North American SynchroPhasor Initiative (NASPI)

Performance & Standards Task Team (PSTT)

Guide for Installation of Multi-Function Phasor Measurement Units (MF-PMUs)

October 10, 2014

Performance Requirements Task Team Chairs:
Damir Novosel, Quanta Technology
Vahid Madani, PG&E

Task Force Contributors:
Yi Hu, Quanta Technology – *Task Force Leader*
James Hackett, Mehta Tech – *Task Force Co-leader*

Dave Bertagnolli, ISO-New England
Dave Burian, PPL
Bill Dickerson, Arbiter
Bill Flerchinger, SEL
Mital Kanabar, GE
Harold Kirkham, PNNL
Jim Kleitsch, ATC
Jay Murphy, Macrodyne, Inc.
Krish Narendra, ERLPHASE
Nuwan Perera, ERLPHASE
Isabella B. Snyder, ORNL
Tony Weekes, Manitoba Hydro
Austin White, OG&E

Revision History

Date	Rev. #	Description
05/31/12	0.1	Initial outline
8/29/12	0.2	Updated outline based on August 29, 2012 teleconference call
9/27/12	0.3	Added definition of multi-function PMU, initial text for DFR-based PMU
12/17/12	0.4	Edited initial 4.1 contributions at 12/17/2012 conference call
1/11/2013	0.5	Edited initial 4.2 contributions at 1/11/2013 conference call
2/1/2013	0.6	Edited initial 4.4 contributions and revised 4.2 at 2/1/2013 conference call
5/21/2013	0.7	Added initial contributions from Austin White, Jay Murphy, Bill Flerchinger
6/19/2013	0.8	Added Mital's initial contribution
8/8/2013	0.9	Revised during the 8/8/13 call
8/20/2013	1.0	Combined the edits provided by Bill Flerchinger and Jay Murphy
10/10/2013	1.1	Replaced 4.3 with Jim Hackett and Tony Weekes new text
10/21/2013	1.2	Deleted 1.3, edited 4.2 and 4.3 to add current scaling text, initial editing of 3
10/31/2013	1.3	ErlPhase revision on 2 and 3
12/10/2013	1.4	Finalized draft
02/14/2014		Finalized document
7/8/14	1.5	Teresa Carlon incorporated comments from: Jay Murphy, Bill Flerchinger, Stephan Picard, and Alison Silverstein.
7/11/14	1.6	Teresa Carlon added more comments from Bill Flerchinger and Paul Ewing (tracked changes). Formatted level 1 heading to capitalize first letter in title. Formatted level 2 heading to capitalize only the first word for consistency.
8/30/2014	1.7	Yi Hu reviewed and accepted edits and comments

i. Disclaimer

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

Table of Contents

1 Overview

This section describes the scope, purpose, and limitation of applicability of this document, Guide for Multi-Function Phasor Measurement Units (MF-PMU), hereafter referred to as the Guide.

1.1 Scope

The Guide will focus on describing considerations and guidelines that are specific to the application and deployment of MF-PMU in a synchrophasor system. The Guide will also reference or point to relevant information, such as the phasor measurement requirements, data transfer methods, calibration, and testing, that is available in published standards, guides, and other documents.

1.2 Purpose

The commercial off-the-shelf PMU products on the market today in general can be divided into two categories: standalone PMU devices and multi-function PMU devices. Combining PMU functionality into a multi-function device brings certain benefits. Major benefits of multi-function PMUs include

- minimal incremental hardware cost to add PMU function to a device with other functions and
- substantial reduction in engineering, installation, and commissioning efforts and cost.

However, combining PMU functionality with protection, fault recording, metering, or other functions raises questions regarding how to use them properly. The purpose of this Guide is to provide some general guidelines to answer these questions.

2 References

This standard should be used in conjunction with the publications listed below.

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

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

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

[4] IEEE Std. C37.111-1999, IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems, June 1999. IEC 60255-24:2001, Electrical relays, part

24: Common Format for Transient Data Exchange (COMTRADE) for Power Systems, International Electro Technical Commission (On line: www.iec.ch).

[5] IEEE Std. 1588-20082, IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems.

[6] IRIG Standard 20004 – IRIG Serial Time Code Formats – September 2004, Timing Committee, Telecommunications and Timing Group, Range Commanders Council, U.S. Army White Sands Missile Range, NM.

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

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

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

[10] IEEE Std. C37.242-IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control

[11] IEEE Std. C37.118.1- IEEE Standard for Synchrophasor Measurements for Power Systems, 2011.

[12] IEEE Std. C37.118.2- IEEE Standard for Synchrophasor Data Transfer for Power Systems, 2011.

[13] IEC TR 61850-90-5, Use of IEC 61850 to Transmit Synchrophasor Information According to IEEE Std. C37.118.

3 Definitions and Acronyms

This section provides definitions and acronyms pertinent to the use of this Guide as they relate to Global Positioning System (GPS)-synchronized devices, communication protocols, communications media, and signal processing.

Absolute Phase Angle – See synchronized phasor definition.

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

COMTRADE (Common Format for Transient Data Exchange) – File format. COMTRADE is a standardized ASCII text or binary file (two formats) originally designed for exchange of transient data files and subsequently adopted by Digital Fault Recorder (DFR) vendors as the standard file format for field records made by DFRs. COMTRADE can be used to transfer locally recorded values from a PMU 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.

CT – Current transformer.

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

HMI – Human-machine interface.

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

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

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

MF-PMU – Multi-Function Phasor Measurement Unit. Any device that is integrated with phasor measurement function. Phasor measurement is an added function to the primary functions (e.g., metering, relaying, fault recording) of a device.

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

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

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

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

PT – Potential or voltage transformer.

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

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

SPS – Samples per second.

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

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

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

TCP/IP – Transmission Control Protocol/Internet Protocol (TCP/IP) is a low-level protocol for use mainly on Ethernet or related networks. Most higher level protocols use TCP/IP to transport data. TCP/IP provides a highly reliable connection over unreliable networks, using checksums, congestion control, and automatic resending of bad or missing data. TCP/IP requires time to handshake new connections and will not hold up other tasks if missing data is being resent.

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

UDP/IP – User Datagram Protocol/Internet Protocol (UDP/IP) is a low-level Internet Protocol (IP) that provides low-latency communication across Ethernet or related networks. UDP/IP does not provide any error control or resending of missing or bad data. The application will need to check data for correctness. Unlike TCP/IP, UDP/IP does not require a handshake making it a good choice for real-time data communications.

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

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

4 Multi-function PMUs

This section describes different types of multi-function PMUs and the main characteristics of each type of multi-function PMU.

4.1 Definition of multi-function PMU

A multi-function PMU is an IED that produces information about the power system in addition to the synchrophasor stream. This additional information could be as simple as a contact output or logic state in the case of a relay-based multi-function PMU or as extensive as point-on-wave data in the case of a digital fault recorder.

Multi-function PMUs are devices, intended for use in the power system, that can act as PMUs while simultaneously performing one or more other functions. These other functions can include protective relaying, fault recording, revenue metering, and power quality analysis. Some users prefer to use multi-function PMUs because they can offer economy of procurement, engineering design, installation, and maintenance. Other reasons to use multi-function PMUs are space savings and leveraging the use of existing equipment.

Concerns can arise regarding adverse interactions between the PMU function and the various other functions in the device. Use of multi-function PMUs may also be constrained by regulatory and company policies. Some of these concerns will be addressed below.

Multi-function PMUs typically consist of common inputs (e.g., CTs/PTs, data acquisition) which attach to one or more buses, feeders, or other sources of power system information. Various functions within multi-function PMUs may or may not share timing reference, communications, analysis/computation results, etc.

The design and application of multi-function PMUs must ensure that interactions between the functions of the device are properly managed so that operation of all functions remains within satisfactory limits. This depends on the nature of the functions integrated together and the application of each function. Protective relays and revenue meters, for instance, can’t normally tolerate impaired performance due to the addition of PMU functionality. Additionally, a PMU used in a wide area measurement system needs to continue to function properly, even in the case of a major system event.

4.2 Relay-based multi-function PMUs

Microprocessor-based protective relay PMUs include protective elements, CT and PT inputs, and event reports and may include one or more of the following: communications interfaces, HMIs, programmable logic, digital contact inputs/outputs, analog inputs/outputs, metering, and other capabilities. Because protective relays are used to control circuit breakers, reclosers, switches, and other devices, they may be incorporated into synchrophasor-based control schemes. Given that relays control primary equipment on the power system, appropriate cyber and physical security practices should be used. Protective relays that provide PMU functionality must be designed and tested so that the protective relay functions and the PMU functions operate independently and without impact on each other for all possible use cases. A multi-function PMU's current channels must be scaled for primary functions (e.g., relay or PMU). Note that different functions may have different current scaling requirements.

4.3 Digital fault recorder (DFR)/dynamic disturbance recorder (DDR)-based multi-function PMUs

DFR-based multi-function PMUs provide a way to get existing infrastructure to collect PMU data. Using DFR-based multi-function PMUs can be cost-effective as well as beneficial because the primary function of recording devices does not directly affect the bulk electric system in the case of any malfunctions. The required channels are already connected to the DFR and do not need to be recommissioned. A communication network with sufficient bandwidth for phasor data streaming may already be established for the DFR. DFRs that provide PMU functionality must be designed and tested to verify that the DFR functions and the PMU functions operate independently and without impact on each other for all possible use cases. A multi-function PMU's current channels must be scaled for primary functions (e.g., DFR or PMU). Note that different functions may have different current scaling requirements.

4.4 Meter-based multi-function PMUs

Both revenue metering and power quality devices may incorporate PMU functions. The operating range of these IEDs is uniquely consistent with PMU operation.

The frequency response, filtering, and connection to metering CTs for these devices may limit the dynamic and transient response of the PMU function. This potential limitation should be evaluated carefully by the user.

5 General Guidelines for using MF-PMUs

This section discusses some interdependency issues users should consider when assessing MF-PMUs and the possibility that the PMU capability may interact with the primary functionality of the multi-function device.

5.1 Cyber security considerations

Cyber security is an important issue facing the deployment of IEDs. The issue is a complex one and one evolving in terms of scope and requirements. It is likely the specific implementations necessary will be changing and because of this the user is cautioned to evaluate the hardware, software, and procedures required at the time of installation. Attention should also be given to anticipated requirements that may require retroactive changes. DHS, NIST, and NERC are dominant in specifying or mandating security requirements and procedures. IEEE PC37.240, Draft Standard for Cyber Security Requirements for Substation Automation, Protection and Control Systems (active project as of October 2014), is an excellent source for such requirements.

5.2 Measurement

When using a MF-PMU, some settings or device configurations may impact the PMU measurement functionality (e.g., a setting for the DFR impacts the PMU measurement). The manufacturer should clearly state any functions in the IED where settings or configurations are coupled to PMU settings and may impact the communications, signal range, measurement accuracy, filtering, dynamic response, etc. A user needs to know which function determines the input circuit settings and the related device configurations.

MF-PMUs may also have some measurement limitations based on their primary functionality. An example is a meter with PMU capability that is optimized for very accurate measurements around nominal values. The meter with PMU capability may not be well suited to accurately measure values that are much higher than nominal (as can be seen during a fault). Some multi-function device types are listed below with a short description of possible measurement limitations or variations that may be expected.

- DFR/DDR – optimized for capturing fault conditions and may not have acceptable accuracy around nominal values.

- Meter/Power Quality Devices – optimized for capturing nominal values and may not accurately capture high fault values.

- Protective relay – optimized for protection of the power system and may not measure nominal values as accurately as a revenue grade meter.

Other considerations are the voltage and current transducers used by each of these devices. The PTs and CTs used may vary depending on the device type, resulting in additional inaccuracy or noise in the PMU measurements.

5.3 Communication of PMU data

Under various operating conditions, communication of PMU data may be disrupted in a MF-PMU device. Examples include delays or interruptions in streaming PMU data due to another operation in the MF device taking precedence. Any such behavior of a MF-PMU should be clearly stated in the data sheet or instruction manual of the device and include details of how to mitigate such behavior.

Such conditions include data transfer during event capture and protection operation. Careful evaluation and understanding of the possible adverse effects on the PMU data transfer should be taken into account. Any testing should be performed under worst case communication loading.

5.4 Operation, testing, and change management processes and procedures

A user of a MF-PMU should establish and prioritize proper operation, test, and change management processes. The MF-PMU user should also specify the need to establish communications and alert processes that give advance notice to users of the timing and nature of both the PMU and non-PMU functions of any testing, updating, or change management efforts. Consideration should be given to which functions in the multi-function device determine the operation, test, and change management processes and procedures. Is it the PMU functionality or the non-PMU functionality? Depending on which function takes precedence, other functions are likely to see some impact in operational availability or in measurement performance. A user needs to keep this in mind as the PMU data may be impacted. Examples of possible operation, test, or change management situations include the following:

- Firmware updates may impact the availability of all functions in a multi-function device.

- Resetting or rebooting the device (due to PMU or non-PMU functionality in the device) will impact the PMU data availability or the availability of the other functions.

- Testing non-PMU functionality of the device will impact PMU data availability. The example below shows the PMU data that was recorded when the protective relay was undergoing some relay function testing. A user needs a method or process to account for PMU data taken during testing of the non-PMU functionality.

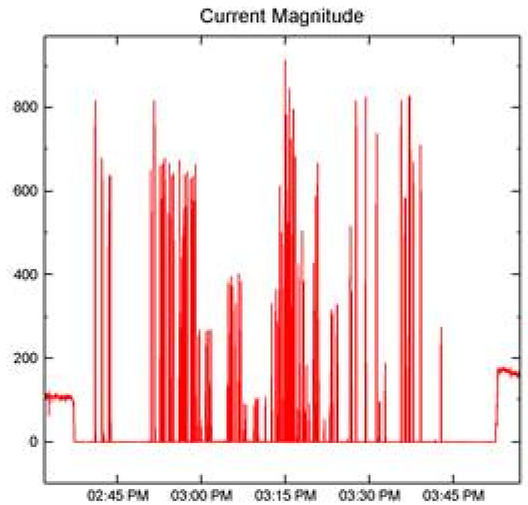

Figure 1. PMU measurements recorded while the protective relay was under test

- Testing PMU functionality of the device will impact non-PMU functionality. A process or method needs to be developed to account for the fact that the measurement data during testing of the PMU functionality did not occur on the power system.

5.5 Calibration and maintenance

A user of a MF-PMU needs to give consideration to calibration and maintenance schedules and procedures. Does the PMU functionality set the schedule, or do they have separate schedules? As an example, many utilities perform maintenance testing on their protective relays every two years. During relay testing, the PMU measurements would be invalid or unavailable. Similarly, the PMU calibration and maintenance schedule could impact the availability of other functions. Scheduling these at the same time may provide some efficiency but may require working across divisions or functions of the same organization.

5.6 Testing and validation

Because the MF-PMU performs various power system functions/applications with additional PMU functionality within the same device, it is important to validate that all functions are performing per the standard requirements and/or device specifications. In addition, the functional testing should also consider worst case scenarios to check the MF-PMU device performance under stressful processing conditions. Below are some of the worst scenarios to be considered in validation testing:

- Enabling all specified or applicable non-PMU functions of the IED in addition to full PMU functionalities.

- Simulating/emulating various power system scenarios (e.g., transient, dynamic, higher harmonics, etc.) as a part of input signals to the MF-PMU device.

- Incorporating simultaneous multiple actions related to both PMU function (e.g., configuration change) and additional functions (e.g., setting change).

- Carrying out multiple streaming of all supported protocols, (e.g., synchrophasor data streaming in addition to file transfer (FTP/SFTP) of recorded data, DNP 3.0, etc.).

- Checking functional interdependencies (change in one function setting may affect PMU configuration or streaming throughput).

If any functionality is compromised (not performed as per specification or standard requirements) during such worst system conditions, the MF-PMU manufacturer should notify users by publications such as instruction manuals or technical notes.

6 Final Comments

Multi-function devices can provide advantages over multiple single function devices. This document has indicated which devices would likely be used to concurrently implement PMU functionality and how PMU function may be impacted. It is up to the user, in cooperation with the vendor, to evaluate any impact and to develop the necessary test procedures to verify operation.

Appendix A – Clock accuracy and reliability

Clock accuracy requirements are defined in IEEE C37.118.1-2011. GPS clock reliability has been an issue for many reasons, which may be common to all PMUs including MF-PMUs. Some of the problems have been encountered include:

- Firmware bugs: various bugs in clock firmware have resulted in clocks locking in one second off, inconsistent handling of leap second.
- Reception issues: loose connections, failing coax or antenna, obstructed view of the sky, other RF antennas mounted nearby.
- Shared clock: some MF-PMUs have a master unit and the GPS signal is passed to additional slave units. When the master is down, all units have no GPS signal. We have also had some issues with certain devices connected to the same clock output and had to separate them.

All PMUs should be properly factory tested to ensure they comply with the accuracy requirements defined in IEEE C37.118.1-2011, and are able to reliably report whether the clock is synchronized to UTC within the accuracy limit.