$$

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

$$3 \quad x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \quad (12)$$

$$4 \quad x_{NOISE(t)} = \frac{X_s \cdot X_{m(pu)}}{2} (\sin(2 \cdot \pi \cdot (f_s + f_m) \cdot t + \varphi) + \sin(2 \cdot \pi \cdot (f_s - f_m) \cdot t + \varphi)) \quad (13)$$

5 Equation 13 conforms to the same scenario as for the case of pure magnitude modulation: two equal
6 components having frequencies symmetrical with respect to the signal frequency are added. Equation 12 is
7 similar to Equation 13, except the sine function is used as a base function instead of the cosine. Therefore
8 Equation 3 and Equation 13 can be generalized as follows:

$$9 \quad x_{NOISE(t)} = \frac{X_s \cdot X_{m(pu)}}{2} (\cos(2 \cdot \pi \cdot (f_s + f_m) \cdot t + \varphi + \varphi_{NOISE}) + \sin(2 \cdot \pi \cdot (f_s - f_m) \cdot t + \varphi + \varphi_{NOISE})) \quad (14)$$

10 Equation 13 is used together with Equation 3 to perform the interfering frequency test. Two specific
11 alignments between the signal (Equation 3) and noise (Equation 13) are defined as follows:

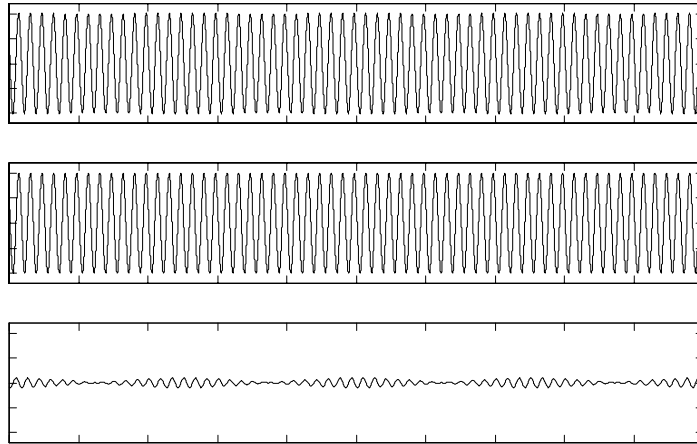
12 $\varphi_{NOISE} = 0$ - magnitude modulation

13 $\varphi_{NOISE} = \frac{\pi}{2}$ - phase modulation

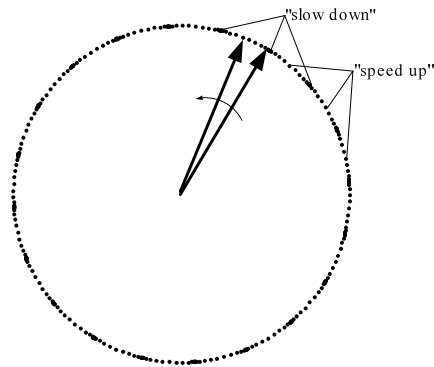
14 The generalized test needs to follow conditions (Equation 9) in terms of the magnitude and frequency of the
15 superimposed noise.

16 Figure P.6 shows the test input signal, true Synchrophasor and the additive noise per the phase modulation
17 interpretation of the interfering frequency test.

18 Figure P.7 presents a trajectory of a phase-modulated phasor. The magnitude remains approximately
19 constant while the “speed of vector rotation” oscillates.



1
2 **Figure P.6—The input signal being a sum of a stationary synchrophasor and an additive**
3 **noise as per the “phase modulation” interpretation of the interfering frequency test**



5
6 **Figure P.7—Trajectory of a phase-modulated phasor**

7 **8.11.1 Single interfering frequency**

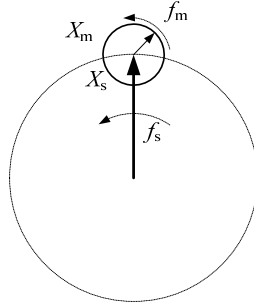
8 Let us explore the consequences of adding a single interfering signal component. Consider signal
9 modulation as in Figure P.8. A modulating vector of magnitude X_m rotating at frequency f_m is added to the
10 magnitude of the true phasor, and such modulated magnitude is further assumed to rotate at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

13
$$x_{(t)} = X_s \cdot \text{Re}\left(\left(1 + X_{m(pu)} \cdot e^{j(2\pi \cdot f_m \cdot t)}\right) \cdot e^{j(2\pi \cdot f_s \cdot t + \varphi)}\right) \quad (15)$$

1 The above expression is equivalent to:

2
$$x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \tag{16}$$

3
$$x_{NOISE(t)} = X_s \cdot X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot (f_s + f_m) \cdot t + \varphi) \tag{17}$$

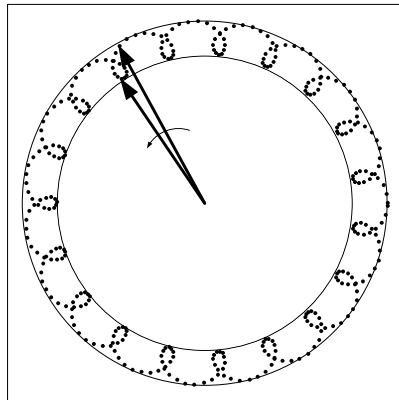


4
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Figure P.8—Modulating a phasor with a single frequency component

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

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



11
12
13

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

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

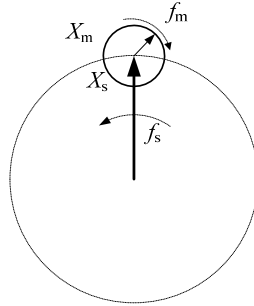
16
$$x_{(t)} = X_s \cdot \text{Re}\left(\left(1 + X_{m(pu)} \cdot e^{-j(2 \cdot \pi \cdot f_m \cdot t)}\right) \cdot e^{j(2 \cdot \pi \cdot f_s \cdot t + \varphi)}\right) \tag{18}$$

1 and is equivalent to:

$$2 \quad x_{(t)} = X_s \cdot \cos(2 \cdot \pi \cdot f_s \cdot t + \varphi) + x_{NOISE(t)} \quad (19)$$

$$3 \quad x_{NOISE(t)} = X_s \cdot X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot (f_s - f_m) \cdot t + \varphi) \quad (20)$$

4

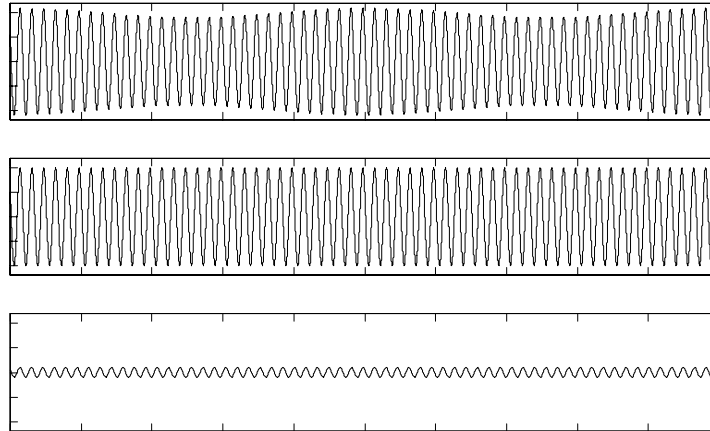


5

6 **Figure P.10—Modulating a phasor with a single frequency component (opposite directions**
 7 **of the base and modulating vectors)**

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

12 Figure P.11 illustrates the single component interfering frequency test signals.



13

Figure P.11—Single component used as an interfering signal

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

Table P.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 4 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 14 is used to generate the interfering noise signal for the tests. The interfering signal is a pair of sine-waves.

N.3.3 Range of the interfering frequency

As shown in Figure P.1, a compliant PMU shall 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 14 and boundary condition (Expression 7), the interference component of frequency above half the reporting rate shall be used for testing. The question is how high the frequency defined by Expression 7 shall become. Naturally, using our signal model (Equation 14), 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. It is considered unnecessary and may potentially cause 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 7 needs to be further specified as:

$$f_s > f_m > \frac{F_s}{2} \quad (21)$$

This solves the irregularity of the two frequency bands. When using Expression 21 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 Expression 21 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? It is assumed that 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 the above is agreed, then Expression 21 needs to be further specified as:

$$\frac{f_2}{2} > f_m > \frac{F_s}{2} \quad (22)$$

Following interpretation (Expression 22) 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 Expression 22 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.

N.4

N.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.

Comment [ARG46]: This section conflicts with Section 8.

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 With reference to Figure P.12, two approaches can be used to generate the input signal for the interfering frequency tests. Scenario a in Figure P.12 uses separate sources for the true phasor and the interfering signal. In this way the true phasor is available for independent 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 Scenario a in Figure P.12 allows such verification. The method of Scenario b in Figure P.12 requires a test 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 sign... [32]

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

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

7 First, the rates of modulation of interest need to be established. Typical system events are of frequency well
 8 below 10Hz. On the other hand one cannot—per Nyquist—observe modulations occurring faster than half
 9 the reporting rate. Therefore the upper limit for phasor modulations to be reported is the lowest number
 10 between about 10Hz of interest, and half the reporting rate of Nyquist limit. For example, when reporting at
 11 30 phasors/sec the band of interest is probably from 0 to 10Hz. When reporting at 10 phasors/sec one shall
 12 not expect a PMU to pass oscillations faster than some 2.5Hz. As a matter of fact a compliant PMU is
 13 mandated to stop oscillations faster than 5Hz. It will probably pass phasor oscillations some band down
 14 from the 5Hz interfering frequency limit.

15 Second, the true phasor must be established so that the TVE definition can be applied to the changing
 16 phasor. With this respect, Equation 1, Equation 10, Equation 15 and Equation 18 can be used.

17 For example, a magnitude-modulated phasor carried by the signal generated with Equation 1 has a dynamic
 18 magnitude of:

$$19 \quad X_{MAG(t)} = X_s \cdot (1 + X_{m(pu)} \cdot \cos(2 \cdot \pi \cdot f_m \cdot t)) \quad (23)$$

20 and phase:

$$21 \quad X_{PHASE(t)} = 2 \cdot \pi \cdot f_s \cdot t + \varphi \quad (24)$$

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

24 Fourth, the magnitude of phasor modulations needs to be established. The interfering frequency test sets a
 25 1% and 10% modulation magnitude. The test to pass phasor oscillations is not bounded by this
 26 requirement. Assuming an unstable power swing as an event of interest, the magnitude of the modulating
 27 component may reach the signal magnitude.

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

31 When both the interference rejection and modulation tests are done, their results can be summarized as in
 32 [Figure P.12](#).

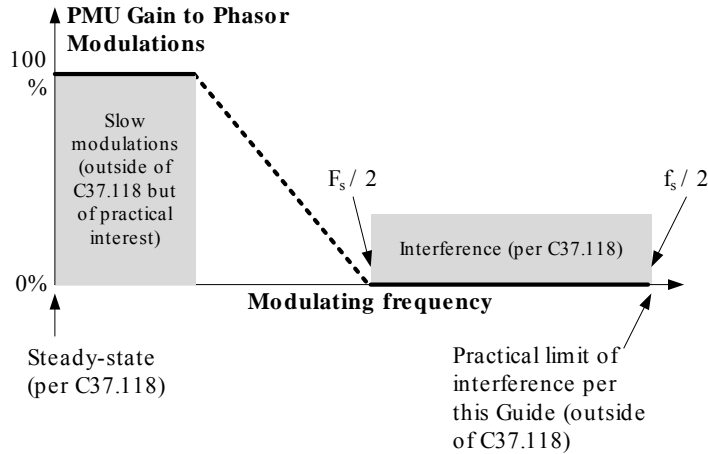


Figure P.12—Comparing the interfering frequency and modulated phasor tests

N.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. It is proposed 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 in 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 Scenario a in 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 P.13](#). Note that the frequency here refers to the frequency of the additive signal component.

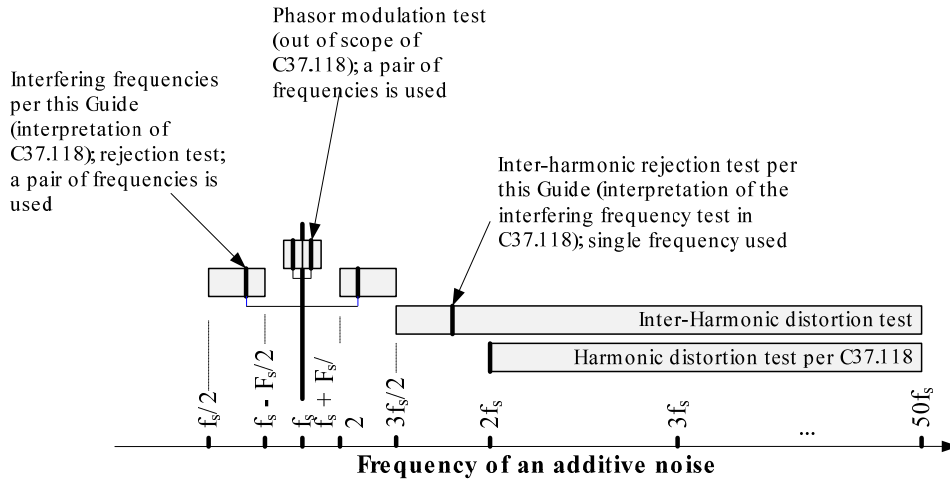


Figure P.13—Overall summary of the interfering frequency test per this guide

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equipment and setup

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The method of Scenario b in Figure P.12 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.

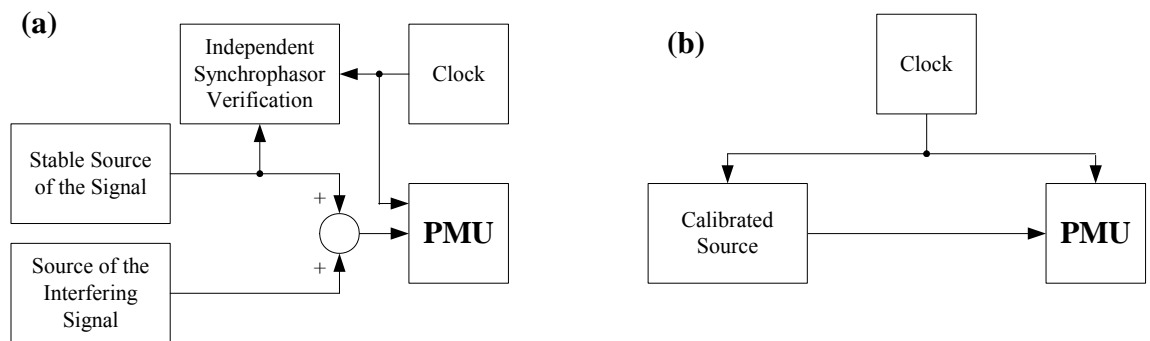


Figure P.12—Simplified setup for the interfering frequency test: true phasor and interference sources separated (a); single source for the true phasor and the interference (b)

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

Test procedure

For illustration purposes it is assumed that interpretation given by Equation 14 of the interfering frequency test; interpretation given by Expression 22 of the out of band frequencies, and test setup of Scenario a in Figure P.12.

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 $\pm 5\text{Hz}$ range; and the magnitude can be varied as required.

The source of the interfering signal is configured to generate a signal as per Equation 14. 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 (Equation 14) is to be varied slowly between half the reporting rate and half the phasor signal frequency. The magnitude $X_{m(\text{pu})}$ in Equation 14 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 14 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.