



Measurement Class Phasor Measurement Unit Compliance for Electrical Grid Monitoring

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Abstract: This article offers synchrophasor transient and steady compliance with IEC/IEEE 60,255-118-1:2018 standard. This power system standard is mainly designed for the synchronized phasor measurement and specifies the synchronized voltage and current phasors, frequency and derivative requirements, time tag, and synchronization of all measurements. The Synchrophasor testbed includes three-phase high-precision power and current signal voltage, system time unit, GPS receiver, server PC, electricity standards, PMUCAL and test-based PMU software. Three-Phase Measurement Units (PMUs) from different machines have been tested individually to confirm compliance with the state-of-the-art international standard, which is essentially a dual logo standard. Such measured information is being used to control the power grid by smart communication utility. The test results of synchrophasor have been analyzed and discussed.

Keywords: Synchrophasor; IEC/IEEE 60,255-118.1:2018; Steady-state; Dynamic compliance; Total vector error

1. Introduction

As smart sensing devices, Phasor measurement units (PMU) or Synchrophasor are used to enable smart grid protection, control, and monitoring [1, 2]. Data from the Phasor Measurement Unit are more accurate than from legacy SCADA systems [3]. The use of Synchrophasor has caused a paradigm shift in the control and operation of the central controller. These synchrophasors have grown rapidly and become more popular among system operators for improving system performance over the last decade.

For the real-time monitoring of the voltage, current, phase angle, frequency, and change rates of frequency, active power, and reactive power measurements, phasor measurement units that monitor wind power are installed at the Point of Interconnection (PoI). PMUs can be used as part of wind farms and/or wind generator relays for transmission protection relays. It is connected to the control and monitoring center via local Phasor Data Concentrator (PDC), Superphasor Data Concentrator (SPDC) [4]. These

data are used at wind farm interconnection points for small-signal/inter-area oscillation detection and voltage stability analysis [5]. Electricity utilities worldwide integrate renewable energy into the grid. The generation of wind power is intermittent, and so the use of real-time information and broad range measurement (WAMs) are the smarter way to model grid advancements.

PMU performance is more helpful especially in terms of visualization for power system grid operators. PMUs are used for various applications such as magnitude/frequency/angle monitoring [6, 7], state estimate, congestion management, stability, back-up protection, main loss, isolation, anti-insulation, model validation, inertia, generator applications, adaptive protection [8, 9], power supply monitoring, oscillation monitoring [10], fault detection, state estimation, small-signal stability, valve model modeling. The real-time PMU is the vital input for developing new control strategy algorithms in applications with real-time power system control. For all applications, the reliability of phasor measuring units is very important, which in turn depends on the frequency precision and its derivatives.

The performance of PMUs is very important and validation for utilities of the measured data is useful. However,

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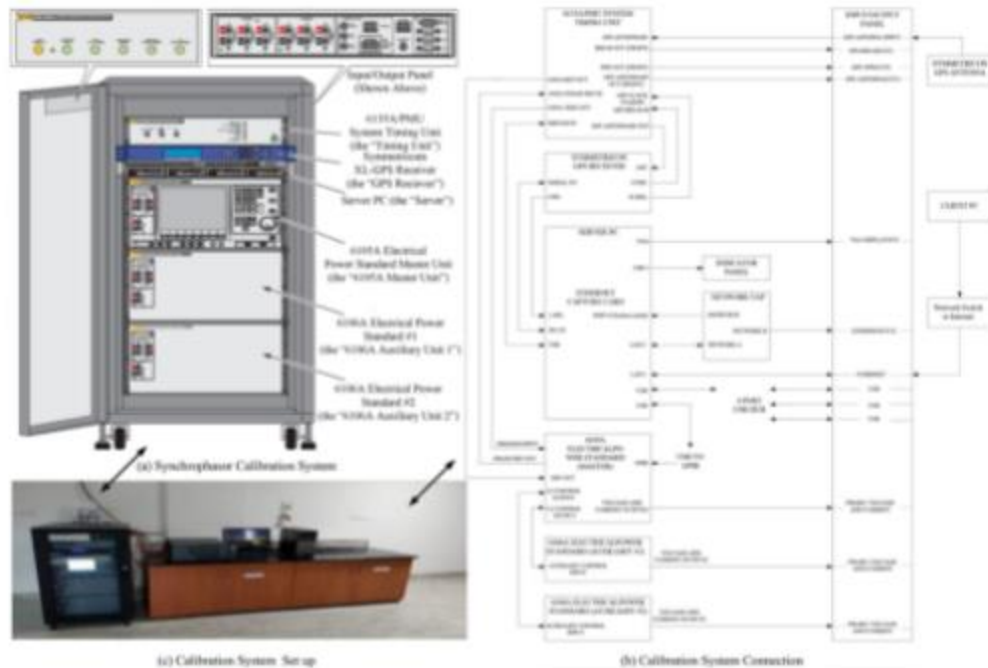


Fig. 1 Synchrophasor calibration system (6135A) with system setup and connection circuit

when greater deployment in the smart grid networks is planned, this is a challenge but an important step. Stable state and dynamic compliance were carried out following the latest IEC/IEEE 60,255-118-1:2018 international standard [11–13]. This standard is developed for synchronized phasor measurement by the IEC Technical Committee in cooperation with the IEEE PES relaying committee. The function and performance requirements for synchrophasor measurements are also specified. Tests, assessment criteria, and error limits are well defined to determine compliance with stable and transitional requirements. The biggest drawbacks are undefined.

1. Methodology for phasor and frequency computation
2. Hardware and software requirements.

In both Std. IEEE C37.118.1 [14] & IEEE C37.118.1a:2014 [15], the performance limits are the same compared to IEC/IEEE 60,255-118-1:2018. Three PMUs are measured with the current status and specific compliance as reported in this paper according to the current standard. According to the guidelines, responses to the input signal variations in terms of amplitude, frequency & phase are studied in a constant state test [16]. The filters are

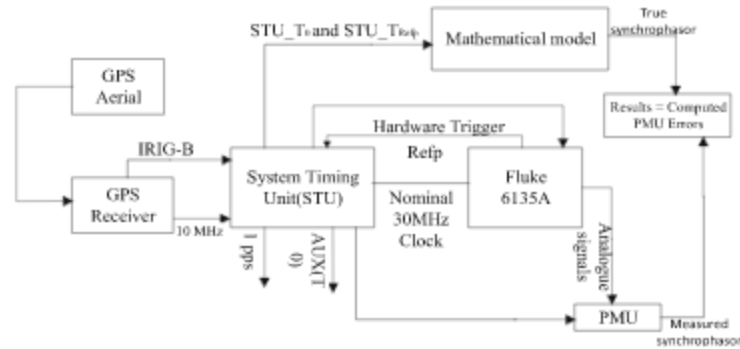
evaluated by bandwidth and harmonic signals. For phasor and frequency estimations the total vector error (TVE) and the frequency error (FE) is used. The amendment acts suspended frequency change rate (ROCOF) error limit (RFE) for the associated harmonic test [17, 18].

The 2018 Standard Steady-State Compliance Tests (SSCT) was recently published. PMUCAL software prepares and loads test plans. This conformity test is a 'static test,' which uses constant magnitude, frequency, and phase offset for a fixed duration of the test. SSCT ensures the performance of PMUs in the IEC/IEEE 60,255-118-1:2018 "Steady-State Compliance" range and limitations. The PMUs are also tested for harmonic rejection and signal out of bandwidth. The phasor evaluation is conducted by TVE. This paper offers test methodology, constant state test results, and dynamic compliance for three MUs from various vendors as well as conclusion and contribution.

2. Synchrophasor Calibration System

The study of the general PMU model, the dynamic quality market assessment, and the significance are detailed in

Fig. 2 Single line block diagram of PMUCAL



[19–21], while the dynamic performance characteristics of the PMU have been discussed in Krish Narendra et al. [22] PSCAD/EMTDC software generates test waveforms for the mathematical models that have been developed, and the Double F6150 power system simulator is used to reproduce PMU test signals together with GPS synchronization. PMUs of various vendors are compared by Tianshu Bi et al. in compliance with China PMU standard and IEEE C37.118.1-2011. Omicron makes the CMC 256 plus GPS feature relay test system for PMU Evaluation [23]. Comprehensive testing programs were developed to evaluate PMU using the NIST PMU calibration system for the Brazilian utility in stable and dynamic/transient conditions under IEEE C37.118-2005 [24]. The PMU MiCOM P847 test is described in [25, 26] details using CMC 256 plus Omicron synchronizing equipment and PMU pre-compliance test techniques. In 2007, NIST introduced the first PMU calibration system [27], and in 2013 NASPI Task Force evaluated the needs and status of the synchrophasor technology testing and certification process [28]. India's first PMU testing facility was established by the Central Power Research Institute (CPRI) [29]. Figure 1 shows the Fluke 6135A/PMUCAL PMU calibration system for calibrating and testing PMUs in CPRI. The 6135A/PMUCAL is IEC/IEEE 60,255-118-1:2018 compliant for the measurement of the synchrophasor power system. This integrated automated system can perform 600 tests daily and simultaneously provide PMU configuration certification.

In Fig. 1, the 6135A Three-Phase System (the 6135A system provides the calibration system with three different ac voltage and current sources for the Unit under Test (UUT). The 6135A system contains one electricity standard 6105A (L1) and two electric power standards 6106A (L2 and L3) [30]. The complete 6135A system is connected and controlled by the system time unit 6135A/PMU and the server PC. The server PC automatically places the 6135A system in remote mode when the calibration system is enabled. The front panel controls on the 6105A master unit

are disabled in remote mode. The 6135A system can be disconnected from the calibration system for applications other than UUT calibration. The 6135A units are phase in order. In this sequence, UUT is linked to the input/output system calibration panel to prevent phase mismatch: phase A, B, and C to L₁, L₂, and L₃.

The voltage and current outputs are connected to the input/output panel on the front panel of the 6135A system. Manual adjustment of the front panel 6105A is prevented to prevent damage to the system or UUT. The UUT is connected directly to the input/output panel outputs. The Symmetric com XL-GPS recipient supplies a UTC (Universal Time Coordinated) time source with the product and UUT. UUT uses the time source to timeline every report that it generates. To use the GPS receiver, a GPS antenna must be installed. The GPS receiver is connected via the time unit to UUT. This allows the time unit to control the UUT's GPS signal. The GPS time information is transmitted via an IRIG-B connection on the rear panel to the calibrator directly. The GPS receiver and the GPS transmitters are simulated by a 10 MHz clock signal from the GPS receiver. When the calibration system is switched on the GPS recipient is configured to lock satellites automatically with a "good signal indication". The LED status indicator and text display on the front of the GPS receiver shows the GPS receiver communication status.

The timing and modulation control unit is the 6135A/PMU system timing unit in the calibration system. This device is connected to the PC server, the system 6135A, the GPS receiver, and the UUT. When a test is running, the PMUCAL software sends test parameters to the Server PC. Then the Server PC sends test parameters to the time unit. The timing unit uses the GPS receiver's UTC signal to accurately control the 6135A system output frequency, voltage, and current to UUT. The UUT is connected directly to the input/output panel outputs. The software status panel 6135A/PMU is located on the cabinet door and shows the software services active. The control interface of

Table 1 Steady-state signal magnitude (voltage and current)—25FPS/M class

Parameters → PMU ↓	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
A phase voltage	0.4748	0.4151	0.04691	0.001	0	0.00003815	0.02	0.02	0.00277
B phase voltage	0.4956	0.4857	0.04842	0.001	0	0.00003815	0.02	0.02	0.00277
C phase voltage	0.3405	0.4126	0.04672	0.001	0	0.00003815	0.02	0.02	0.00277
Voltage + Sequence	0.415	0.4238	0.04707	0.001	0	0.00003815	0.02	0.02	0.00277
A phase current	0.5799	0.5377	0.1287	0.001	0	0.00003815	0.02	0.02	0.00277
B phase current	1.128 Fail	1 Fail	0.09991	0.001	0	0.00003815	0.02	0.02	0.00277
C phase current	0.6599	0.4191	0.1104	0.001	0	0.00003815	0.02	0.02	0.00277
Current + Sequence	0.752	0.5401	0.1287	0.001	0	0.00003815	0.02	0.02	0.00277

*NR: No requirements

the calibration system for testing and calibration of a UUT is the PMUCal software. The software PMUCal is installed on the PC client.

3. Testing Methodology for Phasor Measurement Unit

Figure 2 shows the block diagram of PMU Cal. When a continuous status test is started, the time unit slew the nominal 30 MHz clock frequency to align the reference phase of the 6105A Master Unit (Refp) with the 1 PPS. When alignment is reached, the clock is set to exactly 30 MHz and the output of the 6105As is at a nominal frequency (50 Hz) with the L₁ Phase voltage at zero degrees (concerning the 1 PPS). All other voltages and current outputs are aligned to 1 PPS but offset by the phase angles of the master unit of 6105A for a very precise, balanced, positive output.

Every test starts at 1 PPS. In the mathematical model known as T₀, this is zero times. The timestamp for the

beginning of the test (STU-T₀) and the time for the positive edges) shall be passed to the 6105A Master Unit output mathematical model. When the PMU reports, the time stamp of the synchrophasor is used to calculate the "True" synchrophasor in the mathematical model at that time. Compared to the three synchrophasors, the TVE error is determined. The PMU tests include static signals between nominal and ± 5 Hz frequencies. This is the maximum frequency range for any PMU setup. The 0° Synchrophasor is not always aligned with 1 PPS in non-nominal frequency tests. This does not matter as long as the test begins to align so that the synchrophasor generated by mathematics is correct. The application of out-of-band interference is included in some static tests required under IEC 60,255-118 1:2018 Standard. These are implemented by the application of harmonics and interharmonics in the calibration system.

The power system signal.

The voltage or current in an AC power grid is demonstrated by (1):

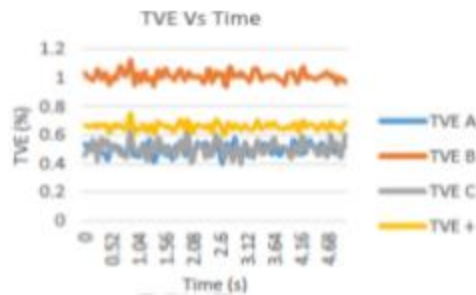
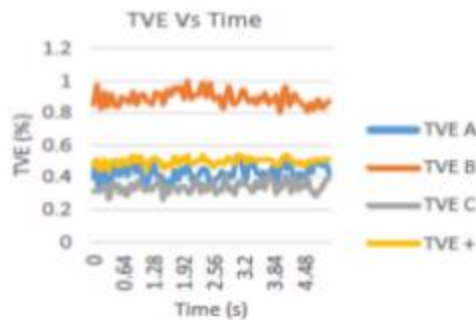
Table 2 Steady-state frequency response—25FPS/M class

Parameters → PMU ↓	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
A phase voltage	0.1511	0.09917	0.05491	0.001	0.001	0.00003055	0.03	0.02	0.001636
B phase voltage	0.1938	0.181	0.05554	0.001	0.001	0.00003055	0.03	0.02	0.001636
C phase voltage	0.1414	0.1492	0.05509	0.001	0.001	0.00003055	0.03	0.02	0.001636
Voltage + Sequence	0.1446	0.1337	0.05504	0.001	0.001	0.00003055	0.03	0.02	0.001636
A phase current	0.508	0.4226	0.08891	0.001	0.001	0.00003055	0.03	0.02	0.001636
B phase current	0.8355	0.6802	0.08875	0.001	0.001	0.00003055	0.03	0.02	0.001636
C phase current	0.5283	0.2318	0.08632	0.001	0.001	0.00003055	0.03	0.02	0.001636
Current + Sequence	0.6175	0.4358	0.08891	0.001	0.001	0.00003055	0.03	0.02	0.001636
Limit	< 1	< 1	< 1	< 0.005	< 0.005	< 0.005	< 0.1	< 0.1	< 0.1
Result	P	P	P	P	P	P	P	P	P

*P—Pass/ F—Fail

Table 3 Measurement requirements—Steady-state synchrophasor, frequency and ROCOF

Influence quantity	Reference condition	M class			Error requirements for compliance	
		Range	Max.TVE (%)			
Frequency	Frequency = f_0 (nominal)	± 2.0 Hz for $F_s \leq 10$ $\pm F_s/5$ for $10 < F_s < 25$ ± 5.0 Hz for $F_s \geq 25$	1		Max. FE 0.005 Hz	Max. RFE 0.1 Hz/s
Voltage	Rated	10–120% rated	1	–	–	–
Current	Rated	10–200% rated	1	–	–	–
Harmonic distortion (single distortion)	$< 0.2\%$ (THD)	10%, each harmonic up to 50th	1	Max. FE	Max. RFE	
	$F_s > 20$			0.025 Hz	No requirements	
	$F_s \leq 20$			0.005 Hz	No requirements	
Out-of-band interference	$< 0.2\%$ of input signal magnitude	10% of input signal magnitude for $F_s \geq 10$ No requirement for $F_s < 10$	1.3	Max. FE	Max. RFE	
				0.01	No requirements	

**Fig. 3** PMU A: TVE versus Time**Fig. 4** PMU B: TVE versus Time

$$x(t) = x_m(t) \cos \theta(t) + D(t) \quad (1)$$

where t —time (seconds), $t = 0$ is coincident with a UTC second rollover; x_m —sinusoidal AC signal peak magnitude (V or A); θ —sinusoidal AC signal angular position (radians); D —disturbance signal which contains additive contributions to the signal, including, but not limited to harmonics, noise, DC offset and out of band interference.

Synchrophasor phase angle

The difference between phase and angular position $\theta(t)$ at nominal frequency f_0 is termed as synchrophasor phase angle $\phi(t)$.

$$\phi(t) = \theta(t) - 2\pi f_0 t \quad (2)$$

Frequency and rate of change of frequency (ROCOF)

It relates to the angular position of the fundamental power system signal (Hz) as shown in Eq. (3):

$$f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} = f_0 + \frac{1}{2\pi} \frac{d\phi(t)}{dt} \quad (3)$$

ROCOF relates to the angular velocity of the power system signal (Hz/s) as shown in Eq. (4):

$$\text{ROCOF}(t) = \frac{df(t)}{dt} = \frac{1}{2\pi} \frac{d^2\theta(t)}{dt^2} = \frac{1}{2\pi} \frac{d^2\phi(t)}{dt^2} \quad (4)$$

Amplitude and phase error of the measured phasor, Magnitude error (ME) and Phase error (PE) is evaluated by (5) and (6), respectively.

Table 4 Steady state—Harmonic distortion (single Harmonic): 25FPS/M class

Parameters →	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
PMU ↓									
A phase voltage	0.1382	0.09203	0.05524	0	0	0.00001526	0	0	0.0008011
B phase voltage	0.1481	0.1176	0.04908	0	0	0.00001526	0	0	0.0008011
C phase voltage	0.05021	0.06323	0.04847	0	0	0.00001526	0	0	0.0008011
Voltage + Sequence	0.1035	0.07404	0.04878	0	0	0.00001526	0	0	0.0008011
A phase current	0.3991	0.3266	0.09535	0	0	0.00001526	0	0	0.0008011
B phase current	0.7002	0.572	0.08806	0	0	0.00001526	0	0	0.0008011
C phase current	0.4363	0.1803	0.08481	0	0	0.00001526	0	0	0.0008011
Current + Sequence	0.5044	0.3468	0.09535	0	0	0.00001526	0	0	0.0008011
Limit	< 1	< 1	< 1	< 0.025	< 0.025	< 0.025	NR	NR	NR
Result	P	P	P	P	P	P	P	P	P

Table 5 Steady-state out-of-band interference test (interharmonics): 25FPS/M class

Parameters →	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
PMU ↓									
A phase voltage	0.1688	0.1158	0.9149	0.001	0.001	0.004316	0.05	0.05	0.2957
B phase voltage	0.1767	0.1587	0.9174	0.001	0.001	0.004316	0.05	0.05	0.2957
C phase voltage	0.09778	0.1099	0.9178	0.001	0.001	0.004316	0.05	0.05	0.2957
Voltage + Sequence	0.1326	0.1047	0.9142	0.001	0.001	0.004316	0.05	0.05	0.2957
A phase current	0.4196	0.3603	0.9482	0.001	0.001	0.004316	0.05	0.05	0.2957
B phase current	0.7051	0.6207	0.9534	0.001	0.001	0.004316	0.05	0.05	0.2957
C phase current	0.4457	0.2065	0.9461	0.001	0.001	0.004316	0.05	0.05	0.2957
Current + Sequence	0.5165	0.3806	0.9482	0.001	0.001	0.004316	0.05	0.05	0.2957
Limit	< 1.3	< 1.3	< 1.3	< 0.01	< 0.01	< 0.01	NR	NR	NR
Result	P	P	P	P	P	P	P	P	P

Table 6 Dynamic—Measurement Bandwidth (Phase Modulation): 25FPS/M class

Parameters →	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
PMU ↓									
A phase voltage	0.2952	0.2653	0.7049	0.1548	0.1552	0.1048	3.409	3.409	3.604
B phase voltage	0.2764	0.2461	0.6969	0.1548	0.1552	0.1048	3.409	3.409	3.604
C phase voltage	0.2274	0.2275	0.7023	0.1548	0.1552	0.1048	3.409	3.409	3.604
Voltage + Sequence	0.2614	0.2416	0.7014	0.1548	0.1552	0.1048	3.409	3.409	3.604
A phase current	0.4929	0.4321	0.7202	0.1548	0.1552	0.1048	3.409	3.409	3.604
B phase current	0.7273	0.6567	0.7201	0.1548	0.1552	0.1048	3.409	3.409	3.604
C phase current	0.495	0.3357	0.72	0.1548	0.1552	0.1048	3.409	3.409	3.604
Current + Sequence	0.5653	0.4603	0.7202	0.1548	0.1552	0.1048	3.409	3.409	3.604
Limit	< 3	< 3	< 3	< 0.3	< 0.3	< 0.3	< 14	< 14	< 14
Result	P	P	P	P	P	P	P	P	P

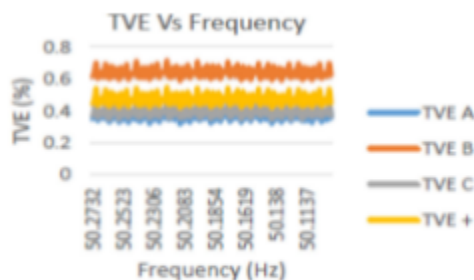


Fig. 5 PMU A: TVE versus frequency (Phase Modulation)

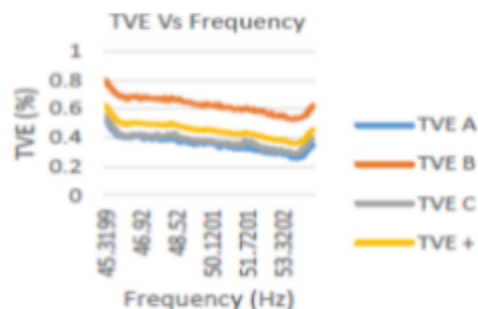


Fig. 6 PMU A TVE versus Frequency

$$ME = \frac{\sqrt{Xr(n)^2 + Xi(n)^2} - \sqrt{Xr(n)^2 + Xi(n)^2}}{\sqrt{Xr(n)^2 + Xi(n)^2}} \times 100\% \quad (5)$$

$$PE = \alpha \tan(\hat{X}_r, \hat{X}_i) - \alpha \tan(X_r, X_i) \quad (6)$$

where $(\hat{X}_r, \hat{X}_i)$, $(\hat{X}_r$ and $\hat{X}_i)$ —real and imaginary of measured and reference phasor.

Table 7 Dynamic—Measurement Bandwidth (Amplitude Modulation): 25FPS/M class

Parameters →	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
PMU ↓									
A phase voltage	0.3825	0.3565	0.4273	0	0	0.001026	0	0.01	0.03128
B phase voltage	0.3576	0.3322	0.4245	0	0	0.001026	0	0.01	0.03128
C phase voltage	0.3197	0.3188	0.4252	0	0	0.001026	0	0.01	0.03128
Voltage + Sequence	0.3486	0.3325	0.4257	0	0	0.001026	0	0.01	0.03128
A phase current	0.5577	0.5023	0.4359	0	0	0.001026	0	0.01	0.03128
B phase current	0.7909	0.7299	0.4247	0	0	0.001026	0	0.01	0.03128
C phase current	0.5539	0.4159	0.4289	0	0	0.001026	0	0.01	0.03128
Current + Sequence	0.6302	0.5321	0.4359	0	0	0.001026	0	0.01	0.03128
Limit	< 3	< 3	< 3	< 0.3	< 0.3	< 0.3	< 14	< 14	< 14
Result (P—Pass/ F—Fail)	P	P	P	P	P	P	P	P	P

Table 8 Dynamic Ramp of System Frequency: 25FPS/M class

Parameters →	TVE (%)			FE (Hz)			RFE (Hz/S)		
	A	B	C	A	B	C	A	B	C
PMU ↓									
A phase voltage	0.2083	0.1488	0.09239	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
B phase voltage	0.2609	0.2455	0.09354	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
C phase voltage	0.1694	0.1965	0.09099	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
Voltage + Sequence	0.2081	0.1923	0.0922	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
A phase current	0.5284	0.4925	0.1264	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
B phase current	0.8041	0.7615	0.125	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
C phase current	0.5564	0.3154	0.1245	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
Current + Sequence	0.6288	0.5221	0.1264	0.001214	0.001214	0.0009473	0.02003	0.01003	0.03665
Limit	< 1	< 1	< 1	< 0.01	< 0.01	< 0.01	< 0.2	< 0.2	< 0.2
Result	P	P	P	P	P	P	P	P	P

Table 9 Dynamic Input Step change PMU A, B & C

25FPS/M class PMU	Phase Response time (s)			Phase delay time (s)			Phase Overshoot (%)			Frequency Response Time (s)			ROCOF Response Time (s)		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
A phase voltage	0.14	0.136	0.148	0.004	0.004	0.004	0.3891	0.3888	0.3896	0.292	0.292	0.252	0.316	0.32	0.284
B phase voltage	0.136	0.136	0.14	0	0	0	0.4889	0.4889	0.4793	0.292	0.292	0.252	0.316	0.32	0.284
C phase voltage	0.14	0.14	0.14	0.0009441	0.000944	0.001296	0.4769	0.4764	0.4592	0.292	0.292	0.252	0.316	0.32	0.284
Voltage + Sequence	0.136	0.136	0.14	0.004	0.004	0.004	0.5056	0.5053	0.4866	0.292	0.292	0.252	0.316	0.32	0.284
A phase current	0.112	0.132	0.144	0.004	0.004	0.004	0.3894	0.3894	0.3894	0.292	0.292	0.252	0.316	0.32	0.284
B phase current	0.204	0.112	0.14	0	0	0	0.4874	0.488	0.4791	0.292	0.292	0.252	0.316	0.32	0.284
C phase current	0.108	0.136	0.14	0.000953	0.0009492	0.001295	0.4762	0.4752	0.4594	0.292	0.292	0.252	0.316	0.32	0.284
Current + Sequence	0.108	0.108	0.144	0.004	0.004	0.004	0.5041	0.5044	0.3894	0.292	0.292	0.252	0.316	0.32	0.284
Limit	< 0.28	< 0.28	< 0.28	< 0.01	< 0.01	< 0.01	< 10	< 10	< 10	< 0.56	< 0.56	< 0.56	< 0.56	< 0.56	< 0.56
Result	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

PMU measurement evaluation is specified in the IEC/IEEE 60,255-118-1:2018 and total vector, frequency, and rate of change of frequency error, is given by (7)–(9):

$$\text{TVE} = \frac{\sqrt{(Xr(n) - XI(n))^2 + (XI(n) - XI(n))^2}}{Xr(n)^2 + XI(n)^2} \quad (7)$$

$$\text{FE} = |f_{\text{true}} - f_{\text{measured}}| = |\Delta f_{\text{true}} - \Delta f_{\text{measured}}| \quad (8)$$

$$\text{RFE} = \left| \left(\frac{df}{dt} \right)_{\text{true}} - \left(\frac{df}{dt} \right)_{\text{measured}} \right| \quad (9)$$

where F_{measured} —frequency estimated by PMU, F_{true} —test signal frequency from PMU.

Calibration System

4. Compliance Outcomes and Discussions

By IEC/IEEE 60,255-118-1:2018 the dynamic test requirements are met. The test results are discussed and analyzed in this section. Test results for the PMU reporting rates of 25 FPS M class are listed in Table 1. Three PMUs were tested for the nominal frequency class of 10 FPS, 25 FPS, and 50 FPS to determine TVE, FE, and RFE. The measurement data points are traced and the limits for M class PMU tested with 25 FPS are observed and discussed.

4.1. Steady-state Compliance

4.1.1. Single-frequency test

The frequency of the signal test is 45–55 Hz for both voltage and current steps, and the results achieved for PMU A, B, and C are shown in Table 2. The obtained data shows clearly that TVE is within the specified limits. PMU A provides the maximum value for TVE.

4.1.2. Voltage and Current Magnitude

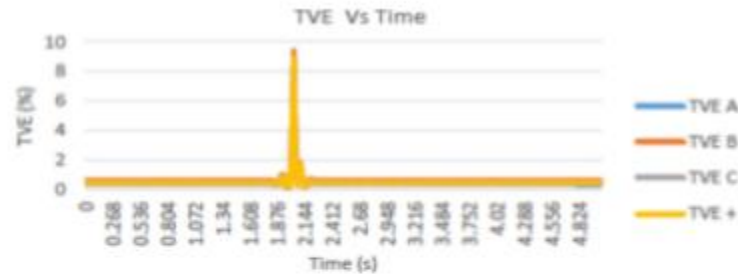
Signal Voltage Magnitude Signal

The voltage range in this test is from 10 to 120% of the rated voltage. The rated voltage of PMU A and PMU B is 63.5 V AC; the rated voltage of PMU C is 230 V AC. The PMU A and B TVE values in Table 1 are higher than the PMU C values of PMU C. However, all TVE values are within the limits of Table 3.

Current Magnitude Signal

The current magnitude is therefore varying from 10 to 200% of the rated current. The current rating for PMU A and PMU B is 1 AC and 5 AC for PMU C. The PMU rating class is M, which always provides high-precision measurements, and is connected to CT core measurements, not the CT core protection. The PMU C TVE values in Table 1

Fig. 7 PMU A—TVE versus Time (Phase)



are within the limits of the PMU A and PMU B TVE values, exceeding the limits in Table 3. Figures 3 and 4 show PMU A & B's max TVE value.

4.1.3. Distortion (Single Harmonic)

The test consists of a test that verifies the impact of harmonics on the accuracy of the PMU. The harmonics from the 2nd to the 50th harmonics are inserted one at a time into the constant input signal. Table 4 shows the measured and calculated values. All PMUs are within limits of their accuracy. This test was passed by all PMUs. For PMU A the max TVE value for B phase current is visible.

4.1.4. Out-of-band interference test (Interharmonics)

Interfering frequency signal is placed on the base signal and varies between 10 and 100 Hz. The filterability is analyzed for all interfering frequencies to be filtered. The PMU A and PMU B TVE values are similar; PMU C TVE is higher than the PMU but within the limits of Table 5. The data show that PMU C is sensitive to interfering signals but PMUs A (except B phase current) and B phase display good angle estimates. The FE is within the limits for all PMUs and does not require a frequency error change rate limit.

4.2. Dynamic Compliance

4.2.1. Dynamic: Measurement Bandwidth (Phase Modulation)

Figure 5 as well as Table 6 show the TVE value of PMU C is higher than the PMU A (except B phase current) and PMU B. The FE and ROCOF are almost similar for PMU A, B & C.

4.2.2. Dynamic: Measurement Bandwidth (Amplitude Modulation)

Table 7 shows that PMU A's TVE value (current) is higher than PMU B and PMU C. The limits are PMU A, B & CTVE, FE, and ROCOF values.

4.2.3. Dynamic Ramp of System Frequency

Figure 6 and Table 8, demonstrates that the PMU A TVE value is higher than the PMU B and PMU C because of the phase error impact. All the TVE, FE, RFE values, however, are within the limits.

4.2.4. Dynamic Input Step Change (Phase)

The phasor response and delay time, overshoot, frequency response, and derivative time were determined and listed in Table 9 in this test and the PMU A details are shown in Fig. 7.

4.2.5. Change the Dynamic Input Step (Amplitude)

The phasor response and delay time, overshoot, frequency response, and derivative time were determined in this test and listed in Table 10.

4.2.6. Maximum Latency of PMU Reporting

The latency test was conducted for PMU A, B & C and was calculated to be 228.365 ms, 228.175 ms, and 198.032 ms, well below the normal limits of < 280 ms.

5. Conclusion

This article presented an approach for the evaluation of any type of PMU using the IEC/IEEE 60,255-118-1:2018 standard PMU calibration system. Three Synchrophasor

Table 10 Dynamic Input Step change (Amplitude) (PMU A, B & C)

PMU	Phasor Response time (s)			Phasor delay time (s)			Amplitude Overhoot (%)			Frequency Response Time (s)			ROCOF Response Time (s)		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
A phase voltage	0.05	0.052	0.056	0.000321	0.000339	0.001502	7.431	7.442	7.169	0.112	0.108	0.12	0.184	0.184	0.18
B phase voltage	0.05	0.052	0.056	0.001465	0.001468	0.002586	7.517	7.519	7.291	0.112	0.108	0.12	0.184	0.184	0.18
C phase voltage	0.05	0.052	0.052	— 0.00013	— 0.000128	— 0.000044	7.52	7.522	7.266	0.112	0.108	0.12	0.184	0.184	0.18
Voltage + Sequence	0.052	0.052	0.052	0.000169	0.000176	0.00135	7.489	7.494	7.231	0.112	0.108	0.12	0.184	0.184	0.18
A phase current	0.09	0.084	0.056	0.000335	0.000378	0.001496	0.1184	0.1174	0.1563	0.112	0.108	0.12	0.184	0.184	0.18
B phase current	0.1	0.096	0.056	0.001507	0.001551	0.0026	0.1179	0.1182	0.1584	0.112	0.108	0.12	0.184	0.184	0.18
C phase current	0.09	0.052	0.052	— 0.0013	— 0.00125	— 0.000084	0.1188	0.1198	0.1583	0.112	0.108	0.12	0.184	0.184	0.18
Current + Sequence	0.09	0.088	0.056	0.000177	0.000235	0.001496	0.1179	0.1184	0.1563	0.112	0.108	0.12	0.184	0.184	0.18
Limit	< 0.28	< 0.28	< 0.28	< 0.01	< 0.01	< 0.01	< 10	< 10	< 10	< 0.56	< 0.56	< 0.56	< 0.56	< 0.56	< 0.56
Result	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

units from various providers have been validated by the latest Std. IEC/IEEE standard 60,255-118-1:2018 defining stable and dynamic/transient tests of compliance.

Due to the high-precision calibrator used to calibrate TVE, FE, and RFE, the PMU calibration system is more accurate. The PMU calibration system produces more than 10 times more precise signals than the standard requirements. This calibrator is capable of producing output signals at various frequencies, voltage & current signal width variations, interference injection harmonics, modulated amplitude, modulated phase, system frequency ramping, phase & phase change steps, and PMU measurement latency needed for dynamic test range capacities.

The PMUCAL software is used for TVE, FE & RFE computing. The calibration system parameter output is used to test PMU compliance. The parameters are calibrated in an ISO/IEC 17,025:2017 accredited standard laboratory. Besides, mathematical models are built into the calibration systems and PMU data measurement is compared to the mathematical model, and TVE, FE, and RFE are calculated.

Results show that PMU A and PMU B are not complied with while PMU C complies with a standard of 25 FPS for M-class performance. Measuring PMU at the lowest current range failed (10–200%). Generally, M class PMU is connected to CT metering to improve precision in the normal operating range. For wide range measurement, the current transform in the lower band, sensitivity needs to be improved and ensure that it is linear as PMU A and PMU B fail in the current magnitude test. To pass all these tests this PMUs need correction in algorithms/firmware upgrading.

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