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Phasor Measurement Unit

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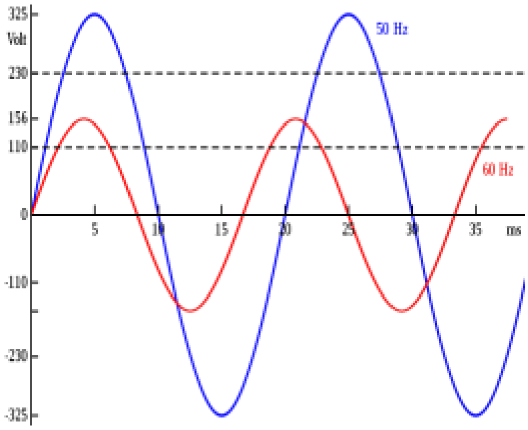
I. INTRODUCTION

In 1893 , CHARLES PROTEUS STEINMETZ presented his paper on simplified mathematical description of waveforms of alternating electricity. STEINMETZ called his representation a phasor.With the invention of phasor measurement units (PMU) in 1988 by Dr.Arun G.Phadke and Dr.James S.Thorp at Virginia Tech, Steinmetz technique of phasor calculation evolved into the calculation of real time phase monitoring. Early prototypes of PMU were built at Virginia Tech and Macro dyne built the first PMU model (Model 1620) in 1992.



1.1 PHASOR

With the help of a PMU, it is simple to detect abnormal waveshapes.A waveform shape described mathematically is called a phasor. A phasor is a complex number which represents both the magnitude and phase angle of sine waves found in electricity.

II. WIDE AREA MEASUREMENT SYSTEM

1. Power grids and major problems seen today: Deregulation, competition and increase in complexity of today's power network have exacerbated the power system stability issues. The specific problem they face today is the system wide disturbances, which are not ably covered by existing protection and network control systems.As power grids get even more heavily by sudden bulk power transfers,the system becomes very vulnerable and even minor equipment failure result in tripping and at the end,blackout.

2. The Need for Real time monitoring and control:To ensure system stability on heavily loaded system,all or most installed components should remain in service and right actions must be taken quickly if the system has not recovered after a accident.

The solution to the problem is real time monitoring.Such a wide area measurement system provides with real time knowledge of various instability issues and events when they occur.This early warning system provides operators with much needed time for counteractions as well as choices for action.It provides a base for automatic wide area measurement and control.

3. Wide area measurement system:

Wide area measurement system is built up on a reliable communication system connecting power stations, network control centres and substations. The GPS time system is used for timing accuracy and number of PMU units are deployed across the power network.

ABB has introduced PS Guard wide area measurement system .It is used to achieve value from the accurate and reliable data stream coming from PMU devices.

2.1 OVERVIEW OF THE WECC WAMS

WAMS completes the data acquisition functions of protection relays, fault recorders, and SCADA . Protection relays and fault recorders make local measurements within a substation at very high data rates of thousands of samples per second, while SCADA traditionally provides central measurements of slow power system behavior at data rates in the order of a few seconds. The overall objective of WAMS is to provide dynamic power system measurements in one or the other of two basic forms; raw point on wave data or raw data that has been converted into phasor. Phasor data computation rates range from 10 to 60 phasor per second(systems include Phasor Measurement Units or PMUs) and point on wave data with rates upwards to 30k (systems include Portable Power System Monitors or PPSMs).

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Precise synchronization is the key to WAMS performance. The phasor network consists of Phasor Measurement Units (**PMU**s) and Phasor Data Concentrators (**PDC**s). A complete WAMS will also accomodate measurements of other types, and it will contain many resources that convert acquired data into useful information.

The test bed for WAMS development has been the Western Interconnection of the North America power system. Throughout the 1980's the Western System Coordinating Council (**WSCC**) recognized an increasingly acute shortfall in Dynamic information , and a general plan to remedy this need was formed in 1990 . However ,Technology and infrastructure for the envisioned WAMS were still in the prototype stages.

The US Department of Energy (**DOE**) recognized these needs as generic to reliable performance of large power systems. Therefore in 1989, the DOE joined with two federal power utilities - the Bonneville Power Administration (**BPA**)and the Western Area Power Administration (**WAPA**) - in the first large scale WAMS project . In 1994 the Electric Power Research Institute (**EPRI**) initiated the several related WAMS project and linked their PMU development projects into the overall WAMS effort.

WAMS has close historical linkages to wide area control ,and to EPRI's Flexible AC Transmission Systems (**FACTS**) program in particular. BPA and what has since become the Western Electricity Coordinating Council (**WECC**) have some three decades of direct operating experience with FACTS technology or precursors to it. The HVDC modulation system installed at Celilo, Oregon operated for some 12 years, and provided considerable insight into the technical and institutional challenges that confront full-scale use of FACTS control. The WAMS technologies were developed partly in response to those technical challenges, in parallel with research projects on techniques for advanced control plus collaborative enhancements to WECC planning resources .

Progress in the development and use of the WECC WAMS is reported roughly once a year. By the end of 2004, the WECC WAMS has reached the following size:

- 11 PDC units, operated by 9 data owners.
- 53 integrated PMUs
- 7 stand-alone PMUs
- ~23 PPSM units
- ~10 monitor units of other kinds

The "backbone" system of PMUs and PPSMs continuously provides some 1500 primary signals, about half of them phasor .

The growing WSCC WAMS provided immediate value when the western North American power system experienced massive breakups on July 2 and August 10, 1996 .The WAMS data was a highly valuable information source for the extensive engineering reviews that followed both events.

For the August 10 event, WAMS information was used even more directly where, within minutes of the breakup, WAMS data records were reviewed as a guide to immediate operating decisions in support of system recovery.

So far, accomplishments of the WECC WAMS include the following:

- Maturing of the WAMS technologies for both PMUs and PDCs .
- Better insight and modeling for power system dynamics
- High performance resources for direct observation and testing of power system dynamic performance
- Development of a prototype system of WAMS-based wide area protection known as the BPA’s WACS-wide area stability and voltage control system.

This paper reviews core WAMS technologies and current status of WAMS applications in the North America. Synchronized phasor measurement and phasor concentration are two basic functions of a WAMS measurement network .WAMS applications include dynamic modeling and validation and wide-area control. New applications are being explored such as state estimation. In the eastern interconnection of the North America, a WAMS-like system is being deployed under the DOE-led project known as the Eastern Interconnection Phasor Project (**EIPP**).

WAMS TECHNOLOGIES

A. Synchronized Phasor Measurement Technology

The original IEEE Standard 1344-1995 (IEEE Standard for Synchro phasors for Power Systems) established a data format and measurement concepts for synchronized phasor measurement. The new standard IEEE C37.118 will be published in 2005 after 10 more years of WAMS experience and research. Both standardizing efforts are led by Mr. Ken Martin of BPA. The latest IEEE C37.118 improves PMUinteroperability with the following three major contributions:

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• Refined definition of a “Absolute Phasor” referred to
GPS-based and nominal frequency phasors, as well as time-stamping rule;
• Introduction of the TVE (Total Vector Error) toquantify the phasor measurement error;
• Introduction of the PMU compliance test procedure.

Synchronized phasor technology is the preferred basis of a WAMS system. Phasor values are usually estimated from digital samples of the AC waveforms. To make sure that all synchronized phasor have the same reference, the standard defines a synchronized phasor angle as an “instantaneous phase angle relative to a cosine function at nominal system frequency synchronized to UTC. This angle is defined to be 0 degrees

When the maximum of the measured sinusoidal waveform occurs at the UTC second rollover (1 pulse per second time signal), and -90 degrees when the positive zero crossing occurs at the UTC second rollover.” Figure 2 illustrates the concept showing the nominal ‘reference’ waveform (dotted line) synchronized with UTC (peaks at 0, T0, 2T0, etc) and the actual waveform (solid line) with growing phase angle (φi) relative to the reference.

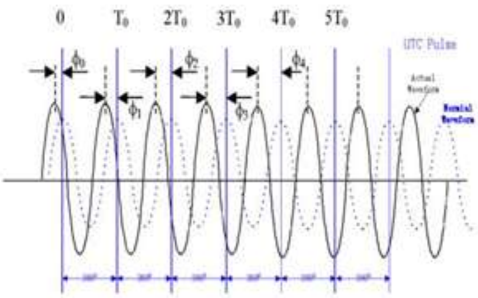


Figure 2 "Absolute Phasor"

The phasor derived from the above definition is an estimated quantity, so we need a way to evaluate the error to make sure all the phasor measurement units in a system have consistent accuracy. IEEE C37.118 introduces the concept of Total Vector Error (**TVE**) to quantify the phasor measurement error,
which is defined as:

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

where “r” and “i” denote the real and imaginary parts of a phasor respectively, Xr(n) and Xi(n) are the measured values ,given by the measuring device, and Xr and Xi are the theoretical values of the input signal at the instant of time of measurement.

Based on the TVE, IEEE C37.118 also recommends the compliance tests which include:
• 10% magnitude step test
• 90° phase step test
• 5Hz frequency step test

In order to accommodate different measurement devices and meet different needs of various applications, IEEE C37.118further defines the influence quantities and allowable error limits for different compliance levels.

The Standard does not attempt to address all factors that affect PMU response to power system dynamic activity .
When applied under field conditions, the TVE will often reflect the presence of signal components other than the fundamental frequency of the power system.

B. Phasor Data Concentrator (PDC) - a Core Component of WAMS
WAMS systems are used for both off-line studies and real-time applications. An important feature of these systems is their ability to provide continuous dynamic measurements that are precisely time synchronized across the power system. With real-time WAMS, the continuous measurements feed out as a data stream which can be applied to on-line applications such as monitoring and control. They can meet real-time control system requirements with time delay less than 1 second(typically 100-200 ms) unlike SCADA which provides only 1-5 second measurement intervals.

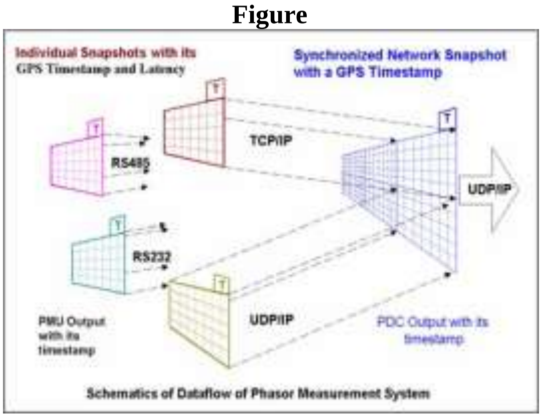
The basic functional requirements of a real-time WAMS for discrete control applications include :
- system wide synchronized phasor data stream broadcasting.
- Maximum and constant response delay in the order of hundreds of milliseconds.
- System wide dynamic measurement.

Applications that involve large scale continuous control may pose additional requirements to assure operational reliability and to avoid adverse interactions ..

To support these requirements, the PDC pioneered by BPA uses a multiple embedded CPU architecture to handle intense communication and data processing. Each PDC may have 4CPUs, and each CPU with up to 8 PMU inputs using serial or network (Ethernet) connections. The PDC processing delay is very short, typically less than 4 ms.

A PDC collects time-stamped phasor measurements from connected PMUs, adjusts for the differing transmission latency times, accounts for timing and/or transmission errors and integrates all valid reporting PMU measurements into a single composite data packet with a single timestamp. These packets are then streamed via Ethernet or a serial link to subscribing WAMS applications (See Figure 3). The PDC output is a system phasor measurement data stream with the protocol PDC Stream via Ethernet or PDCxchng via serial link. Both the protocols were developed by BPA . After the new standard IEEE 37.118 is published, the data stream format defined in the standard will be applicable to PDC output.

Figure



A PDC can automatically or manually trigger an event logger when a PMU trigger is detected. Other WAMS applications make continuous or triggered recordings using the continuous data stream. WAMS applications that subscribe to PDC transmission might fit the generic paradigm of Figure .. Here sequential WAMS data packets are received and decoded and a custom channel selection is made. This data can then be displayed locally or remotely, archived (all data or just interesting data using one or more limit triggers) for short or long term accessibility. Finally the data can undergo critical time and/or frequency domain analysis as well as be inserted into special control algorithms.

PHASOR MEASUREMENT UNIT (PMU)

It measures electrical waves on an electricity grid to determine the health of a system. In power engineering, these are known as synchro phasor. Synchro phasor are considered one of the most important measuring devices in the future of power system. The PMUs are sampled from widely dispersed locations in electrical power system and synchronized from common time source of global positioning system (GPS) radio clock.It is a tool for system operators and planners to measure the state of the electrical system and manage power quality. Synchrophasors measures voltage and current at diverse locations and give accurate output in the form of time stamped voltage and current phasors.Because these phasors are truly snchronized, synchronized comparison of two quantities is possible in real time .The advantage of referring phase angle to a global reference time is helpful in capturing the wide area snap shot of the power system.

This technology has the potential to change the economics of power delivery by allowing increased power flow over existing lines. This technology is helpful in mitigating blackouts and learning the real time behavior of the power system.

Model 1690

The model 1690 phasor measurement unit (PMU) provides instant access to this information providing new opportunities to understand and improve the performance of today's power system.

Capable of both recording long duration electrical disturbances in phasor format and providing continuous phasor measurements in support of real time applications, the PMU adds a new dimension to power system monitoring.

2. PMU with a DFR

The DFR used in this investigation is a multi-time frame recording system used to monitor

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electrical power systems. It can record up to 36 analog channels and 64 digital (status) channels and store up to 1000 recordings. Up to four recorders can be operated as a cooperative group to achieve greater numbers of channels. The DFR can record data simultaneously in three time domains: high-speed transient fault (up to 384 samples/ cycle),low speed dynamic swing (up to 30 minutes), and continuous trend (10 second to 1 hour intervals). Wide varieties of triggers are available to initiate recording. The recording system consists of a recorder, analog input isolation modules and Graphical User Interface (GUI)software. There are various analog input isolation modules available to interface to signal sources. Modules are available to connect to standard signals found in a typical electric power substation including secondary ac voltage and current and low-level dc voltage and current signals. These modules can generally be installed up to 300 meters from the recorder unit , allowing them to be located near the source of the signals being monitored. The GUI software provides tools to configure the recorder, trigger, retrieve and manage records and display real time measured values. The GUI software also includes a graphical record display and an analysis software sub module. An optional data retrieval and management data base program is available to automatically collect and store records from multiple DFRs (refer Figure 1)

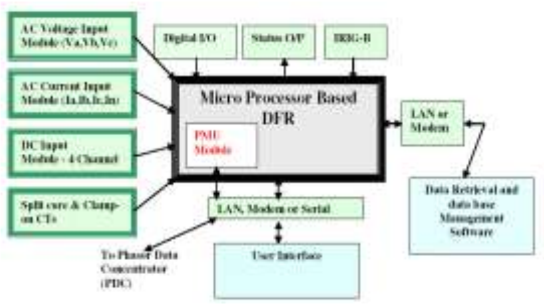

Figure 1: Schematic view of a PMU module in a Microprocessor based DFR

PMU functionality is an optional software product feature on this DFR. The PMU functionality will comply with IEEE C37.118 – 2005 . Up to 12 user selectable phasors - as individual phase quantities or three-phase positive, negative or zero sequence phasors or summated phasors - can be transmitted via Ethernet, Serial port, or Modem at rates up to 60 frames each second. The PMU functionality is designed to work simultaneously with the existing DFR features such as triggering, recording, and trending. This means, simultaneously you can connect to the DFR using the GUI software and view metering quantities, modify configuration settings, transfer records over Modem and stream PMU data over Ethernet or vice-versa. In order to reliably transmit the PMU data, it is required to connect IRIG-B signal from a reliable Global Positioning System (GPS) clock or receiver to the DFR through standard BNC (Bayonet Neill Connector) connector. The GPS signal must comply with the specification as mentioned in the IEEE C37.118 standard ..

PHASOR NETWORK:A phasor network consists of a phasor measurement unit dispersed throughout the electricity system, phasor data concentrator (PDC) to collect information. The PMU functions, phasor calculation and transmission to the PDC , the voltage and current samples ,acquired synchronously with the GPS reference, are processed by discrete fourier transform(DFT) and formatted in data frames using the IEEE std. 1344 format. Each PMU has a GPS receiver to synchronize the samples so that the phasor angles measured by all PMUs in the system are in the same time reference. The PMUs have eight analogue channels (four for voltage and four for current) and 16 digital channels.The PMU generated data are continuously sent to the PDC at a maximum rate of 60HZ using an Ethernet link (UDP/IP protocol).This rate and an angle precision of 0.1 electric degrees are suited for the analysis of long term dynamic phenomena.

PDC

The PDC receives and correlates time-tagged phasor data sent by all the PMUs in the system.It has the following main functions:

- Acquisition of the phasors, continuously sent by the PMUs, handling of transmission errors.
- Storage of phasors in a central database.
- Support for real time system monitoring.
- Support for offline study functions, making available old phasors.

These functions are designed and implemented in computing routines using the object oriented modeling paradigm and c++ programming language. As the PDC needs to support real time applications, it is necessary to rank the routines priorities.For example,the task of phasors acquisition has a higher priority than a request from the offline study application. To solve the problem a real time environment needed to be implemented. The PDC was built using the GNU/Linux operating system which does not have native real time support.The real time support is

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enabled in GNU/Linux applying a patch to the GNU/Linux kernel.There are two main packages for this finality:RT Linux and RTAI.RTAI was chosen since it presents a better support for object oriented programming tasks.

NETWORK:

The PMUs and PDC are connected by Ethernet using the Internet network. The Internet connection was chosen due to its availability and the facilities provided to manage the PMU remotely. The phasors are sent by the PMUs using the UDP/IP protocol and the remote administration is performed by the SSH(Security Shell) application.

For online graphic visualization there is microprocessor that has Ethernet connection with PDC (TCP/IP). It shows phasor modules and angles in a specific time range as well as their frequency spectrum.

IMPLEMENTATIONS

1. The bonneville power administration (BPA) was the first utility to implement synchrophasors in its wide area monitoring system.
2. The FNET project operated by virginia tech and university of tennesse utilizes a network of 80 low cost, high precision frequency disturbance recorders to collect the synchrophasors data from the U.S power grids.
3. In 2006,CHINA’s wide area monitoring system for its 6 grids had 300 PMUs installed mainly at 500KV and 330Kv substations and power plants. By 2012, China plans to have PMUs at all 500KV substations and all power plants of 300MW or above. Since 2002,China builts its own PMU to its own national standards. This type has higher sampling rates than the original one and is used in power plants to measure rotor angle of the generator, excitation voltage, excitation current, valve position and output of the power system stabilizer(PSS).All PMUs are connected via private network and samples are received within 40ms on average.
4. The North American Synchrophasors Initiative(NASPI) previously called Eastern Interconnect phasor project(EIPP) had 120 PMUs connected collecting data into Super phasor data concentrator centered at Tennesse valley Authority(TVA).This data concentration system is now an open source project known as open PDC.
5.The U.S DOE has sponsored several related research projects including GRIDSTAT at Washington state University.

APPLICATIONS
1. Power system automation.
2. Load shedding and other load control techniques such as demand response mechanisms to manage power system i.e.directing power where it is needed in real time.
3. Increase the reliability of the power grids by detecting faults early and prevention of power outages.
4. Increase power quality by precise analysis.
5. Wide area measurement and control ,in very wide area super grids,regional transmission networks and local distribution grids.

STANDARDS

The IEEE 1344 standard for synchrophasors was developed in 1995, reaffirmed in 2001. In 2005, it was replaced by another IEEE C37.118-2005, this was a complete revision and dealt with issues such as measurement, the method of quantifying the measurements, testing and certification requirement for verifying accuracy, data transmission format and protocol for real time data communication.
OPC-DA/OPC-HDA A microsoft windows based protocol.XML is used and run on non-windows computer.
IEC 61850. a standard for electrical substation standard.
BPA-PDC STREAM. used by BPA.

OVERVIEW OF PHASOR MEASUREMENT SYSTEM

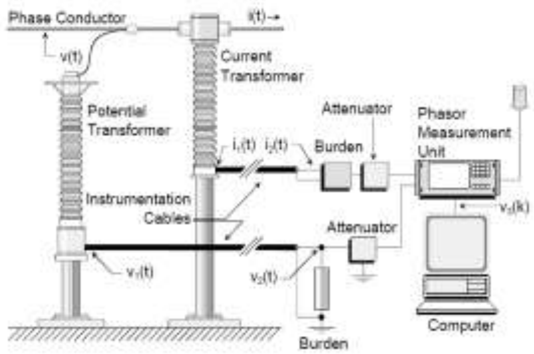

Figure illustrates the devices forming voltage and current phasor measurements typically found in electric power generating stations and substations. The devices consist of two major parts: a PMU and the balance referred to as instrumentation channel including instrument transformers ,control cables, and burdens. Ideally, it is expected that the instrumentation channel will produce at the output a waveform that will be an exact replica of the high voltage or current and

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scaled by a constant factor. In reality, the instrumentation channel introduces an error and contributes to signal degradation to some degree .Furthermore, the error introduced by one device may be affected by interactions with other devices of the channel. It is thus important to characterize the overall channel error.

The core logic in a PMU is the projection of point-on-wave voltage and current signals onto a set of reference waveforms ,known as complex modulation. PMU design must consider the frequency range of signal components to enter and exit the instrument, and how to present appropriate average values for varying phasor parameters. Figure 2 shows the general structure and nomenclature of PMU hardware [20]. Given the complexity in the power system signal environment, good filtering is needed in actual PMU logic, but options of filtering can be many. The indicated logic for “Bus Frequency Estimator” can be as simple as a smoothed numerical derivative of bus angles, or it can be a complicated frequency tracking function used to achieve a uniform number of samples for each cycle of system operating frequency and thereby desensitize the instrument gain to frequency changes. Since PMU logic contains those complex processing steps and the implementation can vary to a great extent, it is necessary to evaluate the performance of a PMU.

Frequency

In response to the needs for evaluating phasor performance, the NASPI PSTT team has made significant progress in developing guidelines, leveraging prior work (esp. in WECC) and international experience, to address how the evaluation should be performed. These guidelines are intended to supplement existing standards for the purpose of procurement specifications and regulatory standards, so as to help users that plan to install PMUs or consider using phasor measurements for specific applications to ensure required phasor quality and phasor inter-operability.

LABORATORY TESTING OF PMUS

The NASPI PSTT group consolidated all these efforts and developed the PMU Testing Guide. PMU laboratory testing equipment consists of the following components (Figure 3):

  A time reference: The best time reference source is agood quality GPS receiver with a GPS antenna. Good reception of GPS signals is needed to ensure the timing accuracy.

  A signal generator: It should be able to generate multiphase steady state and dynamic signals with specified accuracy for magnitude, phase, frequency, phase balance, and rate of change in these parameters.

  A data collection device: The data collection device receives phasor measurements from the PMU and transmits to analysis tools in appropriate formats. It can be a phasor data concentrator (PDC) or just a PC which
has proper software reading the PMU data format.

  Analysis tools: A set of tools are needed to parse the PMU data and analyze them per testing specifications so the PMU performance can be characterized.

If defined, the steady-state tests shall be performed according to the signal range and test conditions specified inC37.118 . In this context, these steady-state tests are conformance tests to evaluate PMU performance against defined criteria in the IEEE C37.118 Standard. In contrast ,other steady-state and dynamic tests are termed performance tests, for which the criteria are yet to be developed.

STEADY STATE PMU TESTING

For steady-state tests, the signals have a constant amplitude and frequency during the data collection part of the test. The steady-state tests are conducted to confirm that the accuracy of a PMU is within the specified limits when exposed to specified steady-state operating conditions. The IEEEC37.118 Standard clearly defined the Total Vector Error(TVE) metric, and established the level 0 and level 1compliance requirements under steady-state conditions for a PMU . These compliance requirements define the TVE level for phasor magnitude measurement, phasor angle measurement, harmonic distortion and out-of-band interference.

The following types of steady-state tests are proposed in the PSTT PMU Testing Guide [18]:

  Magnitude accuracy test*
  Phase accuracy test*
  Frequency accuracy test*
  Rate of change of frequency accuracy test
  Unbalanced magnitude response test.
  Unbalanced phase response test   Off-nominal frequency response test*
  Harmonic frequency response test*: To evaluate PMU performance in response to harmonic signals.
  Out-of-band interference test*: To evaluate PMU performance in response to signals with

frequency outside the pass band of the PMU's filtering characteristics.

  Data reporting test: This is to confirm the PMU phasor protocol (e.g. C37.118), phasor reporting rate (e.g. 30samples per second), and fractional second values corresponding to the reporting rate.

where "*" denotes conformance tests and others are performance tests. Figure 4 shows the voltage magnitude test result of a sample PMU.

Figure 4 Example of voltage magnitude conformance test

B. Dynamic PMU test

For example, a system that measures and records phasor for post-event small signal stability analysis of system dynamics during a large system disturbance, where system frequencies at different locations could change dynamically, would require the PMUs to be able to follow the frequency change quickly and consistently among all PMUs.

One of the key aspects of PMU dynamic performance is its filtering characteristic. Figure 5 shows a 4th-order Butterworth filter with a 12 Hz bandwidth and the WECC filtering requirements for a PMU output rate of 60 samples per second.

The following types of dynamic tests are proposed:

  Dynamic magnitude response test: To characterize PMU performance in terms of rising time, settling time ,and overshoot in response to a step change in the magnitude of an input signal.

  Dynamic phase response test: To characterize PMU performance in terms of rising time, settling time, and overshoot in response to a step change in the phase angle of an input signal.

  Dynamic frequency response test: To characterize PMU performance in terms of rising time, settling time ,and overshoot in response to a step change in the frequency of an input signal.

  Voltage amplitude modulation test: To evaluate PMU performance in response to amplitude-modulated sinusoidal signals, mimicking power system oscillations.

  Frequency modulation test: To evaluate PMU performance in response to frequency modulated sinusoidal signals, mimicking power system oscillations.

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