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Measuring relays and protection equipment – Part 118-1: Synchrophasor for power systems – Measurements

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue
New York, NY 10016-5997
United States of America
stds.ipr@ieee.org
www.ieee.org

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MEASURING RELAYS AND PROTECTION EQUIPMENT –

Part 118-1: Synchrophasor for power systems – Measurements

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INTRODUCTION

This document provides continuation and further development of previous synchrophasor standards, notably the IEEE C37.118 series. It defines synchrophasor, frequency, and rate of change of frequency (ROCOF) measurements as used in this technology. These definitions are in agreement with most research on and analysis of dynamic electric power system measurements, but may differ from those given in other contexts. Function and performance requirements are given for synchrophasor measurements. Tests, evaluation criteria, and error limits are provided to determine compliance with the requirements.

Informative Annexes A, B, C, F, and H provide details about timing aspects, definition application and derivations, PMU measurements, generator power angle, and environmental tests. Informative Annex D details the M and P class reference models used to ensure the requirements can be met; these models are for limit qualification only, as it is expected that most real implementations will perform better than these models. Informative Annex E proposes revised performance requirements for synchrophasors produced from sampled values. These may be used as a basis for normative requirements in a future standard revision. Normative Annexes G and I provide optional qualification of extended steady-state accuracy and measurement bandwidth determination.

A phasor measurement unit (PMU) estimates the parameters magnitude, phase angle, frequency, and rate of change of frequency from the signals appearing at its input terminals or interface. Input signals may be corrupted by harmonics, noise, and changes in state caused by load changes and control and protective actions which complicate parameter estimation. Some examples are harmonics introduced by non-linear loads, step changes in phase introduced by switched reactive elements, and random noise from arc furnaces. These artefacts complicate the process of measuring the generation and load characteristics at or near the system fundamental frequency. The intent of this document is to describe and quantify the performance of a PMU so that it provides a reliable and accurate measurement under real power system conditions.

Synchrophasors are estimated from samples of the voltage and current AC waveforms. Since these signals are alternating current, the estimate uses an interval or "window" over which the samples are taken and used to make the estimate. There could be changes in the waveform parameters during the estimation interval, so the estimate will represent some kind of "average" value for the sinusoid over that window. The length and weighting of the window directly impacts the estimate. A longer window reduces interference but averages out more dynamic changes. In conditions of rapid dynamic changes, such as during a fault, the phasor values can be very inaccurate. The user needs to evaluate their applications and employ appropriate filtering if such conditions could cause a problem.

Frequency and ROCOF are defined as the first and second derivatives of phase angle. They are often computed using finite differencing of the measured angle. Any interference in the angle adversely affects these measurements. Consequently, these measurements are less precise and can produce misleading values. This document presents a set of PMU performance requirements to ensure that compliant instruments will perform similarly when presented with this suite of test signals. The user should be aware that, in the presence of real system interference, higher measurement errors could result. These errors may be substantial, particularly where higher order derivatives (such as ROCOF) are used. Signal processing alternatives may be employed to reduce or eliminate these errors, though they are difficult to implement in a real-time environment. Alternatives are neither described nor evaluated in this document.

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Specific environmental requirements are out of scope for this document, which specifies functional requirements. Testing required by this document will be performed under standard laboratory conditions which do not include environmental conditions that may be specified for some deployments. Devices implementing the functions described in this document may also follow environmental standards such as IEEE Std 1613™ and IEC 60255-1. Vendors are encouraged to provide information regarding the effect of environmental influences on device performance, perhaps including the pass/fail criteria used when determining environmental compliance. Guidance regarding suggested test profiles is included in Annex F.

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MEASURING RELAYS AND PROTECTION EQUIPMENT –

Part 118-1: Synchrophasor for power systems – Measurements

1 Scope

This part of IEC 60255 is for synchronized phasor measurement systems in power systems. It defines a synchronized phasor (synchrophasor), frequency, and rate of change of frequency measurements. It describes time tag and synchronization requirements for measurement of all three of these quantities. It specifies methods for evaluating these measurements and requirements for compliance with the standard under both static and dynamic conditions. It defines a phasor measurement unit (PMU), which can be a stand-alone physical unit or a functional unit within another physical unit. This document does not specify hardware, software or a method for computing phasors, frequency, or rate of change of frequency.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60255-1, *Measuring relays and protection equipment – Part 1: Common requirements*

IEEE Std C37.90™, *IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus*

3 Terms, definitions, and abbreviated terms

For the purpose of this document, the following terms and definitions apply.

ISO, IEC and IEEE maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp
- *IEEE Standards Dictionary Online:* available at http://dictionary.ieee.org

3.1 Terms and definitions

3.1.1
frequency error
FE
difference between the measured frequency and the reference frequency, both at the same time

3.1.2
leap second
positive or negative one-second adjustment to the coordinated universal time (UTC) that keeps it close to mean solar time

3.1.3
measurand
physical or electrical quantity, property, or condition that is to be measured

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3.1.4
Nyquist frequency
frequency that is one-half the sampling frequency of a discrete signal processing system

3.1.5
phasor
complex equivalent of a sinusoidal wave quantity such that the complex modulus is the cosine wave amplitude, and the complex angle (in polar form) is the cosine wave phase angle

3.1.6
phasor data concentrator
data concentrator (DC) used in phasor measurement systems

3.1.7
phasor measurement unit
PMU
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

3.1.8
rate of change of frequency error
RFE
difference between the measured rate-of-change of frequency and the reference rate-of-change of frequency, both at the same time

3.1.9
reference
<of or pertaining to> a time, level, waveform feature, or waveform that is used for comparison with, or evaluation of, other times, levels, waveform features, or waveforms

Note 1 to entry: This type of entity may or may not be an ideal entity.

3.1.10
synchrophasor
synchronized phasor
phasor representing the fundamental of an AC signal whose magnitude is the RMS value of the fundamental amplitude and angle is the difference between the signal fundamental angle and the phase angle of a cosine at the nominal signal frequency that is synchronized to UTC time

3.1.11
total vector error
TVE
normalized value of the difference between the measured synchrophasor and the reference synchrophasor, both at the same time

3.2 Abbreviated terms

BCD	binary coded decimal
f_0	system nominal frequency, either 50 Hz or 60 Hz
ω_0	system nominal frequency ($2\pi f_0$), in radians/s
f_{in}	input frequency of the fundamental; this is the frequency of the measurement input which is normally at or very close to nominal (50 Hz or 60 Hz) but may vary considerably during major disturbances or testing
fps	frames per second; the rate that frames of synchrophasor data are transmitted
F_s	frequency of measurement data reporting, in frames per second (fps) that have the same units as Hz (1/s)

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GNSS	global navigation satellite system
GPS	global positioning system
IRIG-B:	inter-range instrumentation group time code format B
PPS	pulse per second
ROCOF	rate of change of frequency
SCADA	supervisory control and data acquisition
SOC	second of century
THD	total harmonic distortion
THD+N	total harmonic distortion plus noise
UTC	coordinated universal time

4 Synchrophasor measurement

4.1 Input and output quantities

As shown in Figure 1, the input quantities are the time and the power system voltage and current signals. The time signal shall provide UTC time with sufficient accuracy that the PMU can meet the specified performance requirements. The time signal shall meet the input requirements specified by the PMU manufacturer. Annex A reviews common formats.

Voltage and current signals shall be supplied to the PMU as analog quantities over wire or as data packets over communication circuits as specified by the manufacturer. These signals represent the AC power system signals.

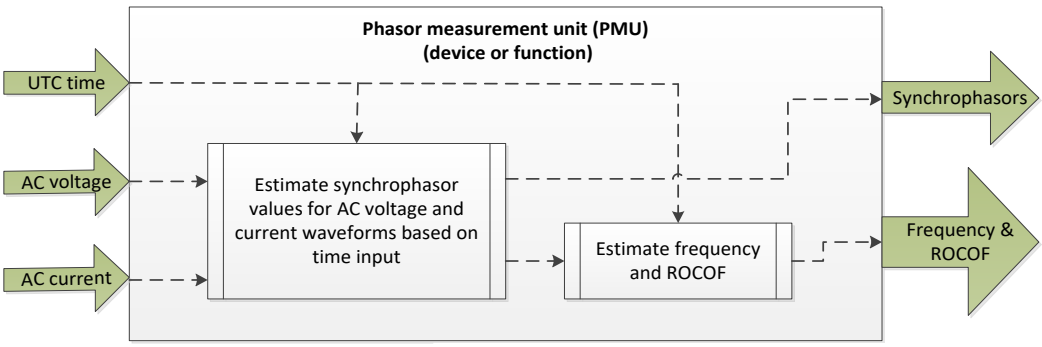

Figure 1 – Input and output quantities

Outputs are the synchrophasor, frequency, and ROCOF estimates made by the PMU. These are normally supplied with a timestamp that is the time of measurement. Additional analog and digital inputs and output may be included by the PMU manufacturer, but are not in the scope of this document so are not considered here.

4.2 Power system signal

The voltage or current in an AC power grid is modelled with the following equation:

$$x(t) = X_{\mathrm{m}}(t)\cos[\theta(t)] + D(t) \tag{1}$$

where

t is time in seconds, where t = 0 is coincident with a UTC second rollover;

X_{m} is the peak magnitude of the sinusoidal AC signal;

θ is the angular position of the sinusoidal AC signal in radians;

D is a disturbance signal that contains additive contributions to the signal, including, but not limited to harmonics, noise, DC offset and out-of-band interference.

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NOTE 1 The disturbance signal, D, does not appear in the measurand definitions because it includes additive interference that is attenuated or rejected by the synchrophasor estimation process.

NOTE 2 X_m, θ, and D are continuous functions of time, as indicated by the (t) notation.

4.3 Measurand definitions

4.3.1 Synchrophasor phase angle

The synchrophasor phase angle $\phi(t)$ is defined as the phase difference between the angular position $\theta(t)$ and phase due to the nominal frequency f_0:

$$\phi(t) = \theta(t) - 2\pi f_0 t \tag{2}$$

NOTE The angular velocity of θ is typically close to angular velocity resulting from the nominal power system frequency, f_0, of 50 Hz or 60 Hz. The synchrophasor is often provided in the form of digital samples, or reports, at a rate substantially lower than the power system nominal frequency (e.g., 10 reports per second for either of a 50 Hz or 60 Hz power system). Sampling theory depends on a sampling rate greater than 120 samples/s to reconstruct a 60 Hz signal without aliasing. Subtracting $2\pi f_0 t$ from θ causes the angular velocity of the synchrophasor phase angle $\phi(t)$ to go to zero as the frequency approaches nominal. This allows synchrophasors to be reported at relatively low rates without aliasing. For example, for an f_0 of 60 Hz, power system signals whose fundamental frequency is between 55 Hz and 65 Hz, exclusive, can be represented by synchrophasors reported at 10 frames/s without aliasing.

4.3.2 Synchrophasor measurand

The synchrophasor measurand is a complex number that can be represented in polar coordinates as:

$$X(t) = \left(\frac{X_m(t)}{\sqrt{2}}, \phi(t)\right) \tag{3}$$

Alternatively, the synchrophasor measurand can be represented in rectangular coordinates as:

$$X(t) = \left(X_r(t), X_i(t)\right) \tag{4}$$

where the real (X_r) and imaginary (X_i) components are:

$$X_r(t) = \frac{X_m(t)}{\sqrt{2}} \cos[\phi(t)] \tag{5}$$

$$X_i(t) = \frac{X_m(t)}{\sqrt{2}} \sin[\phi(t)] \tag{6}$$

NOTE 1 Definition of $X_m(t)$, $\theta(t)$ and $D(t)$ *is* sufficient to define the time domain signal and expected value of all measurands. The discrete time expected measurand can be extracted from continuous time measurand by letting $t = nT$, where n is an integer and T is a measurement reporting period in units of seconds (i.e., the inverse of the reporting rate).

NOTE 2 Examples of the application of the measurand definitions are given in Annex B.

4.4 Frequency measurand definition

The frequency measurand is the angular velocity of the AC power system signal in units of Hz. It relates to the angular position of the fundamental power system signal as shown in Equation (7):

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} = f_0 + \frac{1}{2\pi}\frac{d[\phi(t)]}{dt} \tag{7}$$

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4.5 Rate of change of frequency measurand definition

The ROCOF measurand is the angular acceleration of the AC power system signal in units of Hz/s. It relates to the angular velocity of the power system signal as shown in Equation (8):

$$\text{ROCOF}(t) = \frac{df(t)}{dt} = \frac{1}{2\pi}\frac{d^2\theta(t)}{dt^2} = \frac{1}{2\pi}\frac{d^2\phi(t)}{dt^2} \quad (8)$$

4.6 Measurement time synchronization

The PMU shall be capable of receiving time from a reliable and accurate source, such as a global navigation satellite system (GNSS), that can provide time traceable to UTC with sufficient accuracy to keep the total vector error (TVE), the frequency error (FE), and the rate of change of frequency (ROCOF) error (RFE) within the required limits. All measurements shall be synchronized to UTC time with accuracy sufficient to meet the requirements of this document. A time error of 1 µs corresponds to a synchrophasor phase error of 0,022° for a 60 Hz system and 0,018° for a 50 Hz system. A phase error of 0,57°(0,01 radian) will by itself cause 1 % TVE as defined in Equation (9). This corresponds to a time error of ± 26 µs for a 60 Hz system, and ± 31 µs for a 50 Hz system. A time source that reliably provides time, frequency, and frequency stability at least 10 times better than these values corresponding to 1 % TVE is highly recommended. The time source shall also provide an indication of traceability to UTC and leap second changes.

For each measurement, the PMU shall assign a time tag that includes the time and time quality at the time of measurement. The time tag shall accurately resolve time of measurement to at least 1 µs within a specified 100 year period. The time status shall include time quality that clearly indicates traceability to UTC, time accuracy, and leap second status. Time and time quality for reporting and recording shall be derived from the PMU time tag and converted to the format and content as required.

5 Measurement compliance evaluation

5.1 PMU measurement capability

A PMU shall calculate and be capable of reporting synchrophasor, frequency, and ROCOF estimates as defined and described in Clause 4. The estimates shall include single phase or positive sequence synchrophasors, or both. Provision shall be made for the user selection of the measured values. Measurement evaluation, reporting times, and evaluation criteria are given in Clause 5. A test description and evaluation limits are provided in Clause 6. Measurements are actually estimates of a certain value; the terms "measurement" and "estimate" are used interchangeably in this document.

PMU performance shall be determined by comparing the measured values with the reference values using the TVE, FE, and RFE formulas defined in subclauses 5.2.1 and 5.2.2. Reference values are determined by applying the measurand definitions to the prescribed signals used in these tests.

5.2 Measurement evaluation

5.2.1 Synchrophasor measurement evaluation

The synchrophasor reference values and the values obtained from a PMU may differ in both amplitude and phase. While they could be separately specified, the amplitude and phase differences are considered together in this document in the quantity called total vector error (TVE). TVE expresses the difference between a reference value and the PMU estimate at the same time and is normalized to the measurand reference value.

Total vector error (TVE) is defined as shown in Equation (9):

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$$\text{TVE}(n) = \sqrt{\frac{(\hat{X}_\text{r}(n) - X_\text{r}(n))^2 + (\hat{X}_\text{i}(n) - X_\text{i}(n))^2}{(X_\text{r}(n))^2 + (X_\text{i}(n))^2}} \tag{9}$$

where

$\hat{X}_\text{r}(n)$ and $\hat{X}_\text{i}(n)$	are the real and imaginary PMU estimates at report time n;
$X_\text{r}(n)$ and $X_\text{i}(n)$	are the real and imaginary reference values at report time n;
n	is the report number representing the report time (the nth report in a series of discrete reports).

Synchrophasor measurements shall be evaluated using the TVE criterion of Equation (9).

5.2.2 Frequency and ROCOF measurement evaluation

Frequency and ROCOF measurements shall be evaluated as the difference between the measured values provided by the PMU (measured) and the reference values (ref). These are defined as FE and RFE in Hz and Hz/s respectively:

Frequency measurement error: $\text{FE}(n) = f_\text{measured}(n) - f_\text{ref}(n)$ (10)

ROCOF error: $\text{RFE}(n) = (\text{d}f/\text{d}t)_\text{measured}(n) - (\text{df/dt})_\text{ref}(n)$ (11)

The measured and reference values are for the same time, which are given by the time tag of the measured values and the time of the reference equation solution respectively.

5.2.3 Measurement response time and delay time

Measurement response time is the time to transition between two steady-state measurements before and after a step change is applied to the input. It shall be determined as difference between the time that the measurement leaves a specified accuracy limit and the time it re-enters and stays within that limit when a step change is applied to the PMU input (see Figure C.5). This shall be measured by applying a positive or negative step change in phase or magnitude to the PMU input signal. The input signal shall be held at a steady-state condition before and after the step change. The only input signal change during this test shall be the parameter(s) that have been stepped. Accuracy limits are the TVE, FE, and RFE values for the phasor, frequency and ROCOF measurements, respectively. The limits are specified in 6.6. The response time is determined from the accuracy evaluation of the TVE, FE, or RFE measurements, not the step time or the stepped parameters themselves.

Measurement delay time is defined as the time interval between the instant that a step change is applied to the input of a PMU and measurement time that the stepped parameter achieves a value that is half way between the initial and final steady-state values (see Figure C.5). Both the step time and measurement time are measured on the UTC time scale. This measurement shall be determined by applying a positive or negative step change in phase or magnitude to the PMU input signal. The input signal shall be held at a steady-state condition before and after the step change. The only input signal change during this test shall be the parameter(s) that have been stepped. This measurement requires comparing a step in magnitude with the magnitude measurement and a step in phase angle with the phase angle measurement.

The purpose of evaluating the measurement delay time is to verify that the time tagging of the synchrophasor measurement (measurement time) has been properly compensated for the filtering system group delay. It is expected that the time tag as provided by the PMU has been properly compensated for the filtering system group delay, so that the delay will be near zero.

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A step change is instantaneous by definition; however, if the slewing rate of an applied signal is slow enough to introduce significant uncertainty in the time of application, the time of the midpoint of the step shall be used as the step time. Annex C details a method to help evaluate the response and delay times for a step input.

5.2.4 Overshoot and undershoot

Overshoot and undershoot are aberrations before and after a transition such a step in phase or magnitude. The overshoot and undershoot magnitudes relative to the amplitude of the step are limited. Figure 2a and Figure 2b graphically illustrate the determination of overshoot and undershoot. The text following Figure 2 describes the elements of the illustrations.

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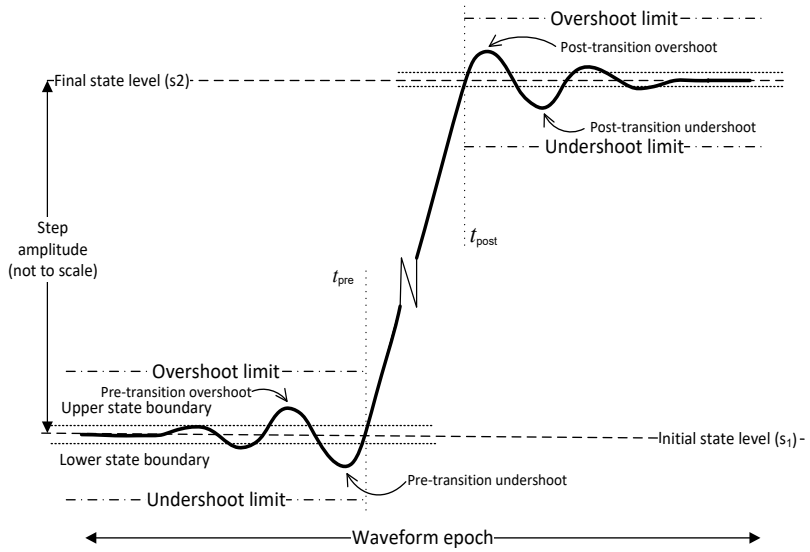
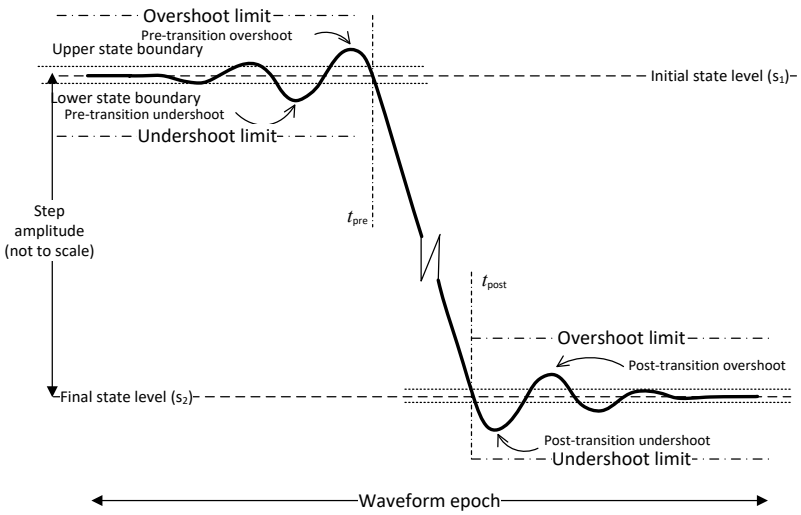


a) Positive step of signal



b) Negative step of signal

Figure 2 – Step transition examples

In order to determine overshoot and undershoot, the PMU output is used to construct waveforms from which the following parameters are defined.

1) Waveform epoch: The duration (interval) of the waveform analyzed, including the period before the transition and the period after the transition. The waveform epoch duration shall be 2 s plus 4 times the response time limit given for the reporting rate being tested.
2) State levels: s_1 and s_2 of Figure 2. The initial state level s_1 is defined as the average value of the waveform values from the first 1 s of data of the waveform epoch. The final state level s_2 is the average value of the last 1 s of data of the waveform epoch.
3) Step amplitude: The difference between state levels s_1 and s_2. The synchrophasor step test specifies the input signal transition (see Table 8).
4) State boundaries: The upper and lower limits of the initial and final states of the waveform. Specified here to be ± 0,5 % of the step amplitude:
   a) for magnitude steps, the state boundaries are the state levels ± 0,5 % of the 10 % step, which is ± 0,05 % of the magnitude;

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b) for phase steps, the state boundaries are the state levels ± 0,05°, which is ± 0,5 % of the 10° phase step.

5) Pre- and post-transition times and periods: t_{pre} and t_{post}:

a) t_{pre} is the time that the waveform last crosses the initial state level's upper state boundary for a positive-going step or lower state boundary for a negative-going step. The pre-transition period is the period of time before t_{pre} not including time t_{pre}.

b) t_{post} is the time that the waveform first crosses the final state level lower boundary for a positive-going step or upper state boundary for a negative-going step. The post-transition period is the period of time after t_{post} including t_{post}.

6) Overshoot: The relative maximum waveform value that is above the upper state boundary reached during the pre- and post-transition periods.

a) Pre-transition overshoot is the difference between the maximum value reached above the pre transition upper state boundary during the pre-transition period and the initial state level s_1.

b) Post-transition overshoot is the difference between the maximum value reached above the post-transition upper state boundary during the post transition period and the final state level s_2.

Overshoot shall be reported in percent of step amplitude. The pre- and/or post-transition overshoot shall not be greater than the overshoot limit.

7) Undershoot: The waveform value that is below the lower state boundary during the pre- and post-transition periods.

a) Pre-transition undershoot is the difference between the minimum value reached below the pre-transition lower state boundary during the pre-transition period and the initial state value s_1.

b) Post-transition undershoot is the difference between the minimum value reached below the pre-transition lower state boundary during the post-transition period and the final state level s_2.

Undershoot shall be reported in percent of step amplitude. The pre- and/or post-transition undershoot shall not be greater than the undershoot limit.

5.2.5 Measurement reporting latency

Latency in measurement reporting is the time delay from when an event occurs on the power system to the time that it is reported in data. This latency includes many factors, such as the window over which data is gathered to make a measurement, the estimation method, measurement filtering, the PMU processing time, and where the event occurs within the reporting interval. The reporting rate and performance class are often the largest factors, since these will determine the measurement window, filtering, and the length of the interval over which an event will be reported.

For the purposes of this document, PMU reporting latency is defined as the maximum time interval between the data report time as indicated by the data time stamp, and the time when the data becomes available at the PMU output (denoted by the first transition of the first bit of the output message at the communication interface point).

5.2.6 Measurement and operational errors

The PMU shall indicate internal problems encountered during the measurement process. This indication shall include errors detectable by the PMU including A/D errors, memory overflow, calculation overflow and any other condition that could cause an error in the measurement.

EXAMPLE: When IEEE C37.118.2 reporting is used, this indication is reported as bit 14, PMU error, in the status word (under this example, all measurement and operational error conditions are combined into a single error indication bit).

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5.3 Measurement reporting

5.3.1 General

Synchrophasor, frequency, and ROCOF estimates shall be made so they can be reported at a constant rate, F_s, which is an integer number of times per second when the rate is greater than one per second, or an integer number of seconds between measurements when the measurement rate is equal to or slower than one per second. All three measurements shall be made and reported for the same reporting time. The reporting times shall be evenly spaced so the intervals between reports are all the same. The PMU may make other measurements synchronously with these specified measurements, such as Boolean status, waveform sampling, or other calculated data.

5.3.2 Reporting rates

The PMU shall support data reporting (by recording or output) at one or more rates that are sub-multiples or multiples of the nominal power-line (system) frequency. Standard reporting rates for 50 Hz and 60 Hz systems are listed in Table 1. The manufacturer shall declare the reporting rates under which the PMU complies with the requirements of this document. At least one reporting rate shall be chosen from Table 1.

Table 1 – Standard PMU reporting rates

System frequency	50 Hz				60 Hz						
Reporting rates (F_s in frames per second (fps))	10	25	50	100	10	12	15	20	30	60	120

Support for other reporting rates is permissible. The actual rate to be used shall be user selectable if multiple rates are supported. Rates lower than 10/s are not subject to the dynamic requirements of this document. This means no filtering is required, so lower rate data (< 10/s) can be provided directly by selecting every n^{th} sample from a higher rate stream.

5.3.3 Reporting times

In this document, a "data frame" or a "frame of data" is a set of synchrophasor, frequency, and ROCOF measurements that corresponds to the same single time stamp. The term "frame" is used to differentiate it from "samples", which are understood as points on an analog waveform.

For a reporting rate N frames per second (fps) where N is a positive integer, the reporting times shall be evenly spaced through each second with frame number 0 (numbered 0 through N-1) coincident with the UTC second rollover (e.g., coincident with a 1 PPS provided by GPS). These reporting times (time tags) shall be used for determining the instantaneous values of the synchrophasor. If rates lower than 1/s are used, there shall be one report on the hour (xx:00:00) and evenly spaced thereafter with an integer number of seconds between reports according to the chosen rate in the absence of leap seconds. If a leap second occurs, the last interval in the hour shall be shorter or longer by that leap second.

5.4 Measurement compliance

5.4.1 Performance classes

Compliance with the requirements shall be evaluated by class of performance. This document defines two classes of performance: P class and M class.

In general, P class has shorter measurement latency time, narrower frequency range, and lower harmonic signal rejection requirements than M class as well as no out-of-band signal rejection requirement. M class allows for longer latencies, allowing more filtering for a wider frequency range requirement and increased harmonic and out-of-band signal rejection requirements.

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P class is intended for applications requiring fast response such as protection applications. As an example, the P-class reference model filter (Annex D) has a step response that is monotonic (free of over and undershoot) and fully settled within one cycle.

M class is intended for applications which could be adversely effected by aliased signals caused by out-of-band interference yet do not require low measurement reporting latency or short step response time. As an example, the M-class reference model filters (Annex D) have step responses with some overshoot and ringing, and significantly more measurement reporting latency than the P class model.

These two class designations do not indicate that either class is adequate or required for a particular application. The user shall choose a performance class that matches the requirements of each application. The user should consider the inherent trade-off between frequency domain and time domain performance.

All compliance requirements are specified by performance class. A PMU shall meet all the requirements as specified for a class, in order to be considered as compliant with this document for that class. If the vendor provides both P and M class performance, these shall be user selectable.

5.4.2 Compliance verification

For compliance with this document, a PMU shall provide synchrophasor, frequency, and ROCOF measurements that meet the requirements listed in Clause 6. The requirements are specified by class of performance and reporting rate. To be compliant, all measurements shall meet all requirements for the given class and reporting rate.

Nominal voltage and current levels shall be selected by the vendor. These levels shall be consistent with recommended levels stated in IEEE Std C37.90 or IEC 60255-1. Reference and test conditions are specified in 6.2. Additional discussion about evaluation and testing is provided in Annex C.

A testing device or system used to verify performance in accordance with this document shall be traceable to national standards, and have a "test uncertainty ratio" of at least ten (10) compared with these test requirements (for example, provide a TVE measurement within 0,1 % where TVE is 1 %).

Documentation shall be provided in accordance with Clause 7.

6 Measurement compliance test and evaluation

6.1 Testing considerations

Clause 6 details the measurement compliance tests and performance limits. For each test, the equations describing the reference test signals are given from which the resulting synchrophasor, frequency, and ROCOF values can be computed. The error limits for each test are provided with breakdown for class and reporting rate. All error limits were found to be achievable using basic computation algorithms and including a margin for PMU error and noise. These algorithms are described in Annex D. They are provided for reference and example only, and do not constitute a recommendation.

The steady-state and measurement bandwidth tests both require determining the measured value at constant amplitude and frequency. An adequate settling time shall be provided after each test signal change to prevent transient effects from affecting the measurement.

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6.2 Reference and test conditions

All compliance tests shall be performed with all parameters set to standard reference conditions, except those being varied as specified for the test. The reference condition specified for each test is the value of the quantity being tested when not being varied. Standard reference conditions for all tests are as follows:

a) voltage at nominal;
b) current at nominal;
c) frequency at nominal;
d) voltage, current, phase, and frequency constant;
e) signal THD+N < 0,2 % of the fundamental (where N = noise);
f) all interfering signals < 0,2 % of the fundamental.

It is assumed that voltage and current signals will be provided as analog quantities. This is generally expected for PMUs available at the time of publication of this document. The use of signals provided as digital samples are discussed in Annex E. Requirements specifically for testing with sampled values may be included in a future revision of this document.

Measurements at reporting rates (F_s) lower than 10/s shall not be subject to dynamic performance requirements. Such measurements shall be subject to all steady-state requirements (Table 2) except out-of-band rejection. This paragraph applies to all performance classes (P and M) that are described in 5.4.1.

Unless otherwise specified, all testing to certify compliance shall be performed at standard laboratory test conditions that include the following:

- temperature 23 ºC ± 3 ºC;
- humidity < 90 %.

Discussion and reference for further environmental test conditions is presented in Annex F.

In subclause 6.3, f_{in} is the frequency of the fundamental signal component. It is normally 50 Hz or 60 Hz, but in the course of testing may be varied from nominal. Also, f_0 always represents the nominal frequency, exactly 50 Hz or 60 Hz. Similarly $\omega_0 = 2\pi f_0$ always represents the nominal frequency in radians/s.

6.3 Steady-state compliance

Steady-state compliance shall be confirmed by comparing the synchrophasor, frequency, and ROCOF estimates obtained under steady-state conditions to the corresponding reference values of X_r, X_i, F, and ROCOF. Steady-state conditions are where amplitude, frequency, and phase angle of the test signal, and all other influence quantities are fixed for the period of the measurement, which shall be no less than 5 s. (For off-nominal frequencies, the synchrophasor angle will change even though the test signal phase angle is constant.) The same tests are used for phasor and frequency/ROCOF measurements. Table 2 and Table 3 specify the conditions and performance requirements for these steady-state tests. Annex G presents requirements for PMU testing and compliance verification at higher accuracy and extended current range.

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Table 2 – Steady-state synchrophasor measurement requirements

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		Performance – P class		Performance – M class	
		Range	Max. TVE %	Range	Max. TVE %
Signal frequency	Frequency = f_0 ($f_{nominal}$)	± 2,0 Hz	1	± 2,0 Hz for F_s < 10 ± F_s/5 for 10 ≤ F_s < 25 ± 5,0 Hz for F_s ≥ 25	1
Voltage signal magnitude	100 % rated	80 % to 120 % rated	1	10 % to 120 % rated	1
Current signal magnitude	100 % rated	10 % to 200 % rated	1	10 % to 200 % rated	1
Harmonic distortion (single harmonic)	< 0,2% (THD)	1 %, each harmonic up to 50th	1	10 %, each harmonic up to 50th	1
Out-of-band interference as described below	< 0,2% of input signal magnitude		None	10 % of input signal magnitude for F_s ≥ 10. No requirement for F_s < 10.	1,3

Out-of-band interference testing:

The input test signal frequency f_{in} is varied between f_0 and ± 10 % of F_s/2 with the maximum variation limited to ± 5 Hz.

These limits are: $f_0 - 0{,}1\ (F_s/2) \le f_{in} \le f_0 + 0{,}1\ (F_s/2)$ for $F_s \le 100$ and $f_0 - 5 \le f_{in} \le f_0 + 5$ for $F_s > 100$

where

F_s is the phasor reporting rate (in Hz);

f_0 is the nominal system frequency (in Hz);

f_{in} is the fundamental frequency of the input test signal (in Hz).

The passband at each reporting rate is defined as $|f - f_0| < F_s/2$. An interfering signal outside the filter passband is a signal at frequency f where: $|f - f_0| \ge F_s/2$

Compliance with out-of-band rejection can be confirmed by using a single frequency sinusoid added to the fundamental power signal at the required magnitude level. The minimum sinusoid frequency range shall be 10 Hz to the second harmonic (2 × f_0), excluding the passband. These frequencies shall include the frequencies f_0 ± F_s/2, 10 Hz, the second harmonic (2 × f_0), and enough frequency points to clearly determine the response. This should include frequencies with exponentially narrower intervals near the passband limit frequencies as follows:

– frequency points below the passband using frequencies $f = f_0 - F_s/2 - (0{,}1\ \text{Hz} \times 2^n)$ for n = 0, 1, 2 … until $f \le 10$ Hz; and

– frequency points above the passband using frequencies $f = f_0 + F_s/2 + (0{,}1\ \text{Hz} \times 2^n)$ for n = 0, 1, 2 … until $f \ge 2 \times f_0$ Hz.

For the special case where $F_s = 2 \times f_0$, all frequencies from 0 to 2 × f_0 are in-band, so OOB testing will be done from the 2nd to 3rd harmonic; that is $2 \times f_0 \le f \le 3 \times f_0$.

The phase angle rotates when the frequency is off nominal, so phase angle accuracy around the circle is covered by phase rotation that occurs during the signal frequency range tests. Phase angle can be related to generator rotor angle, which can also be related to synchrophasor angle as discussed in Annex H.

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