

Synchrophasor Measurements for Power Systems under the Standard IEC/IEEE 60255-118-1

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Abstract

Phasor Measurement Units (PMU) provide the basic measurement of synchrophasors, frequency and rate of change of frequency (ROCOF). PMUs were first introduced in the 1980s and have proven to be indispensable for power system wide area measurement, protection and control. Standards for measurement promote accuracy and comparability in measurement. The first “IEEE Standard for Synchrophasors for Power Systems” was IEEE 1344-1995 [1]. IEEE C37.118-2005 [2] was much more comprehensive and the basis for synchrophasor standards today. It provided compliance tests using total vector error (TVE) for evaluation, and a communication protocol for transferring the measurements in real-time. The standard was split into two standards in 2011: measurement standard, IEEE C37.118.1 [3], and communication standard, IEEE C37.118.2 [4]. C37.118.1 extended test requirements for dynamic performance and added frequency and ROCOF qualification. Amendment IEEE C37.118.1a-2014 [5] resolved some ambiguities and modified a few requirements to assure that all requirements could reasonably be met.

A new standard, IEC/IEEE 60255-118-1 [6] was prepared by a joint IEC/IEEE working group (WG). The basic provisions and requirements of C37.118.1 have not substantially changed but several small issues have been clarified and test procedures improved. Options have been added for extended accuracy and range certification and extended bandwidth determination. This paper reviews the history of standard development, the differences of this latest standard and test and performance evaluation.

I. Introduction

A phasor measurement unit (PMU) is a device, or function in a multifunction device that produces synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal (Figure 1). The first PMUs were specially built devices, but as the concept evolved, other devices such as DFR’s and relays were built with the required internal time synchronization to enable PMU functions. The standards history tracks the evolution of PMUs.

a. Standards Development History

The first PMUs were built and tested in the late 1980’s. Since synchrophasors were a completely new technology, development could easily go in many different directions resulting in incompatible devices and measurement data. This would slow development and deployment of this very promising technology. To deal with this, Prof. Arun Phadke formed an IEEE working group (WG) in 1992 to create a standard that could guide development to assure different products produced compatible results. This WG completed the first synchrophasor standard IEEE 1344-1995 [1].

Characteristics of the technology and its ramifications were not fully appreciated, so the first standard focused on the timing signal, sampling rates, and a simple byte-oriented communication protocol only

suitable for communication from a PMU to a data collector, usually a computer at a control center. There were no measurement performance requirements.

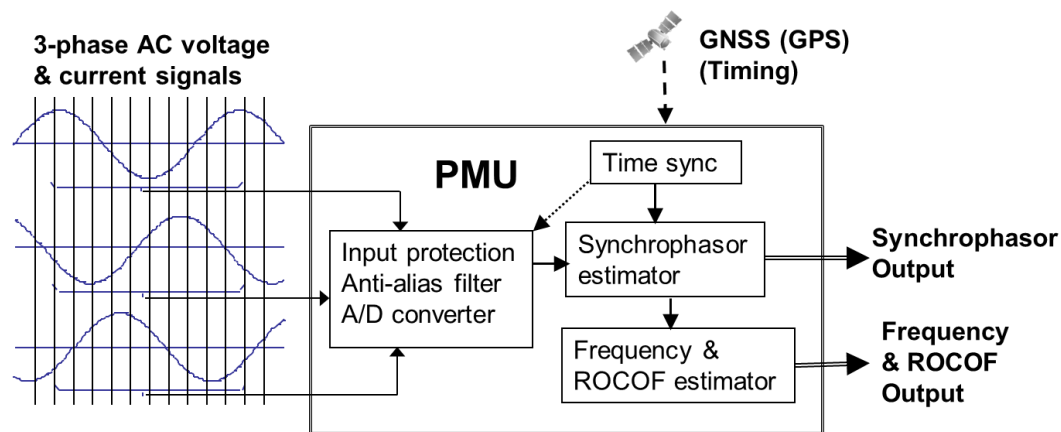


Figure 1. Basic PMU functionality.

Shortcomings of the first standard became apparent: The standard had a timing accuracy requirement but it was not always possible to validate it. Different PMUs could give different measurements from the same voltage or current signal but the standard provided no accuracy requirements. The communication protocol did not provide complete status information. Users realized that the standard needed an update.

In 1999, a WG was established to revise the standard. The communication protocol was thoroughly revised to include a synchronizing byte, measurement status, and multiple PMU reporting capability. The measurement status allowed indicating known data errors such as a synchronization failure or PMU error. The time stamp was referenced to UTC using a second-of-century that is continuous past 2100 (mitigating the year 2000 rollover concern) and included a 24-bit fractional time with a time quality byte. PMU data could be represented in rectangular or polar format, integer or floating point expression.

A criterion called total vector error (TVE) was created to evaluate phasor measurements. This technique compares the measured value with an expected or theoretical value. It combines the phase angle and magnitude errors into one scalar error value, thus simplifying evaluation and specification of a performance limit.

Requirements were specified for evaluating measurement accuracy using TVE to evaluate compliance. These included measurement accuracy over a range of magnitudes, frequencies and phase angles as well as for rejection of interference from harmonics and out-of-band signals. These criteria were specified for 2 levels of compliance, designated “level 0” and “level 1”. This was done to account for differences in the performance of commercial PMUs available at that time: some PMUs had little filtering but faster response, others were more immune to noise but slower to respond. All of these criteria applied to steady-state operation only. There was little consensus in the WG on how to qualify dynamic performance, and the synchrophasor definition in the standard applied only to steady-state. The standard also did not include requirements for frequency or ROCOF accuracy. The standard was published as IEEE C37.118-2005 [2].

This standard was quickly adopted and is still widely used today. However, it did not require accuracy measurement under dynamic operating conditions or frequency and ROCOF measurements. To address the shortcomings, the WG initiated a revision of the standard in 2008 to include dynamic measurement accuracy requirements, provide frequency and ROCOF accuracy requirements and make other improvements and clarifications.

The IEC was also interested in having a synchrophasor standard, but C37.118 could not be adopted because it included both measurement and communication aspects, which the IEC always provides in separate standards. To enable adoption or joint development, IEEE C37.118 was split into two standards for this next stage of development: the measurement portion became IEEE C37.118.1-2011 [3] and the communication portion IEEE C37.118.2-2011 [4].

The measurement part, IEEE C37.118.1-2011, was updated with synchrophasor definition formulas and dynamic performance specifications for phasors, frequency and ROCOF. Compliance levels 0 and 1 were replaced with performance classes M and P. A minimum requirement for data reporting latency (delay) was added. The steady-state performance requirements were clarified and further refined, and testing over a temperature range was added.

After publication, some vendors found that they could not meet all the requirements, particularly ROCOF, with existing technology. Investigation by the WG showed that the additional filtering required to meet the ROCOF definitions would require increasing latency which would harm the performance for phasor and frequency measurement. Rather than relaxing the ROCOF requirements to a rather unusable level, the WG decided to suspend M-class ROCOF performance requirements in the presence of harmonic and out-of-band signal interference, and widen a few other ROCOF requirements. Several other clarifications and adjustments were included in the amendment, IEEE C37.118.1a-2014 [5].

The most current standard, IEC/IEEE 60255-118-1 [6], started with the amended IEEE C37.118.1 standard. It has the same performance requirements, improves the definitions, adds optional extended range and bandwidth testing, and makes a number of clarifications and simplifications. It was published in December 2018 and replaces C37.118.1 and its amendment.

b. Differences between IEC/IEEE 60255-118-1 and the IEEE C37.118 series

In order to minimize the problems that a change in standard would have on industry, the WG minimized the requirement changes from C37.118.1 to 60255-118-1. The 2011 standard and 2014 amendment had not been available very long, and there were no compelling reasons to make changes. The WG focused on simplifications, clarifications, and anticipation of future development. The changes can be summarized as follows:

1. The most significant change was reducing the certification requirement from testing at all reporting rates for a particular system frequency to certification at individual reporting rates. To certify to IEEE C37.118.1 requirements, a PMU must be fully tested at each reporting rate for a given class and nominal system frequency. For example, certification for M class performance in a 60 Hz system requires performing all tests at reporting rates of 10, 12, 15, 30 and 60 frames per second (fps). In the revised standard, a PMU must be tested and certified at for at least one rate, but not for all rates. Since most PMUs are purchased and installed to run at a particular reporting rate, this saves on testing requirements and encourages certification. Vendors may opt to be certified at multiple rates and nominal frequencies that may be available for their customers to use.
2. The next most significant change concerns the definition of the synchrophasor. In IEEE C37.118.1, it was defined in terms of dynamic frequency component. This is mathematically correct, and certainly clarifies many issues. However, the phasor is described in terms of a nominal frequency and changing phase component. Phase changes include frequency changes and phase dynamics. The definitions have been modified to conform more closely to the way phasors are used to represent the power system and in a form more familiar to power engineers. Section II details this difference.
3. Testing over temperature required by IEEE C37.118.1 was removed. This was a very limited requirement and only one of the many environmental tests that utilities typically require. Rather than citing only one environmental requirement, the standard leaves it up to the user to specify the

requirements suitable to their system. Annex F provides guidance on standards and tests that would be appropriate.

4. Normative annexes were added for optional certifications. The standard has been oriented to establish basic requirements so PMUs would provide accurate and trustworthy measurements that are compatible across all (certified) PMU models. This common basis allows users to combine measurements from many (certified) PMUs and use them together for operation and analysis. Because basic testing does not show full performance capability, **Annex G** was added to provide requirements and test procedures to certify PMUs for higher accuracy and wider operating ranges than the basic standard requires. **Annex I** was added to provide procedures for testing the actual PMU measurement bandwidth rather than the limited range required in the basic standard. These annexes are normative but their use is optional and needed only to provide a way to inform a user of extended capability.
5. Annex E discusses using (digital) sample values for synchrophasor estimation. Sample value systems digitize the AC waveforms at the CT/PT device and distribute those values with a timetag in place of routing the AC waveforms. This removes the analog processing and A/D function from the PMU function. The PMU only estimates the phasor value (the algorithm part) which changes the PMU error budget considerably. Since sample value standards are recently developed and there is limited experience in their use, annex E foresees changes for a future revision of the standard.

Other changes help to clarify and simplify requirements. The Frequency and ROCOF error definitions were changed from absolute to signed values to aid understanding the error values and their impact on the system. Limits are placed on the maximum absolute value of the signed error. Testing of dynamic frequency changes (frequency ramp) was clarified. Reporting latency was clarified as to the time from measurement to egress from the PMU, which is the time required in the latency test. The standard test requirements were clarified.

II. Synchrophasor definitions and their application

Synchrophasors were defined in the first two standards as a phasor equivalent of a sinusoidal signal that has a reference phase angle of 0° at the UTC one-second rollover. This definition was adequate for measurement of steady-state signals, but it was not clear this was adequate for power system signals in general which change during the measurement process. While signals that are slowly changing might be adequately measured using a steady-state approximation, it was thought many signals change too fast to address with this approximation. In order to validate PMU measurements under dynamic signal conditions, the synchrophasor standard IEEE C37.118.1 introduced test signals that change in time (dynamically). This requires a synchrophasor definition that supports analysis of dynamic signals.

The traditional phasor is defined in terms of a fixed frequency that is common to all phasors in an analysis. The phase angle and magnitude can vary over time, but they are considered constant at each measurement. Synchrophasors use the nominal frequency as the common, fixed frequency and capture changes over time in the phase angle. C37.118.1 expressed dynamic changes in phase in terms of a dynamically changing frequency and a fixed reference phasor angle. Synchrophasor phase is then the integral of this value. While this is adequate and mathematically correct, a simpler approach is to remove the fixed nominal frequency and analyze all dynamic signal changes as a dynamic phase angle function. This is the approach taken for IEC/IEEE 60255-118-1 [6] and is a better fit with the original steady-state phasor definition.

a. Definitions from IEC/IEEE 60255-118-1 [6]

The standard models the AC voltage and current as a cosine with dynamically changing amplitude and phase, and with an additive signal:

$$x(t) = X_m(t)\cos[\theta(t)] + D(t) \quad (1)$$

where:

- t is time in seconds, where $t = 0$ is coincident with a UTC second rollover
- $X_m(t)$ is the peak magnitude of the sinusoidal AC signal
- $\theta(t)$ is the angular position of the sinusoidal AC signal in radians
- $D(t)$ is an additive disturbance signal that could include harmonics, noise, and DC offset

The standard further expands the phase function as $\theta(t) = 2\pi f_0 t + \phi(t)$, so the phasor is the complex number:

$$\mathbf{X}(t) = \left(\frac{X_m(t)}{\sqrt{2}}, \phi(t) \right) = \frac{X_m(t)}{\sqrt{2}} e^{j\phi(t)} \quad (2)$$

The synchrophasor is shown here both as an ordered pair and also using complex exponential notation. This is the usual definition of phasor except that the amplitude and phase are functions of time. Representing it with time varying parameters allows analytic derivations of the response to non-stationary signals (i.e., signals whose parameters vary with time).

Frequency is defined as the rate of change of phase angle relative to the nominal system frequency, and ROCOF is the derivative of frequency:

$$f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} = f_0 + \frac{1}{2\pi} \frac{d[\phi(t)]}{dt} \quad (3)$$

$$\text{ROCOF}(t) = \frac{df(t)}{dt} = \frac{1}{2\pi} \frac{d^2\phi(t)}{dt^2} \quad (4)$$

b. Comparison of synchrophasor definitions in IEEE C37.118.1 Error! Reference source not found. and IEC/IEEE 60255-118-1 [6]

In IEEE C37.118.1 the synchrophasor is defined:

$$\mathbf{X}(t) = (X_m(t)/\sqrt{2})e^{j(2\pi\int g dt + \phi)} \quad (5)$$

where $g(t) = f(t) - f_0$ is the difference between the nominal frequency f_0 and the actual time varying frequency $f(t)$ and ϕ is a constant value. In this definition the time variations of the cosine phase function are included in $g(t)$ as a variation of frequency. In the new standard IEC/IEEE 60255-118-1 the time variations in phase and frequency are included in the phase function $\phi(t)$. The equivalence of these two approaches can be shown by setting both phase functions equal and solving for $\phi(t)$:

$$2\pi f_0 t + \phi(t) = \theta(t) = 2\pi f_0 t + 2\pi \int g dt + \phi \quad (6)$$

$$\phi(t) = 2\pi \int g dt + \phi \quad (7)$$

Thus the time variation in the phase argument can be represented as a variation in the system frequency or the system phase angle. This latter representation is more like the traditional representation of phasor angles and simplifies derivation of phasor response functions. Further details can be found in [5] which addresses approaches to defining instantaneous frequency.

c. Application of the definitions

The simplest case of applying the synchrophasor definition is where the amplitude and phase angle are constant, and the system frequency is at nominal (steady-state). It can easily be seen that this is the typical phasor, $X_m/\sqrt{2} e^{j\phi}$.

A more interesting case is when the amplitude and nominal phase angle are constant, but the frequency is not nominal (noting that when the frequency is not nominal, the synchrophasor phase angle changes). That is, $f(t) = f_0 + \Delta f$ where Δf is the offset from the nominal frequency. The sinusoidal phase is found by integrating the frequency:

$$\theta(t) = \int_0^t 2\pi f(t) dt = 2\pi f_0 t + 2\pi \Delta f t + \phi_0 \quad (8)$$

where ϕ_0 is the phase at $t = 0$.

Then $\phi(t) = 2\pi f_0 t + 2\pi \Delta f t + \phi_0 - 2\pi f_0 t = 2\pi \Delta f t + \phi_0$, so the synchrophasor is

$$\mathbf{X}(t) = \frac{X_m}{\sqrt{2}} e^{j(2\pi \Delta f t + \phi_0)} \quad (9)$$

In this case the synchrophasor rotates at a constant rate of Δf Hz/s, which is the difference between the actual and nominal frequency. If the power system frequency is above nominal the phase angle will increase causing the phasor to rotate counter-clockwise. A normal power system commonly has a slowly varying phase angle, since the power system is usually a little off the nominal frequency.

Another example of power system phenomenon that provides a good analysis example is a system oscillation. It can be modeled as a simultaneous phase and amplitude modulations with a 180° offset between them. The power system signal is thus:

$$x(t) = X_m [1 + k_x \cos(2\pi f_m t)] \cos[2\pi f_0 t + k_a \cos(2\pi f_m t - \pi)] \quad (10)$$

where f_m is the modulation frequency in Hz;

k_x and k_a are the amplitude and phase modulation indexes respectively;

This is the same as the modulation test prescribed in the standard for determining the bandwidth. For a system oscillation, in this example we require that $f_m < f_0$, and k_x & $k_a < 1$ to simplify the analysis.

In this example, $X_m(t) = X_m [1 + k_x \cos(2\pi f_m t)]$, $\phi(t) = k_a \cos(2\pi f_m t - \pi)$ and $D(t) = 0$.

The synchrophasor is then:

$$\mathbf{X}(t) = X_m / \sqrt{2} [1 + k_x \cos(2\pi f_m t)] e^{j[k_a \cos(2\pi f_m t - \pi)]} \quad (11)$$

The frequency is the differential of the cosine argument:

$$f(t) = f_0 - k_a \frac{2\pi f_m}{2\pi} \sin(2\pi f_m t - \pi) \quad (12)$$

And ROCOF is the derivative of frequency:

$$\text{ROCOF}(t) = \frac{df(t)}{dt} = -k_a \frac{(2\pi f_m)^2}{2\pi} \cos(2\pi f_m t - \pi) \quad (13)$$

In a system oscillation, the synchrophasor oscillates in magnitude and phase like the power signal. Both frequency and ROCOF also oscillate but with phase shifts and with amplitude increased by the oscillation argument ($2\pi f_m$) due to differentiation.

III. Evaluation of Performance

As with IEEE C37.118.1, this standard evaluates both steady-state and dynamic performances of PMUs by comparing the estimated values with reference values derived from the signal formulas. The comparison is done using total vector error (TVE), frequency error (FE) and rate of change of frequency error (RFE).

a. Total vector error (TVE)

TVE is the difference between a reference phasor and the estimated phasor for the same time of measurement and is normalized to the reference phasor. TVE is defined as:

$$TVE(n) = \frac{|\hat{X}(n) - X(n)|}{|X(n)|} \quad (14)$$

where $\hat{X}(n)$ is the estimated phasor and $X(n)$ is the reference phasor both at report time n . The relationship between the estimated phasor, the reference phasor and TVE is illustrated in Fig. 2.

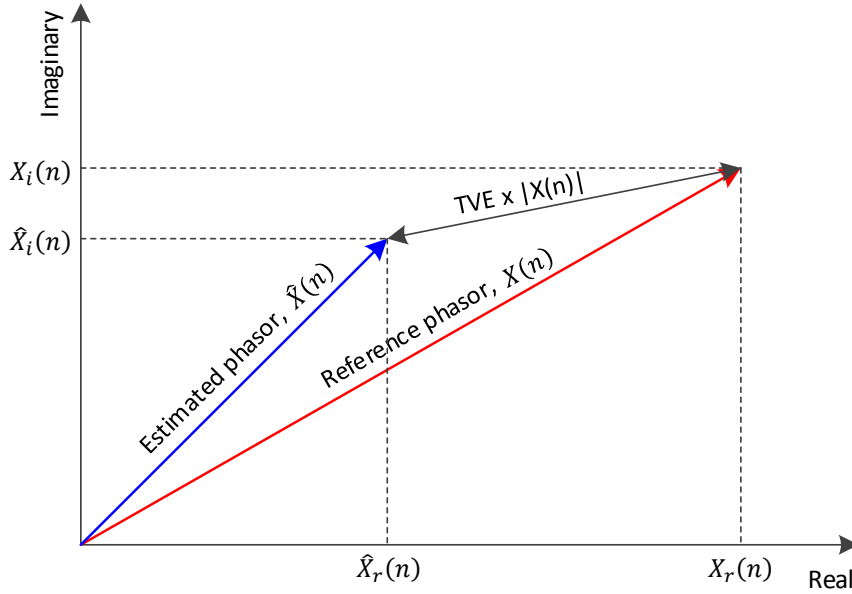


Fig. 2 Total vector is the magnitude of the error vector

In Fig. 2, $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the real and imaginary values of the estimated phasor while $X_r(n)$ and $X_i(n)$ are the real and imaginary values of the reference phasor, both at report time n . Thus:

$$\hat{X}(n) = \hat{X}_r(n) + j\hat{X}_i(n) \quad (15)$$

$$X(n) = X_r(n) + jX_i(n) \quad (16)$$

The TVE is usually defined as:

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{(X_r(n))^2 + (X_i(n))^2}} \quad (17)$$

b. Phase and magnitude errors in relation to TVE

Another perhaps more traditional way of expressing phasor measurement errors would be considering the magnitude and phase angle errors separately. These values can be determined individually from the phasor quantities using the following equations:

$$ME(n) = \frac{\sqrt{\hat{X}_r(n)^2 + \hat{X}_i(n)^2} - \sqrt{X_r(n)^2 + X_i(n)^2}}{\sqrt{X_r(n)^2 + X_i(n)^2}} \quad (18)$$

$$PE(n) = \tan^{-1}(\hat{X}_r(n), \hat{X}_i(n)) - \tan^{-1}(X_r(n), X_i(n)) \quad (19)$$

where $ME(n)$ is the magnitude error (in pu) at report time n and $PE(n)$ is the phase error (in deg or rad) at report time n and $\hat{X}_r(n)$, $\hat{X}_i(n)$, $X_r(n)$ and $X_i(n)$ areas described previously. Since the TVE combines magnitude and phase angle errors, TVE can also be directly determined from those error values using PE in rad with the equation,

$$TVE(n) = \sqrt{2(1 + ME(n))(1 - \cos(PE(n))) + ME(n)^2} \quad (20)$$

Synchrophasor standards define a 1% TVE criterion for most performance tests. The maximum allowable magnitude error is 1% when phase angle error is zero and the maximum allowable phase angle error is 0.573° when the magnitude error is zero. Under the measurement bandwidth test, maximum magnitude and phase angle errors are increased to 3% and 1.719° respectively as the TVE criterion is relaxed to 3%.

c. Timing errors

Timing errors create phase angle errors as can be seen from the basic equations (1) & (2). Other factors including analog (front-end) phase shifts, and the signal sampling and algorithm can also impact the phase angle accuracy. Therefore, the standard does not specify timing accuracy separately, leaving it as a part of the overall phase angle evaluation. Also note the effect of timing error varies with the power system frequency. For example, a $100 \mu\text{s}$ timing error creates a 2.16° phase angle error at 60 Hz and a 1.8° phase angle error at 50 Hz. Conversely a 1° phase angle error at 50 Hz is $55.6 \mu\text{s}$ and $46.3 \mu\text{s}$ at 60 Hz. For 1% TVE criterion, the maximum allowable timing error at 50 Hz is $\pm 31.833 \mu\text{s}$ and $\pm 26.527 \mu\text{s}$ at 60 Hz when the magnitude error is zero and all of the phase error is due to timing.

d. Frequency error (FE) and Rate of change of frequency error (RFE)

FE is the difference between the estimated frequency, $\hat{f}(n)$ at report time n and the reference frequency, $f_{ref}(n)$ at report time.

$$FE(n) = \hat{f}(n) - f_{ref}(n) \quad (21)$$

RFE is the difference between the estimated ROCOF, $d\hat{f}/dt(n)$ at report time n and the reference ROCOF, $df_{ref}/dt(n)$ at report time n .

$$RFE(n) = \frac{d\hat{f}}{dt}(n) - \frac{df_{ref}}{dt}(n) \quad (22)$$

In the previous standard, IEEE C37.118.1, FE and RFE were defined as the absolute value of differences. In this standard, they are defined as signed values. This was changed because the signed values provide some insight into the nature and cause of the error itself. For example, a constant negative FE in a

positive system frequency ramp test indicates that the frequency measurement is delayed relative to the time stamp; the time difference can be calculated from the value of the error.

IV. Performance Tests

IEC/IEEE 60255-118-1 sets forth performance evaluation criteria for PMU compliance to the standard. These criteria include testing conditions, evaluation methods, and performance limits. The test signals are designed to evaluate PMU performance characteristics and are specified for each test. There has not been any significant change to the PMU performance limits since the 2014 amendment to the 2011 PMU standard. This new standard however has improved explanations of the test signal requirements and eliminates some ambiguities in the earlier version. In this paper, we give an overview of the requirements as well as some of the considerations for creating them.

a. Overview

Performance tests can be considered in three main categories: steady-state tests, dynamic tests, and reporting latency tests.

- Steady-state tests check measurement accuracy across ranges of magnitude, phase angle and frequency that are expected to occur under normal operating conditions. Immunity to harmonics and out-of-band interfering signals which may cause measurement errors is also checked in steady-state testing.
- Dynamic tests check the measurement system performance while input signals are changing in magnitude or frequency.
- Reporting latency tests examine how long the PMU takes to compute and transmit a phasor value. This parameter is particularly important to real-time applications, like control functions.

Performance evaluation is broken into categories of reporting rate and performance class, both of which shape performance characteristics. Reporting rate is the rate at which measurements are sent from the PMU. The measurement bandwidth is limited to $\frac{1}{2}$ of this rate (Nyquist frequency) due to sampling effects. Performance class also affects bandwidth by requiring filtering to reduce aliasing. Measurement bandwidth affects some of the performance evaluation tests, so these factors that affect bandwidth are included in the requirements.

The performance classes described in C37.118.1 are carried into this standard. P class is intended for lower latency applications, such as high-speed controls. This class requires the fastest processing speed. Consequently, the measurements may have less filtering, and so are more subject to interference and noise. M class is less susceptible to noise and out-of-band interference in applications where errors could be problematic but more latency can be tolerated. M class measurements can have more processing for noise reduction, frequency compensation, and interfering signal reduction.

b. Steady-state performance

Steady-state performance tests cover the range of amplitude and frequency over which the PMU is expected to operate reliably. Voltage in a power system tends to be more consistently near nominal than current, so voltage is only tested up to 120% of nominal while current is tested 10% to 200% of nominal. Signal frequency range is tested to ± 2 Hz for P class and to ± 5 Hz for M class. If a particular utility experiences wider amplitude or frequency ranges in their system, they are encouraged to have their PMUs tested under these extended conditions in accordance with the annexes. The standard requires a maximum 1% TVE for all tests.

Frequency and ROCOF are also evaluated under these same test requirements. Under steady-state conditions, the frequency error limit is 0.005 Hz and ROCOF error is 0.4 Hz/s (P class) and 0.1 Hz/s (M class).

Steady-state tests also include rejection of interference from harmonics and interfering signals. PMUs are tested with the injection of harmonics from the 2nd to the 50th. The harmonics are tested one at a time as the PMUs are expected to be linear and not produce signal mixing. Some investigation has been done using multiple harmonics at the same time, but this has not been found to produce a significant difference [8]. The compliance requirement is again 1% TVE.

Out-of-band (OOB) interfering signals can be any type of signal that is outside of the measured signal passband. The power signal contains the fundamental signal (near 50 or 60 Hz), but may also contain other components due to oscillations and disturbances. If the frequencies of these signals are within the passband of the PMU, they should be included in the measurement. Signals whose frequency is outside the PMU passband need to be removed by the PMU to prevent measurement error. The OOB test introduces interfering signals outside of the measurement passband but below the 2nd harmonic to assess their effects. OOB testing is not applied to P class, and has a TVE limit of 1.3% for M class.

Frequency and ROCOF estimates are the first and second derivatives of phase and tend to be highly susceptible to error from out-of-band interference. Consequently, frequency requirements are suspended for P class OOB tests. ROCOF requirements are suspended for M class harmonic testing both classes during OOB testing.

c. Dynamic performance

PMU measurement performance under dynamically-changing conditions is evaluated with modulation, frequency ramp, and step change tests. Each of these tests evaluates a specific characteristic of the measurement capability and mimics a situation that can be found in the power system.

In the modulation test, either the amplitude or the phase angle of the fundamental AC signal is modulated with a low amplitude sinusoidal wave. The frequency of the modulation is increased in small steps starting at 0.1 Hz to a maximum test frequency and the phasor response is observed at each step. The measurement bandwidth is the point at which the response drops off by 3 dB as the frequency is increased. In this test, we are only concerned that the bandwidth is adequate to carry the response of the most common signals, so the maximum test frequency is $F_s/10$ or 2 Hz for P class and $F_s/5$ or 5 Hz for M class, where F_s is the reporting rate.

The test objective is to evaluate the drop in the modulated signal response, but the measurement is the TVE of the fundamental signal. The modulated signal is approximately 10% of the fundamental signal, so a 3 dB (~30%) drop in the modulated value is equivalent to a 3% drop in the fundamental signal. Hence for this test, the response limit is 3% TVE. Frequency and ROCOF are also evaluated and have appropriately graduated performance limits. Little noise is generated in this test, so frequency measurements should be relatively accurate, but delay between the timestamp and the time of the frequency or ROCOF measurement becomes evident with increasing modulation frequency.

When the power system has an oscillation, it generates a swing between generators and other elements which effectively modulates the AC signal. Most oscillations currently observed are at frequencies <5 Hz, but higher frequencies are now being experienced, particularly due to the many inverters and other solid-state controls now being installed with renewables. Since PMUs may be expected to give good measurements of these higher-frequency oscillations, the option to certify wider bandwidths has been included in the new standard.

The frequency ramp test changes the frequency of the AC signal over a limited range above and below the nominal frequency. The results of the test enable determination of how well the measurement results track the signal change in both accuracy and time of measurement. The test changes frequency at a constant rate of 1 Hz/s. The ramp range is the same as the steady-state frequency tests, which are ± 2 Hz for P class and ± 5 Hz for M class. The ramp starts at the limit below nominal and ramps up to the limit above nominal for the positive ramp, and the reverse for the negative ramp. Since the transition from a constant frequency to a ramped frequency is a very non-linear change (a step in ROCOF), there is an exclusion period at each ramp transition end point specified in the test since this test is not intended to evaluate the PMU's step response. The TVE limit for ramp tests is 1%. The FE limit is 0.01 Hz and the RFE limits are 0.2 and 0.4 Hz/s for P and M classes respectively.

In the power system, whenever there is a generator or load loss, there will be a ramp in frequency until control systems restore the power balance. This test mimics the effect of generator/load loss. The test rate of 1 Hz/s was selected to represent a rate of change of frequency that is in the order of but faster than a large power system would experience. Very small systems and future systems with very little inertia could ramp faster, but these will have to be addressed as the case arises.

The last of the three dynamic tests is the step test. Step changes occur naturally during faults on the power system and during switching activity. These tests are done to assure that the PMU will make a quick recovery from such a change even if it cannot provide a highly accurate measurement during the event. In many cases, such as during a fault, the signal is highly distorted, and could not reasonably be represented as a phasor. The standard is based on the reasonable principle that the most important aspect is regaining the ability to make a usable measurement as quickly as possible. The evaluation requirements also include accurate representation of the time of the step change (delay measurement) and limited extraneous effects (over/undershoot). These help the user to determine the time of the event and the extent of the system reaction.

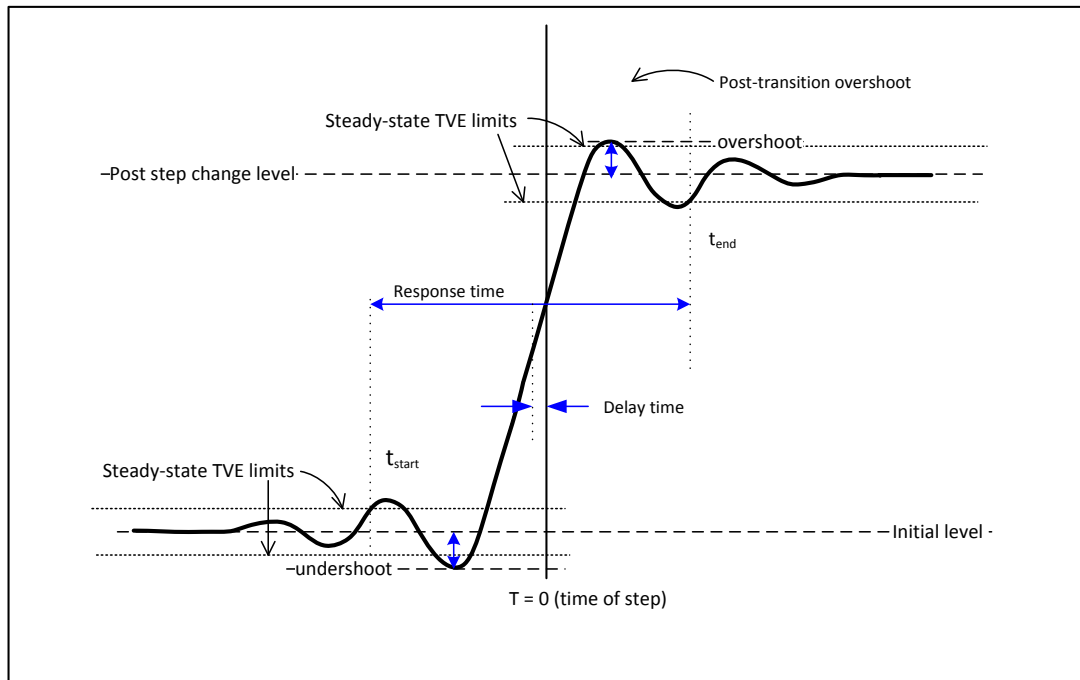


Figure 3. Step change in magnitude or phase angle, showing parameters that are evaluated.

The test introduces a step change in amplitude or phase. The purpose of this test is to help determine how quickly the PMU responds to the sudden change, whether the timing is correctly implemented, and if there are spurious reactions like excessive overshoot or undershoot (Figure 3). When there is a sudden change in the sinusoidal input signal during the observation period, as in the step test, the signal no longer matches the PMU signal model and the estimate can contain significant error. Consequently phasor values *during* the step are not evaluated.

Response time is defined as the time from when the measurement leaves steady-state limits (1% TVE) to when it returns to and remains within those limits. All requirements are specified as the response expressed in cycles of the system frequency or reporting periods (the inverse of reporting rate). For P class, phasor measurements must respond within 2 cycles, frequency measurement within 4.5 cycles and ROCOF within 6 cycles. For M class, phasors are allowed the larger of 7 cycles or reporting periods and for both frequency and ROCOF the greater of 14 cycles or reporting periods.

Delay time is the delay in measurement transition between steps. Due to processing techniques, it can be positive or negative. To assure the timing is correctly applied, all phasors are only allowed $\frac{1}{4}$ of a reporting interval delay time.

P class is allowed over/undershoot of 5% of the step size, and M class is allowed 10% of the step size.

All requirements for step changes in phase and amplitude are the same.

d. Latency

Latency is defined in the standard as the time difference between the data time and the time when the data leaves the PMU. The data time is indicated by the time stamp in the data and is the time of the measurement; i.e., corresponding to the electrical signal applied to the PMU's inputs. The maximum latency allowed is the greater of 2 (P class) or 7 (M class) reporting periods or system frequency cycles. The transmissions must be observed for a period of time to be sure the maximum latency time is observed, since testing has shown latency to vary, apparently due to internal PMU processing and communications interactions.

V. Extended performance options

a. Higher precision measurements

IEC/IEEE 60255-118-1 is not based on application requirements, but rather represents a level of performance that the WG thought should be achieved in order to meet a variety of applications. The WG believes that some applications will require enhanced performance – better accuracy and/or wider dynamic range for instance. Many of these requirements were addressed for the first time in IEC/IEEE 60255-118-1 - Annex G [6]. These include:

- Specification of amplitude and phase accuracy separately, in addition to TVE
- Specification of measurement accuracy higher than 1 % TVE
- Specification of accuracy over different ranges of input signal magnitude, particularly including short-term currents that exceed the continuous thermal rating of the PMU
- Specification of improved frequency measurement accuracy

The standard now allows a vendor to state this improved performance in a standardized way. Conformity to this annex is optional.

b. Full bandwidth determination

Annex I further provides that a manufacturer may state a wider modulation bandwidth than required by the base requirements of the standard. The requirement is still 3% TVE (approximately 3 dB filter bandwidth) and is the lower of the AM and PM bandwidths. Conformity to this annex is optional.

VI. Future developments

a. Synchrophasors from sampled values

Electronic transducers and merging units (MU) provide time-tagged digital samples of power system voltage and current for measurement and control applications. This new point-on-wave data source can be used by a PMU function to compute synchrophasor values, from sampled values. Annex E explores performance requirement changes required for qualification of PMUs that compute phasors estimated from sampled values.

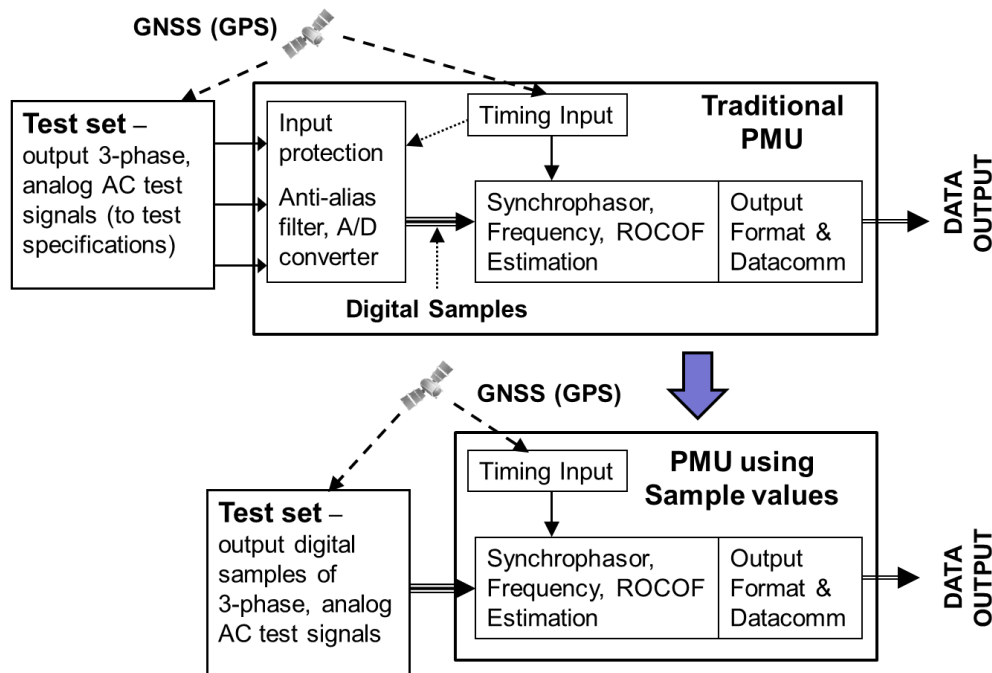


Figure 4. Testing a PMU with digital sample values generated directly from the test signal formulas removes the errors added by the input conditioning required by a traditional PMU with analog inputs.

In the past, the analog voltage and current signals were input to the PMU which included signal conditioning and analog-to-digital (A/D) conversion as well as the phasor computation algorithms. With sample value systems, the signal conditioning and A/D are moved to the MU and the PMU only has the phasor estimation algorithms. For testing, the signal input to the PMU will be digital, so the PMU estimate will not be degraded by signal conditioning and A/D errors. Consequently this type of PMU does not need an allowance for errors from these functions. Some measurements, specifically frequency and ROCOF, are primarily affected by noise and A/D linearity which would be generated in the MU. Steady-state TVE are also affected by MU errors in gain scaling, time delays and filter delay and well as the phasor algorithms. Out-of-band rejection, bandwidth requirements and step response are mostly affected by PMU signal processing. Annex E discusses the error contributions and suggests an allocation of the errors between the MU and PMU function. The standard is for the PMU function and requires applying

test signals to the input and evaluating the PMU output. In effect this removes the MU function and its errors from the test (Figure 4). The suggested error limits only allow for the PMU algorithm error and consequently are tighter than in the current standard in some cases. The annex also recommends vendors state MU performance needed to meet acceptable limits.

Annex E is informative, because the state of the art for estimating synchrophasors from sampled values is still in its infancy. With experience, further clarification of the requirements is anticipated.

b. Future improvements

The WG hopes that more information from applications in the field will allow this standard to evolve. With increasing penetration of renewable and other energy sources, reduction in inertia and higher frequency dynamics are expected to shift PMU requirements towards wider bandwidth and higher dynamic accuracy. Interest in the use of PMUs in distribution systems may require significantly greater immunity to interfering signals, and possibly greater phase accuracy.

VII. Summary

Synchrophasor standards were first issued a few years after the concept of synchrophasor measurement was developed. The standards have evolved over more than twenty years as the measurement technology was further developed and applied. The standards have followed development to codify technological advances to provide measurement consistency and pushed industry to improve the measurements. The standards have been crafted to assure a level of compatibility in measurement yet not be so prescriptive that they impede development.

This latest measurement standard, IEC/IEEE 60255-118-1, includes the most recent performance requirements from the IEEE standards and improves the clarity of the definitions and procedures. It adds additional certification options for extended measurement capability and higher accuracy. It proposes limits on synchrophasor measurement from sample value systems. It is a standard jointly developed and published by the IEC and the IEEE, which are the most widely recognized standards organizations for power system measurement and control technology.

VIII. References

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- [7] B. Boashash, "Estimating and Interpreting The Instantaneous Frequency of a Signal – Part 1: Fundamentals," Proceedings of the IEEE, Vol. 80, No. 4, pp. 520-538, April 1992
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