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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 (dϕ 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 dϕ = 0.03 rad; below these values, the error is less.

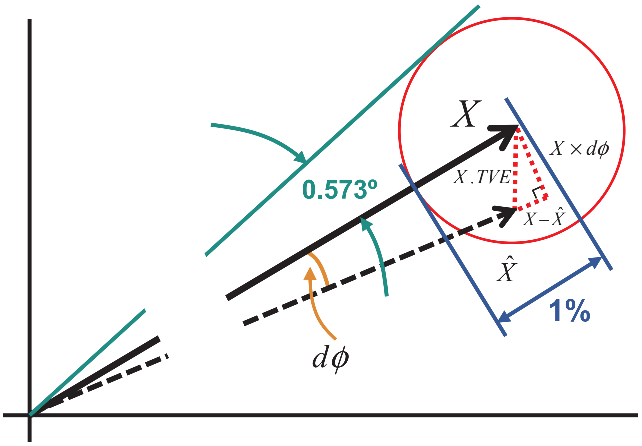

Fig. 1. Permissible region for estimated phasor, $\hat{X}$, shown as a circle around the theoretical phasor, X. Maximum magnitude error is 1%, maximum phase error is 0.573° (0.01 rad). Pythagoras' Theorem can be used to calculate TVE.

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.

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

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].

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

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):

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

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
R_f is the frequency ramp rate in Hz/s (df/dt)

Tests are started with 100% rated signal amplitude and at nominal frequency. Ramps are applied at rates of ± 1.0 Hz/s (positive and negative). For Synchrophasor estimation, in order to be compliant, a P-class PMU must maintain 1% TVE over a range of ± 2 Hz from nominal frequency and an M-class PMU must maintain 1% TVE in the range ± 5 Hz or ± (Fs/5), whichever is the lesser.

For a PMU with a reporting rate of 50 frames per second (Fs) the following requirements apply. P-class units must track frequency during the ramp to within 0.4 Hz. M-class units must track frequency during the ramp to within 0.01

Errors that occur during the measurement exclusion interval [6] are ignored; these exclusions centre on the inflection points when the frequency ramp inverts.

2.4. Step change in phase/magnitude

Step changes in phase angle and magnitude are applied in order to determine response time, delay time and overshoot in the measurement. The tests are applied as a transition between two steady-state conditions. This is expressed mathematically in [5] as shown in Eq. (4):

$$X_1 = X_m[1 + k_x f_1(t)] \times \cos[\omega_0 t + k_a f_1(t)] \tag{4}$$

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
k_x is the magnitude step size
k_a is the phase step size
$f_1(t)$ is a unit step function

Response time and delay time are defined in [5] subclause 5.3.3 and amended in [6]. Measurement delay time is evaluated in order to verify that time tagging of synchrophasors has been compensated for the group delay of the filtering system, such that the delay is near zero. An ideal step change is instantaneous by definition [5]; however, since the test signals may slew, the delay time is determined as the time when the stepped parameter achieves a value halfway between the starting and ending steady-state values.

It is worth noting that test signals are usually discrete time sampled at around 8 kHz; as such a minimum step time of 125 µs, equating to a phase angle of 2.25° at 50 Hz or 2.7° at 60 Hz, is inevitable (this is taken into consideration in C37.118.1).

3. Test methodology

In this paper the PMU under test is certified as C37.118-2005 compliant and has been established as such through in-house testing. We do not feel it is necessary to outline these tests as they are well established in existing literature [7,11]. An overview of the method employed is presented in Fig. 2.

3.1. Test waveform creation

Three phase waveforms which represent the tests described in the subclauses of the IEEE standard have been created using both the Matlab and Python environment. The waveforms are modulated according to the parameters identified by each subclause. The nominal frequency can be set for 50 Hz, 60 Hz or any other arbitrary value, and the waveforms can be of any duration or sampling rate. The waveforms are exported as a 3-channel audio file in the commonly used Microsoft/IBM WAVE format (.wav), or Comma Separated Value (CSV), which can be interpreted by a variety of test equipment.

The equations in C37.118.1 describe dynamic theoretical phasors, with real and imaginary components. The algebraic phasor equations are turned into a discrete time series by incrementing the phasor by a discrete time step. The point on wave data is generated by recording the real component of the phasor at appropriate time intervals (usually 8 or 10 kHz); this point on wave data is saved as a CSV or WAVE file for loading into the relay tester. The full phasor is also saved to a CSV file at appropriate time intervals (50–60 Hz) for comparison to the PMU output (derived from the point on wave replay).

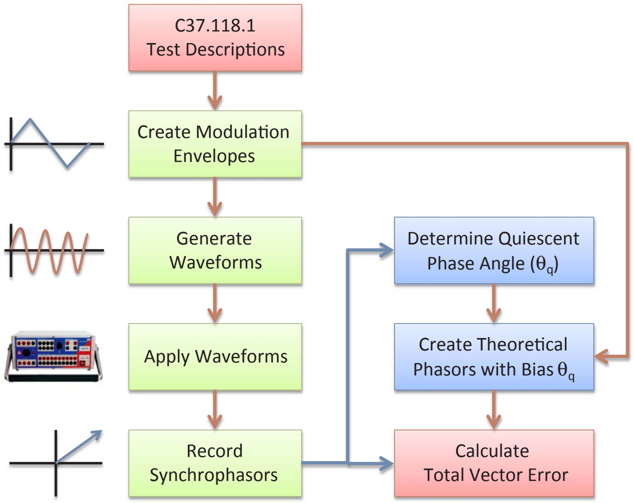

Fig. 2. Flow diagram describing the pre-compliance test methodology. A set of theoretical phasors (for comparison to the recorded phasors) are created alongside the point on wave files. The recorded phasors will not match the theoretical phasors due to temporal inaccuracy in replaying the waveform. The temporal error can be calculated from the recorded phase angle during the quiescent period (i.e. 18 = 1 ms at 50 Hz). The temporal error is fed back into the code to generate a new set of theoretical phasors that account for the measured temporal error.

In this method, the WAVE/CSV file is created at the same time as the theoretical phasors described in [5]. The theoretical phasor is the magnitude and angle of the phasor that is creating the point on wave test file at the given moment in time. If perfect temporal accuracy was achieved in replaying the test files then the initial theoretical phasors could be used to test the accuracy of the PMU; but for commonly available equipment this is not the case. The frequency and rate of change of frequency, that drive the theoretical phasor, are also recorded and are necessary for C37.118.1 testing.

The test waveforms created contain a nominal lead in and lead out period, during which voltage magnitude should be nominal and phase angle equal to zero. The lead in period is employed to identify the delay in starting the test file and the lead out period is used to identify any temporal drift during the application of the test.

The Matlab and Python code used to create the test files are provided under an open source license via the OpenPMU project [12]. The software used to create the test files is under continued development and it is hoped that other researchers might benefit from this work, or contribute to further development.

3.2. Applying test waveforms to PMU

The resultant CSV or WAVE file was applied to a PMU via an 'Omicron CMC 156' protection relay test set. 'Test Universe' is the software used to control the Omicron 156 and it contains the package 'Trans Play' that can replay WAVE and CSV files. Software from manufacturers of other relay test equipment can provide similar functionality.

The test file was initiated with the leading edge of a 1-pulse per second input from an 'Omicron CMGPS' GPS time signal receiver applied to the Omicron CMC 156. This equipment suffers from a characteristic time delay of 1 ms on this channel and a sampling uncertainty of 0.1 ms. In tests nominal wave forms thus applied had a phase angle of 18° ± 0.9° at 50 Hz. In theory no temporal synchronization is required as this is rectified through calibrating the theoretical phasors; however, a small, predictable temporal error is preferable to a random error as it aids data analysis.

In this test the output from the Omicron 156 was applied solely to the voltage inputs of the PMU under test. The purpose of this test is to identify intrinsic errors that arise in the estimation of phasors in a dynamic environment. By avoiding the use of CTs, and their potential inaccuracies, the ADC, time synchronization and the phasor estimation algorithm within the PMU are isolated.

While the temporal accuracy in initiating the waveform is low, the accuracy of the analogue outputs is high. The technical data on the Omicron CMC 156 claims accuracy in voltage and current output of ± 0.015%. The contribution to TVE from the signal output error would then be in the region of < 0.02%, this is 2% of the required minimum error of 1% TVE stipulated in [5].

3.3. Recording PMU data

The measurements made with the PMU are exported in the IEEE C37.118.2 data representation format [13]. For analysis, it was desirable to access the measurements in simple formats such as Comma Separated Values (CSV). We utilized the open source tool “PMU Connection Tester” [14].

3.4. Calibrating the theoretical phasors

The first step in the numerical analysis of the synchrophasor data involves the creation of a new set of theoretical phasors that are biased to correct for the time delay in starting the test file. The lead-in period of the signal is used to determine the quiescent phase angle, θq, of the recorded synchrophasors. The quiescent phase angle can then be used to precisely identify the delay in starting the test file (1° = 55.5 μs at 50 Hz, during the quiescent period).

The code that creates the WAVE, CSV and theoretical phasors can be biased in terms of its angle and magnitude. The phase angle and magnitude recorded during the quiescent period are thus used to create a new set of WAVE, CSV and theoretical phasors, only the theoretical phasors are of interest. In theory, the recorded phasors and the theoretical phasors should match exactly during the quiescent lead in period; this is exactly analogous to a PMU being calibrated to a nominal signal upon commissioning.

The method described isolates the TVE that arises due to dynamic operation; these errors are result from intrinsic PMU functions such as sampling time, dynamic accuracy and phasor estimation. The nominal behaviour at the end of the waveform allows any temporal drift to be identified, quantified and, if necessary, removed by slewing the theoretical phasors.

The testbench described is representative of standard relay test equipment. Equipment offering superior temporal accuracy is available in the marketplace, but can be prohibitively expensive and is not necessary for testing dynamics using the presented method.

3.5. Numerical analysis

The accuracy of PMUs are tested, according to C37.118.1, with the TVE, frequency error, rate of change of frequency error, response time and delay time. Frequency error and rate of change of frequency error are simply calculated as the difference between the real and theoretical value. The TVE is calculated using Eq. (1), when comparing the theoretical and measured phasor. The response and delay time are deduced from inspecting the step changes described below.

The numerical analysis can be carried out in any appropriate numerical environment (MS Excel, Matlab or Python). It is desirable to automate many of the processes, however it may be necessary to visually identify (or verify) the beginning of the test from the PMU output and identify the phase and magnitude error.

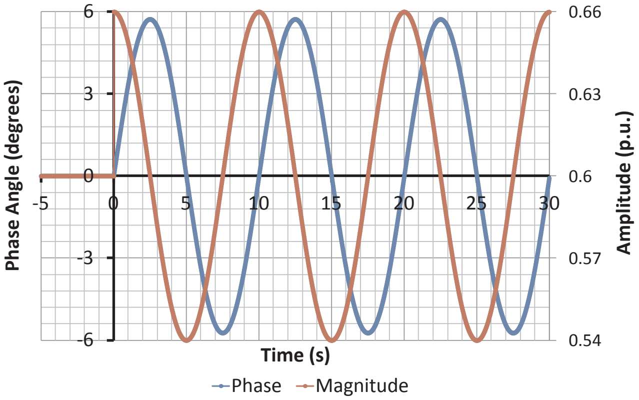

Fig. 3. Plot of the theoretical phasor amplitude and phase angle during the dynamic test 5.5.6 with modulation factors kx = 0.1 or ka = 0.1 rad.

3.6. Tests applied to the PMU

As outlined previously, three dynamic tests are specified in the C37.118.1 document and these are:

(1) Measurement bandwidth (subclause 5.5.6)
(2) Ramp in frequency (subclause 5.5.7)
(3) Step change in phase/magnitude (subclause 5.5.8)

Measurement bandwidth compliance waveforms are generated by modulating amplitude and phase angle. The modulation envelopes for kx = 0.1 and ka = 0.1 are presented in Fig. 3.

Frequency ramping is achieved in a similar way. Using a frequency ramp Rf = 1.0 Hz/s, this yields a modulation envelope such as shown in Fig. 4.

Step change in phase and magnitude is achieved in much the same way. Fig. 5 shows the modulation envelopes to achieve step change in amplitude of kx = 0.1, and step change in phase ka = 0.1 rad. Since the objective is to determine the PMU response/delay time to these events, these modulations would be applied independently. Using the technique of a modulation envelope eliminates concerns regarding discontinuities at the moment of the step change, since the fundamental tone otherwise continues to vary according to its original timebase.

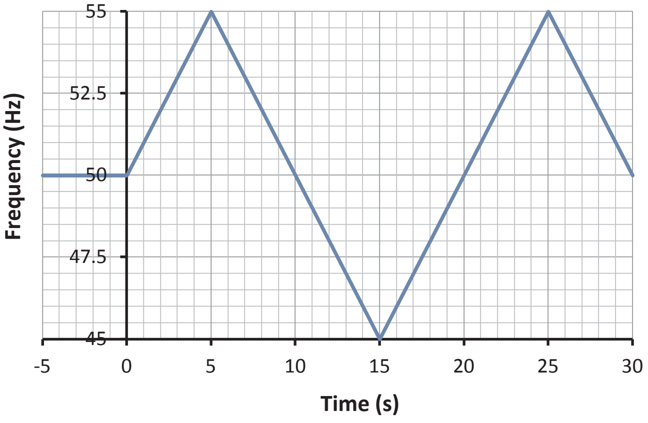

Fig. 4. Frequency envelope for theoretical phasor frequency during ramp test 5.5.7, Rf = 1.0 Hz/s.

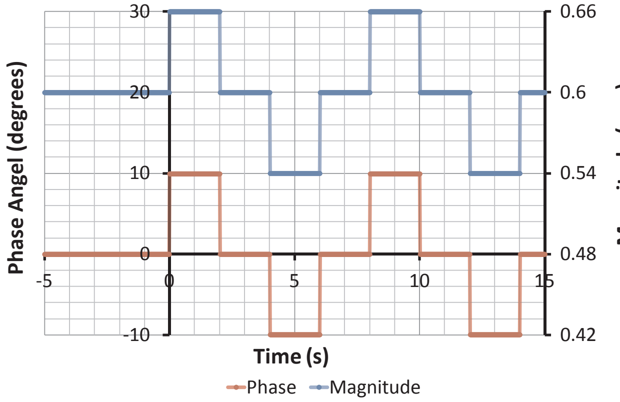

Fig. 5. Step change in phase and magnitude for the theoretically applied phasor in test 5.5.8, kx = 0.1, ka = 10° (π/18 rad).

4. Results

The compliance test was applied to a readily available commercial PMU that is in use with many European utilities. The results are presented in this paper to demonstrate the output of the pre-compliance testing method and are not to be taken as a critique of the actual PMU in question.

Both the theoretical synchrophasors and the measured synchrophasors were recorded in CSV format. Preprocessing steps include the removal of measurements pre- and post- test waveform playback, as well as discontinuities stipulated in [5]. The theoretical and recorded synchrophasors were then time aligned and compared. For each pair of synchrophasors, the frequency and rate of change of frequency (*df/dt*) error was easily calculated, likewise for phase and magnitude error; from which the TVE was determined, Eq. (1).

As stated in the IEEE Std., a PMU can be classified as either M or P class; for the purposes of this investigation we decided to apply the most onerous tests specified in the C37.118.1 standard and judge the PMU from the results.

4.1. Bandwidth test – Sec. 5.5.6

Test wave files were created with a modulation frequency between 0 and 5 Hz. Between 0 and 2 Hz a test was conducted every 0.2 Hz, as specified in the C37.118.1 standard. Between 2 Hz and 5 Hz a test was conducted every 0.5 Hz, for ease of testing.

The C37.118.1 standard has specific requirements in relation to TVE, frequency error and rate of change of frequency error; shown in Fig. 6 is TVE against modulation frequency. It was assumed that TVE would increase linearly or exponentially with modulation frequency, however the measured TVE varies in a complex manner as modulation frequency increases. The noteworthy outcome is that the TVE never exceeds, or encroaches upon, the 3% limit set in [6], thus fulfilling all P and M class requirements.

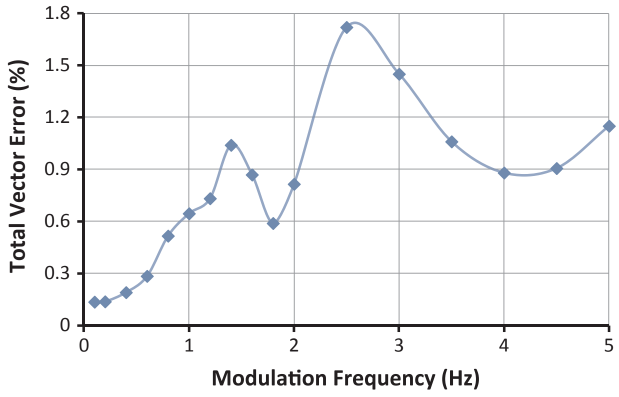

Fig. 6. Plot of total vector error against modulation frequency, as specified in the IEEE C37.118.1 standard Sec 5.5.6.

Table 1
Summary of phase and magnitude step test (Subclause 5.5.8).

Attribute	TVE (%)	Freq. Err. (Hz)	RoCoF Err. (Hz/s)
P Class Limit [6]	3.00	0.06	2.30
Max Recorded	1.72	0.372	5.76
Result	**Pass**	**Fail**	**Fail**
M Class Limit [6]	3.00	0.30	14
Max Recorded	1.04	0.797	21
Result	**Pass**	**Fail**	**Fail**

The results for frequency error and ROCOF error (displayed in Table 1) were more straightforward as the gradient of the error was always positive and generally linear; though step changes in gradient occurred. In this test the PMU passed the less onerous M class requirements for ROCOF, but fell far short of the stringent P class requirements. In the frequency error test the PMU failed both the P and M class requirements, see Table 1.

4.2. Frequency ramp test – Sec. 5.5.7

Only one test file is required to run either the P or M class tests, as the ramp rate is fixed in either case. The difference between the protection (P) and measurement (M) cases is simply the maximum frequency deviation, from nominal. As before, the M class PMU must operate over a greater frequency range, but this time the error constraints on the M class are also tighter. The C37.118.1 standard permits erroneous readings around the discontinuities in ramp rate, the two recordings immediately before and after a discontinuity are discarded.

It could be said that the PMU did not perform well in this test, as can be seen in Table 2. The PMU suffered from a consistently high TVE, often in excess of 2%, when the frequency was outside the range of 48.3–51.5 Hz and exceeding 3% when the frequency was outside the range of 46.7–54.5 Hz. The IEEE C37.118.1 standard is quite specific about the recorded TVE, 'The maximum is the highest value observed at the given reporting rate over the full test interval' (C37.118.1 Sec 5.5.6 page 17, [5]). The excessively high TVE was investigated by interpreting the phase and magnitude error separately; the results are shown in Fig. 7. Both the magnitude error, in percent, and the phase error, in degrees, are plotted on the same axis. It can be seen that the magnitude error does not exceed 0.255%, so although it contributes to the TVE it is not the primary cause of the excessive TVE. The TVE limit of 1% is exceeded if the phase error exceeds 0.573° (0.01 rad), it is apparent from Fig. 7 that this is often the case. The maximum phase angle error was −2.02° at 45.12 Hz, while the maximum phase error at frequencies above nominal was 1.82° at 54.94 Hz.

The PMU also performed poorly in regards to frequency error, with a typical error around 0.05 Hz, five times in excess of the P class requirements and the M class requirements that were moderated up in [6] (See Table 2); there were also many outlying frequency errors up to 0.15 Hz (M class 45–55 Hz) and 0.11 Hz (P class 48–52 Hz). The PMU

Table 2
Summary of freq. ramp test (Subclause 5.5.7).

Attribute	TVE (%)	Freq. Err. (Hz)	RoCoF Err. (Hz/s)
P Class Limit [6]	1.00	0.01	0.40
Max Recorded	2.29	0.11	1.87
Result	**Fail**	**Fail**	**Fail**
M Class Limit [6]	1.00	0.01	0.20
Max Recorded	3.53	0.153	1.64
Result	**Fail**	**Fail**	**Fail**

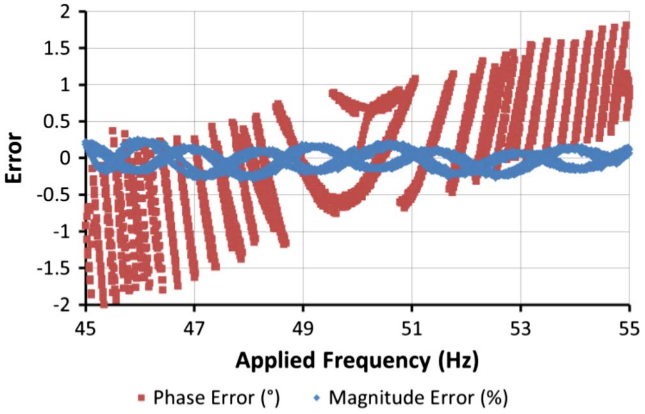

Fig. 7. Plot of magnitude and phase error against applied frequency during frequency ramp test, as specified in the IEEE C37.118.1 standard Sec 5.5.7. Four sweeps are shown.

also performed poorly in regards to ROCOF error, with a typical error between 0.25 and 0.5 Hz/s, the C37.118.1-2014 Std. requires an error of less than 0.4 Hz/s (P Class) and 0.2 Hz/s (M Class). Although the relaxed requirements of the C37.118.1 are moving the standard error of the PMU into the P Class category, the PMU none-the-less generated a small but significant number of values with an error of greater than 1 Hz/s, giving it a solid fail in this test.

4.3. Phase and magnitude step – Sec. 5.5.8

It is essential that the steps in magnitude and phase occur at various phase angles, in order to get a complete understanding of step detection. Each step change was incremented by 2.00125 s, resulting in the step change occurring at 22.5° (π/8 rad) intervals on the waveform. The transitions can be considered as occurring either 10 ms before or after a PMU report or ± 10 π radians. In Figs. 8 and 9 the error that resulted from a step change occurring at a specific time (pre or post PMU report) is specified. Fig. 8 shows the maximum TVE recorded during the step changes, as defined in the 2011 standard. These limits were relaxed in the 2014 amendment (as discussed below), but the observations provide an insight into PMU operation.

When the TVE exceeded 1% it only did so for a single report. The error occurred because the PMU attributed the step change to the reporting interval before the step change occurred. This observation is the cause of the high TVE when a step change occurs less than 2.5 ms after a PMU report, the PMU erroneously reports the step milliseconds before it occurs. The TVE drops as less of the step change is attributed to the preceding report. The TVE drops to it's nominal value when the step occurs 7 ms before the PMU report, as it is now entirely attributed to the forth coming report. This is likely caused by the phasor being derived over multiple cycles. At no point were frequency or ROCOF recordings effected by the step change, therefore they did not contribute to the response or delay times. As there was no significant error in phasor estimation, only temporal shift, the overshoot was always effectively zero.

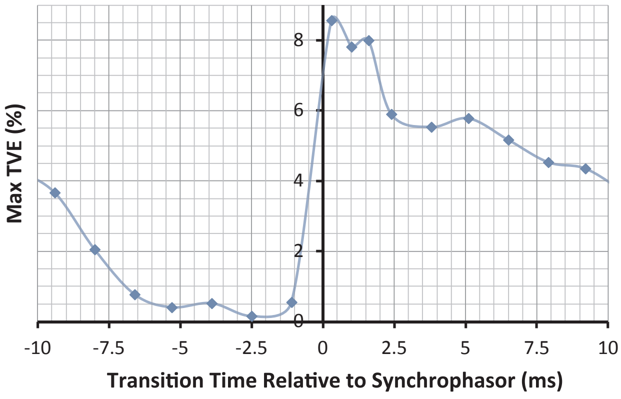

Fig. 8. Plot of the TVE of the report immediately preceding the step change in magnitude, all other TVE values were < 1% and the phase step graph is equivalent.

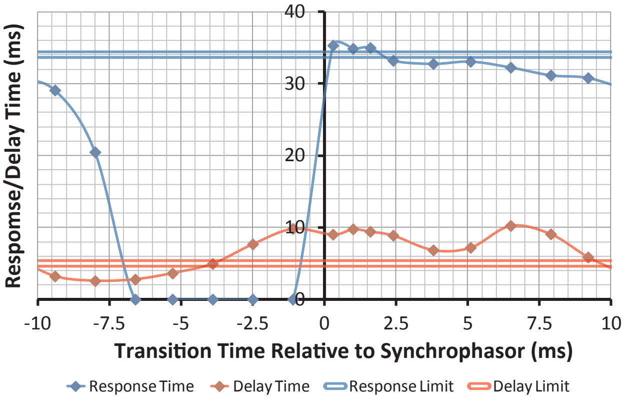

Fig. 9. Plot of measurement time and delay time, as defined in IEEE C37.118.1, against the time when the magnitude step was introduced, relative to UTC. The response and delay times are negative relative to the synchrophasor output.

Shown in Fig. 9 are the measurement response times and measurement delay times for the data points shown in Fig. 9 [5]. As the error occurred before the reporting interval, the measurement response time and measurement delay time are negative, as can be interpreted from Sec 5.5.8 [5]. It can be observed in Fig. 9 that the measurement time, as defined in C37.118.1-2011, is zero if the step change occurred between 7 ms and 1 ms before the synchrophasor output from the PMU. This occurred because measurement response time is purely based on TVE, starting when the TVE exceeds 1% and stopping when TVE drops below 1%; as TVE did not exceed 1% in this region the measurement time is zero.

For every recorded phase step a maximum of one phasor deviation was observed; in this case if a graph of PMU error is plotted against time a triangle is formed when an error occurs. To examine the limits of error under these circumstances we can note that delay time tends to 40 ms as the TVE tends to infinity. The measurement response time required by [5] is $1.7 \times f$ (34 ms at 50 Hz sampling), this is exceeded if the TVE exceeds 6.66%. The amendments made in [6] allow a response time of $2.0 \times f_0$ (40 ms at 50 Hz sampling) effectively allowing a single wrong value.

Fig. 8 shows that the PMU only failed to meet the stringent criteria in [5] when the step occurs between 0 and 2.4 ms after the synchrophasor output. In real terms this failing is not very significant as the phasor output, though technical inaccurate, in many ways reflects the situation to which it is being subjected. For this reason the update to this requirement in [6] is welcomed, but is nominally the same as allowing a single deviation at a discontinuity, as in the frequency test. A compromise could exist where deviations in the region 0–5 ms after a transition are discounted.

The delay time is purely based on the variable (magnitude or phase) that is being acted upon, timing starts when the step occurs and ends when the PMU output exceeds 50% of the step (see IEEE C37.118.1 Sec 5.5.8). As the PMU output stream consistently reported the transition before the step was applied, the delay time is always negative and generally less than half a cycle (10 ms). The C37.118.1 standard requires that the delay time be less than 5 ms on a 50 Hz system $(1/(4 \times f_0))$, this effectively allows no room for error in PMU output. If a transition occurs exactly 10 ms before/after a synchrophasor output (at 50 Hz) then the PMU can report the transition on the phasor before or after the transition, otherwise the PMU transition must occur at the report closest to the step. The contributions to the delay time occurred due to the delay before the erroneous PMU output and the interval

Table 3
Summary of bandwidth test (Subclause 5.5.6).

Attribute	Response time (ms)	Delay time (ms)	Overshoot (%)
P Class Limit [6]	40	5.0	5.0
Max Recorded	35.3	10.25	0.0
Result	**Pass**	**Fail**	**Pass**
M Class Limit [6]	199	5.0	10.0
Max Recorded	35.3	10.25	0.0
Result	**Pass**	**Fail**	**Pass**

No frequency or ROCOF deviation, therefore all these tests were passed.

between the PMU output and the step.

The requirements for delay time in [5,6] are very strict and potentially unrealizable; therefore the PMU fails when the transition occurs between −5 ms and 10 ms after the phasor reporting time. The delay time definition and requirements were not altered in the 2014 amendment [6]; a case could be made for redefining the delay time or permitting the phasor to transition prematurely, for instance if the step occurs in the first 5 ms after the phasor is reported.

The results for measurement response time and measurement delay time under phase step conditions are roughly transposable onto the results for magnitude step. It can be taken from Table 3 that the PMU only narrowly fails the C37.118.1-2011 requirements, but it is our opinion that the synchrophasor output is desirable and the PMU should pass this test.

4.4. Summary of results

Shown in Tables 1-3 are the summary of results for the PMU under investigation during the dynamic tests specified in C37.118.1-2011 subclause 5.5.6, 5.5.7 and 5.5.8; the updated requirements in [6] are also commented upon. The PMU seems to be slightly more inclined towards the less onerous requirements of the M class. However, note that the PMU design dates to pre-2011 and only claims compliance against the 2005 edition of the C37.118 Std.

5. Conclusion

Many academic and industrial institutions are placing considerable faith in the fidelity of the measurements provided by PMUs. The data coming in from these PMUs may determine decisions relevant to design of protection and control schemes; consequently it is vital that these units operate at the highest standards. The pre-compliance testing outlined in this paper requires less specialized knowledge and equipment than generally assumed; bringing it within the reach of many more institutions. It is also hoped that the WAVE files and Matlab scripts provided online could save researchers development time and prove informative for those working in this area.

The PMU tested for this paper states that it supports the IEEE standard C37.118-2005 for synchrophasors and can act as a phasor measurement unit (PMU) within a power system. It is known from testing that this PMU fulfills the steady state requirements set out in the 2005 standard, but appears to struggle with the dynamic tests stipulated in the IEEE Standard C37.118.1-2011 and the amendments made in 2014 [6]. The inclusion of dynamic tests in the 2011 and 2014 editions of the standard go some way to addressing the previously identified inconsistent response of PMU in dynamic conditions [10,7,8].

It is possible that some of the specifications outlined in the C37.118.1 document are extremely challenging to attain. For example, the conditions set out for response time (5.5.8) are of particular note as they effectively allow no error. To truly address how practical this test is, more commercial PMUs must be tested. To test the feasibility of fulfilling the C37.118.1-2011 standard, the phasor estimation algorithm outlined in [9] was applied to the waveform data and it was found to perform incredibly well, as outlined in the paper.

Through the process of testing, analyzing and evaluating the PMU, various aspects of its performance could be tested and insights made, well beyond a simple pass-fail appraisal. Various strengths of the PMU were identified, for example minimizing TVE during bandwidth tests. Various weaknesses were also identified, especially during the frequency ramp test. These insights show when a particular PMU will perform well or poorly and where improvements in hardware and software can or should be made.

The tests on this PMU demonstrate that it maintains a small TVE under minor oscillations characteristic of the bandwidth test; similarly it has proved to be very accurate at identifying step changes. The phasor output from such a PMU would be useful in identifying phase angles across an electrical network or for island detection. The poor TVE results presented in this paper demonstrate that the phasor from this PMU should not be relied upon during significant RoCoF events; suggesting it should not be relied upon for rapid grid synchronization. Similarly, mHz analysis of frequency data from this PMU should not be conducted under dynamic conditions. Using tests such as this, PMUs that are widely deployed have shown significant errors even under steady state conditions; this is an important consideration for grid operators when interpreting and analyzing results, especially when wide-area comparisons are being made.

As a general note, we identify the low waveform sampling rates on some relay test equipment as an obstacle to PMU compliance testing (an 8 kHz sample rate generates points on wave that are 2.25° apart, for a 50 Hz signal). The sampling rate of the algorithms used to generate the test waveforms in this paper is a variable and should be set to the highest rate the test equipment supports.

This work falls under the wider umbrella of the OpenPMU project and these test WAVE files were originally developed for the testing of the open source PMU described in [15,16]. At present this method is being utilized to test the variation in accuracy between PMUs from different vendors and to benchmark the performance of the next generation of OpenPMU. It is hoped that this method and the associated test files will be of use to researchers and developers building PMUs, and that the test WAVE files can be developed into a complete testing suite for this and future testing standards.

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