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colour inside

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

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This publication is published as an IEC/IEEE Dual Logo standard.

The text of this document is based on the following documents:

FDIS	Report on voting
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Full information on the voting for the approval of this document can be found in the report on voting indicated in the above table.

International standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

A list of all parts in the 60255 International Standard, published under the general title *Measuring relays and protection equipment*, can be found on the IEC website.

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- withdrawn,
- replaced by a revised edition, or
- amended.

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1 A list of IEEE participants can be found at the following URL: https://standards.ieee.org/standard/60255-118-1-2018.html

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.

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.

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

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)

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.

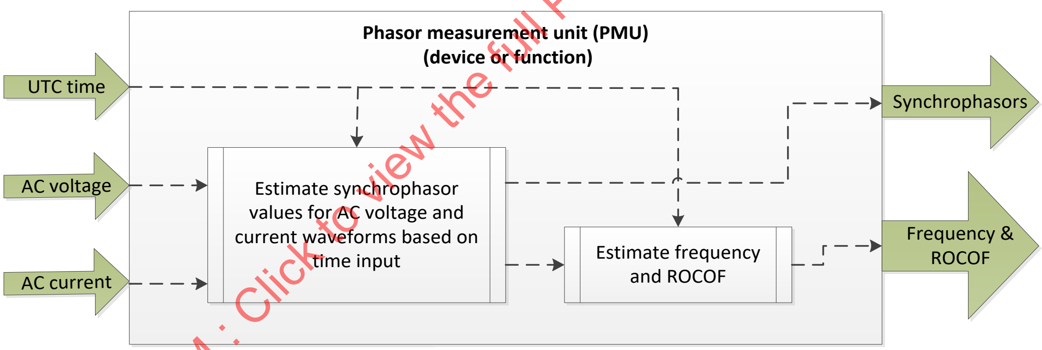


Figure 1 – Input and output quantities

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:

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

where

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

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):

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

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):

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

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):

$$\text{TVE}(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{(X_r(n))^2 + (X_i(n))^2}} \quad (9)$$

where

$\hat{X}_r(n)$ and $\hat{X}_i(n)$	are the real and imaginary PMU estimates at report time n;
$X_r(n)$ and $X_i(n)$	are the real and imaginary reference values at report time n;
n	is the report number representing the report time (the n^{th} 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: $\text{RFE}(n) = (\text{d}f/\text{d}t)_{\text{measured}}(n) - (\text{d}f/\text{d}t)_{\text{ref}}(n)$ (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.

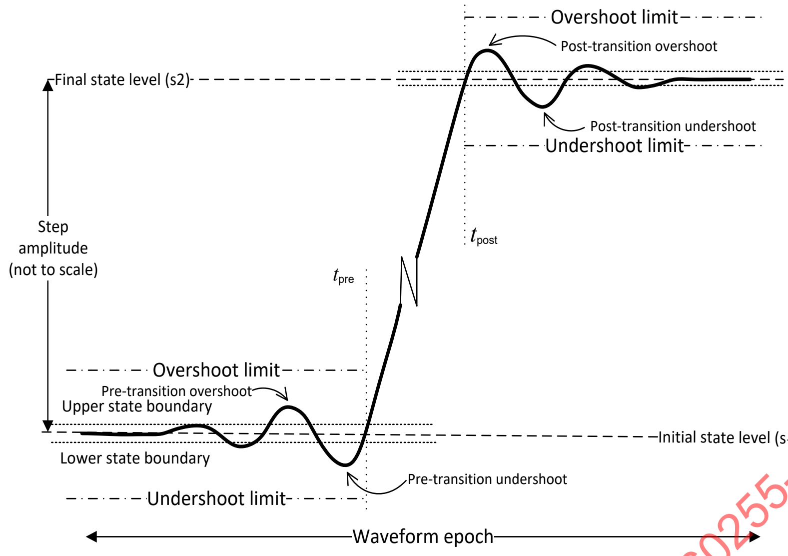
Measurement delay time is defined as the time interval between the instant that a step change is applied to the input of a PMU and measurement time that the stepped parameter achieves a value that is half way between the initial and final steady-state values (see Figure C.5). Both the step time and measurement 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.

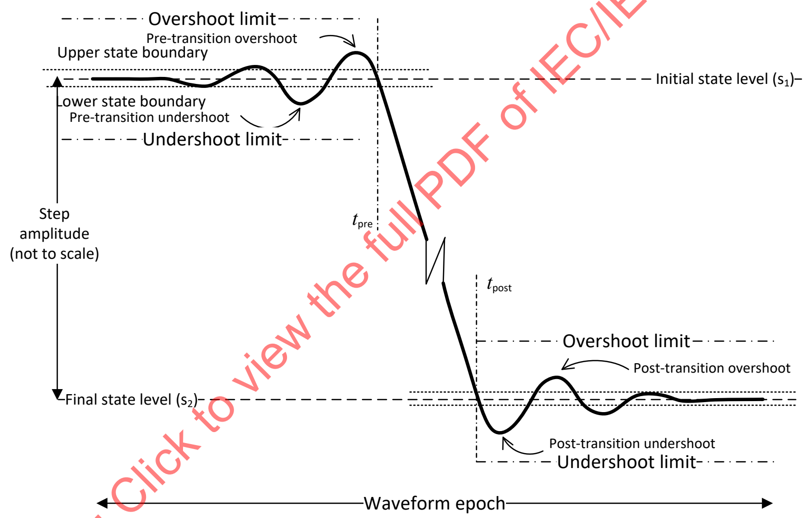
A step change is instantaneous by definition; however, if the slewing rate of an applied signal is slow enough to introduce significant uncertainty in the time of application, the time of the midpoint of the step shall be used as the step time. Annex C details a method to help evaluate the response and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



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;

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).

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.

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.

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 °C ± 3 °C;
- 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.

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 $F_s < 10$ $\pm F_s/5$ for $10 \le F_s < 25$ ± 5,0 Hz for $F_s \ge 25$	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 $F_s \ge 10$. 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 ($2 \times f_0$), excluding the passband. These frequencies shall include the frequencies $f_0 \pm F_s/2$, 10 Hz, the second harmonic ($2 \times f_0$), 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 $2 \times f_0$ 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.

For the signal frequency test and magnitude tests, the input signals shall be represented by Equation (12), Equation (13), and Equation (14):

$$X_a = X_m \cos(2\pi f_{in} t) \qquad (12)$$

$$X_b = X_m \cos(2\pi f_{in} t - 2\pi/3) \qquad (13)$$

$$X_c = X_m \cos(2\pi f_{in} t + 2\pi/3) \qquad (14)$$

where

X_a, X_b, and X_c are the A, B, and C phase signals;

X_m is the amplitude of the input signal;

f_{in} is the input signal frequency in Hz.

For the harmonic distortion test, the input signals shall be represented by Equation (15), Equation (16), and Equation (17):

$$X_a = X_m \cos(2\pi f_0 t) + X_m k_x \cos(2\pi n f_0 t) \qquad (15)$$

$$X_b = X_m \cos(2\pi f_0 t - 2\pi/3) + X_m k_x \cos(2\pi n f_0 t - 2\pi n/3) \qquad (16)$$

$$X_c = X_m \cos(2\pi f_0 t + 2\pi/3) + X_m k_x \cos(2\pi n f_0 t + 2\pi n/3) \qquad (17)$$

where

X_m is the amplitude of the input signal;

f_0 is the nominal power system frequency in Hz;

k_x is the harmonic amplitude factor, and n is the harmonic order.

See Table C.1 for the harmonic phase sequence.

For the out-of-band interference test, the input signals shall be represented by Equation (18), Equation (19), and Equation (20):

$$X_a = X_m \cos(2\pi f_{in} t) + X_m k_x \cos(2\pi f_i t) \qquad (18)$$

$$X_b = X_m \cos(2\pi f_{in} t - 2\pi/3) + X_m k_x \cos(2\pi f_i t - 2\pi/3) \qquad (19)$$

$$X_c = X_m \cos(2\pi f_{in} t + 2\pi/3) + X_m k_x \cos(2\pi f_i t + 2\pi/3) \qquad (20)$$

where

X_m is the amplitude of the input signal;

f_{in} is the power system input frequency in Hz (which may not be at the nominal value of 50 or 60);

k_x is the interference frequency amplitude factor;

f_i is interference frequency in Hz.

For all the steady-state tests, at reporting time tags t = nT (where n is an integer and T is the phasor reporting interval), the PMU shall produce a phasor measurement:

$$X(nT) = (X_m/\sqrt{2})\angle\{2\pi\Delta f\, nT + p2\pi/3\} \quad (21)$$

where

p = 0 for A phase and positive sequence

p = –1 for B phase;

p = 1 for C phase phasors.

Δf is the offset frequency and is: $\Delta f = f_{in} - f_0$.

It shall also produce the corresponding frequency and ROCOF measurements:

$$f(nT) = f_0 + \Delta f \quad (22)$$

$$\Delta f(nT) = \Delta f \quad (23)$$

$$ROCOF(nT) = 0 \quad (24)$$

Table 3 – Steady-state frequency and ROCOF measurement requirements

<table>
<tr><th rowspan="2">Influence quantity</th><th rowspan="2">Reference condition</th><th colspan="4">Error requirements for compliance</th></tr>
<tr><th colspan="2">P class</th><th colspan="2">M class</th></tr>
<tr><td rowspan="3">Signal frequency</td><td rowspan="3">Frequency = f_0 ($f_{nominal}$)
Phase angle constant</td><td colspan="2">Range: f_0 ± 2,0 Hz</td><td colspan="2">Range:
f_0 ± 2,0 Hz for F_s ≤ 10
± F_s/5 for 10 ≤ F_s < 25
± 5,0 Hz for F_s ≥ 25</td></tr>
<tr><td>Max. |FE|</td><td>Max. |RFE|</td><td>Max. |FE|</td><td>Max. |RFE|</td></tr>
<tr><td>0,005 Hz</td><td>0,4 Hz/s</td><td>0,005 Hz</td><td>0,1 Hz/s</td></tr>
<tr><td rowspan="4">Harmonic distortion (same as Table 2)

(single harmonic)</td><td rowspan="2">< 0,2 % THD</td><td colspan="2">1 % each harmonic up to 50th</td><td colspan="2">10 % each harmonic up to 50th</td></tr>
<tr><td>Max. |FE|</td><td>Max. |RFE|</td><td>Max. |FE|</td><td>Max. |RFE|</td></tr>
<tr><td>F_s > 20</td><td>0,005 Hz</td><td>0,4 Hz/s</td><td>0,025 Hz</td><td>No requirements</td></tr>
<tr><td>F_s ≤ 20</td><td>0,005 Hz</td><td>0,4 Hz/s</td><td>0,005 Hz</td><td>No requirements</td></tr>
<tr><td rowspan="3">Out-of-band interference (same as Table 2)</td><td rowspan="3">< 0,2 % of input signal magnitude</td><td colspan="2">No requirements</td><td colspan="2">Interfering signal 10 % of signal magnitude</td></tr>
<tr><td></td><td></td><td>Max. |FE|</td><td>Max. |RFE|</td></tr>
<tr><td>None</td><td>None</td><td>0,01 Hz</td><td>No requirements</td></tr>
</table>

6.4 Dynamic compliance – Measurement bandwidth

The minimum required synchrophasor measurement bandwidth shall be ensured by sweeping the input with sinusoidal amplitude and phase modulation. This shall be done by modulating balanced three-phase input signals (voltages and currents) with sinusoidal signals applied to signal amplitudes and phase angles in accordance with Table 4 and Table 5. Mathematically, the input signals may be represented by Equation (25), Equation (26), and Equation (27):

$$X_a = X_m\,[1+k_x\cos(2\pi f_m t)] \times \cos\,[2\pi f_0 t+k_a\cos(2\pi f_m t-\pi)] \qquad (25)$$

$$X_b = X_m\,[1+k_x\cos(2\pi f_m t)] \times \cos\,[2\pi f_0 t-2\pi/3+k_a\cos(2\pi f_m t-\pi)] \qquad (26)$$

$$X_c = X_m\,[1+k_x\cos(2\pi f_m t)] \times \cos\,[2\pi f_0 t+2\pi/3+k_a\cos(2\pi f_m t-\pi)] \qquad (27)$$

where

- X_m is the amplitude of the input signal;
- f_0 is the nominal power system frequency in Hz;
- f_m is the modulation frequency in Hz;
- k_x is the amplitude modulation factor
- k_a is the phase angle modulation factor.

The positive sequence signal corresponding to the above three phase inputs is given by Equation (28):

$$X_1 = X_m\,[1+k_x\cos(2\pi f_m t)] \times \cos\,[2\pi f_0 t+k_a\cos\,(2\pi f_m t-\pi)] \qquad (28)$$

Since the signal described is balanced, there is no negative (X_2) or zero (X_0) sequence signal.

At reporting time tags t = nT (where n is an integer and T is the phasor reporting interval), the PMU shall produce a phasor measurement of:

$$X(nT) = \{X_m/\sqrt{2}\}[1+k_x\cos(2\pi f_m nT)]\angle\{\,p2\pi/3 + k_a\cos(2\pi f_m nT-\pi)\} \qquad (29)$$

where

- p = 0 for A phase and positive sequence;
- p = −1 for B phase;
- p = 1 for C phase phasors.

The value shall be within the error limits given in Table 4.

Frequency and ROCOF measurement performance shall also be determined during this test. For the input signals defined above and at reporting times t = nT, frequency, frequency deviation, and ROCOF are given respectively by Equation (30), Equation (31), and Equation (32):

$$f(nT) = f_0 - k_a\,(f_m)\,\sin\,(2\pi f_m nT-\pi) \qquad (30)$$

$$\Delta f(nT) = -k_a\,(f_m)\,\sin\,(2\pi f_m nT-\pi) \qquad (31)$$

$$ROCOF(nT) = d/dt[f(nT)] = -\,k_a\,(2\pi f_m^2)\,\cos\,(2\pi f_m nT-\pi) \qquad (32)$$

The modulation tests shall be performed with f_m, k_x and k_a varied over the values specified in Table 4. The modulation frequency shall be varied in steps of 0,2 Hz or smaller over the range specified in Table 4. The TVE, FE, and RFE shall be measured over at least 5 s or two full cycles of modulation, whichever is greater, and the maximum value determined. The maximum is the highest value observed at the given reporting rate over the full test interval. This maximum shall be within the specified limits for P class and M class compliance at the given reporting rate. The tests given here ensure the PMU bandwidth is at least as wide as the specified range. Annex I (normative) presents tests and requirements for determining and reporting the actual PMU measurement bandwidth.

Table 4 – Synchrophasor measurement bandwidth requirements using modulated test signals

Modulation level	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max. TVE	Range	Max. TVE
k_x = 0,1, k_a = 0	100 % rated signal magnitude, $f_{nominal}$	Modulation frequency 0,1 to lesser of F_s/10 or 2 Hz	3 %	Modulation frequency 0,1 to lesser of F_s/5 or 5 Hz	3 %
k_x = 0, k_a = 0,1	100 % rated signal magnitude, $f_{nominal}$		3 %		3 %

Table 5 – Frequency and ROCOF performance requirements under modulation tests

Frequency and ROCOF performance limits	Error requirements for compliance					
	P class			M class		
Reporting rate F_s Hz	F_r Hz	Max. |FE| Hz	Max. |RFE| Hz/s	F_r Hz	Max. |FE| Hz	Max. |RFE| Hz/s
10	1	0,03	0,6	2	0,12	2,3
12	1,2	0,04	0,8	2,4	0,14	3,3
15	1,5	0,05	1,3	3	0,18	5,1
20	2	0,06	2,3	4	0,24	9,0
25	2	0,06	2,3	5	0,30	14
30	2	0,06	2,3	5	0,30	14
50	2	0,06	2,3	5	0,30	14
60	2	0,06	2,3	5	0,30	14
100	2	0,06	2,3	5	0,30	14
120	2	0,06	2,3	5	0,30	14
Formulas	min(F_s/10;2)	0,03 × F_r	0,18 × π × F_r^2	min(F_s/5;5)	0,06 × F_r	0,18 × π × F_r^2

NOTE 1 Maximum frequency (F_r) in the modulation test range is determined by the reporting rate (F_s) and capped to 2 Hz or 5 Hz for the P and M class respectively as shown under "Range" in Table 4.

NOTE 2 The formulas for the maximum allowable error are based on the peak value that the frequency or ROCOF measurement will achieve over the modulation frequency range. This value is 0,1 × F_r for frequency and 0,1 × 2π × F_r^2 for ROCOF, where 0,1 is the index of modulation. For test compliance, use the rounded values shown in the table, not the formulas.

NOTE 3 The error limits are a percent of these maximum values: the FE limit is 30 % for P class and 60 % for M class; the RFE limits are both 90 %.

Frequency and ROCOF follow the modulated signal and measure the combined effects of the fundamental signal and the modulation. The errors in both measurements are a small fraction of the measured values, but since ROCOF (the second derivative of phase) becomes a large value, the expected error is also large. As shown by the given formulas, the magnitude of frequency deviation increases linearly with modulation frequency and ROCOF increases by frequency squared.

6.5 Dynamic compliance – Performance during ramp of system frequency

Measurement performance during system frequency change shall be tested with linear ramp of the system frequency applied as balanced three phase input signals (voltages and currents). Mathematically, the input signals may be represented by Equation (33), Equation (34), and Equation (35):

$$X_a = X_m \cos\,[2\pi f_0 t + \pi R_f t^2] \tag{33}$$

$$X_b = X_m \cos\,[2\pi f_0 t - 2\pi/3 + \pi R_f t^2] \tag{34}$$

$$X_c = X_m \cos\,[2\pi f_0 t + 2\pi/3 + \pi R_f t^2] \tag{35}$$

where

X_m is the amplitude of the input signal;

f_0 is the nominal power system frequency in Hz;

R_f (= df/dt) is the frequency ramp rate in Hz/s (a constant value in this test).

The positive sequence signal corresponding to the above three phase inputs is given by Equation (36):

$$X_1 = X_m \cos\,[2\pi f_0 t + \pi R_f t^2] \tag{36}$$

This signal is balanced, so there is no negative or zero sequence signal.

At reporting time tags t = nT (where n is an integer and T is the phasor reporting interval), the PMU shall produce the phasor measurement:

$$X(nT) = \{X_m/\sqrt{2}\}\angle\{\, p2\pi/3 + \pi R_f\,(nT)^2\} \tag{37}$$

where

p = 0 for A phase and positive sequence;

p = –1 for B phase;

p = 1 for C phase phasors.

During ramp tests, the reference values of frequency, frequency deviation, and ROCOF for the specified test signals at reporting time tags t = nT are given respectively by Equation (38), Equation (39), and Equation (40):

$$f(nT) = f_0 + (R_f)(nT) \tag{38}$$

$$\Delta f(\mathrm{nT}) = (R_\mathrm{f})(\mathrm{nT}) \quad (39)$$

$$\mathrm{d/dt}[f(\mathrm{nT})] = R_\mathrm{f} \quad (40)$$

The ramp test frequency range, ramp rate, measurement exclusion interval, and measurement error limits for each class are shown in Table 6 and Table 7. The frequency range is the same as that specified in the steady-state frequency test (see Table 2). The exclusion interval removes portions of the ramp from measurement evaluation during which non-linear transitions or measurement limits may affect the measurements.

The test shall include both positive and negative frequency ramps. Each ramp shall extend continuously at a constant ramp rate between the range limits specified in Table 6. The measurements made on the portions of the ramp next to the frequency limits are excluded from the evaluation. Since the ramp is continuous and with a constant rate between limits, the only non-linear transitions will be at or outside the frequency limits.

The exclusion interval, $t_\mathrm{exclusion}$, is based on the time window over which the phasor is estimated. This is determined by the reporting rate and class as follows:

$$t_\mathrm{exclusion} = \mathrm{n}/\mathrm{F_s}$$

where

n is 2 (P class) or 7 (M class);

$\mathrm{F_s}$ is the reporting rate.

There shall be an exclusion interval at the start of the ramp to exclude the transition from the starting steady-state frequency to the ramping frequency and another at the end of the ramp to exclude the transition from the ramping frequency to an ending steady-state frequency. The starting exclusion interval is the portion of the ramp that begins at the point where the signal changes from the starting frequency limit to the ramping frequency. The ending exclusion interval is the portion of the ramp that ends at the ending frequency limit. The end points shall be included with the interval (i.e., the end points of the interval are excluded from the evaluation). Since reports are discrete, if a reporting point coincides with a frequency limit, 2 (P class) or 7 (M class) additional points will be excluded (the interval is n/$\mathrm{F_s}$ long and will include n+1 points if a reporting point is at the end).

For example, consider a case with a system frequency of 60 Hz and reporting rate $\mathrm{F_s}$ = 30 fps. For P class, the frequency range is ± 2 Hz and the exclusion interval is $t_\mathrm{exclusion}$ = 2/$\mathrm{F_s}$ = 0,067 s. The positive ramp test will start with a 58 Hz steady-state signal and ramp up to a 62 Hz steady-state signal. This exclusion interval is two reporting periods, so if one report is coincident with the 58 Hz limit, that report and the next two reports will be excluded. By symmetry, a report will be coincident with the point that the ramp reaches the 62 Hz limit so that report and the two previous reports will be excluded. Since the ramp rate is 1 Hz/s, measurements at and below 58,067 Hz and at and above 61,933 Hz will be excluded. The negative ramp test will start with a 62 Hz steady-state signal and ramp down to a 58 Hz steady-state, so will similarly exclude the same measurements and frequencies from the evaluation. For M class, the principle is the same except the exclusion interval is $t_\mathrm{exclusion}$ = 7/30 = 0,233 s and the test frequency limits are ± 5 Hz. The positive ramp shall start at 55 Hz and ramp up to 65 Hz. The sample coincident with the limit and the following seven measurements will be excluded. This removes measurements at and outside of the frequency range of 55,234 Hz to 64,767 Hz. The excluded range is the same for the negative frequency ramp.

Table 6 – Synchrophasor performance requirements under frequency ramp tests

Test signal	Reference condition	Influence quantity test limits over which PMU shall be within given TVE limit[a]				
		Ramp rate (R_f) (positive and negative ramp)	Performance class	Exclusion interval	Ramp range	Max. TVE
Linear frequency ramp	100 % rated signal magnitude, and $f_{nominal}$ at a non-excluded point during the test	±1,0 Hz/s	P class	Larger of 2/Fs or $2/f_0$	± 2 Hz	1 %
			M class	Larger of 7/Fs or $7/f_0$	Lesser of ± (F_s/5) Hz or ± 5 Hz[b]	1 %

[a] Minimum range. This does not include the exclusion interval multiplied by the ramp rate.

[b] For Fs = 12 fps, ramp range shall be ± 2 1/3 (two and one-third) Hz to allow for an integer number of samples in the result.

Table 7 – Frequency and ROCOF performance requirements under frequency ramp tests

Signal specification	Reference condition	Exclusion interval	Error requirements for compliance			
			P class		M class	
			Max. |FE|	Max. |RFE|	Max. |FE|	Max. |RFE|
Ramp tests – same as specified in Table 6.	100 % rated signal magnitude and 0 radian base angle	Same as specified in Table 6	0,01 Hz	0,4 Hz/s	0,01 Hz	0,2 Hz/s

6.6 Dynamic compliance – Performance under step changes in phase and magnitude

Performance during step changes in magnitude and phase shall be determined by applying balanced step changes to balanced three phase input signals (voltages and currents). This test is mathematically represented in the following formulas:

$$X_a = X_m [1+k_x u(t)] \times \cos [2\pi f_0 t+k_a u(t)] \quad (41)$$

$$X_b = X_m [1+ k_x u(t)] \times \cos [2\pi f_0 t-2\pi/3+ k_a u(t)] \quad (42)$$

$$X_c = X_m [1+ k_x u(t)] \times \cos [2\pi f_0 t+2\pi/3+ k_a u(t)] \quad (43)$$

where

X_m is the amplitude of the input signal;

f_0 is the nominal power system frequency in Hz;

u(t) is a unit step function;

k_x is the magnitude step size;

k_a is the phase step size.

This test is a transition between two steady states used to determine response time, delay time, and overshoot in the measurement. Step functions with parameters as specified in Table 8 shall be applied, and the measurements shall meet the requirements in Table 8 and Table 9. Figure C.5 illustrates the measurements. Response time and delay time are defined in 5.2.3. The steady-state error limits from Table 2 and Table 3 shall be used for determining the response time. These limits are 1 % TVE, 0,005 Hz |FE|, and 0,4 Hz/s (P class) and 0,1 Hz/s (M class) |RFE|.

Table 8 – Phasor performance requirements for input step change

Step change specification	Reference condition	Maximum response time, delay time, and overshoot					
		P class			M class		
		Response time s	|Delay time| s	Max. Overshoot/ undershoot	Response time s	|Delay time| s	Max. overshoot/ undershoot
Magnitude = ± 10%, k_x = ± 0,1, k_a = 0	All test conditions nominal at start or end of step	$2/f_0$	$1/(4 \times F_s)$	5 % of step magnitude	Larger of $7/F_s$ or $7/f_0$	$1/(4 \times F_s)$	10 % of step magnitude
Angle ± 10°, k_x = 0, k_a = ± π/18	All test conditions nominal at start or end of step	$2/f_0$	$1/(4 \times F_s)$	5 % of step magnitude	Larger of $7/F_s$ or $7/f_0$	$1/(4 \times F_s)$	10 % of step magnitude

Table 9 – Frequency and ROCOF performance requirements for input step change

Signal specification	Reference condition	Maximum susceptibility response time			
		P class		M class	
		Frequency response time s	ROCOF response time s	Frequency response time s	ROCOF response time s
Magnitude test as in Table 8	Same as in Table 8	$4{,}5/f_0$	$6/f_0$	Greater of $14/F_s$ or $14/f_0$	Greater of $14/F_s$ or $14/f_0$
Phase test as in Table 8	Same as in Table 8	$4{,}5/f_0$	$6/f_0$	Greater of $14/F_s$ or $14/f_0$	Greater of $14/F_s$ or $14/f_0$

6.7 PMU reporting latency compliance

As defined in 5.2.5, PMU reporting latency is 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). The PMU reporting latency shall be within the requirements shown in Table 10. The latency shall be determined to an accuracy of at least 0,002 s.

Table 10 – PMU reporting latency

Performance class	Maximum PMU reporting latency s
P class	Greater of $2/F_s$ or $2/f_0$
M class	Greater of $7/F_s$ or $7/f_0$
NOTE Latency is limited by the need to include at least one cycle of the power system waveform for synchrophasor calculation.	

The PMU output shall be observed for at least 20 min to determine the maximum latency. If the required maximum reporting latency appears to trend up or down, the PMU output shall be further observed for the maximum until a local maxima is observed, the slope of the trend line becomes zero, or the maximum allowable reporting latency is exceeded. See Clause C.7 for discussion.

7 Documentation

Documentation shall be provided by any vendor claiming compliance with this document that shall include the following information:

a) performance class;
b) measurements that meet this class of performance;
c) selectable reporting rates;
d) nominal voltage and current magnitudes;
e) input(s) used for the frequency and ROCOF measurements;
f) PMU settings;
g) test results demonstrating performance;
h) test equipment description;
i) environmental conditions during the testing.

Annex A
(informative)

Time tagging and dynamic response

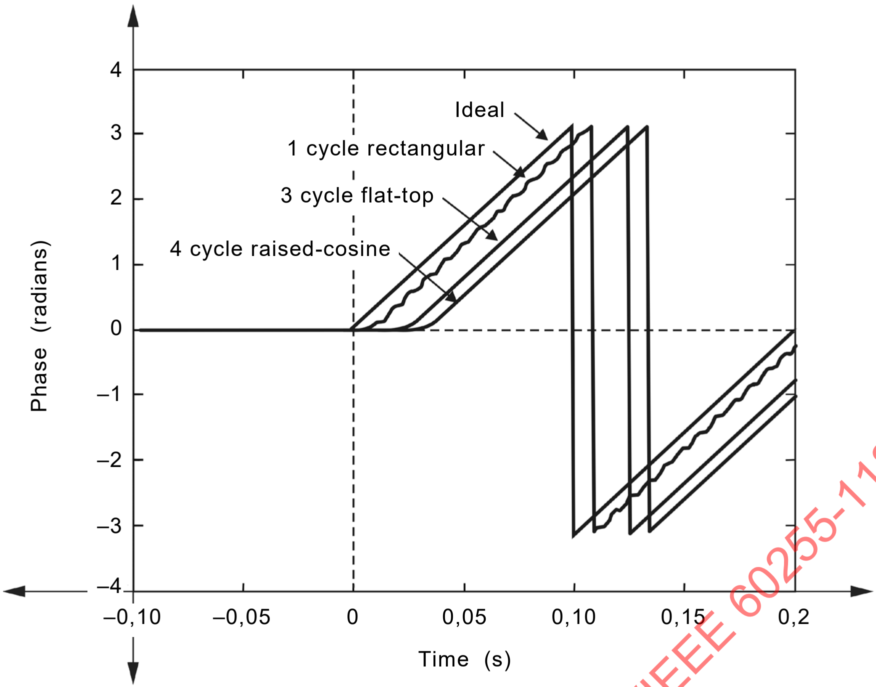
A.1 Dynamic response

Identical PMUs (defined as having identical hardware and algorithms) should yield the same phasor measurement under all conditions. However, two PMUs with different algorithms and/or different analog circuitry can be expected to yield somewhat different results for the same phasor measurement in transient state (the time during which a change in magnitude, phase angle, or frequency takes place). Test requirements and measurement evaluation described in Clause 6 detail requirements to ensure that measurements in both steady-state and transient conditions are comparable.

A.2 Time tags

Phasor measurements are the estimated phasor representation of a sinusoidal signal. The estimation is made for the signal at a particular instant of time, and that time is represented by the phasor time tag. The process of making a phasor estimate will require sampling the waveform over some interval of time, which can lead to some confusion as to which time within that window is the correct time tag for the phasor. The time tag is defined as the time of the reference phasor that the estimated phasor represents. This acknowledges that the synchrophasor is actually an estimate of the sinusoid parameters over the window of observation. The estimate covers a short period of time, so will represent some kind of "average" of the parameters, which may be changing during that window. In most cases, the phasor estimate will be best represented by a time at the center of the estimation window. It is up to the designer to create an estimation process that ensures that the magnitude and phase angle are properly represented, according to the TVE evaluation defined in 5.2.

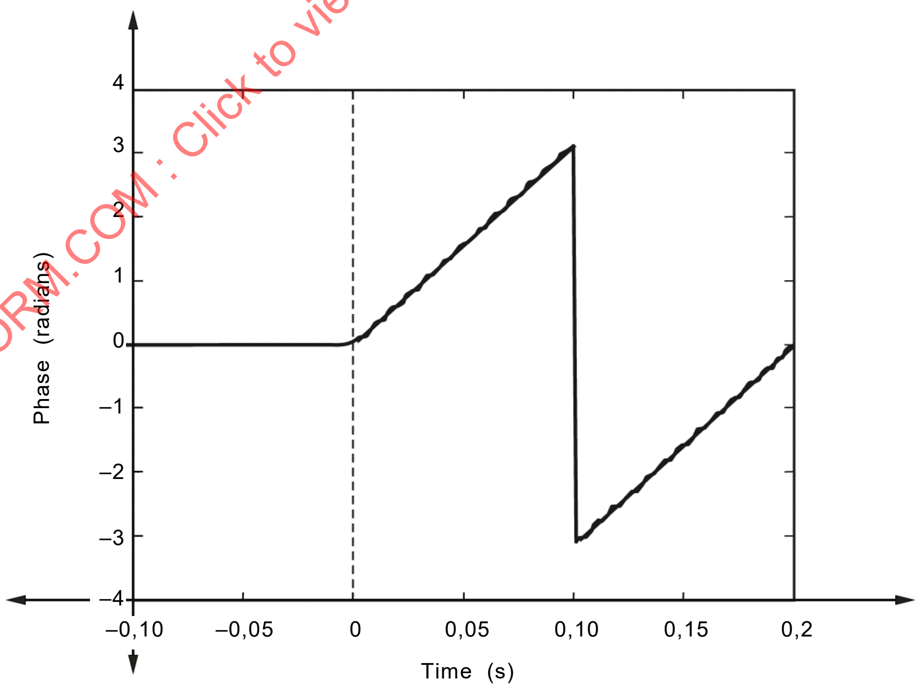
If the power system frequency is different from its nominal value, the phasor will rotate as illustrated by Figure B.1. Although this represents a steady-state condition (as defined in 6.3), it is easy to show that the instantaneous value of the phasor phase angle will be determined by the choice of the time tag and the inherent group delay associated with the actual measurement algorithm. This behavior is illustrated in Figure A.1, where a step in frequency from f_0 to f_0 + 5 Hz is applied at t = 0. The curves illustrate the estimate produced by three different algorithms without group delay compensation.



NOTE +5 Hz frequency step at t = 0.

Figure A.1 – Frequency step test phase response without group delay compensation

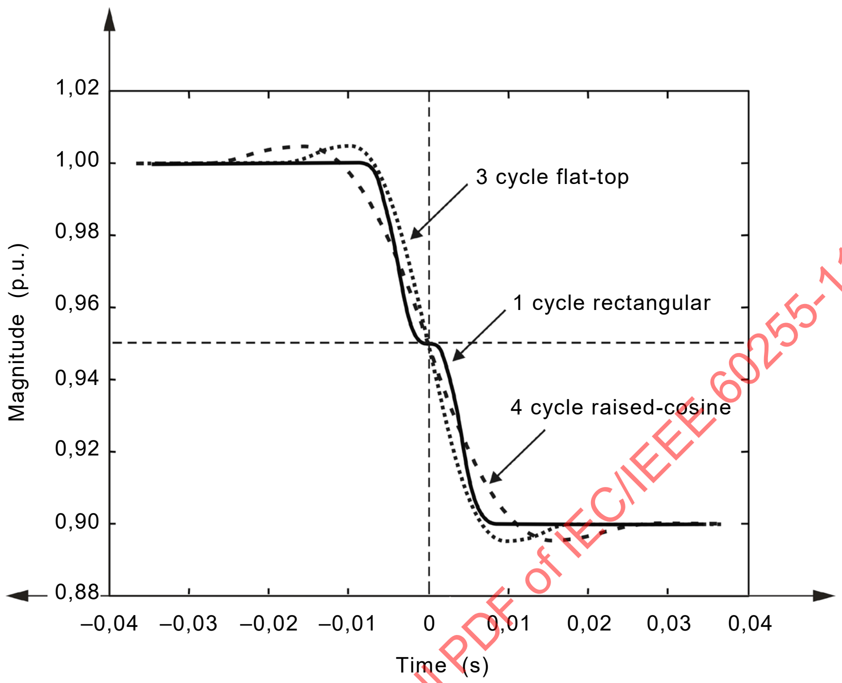
By relying on the TVE defined in 5.2, this document eliminates the off nominal frequency phase angle ambiguity and helps ensure the compatibility between different PMUs. All compensation for group delay or other deficiencies of the estimation shall be done by the manufacturer. Figure A.2 shows multiple device outputs (from Figure A.1) after group delay compensation. In Figure A.2, devices closely track each other, with four traces virtually indistinguishable from each other.



NOTE Ideal +3 algorithms, corresponding to Figure A.1.

Figure A.2 – Frequency step test phase response after group delay compensation

Figure A.3 shows the results of these same three algorithms with group delay compensation under a 10 % negative step in magnitude. This shows there will be differences in responses even though the group delay is compensated. The differences are small, and will be imperceptible under most data reporting rates since sample rates are much slower than what is illustrated here. The responses are centered at the step (t = 0); they meet the response time requirement for P class at 180 fps (and all lower reporting rates), and all overshoot requirements.



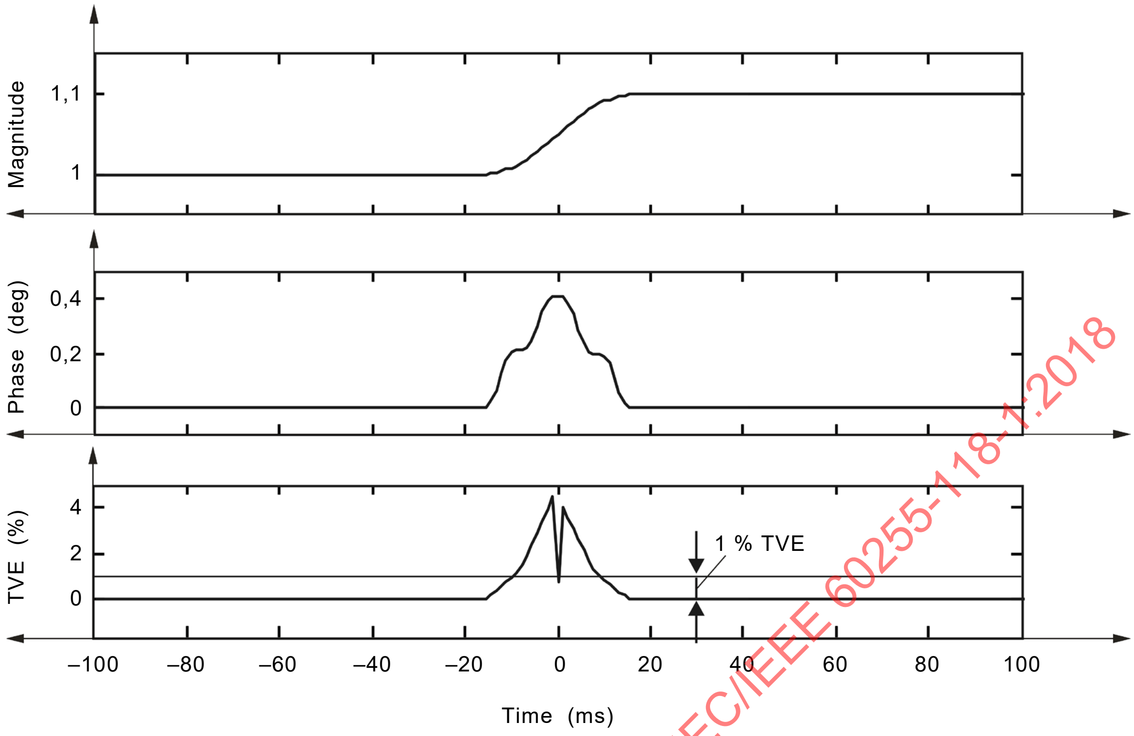
NOTE Group delay compensated, corresponding to Figure A.2. Per Unit (PU) voltage or current is normalized to the reference (V/V_{ref} or I/I_{ref}).

Figure A.3 – Magnitude step test results for 3 different algorithms

Group delay of a finite Impulse Response (FIR) filter based algorithm with symmetric or anti-symmetric coefficients is equal to one-half of the window length (time tag in the centre of the window). Infinite Impulse Response (IIR) filters, asymmetric FIR filters, and optimization-based algorithms may stretch the trailing edge, making the time response asymmetrical. Furthermore, as indicated in Figure A.3, the "transient" behaviour will vary depending on the type of algorithm used for phasor estimation. Instead of mandating a single measurement algorithm, this document defines the performance under a variety of conditions and the use of TVE as the primary tool for phasor measurement device performance assurance.

A.3 Magnitude step test example

Results of a simulated magnitude step test obtained with the P class algorithm presented in Annex D are illustrated in Figure A.4. The TVE limit defined in 5.2 is indicated by a thin horizontal line. It is clear that under steady-state conditions, simulated PMU response stays within the prescribed TVE requirement. However, during the step, the TVE significantly exceeds the steady-state requirement. For this reason, the performance requirements in 6.6 do not specify a maximum TVE during a specified time period before and after the step time for both P class and M class devices.



NOTE 10 % step, P class algorithm.

Figure A.4 – Magnitude step test example

A.4 PMU time input

A PMU requires a source of UTC time synchronization. This may be supplied directly from a time broadcast such as GPS or from a local clock using a standard time code. IRIG-B is commonly used for local time dissemination. It may be provided in a level shift, a 1 kHz amplitude modulated signal, or in the bi-phase Manchester modulated format (modulation type 2, B2xx). If the amplitude modulation is used, it may need to be supplemented with a 1 PPS pulse train to achieve the required accuracy. The IRIG-B amplitude modulated format is commonly available and hence is the most readily implemented. The newer Manchester format is more compatible with fibre optic and digital systems and provides complete synchronization without additional signals. Other forms of precise time distribution, such as standard Ethernet using IEEE Std 1588™[1] [2], are also available. These distribution signals are further detailed as follows:

- 1 PPS

  A common feature of timing systems is a pulse train of positive pulses at a rate of one pulse per second (1 PPS). The rising edge of the pulses coincides with the seconds change in the clock and provides a very precise time reference. The pulse widths vary from 5 µs to 0,5 s, and the signal is usually a 5,0 V. magnitude driving a 50 Ω load. A 1 PPS timing signal can be used with another system such as a serial timing message or IRIG-B to supply the full time synchronization.

- IRIG-B

  IRIG-B is fully described in IRIG STANDARD 200-04 [2] published by the Range Commanders Council of the U.S. Army White Sands Missile Range. Time is provided once per second in seconds through day of year in a binary coded decimal (BCD) format and an optional binary second-of-day count. The standard allows a number of configurations which

2 Numbers in square brackets refer to the bibliography.

are designated as Bxyz where x indicates the modulation technique, y indicates the counts included in the message, and z indicates the interval. The most commonly used form is B122, which has seconds through day-of-year coded in BCD and is amplitude modulated on a 1 kHz carrier. The amplitude should have a peak-to-peak amplitude of 1 V to 6 V for the mark (peak) with a mark-to-space amplitude ratio 10:3 as provided in [2]. A block of 27 control bits are available for user assignment and can be used to supplement the standard code for continuous timekeeping. The time code format is:

<sync> SS:MM:HH:DDD <control> <binary seconds>

where

<sync>	is the on-time sync marker;
SS	is the second of the minute(00 to 59 (60 during leap seconds));
MM	is the minute of the hour (00 to 59);
HH	is the hour of day in 24 format (00 to 23);
DDD	is the day of year (001 to 366);
<control>	is a block of 27 binary control characters;
<binary seconds>	is a 17 bit second of day in binary.

IRIG-B includes 27 control bits for user provided information in addition to the specified time codes. Assignment of these bits to enable coding the year of century, non-sequential changes (leap seconds and daylight savings time), local time offsets, and time quality into the message was detailed in previous synchrophasor standards, starting with IEEE Std 1344™-1995 [3] and continuing through IEEE Std C37.118.1TM-2011 [4]. This has been transferred to IEEE PC37.237 [5], which deals with time tagging and event timing which is a more compatible venue for coordinating future development.

- IEEE 1588

  IEEE Std 1588-2008 allows timing accuracies better than 1 µs for devices connected via a network such as Ethernet (IEEE Std 802.3). IEC/IEEE 61850-9-3 [6] and IEEE Std C37.238™ [7] specify a subset of IEEE 1588 functionality to be supported for power system protection, control, automation, and data communication applications utilizing Ethernet communication architecture. Several commercially available Ethernet switches, grandmaster clocks and slave clocks have implemented the IEEE C37.238 functionality and demonstrated this performance. Both standards may be obtained through the IEEE-SA web site. Newer revisions of these standards may be available; the reader is advised to check for the latest versions as well as assuring that equipment conforms to versions with compatible requirements.

Annex B
(informative)

Parameter representation and definition application examples

B.1 General

Annex B compares the definition of synchrophasor, frequency, and ROCOF measurands given in this document and the definition used in IEEE Std C37.118.1, demonstrating they are mathematically equivalent even though semantically different. It also provides examples that illustrate the application of the synchrophasor, frequency, and ROCOF definition equations given in Clause 5. They are applied to signals that are commonly found in power system signal analysis and include the test signals prescribed in Clause 6 that are used for performance validation. Reconstruction of the power system sinusoid from the synchrophasor values is also demonstrated.

B.2 Representing non-stationary sinusoids

The voltage and current waveforms are generally represented as a sine or cosine wave whose frequency is near the nominal value of the system. The amplitude is nearly constant and the phase angle is determined by a specific time reference. In reality, the amplitude, frequency, and phase angle vary constantly in time so the sinusoidal signal is non-stationary. These variations occur in both the sinusoidal signal parameters as well as the additive disturbances as shown in Equation (1). The phase function $\theta(t)$ includes both frequency and phase angle. These parameters can be defined differently depending on the intended usage.

In this document, we have defined $\theta(t) = 2\pi f_0 t + \phi(t)$ to emphasize the fact the synchrophasor phase angle is determined as the phase angle relative to the nominal system frequency at the given point in time. Any variation of frequency is included as the time variation of phase as shown in the examples below.

The previous synchrophasor standard, IEEE Std C37.118.1, included the variation of frequency as a separate term in the definition of sinusoidal phase, $\theta(t)$. That standard defined $\theta(t) = 2\pi f_0 t + 2\pi \int g\, dt + \phi$, and the actual sinusoidal frequency was defined as $f(t) = g(t) + f_0$. In this definition, the phase angle, ϕ, is constant for a calculation and can be different for a successive calculation. This indefinite integral form does not make clear the estimation of the phase value.

These two approaches to defining the non-stationary phase are equivalent, only differing in their semantic expression. Setting the two phasor values equal (making $\phi = \phi_0$ to show it as a fixed value):

$$2\pi f_0 t + \phi(t) = \theta(t) = 2\pi f_0 t + 2\pi \int g\, dt + \phi_0 \quad \text{(B.1)}$$

$$\phi(t) = 2\pi \int g\, dt + \phi_0 \quad \text{(B.2)}$$

The frequency definitions in this document and IEEE Std C37.118.1 are the same (the derivative of phase divided by 2π). Setting the two definitions equal (showing the formula of IEEE Std C37.118.1 on the right):

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

$$g(t) = \frac{1}{2\pi}\frac{d[\phi(t)]}{dt} \quad \text{(B.4)}$$

We see that $g(t)$ is the rate of change in phase angle that is in addition to the change in phase due to the nominal frequency, which we might call "offset frequency". Conversely, we can solve phi:

$$\phi(t) = 2\pi \int_{t0}^{t} g(\tau)d\tau + \phi(t_0) \quad \text{(B.5)}$$

which shows the changing phase angle is the integral of the offset frequency function plus a constant. Given either an offset frequency or time varying phase allows solving for the other form. For example, when the system frequency is a constant difference from the nominal frequency, $g(t) = \Delta f$, the phase function $\phi(t)$ can be calculated:

$$\phi(t) = 2\pi \int_{t0}^{t} g(\tau)d\tau = 2\pi \int_{t0}^{t} \Delta f\, d\tau = 2\pi\, \Delta f\,(t - t_0) + \phi(t_0) \quad \text{(B.7)}$$

The synchrophasor phase angle is a linear ramp from the angle $\phi(t_0)$ at time $t = t_0$.

Further discussion of these approaches and frequency definitions can be found in [9]. Clause B.3 presents specific examples of application of these definitions.

B.3 Introduction of definition application examples

B.3.1 General

The basic sinusoidal signal equation repeated from Clause 4 is:

$$x(t) = X_{\mathrm{m}}(t)\cos\left[2\pi f_0 t + \phi(t)\right] + D(t) \quad \text{(B.8)}$$

The synchrophasor is defined as the complex number:

$$X(t) = \left(\frac{X_{\mathrm{m}}(t)}{\sqrt{2}}, \phi(t)\right) = \frac{X_{\mathrm{m}}(t)}{\sqrt{2}} e^{\mathrm{j}\phi(t)} \quad \text{(B.9)}$$

In the derivations of B.3.2 to B.3.5, the complex exponential form of the synchrophasor is used.

B.3.2 Example 1: steady-state at nominal frequency

All parameters are constant. Here, $X_{\mathrm{m}}(t) = \frac{X_{\mathrm{m}}}{\sqrt{2}}$, $\phi(t) = \phi$, frequency $f(t) = f_0$, ROCOF(t) = 0, and $D(t) = 0$.

Then the synchrophasor is $X(t) = (X_{\mathrm{m}}/\sqrt{2})\, e^{\mathrm{j}\phi}$, and ϕ is the constant phase difference between the signal and the reference wave.

B.3.3 Example 2: steady-state and constant off-nominal frequency

The parameters are constant, $X_{\mathrm{m}}(t) = \frac{X_{\mathrm{m}}}{\sqrt{2}}$, $\phi(t) = \phi$, ROCOF(t) = 0, D(t) = 0 and the off-nominal frequency is

$$f(t) = f_0 + \Delta f \quad \text{(B.10)}$$

where Δf is the offset from the nominal frequency.

The sinusoidal phase is found by integrating Equation (7):

$$\theta(t) = \int_0^t 2\pi f(t)\,dt = 2\pi f_0 t + 2\pi \Delta f t + \phi_0 \tag{B.11}$$

where $\emptyset_0$ is the phase at t = 0.

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

$$X(t) = \frac{X_m}{\sqrt{2}} e^{j(2\pi\Delta f t + \phi_0)} \tag{B.12}$$

This synchrophasor will rotate at the uniform rate Δf Hz/s, which is the difference between the actual and nominal frequency. This is illustrated in Figure B.1 showing the increasing phase angle value where $\Delta f > 0$.

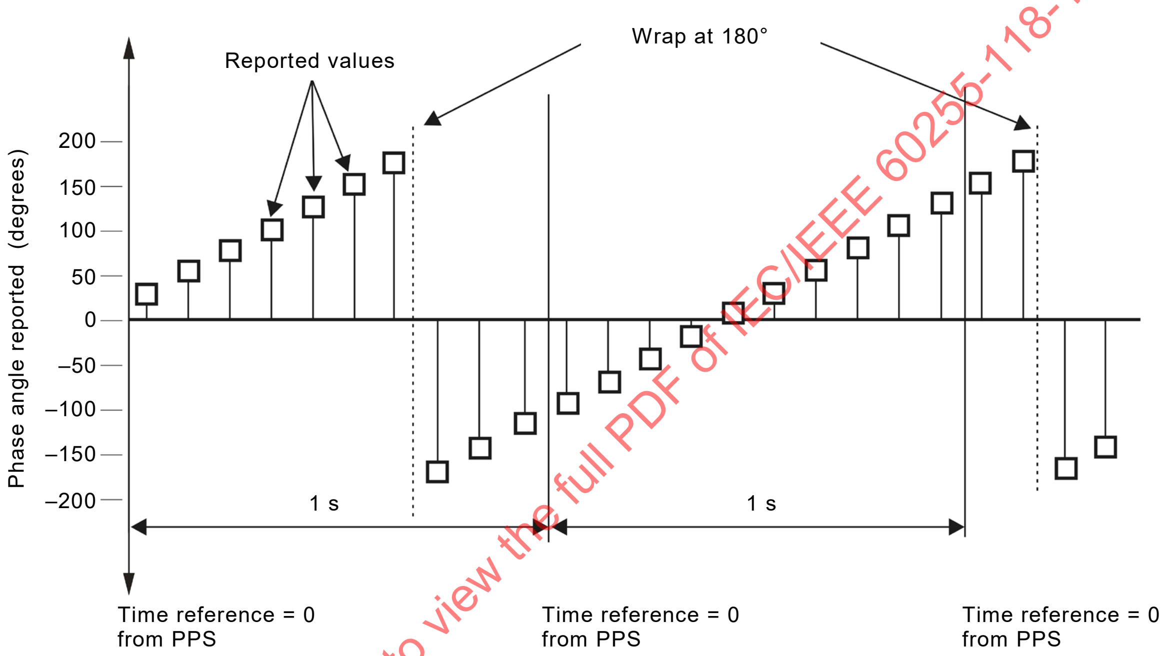


Figure B.1 – Sampling a power frequency sinusoid at off-nominal frequency

B.3.4 Example 3: oscillation of the phase and amplitude of the power signal

In this example, there is a sinusoidal modulation of the amplitude and phase angle of the basic sinusoidal power system signal. These modulations are represented in the signal as:

$$x(t) = X_m[1 + k_x \cos(2\pi f_m t)]\cos[2\pi f_0 t + k_a \cos(2\pi f_m t - \pi)] \tag{B.13}$$

where

f_m is the modulation frequency in Hz;

k_x is the amplitude modulation index;

k_a is the phase modulation index.

For this example, we require that $f_m < f_0$, $k_x < 1$, and $k_a < 1$. This eliminates extraneous solution possibilities and best represents power system applications. In this example the phase and amplitude modulation are 180° out of phase; this is not a universal requirement but is the relationship that has been demonstrated for two machines oscillating against each other.

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:

$$X(t) = X_m/\sqrt{2}\,[1+k_x\cos(2\pi f_m t)]\, e^{j\,[k_a\cos(2\pi f_m t-\pi)]} \quad (B.14)$$

The frequency is the differential of the cosine argument (Equation (7)):

$$f(t) = f_0 + \frac{1}{2\pi}\frac{d\,[k_a\cos(2\pi f_m t-\pi)]}{dt} = f_0 - k_a\frac{2\pi f_m}{2\pi}\sin(2\pi f_m t-\pi) \quad (B.15)$$

Differentiating frequency to derive ROCOF (Equation (8)):

$$\text{ROCOF}(t) = \frac{df(t)}{dt} = -k_a\frac{(2\pi f_m)^2}{2\pi}\cos(2\pi f_m t-\pi) \quad (B.16)$$

The synchrophasor oscillates in magnitude and phase, the same as the power signal. Frequency and ROCOF only oscillate in response to phase modulation. Under amplitude oscillation only ($k_x \neq 0$ and $k_a = 0$), frequency and ROCOF are constant; under phase oscillation only ($k_x = 0$ and $k_a \neq 0$), all measurements oscillate.

This example shows the derivation of reference parameter values for the dynamic performance modulation test in 6.4.

B.3.5 Example 4: constant, non-zero rate of change of frequency

In this example, $X_m(t) = \frac{X_m}{\sqrt{2}}$, $D(t) = 0$, and ROCOF$(t) = R_f \neq 0$ are all constant.

Integrating ROCOF using Equation (8) to find $f(t)$, we get:

$$f(t) = \int_0^t R_f d\tau = R_f t + f_a \quad (B.17)$$

where f_a is the frequency at t = 0. This equation describes a linear change in frequency.

Integrating $f(t)$ to find $\theta(t)$, we get:

$$\theta(t) = \int_0^t 2\pi f(\tau)d\tau = 2\pi\int_0^t (R_f\tau + f_a)d\tau = 2\pi\left(R_f\frac{t^2}{2} + f_a t\right) + \phi_0 = \pi R_f t^2 + 2\pi f_a t + \phi_0 \quad (B.18)$$

where $\emptyset_0$ is the phase angle at t = 0.

The synchrophasor phase angle $\phi(t) = \pi R_f t^2 + 2\pi(f_a - f_0)t + \phi_0$ so the synchrophasor is:

$$X(t) = \frac{X_m}{\sqrt{2}} e^{j(\pi R_f t^2 + 2\pi(f_a - f_0)t + \phi_0)} \quad (B.19)$$

The synchrophasor has an initial phase angle ϕ_0 at time t = 0 which increases parabolically at the rate $\pi R_f t^2 + 2\pi(f_a - f_0)t$ from t = 0. The frequency $f(t) = f_a + R_f t$ is a linear ramp.

This example shows the derivation of reference parameter values for the dynamic performance system frequency ramp test in 6.5.

B.4 Reconstruction of the power system sinusoidal signal from the synchrophasor

The original sinusoidal signal exclusive of the interference $D(t)$ (which is preserved by the synchrophasor) can be reconstructed using the parameters of the synchrophasor. Given the real and imaginary values $X_r(t)$ and $X_i(t)$ (rectangular coordinates) as defined in Equation (5) and Equation (6) respectively, the sinusoidal signal is expressed as follows:

$$x(t) = X_m(t)\cos[2\pi f_0 t + \phi(t)] = \sqrt{2}\,X_r(t)\cos(2\pi f_0 t) - \sqrt{2}\,X_i(t)\sin(2\pi f_0 t) \quad \text{(B.20)}$$

using the trig identity $\cos(a + b) = \cos(a)\cos(b) - \sin(a)\sin(b)$.

Discrete time measurands can be determined as the value of the continuous time measurands by setting t = nT where n is an integer and T is the measurement reporting period in units of seconds.

Annex C
(informative)

PMU evaluation and testing

C.1 General

Annex C covers several topics of interest to those evaluating the accuracy of PMUs. Annex C begins with a discussion of total vector error (TVE), and continues with a discussion of the relation of magnitude errors and phase errors to the TVE metric. A detailed discussion of PMU response to steps in magnitude and phase will help evaluators understand the recommended method for performing step tests. Steady-state harmonic distortion test input signals are specified by equations, but a table showing the phase relation, in terms of symmetrical components (positive, negative and zero sequence) is shown. Annex C closes with a discussion of rate of change of frequency (ROCOF) limits and why some tests specify no limits for ROCOF error.

There are many ways of implementing PMU tests in accordance with this document. If implemented correctly, all methods are expected to yield the same results. The IEEE Conformity Assessment Program (ICAP) has published a synchrophasor measurement test suite specification (TSS) [10] that specifies test methodology to be used for conformity assessment in accordance with the ICAP certification program.

C.2 TVE measurement evaluation

The total vector error (TVE) is a measure of the difference between the synchrophasor estimates from a PMU and the reference value determined by evaluating the formulas describing the measurand.

TVE combines magnitude and angle error into a single quantity. This allowable error criterion combines all error sources, including time synchronization, phasor angle, and phasor magnitude estimation errors. TVE is defined by Equation (9). In the qualification tests, the reference values are determined mathematically from the specified test signals with the expectation that they will be faithfully produced and applied to the PMU by the test equipment. Test equipment can be calibrated to determine if their reference values meet the specified criteria of 10:1 test uncertainty ratio (TUR). Figure C.1 shows how magnitude and phase errors combine into the total vector error metric.

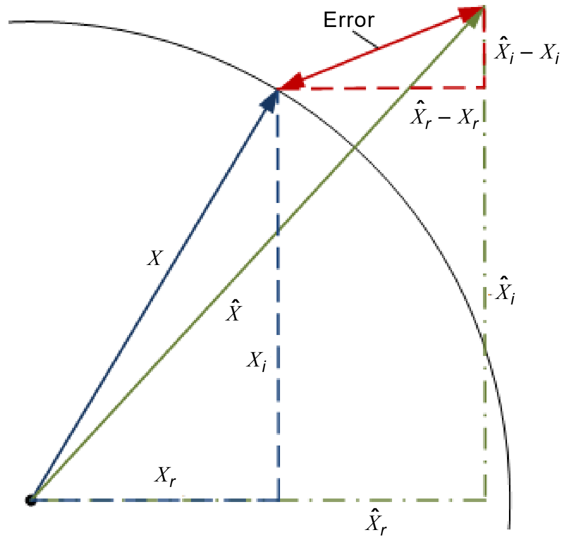


Figure C.1 – Total vector error (TVE)

In Figure C1, X is the reference synchrophasor, represented by real and imaginary components X_r and X_i . $\hat{X}$ is the PMU synchrophasor estimate with real and imaginary components $\hat{X}_r$ and $\hat{X}_i$.

This document establishes a criterion of 1 % for the value of the TVE for most performance tests in this document. The 1 % criterion can be visualized as a small circle drawn on the end of the phasor. The maximum magnitude error is 1 % when the error in phase is zero, and the maximum error in angle is just under 0,573° when the magnitude error is 0. Provided the observed samples do not lie outside the circle, the measurement is compliant. Figure C.2 shows the circle, with size greatly exaggerated for clarity.

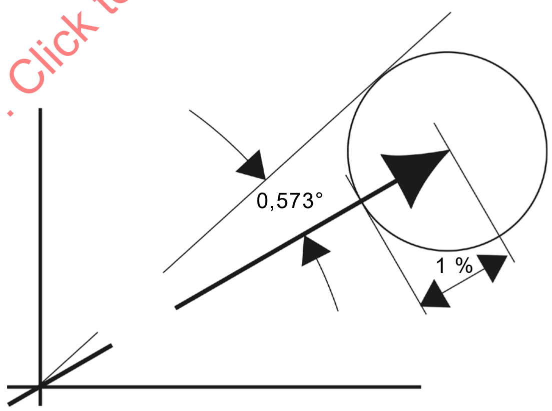


Figure C.2 – The 1 % TVE criterion shown on the end of a phasor

C.3 Phase-magnitude relation in TVE and timing

TVE combines magnitude and phase errors. TVE can be determined directly from magnitude and phase error by the formula:

$$\text{TVE} = \sqrt{2(1+ME)(1-\cos(PE))+ME^2} \tag{C.1}$$

where ME is magnitude error (in pu):

$$\text{ME} = \frac{\sqrt{\hat{X}_r(n)^2 + \hat{X}_i(n)^2} - \sqrt{X_r(n)^2 + X_i(n)^2}}{\sqrt{X_r(n)^2 + X_i(n)^2}} \tag{C.2}$$

PE is phase error (in deg or rad):

$$\text{PE} = \text{atan}(\hat{X}_r, \hat{X}_i) - \text{atan}(X_r, X_i) \tag{C.3}$$

Figure C.3 shows the variation in TVE as a function of magnitude for various phase errors and Figure C.4 shows the variation in TVE as a function of phase for various magnitude errors. Each parameter has the same parabolic influence on the other only differing in the intercept values for TVE.

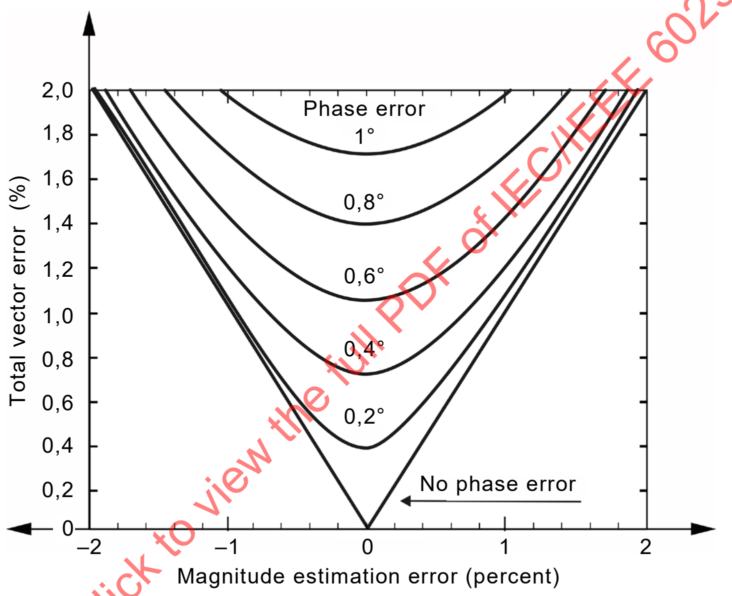


Figure C.3 – TVE as a function of magnitude for various phase errors

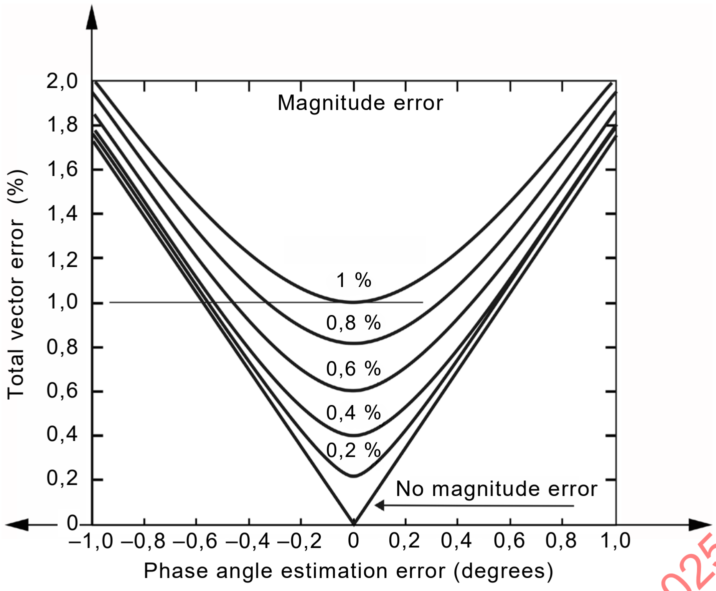


Figure C.4 – TVE as a function of phase for various magnitude errors

Phase angle is determined by the relation of the power system signal to a time synchronized reference at nominal system frequency. If the reference is displaced by a certain time interval, the angle of the power system signal will be displaced by that same time interval, creating an error in the estimated phase angle. Thus timing errors translate directly to phase errors. The TVE is computed relative to measurement magnitude and phase at the power system frequency. Consequently, timing errors will result in different TVE depending on system frequency. One cycle is 20 ms at 50 Hz and 16,67 ms at 60 Hz. One degree of phase angle at 50 Hz is 55,6 µs and 46,3 µs at 60 Hz. A timing error that will cause a 1 % TVE error at 50 Hz is ± 31,7 µs and at 60 Hz is ± 26 µs (with 0 magnitude error).

C.4 Evaluation of response to stepped input signals

The PMU response and delay times are small compared to the PMU reporting intervals. The specified response time (P class in Table 8) is less than 3 reporting intervals, and delay time is less than a quarter of a reporting interval. It is unlikely that reported data points will fall on the specified measurement points, so determining those points with a single step test may be insufficient. A series of tests with the step applied at varying times relative to the reporting times can be used to achieve this result. This "equivalent time sampling" approach can achieve the required measurement resolution. In effect, this technique moves the time that the step is applied to derive points on the measurement to "fill in" a curve. The PMU measurement reports are at fixed points in time relative to the UTC second, so moving the steps a fraction of the reporting interval gives reports at different points on the measurement curve. These measurements are combined by translating the step and response measurement points back to the reference point to give a step response result with a time resolution less than the reporting interval. This technique controls the relation between the step time t in the unit step function $f_1(t)$ and one of the reporting times. The unit step function time is adjusted to fall on a reporting time for one step test. Successive step tests are performed with the unit step function times falling at increasing fractions of a reporting interval after a reporting time. Thus, if t_r is a general reporting time, T is the reporting interval, and n is the number of tests to be performed, one test is performed with a $f_1(t_r)$. The next test is performed with a $f_1(t_r+T/n)$, and the next with a $f_1(tr+2T/n)$, and so on until the nth test is performed with a $f_1(t_r+(n-1)T/n)$. The resulting measurement points are interleaved by aligning all of the steps at the same point and combining the measurements with their corresponding offsets from the step. This gives an equivalent measurement step response with a time resolution of T/n. In general, an accurate measurement of the PMU response time, the delay time, and the overshoot percentage can be made with n = 10 (however for low reporting rates where the test result may be indeterminate, higher numbers for interleaving – such as n = 20 – should be used). To determine the boundaries for these measurements, linear interpolation should be used between two F_s/n measurements. Overshoot and undershoot are measured on either side of a waveform transition. In the case of the synchrophasor step tests, the waveform is the sequence of phasor magnitudes or phases reported by the PMU under test and the transition is a step change in magnitude or phase respectively.

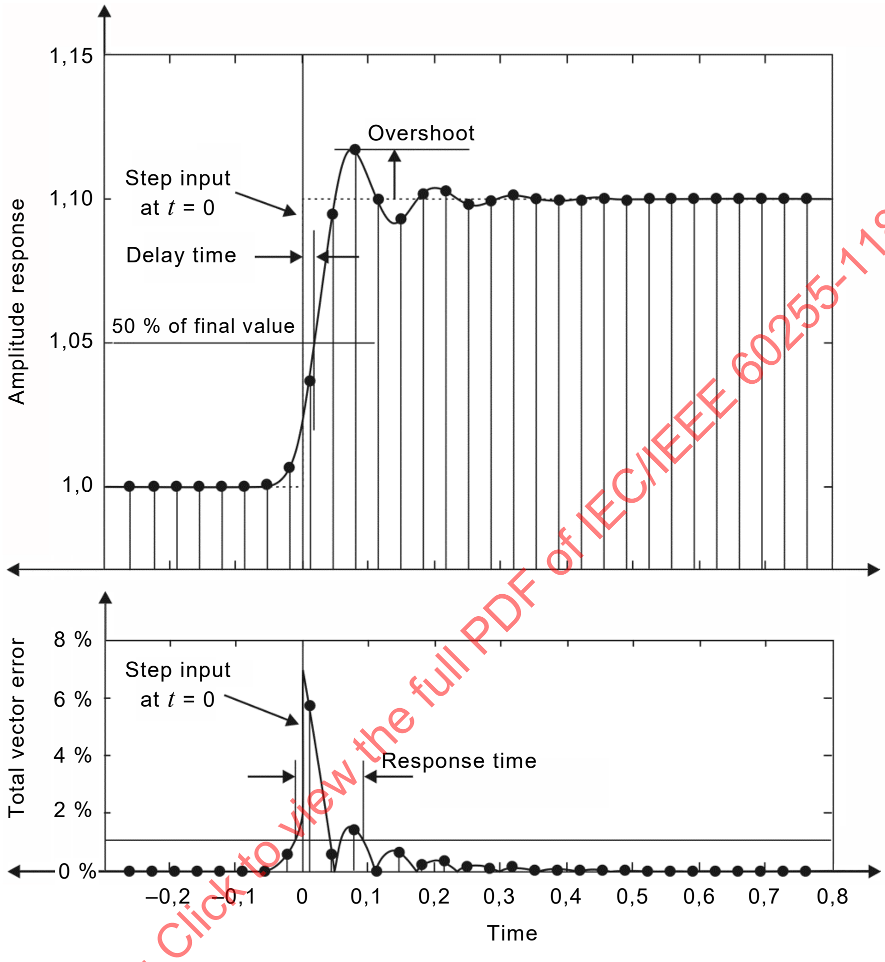


Figure C.5 – Example of step change measurements using a magnitude step at *t* = 0

In Figure C.5 reported values are represented by the dots along the waveform on top of a vertical line. The continuous response line will be determined by the equivalent time sampling described above. The response delay time is the time that the measurement equals 50 % of the step change in magnitude or phase. The response time is the difference between the times that the interpolated measurement leaves the specified accuracy limit and the time it returns to and remains within that limit.

Figure C.5 illustrates response time, delay time, and overshoot measurements. Response time is determined from the error measurement (here TVE, but FE and RFE are done similarly). Delay and overshoot are determined by the curve of the parameter being stepped. The maximum overshoot may be over or under the final value (corresponding to positive and negative steps), and the delay time may be positive or negative (since the response is based on the estimated phasor/frequency/ROCOF value, the time of 50 % response may vary a little from the time of the actual step input).

C.5 Harmonic distortion test signal phasing

Input signals for steady-state tests are specified mathematically in 6.3. Three phases of input signals are shown in positive sequence. For the out-of-band interfering signals test, the interfering signal is also specified to be positive sequence. However, for the harmonic distortion test, the harmonic signals are not always positive sequence.

For harmonic distortion tests, a balanced three-phase system is used and the harmonic sequence will cycle from positive to negative to zero depending on the harmonic number being injected. In other words, when the fundamental power signal of each phase crosses zero in the positive going direction, the injected harmonic signal should also be crossing zero in the positive direction. In this case, the second harmonic will be negative sequence, the third harmonic will be zero sequence, and the fourth harmonic will be positive sequence. The cycle repeats with the fifth harmonic being negative sequence and so on, as shown in Table C.1.

Table C.1 – Harmonic phase sequence in a balanced three-phase system

Harmonic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sequence	+	–	0	+	–	0	+	–	0	+	–	0	+	–	0
Harmonic	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Sequence	+	–	0	+	–	0	+	–	0	+	–	0	+	–	0
Harmonic	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Sequence	+	–	0	+	–	0	+	–	0	+	–	0	+	–	0
Harmonic	46	47	48	49	50										
Sequence	+	–	0	+	–										

C.6 ROCOF limits

C.6.1 General

Limits for RFE for M class were not established for the harmonic distortion and out-of-band interfering signal (OOB) tests. The requirements for applications that use ROCOF measurement are not well enough developed at the time of this document's publication to ensure that useful limits for ROCOF in these tests can be established without unjustified constraint on the phasor or frequency measurement. To best serve the user community, this document focuses on phasor and frequency measurement, the use of which is well established and widely used. However, for sinusoidal interfering signals such as those prescribed for the OOB and harmonics tests, the limit on FE also implies a limit on RFE. This relationship is explored in Clause C.6.

If no filtering is applied to the frequency and ROCOF measurements, the limit on frequency error (FE) implies limit on ROCOF (RFE), which is:

$$|\text{RFE}| = |\text{FE}| \times 2\pi \times |f_{\text{int}} - f_0| \quad \text{(C.4)}$$

where

f_{int} is the frequency of an interfering signal or its alias;

f_0 is the nominal system frequency.

For example, for the 2nd harmonic of f_0 = 50 Hz (100 Hz), the difference (100 − 50) is 50 Hz, and the resulting implied limit is 7,85 Hz/s. In other words, a PMU which is at the FE limit with exactly 0,025 Hz frequency error due to the 100 Hz harmonic will produce a ROCOF error (RFE) of 7,85 Hz/s.

As another example, consider the 20th harmonic of f_0 = 60 Hz which is 1 200 Hz. If it is sampled at 960 sps as in Annex D, the harmonic will be aliased to 240 Hz (= 1 200 – 960), and the difference here (240 – 60) is 180 Hz. The resulting implied RFE limit is 28,3 Hz/s for an FE of 0,025 Hz due to this harmonic (180 × 2π × 0,025).

This derivation relates the limits of FE and RFE based on the assumption that no filtering is applied to the ROCOF computation. Filtering will create additional delay in ROCOF which: (1) misaligns the measurement, or (2) requires delaying reporting the measurement set, or (3) requires separate ROCOF reporting. For the reasons cited above, this document supports a time aligned measurement set with minimal phasor delay, so filtering is not assumed.

Frequency and ROCOF are required to comply with the measurement limits only over the same range of frequencies specified for phasors. However, most frequency and ROCOF measurements will operate successfully over a much wider range. Vendors are encouraged to extend their measurement reporting over the widest practical range.

C.6.2 Derivation

Interfering sinusoidal signals (single frequency, low amplitude sinusoids) can be represented as a combination of (equal) angle and amplitude modulation of the basic cosine from which the phasor is computed.

NOTE Amplitude modulation produces sum and difference sidebands in phase, and narrowband angle modulation produces sum and difference sidebands, one in phase and one out of phase. When both modulations are present at the same frequency and amplitude, the anti-phase component cancels one in phase so only a single sideband is left. This is the same spectrum as additive single frequency produces.

The interfering sinusoidal signal can be represented as:

$$X = A_F\,[1+A_M \cos(\omega t)] \text{ x } \cos[\omega_0 t + A_a \cos(\omega t)] \quad \text{(C.5)}$$

where

ω is the interfering signal frequency;

ω_0 is the nominal system frequency.

A_M is the single frequency interfering signal amplitude. Anti-phase cancellation requires A_a = A_M. The amplitude modulation has no effect on the frequency and is ignored. Frequency is the derivative of the cosine argument (see 4.4) so the frequency of this modulated signal is:

$$f(t) = 1/2\pi\,[\omega_0 - \omega A_a \sin(\omega t)] = f_0 - f_M A_a \sin(\omega t) \quad \text{(C.6)}$$

The peak deviation of frequency from nominal (f_0) is

$$\Delta F = f_M A_a \quad \text{(C.7)}$$

where ΔF is in the same units as f_M, i.e. if f_M is in Hz, so is ΔF. Differentiating the frequency to obtain ROCOF (see Equation (8)) gives:

$$\text{ROCOF}(t) = -f_M A_a\, 2\pi f_M \cos(\omega t) \quad \text{(C.8)}$$

Substituting Equation (C.7) to get the maximum ROCOF error:

$$\text{ROCOF} = 2\pi \times \Delta F \times f_M \quad \text{(C.9)}$$

In this derivation, the modulating frequency f_M is the difference between the system frequency f_o and the (aliased) interfering signal f_{int}. And, since the ROCOF here is an undesired result of an interfering signal (i.e., ROCOF should be zero), RFE = ROCOF.

C.7 PMU reporting latency

PMU reporting latency may be thought of as the maximum time interval from when the measurement is made until the measurement is sent from the PMU. It is evaluated by comparing the difference between the timestamp in a PMU report and the time that the report begins to leave the output port (see 5.2.5 and 6.7). It may be difficult to measure the time the report leaves the PMU output port, but it can be measured indirectly by measuring the message arrival time on the input port on a system connected directly to the output port of the PMU under test. The port-to-port transition time of this setup is very small, and well within the 2 ms uncertainty allowed for this test.

In typical PMU implementations, the clock which is creating reports is disciplined to UTC, but the clock driving the reporting communications system is often not disciplined. The effect of this is that the measurement latency will likely drift over time. For this reason, measurement latency is required to be measured until the maximum value has been determined.

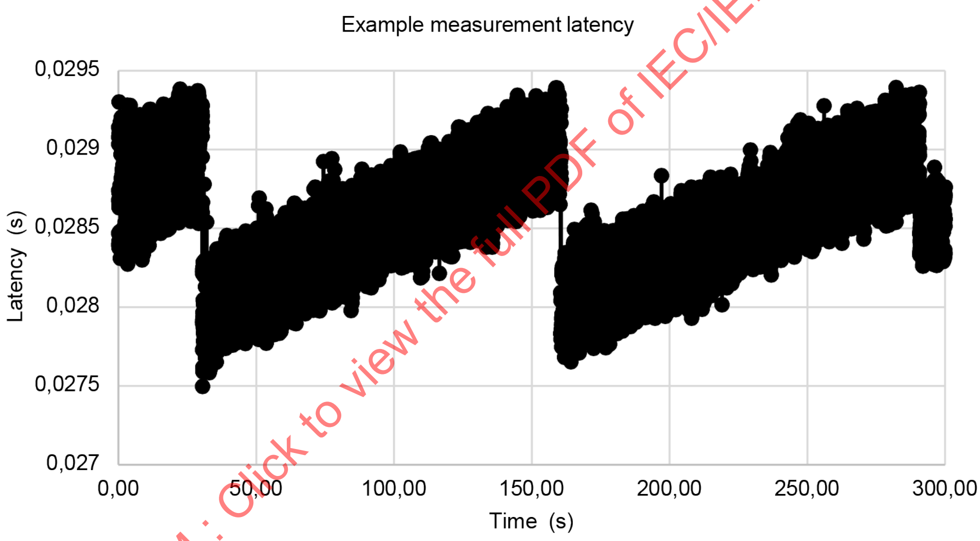


Figure C.6 – PMU reporting latency example (actual PMU measurement)

Figure C.6 is a plot of a PMU reporting latency measurement over a 300 s time interval. The measurements are made at a 30/s rate. The wide black lines show the short term variations are about 0,75 ms peak-to-peak; however there is also an overall positive drift that resets about every 130 s. The local maximum observed just before reset is the value to use for the reporting latency. This example has a positive trend so the maximum is before the reset; it is just as likely that the drift will have a negative trend and the maximum will be just after reset. This document requires an observation interval of at least 20 min to determine if the measurement latency has reached a local maximum or the latency is trending upward or downward. If no local maximum is reached during the first 20 min, and the latency is trending upward and downward, subclause 6.7 of this document requires that testing continue until a local maximum has been reached.

Annex D
(informative)

Reference signal processing models

D.1 General

Annex D presents the reference signal processing models used to develop and verify performance requirements in this document. It is given for information purposes only, and does not imply being the only (or recommended) method for estimating synchrophasors. Its purpose is to establish common ground for understanding performance requirements and confirming their achievability.

Clause D.2 includes a reference model for the general synchrophasor derivation. This model is the same for the algorithms presented in Clauses D.5 and D.7.

Clause D.3 discusses time compensation of the PMU output so the phasor, frequency, and ROCOF estimates are aligned with the time stamp.

Clause D.4 describes the estimation of the positive sequence phasor from the three single-phase phasor estimates and how to estimate frequency and ROCOF from the positive sequence phasors.

Clauses D.5, D.6 and D.7 describe the P class and M class reference models, including filter details. Clause D.8 discusses a method of reducing the PMU data rate (reporting rate) using filtering and decimation.

Clause D.9 describes trade-offs that PMU designers need to consider which affect the noise immunity, reporting latency, and time alignment of the phasor, frequency, and ROCOF estimates. Clause D.9 also discusses the accuracy and noise immunity of phasor, frequency, and ROCOF estimates in relation to the response time of the PMU.

D.2 Basic synchrophasor estimation model

Figure D.1 shows typical processing steps performed within the PMU. It assumes fixed frequency sampling synchronized to an absolute time reference, followed by complex multiplication with the nominal frequency carrier. Other implementations using frequency tracked sampling, frequency tracked carrier or nonlinear estimation methods are also possible and are permitted by this document. Depending on the algorithm and windowing, the output from this conversion may be at the original sample rate or lower.

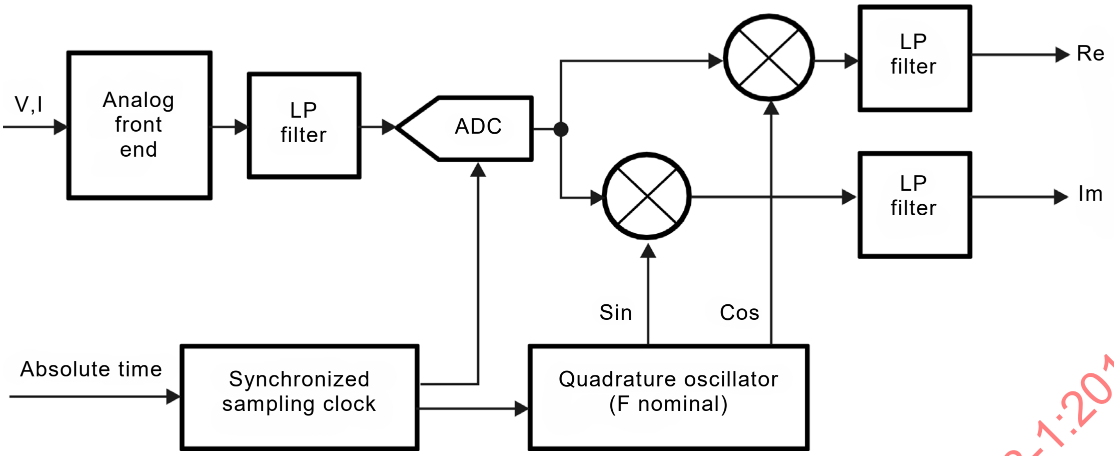


Figure D.1 – Single phase section of the PMU phasor signal processing model

Given a set of samples of a single phase of the power signal $\{x_i\}$, the synchrophasor estimate X(i) at the i^{th} sample time is:

$$X(i) = \frac{\sqrt{2}}{G} \times \sum_{k=-N/2}^{N/2} x_{(i+k)} \times W_{(k)} \times \exp(-j(i+k)\Delta t \omega_0) \quad \text{(D.1)}$$

$$G = \sum_{k=-N/2}^{N/2} W(k) \quad \text{(D.2)}$$

where

G is the gain;

ω_0 is the angular frequency $2\pi f_0$ where f_0 is the nominal power system frequency (50 Hz or 60 Hz);

N is the FIR filter order (number of filter taps is equal to N + 1);

Δt is the sampling interval (1/Sampling Frequency);

x_i is the sample of the waveform at time $t = i\ \Delta t$, where the time t = 0 coincides with a 1 s rollover;

$W_{(k)}$ is the low pass filter coefficients (depending on P or M class filtering).

Equation (D.1) represents the complex demodulation and low pass filtering shown in Figure D.1. $\exp(-j(i+k)\Delta t \omega_0)$ is Euler's equation and includes multiplication of the input by the quadrature oscillator (sine and cosine) shown in Figure D.1 above. The low pass filtering ($W_{(k)}$) can be applied individually to the real and imaginary outputs of the complex demodulator as shown in Figure D.1.

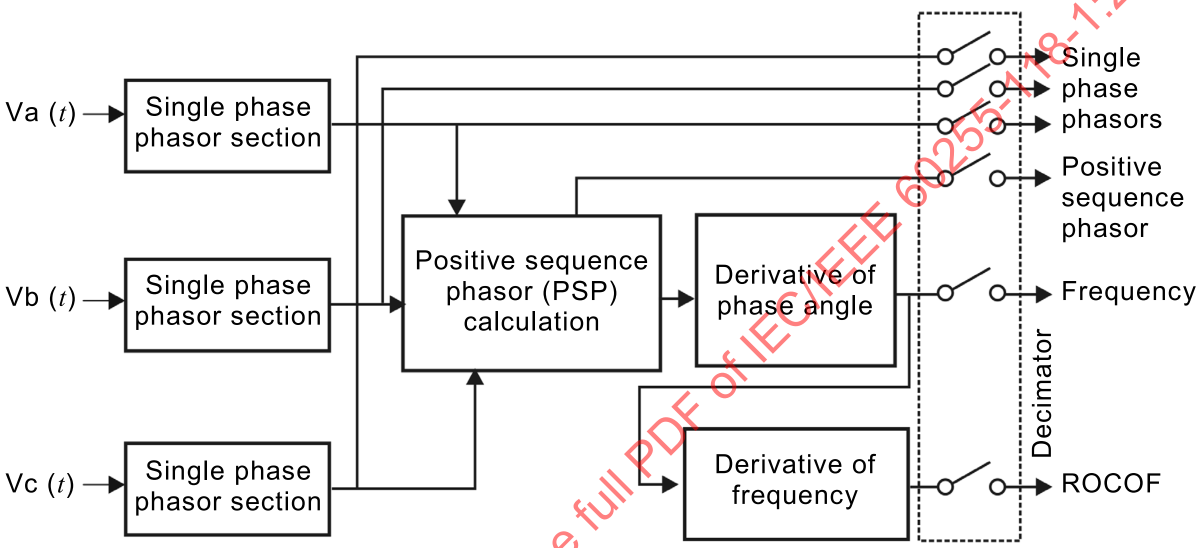
D.3 Timestamp compensation for low-pass filter group delay

The timestamp of the PMU output represents the phasor equivalent, frequency, and ROCOF of the power system signal at the time it is applied to the PMU input. All of these estimates shall be compensated for PMU processing delays including analog input filtering, sampling, and estimation group delay. If the sample time tags are compensated for all input delays, the time tag of the sample in the middle of the estimation window can be used for the phasor estimation (output) time tag as long as the filtering coefficients are symmetrical across the filtering window.

This method of group delay compensation is used with both the P class and the M class algorithms presented in Annex D.

The filter coefficients for P class and M class low-pass filters are listed below in Clauses D.6 and D.7. Filter order for FIR filters is determined by the number of elements in the filter; the order is one less than the number of elements (taps) of the filter. For example, a 1 cycle Fourier filter using 16 samples/cycle is a N = 16 – 1 = 15th order filter. Examples provided in Annex D use even order filters (odd number of taps). Resulting filter group delay is an integer multiple of the sampling frequency: $G_d = N/2 \times \Delta t$.

D.4 Positive sequence, frequency, and ROCOF



NOTE All processing shown is at the ADC sampling rate; reporting rate is produced by resampling at the system output (decimator stage).

Figure D.2 – Complete PMU signal processing model

The normal positive sequence voltage phasor in Figure D.2 is calculated using the symmetrical component transformation. Frequency is then calculated from the rate of change of phase angle of the positive sequence [9]. Since phase angle changes relative to the difference between the actual frequency and the nominal frequency, this approach yields the offset from nominal. This frequency estimation method uses phase angles estimated internally at the waveform sample rate of the PMU (not the decimated phase angles reported by the PMU). To estimate the frequency, two phase angles, one before and one after the estimation point (i), are used. The frequency estimation algorithm for the frequency at the i^{th} phase estimate is shown in Equation (D.3):

$$\Delta F(i) = [\theta(i+1) - \theta(i-1)] / [4\pi \times \Delta t] \quad \text{(D.3)}$$

where

$\theta(i)$ is the angle of the i^{th} positive sequence estimate $X(i)$;

$\theta(i+1)$ is the angle of the phasor estimate following the i^{th} estimate;

$\theta(i\text{-}1)$ is the angle of the previous estimate.

Using the same angle estimates, the ROCOF estimate is computed as shown in Equation (D.4):

$$DF(i) = [\theta(i+1) + \theta(i-1) - 2\theta(i)] / [2\pi \times \Delta t^2] \quad \text{(D.4)}$$

The i^{th} frequency estimate is exactly aligned with the i^{th} phasor estimate by waiting for the next internal phasor estimate $\theta(i + 1)$ and then computing frequency using one angle ahead and one angle behind the i^{th} phasor. When the i^{th} phasor, frequency, and ROCOF are reported together, the report shall be delayed until the next internal phasor is available. This delay is one internal sample period (Δt), which is small. Many other frequency and ROCOF estimation methods such as 2nd order fit or weighted least squares will also meet the requirements of this document, but all methods will require trade-offs which are discussed in Clause D.9. Simple finite difference equations like these are commonly used but are also very sensitive to noise.

D.5 P Class reference model for phasor

The P Class phasor estimation algorithm presented here uses fixed length two cycle triangular weighted FIR filter which is not changed for different PMU reporting rates. This reference algorithm implementation uses a sample rate of 16 samples/cycle, which is 60 × 16 = 960 samples/s for a 60 Hz system or 50 × 16 = 800 samples/s for a 50 Hz system. This algorithm can be implemented using the triangular window coefficients shown in Figure D.3 (with filter order N being equal to N = 2 × (16 – 1) = 30) or in two stages with a one-cycle Fourier conversion followed by uniform averaging over one cycle (cascaded boxcar filter approach). As long as the sample times are compensated for input delays, the timestamp at the centre of the window produces an estimate whose phase follows the actual power system frequency and does not need further phase or delay correction. It does require magnitude correction for off nominal frequency which is applied to the final phasor based on the frequency estimate.

D.6 P class filter details

The P class filter coefficients $W_{(k)}$ are defined as:

$$W_{(k)} = (1 - \frac{2}{N+2}|k|) \qquad \text{(D.5)}$$

where

k = $-N/2$: $N/2$ (integer values only)

N is the filter order (N = (16 – 1) × 2 = 30 for sampling frequency example with 16 samples per cycle)

These filter coefficients are plotted in Figure D.3.

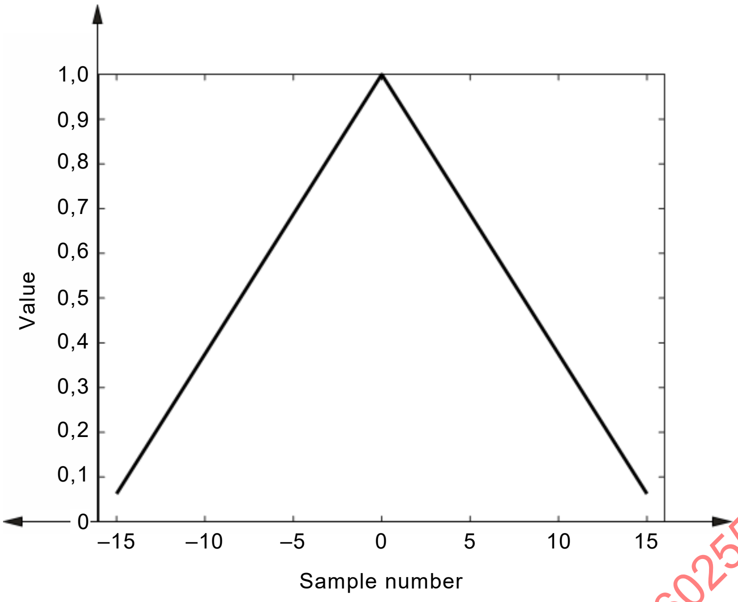
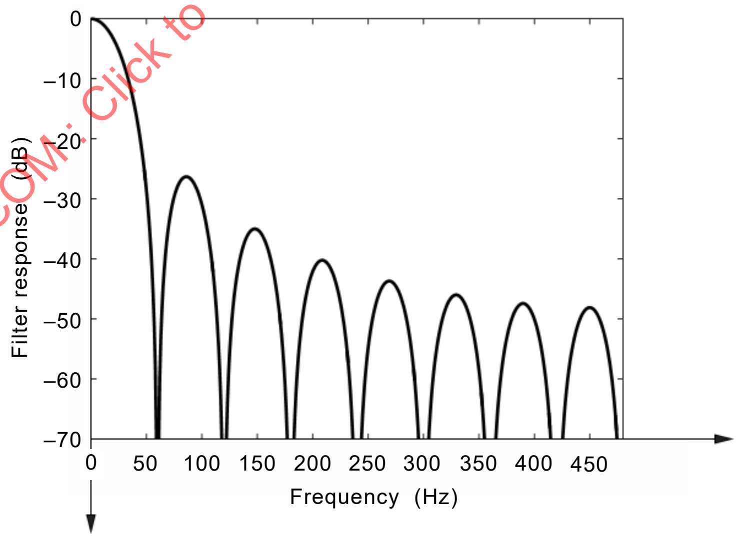


Figure D.3 – P class filter coefficient example (N = 2 × (16 – 1) = 30)

The P class filter is effective at the nominal frequency for all but out-of-band rejection. For off nominal frequency, the period of estimation does not match the actual period of the signal. Phase estimation is accurate because the signal is centered on the estimate. However, the estimate magnitude rolls off and needs compensation. The harmonic rejection is excellent when the conversion matches the system frequency. When it does not, such as under off-nominal frequency, harmonics are not fully suppressed, which causes some problems with frequency and ROCOF estimation.

The phasor magnitude will roll off as the actual signal frequency deviates from f_0. The result is a $(\sin(x)/x)^2$ curve determined by the 2-cycle low pass filter response shown in Figure D.4.



NOTE The example shows: f_0 = 60Hz, $f_{sampling}$ = 16 x 60 = 960Hz, N = 2 × (16-1) = 30.

Figure D.4 – P class filter response as a function of frequency

Over a limited frequency range, this deviation can be compensated by dividing the phasor magnitude by the P class filter response at the measured frequency. With this algorithm, the phase angle measurement is accurately computed at all frequencies using the estimate centered in the window. The magnitude is compensated by dividing the magnitude with a sine at the actual signal frequency. The two cycle triangular window produces a faster roll-off than a standard one cycle rectangular window, so the frequency deviation is spread with an additional factor of 1,625 to increase compensation (the factor was derived experimentally) as shown in the following formula:

$$\hat{X}(i) = \frac{X(i)}{\sin\left(\pi \frac{(f_0 + 1{,}625 \Delta F(i))}{2 f_0}\right)} \quad \text{(D.6)}$$

where

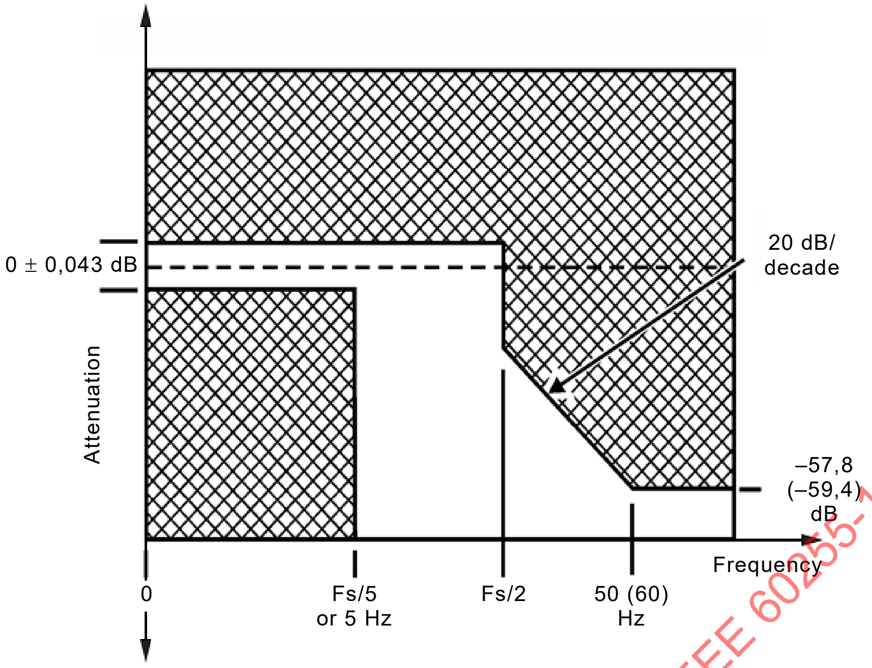
$\Delta F(i)$ is the deviation of frequency from nominal computed at point i.

Formula (D.6), Formula (D.3), and Formula (D.4) are used for synchrophasor, frequency, and ROCOF estimation respectively in the P class model.

D.7 M class reference model for phasor

The principal difference between P class and M class is that the M class has a requirement for filtering to significantly attenuate signals that are above the Nyquist frequency for the given reporting rate. This filtering will result in longer reporting delays but will also reduce the likelihood of aliasing and will improve the frequency estimate in the presence of noise and interfering signals, particularly as determined by the steady-state out-of-band interfering signals test. Because of the required filtering, the M class can produce somewhat higher accuracy, a fact that is reflected in the requirements.

The M class requirements for passband and stopband filtering are shown in Figure D.5. The figure is based on the M class requirements given in Table 2 and Table 4, with corner frequency specifications linked to the PMU reporting rate. This mask is used as the mask for designing the reference filter. A finite impulse response (FIR) filter implementation was used to achieve linear phase response. The reference filter coefficients were obtained by using well known "brick wall" filter design methodology based on "sinc" function $\frac{\sin(x)}{x}$ multiplied with a Hamming window. The filter order (length) is adjusted to meet frequency response requirements. This model assumes correct implementation of the front end scaling, anti-aliasing filter, A/D converter and adequate sampling rate which was set to 960 Hz in this example.



NOTE The frequency response curve is within the unshaded region.

Figure D.5 – Reference algorithm filter frequency response mask specification for M Class

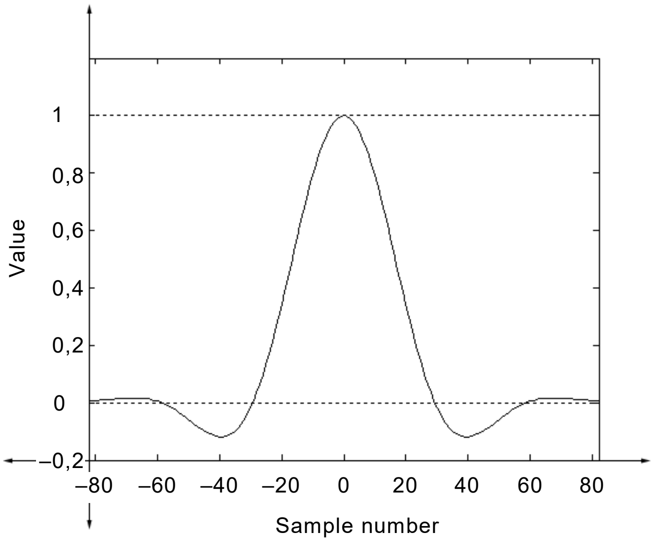
For Figure D.5, the filter response shall remain outside the shaded areas.

Equation D.7 produces a vector of filter coefficients:

$$W(k)=\frac{\sin\left(2\pi\times\frac{2F_{\text{fr}}}{F_{\text{sampling}}}\times k\right)}{2\pi\times\frac{2F_{\text{fr}}}{F_{\text{sampling}}}\times k}h(\text{k}) \qquad \text{(D.7)}$$

where

k	= – N/2: N/2;
N	is the filter order from Table D.1;
F_{fr}	is the low pass filter reference frequency from Table D.1;
F_{sampling}	is the sampling frequency of the system (960 samples/second for the 60 Hz reference model);
$h(\text{k})$	is the hamming function;
$W(0)$	= 1 (note when k = 0, W = 0/0 is indeterminate and shall be replaced by 1).



NOTE F_s = 60 fps, $F_{sampling}$ = 960 Hz, N = 164.

Figure D.6 – M class filter coefficient example

Table D.1 shows input parameters to generate the filter coefficients used to verify limits in this document. It is given for information purposes only, and does not imply being the only (or recommended) filter.

Table D.1 – M class low pass filter parameters

Reporting rate F_s		Filter reference frequency F_{fr} (Hz)	Filter order N
50 Hz	10	1,779	806
	25	4,355	338
	50	7,75	142
	100	14,1	66
60 Hz	10	1,78	968
	12	2,125	816
	15	2,64	662
	20	3,50	502
	30	5,02	306
	60	8,19	164
	120	16,25	70

D.8 Data rate reduction model

The reference model shown in Figure D.1 and Figure D.2 can be used to directly produce any of the output rates shown in Table 1 (see 5.3.2). If the PMU produces phasors, frequency, and ROCOF internally at a high rate and reduces the data stream for output, similar filters can be used to perform further decimation (derive lower rates) for M class outputs as shown in Figure D.7. This method can be used when multiple rate outputs are required from the same PMU and in the case of a phasor data concentrator (PDC) application. It is important to observe that the out-of-band rejection requirements specified in this document for M class apply equally to lower frequency (decimated) synchrophasor data streams produced by both PMUs and PDCs. Consequently, decimated output data (lower rates) generated by the PDC are expected to remain comparable (have the same dynamic behaviour) as those generated by the PMU. These same methods can be used for P class, but the additional filtering is not required. P class data reduction can be accomplished by a simple 1/N resampling (i.e., taking every N^{th} sample).

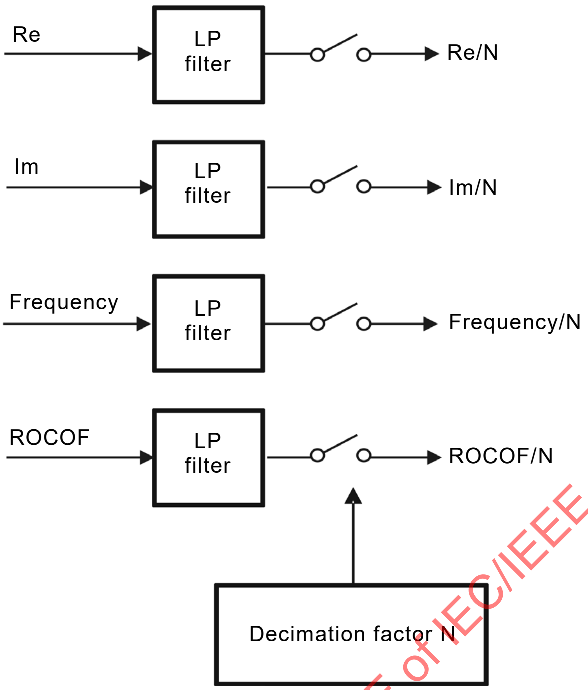


Figure D.7 – Data rate reduction signal processing model

D.9 Trade-offs in the reference model

D.9.1 Immunity to off-nominal components, reporting latency and time alignment

Designers and users of PMUs need to consider three interrelated factors affecting the estimation of phasors, frequency and ROCOF. The three factors, shown in Figure D.8, are:

- immunity to noise, such as harmonics, interharmonics (out-of-band interfering signals), or modulations on the input signal;
- alignment of the phasor, frequency and ROCOF estimation to the timestamp of the phasor estimation;
- reporting latency (the time to complete the estimations and transmit from the PMU).

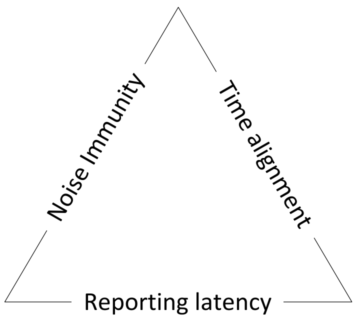


Figure D.8 – Factors affecting estimation

The PMU reference model was designed to have relatively short reporting latency and good time alignment between the phasor, frequency and ROCOF estimates. Good alignment and short latency comes at the cost of some immunity, as illustrated in Figure D.8. This model is meant to verify PMU performance limits, be relatively simple to understand and implement, and leave margin for actual PMUs. It is not intended to illustrate the ideal solution.

D.9.2 Response time and the accuracy of synchrophasors, frequency and ROCOF measurements

The accuracy of the synchrophasors, frequency, and ROCOF measurements, when non-fundamental components are present in the signals, is directly affected by the reference filter gain and frequency response. In particular, the frequency components beyond the Nyquist frequency (half the value of the applied reporting rate) should be attenuated.

Figure D.9 exhibits the gain/frequency response of the reference filter with a reporting rate F_s = 60 fps and a data acquisition sampling frequency of 960 Hz. The attenuation level beyond the Nyquist frequency of 30 Hz is greater than 50 dB.

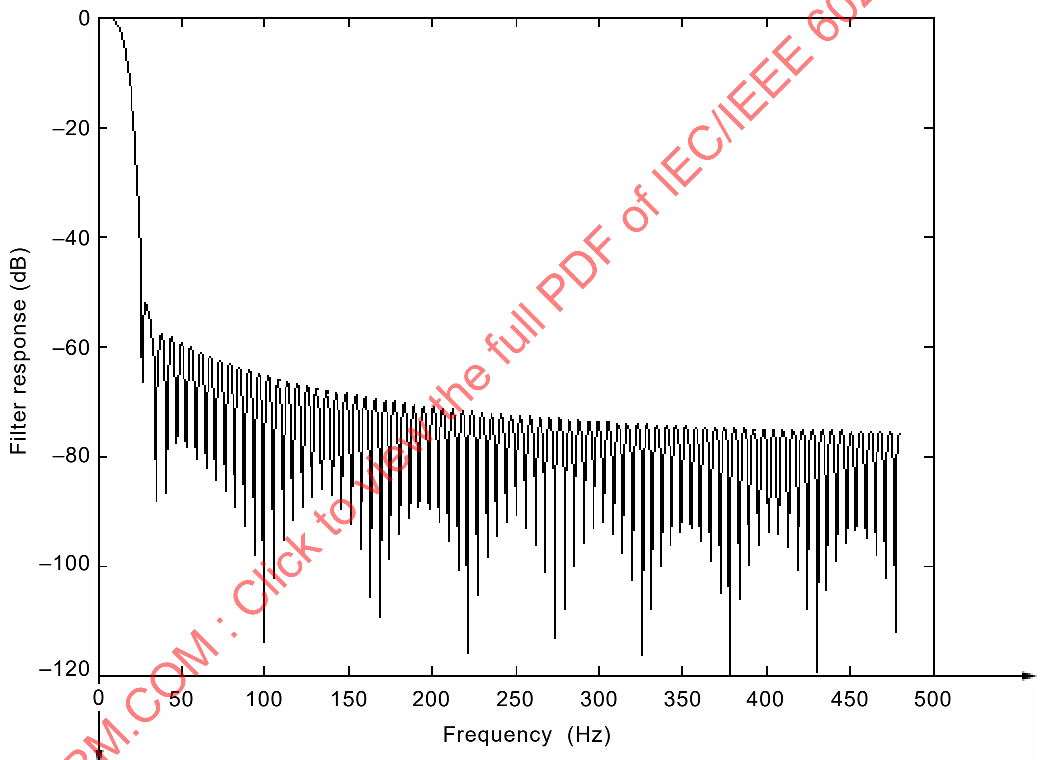


Figure D.9 – Reference filter magnitude frequency response with F_s = 60 fps

Let us assume as an example that the voltage signals are at fundamental frequency with some added 2nd harmonic component. After the demodulation has taken place when applying the reference algorithm, the 2nd harmonic component will translate into two frequency components at 60 Hz and 180 Hz that are above the Nyquist frequency. The impact of the 2nd harmonic on the synchrophasor, frequency and ROCOF measurement accuracy depends on the attenuation provided by the reference filter at these two specific components: the higher the attenuation, the better the measurement accuracy. The same rationale could be applied to any non-fundamental component.

The model reference filter has been designed so that it allows a fast response time (66 ms for a 10° phase step at F_s = 60 fps) together with a good accuracy for the synchrophasor measurement. Better accuracy figures could be obtained for the frequency and ROCOF measurements by increasing the attenuation level beyond the Nyquist frequency, but that would be done at the expense of the synchrophasor measurement response time, which would become slower.