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Technique for pre-compliance testing of phasor measurement units

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ABSTRACT

This paper introduces a technique for 'pre-compliance' testing of Phasor Measurement Units (PMUs) against the dynamic requirements of the IEEE C37.118.1-2014 standard, which include dynamic and steady-state test scenarios. The tests described are a necessary, but not complete, requirement for passing the IEEE standard and quickly highlight shortcomings in PMU operation during dynamic conditions. The pre-compliance test presented in this paper only requires typical relay test equipment, with little requirement for significant temporal accuracy when initiating waveform test files. The compliance test is intended to allow PMU owners to assess a device's performance before considering its use in monitoring dynamic performance. Failure of these tests can indicate the need to recalibrate or replace the PMU or find another vendor. The described method is applied to the voltage inputs of a typical commercial PMU and the results presented. The process for the creation of test waveforms is described, along with the data analysis technique used. The test waveforms and analysis source code are made available under open source licenses.

1. Introduction

Phasor Measurement Units (PMU) provide very useful measurements for the analysis of electrical power systems. Over the last decade, PMU technology has seen considerable deployment across transmission systems. In more recent years a broad spectrum of applications where PMUs can be exploited in the distribution network, including monitoring, protection and control, have been proposed [1–3]. In these situations, the value of a PMU greatly exceeds its cost and failure of a PMU can result in missed opportunities and lost man-hours.

Many companies and institutions purchase PMUs with a degree of trust that the PMU they purchase meets particular standards. Research organisations may also operate PMUs outside their intended purposes and wish to know how well the device performs. Usually expensive equipment, with microsecond precision, is required to accurately test PMUs. In this paper, a method of achieving similar results on relatively common relay test equipment is presented.

By definition, phasors are only truly accurate when describing time invariant signals [4]. Therefore, there is a need to ensure uniformity in phasor estimation between PMUs for use with critical infrastructure. The IEEE has addressed this issue through the release of the C37.118.1a-2014 [6] standard, and its 2011 predecessor [5]. The C37.118.1 standard specifies how the error of PMU measurements is calculated and states maximum permissible errors under described steady-state and dynamic test conditions. The dynamic tests specify changes in bulk properties of the sinusoidal wave, such as magnitude, frequency and phase, and do not consider harmonic behaviour.

Although the IEEE dynamic standards have been in existence for over six years, at the time of writing, many PMUs in the marketplace commonly cite compliance against the prior version of the standard, C37.118-2005 – this edition does not mandate dynamic performance. Some devices may have been designed prior to the 2011 edition while other may struggle to meet the exacting standard; consequently their performance under dynamic scenarios is not specified by the manufacturer. Many utility companies will own and operate PMUs manufactured prior to the 2011 standard and may wish to test their performance. Other PMU operators question the consistency of phasor estimation between PMUs of differing designs, as in [6–8].

The present authors sought out and developed a technique for pre-compliance testing of PMUs against the requirements of the 2014 edition of the IEEE C37.118.1 standard. The requirements were:

- Can be applied with standard test equipment
- Widely available waveform development environment
- Assess the performance of a PMU under dynamic tests
- Be a necessary requirement for passing C37.118.1 tests

This paper describes how test waveforms have been generated to

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represent the dynamic test scenarios described in the C37.118.1a-2014 standard. These three-phase waveforms are applied to a commercially available PMU and the estimated synchrophasors are recorded. Following this, we describe how the PMU's estimated phasors can be compared against the theoretical phasors [5] without need for GPS synchronization of the test equipment. The performance of the physical PMU is discussed and compared against the synchrophasor that produced the waveform sample data. Errors in synchrophasor estimation are compared against the C37.118.1a-2014 requirements. As a sanity check the phasor estimation algorithm described in [9] was applied to the raw point on wave data files and it was found to be as accurate as described in that publication.

The technique presented aims to give PMU owners a cost effective method of determining the dynamic characteristics of their PMUs. PMU owners can then make comparisons between vendors, identify degradation in PMUs and determine if costly compliance testing or recalibration is required. In this way, PMUs suitable for protection, control and analysis applications can be identified.

2. Compliance test specifications

Test specifications for PMU devices are described in IEEE Std C37.118-2011 [5], with amendments in the 2014 update [6]. The standard describes permissible error limits for PMUs under both nominal and dynamic conditions. Phasor estimation algorithms usually expect cyclical, time invariant waveforms. Distortions in the waveform, due to system transients and other operation behaviour, cause the input to the phasor estimation algorithm to be time variant, thus the estimation is of reduced accuracy.

Phadke describes in [4,6,10] the problem of estimating phasors under dynamic conditions and reaches the conclusion that either a set of input signals should be described for which the performance of PMUs is defined, as is the approach taken in IEEE Std. C37.118.1-2011, or alternatively the phase estimation algorithms should be uniformly specified.

The IEEE standard defines two classes of PMU, M-class and P-class. P-class PMUs are optimized for accuracy in a dynamic environment, such as the bandwidth and step tests in Subclause 5.5.6 and 5.5.8; while M-class PMUs are expected to remain accurate over a wider range of frequencies (Subclause 5.5.6 and 5.5.7). Maximum permissible errors are mandated for each class of PMU under the following categories:

(1) Steady-state (subclause 5.5.5)
(2) Measurement bandwidth (subclause 5.5.6)
(3) Ramp in frequency (subclause 5.5.7)
(4) Step change in phase/magnitude (subclause 5.5.8)

The C37.118.1 standard describes how these conditions should be applied and assessed.

2.1. Total vector error

The accuracy of an estimated phasor is expressed as the Total Vector Error (TVE), in percent. TVE is a function of both magnitude error and phase angle error. The TVE is derived from the vector separating the theoretically applied phasor and the estimated phasor, see Fig. 1. The resultant vector magnitude is normalized by dividing it by the theoretical vector magnitude, giving the TVE.

A convenient method for calculating TVE, from phasors in polar format, is presented in (1); this utilizes the small angle approximation in radians and is shown graphically in Fig. 1. For small phase error ($d\phi$ in radians) and with estimated magnitude ($\hat{X}$) approximately equal to theoretical magnitude (X); the equation for TVE, from [5], can be rewritten as shown in (1). The approximation has a maximum error of -6.75×10^{-4}% when TVE = 3% due to a $d\phi = 0.03$ rad; below these values, the error is less.

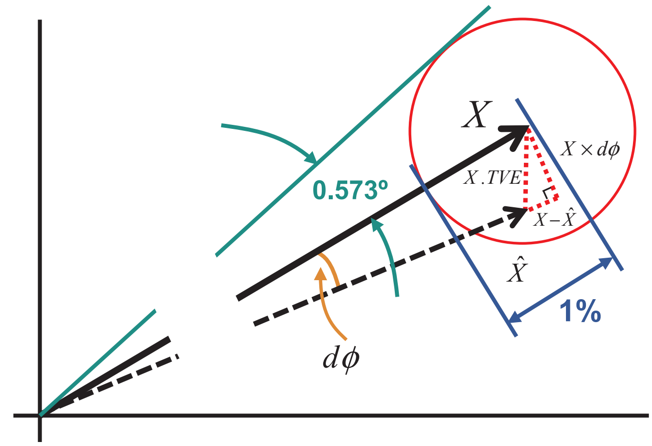

Fig. 1. Permissible region for estimated phasor, $\hat{X}$, shown as a circle around the theoretical phasor, X. Maximum magnitude error is 1%, maximum phase error is 0.573° (0.01 rad). Pythagoras' Theorem can be used to calculate TVE.

Under steady-state conditions, the maximum permissible TVE is 1%. This means that if the amplitude error is 1%, phase error must be 0°. If amplitude error is 0%, the maximum permissible phase error is ± 0.573° (0.01 rad). The standard gives definitions of the permissible error limits under each of the test conditions.

$$TVE\ (\%) = [100/X] \times \sqrt{(X-\hat{X})^2 + (\hat{X} \times d\phi)^2} \quad (1)$$

2.2. Measurement bandwidth

Measurement bandwidth is assessed by applying sinusoidal amplitude and phase modulation to a set of balanced three-phase voltage and current waveforms. This is expressed mathematically in [5] as shown in Eq. (2), the revised application of Eq. (2) in the test environment is described in [6].

$$X_1 = X_m[1 + k_x\cos(\omega t)] \times \cos[w_0 t + k_a\cos(\omega t-\pi)] \quad (2)$$

where X_1 is the positive sequence component

X_m is the amplitude of the input signal
ω_0 is the nominal frequency of the power system
ω is the modulation frequency in radians/s
k_x is the amplitude modulation factor
k_a is the phase angle modulation factor

The maximum TVE over the range of measurement bandwidth tests (Sub 5.5.6) must not exceed 3%. P-class PMUs are to be assessed in the range from 0.1 Hz to the lesser of 2 Hz to Fs/10 (5 Hz, where Fs is PMU reporting rate, in this case 50 frames per second); M-class PMUs are assessed to the lesser of 5 Hz to Fs/5 (10 Hz). The accuracy of frequency and Rate-of-Change-of-Frequency (ROCOF) estimation are also stipulated for this test [6].

2.3. Ramp in frequency

PMUs are subjected to a linear ramp in system frequency, applied as balanced three-phase input signals. The positive sequence signal corresponding to this test is described mathematically in [5] as shown in Eq. (3):

$$X_1 = X_m\cos[\omega_0 t + \pi R_f t^2] \quad (3)$$

where X_1 is the positive sequence component

X_m is the amplitude of the input signal