New Standards for Test and Calibration of Phasor Measurement Units

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Abstract: In the evolving Smart Grid, the proliferation of time-variant sources and loads 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, recent deployment of PMUs has exposed inconsistent measurements and poor interoperability across brands and models of PMU. Three recent developments promise to enhance the accuracy and consistency of PMU measurements through the application of sound metrology practices.

1. IEEE C37.118.1:2011, *IEEE Standard for Synchrophasor Measurements for Power Systems*, established new performance limits for PMU test and calibration. Existing concepts were more clearly defined, steady state tests were enhanced and new dynamic tests were added.
2. Automated systems provide consistent execution of the new standard tests during type testing and calibration of PMUs.
3. Sound traceability practices for PMU calibration ensure the accuracy of measurements made by PMUs.

This paper describes the recently-ratified improvements to IEC C37.118.1:2005 which, when combined with sound traceability practices, enhance the measurement performance of PMUs deployed to the Smart Grid.

1. Time-variant sources impact stability of the power grid

In the early days of the electrical grid, a few concentrated and inertial power sources fed power unidirectionally to predictable and well-behaved loads. Today’s “Smart Grid” is a real-time network of electrical demand and supply. A much greater number of time-variant and non-inertial sources, such as wind and solar, are joining the grid. Many customers now have generation and storage capacity and with to push power back into the grid. Switching power supplies and adjustable speed motor drives have begun to degrade power quality by pushing harmonic distortion back onto the grid. This increasing complexity and variability is threatening the stability and reliability of power that consumers have come to expect. Real-time computer-assisted control will eventually be required to keep the lights on. One enabler of that computer control is SynchroPhasor technology.

2. Role of a Phasor Measurement Unit in the Smart Grid

2.1 Phasors and SynchroPhasors. A phasor is a rotating "Phase Vector", an alternative expression of a sine wave. A phasor, captured synchronously with sufficiently precise time, is a Synchrophasor. Per the North American SynchroPhasor Initiative (NASPI) [1];

"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."

2.3 Applications of PMUs

A definitive look at specific PMU applications is offered by Patel, et al, in "NERC Real-Time Application of Synchrophasors for Improving Reliability" [2]. Some leading examples include:

Analysis
- Wide Area Situational Awareness (WASA)
- Steady-state and dynamic modeling
- Post-mortem fault analysis

Protection
- Early warning and backup protection
- Load demand variation (load shedding)
- Adaptive protection

Control
- Variable / intermittent source integration (e.g. wind and solar)
- Real-time wide-area system control
- Synchronization, loop closing assist

2.4 Limitations of deployed PMUs

The PMU was invented by Phadke and Thorp at Virginia Tech in 1988 and commercialized by Macrodyne in 1992. Recently, the consistency and reliability of various PMUs have come into question. Most PMUs have been found to be out of compliance with emerging dynamic performance requirements. An Electric Power Research Institute (EPRI) report [3] 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."

2.5. The promise of the PMU – increased grid reliability

On September 8, 2011, a single failure of a 500 kV transmission line in the American southwest resulted in a cascading sequence of shutdowns that, 11 minutes later, had removed 8 MW of load and close to 3 million customers from the grid. San Diego was dark for over 12 hours. The failure was attributed to weaknesses in operations planning and situational awareness. Properly deployed, SynchroPhasor-based control systems could have quickly mitigated the loss and sustained service. As deployed, SynchroPhasors were only able to assist in the post-mortem failure analysis.

"PMUs did not play a role in observing the September 8th event in real time, but may prove increasingly important in situational awareness. Of the affected entities, California Independent System Operator (CAISO), Southern California Edison (SCE), and Arizona Public Service (APS) are equipped with PMUs. PMUs are widely distributed throughout the Western Electricity Coordinating Council (WECC) as the result of a WECC-wide initiative known as the Western Interconnection Synchrophasor Program (WISP). Their high sampling speed (up to 30 samples per second) and excellent GPS-based time synchronization offer new granularity in information about voltage phase angles and other grid conditions. PMUs are expected to be used to identify and monitor for grid stress, grid robustness, dangerous oscillations, frequency instability, voltage instability, and reliability margins. While not yet sufficiently integrated to have been used by the affected entities in their control rooms on September 8th, as discussed earlier, PMU data proved valuable in constructing the sequence of events and other post-event analysis." [4]

3. IEEE C37.118.1:2011 redefines the limits of PMU performance

Since 2005, IEEE C37.118.1 has set the performance standard for PMUs. A new standard, IEEE C37.118.1:2011 [5] includes these improvements over the 2005 version:

- Definitions of phasors and synchronized phasors have been clarified.
- Concepts of total vector error and compliance tests are retained but 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 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"

**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.*

Figure 1 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.

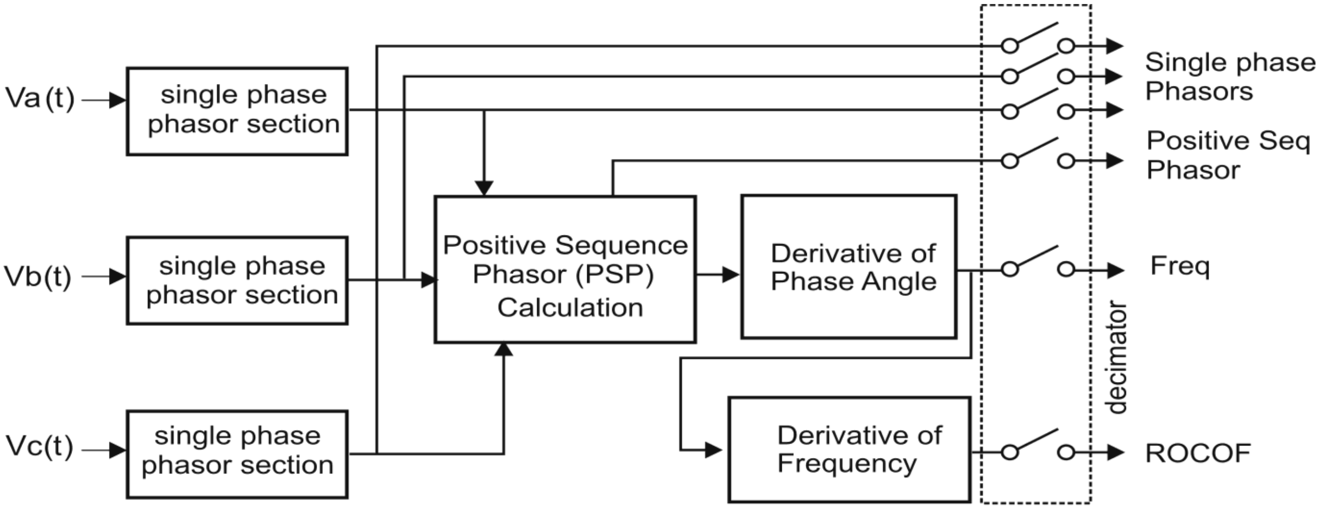

Figure 1. Block diagram of a PMU under test

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Normative standard C37.118.1 has 2 main performance sections:

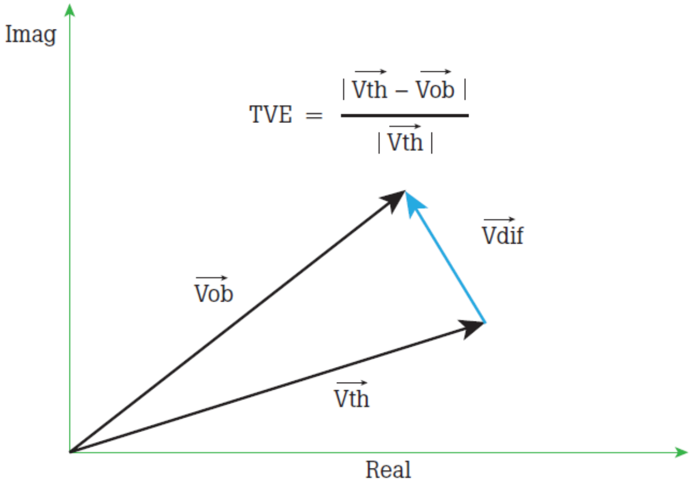
- **Steady State** testing where the input signal does not vary in frequency or magnitude for the data gathering period. Steady state tests are performed with unchanging voltage and current inputs to the device under test. Measurements are performed after the Settling period (number of PMU reports) following Settling Time to any transients so that the system is settled.
- **Dynamic** testing where one or more input signal parameters vary during data gathering. Dynamic tests are performed by modulating or ramping the magnitude or frequency of the input signal or by stepping the magnitude or phase of the input signal during the test.

Table 1. Parameters, ranges and limits of PMU testing per IEEE C37.118.1:2011

118.1:2011 Section	Test Parameter	Range	Limits expressed as:
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	Total Vector Error, TVE (%) Hz Hz/s
	Signal magnitude: voltage	80 to 120 % of nominal	
	Signal magnitude: current	20 to 200 % of nominal	
	Phase angle	-180 to +180 degrees	
	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	Simultaneous modulation of amplitude and phase, individually or in combination	TVE in % Hz Hz/s Deg S Volts Amps
	Ramp of system frequency	Linear ramp of system frequency	
	Step changes in amplitude or phase	Evaluated for response time, response delay, and maximum overshoot	
	Measurement reporting latency	Number of reporting intervals	

For more detail on tests and limits, see Table 2, test results viewer, in section 4.

The concept of Total Vector Error (TVE), used in Table 1 above is shown in Figure 2:



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

Figure 2. Total Vector Error.

An informative standard directly corresponding to C37.118.1 is IEEE C37.242:2012, "Guide for Synchronization, Calibration, Testing, and Installation of PMUs". [6] This standard provides illustrative "how to" guidance related to the limits defined in 118.1.

4. Automated systems provide consistent execution

Under a grant from NIST, Fluke Calibration is developing a commercially-available, automated PMU Calibration System to deliver accurate, traceable, fully documented, IEEE C37.118.1 compliant calibrations. The Calibration System is made up of six individual products, assembled per Figure 3.

1. Server PC receives commands from the Client PC and controls the PMU Cal System
2. GPS receiver uses the 1 Pulse Per Second (PPS) signal distributed via the Global Positioning System (GPS) to provide a UTC time signal to the PMU Calibrator and ultimately to the PMU under test
3. 6105A/PMU Phasor Measurement Unit Calibrator is the timing and modulation control device in the Calibration System.
4. 6105A Electrical Standard provides phase A voltage and current
5. 6106A Electrical Standard provides phase B voltage and current
6. 6106A Electrical Standard provides phase C voltage and current

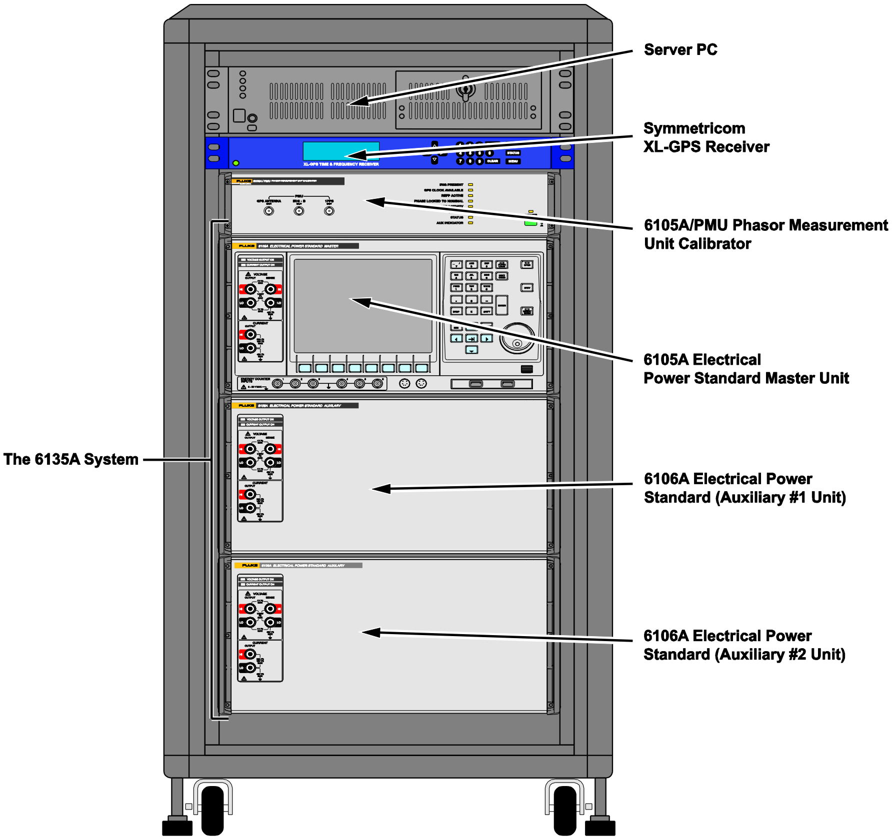
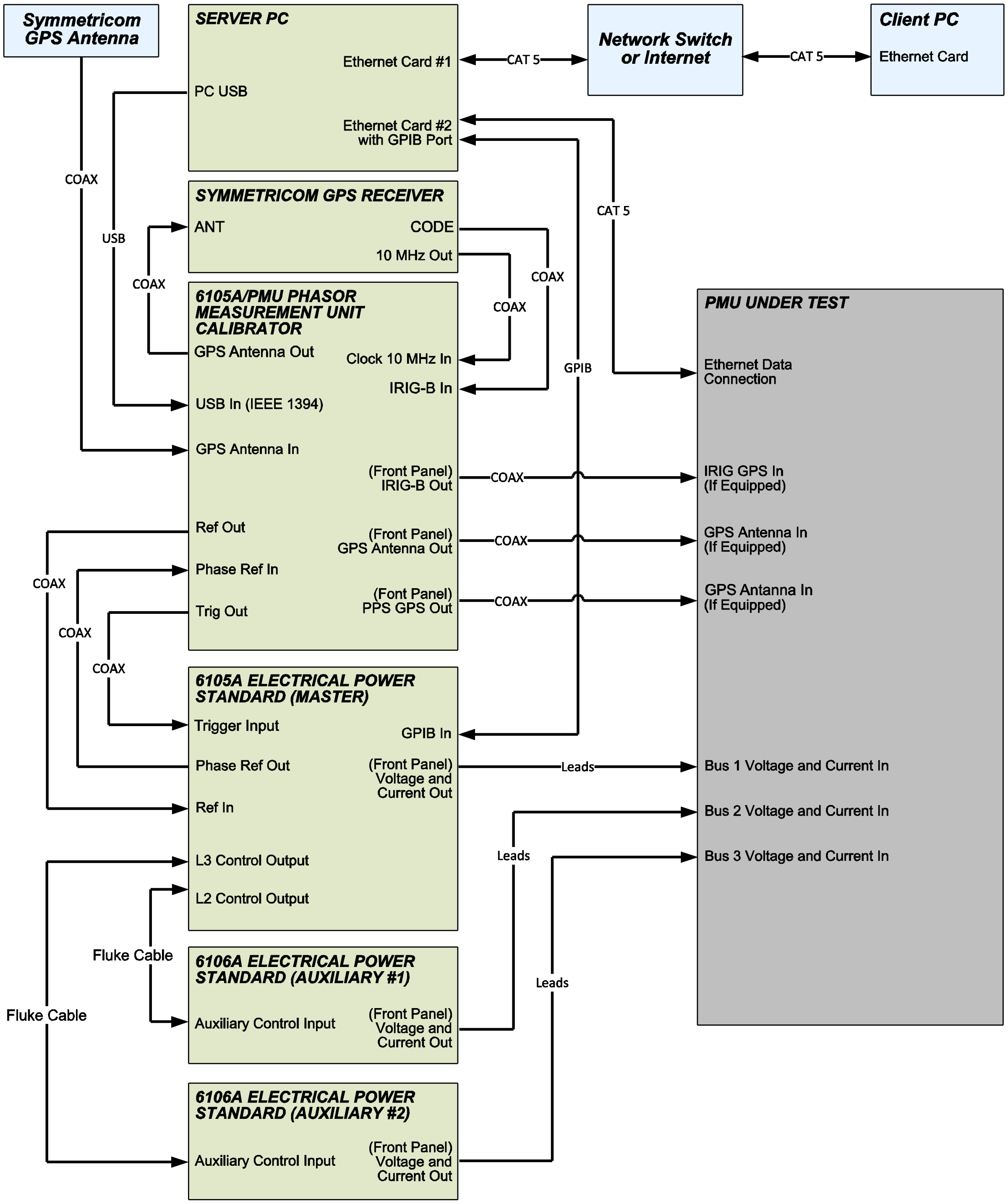


Figure 3. PMU Calibration System

The interconnections of the PMU Calibration System are shown in Figure 4.



Note: Client PC is provided by the User.

Figure 4. Block Diagram of PMU Calibration System

With the PMU Calibration System, you can:

- Quickly setup and configure a PMU for calibration.
- Calibrate and test a PMU with a PC, in a laboratory or remotely via the Internet.
- Use Automated or Interactive Testing methods to speed up the PMU calibration procedure.
- Verify compliance with IEEE C37.118.1:2011.
- Make formal calibration reports, in printed or electronic format

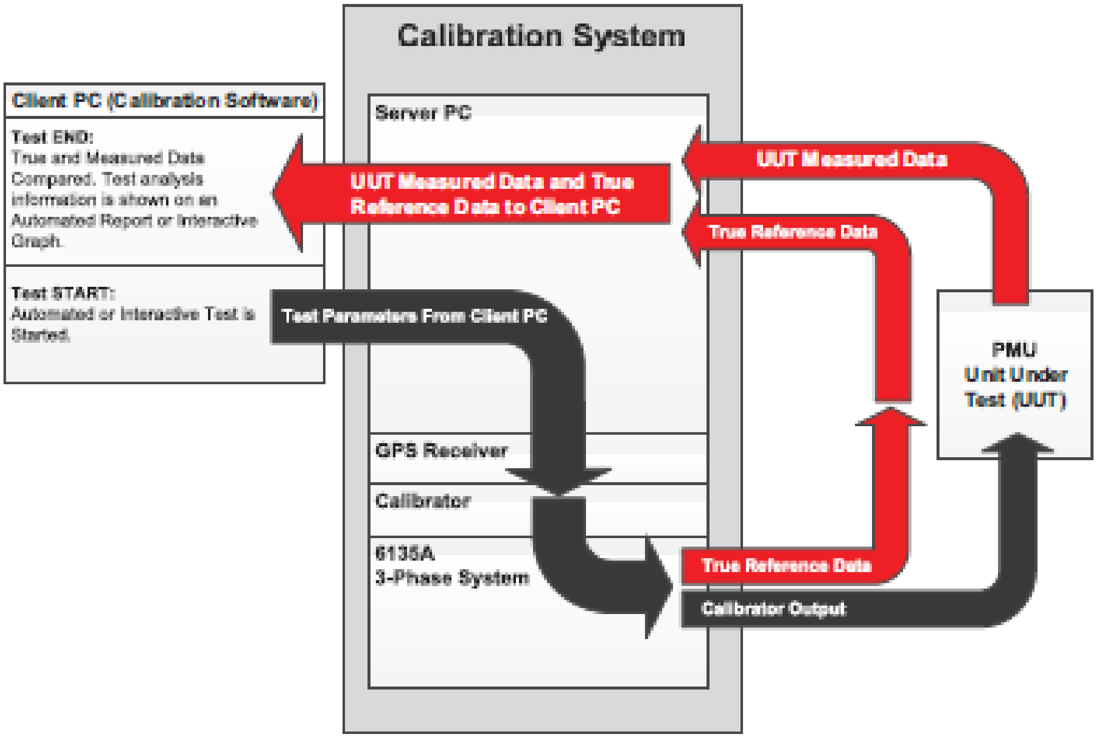
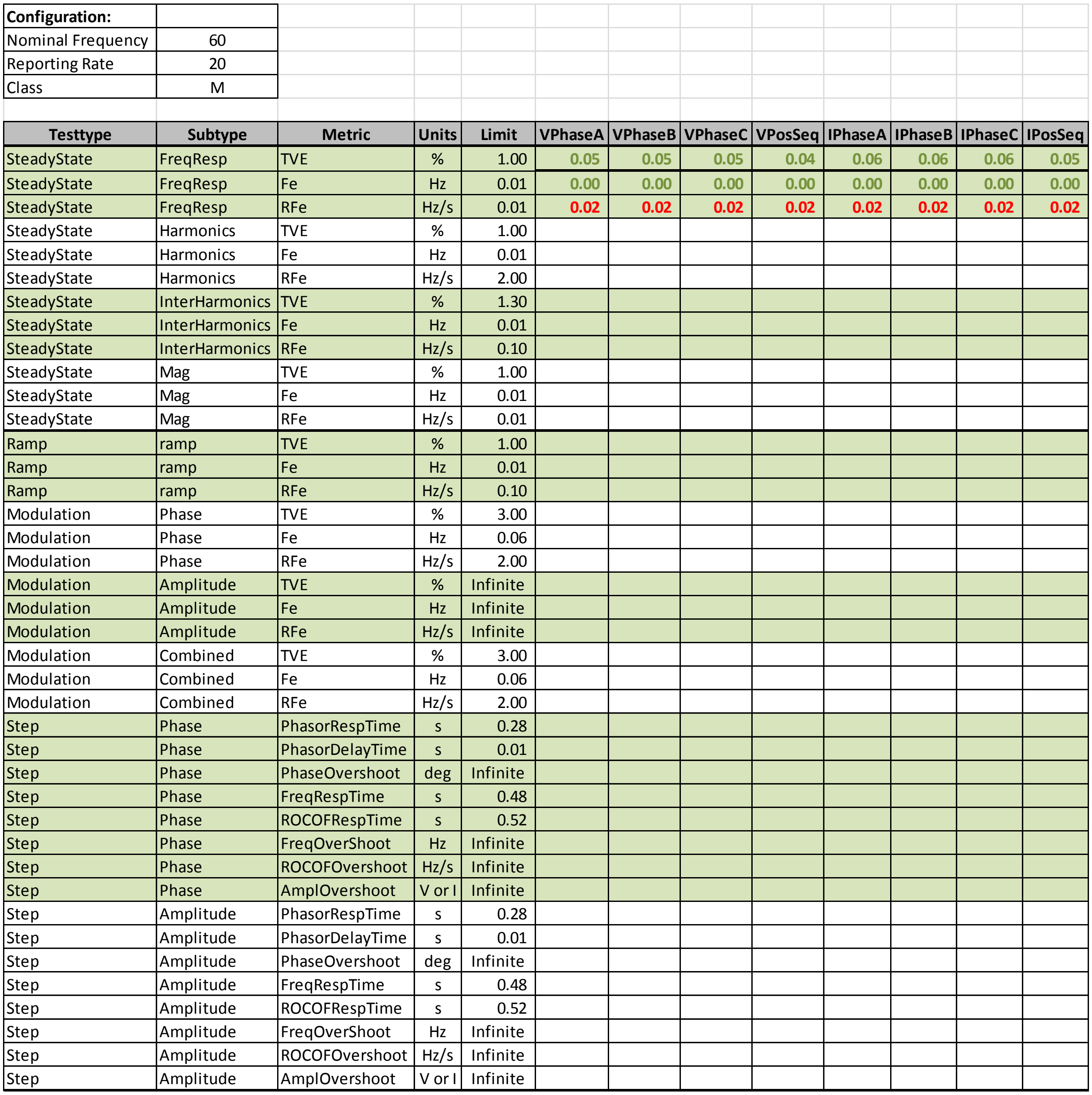


Figure 5. Flow diagram for the PMU Calibration Process

The PMU calibration process in Figure 5 is a remotely operated procedure controlled via a Calibration Software application running on the client PC. To certify a PMU, run an automated test procedure that contains a list of sequenced tests. The Calibration Software on the Client PC sends the Server PC all the necessary test parameters to configure the test. The Server PC receives the test parameters and configures and initializes the Calibration System. The Server PC starts the test and actively controls all of the Calibration System outputs. The Server PC records the true data from the 6135A System and the measured data from the PMU. The true and measured data are sent to the Client PC and the maximum test values are saved to the active test results file. An example of this file, in process, is shown in Table 2. When the test is complete, the Calibration Software reads the active test results file. Unique test results are stored in structured file storage. A test report is provided as a formatted Excel spreadsheet, with charts provided where appropriate.



Configuration:	
Nominal Frequency	60
Reporting Rate	20
Class	M

Testtype	Subtype	Metric	Units	Limit	VPhaseA	VPhaseB	VPhaseC	VPosSeq	IPhaseA	IPhaseB	IPhaseC	IPosSeq
SteadyState	FreqResp	TVE	%	1.00	0.05	0.05	0.05	0.04	0.06	0.06	0.06	0.05
SteadyState	FreqResp	Fe	Hz	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SteadyState	FreqResp	RFe	Hz/s	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
SteadyState	Harmonics	TVE	%	1.00								
SteadyState	Harmonics	Fe	Hz	0.01								
SteadyState	Harmonics	RFe	Hz/s	2.00								
SteadyState	InterHarmonics	TVE	%	1.30								
SteadyState	InterHarmonics	Fe	Hz	0.01								
SteadyState	InterHarmonics	RFe	Hz/s	0.10								
SteadyState	Mag	TVE	%	1.00								
SteadyState	Mag	Fe	Hz	0.01								
SteadyState	Mag	RFe	Hz/s	0.01								
Ramp	ramp	TVE	%	1.00								
Ramp	ramp	Fe	Hz	0.01								
Ramp	ramp	RFe	Hz/s	0.10								
Modulation	Phase	TVE	%	3.00								
Modulation	Phase	Fe	Hz	0.06								
Modulation	Phase	RFe	Hz/s	2.00								
Modulation	Amplitude	TVE	%	Infinite								
Modulation	Amplitude	Fe	Hz	Infinite								
Modulation	Amplitude	RFe	Hz/s	Infinite								
Modulation	Combined	TVE	%	3.00								
Modulation	Combined	Fe	Hz	0.06								
Modulation	Combined	RFe	Hz/s	2.00								
Step	Phase	PhasorRespTime	s	0.28								
Step	Phase	PhasorDelayTime	s	0.01								
Step	Phase	PhaseOvershoot	deg	Infinite								
Step	Phase	FreqRespTime	s	0.48								
Step	Phase	ROCOFRespTime	s	0.52								
Step	Phase	FreqOverShoot	Hz	Infinite								
Step	Phase	ROCOFOvershoot	Hz/s	Infinite								
Step	Phase	AmplOvershoot	V or I	Infinite								
Step	Amplitude	PhasorRespTime	s	0.28								
Step	Amplitude	PhasorDelayTime	s	0.01								
Step	Amplitude	PhaseOvershoot	deg	Infinite								
Step	Amplitude	FreqRespTime	s	0.48								
Step	Amplitude	ROCOFRespTime	s	0.52								
Step	Amplitude	FreqOverShoot	Hz	Infinite								
Step	Amplitude	ROCOFOvershoot	Hz/s	Infinite								
Step	Amplitude	AmplOvershoot	V or I	Infinite								

Table 2. Example of Test Results Viewer of a test in progress

The common measurements are, along with the relevant units of measure, are:

Steady state tests

• Total Vector Error (TVE)	%
• Frequency Error (Fe)	Hz
• Rate of Change of Frequency Error (RFe)	Hz/s

Step test results

• Response Time	s
• Delay Time	s
• Overshoot	deg, V, I, Hz or Hz/s

A single PMU test configuration consists of one nominal frequency setting, one reporting rate setting, and a class setting (M = measurement or P = protection), as in Table 2. A certification test of a configuration contains more than 1,000 individual sequenced tests. As the test progresses, the maximum observed value for each cell is updated and evaluated against the limit column. Green numbers reflect passing values, red numbers a failing value. For configurations for which all results are within limits, a formal certification report may be generated. The advantages of automated PMU testing are shown in Table 3, the most profound difference being the difference in total test time.

Manual	**Criterion**	**Automated**
High	**Operator Proficiency**	Modest
Continuous	**Operator interaction**	Limited, at start
Complex	**Test setup**	Routine
Manual	**Operation**	Automated
2 to 6 weeks	**Total test time**	1 to 2 days

Table 3. Manual versus automated test metrics for a single PMU configuration

5. Traceability established and maintained

Measurement traceability for the calibration rests upon the demonstrated accuracy of 1) the electrical signal sources, 2) the maintenance of time accuracy and 3) the performance verification of the entire integrated system.

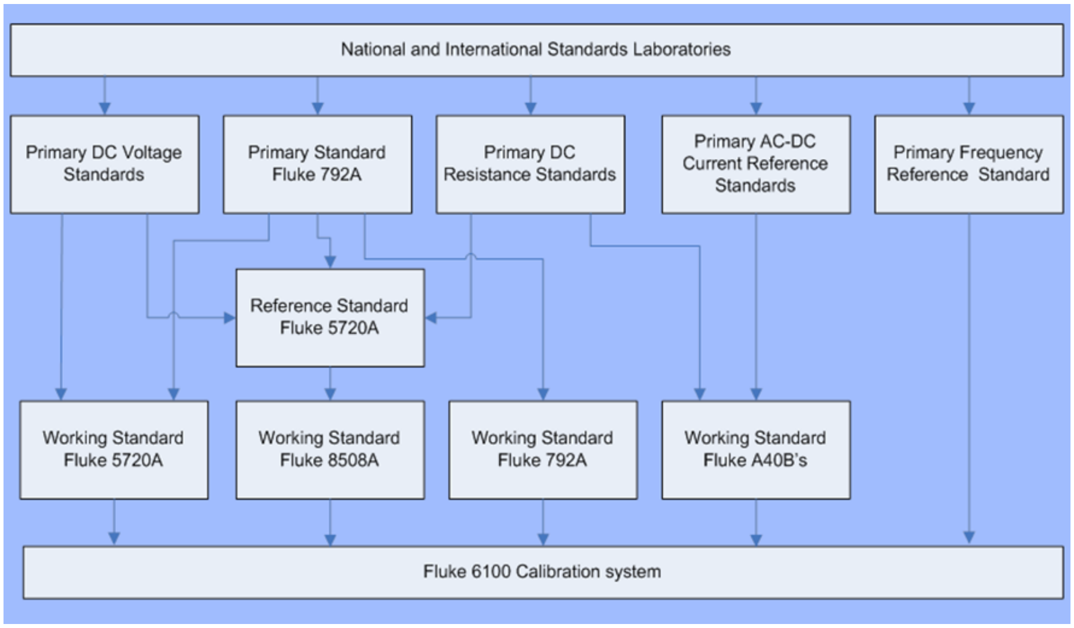


Figure 6. Traceability of PMU Test Instrumentation

Figure 6 graphically describes the traceability chain from the 6135A Electrical Power Standard to recognized international standards. One year accuracy for 70 volts, 50/60 Hz is 54 ppm and for 5 Amps, 50/60 Hz, 57 ppm.

Traceability to Coordinated Universal Time (UTC) is maintained using GPS-derived time, good to << 1 µs for phase accuracies of < 0.022^{o} at 60 Hz.

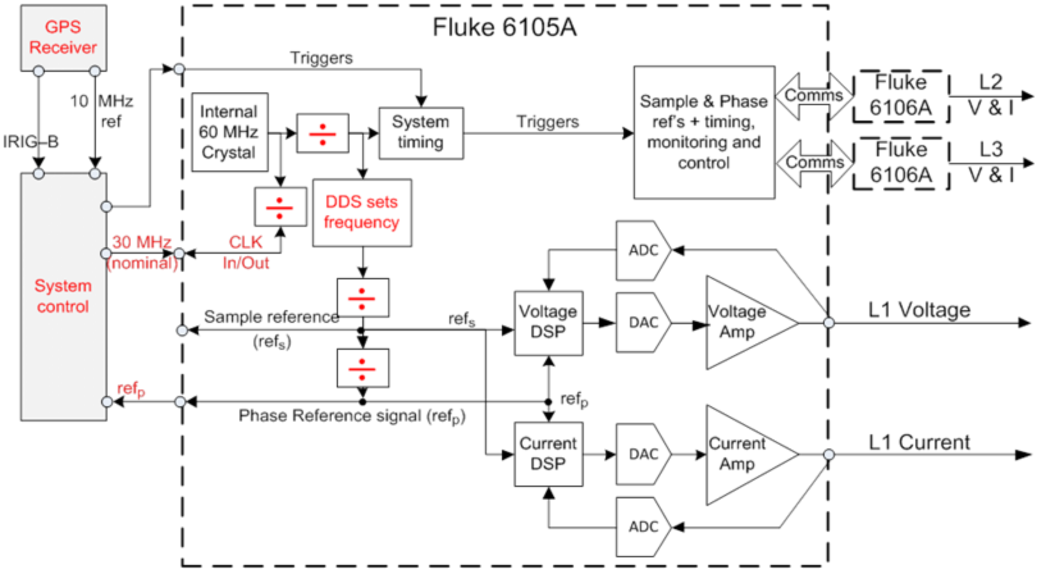


Figure 7. Traceability of time synchronization

Using the 6135A Electrical Power Standard, governed per the schematic in Figure 7, results in these Test Accuracy Ratios for the following time-dependent tests:

- Measurement bandwidth test accuracy expected to be < 0.025% TAR > 100:1
- Amplitude step using Dip/Swell function, Pre/post step TVE±0.025% TAR = 40:1
- Phase step by shifting DSP pointer, Pre/post step TVE± 0.0142^{0} TAR = 70:1

Each 6135A/PMUCAL System is delivered with a traceable certificate of calibration at time of manufacture. For regular calibrations at one-year intervals, a reusable shipping crate is provided for transport to one of three calibration depots; Everett, Washington, USA; Norwich, England; Beijing, China.

Conclusion: New test and calibration standards for Phasor Measurement Units, when combined with automated test execution and sound metrology, will result in improved interoperability across various makes and models of PMU. This improved credibility as a measurement device, combined with better economics of initial type testing and ongoing calibration, will result in increased deployment of PMUs. This, in turn, will help SynchroPhasor and PMU technology take its rightful place as the real-time guardian of the availability and reliability of the Smart Grid.

References:

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Bio: Jack Somppi manages DC/LF calibrators for Fluke Calibration. At Fluke since 1976, Jack has worked extensively with the metrology communities in Asia/Pacific and Europe. He is on the NCSLI Board of Directors and presently serves as Secretary and as the Asia Pacific Region Deputy. He holds a BSEE and MSEE from Montana State University. He is a Vice President of the Mt. Baker Council of the Boy Scouts of America. Jack’s hobbies include his vintage 190SL and photography.