Testing and Calibration of Phasor Measurement Units

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Abstract: A Phasor Measurement Unit (PMU) is an electronic device that enables real-time computer control to protect the stability and reliability of a power grid. Using GPS-derived timing, the PMU synchronously captures voltage and current phase vectors to create SynchroPhasor data. Synchronous data from multiple PMUs are forwarded to a common point where analysis, control, and protection may be accomplished. Real-world application of PMUs has revealed a need for uniform performance across the various manufacturers of PMUs. Fluke Calibration, under a grant from NIST, is developing an automated system to execute and document PMU calibrations that conform to IEEE C37.118.1.

Learning Objectives: This paper will enable the reader to:

- Describe a Phasor Measurement Unit
- Explain the role of a PMU in a Smart Grid
- Identify the importance of consistent performance upon the deployment rate of PMUs
- Interpret the new PMU test and calibration standards
- Understand how the NIST / Fluke PMU Calibrator project benefits the calibration community

1. Evolution of the electrical power grid

In the United States, 3,000 electrical utility companies operate 10,000 concentrated generation facilities and 200,000 miles of transmission lines. Per Gillerman, et al [1]:

> *"It is often said that electrical grids represent the world's most complex machines. However, one can argue that this analogy understates the problem. For example, how many airliners or factories are operated by a team whose members are employed by different companies with competing interests or whose members don't traditionally talk to each other much? While the grid has been run with remarkable reliability in the past, it is likely that business and operating pressures will only increase in the future."*

It was not always so. Roll the clock back to 1940, in Table 1, below. The Empire State Building, the Chrysler Building, and the S.S. Normandie were state-of-the art. The new Douglas DC-3, typical of the period, was slow, docile, aerodynamically stable and controlled by manual cables. Grand Coulee Dam would come on-line in 1942, governed by manual and analog controls that could regulate the 60 Hz generators to within a few cycles per day. Time resolution on the order of a second was just fine. Electrical power flowed from a few concentrated sources to load-only customers whose usage varied predictably according to season and time of day.

Table 1. Flight and power technology, then and now.

1940	2010
DC-3, Control Cables	F-16, Fly-by-wire
Few concentrated sources	Many distributed sources
Slowly varying loads	Time-variant sources / loads
Analog / manual control	Real-time computer control
1 second time accuracy	<< 1 μs time accuracy

Fast forward 70 years, to 2010. Today's "Smart Grid" is a real-time, dynamic network of electrical demand and supply. There are many distributed, time-variant, renewable sources, like solar and wind. Customers can now elect to buy power when it is cheap, and even want to sell power back to the grid. New electronic power supplies push distortion back into the grid. Demand from Electric Vehicles is ramping up. Today's grid looks less like the DC-3 and more like the fly-by-wire F-16, a high-performance, inherently unstable aircraft that cannot fly without computer assistance. Real-time computer control of the grid will maintain the stellar reliability record of the generation, transmission and distribution utilities. Real-time state measurement at widely-spaced nodes, with <1 μs time accuracy, is the foundation of this control. That's where the Phasor Measurement Unit, or PMU, comes in.

2. Fundamentals of phasors, SynchroPhasors, PMUs and their Applications

2.1 Phasors. A phasor is a rotating "Phase Vector", an alternative expression of a sine wave. Instantaneous voltage V equals amplitude A times the Sine of (angular frequency ω x time t, offset by a phase angle ϕ), per Figure 1.

$$V = A \sin(\omega t + \phi)$$

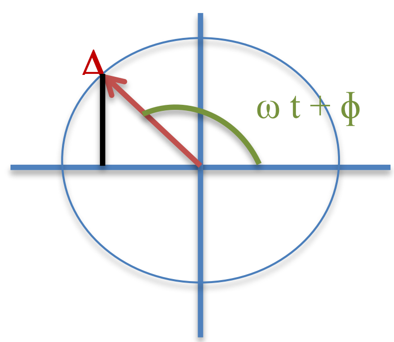

Figure 1. Phasor representation of a sine wave.

A phasor can express voltage or current at any point in a power grid. While the word sounds very 21st century, the phasor is a 19th century invention. Charles Proteus Steinmetz, contemporary of Edison and Einstein, first expressed the concept in 1893. Note that, at 60 Hz, a phasor sweeps 22^{o} in only 1 ms. To compare voltage or phase at different points in a grid, recording of time will need to be much more accurate than 1 ms.

2.2 Synchrophasors and PMUs. A phasor, captured synchronously with sufficiently precise time, is a Synchrophasor. Per the North American SynchroPhasor Initiative (NASPI) [2];

> *"Synchrophasors are precise grid measurements now available from monitors called phasor measurement units (PMUs). PMU measurements are taken at high speed (typically 30 observations per second – compared to one every 4 seconds using conventional technology). Each measurement is time-stamped according to a common time reference. Time stamping allows synchrophasors from different utilities to be time-aligned (or "synchronized") and combined together providing a precise and comprehensive view of the entire interconnection. Synchrophasors enable a better indication of grid stress, and can be used to trigger corrective actions to maintain reliability."*

A PMU can be a standalone device or can be integrated with other functions such as relay protection or digital fault recording. As of 2010, approximately 2000 PMUs are deployed worldwide:

- 1000 in the Chinese power grid (Per North China Electric Power University)
- 272 in Mexico (Per Comision Federal De Electridad)
- 250 in North America (Per NERC)
- 80 planned for India
- 20 in Finland, 8 in Iceland, 8 in Sweden, 4 in Slovenia
- 6 PMUs in Colombia, 100's planned for Brazil
- 12 in Australia, 10 in New Zealand

Deployed numbers are likely to grow significantly by 2012 due to infrastructure investments. In the US, PMU projects are funded via Smart Grid Investment Grants (SGIG) and the American Recovery and Reinvestment Act (ARRA).

Using GPS-derived time, good to $\ll 1\ \mu s$, the PMU has captured Synchrophasors that, at 60 Hz, have phase uncertainties $\ll 0.022^{o}$. Data from multiple PMUs is concentrated and forwarded to a common point where the data can be used to increase the efficiency and reliability of the grid.

2.3 Applications for synchrophasor data.

The first applications for Synchrophasor data were modeling and analysis. As utilities have become more familiar and comfortable with the technology, applications have expanded to fulfill the promise of real-time control and protection. Table 2, below, is a summary of common applications. For another perspective on applications, the NASPI roadmap [3] examines each potential application along the dimensions of time to implementation, priority, and technical difficulty. Finally, a definitive look at specific applications is offered by Patel, et al, in "NERC Real-Time Application of Synchrophasors for Improving Reliability" [4].

Table 2. Applications for synchrophasor data.

Analysis	Control	Protection
• Wide Area Situational Awareness (WASA) • Steady-state and dynamic model benchmarking • Voltage stability monitoring • State estimation • Post-mortem fault analysis • Phase angle difference stress monitoring	• Real-time wide-area system control • Generator governor stability control • Synchronization, loop closing assist • Variable / intermittent source integration (e.g. wind and solar) • Reserve generation management • Control of distributed generation system	• Low frequency oscillation management • Early warning and backup protection • Load demand variation (load shedding) • Adaptive protection • Self-healing grids • Adaptive islanding

3. Real-world issues in PMU deployment

As with all new technologies, there are forces and factors that retard early adoption. For PMUs, these include:

- Risk-aversion; Uptime and reliability are primary
- Capital expense; installation and commissioning
- Distrust of the data; "PMUs drift"
- Placement of PMUs; locating the high priority nodes for PMU deployment
- Lack of proven interoperability; no two PMU models deliver the same answers
- Operating Expense; Maintenance and Calibration

Improved testing and calibration of PMUs impact all of these, but two stand out:

<u>Interoperability:</u> Industry needs to converge on consistent and reliable performance of PMUs. Most PMUs have been found to be out of compliance with emerging performance requirements. An Electric Power Research Institute (EPRI) report [5] states;

"The reliable power sources, samplers and associated standards for PMU testing and calibration have become a major hurdle to the further development and implementation of PMU applications in power system. Utilities need the guarantee of reliability and accuracy of PMUs and also the seamless interchangeability among the PMUs from different vendors before they will invest heavily in them." See section 4, following.

<u>Calibration expense:</u> Standardized procedures and automated calibration can greatly reduce the burden of testing and calibrating PMUs, in development, production, or ongoing use. See section 5, below.

4. New test and calibration standards

IEEE standards for PMU test and calibration are being revised. The standards ensure that compliant PMUs will perform consistently (within tolerance) when presented with the standard suite of test signals.

Changes in IEEE C37.118.1:2011 include:

- Clarification for the phasor and synchronized phasor definitions.
- Concepts of total vector error and compliance tests are retained and expanded.
- Tests over temperature variation have been added.
- Dynamic performance tests have been introduced.
- Limits and characteristics of frequency measurement and rate of change of frequency (ROCOF) measurement have been developed.

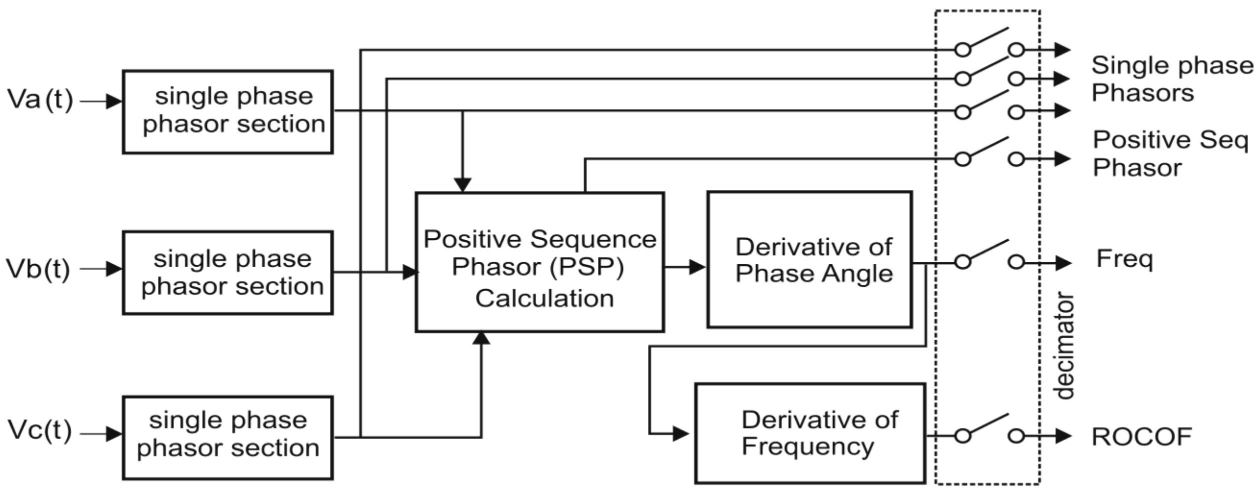

Figure 2. Block diagram of a PMU under test

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Figure 2 shows a block diagram of a PMU under test. Outside stimuli are applied on the left, while PMU outputs are on the right. Three single phase estimators are combined to create a Positive Sequence Phasor. The derivative of the positive sequence phasor is the frequency. The derivative of frequency is the ROCOF. The decimator band limits and reduces the internal data rate of the PMU to the external reporting rate. Output of the PMU is compared and evaluated against the applied stimulus.

Normative standard C37.118.1 has 2 main performance sections: [6]

- **Steady State** testing where the input signal does not vary in frequency or magnitude for the data gathering period
- **Dynamic** testing where one or more input signal parameters vary during data gathering.

The related informative standard C37.242 is “Guide for Synchronization, Calibration, Testing, and Installation of PMUs” [7]. See Table 3 for an overview. Communication of phasor measurement data is covered in the companion standard IEEE C37.118.2 (Standard for Synchrophasor Data Transfer for Power Systems).

Table 3. Synopsis of the PMU testing prescribed in IEEE C37.118.1:2011

Normative IEEE C37.118.1:2011 Limits	Informative IEEE C37.242 Guidelines	Test Parameters
5. 3	8.9.1	Errors; Total Vector Error (TVE), Frequency and ROCOF (See Figure 3)
5.5.5	8.9.3	**Steady-state** compliance tests • Signal frequency (range) • Signal magnitude: voltage • Signal magnitude: current • Phase angle • Harmonic distortion • Out of band interfering signals (Measurement class PMU only)
5.5.6 5.5.7 5.5.8 5.5.9	8.9.4	**Dynamic** compliance tests • Measurement bandwidth; simultaneous modulation of amplitude and phase • Ramp of system frequency • Step changes, amplitude or phase • Measurement reporting latency

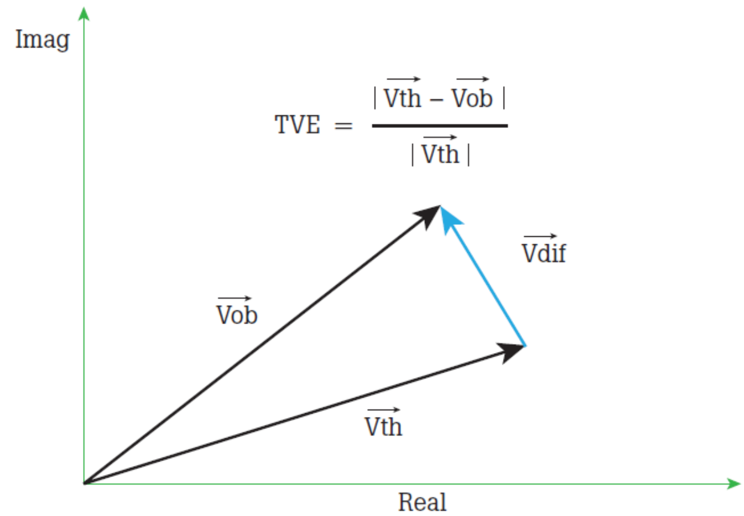
Steady-state compliance tests (to 1% TVE):

- Frequency range test: ±2Hz for P=Protection class PMU, up to ±5Hz for M=Measurement class PMU.
- Voltage and current magnitude: 80-120% of nominal for voltage, 20-200% for current.
- Phase angle tests: -180 to +180 degrees.
- Harmonic distortion to 50th harmonic
- Out of band interfering signals (interharmonics) for M=Measurement class only

Dynamic compliance tests:

- Measurement bandwidth; simultaneous modulation of amplitude and phase (to 3% TVE).
- Linear ramp of system frequency (to 1% TVE).
- Step changes in amplitude or phase (for response time, response delay, and maximum overshoot).
- Measurement reporting latency (number of reporting intervals).

The concept of Total Vector Error (TVE), used in Table 3 above is shown in Figure 3:



Where:

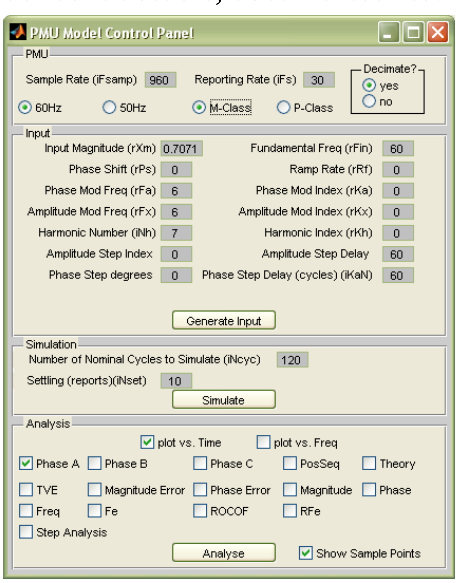
$\vec{V}_{th}$ is the theoretical or true phasor

$\vec{V}_{ob}$ is the PMU observed or measured phasor

Figure 3. Total Vector Error.

5. Benefits to the calibration community from the NIST / Fluke project

Today, calibration of a PMU occurs only at a few select locations including NIST, China EPRI, Bonneville Power Administration and Virginia Tech. A custom-built, complex test setup, manually operated by a highly proficient operator will yield a complete type test in two to six weeks. The U.S. government identified the need for a commercially available PMU calibration system. NIST preferred to calibrate standards rather than PMUs. In February 2010, NIST sponsored a project with Fluke to develop a more consistent and efficient calibration process. The output of the project will be an automated system to execute standardized procedures and deliver traceable, documented results.



PMU Settings

Input Signal Settings

- Steady State
- Ramp
- Amplitude & Phase Modulation
- Step

Simulation Settings

Analysis Settings

Figure 4. PMU Simulation Model

The benefits to the calibration community from the NIST / Fluke project are:

- Access to a PMU Simulation Model (Figure 4) via the NASPI Phasor Tool Repository [8]
- Interoperability across PMUs derived from new standards and procedures
    - IEEE C37.118 Normative standard, in revision, to be published January 2012
        - 118.1 – Measurement; dynamic tests added
        - 118.2 - Data Transfer
- IEEE C37.242 Informative Guideline, in revision, to be published in late 2012
- Pathway to worldwide standard adoption
    - 118.1 to IEC via IEC TC57
    - 118.2 to IEC 61850
- An inter-comparison of PMU measurement performance using the calibration facilities of Fluke, NIST, EPRI and selected universities
- A commercially-available, automated PMU calibration system to deliver accurate, traceable, fully documented, IEEE C37.118.1 compliant calibrations (See Figure 5). The anticipated users, applications and benefits of an automated system are shown in Table 4.

The delivery milestones for the project are:

- Feb 2010 NIST grant announced
- July 2010 Requirements survey
- Dec 2010 Product requirement specification
- Aug 2011 System shown at NCSLI
- Sept 2011 First system to NIST
- Q4 2011 Beta sites, intercomparisons
- Q1 2012 Commercial system availability

Figure 5. Fluke PMU Calibration System

Table 4. User advantages of an automated PMU Calibration System

User	Calibration / Standards Labs • National • 3rd Party • Manufacturers'	PMU Vendors • ABB • SEL • Macrodyne • GE MultiLin • Qualitrol	Utilities • Generation • Transmission • Distribution
Application	Certify compliance for: • Utilities • Manufacturers • Governments	Design verification Production test Calibration	Type testing Installation/Commissioning Troubleshooting
Benefits	Accuracy Traceability Repeatability	Max. report utility Low capital expense Low operating expense	Interoperability Min. test time Min. user interaction Min. user expertise Min. report time

Conclusion: Phasor Measurement Units enable real-time computer control to safeguard the stability and reliability of modern power grids. New test and calibration standards for PMUs will promote consistent performance across PMU manufacturers. New automated calibration processes will control costs and encourage PMU adoption.

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