Report of Uncertainty:  
NIST PMU Calibration Systems

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1. PMU test equipment requirements

Subclause 5.5.3 of IEEE StdC37.118.1:2011states that:

“(a) calibration device … shall be traceable to national standards, and have a *test uncertainty ratio* of at least (4) compared with these test requirements (for example, provide a TVE measurement within 0.25% where TVE is 1%)”.

The components that make up a “calibration device” are described herein. The description will be followed by a discussion of *test uncertainty ratio* (TUR) and why a TUR of 4 can lead to problems when determining whether or not a PMU passes any given test.

* 1. Calibration device components

In general, the following functions are required for PMU calibration devices:

1. Shall provide timing reference to the PMU and to the calibrator itself.
2. Shall provide voltage and current input signals [Signal source(s)]
3. Shall receive measurements from PMU under test (Receiver)
4. Shall compare phasor, frequency and ROCOF measurements from PMU to “true” (reference) phasor, frequency and rate of change of frequency (ROCOF) represent the signal source input to the PMU.
5. Shall perform calculations for total vector error (TVE), frequency error (FE) and rate of change of frequency error (RFE), and additional calculations for the dynamic step test results.
6. Shall have a means of determining the time of arrival of PMU data messages and comparing that time against the message timestamp.
7. Shall provide test result documentation.

Furthermore, tests shall be made under controlled temperature and humidity conditions.

* 1. Timing reference

PMUs under tests may require one of a variety of timing signals:

* GPS antenna
* IRIG B (DC level or AM possibly with the addition of IEEE Std 1344™ extension)
* IEEE Std 1588 (power profile)

The timing reference shall be traceable to UTC and shall have an uncertainty ≤ 1 microsecond (µs).

* 1. Signal source(s)

PMU calibration devices shall provide 3-phase voltage and current input signals to PMUs under test. The signals shall comply with both steady state and dynamic test conditions as specified by 5.5.5 through 5.5.9 of IEEE Std C37.118.1:2011. Additionally, the total harmonic distortion (THD) of the input signal shall be less than 0.2% of the fundamental (except where otherwise specified by harmonic distortion or out-of-band interference[[1]](#footnote-1) tests).

Phase offset control is required. The phase C and B signals shall be ± 120° offset from the phase A signal. All required tests shall be performed with balanced input signals.

The voltage and current amplitudes must be at “nominal level” except where specified in signal magnitude tests and measurement bandwidth[[2]](#footnote-2) tests. Nominal level or nominal amplitude is not defined in IEEE Std C37.118.1-2011 but are specified by IEEE Std. C37.90-2005 table 3 shown below:

Table 1 IEEE std. C37.90-2005 standard current and voltage rating for relays

|  |  |  |
| --- | --- | --- |
| **V rms** | **V dc** | **A rms** |
| 12/24/48 | 12 | 1 |
| 100/110/120b | 24 | 2 |
| 220/240c | 40/48/60 | 5 |
| 480c | 110/125 | 10 |
| 600c | 220/250 | 15 |

a Other values are also acceptable, but are not preferred.

b and values multiplied by √3 or 1/√3

c and values multiplied by 1/√3

PMUs shall be certified only at the tested nominal magnitude as documented in the test report. For certification at multiple nominal levels, full testing is required for each nominal magnitude.

Signal magnitude tests require input voltage at 120% nominal and input current at 200% nominal so PMU calibrator equipment shall be capable of supplying at least 120% of the selected nominal voltage and 200% of the nominal selected nominal current per phase.

* + 1. Signal sources for steady state tests

Signal frequency range tests require input frequencies at nominal frequencies of 50 Hz and 60 Hz ± 5Hz frequency range. Signal sources shall be capable of providing signal frequencies from 45 Hz to 65 Hz.

Signal magnitude tests require input frequencies at nominal frequencies; Voltage levels from 80% nominal level to 120% nominal level, and current levels from 10% nominal level to 200% nominal level shall be available from the signal source.

Phase angle tests can provide *either* constant phase at ±π radians or a “slowly varying” phase angle with the input frequency ≤ 0.25Hz from the nominal frequency for a duration which allows at least 360° of phase rotation.

Harmonic distortion tests require the addition of a single harmonic from the second harmonic up to the 50th harmonic of the nominal frequency. Harmonic magnitude shall be 10% of nominal magnitude for M class tests and 1% of nominal for P class.

Out of band interference test require interfering signals at 10% of nominal magnitude to be added to the fundamental where the interfering signal will be from 10 Hz up to twice the nominal frequency.

* + 1. Signal sources for dynamic tests

Measurement bandwidth tests require modulation of the input signals in phase and in amplitudeindividually. The modulation frequencies range from 0.1 Hz to 5 Hz and the index of modulation is 10%.

Frequency ramp tests require a linear sweep (chirp) of frequency from up to 5 Hz below to 5 Hz above the nominal frequency at rates of ± 1 Hz per second.

Step tests require steps of ± 10% of nominal magnitude and (separately) ± 10° of phase. These tests are performed repeatedly with the relative time between a UTC second and the step being adjusted by 1/10th of a reporting period. The PMU measurements from these 10 test “iterations” are combined to provide an “equivalent time sampled” result with a time resolution of 1/10th of the reporting period.

* 1. PMU measurement receiver

PMUs may transmit their measurements over a variety of physical media using a variety of protocols:

Physical media:

1. TCP, UDP or combined UDP/TCP Ethernet via:
   1. twisted pair copper using RG45 connector
   2. optical Ethernet using ST or LT connectors
2. RS-232 (obsolete and may not be required for modern PMU calibration systems)

Protocols[[3]](#footnote-3):

1. IEEE Std C37.118-2005
2. IEEE Std C37.118.2:2011
3. IEC Std. 61850 (using IEC TR 90-5)
   1. Per the GE “implementation agreement”
   2. Per a custom configuration file

Some PMUs are able to transmit measurements using multiple protocols and over a variety of physical media. For those PMUs, full testing shall be conducted using one protocol and limited testing shall be conducted at one reporting rate using the other protocol or protocols. The limited testing shall consist of:

* Dynamic step changes in phase and magnitude (see 5.5.8 of IEEE Std C37.118.1-2011-)
* PMU Latency (see 5.5.9 IEEE PC37.118.1a/2013)

The test results shall document which protocol was fully tested and which was spot checked.

The test results shall report the configuration of the protocol being tested, for example floating point or integer data types and polar or rectangular notation.

* 1. Reference (“true”) values and result calculation

According to IEEE Std C37.118.1-2011, the PMU measurement is compared to the “true” value. Typically, measurement labs and metrologists prefer to use the word “reference” rather than the word “true” because there is always some level of uncertainty in the representation of a physical quantity. In order to determine the error of the PMU measurements, the phase, frequency and ROCOF of the signal source must be known at the times of each PMU measurement. It is very important that the uncertainty of the reference also be known because uncertainty in the reference value contributes to the *test uncertainty ratio* (TUR) of the calibrator. The TUR establishes a range of results where it is impossible to determine whether or not the results exceed the limits of the test. There will be more on this topic later in 5.8.

There are several methods to determine the reference uncertainty:

1. Direct Measurement: A calibrated data acquisition system (using analog to digital converters) is connected to the signal source along with the PMU under test. Since the parameters of the signal are known, a combination of techniques (such as curve fitting) can be applied to determine the reference with a known uncertainty.
2. Inference: The signal source is calibrated such that, given the parameters of the signals, the reference can be inferred. Some information can be fed back into the system such as the time of the zero crossing of one of the phases.
3. Transfer Measurement: A calibrated PMU with uncertainty which exceeds the TUR requirements for the calibration system is connected to the signal source. This “reference PMU” receives the reference signal. The drawback to this method is that PMUs do not know the parameters of the input signal so tend to have a higher uncertainty than either of the preceding methods.
   1. Environmental conditions

Tests are required to be performed at a temperature of 23°C ± 3° and at humidity < 90%. Some tests are also required at temperatures of 0°C and 50°C ± 3°.

* 1. Test uncertainty ratio

The test uncertainty ratio (TUR) is the ratio between the uncertainty of a device under test and the instrument testing it. When there is a performance limit, the TUR determines a region on either side of the limit within which the test instrument is incapable of determining if the device under test exceed or is within the test limit. IEEE Std C37.118.1:2011 states that a calibrator shall have a TUR of 4 *compared to the test requirements.*

|  |  |
| --- | --- |
| As an example of the effect of TUR\* on TVE measurements, Figure 1‑1 shows a phasor diagram of a single, time stamped reference (true) value from a PMU calibrator and a single time stamped measurement from a PMU under test. An exaggerated circle around the reference value shows a TVE limit of 1%. On either side of the TVE limit is an annular ring the width of the calibrator uncertainty on either side of the limit.  Note that the measured value is within the TUR\* ring around the limit. The measured value is within the TVE limit of 1%, but the uncertainty of the calibrator is such that it cannot be determined if the measurement is within or outside of the limit.  For many devices, such as voltmeters, the error of the device is expected to be small, so a calibration device can have a TUR of 4 with respect to the device under test and only about 2% of tests would be indeterminate. But PMUs are tested in such a way that their measurements are expected to be well within 75% of the limit (for example, for measurements near the bandwidth of the PMU, TVE is expected to be greater than 0.75%) Therefore a TUR of 4 *with respect to the limit* is insufficient for a PMU calibrator. An uncertainty of 0.010 (TUR\* of 10) would be much more appropriate and allow most test results to be determined. | Figure **Error! No text of specified style in document.**‑1 —The effect of test uncertainty ratio\*  \*TUR with respect to the test limits |

Metrologists normally determine TUR with respect to the uncertainty of the device under test and not the test requirements so it is important to note that for the purpose of this section, TUR is the uncertainty of the calibrator with respect to the test limits.

1. Error and uncertainty metrics
   1. Total vector error (TVE)

The measure of error between the theoretical phasor value of the signal being measured and the phasor estimate is the Total Vector Error (TVE). TVE is a scalar value which represents the magnitude of the vector between the theoretical Phasor and the measured vector. According to IEEE Std C37.118.1 equation 12:

where:

and are sequences of phasor estimates given by the PMU under test at time *n*.

and are sequences of theoretical Phasor values of the input signal at time *n*.

* 1. Frequency error (Fe)

According to IEEE Std C37.118.1-2011equation 13 frequency error (FE) is the absolute value of the difference between the theoretical (“true”) frequency of the input signal at time *n* and the estimated frequency given by the PMU under test

The frequency error limits are given as positive numbers and are compared against a maximum absolute value of the error over the test, However it is important to realize that the signed difference between the PMU measured value and the theoretical value of the input signal informs us of some underlying causes of the error. For example, a fixed frequency error across the duration of a frequency ramp test indicates a difference in time between the frequency estimate and the time stamp of the report. Note also the order of the difference given by equation 13. Since the PMU estimated frequency is subtracted from the theoretical input, a PMU estimated frequency which is greater than the theoretical input will yield a negative value. In the ramp example a fixed negative offset would be due to a positive time offset.

* 1. Rate of change of frequency error (RFe)

According to IEEE Std C37.118.1-2011equation 14 rate of change of frequency error (RFE) is the absolute value of the difference between the theoretical (“true”) ROCOF of the input signal at time *n* and the estimated ROCOF given by the PMU under test

* 1. Step response time

The step response time is called the “measurement response time” by IEEE Std C37.118.1-2011. It shall be determined as the difference between the time that the measurement leaves the specified accuracy limit and the time when it returns to and remains within the limit. The limits are:

TVE ≤ 1%

FE ≤ 0.005 Hz

RFE ≤ 0.1 Hz/s

* + 1. Ambiguity in the step response time

IEEE Std C37.118.1-2011 is not clear what “times” are used when determining the time when the accuracy leaves and returns to the limit. The standard specifies an equivalent time sampling approach and *suggests* that a 10 step test is suitably accurate, however it does not say if the time begins and ends woth the sample before leaving or returning to the limit, the sample after leaving or returning to the limit or by interpolating the time between two samples.

* 1. Step delay time

The step delay time is called the “measurement delay time by IEEE Std C37.118.1-2011. It is the time interval between the instant that a step change is applied to the input of a PMU and the measurement time that the stepped parameter achieves a value that is halfway between the initial and final values.

Unlike the response time, there is no ambiguity in the delay time. The standard clearly states that the time to use it the measurement time (the time of the report). Since the step test uses an equivalent time sampling approach, the times are indexed against the time of the step and the delay time is the measurement time of the first measurement equal to or beyond 50% of the step magnitude or phase.

* 1. Step overshoot/undershoot

Overshoot and undershoot are not completely described by IEEE Std C37.118.1-2011. They are determined by the curve of the measurements on either side of the stepped parameter. For phase step it is the curve of the phase on either side of the phase step and for magnitude step it is the curve of the magnitude on either side of the magnitude step. There are no limits for frequency or ROCOF overshoot/undershoot.

Overshoot/undershoot may occur before and after the step in the input. It is measured not just outside the response time but for all time except for the time then the measurements are transitioning from the before-step level to the after-step level.

The overshoot and undershoot measurements are the difference between the measurement and average of the settled measured values before and after the step. The values are normalized and given as a percentage of the step size. The average of the settled measured values are not necessarily the true values of the input before and after the step.

* 1. PMU reporting latency

The PMU latency is defined in IEEE Std C37.118.1-2011 5.3.4 and in IEEE draft PC37.118.1a as the maximum time interval between the data report time as indicated by the data time stamp and the time when data becomes available at the PMU output.

The PMU reporting latency is the maximum value over at least 1000 consecutive messeges. IEEE draft PN37.118.1a amended the accuracy to at least 0.002 seconds which should allow for the uncertainty of standard hardware and software on the test instrument receiving the PMU messages to determine the time of arrival.

* 1. PMU calibrator metrics

Determining the uncertainty of a PMU calibrator is different from determining whether a PMU has exceeded a required limit. For PMU compliance, only the maximum of TVE, Fe and RFe are used, but when determining calibrator uncertainty, the minimum, mean and standard deviations of these metrics are important. Furthermore, TVE is a *scalar* value: the length of the error *vector.* The magnitude error (Me) and phase error (Pe) components of TVE are also important and so their max, min, mean and standard deviation should also be evaluated.

* + 1. Phase uncertainty due to calibrator system delay

Time delay exists in PMU calibrator systems and can be compensated by a delay factor parameter in the calibrator software. Time delay uncertainty contributes to phase uncertainty.

The phase uncertainty due to time delay uncertainty varies proportionally with the input frequency. When testing PMUs, the maximum input frequency is 65 Hz so a 1 microsecond phase uncertainty yields 0.4084 milliradian or 23.4 millidegree uncertainty. This would yield a 0.04084% TVE uncertainty.

* + 1. Total steady state TVE

The total steady state TVE is the root sum of squares of all the uncertainties:

The CT gain uncertainty only applies to the current channels.

1. NIST PMU calibration systems overview

NIST performs calibrations on Phasor Measurement Units (PMU) using a collection of devices organized into four distinct PMU calibration systems. Each system is used to perform a subset of tests from which results are collected together to form a complete calibration report. The four systems have been designated using the following names:

1. NIST Steady State Calibration System
2. NIST Dynamic Calibration System 1
3. NIST Dynamic Calibration System 2
4. Fluke 6105a PMU Calibration System

The NIST steady State Calibration System is located in NIST Gaithersburg building 220 room B255 along with a Thermotron SE 1000-3 environmental chamber. This system is used to perform the steady state PMU testing at 0° C and 50° C.

NIST Dynamic Calibration Systems 1 and 2 and the Fluke 6105a PMU Calibration System are located in NIST Gaithersburg building 218 Room B225 which is maintained at 23° C ± 1°C.

The Fluke 6105a PMU Calibration System (hereafter know as the Fluke system) is used to perform all steady state and dynamic tests required of PMUs at reporting rates of 10 FPS through 60 FPS, 50 Hz and 60 Hz nominal frequencies inclusive, which use the IEEE C37.118.2-2011 Data Transmission Protocol.

NIST Dynamic Calibration System 2 (hereafter known as NIST Dyn 2) is used to perform steady state and dynamic testing at reporting rates above 60 FPS and/or that use the IEC 61850 90-5 Data Transmission Protocol. NIST DYN 2 is also the system used to do all PMU Reporting Latency Tests.

NIST Dynamic System 1 (hereafter known as NIST Dyn 1) is used primarily as a platform to develop systems to calibrate PMU calibrators and all the measurements of uncertainty for the Fluke system were made on NIST DYN 1.

1. NIST dynamic 1 PMU calibration system
   1. NIST dyn 1 system description

The NIST Dynamic Calibration System 1 block diagram is shown below. The system applies dynamic three-phase signals to PMUs.

|  |  |
| --- | --- |
| The waveforms are generated in the Synchronized Sampling and Generation unit (control unit) and output as voltages with a range of up to ±10 V peak-to-peak. The six output channels have strobe rates of 200 kilo-samples per second. Three voltage and three transconductance amplifiers to provide test signals to the DUT.  Six input channels sample the voltages and currents applied to the DUT at 50 kilo-samples per second. The three voltage amplifiers output voltages with up to 140 V rms, and the three transconductance amplifiers output currents up to 6 A rms, which cover typical test levels for electric power instrumentation. | DynSamplSys1pp  Figure 5‑3: NIST dynamic 1 PMU calibration system |

The test signals generated have linearly varying magnitudes or frequencies, as well as sinusoidal magnitude and frequency variations. Analysis models are used for calculating the dynamic parameters of the test signals. These analysis model values are used as an estimate of the “true” values to which the DUT values are compared.

* 1. NIST Dyn 1 uncertainty determination
     1. Steady state magnitude uncertainty determination

|  |  |
| --- | --- |
| Figure 5‑4 shows the system for calibrating magnitude in the NIST Dynamic 1 PMU calibration system.  The PXI-6733 generates steady state sinusoidal voltage which is amplified by the Khron-Hite 7602 Voltage amplifier when calibrating voltage magnitude. When calibrating current magnitude, the voltage output is converted to a current by the NIST SML-5A transconductance amplifier and the current is input to one phase of the NIST calibrated current transformer (CT) which outputs a voltage.  The voltage being calibrated is input in parallel to both a Hewlett Packard (HP) 3458 multimeter and to three channels of Dyn 1’s NI-6123 16-bit multifunction data acquisition card. The three channels are the phase inputs for either the voltage calibration or the current calibration depending on which calibration is being conducted.  The HP 3458 multimeter performs high speed sampling of the steady state voltage and provides those samples to Dyn 1’s PXI-8196 embedded controller which calculates the RMS value to an uncertainty of less than 20 ppm.  Software running on Dyn 1’s embedded controller calculates the RMS value of the input each channel of the PXI-6123 DAC and multiplies the value by a gain factor (which is set to 1 for the first test run). The scaled RMS value is compared to the RMS value from the HP 3458. And an error in PPM is determined as well as a new gain factor which will be used for the next test run.  Each test run has multiple iterations of error calculation and the standard deviation (in PPM) of the error for all iterations is calculated. The operator has control of how many iterations are run and typically runs 10 iterations per gain factor calculation. The new gain factor is then applied and the test run is repeated for 10 iterations until the gain error does not change appreciably.  Magnitude calibration is repeated as above for steady state frequencies from 45 Hz to 65 Hz in 5 Hz increments and the mean gain error is used. The standard deviations across all the frequencies contribute to the magnitude uncertainty. | Dyn1MagCal.wmf  Figure Error! No text of specified style in document.‑4: Dyn 1 Magnitude Calibration |

For the current magnitude calibration the gain of the current transformer at the frequencies being tested is subtracted from the gain factor before the gain error is calculated. The CT’s gain across it’s usable frequency spectrum was measured during CT calibration and is tabulated in the CT calibration report.

* + - 1. Dyn 1 magnitude uncertainty
      2. Uncertainty in the gain factor

|  |  |  |  |
| --- | --- | --- | --- |
| **Phase** | **Gain Factor** | **Gain Factor StD (ppm)** | **% TVE uncertainty** |
| VA | 21.0111154 | 250.2146978 | 0.0500% |
| VB | 21.0040194 | 247.5610288 | 0.0495% |
| VC | 21.0001532 | 263.821233 | 0.0528% |
| IA | 10.0039520 | 117.1324037 | 0.0234% |
| IB | 10.0025420 | 104.2592922 | 0.0209% |
| IC | 10.0046560 | 104.5466403 | 0.0209% |

* + - 1. Current transformer gain uncertainty

|  |  |  |  |
| --- | --- | --- | --- |
| **Phase** | **Mean Gain (ppm)** | **Gain StD (ppm)** | **%TVE uncertainty** |
| IA | 427 | 11.24 | 0.0022% |
| IB | 344 | 9.54 | 0.0019% |
| IC | 489 | 10.05 | 0.0020% |

* + - 1. HP-3458 RMS voltage measurement uncertainty

For all phases, the HP-3458 RMS voltage measurement uncertainty is less than 10 ppm so the % TVE contribution from the multimeter is less than 0.0010%

* + 1. Dyn1 delay uncertainty determination

|  |  |
| --- | --- |
| shows the system for calibrating the time delay in the NIST Dynamic 1 PMU calibration system.  The PXI-6733 generates steady state sinusoidal voltage which is amplified by the Khron-Hite 7602 Voltage amplifier when calibrating voltage magnitude. When calibrating current delay, the voltage output is converted to a current by the NIST SML-5A transconductance amplifier and the current is input to one phase of the NIST calibrated current transformer (CT) which outputs a voltage.  The voltage being calibrated is input in parallel to both a Tektronix TDS 744A digitizing oscilloscope and to three channels of Dyn 1’s NI-6123 16-bit multifunction data acquisition card. The three channels are the phase inputs for either the voltage calibration or the current calibration depending on which calibration is being conducted.  The oscilloscope is triggered by the 1 pulse per second (PPS) signal output from the NI PXI-6682 timing module which is disciplined to the UTC time provided by GPS. The operator goes through a procedure to align the steady state sinusoidal signal generated by the Dyn 1 system so that a zero crossing occurs as close to the PPS trigger as possible. Because a small DC offset may exist in the signal, it is inverted so that positive and negative going crossings occur on both sides and as close as possible to the PPS trigger.  The oscilloscope scale is set to 200 ns per division with a vertical gain such that the displayed input signal maximized but not clipped. During the run, the oscilloscope sends the digitized signal to Dyn 1’s embedded controller via GPIB. The samples from the oscilloscope are fitted to a second order polynomial and the root of the polynomial is the time difference from the PPS trigger.  Software calculates the time of the zero crossing of the input to the PXI-6123 data acquisition module relative to the PPS by performing a cosine fit on the data. The curve fit is the same algorithm used when calibrating PMU devices. Absolute phase angle at the zero is compared with a theoretical 90° (since the nominal power system signal is a cosine) and the difference is divided by the input frequency which results in a time difference from the PPS. This time is compared with the zero crossing time from the oscilloscope. | Dyn1DlyCal.wmf  Figure Error! No text of specified style in document.‑5: Dyn 1 Time Delay Calibration |

Software applies a delay correction factor (which is set to zero for the first run). The zero crossing times of the oscilloscope and the DAC module are compared and a time error (in nanoseconds) and a new time delay factor which will be used for the next run is determined.

Each test run has multiple iterations of delay calculation and the standard deviation (in ns) for all test runs is calculated. With each iteration, the generated signal is phase inverted so one degree of freedom is made up of two test iterations The operator has control of how many iterations occur each run and typically 30 iterations are run for a 15 degrees of freedom of 15.

Delay calibration is repeated as above for frequencies of 5000 Hz, 2000 Hz, 1000, Hz, 500 Hz, 100 Hz, 60 Hz and 50 Hz. The mean delay factor is used.

* + - 1. NIST dyn1 delay factor uncertainty

|  |  |  |  |
| --- | --- | --- | --- |
| **Phase** | **Dly Factor mean (ns)** | **Dly Factor StD (ns)** | **% TVE uncertainty @ 65 Hz input frequency** |
| VA | -169 | 64.89 | 0.0053% |
| VB | -200 | 68.33 | 0.0056% |
| VC | 61 | 64.64 | 0.0053% |
| IA | 472 | 124.59 | 0.0102% |
| IB | 478 | 125.93 | 0.0103% |
| IC | 473 | 126.46 | 0.0103% |

* + - 1. Delay of the current transformers
      2. effect of odd harmonics on delay factor calculation
    1. Dyn 1 total steady state TVE

The total steady state TVE uncertainty is the root sum of squares of all the uncertainties:

The CT gain uncertainty only applies to the current channels.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Phase** | **Total % TVE** |  | **gain factor uncertainty** | **HP3458 RMS uncertainty** | **Sin (delay uncertainty)** | **CT gain uncertainty** |
| VA | 0.0503% |  | 5.00E-04 | 1.00E-05 | 5.30035E-05 | 0 |
| VB | 0.0498% |  | 4.95E-04 | 1.00E-05 | 5.58113E-05 | 0 |
| VC | 0.0530% |  | 5.28E-04 | 1.00E-05 | 5.27959E-05 | 0 |
| IA | 0.0257% |  | 2.34E-04 | 1.00E-05 | 0.000101765 | 2.24796E-05 |
| IB | 0.0234% |  | 2.09E-04 | 1.00E-05 | 0.000102864 | 1.907E-05 |
| IC | 0.0234% |  | 2.09E-04 | 1.00E-05 | 0.000103296 | 2.00915E-05 |

1. NIST steady state calibration system
   1. NIST steady state system description

The NIST steady state calibration system is co-located with an environmental chamber in order to perform testing on PMUs at other than room temperatures. The PMU standards require steady state frequency range tests to be performed at 0° C and 50° C ± 1° C. This is the only test required to be performed at temperatures other than 23° C.

The steady state PMU performance calibration test setup using the NIST PMU steady-state performance calibration system is shown in Figure 4‑2

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| The calibration system is synchronized to UTC via a Symmetricom GPS/Xli Global Positioning System (GPS) clock. It provides UTC synchronized three-phase power signals to the DUT being calibrated. The PMU outputs a C37.118.2-2011 Standard formatted continuous data stream and each message is time-stamped to UTC.  Three ROTEK 8100 power/energy calibrators generate the voltage and current signals to the PMU. The manufacturer has modified the simulator so it can receive a sampling synchronization signal from the Synchronized Sampling and Generation unit (control unit). The control unit includes a computer with control software that automates much of the testing sequences. It also includes a six-channel sampling system to measure the voltage and current waveforms supplied to the DUT under test using compensated resistive attenuators and current transformers (CTs). The time synchronization of the calibrator is maintained by triggering the waveform sampling with the one pulse-per-second (1 pps) signal from the clock. | SamplSys1pp  Figure Error! No text of specified style in document.‑2: NIST steady state calibration system block diagram |

The voltage signal is attached in parallel with the PMU to a calibrated voltage attenuator and then to a National Instruments (NI) PXI-6123 Data Acquisition Card located in a PXI-1042Q chassis along with an NI PXI-6608 High Precision Counter Timer which received UTC disciplined 10 MHz and 1 Pulse Per Second (PPS) signals from the GPS receiver. the current signal to the PMU is attached in series with the PMU to NIST made calibrated current transformers complete with calibrated burdens on the secondary side which are also measured by the PXI-6123.

Software running on the NI system calculates the reference signal and receives the PMU data, comparing the two and calculating the PMU test results which can be saved by the operator on the systems hard disk drive.

* 1. NIST steady state calibration system intercomparison

Since only the steady state frequency range test is performed by the steady state system, a transfer calibration (intercomparison) may be used to determine the 95.4% confidence interval of TVE, FE, and RFE when compared with the dynamic 1 system which has performed the same test on the transfer standard PMU. For this intercomparison, the transfer standard is a PMU which has errors that fall within the uncertainties of either the NIST dynamic 1 PMU calibration system or the Fluke PMU calibration system.

* + 1. 95% confidence interval

For each measurement of TVE, FE, and RFE made by the steady state calibration system, we can be 95% certain that the measurement lies within a confidence interval around the actual value. The 95% confidence interval is determined by:

1. Determining a “bias level” by subtracting the mean magnitude error (ME) and phase error (PE) for each frequency measurement made by the reference calibrator (the dynamic 1 test system) from the mean ME and PE of measurements made by the calibrator under test (the steady state test system).
2. Determining a “common standard deviation” (StDc) by taking the root sum of squares of the dynamic and steady state ME and PE standard deviations.
3. Determining the 95% confidence interval for ME or PE by adding the absolute value of the ME or PE bias to twice the values of the ME or PE StDc (2 sigma),

The PE confidence level is calculated in percent. Since the PE and PE StD is measured in degrees, they are converted to radians and multiplied by 100 to approximate the PE in percent. If the PE and StD in radians is small, 100 times them are a very close approximations to percent phase error. If they were not small, then to determine the phase error in percent, the sin(PE) or sin(StD) must be taken. In these transfer calibrations, the PE is much smaller than 1% (as will be shown in the plots below). For 1% PE, the arcsin of .01 radian is 0.0100001667 (1.00001667%) or 16.7 ppm different from 1% which is insignificant for these calculations.

The TVE confidence interval is the root sum of squares of the ME and PE confidence intervals given in percent.

* + 1. Steady state system frequency range 95% TVE confidence intervals
       1. Steady State system voltage confidence interval

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| |  |  |  |  |  | | --- | --- | --- | --- | --- | |  | VA | VB | VC | V+ | | Max TVE 95% Conf | 0.091% | 0.089% | 0.088% | 0.047% | | Max ME 95% Conf | 0.067% | 0.048% | 0.064% | 0.024% | | Max PE 95% Conf | 0.071% | 0.076% | 0.067% | 0.041% |   The 95% confidence intervals for voltage TVE, magnitude error and phase error.  The maximum voltage TVE 95% confidence interval for all phases is 0.095% |  |

* + - 1. Steady State system current confidence interval

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| |  |  |  |  | | --- | --- | --- | --- | |  | IA | IB | IC | | Max TVE 95% Conf | 0.049% | 0.056% | 0.057% | | Max ME 95% Conf | 0.040% | 0.046% | 0.028% | | Max PE 95% Conf | 0.033% | 0.032% | 0.052% |   The 95% confidence intervals for current TVE, magnitude error and phase error.  The maximum current TVE 95% confidence interval for all phases is 0.057% |  |

* + - 1. Steady State system frequency confidence interval

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| Max FE 95% conf | 0.000225 Hz |

* + - 1. Steady State system ROCOF confidence interval

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| Max RFE 95% conf | 0.010816 Hz/s |

1. NIST dynamic 2 PMU calibration system
   1. NIST dyn2 system description
   2. NIST dyn 2 uncertainty determination method
   3. NIST dyn 2 uncertainty
2. Fluke PMU calibration system
   1. Fluke system description

The Fluke system is a prototype model of a commercially available PMU calibration system offered by Fluke Corporation’s Calibration Division. The system development was partially funded by an American Recovery and Reinvestment Act (ARRA) Grant administered by NIST. The system was the second prototype developed by Fluke and is on permanent loan to NIST.

The system is comprised of three Fluke Model 6105a electrical power standards which have system clocks provided by a Fluke 6105a/PMU timing unit. The timing unit receives GPS disciplined 10 MHz clock signal from a Symmetricom GPS XL GPS receiver. The timing unit also receives IRIG-B000 standard time protocol using the IEEE 1344 extension from the GPS receiver. A rack-mounted industrial personal computer running the Windows Operating System and the Fluke PMU Calibrator Server software control the three 6105a power standards and the 6105a/PMU timing unit and communicates raw test data to another personal computer which runs the Fluke PMU calibration client software.

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| PMU_Cal_180px_x_237px.jpg | Fluke Block.jpg  Figure 6: Fluke 6105a PMU Calibration System |

* + 1. Fluke system operation

The Fluke PMU calibrator server pc receives parameters for individual tests from a client pc running the Fluke PMU calibrator client software. The sever configures the 6105a electrical power standard and the 6105a/PMU timing unit parameters for nominal voltage and current signals to be synchronized to UTC. The calibrator voltage and current sources then generate nominal signal, wait for the PMU to settle then adjusts the phase and amplitude to nominal magnitude and absolute phase synchronous to UTC. The voltage and current outputs are turned off then the test parameters are loaded into the power standard and timing unit. The current and voltage sources are then turned on and the PMU is sent a command to begin transmitting PMU data. The system waits for the PMU to settle then triggers any dynamic modulation to begin. This trigger usually occurs within a few nanoseconds of the UTC second. PMU data is received and sent to the client which calculates a reference signal based on output signal parameters measured by the server at the time of the modulation trigger. The reference signal is compared to the PMU data and PMU test results for each reporting period and saved on the client pc’s hard disk drive. After the test has concluded, the Fluke system proceeds to automatically run the next test.

* 1. Fluke uncertainty determination method

Figure 4‑5 shows the signal flow for determining the uncertainty of the Fluke PMU calibration system. The data from the PMU is not used in making direct uncertainty measurement but can be used to make transfer evaluation of the reference signal uncertainty at the same time as the direct measurement.

CalCal.wmf

Figure 7: Signal flow diagram for determining the uncertainty of the Fluke system

The 3-phase voltage outputs of the Fluke electrical power standards are attached in parallel to a PMU and to a NIST calibrated voltage attenuator. The 3-phase current output of the Fluke system is attached in series with the PMU and with a NIST calibrated current transformer. The output of the NIST voltage attenuator and current transformer are attached to the NIST Dyn 1 system’s PXI-6123 data acquisition card which sample the inputs synchronously with UTC.

The NIST system performs measurement of the input signal by using a curve fitting algorithm based on the test signal parameters input by the operator. The NIST system also performs total harmonic distortion and noise measurements and measures the magnitude, frequency and phase of harmonics and interharmonics accompanying the fundamental frequency. When the test has concluded, the operator saves all measurements in a comma separated value text file. The Dyn 1 data also contains the PMU reported data and measurements of the PMU performance. At the completion of each test, the Fluke system saves its signal reference values, the PMU reports, and the measurements of PMU performance. Once the data has been saved, the PMU reference values are subtracted from the NIST curve fitted measurements and TVE, Me, Pe, Fe, and RFe for each PMU reporting period are calculated and saved.

Once all tests of a particular type have been run (for example, all the frequency range tests across the ± 5 Hz PMU bandwidth) all test files are post-processed to calculate summary statistical data for each test run. The max, min, mean, and standard deviation for all the metrics for each test run are recorded in a results file which included plots of the statistical data.

* + 1. Uncertainty in the dyn 1 system used to measure the Fluke output

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| The uncertainty in the Fluke measurements cannot be determined with any more accuracy than the system used to measure it. In the NIST Dyn 1 system, magnitude uncertainty and signal measurement delay uncertainty limit the accuracy of the curve fitted measurements of the input signal. | |  |  | | --- | --- | | **Phase** | **NIST dyn 1 TVE uncertainty** | | VA | 0.0503% | | VB | 0.0498% | | VC | 0.0530% | | IA | 0.0107% | | IB | 0.0107% | | IC | 0.0108% | |

* 1. Fluke uncertainty
     1. Steady state frequency range reference error

Figure 7‑8 shows the voltage TVE error measurements of steady state voltage reference at 0.5 Hz intervals from 45 to 55 Hz. The vertical bars show all errors over a 20 second test duration for each of the voltage phases. The green line at 0.05% TVE shows the uncertainty of NIST Dyn 1 system used to make the measurements. This figure shows that the Fluke steady state reference error is well below the uncertainty of the measurement system.

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| Figure 7‑8: Fluke steady state voltage TVE error | Figure 7‑9: Fluke steady state current TVE error |

Figure 7‑9 shows the current TVE error measurements of steady state current reference at 0.5 Hz intervals from 45 to 55 Hz. The vertical bars show all errors over a 20 second test duration for each of the voltage phases. The green line at 0.01% TVE shows the uncertainty of NIST Dyn 1 system used to make the measurements.

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| **Phase** | **% TVE Mean + 2 x StD** |  | **Mean TVE error** | **StD TVE error** |
| VA | 0.01655\* |  | 0.00951 | 0.00352 |
| VB | 0.01814\* |  | 0.01089 | 0.00362 |
| VC | 0.01836\* |  | 0.01112 | 0.00362 |
| IA | 0.02278 |  | 0.01141 | 0.00569 |
| IB | 0.01023 |  | 0.00427 | 0.00298 |
| IC | 0.01068 |  | 0.00489 | 0.00289 |

\* Within the uncertainty of the NIST dyn 1 system used to make these measurements

* + 1. Fluke magnitude range uncertainty
    2. Fluke Harmonic distortion uncertainty

PMUs should filter harmonic distortion and be “immune” to harmonics in the synchrophasor estimate. The harmonic distortion test subjects the PMU to a single harmonic with specified magnitude. Individual tests of 2nd harmonic through 50th harmonic are required. While the relative phase of the harmonic to the fundamental is not specified by the synchrophasor standard, research has shown that test results, especially frequency and frequency error, will differ with different harmonic phases to the IEEE ICAP Test Suite Specification requires that the harmonics be in-phase with the fundamental such that then the fundamental crosses zero in the positive direction, the harmonic is also crossing zero in the positive direction. In terms of symmetrical components, this means that the second harmonic will be negative sequence, the third harmonic will be zero sequence and the forth harmonic will be positive sequence. The cycle repeats with the fifth harmonic and so on. In order to meet the requirement that the test signal be compliant with the standard, harmonic magnitudes and phases are measured and documented.

* + 1. Fluke out-of-band interfering signals uncertainty
    2. Fluke measurement bandwidth uncertainties
       1. Phase modulation
       2. Amplitude modulation
    3. Fluke ramp of system frequency uncertainties

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1. Out of band interference tests are also called “interharmonic” tests. [↑](#footnote-ref-1)
2. Measurement bandwidth tests are also called “modulation” tests. [↑](#footnote-ref-2)
3. IEEE Std 1344 is obsolete and will not be addressed. [↑](#footnote-ref-3)