IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE Power & Energy Society

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Power System Relaying Committee

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USA

28 December 2011

IEEE Std C37.118.1™-2011
(Revision of
IEEE Std C37.118™-2005)

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Approved 7 December 2011

IEEE-SA Standards Board

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Abstract: Synchronized phasor (synchrophasor) measurements for power systems are presented. This standard defines synchrophasors, frequency, and rate of change of frequency (ROCOF) measurement under all operating conditions. It specifies methods for evaluating these measurements and requirements for compliance with the standard under both steady-state and dynamic conditions. Time tag and synchronization requirements are included. Performance requirements are confirmed with a reference model, provided in detail. This document defines a *phasor measurement unit* (PMU), which can be a stand-alone physical unit or a functional unit within another physical unit. This standard does not specify hardware, software, or a method for computing phasors, frequency, or ROCOF.
Keywords: data concentrator, DC, FE, frequency error, IEEE C37.118.1, IRIG-B, PDC, phasor, phasor measurement, phasor measurement unit, PMU, RFE, ROCOF, ROCOF error, synchronized phasor, synchrophasor, total vector error, TVE

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Introduction

This introduction is not part of IEEE Std C37.118.1-2011, IEEE Standard for Synchrophasor Measurements for Power Systems.

The original synchrophasor standard was IEEE Std 1344™-1995 [B5].[a] It was replaced by IEEE Std C37.118-2005 [B8]. This has now been split into two standards: IEEE Std 37.118.1-2011 (this standard), covering measurement provisions, and IEEE Std 37.118.2™-2011 [B9], covering data communication. Both standards contain the previous material with updates and additional provisions.

In this standard, additional clarification is provided for the phasor and synchronized phasor definitions. The concepts of total vector error (TVE) and compliance tests are retained and expanded, tests over temperature variation have been added, and dynamic performance tests have been introduced. In addition, limits and characteristics of frequency measurement and rate of change of frequency (ROCOF) measurement have been developed. Annex C includes a system model intended to verify the ability to implement the required performance measures. The model is meant as a reference benchmark only; it is assumed that many real implementations will surpass this model in performance.

Phasors are used in many protection and data acquisition functions. By referencing them to a common time base they become comparable over a wide area of measurement. A synchrophasor is a phasor value obtained from voltage or current waveforms and precisely referenced to a common time base. Simultaneous measurement sets derived from synchronized phasors provide a vastly improved method for tracking power system dynamic phenomena for improved power system monitoring, protection, operation, and control.

The intent of any instrument connected to the power grid is to monitor power system parameters. The intent of this standard is to describe and quantify the performance of the *phasor measurement unit* (PMU) instrument deployed to monitor the power grid. The PMU extracts the parameters magnitude, phase angle, frequency, and ROCOF from the signals appearing at its input terminals. These signals may be corrupted by harmonic content, noise, and changes in state caused by system loads, and control and protective actions. Some examples are harmonics introduced by large non-linear loads, step changes in phase introduced by switched reactive elements, and random noise from arc furnaces. These artifacts complicate the process of measuring the generation and load characteristics at or near the system fundamental frequency.

The filtering associated with the computation of the synchrophasors rejects the undesirable signal components appearing at the PMU input within the limits provided by the filter attenuation. The frequency is computed as the first derivative of the synchrophasor phase angle, and ROCOF is computed as the second derivative of the same phase angle. These two quantities are less reliable measurements, particularly ROCOF, because they are more sensitive to undesirable components in the signal like harmonics, off-nominal components, or noise.

This standard 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 shall be aware that in the presence of the previously mentioned undesirable components in the input signal, 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. They are difficult to implement in a real-time environment and could adversely affect the measurement latency or the synchrophasor measurement response time. Alternatives are neither described nor evaluated in this document.

[a]The numbers in brackets correspond to those of the bibliography in Annex A.

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1. Overview

1.1 Scope

This standard is for synchronized phasor measurement systems in power systems. It defines a synchronized phasor (synchrophasor), frequency, and rate of change of frequency (ROCOF) 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 standard does not specify hardware, software, or a method for computing phasors, frequency, or ROCOF.

1.2 Purpose

This standard defines synchronized phasor and frequency measurements in substations along with methods and requirements for measurement verification. Measurements compliant with the standard and taken at various locations in the power system can be readily and accurately combined for power system analysis and operations. Time tag and other essential associations are also described to facilitate communication and reliable data application. Communication and recording of phasor measurements are covered in other standards, such as the companion standard IEEE Std C37.118.2™-2011 [B9].[1]

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1.3 General overview

This standard covers synchronized phasor measurements used in electric power systems. It defines the measurement, provides methods of quantifying the measurements, defines performance tests, and specifies acceptable limits. The following clauses are provided:

— Clause 1 provides the scope and needs for the standard.

— Clause 2 references other standards that are related or may be useful in the study and application of this standard.

— Clause 3 defines terms and abbreviations found in this standard.

— Clause 4 defines the measurement.

— Clause 5 defines measurement requirements, a method of quantifying the measurement, a test method, and accuracy limits.

Six informative annexes are also provided to clarify the standard and give supporting information, as follows:

— Annex A is a bibliography.

— Annex B explores the effects of time tagging and transient response relevant to this measurement technique.

— Annex C provides the algorithms that were used to confirm the performance requirements.

— Annex D discusses time synchronization.

— Annex E explains the total vector error (TVE) concept of measurement quality and gives plots of error results.

— Annex F describes two methods that can be used for measuring the internal voltages and power angles of generators.

1.4 Need for this standard

The 2005 version of the standard, commonly followed by equipment manufacturers and system integrators, specifies the performance of phasor measurements only under steady-state conditions. Synchrophasor applications, particularly during severe system disturbances, will utilize dynamic synchronized measurements. This revision of the standard extends the synchrophasor definition and specifies measurement requirements and test conditions to include practical dynamic power system conditions.

The original synchrophasor standard, IEEE Std 1344™-1995 [B5], and its successor, IEEE Std C37.118™-2005 [B8], provide for reporting of system frequency and rate of change of system frequency. These quantities are not defined, however, and no measurement requirements are mandated.

This revision provides definition and measurement requirements for power system frequency and ROCOF under practical power system conditions. A number of issues in the standard have been identified that require clarification or modification. This revision also separates the measurement and communication subclauses of IEEE Std C37.118-2005 [B8] into individual standards. This simplifies widespread adoption and aids deployment by allowing freer use of other standards for synchrophasor communication.

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2. Normative references

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IEEE Std 754™-1985, IEEE Standard for Binary Floating-Point Arithmetic.[2, 3]

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions* [B2] should be consulted for terms not defined in this clause.[4]

3.1 Definitions

anti-aliasing: The process of filtering a signal before sampling to remove components of that signal whose frequency is equal to or greater than the Nyquist frequency (one-half the sample rate). If not removed, these signal components would appear as a lower frequency component (an alias).

Coordinated Universal Time (UTC): (Initials are ordered based on French language.) The time of day at the Earth's prime meridian (0° longitude). It is distributed by various media, including the Global Positioning System (GPS) system.

data concentrator (DC): A device that combines data from several measurement devices.

frequency error (FE): The measure of error between the theoretical frequency and the measured frequency for the given instant of time.

Global Positioning System (GPS): A U.S. Department of Defense (DoD) navigation system that uses a constellation of 24 satellites broadcasting a precision signal for location and time synchronization. Basic time synchronization accuracy is ± 0.2 microseconds (μs).

IEEE floating point: A 32-bit representation of a real number.

NOTE—This definition is in accordance with IEEE Std 754-1985.[5]

leap second: A positive or negative one-second adjustment to the Coordinated Universal Time (UTC) that keeps it close to mean solar time.

Nyquist frequency: A frequency that is one-half the sampling frequency of a discrete signal processing system.

Nyquist rate: A sampling rate that is twice the bandwidth of a band-limited signal. It is the minimum sample rate that will result in an alias-free representation of a signal. It must therefore be greater than twice the highest frequency component in the signal.

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phasor: A 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.

phasor data concentrator (PDC): A data concentrator (DC) used in phasor measurement systems.

rate of change of frequency (ROCOF) error (RFE): The measure of error between the theoretical ROCOF and the measured ROCOF for the given instant of time.

synchronism: The state in which connected alternating-current systems, machines, or a combination operate at the same frequency, and in which the phase angle displacements between voltages in them are constant or vary about a steady and stable average value.

synchronized phasor or synchrophasor: A phasor calculated from data samples using a standard time signal as the reference for the measurement.

NOTE—In this standard, the phasors from remote sites have a defined common phase relationship.

total vector error (TVE): The measure of error between the theoretical phasor value of the signal being measured and the phasor estimate.

NOTE—See 5.2.

3.2 Special terms

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

phasor measurement unit (PMU): In this standard, a device that produces synchronized phasor, frequency, and ROCOF estimates from voltage and/or current signals and a time synchronizing signal. Note that the same device may perform other functions and include another functional name [e.g., the device may also record power system waveforms and be called a *digital fault recorder* (DFR)].

3.3 Acronyms and abbreviations

BCD	binary coded decimal
DoD	U.S. Department of Defense
f_0	system nominal frequency, either 50 Hz or 60 Hz
f_{in}	Input frequency of the fundamental; this is the frequency of the measurement input that 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)
IRIG-B	InterRange Instrumentation Group Time Code Format B
PPS	pulse per second
rms	root mean square

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ROCOF	rate of change of frequency
SBS	straight binary seconds
SCADA	Supervisory Control and Data Acquisition
SOC	second of century
THD	total harmonic distortion

4. Synchrophasor measurement

4.1 Phasor definition

Phasor representation of sinusoidal signals is commonly used in ac power system analysis. The sinusoidal waveform defined in Equation (1):

$$x(t) = X_m \cos(\omega t + \phi) \tag{1}$$

is commonly represented as the phasor as shown in Equation (2):

$$\begin{aligned} \boldsymbol{X} &= (X_m/\sqrt{2})\, e^{j\phi} \\ &= (X_m/\sqrt{2})(\cos\phi + j\sin\phi) \\ &= X_r + jX_i \end{aligned} \tag{2}$$

where the magnitude is the root-mean-square (rms) value, $X_m/\sqrt{2}$, of the waveform, and the subscripts r and i signify real and imaginary parts of a complex value in rectangular components. The value of ϕ depends on the time scale, particularly where $t = 0$. It is important to note this phasor is defined for the angular frequency ω; evaluation with other phasors must be done with the same time scale and frequency.

4.2 Synchrophasor definition

The *synchrophasor* representation of the signal $x(t)$ in Equation (1) is the value $\boldsymbol{X}$ in Equation (2) where ϕ is the instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to UTC.

Under this definition, ϕ is the offset from a cosine function at the nominal system frequency synchronized to UTC. A cosine has a maximum at $t = 0$, so the synchrophasor angle is 0 degrees when the maximum of $x(t)$ occurs at the UTC second rollover (1 PPS time signal), and –90 degrees when the positive zero crossing occurs at the UTC second rollover (sin waveform). Figure 1 illustrates the phase angle/UTC time relationship.

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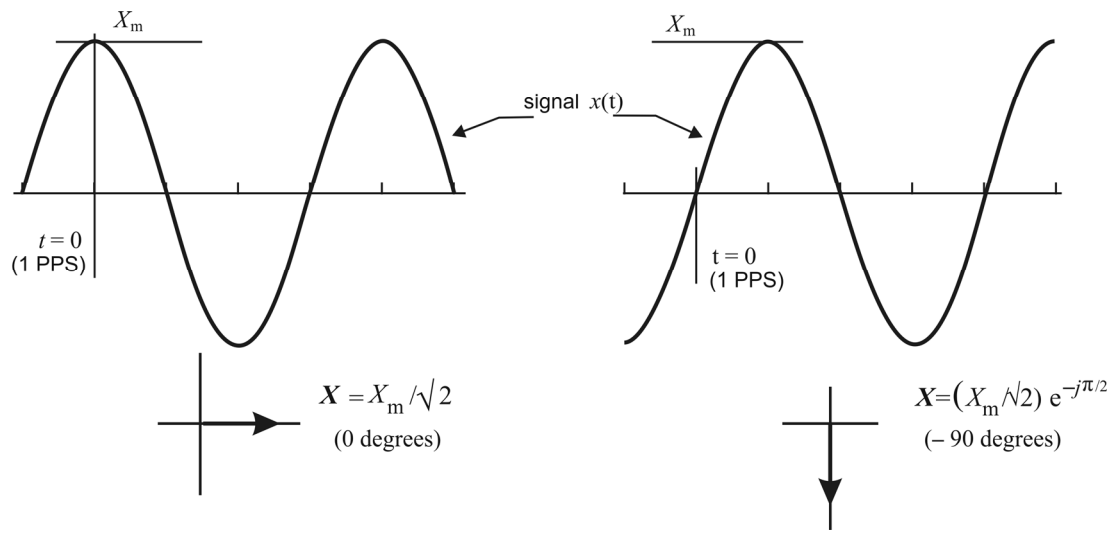

Figure 1—Convention for synchrophasor representation

The sinusoid is shown in Equation (3):

$$x(t) = X_m \cos(\omega_0 t + \phi) = X_m \cos(2\pi f_0 t + \phi) \tag{3}$$

where f_0 is the nominal angular system frequency (50 Hz or 60 Hz) directly represented by the phasor in Equation (2). In the general case where the amplitude is a function of time $X_m(t)$ and the sinusoid frequency is also a function of time $f(t)$, we can define the function $g = f - f_0$ where f_0 is the nominal frequency and g is the difference between the actual and nominal frequencies (note that g will also be a function of time, e.g., $g(t) = f(t) - f_0$. The sinusoid can then be written as shown in Equation (4):

$$\begin{aligned} x(t) &= X_m(t) \cos(2\pi \textstyle\int f \mathrm{d}t + \phi) \\ &= X_m(t) \cos(2\pi \textstyle\int (f_0 + g) \mathrm{d}t + \phi) \\ &= X_m(t) \cos(2\pi f_0 t + (2\pi \textstyle\int g \mathrm{d}t + \phi)) \end{aligned} \tag{4}$$

The synchrophasor representation for this waveform is shown in Equation (5):

$$\boldsymbol{X}(t) = (X_m(t)/\sqrt{2}) e^{j(2\pi \int g \mathrm{d}t + \phi)} \tag{5}$$

For the special case where $X_m(t) = X_m$ is constant and $g = \Delta f$ is a constant offset from the nominal frequency, $\int g(t)\, \mathrm{d}t = \int \Delta f\, \mathrm{d}t = \Delta f\, t$ so the synchrophasor is simply as shown in Equation (6):

$$\boldsymbol{X}(t) = (X_m/\sqrt{2}) e^{j(2\pi \Delta f\, t + \phi)} \tag{6}$$

that will rotate at the uniform rate Δf, the difference between the actual and off-nominal frequency.

This concept is illustrated in Figure 2. Consider that a sinusoid off-nominal system frequency is observed at intervals $\{0, T_0, 2T_0, 3T_0, .., nT_0, \ldots\}$ where $T_0 = 1/f_0$ (the nominal power system period) and the corresponding phasor representations are $\{\boldsymbol{X_0, X_1, X_2, X_3, \ldots X_n, \ldots}\}$. If the sinusoid frequency $f \neq f_0$ and $f < 2f_0$, the observed phasor will have a constant magnitude, but the phase angles of the sequence of phasors $\{\boldsymbol{X_0, X_1, X_2, X_3, \ldots X_n, \ldots}\}$ will change uniformly at a rate $2\pi(f - f_0)T_0$, as illustrated. If these values were reported over time, they would continuously increase until they reached 180 degrees where they would wrap around to –180 degrees and continue to increase as shown in Figure 3 (synchrophasors are commonly reported in angles –180 degrees to +180 degrees rather than 0 to 360 degrees).

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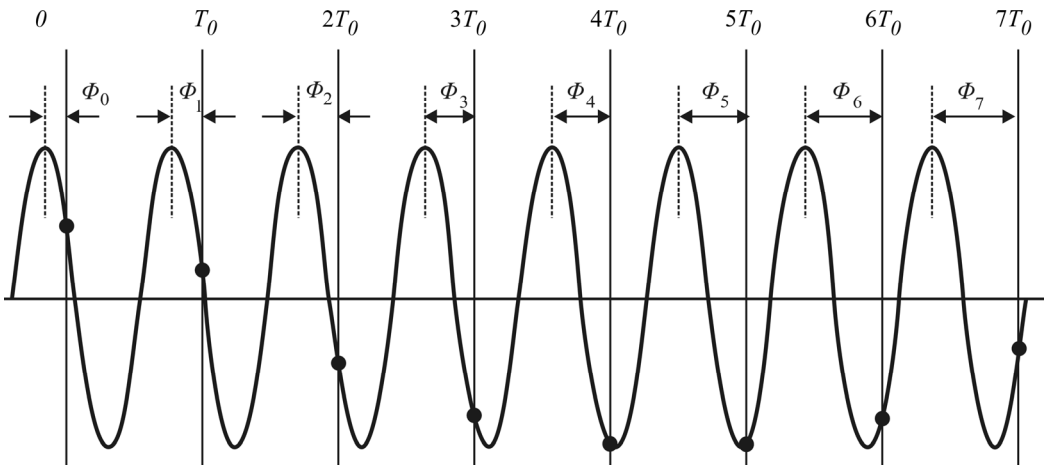

Figure 2—A sinusoid with a frequency $f > f_0$ is observed at instants that are T_0 seconds apart—the phase angle Φ increases uniformly in relation to the frequency difference, $f - f_0$

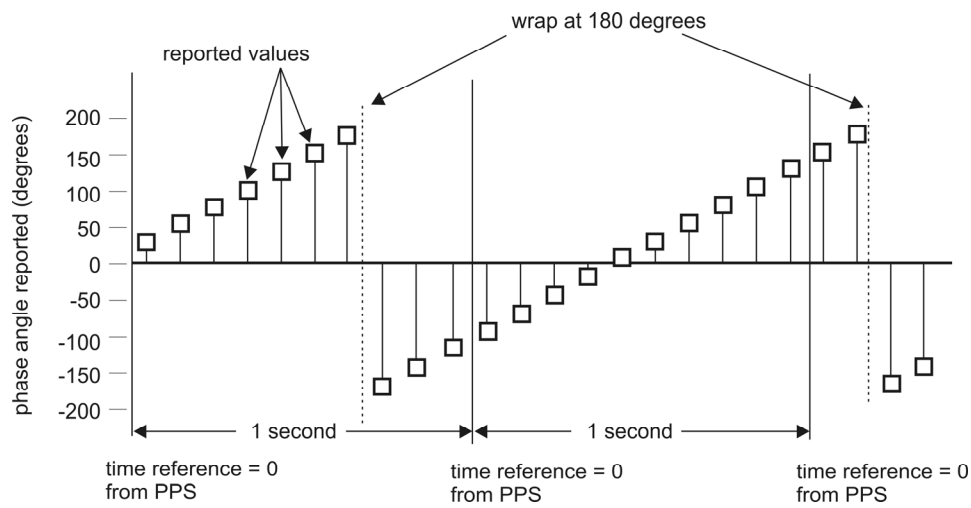

Figure 3—Sampling a power frequency sinusoid at off-nominal frequency

Several details of the synchrophasor definition shall be emphasized. All measurements are on a common time base and related to a common frequency, so the phase angle measurements are directly comparable. Differences in the actual frequency are included in the phase angle estimation. The synchrophasor estimate also includes the effects of all other signal contributions such as oscillations and local frequency swings. Synchrophasors are functions of time and will change from one value to the next unless the signal is a pure sinusoid at nominal system frequency. A precise time reference (clock) is required to provide the UTC time to determine the phase angle ϕ.

4.3 Measurement time synchronization

The PMU shall be capable of receiving time from a reliable and accurate source, such as the Global Positioning System (GPS), 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 standard. Note that a time error of 1 µs corresponds to a synchrophasor phase

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