Testing and Calibration of Phasor Measurement Units

Richard Pirret

Abstract: In the evolving Smart Grid, time-variant sources and loads introduce disturbances that can threaten the stability of the grid. Sophisticated protection and control systems are required to preserve reliability. These systems rely on accurate, synchronous measurements of voltage, current and frequency made by Phasor Measurement Units (PMUs). Although PMUs first appeared in 1988, their recent deployment has exposed inconsistent measurements and poor interoperability across brands and models. However, several recent developments promise to enhance the accuracy and consistency of PMU measurements. *IEEE C37.118.1:2011*, "Standard for Synchrophasor Measurements for Power Systems", established new performance limits for PMU test and calibration. The revised standard more clearly defines existing concepts, and enhanced and added material to the sections on steady state and dynamic tests. The emergence of automated systems supports the consistent execution of standard tests during PMU calibrations, and the observance of sound traceability practices for PMU ensures the accuracy of those calibrations. This paper describes the fundamentals of phasor measurements, the recent revisions to the *IEEE C37.118.1* standard, a new automated PMU calibration system developed at Fluke, and the establishment of traceability for PMU calibrations.

1. Evolution of the Electrical Power Grid

In the United States, some 3,000 electrical utility companies operate about 10,000 concentrated generation facilities and 200,000 miles of transmission lines. As one observer noted:

"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." [1]

In 1942, when the power utility station at Grand Coulee Dam came on-line, its highly inertial system was governed by manual and analog controls that could regulate the 60 Hz generators to within a few cycles per day. For reporting and control purposes, time resolution on the order of several seconds was adequate. Electrical power flowed from a few concentrated sources to linear loads that predictably consumed power according to season and time of day.

Seventy years later, the environment has radically changed. Today's "Smart Grid" [2] is a real-time, dynamic network of electrical demand and supply (Fig. 1). There are many distributed, time-variant, non-inertial, renewable sources, such as solar and wind power. Customers can now elect to buy power when it is cheap, and often wish to sell power back to the grid. New electronic power supplies push distortion back into the grid. The demand from electric vehicles is ramping up. With so many low-inertia sources, today's grid lacks the inherent stability previously enjoyed. Real-time computer protection and control of the grid will be required to preserve the 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 [3]. The Phasor Measurement Unit (PMU) makes these measurements possible.

2. Fundamentals of Phasors, SynchroPhasors, and PMUs

2.1 Phasors

A phasor is a rotating "phase vector", an alternative expression of a sine wave. Instantaneous voltage V equals amplitude, A, multiplied by the Sine of angular frequency (ω) × time (t), per Fig. 2.

A phasor can express instantaneous 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, a contemporary of Edison, Einstein and Tesla, first expressed the concept in 1893. Note that, at 60 Hz, a phasor sweeps 22^{o} in only 1 ms. Thus, to compare voltage or phase at different points in a grid, the recording of time will need to be much more accurate than 1 ms.

2.2 Synchrophasors and PMUs

A phasor measurement, captured synchronously with sufficiently precise time, is a synchrophasor. Per the North American SynchroPhasor Initiative (NASPI) web site (www.naspi.org):

"Synchrophasors are precise grid measurements now available from monitors called phasor measurement units (PMUs).

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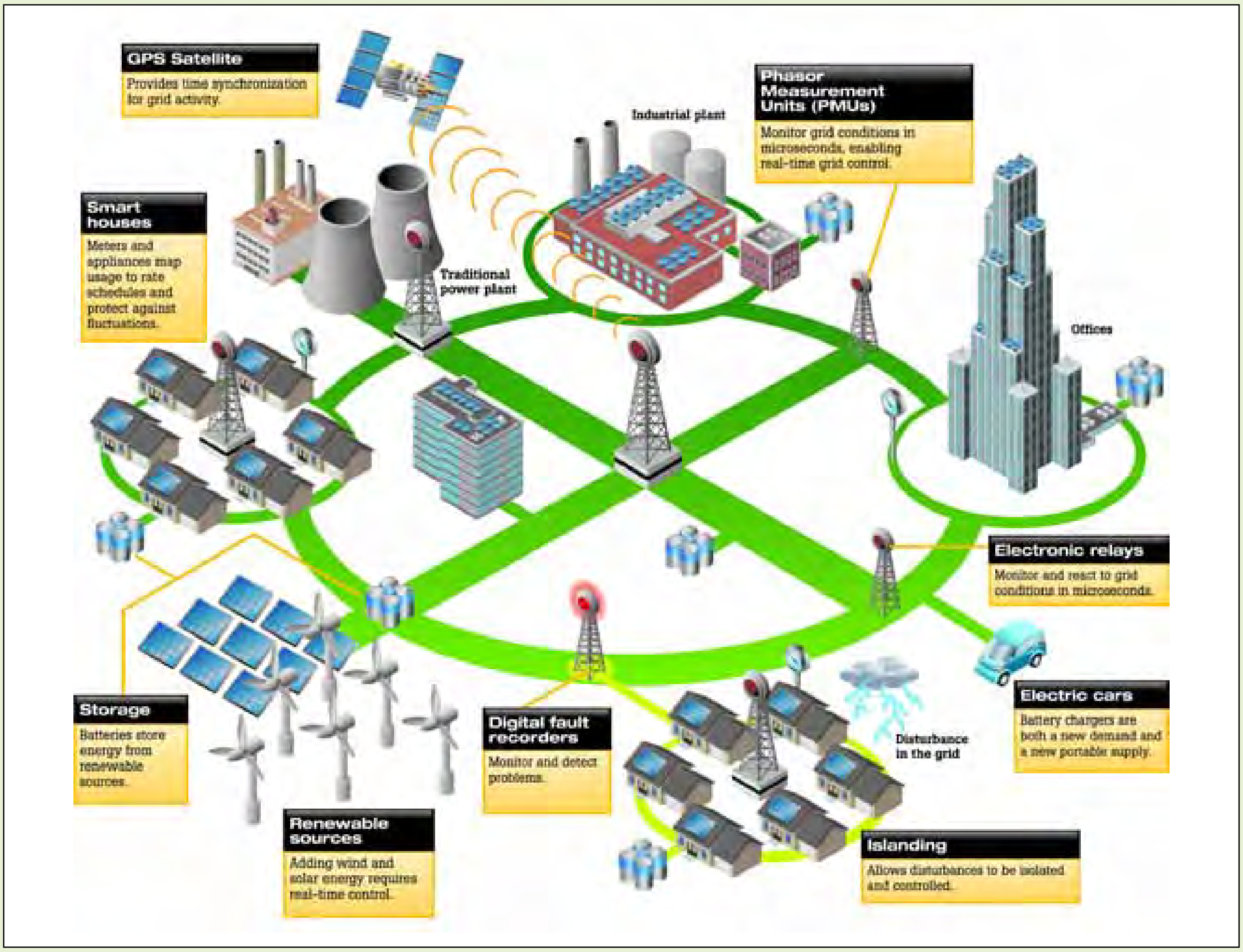

Figure 1. Dynamic supply and demand in the Smart Grid.

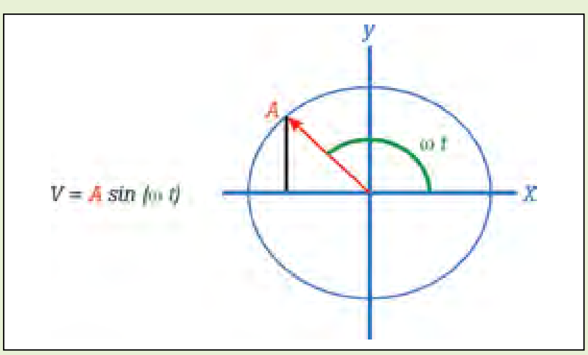

Figure 2. Phasor representation of a sine wave.

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 [4]. As of 2012, several thousand PMUs are deployed worldwide, and numbers are growing rapidly today due to infrastructure investments. In the United States, PMU projects were funded via Smart Grid Investment Grants (SGIG) and the American Recovery and Reinvestment Act (ARRA).

Using time traceable to Coordinated Universal Time (UTC), accurate to within 1 µs, the PMU has captured synchrophasors that, at a power line frequency of 60 Hz, have phase uncertainties of $< 0.022^{o}$. Data from multiple PMUs is concentrated and forwarded to a common point where it can be used to protect and control the grid. The Global Positioning System (GPS) usually provides the time reference. An alternative to GPS is the Precision Time Protocol (PTP). PTP Version 2, as represented within the *IEEE 1588-2008* standard, can synchronize clocks in a local area computer network to within 1 µs. However, unlike GPS, it requires a reference synchronization source, and is less accurate and more difficult to implement when used across a wide area network.

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

Table 1. Applications for synchrophasor data.

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 1, above, is a summary of common applications. For another perspective on applications, the NASPI roadmap [5] examines each potential application along the dimensions of time to implementation, priority, and technical difficulty. Finally, a definitive look at specific applications is offered in a North American Electric Reliability Corporation (NERC) document [6].

3. Real-World Issues in PMU Deployment

As with all new technologies, there are forces and factors that inhibit early adoption. In the case of PMUs, two limiting factors have been interoperability and calibration expense.

To improve interoperability, industry needs to agree on standards for the 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 [7] 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."

PMU calibrations have historically been expensive because the complete type testing of a PMU requires an expert operator, manual operation of a complex test setup, and a long and intricate test procedure that can take from two to six weeks to complete. It seems clear that standardized procedures and automated calibration systems will greatly reduce the burden of testing and calibrating PMU.

4. New Test and Calibration Standards

In late 2011, the standards for PMU test and calibration were significantly revised. *IEEE C37.118.1-2011*, "Standard for Synchrophasor Measurements for Power Systems" [8] ensures that compliant PMUs will perform consistently (within tolerance) when presented with a standard suite of test signals. The changes in the revised standard 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.

The revised standard [9] defines two classes of performance: P class and M class:

"P class is intended for applications requiring fast response and mandates no explicit filtering. The letter P is used since protection applications require fast response. M class is intended for applications that could be adversely effected by aliased signals and do not require the fastest reporting speed. The letter M is used since analytic measurements often require greater precision but do not require minimal reporting delay."

The essence of the revised standard is found in clause 5.5.3, Compliance Verification:

"Documentation shall be provided by any vendor claiming compliance with this standard that shall include the following information:
a) Performance class
b) Measurements that meet this class of performance
c) Test results demonstrating performance
d) Equipment settings that were used in testing
e) Environmental conditions during the testing
f) Error analysis if the verification system is based on an error analysis as previously called for"

Figure 3 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 Rate of Change of Frequency (ROCOF). The decimator band limits and reduces the internal data rate of the PMU to the external reporting rate. The output of the PMU is compared and evaluated against the applied stimulus.

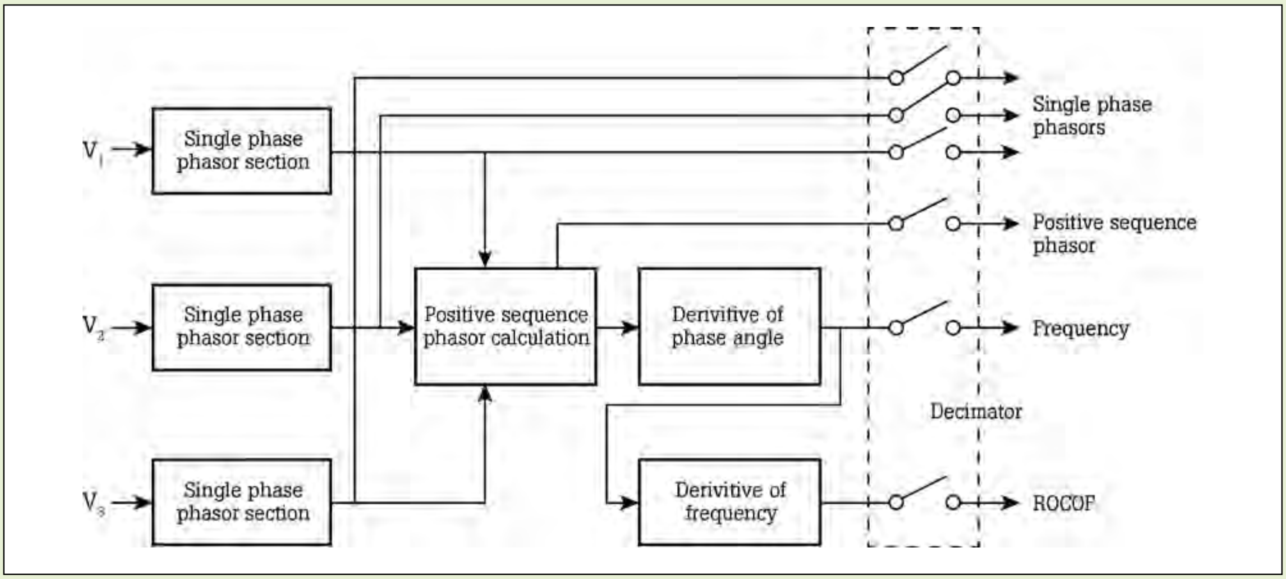

Figure 3. Complete PMU signal processing model per Annex C.4 [8].

118.1:2011 Section	Test Parameter	Range and Limit
Steady-state compliance tests per 5.5.5	Signal frequency	±2 Hz for P = Protection class PMU Up to ±5 Hz for M = Measurement class, to 1 % Total Vector Error (TVE)
	Signal magnitude: voltage	80 to 120 % of nominal, to 1 % TVE
	Signal magnitude: current	20 to 200 % of nominal, to 1 % TVE
	Phase angle	-180 to +180 degrees, to 1 % TVE
	Harmonic distortion	To 50th harmonic
	Out of band interfering signals (interharmonics)	For M = Measurement class only
Dynamic compliance tests per 5.5.6 through 5.5.9	Measurement bandwidth	Modulation of amplitude and phase, individually or in combination (to 3 % TVE).
	Ramp of system frequency	Linear ramp (to 1 % TVE).
	Step changes, amplitude or phase	Evaluated for response time, response delay, and maximum overshoot
	Measurement reporting latency	Number of reporting intervals

Table 2. Simplified summary of the PMU testing prescribed in *IEEE C37.118.1:2011*.

The normative *IEEE C37.118.1* standard [8] has two main performance sections. One is for steady state testing where the input signal does not vary in frequency or magnitude for the data gathering period. The other is for dynamic testing where one or more input signal parameters vary during data gathering. Table 2 summarizes these two performance sections.

The concept of Total Vector Error (TVE), is presented in Fig. 4, where:

$\vec{V}_{th}$ is the theoretical or true phasor
$\vec{V}_{ob}$ is the PMU observed or measured phasor
TVE is the magnitude, $|V_{dif}|$

Note that informative standard *IEEE PC37.242*, "Guide for Synchronization, Calibration, Testing, and Installation of PMUs" [9] is closely related to the normative *IEEE C37.118.1* standard. Also note that the communication of phasor measurement data is covered in the companion standard, *IEEE C37.118.2*, "Standard for Synchrophasor Data Transfer for Power Systems" [10].

The Fluke 6135A Electrical Power Standard provides the voltage and current stimuli to the PMU Unit Under Test (UUT). The 6135A consists of one 6105A master unit to deliver phase L1, and two 6106A auxiliary units to deliver L2 and L3. Their control relationship is shown in Fig. 5. The 6135A has good static accuracy, but proper timing between digitally generated internal signals and the analog output must be maintained. A digitally generated signal runs at the Ref_s frequency.

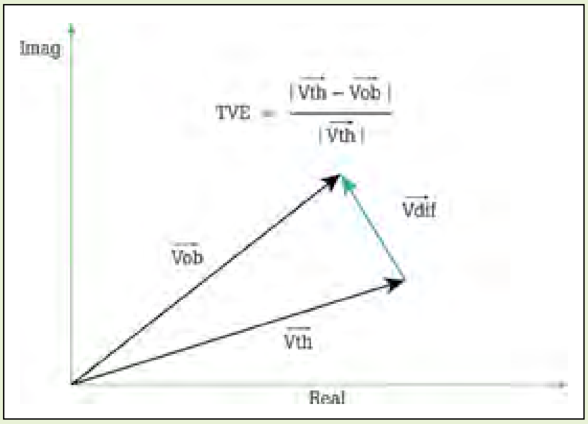

Figure 4. Total Vector Error (TVE).

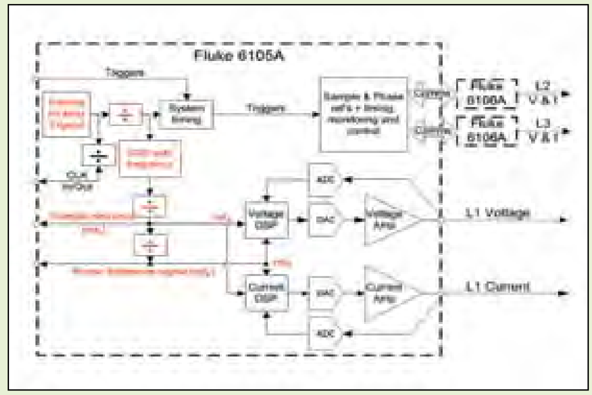

Figure 5. Control relationships within the Fluke 6135A Electrical Power Standard.

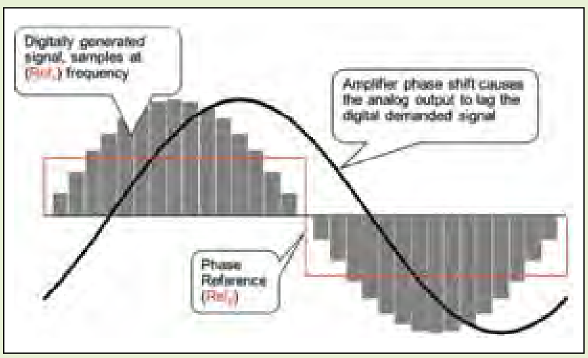

Figure 6. Output and phase reference relationship, before adjustment.

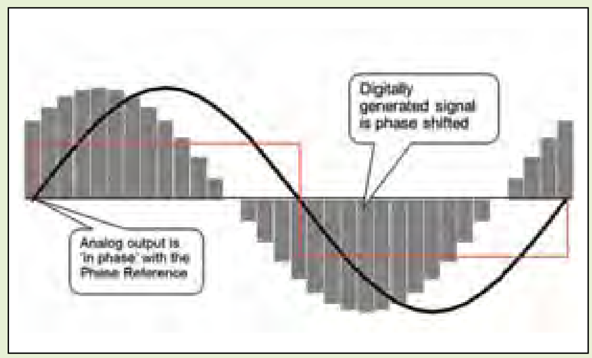

Figure 7. After adjustment, analog output signal aligns with the phase reference.

However, an amplifier phase shift may cause the analog output to lag the digital demanded signal, and to lag the phase reference (Ref_p), as shown in Fig. 6. The digital wave shape is phase shifted with respect to the phase reference until the zero-crossing of the analog output is coincident with the zero-crossing of the phase reference (Fig. 7).

5. Development of an Automated PMU Calibration System

Today, PMU calibrations are only performed at a few select locations, including the National Institute of Standards and Technology (NIST) [11], China EPRI, Bonneville Power Administration [12] and Virginia Tech University [13]. 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 has identified the need for a commercially available PMU calibration system, and in February 2010, NIST sponsored a project with Fluke to develop a more consistent and efficient calibration process.

There are four deliverables under the terms of the project:

1. A requirements survey completed July 2010.
2. A product requirement specification, completed December 2010.
3. The delivery of a commercially-available automated PMU Calibration System in the second quarter of 2012.
4. An intercomparison of PMU measurement performance using the calibration facilities of Fluke, NIST, EPRI and selected universities.

Specifically, item three is an automated hardware and software solution that outputs three-phases of voltage (V) and current (I) in accordance with *IEEE C37.118.1:2011* for measurement limits, *IEEE C37.118.2* for data transfer and *IEEE PC37.242* for test guidelines. This system references the phase of voltage and current outputs to the 1 pulse per second (pps) signal distributed via satellite transmission from GPS. The system also controls the PMU, enabling three types of automated testing. Message validation tests confirm each of the message types as well as the clock status and quality bits. Steady state tests apply unchanging voltage and current inputs to the device under test. Dynamic tests modulate and ramp the magnitude or frequency of the input signal and step the magnitude or phase of the input signal. The calibration system collects data from all three tests, and compares the PMU output with the known input, and calculates parametric error information. Finally, the system creates fully documented certification reports that demonstrate the traceability of the system's measurements. A photograph of the PMU Calibration System is shown in Fig. 8 and a block diagram is shown in Fig. 9.

The primary beneficiaries of the new PMU test standards are the electrical utilities, who will enjoy improved interoperability and consistent performance as they deploy PMUs in their grids. The secondary beneficiaries are the national and third-party calibration and standards laboratories, plus the PMU manufacturers charged with the traceable calibration of PMUs. The type test of a PMU, a

Figure 8. Fluke 6135A/PMUCAL PMU Calibration System.

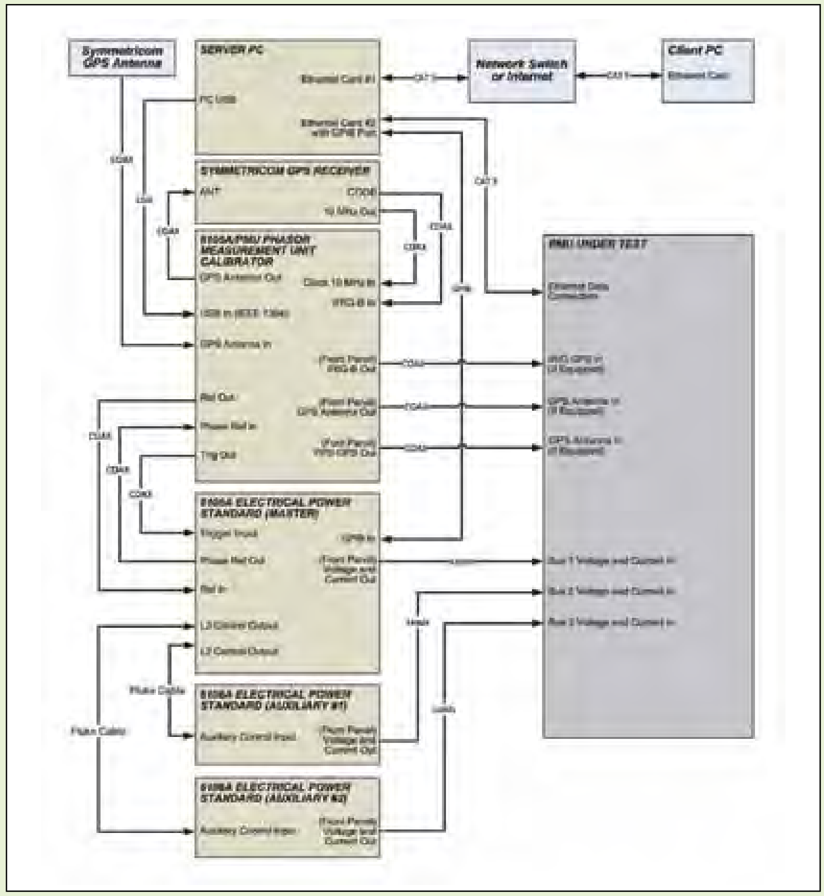

Figure 9. Block diagram of Fluke PMU Calibration System.

complex manual process occupying an expert continuously for two to six weeks, can now be completed by a modestly-skilled operator with limited interaction in one to two days. An additional long-term benefit to the calibration community from the NIST / Fluke project is access to a PMU Simulation Model, per Annex C of 118.1 (see Fig. 10) via the NASPI Phasor Tool Repository [14]. Finally, the project opens a potential pathway to worldwide standards adoption, as the advances in *IEEE C37.118.1* and *IEEE C37.118.2* propagate to International Electrotechnical Commission (IEC) standards.

The PMU Simulation Model user interface is organized in four sections that are configured and executed in sequence. In the first section, PMU settings such as frequency and class are specified. In the second section, a wide variety of steady state and dynamic signals are constructed for presentation to the PMU. In the simulation section, the number of cycles to simulate is chosen and the simulation is run. In the final section, the simulation can be analyzed by plotting versus time or frequency, by examining individual phases or the positive sequence, or by examining magnitude error, phase error, or total vector error.

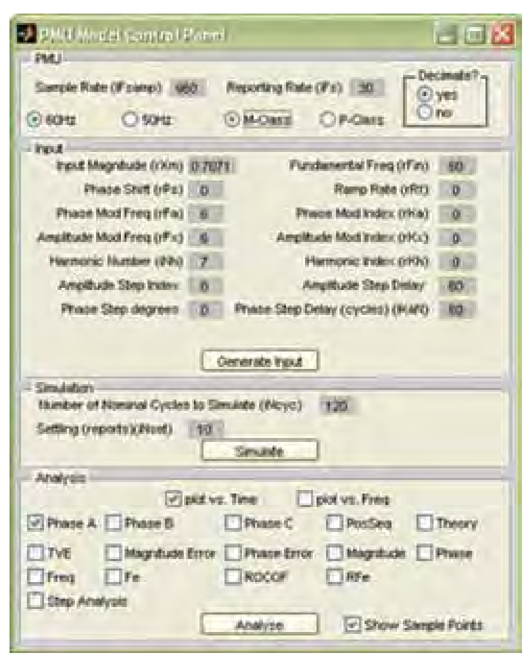

Figure 10. PMU Simulation Model.

6. Traceability

The *IEEE C37.118.1* standard discusses traceability in sub-clause 5.5.3:

"A calibration device used to verify performance in accordance with this sub-clause shall be traceable to national standards, and have a test uncertainty ratio of at least four (4) compared with these test requirements (for example, provide a TVE measurement within 0.25% where TVE is 1%)." [8]

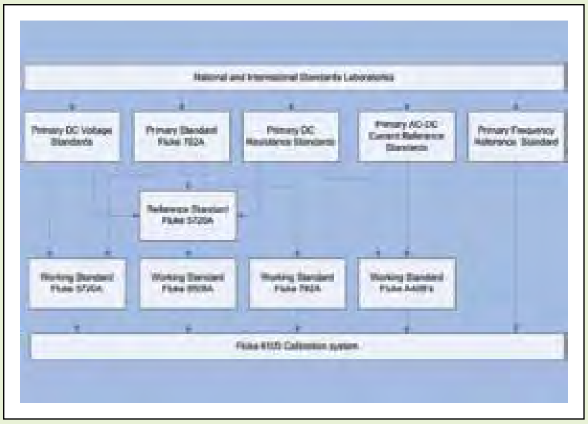

Figure 11. Traceability chain of the Fluke 6100 Series Electrical Power Standard.

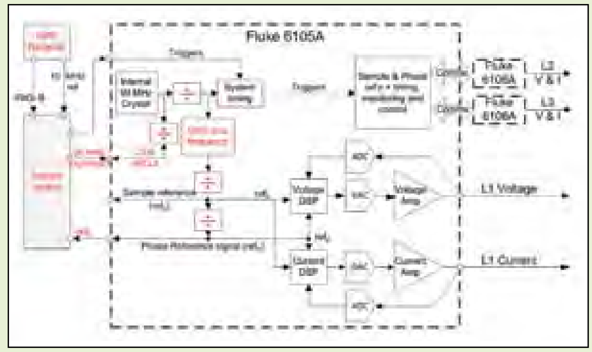

Figure 12. 6135A and its UTC source

The process of establishing traceability for a PMU calibrator begins with the sources used to supply test signals to the PMU under test. The traceability chain of the three-phase Fluke 6100 Series Electrical Power Standard is shown in Fig. 11. A calibration of the entire PMU calibration system, at the time of manufacture and at annual intervals thereafter, is necessary to confirm functional integration and timing of the complete system. Finally, an intercomparison program, featuring the round-robin comparison of a known PMU across a number of PMU calibrators, can solidify the metrological credentials of all the PMU calibrators in a region or country.

A source of uncertainty for the PMU calibration system is its synchronization error with respect to UTC, as provided by the GPS receiver (Fig. 12). In a steady state test, the observed synchronization phase angle error is 0.004^0. The typical amplitude error is 0.0113 %, and the resulting TVE is 0.0133 %. When compared with the worst case PMU accuracy requirement of 1 % TVE, the resulting test uncertainty ratio is approximately 75:1.

7. Summary

Phasor Measurement Units (PMUs) enable real-time computer control to safeguard the stability and reliability of modern power grids. New test and calibration standards for PMUs, supported by documented traceability chains, will drive PMU interoperability and promote PMU deployment. Automated calibration processes will reduce development and maintenance costs and encourage PMU adoption. Due to the rapid deployment of the Smart Grid, PMU calibrations represent a potential new client base and workload for national and commercial laboratories that are responsible for ensuring measurement traceability.

8. References

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