Testing of Phasor Measurement Units as per IEC/IEEE Standards – The Whats and the Hows?

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***Abstract*—Synchrophasors are phasor data that are captured in a synchronized manner with the help of a reference time signal. This task of capturing the synchrophasor data is performed by Phasor Measurement Units (PMUs). PMUs also capture frequency and ROCOF measurements using input voltage and current signals with the help of a reference time signal for time stamping the measured data. Reference time signal is obtained by high accuracy source such as a GPS receiver for example. PMUs are considered highly significant to a power system network since they capture and share time stamped synchrophasor data with multiple devices in real-time. PMUs are used for applications such as Wide-area protection schemes, disturbance analysis, power system health monitoring, etc.**

In 2018, a new standard was developed for synchrophasor measurement in power systems jointly by IEC and IEEE which is IEC/IEEE 60255-118-1. This standard also includes the accuracy requirements to evaluate the synchrophasor, frequency and ROCOF measurements. Another IEC standard 60255-181 which was published in 2019 sheds light on test methods to validate the frequency protection as well as accuracy requirements for the test results. In this paper, we explore aspects of PMU validation using different tests that need to be performed, different test methods, synchronization methods and accuracy requirements with respect to both the above-mentioned standards. Test results are analyzed and presented in relation to the accuracy requirements.

I. Introduction

Synchrophasors are phasor data that are captured in a synchronized manner with the help of a reference time signal. They represent the magnitude and phase angle of the sine wave. This task of capturing the synchrophasor data is performed by Phasor Measurement Units (PMUs). PMUs are 100 times faster than SCADA and can capture frequency and ROCOF measurements using voltage and current signals with the help of a reference time signal for time stamping the measured data. The reference time signal is obtained using high accuracy sources such as a GPS receiver. PMUs are considered highly significant to a power system network since they capture and share time stamped synchrophasor data from multiple devices in real-time. A PMU records grid data which can be used to provide insight into grid stability. PMUs are used for applications such as wide-area protection schemes, disturbance analysis, power system health monitoring, model validation, post-event analysis etc.

Figure 1 PMU inputs and outputs

In Figure 1, AC voltages, AC currents and timing reference signals are being provided to the PMU. The analog current and voltage inputs represent the AC power system signals. The time reference signal can be an IRIG-B signal. The PMU estimates synchrophasor data for voltages and currents based on the timing signal. It also estimates the frequency of the system and the rate of change of frequency. The outputs of the PMU would be the synchrophasor data as well as frequency and ROCOF. The outputs are usually associated with a time stamp which is the time of measurement.

For each measurement, a time stamp is assigned by the PMU which includes the time and the quality of time stamp.

II. Summary of IEEE/IEC 60255-118-1 Standard

In 2018, a new standard was developed for synchrophasor measurement in power systems jointly by IEC and IEEE which is IEC/IEEE 60255-118-1[1]. The standard also provides requirements for time tagging, synchronization, evaluation methods and compliance for static and dynamic condition. PMUs require certain inputs to be able to make the measurements and provide the expected outputs related to the power system. The standard describes the requirements for synchrophasor measurement, measurement response time, measurement reporting latency, measurement reporting and compliance verification. The standard also describes in detail the measurement compliance testing considerations, steady-state compliance, and dynamic compliance for different conditions.

The PMU measurements and the reference signals could be different from one another with both amplitude and phase angles. However, both are under a single quantity when evaluating the error. One of the important factors for PMU evaluation is the TVE which stands for total vector error. TVE is the measure of difference between a measured quantity from PMU when compared with a reference quantity. This is defined by Equation 1 below[1]:

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

Equation 1 Total Vector Error calculated from phasors

where:

$\hat{X}_r(n)$ *and* $\hat{X}_i(n)$ are the real and imaginary PMU estimates at report time *n;*

$X_r(n)$ *and* $X_i(n)$ are the real and imaginary PMU reference values at report time *n;*

n is the report number representing the report time (the n^{th} report in a series of discrete reports)

As per the standard, TVE considered for all the performance tests is about 1%. This tolerance can be seen in the circle in the Figure 2. The maximum magnitude error is 1% when the phase error is zero. The maximum error is 0.573 for the angle, when magnitude error is 0. The measurement is said to be compliant if it is within the circle as shown in Figure 2 below[1].

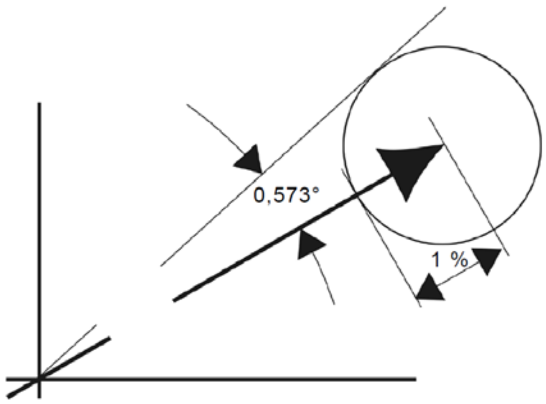


Figure 2 TVE evaluation

Magnitude and phase errors are combined in TVE. TVE is determined using magnitude and phase errors using Equation 2[1]

$$TVE = \sqrt{2(1 + ME)\big(1 - cos(PE)\big) + ME^2}$$

Equation 2 TVE calculated from magnitude and phase errors

Where ME is magnitude error –

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

Equation 3 Magnitude errors used in TVE

And PE is the phase error –

$$PE = \text{atan}\,(\widehat{X_r}, \widehat{X_\iota}) - \text{atan}\,(X_r, X_i)$$

Equation 4 Phase Error used in TVE

III. Test Considerations

As per the standard, compliance tests are validated with respect to class of performance of the PMUs. There are two classes of performance – P class and M class.

To perform the compliance tests as per standards, it is recommended that the tests be conducted with all parameters set to standard reference conditions except ones that are being varied during the test. The values that are not being varied would be considered the reference condition value. Some of the standard reference conditions for all tests are as follows –

- Nominal voltage
- Nominal current
- Nominal frequency
- Constant voltage, current, phase and frequency
- signal THD+N < 0,2 % of the fundamental (where N = noise);
- all interfering signals < 0,2 % of the fundamental

The voltages and currents used for testing are provided as analog signals. As per the standard, testing that would be performed in a laboratory condition would also comply with the following –

- temperature 23 ºC ± 3 ºC;
- humidity < 90 %.

A. *Steady State Compliance Testing*

Steady state compliance can be validated by comparing the PMU outputs obtained under steady-state conditions to the corresponding reference signals. Steady state conditions are defined by a condition where the amplitude, phase and frequency of test signals are constant for the duration of the measurement. Table 1 shows the steady state synchrophasor measurement requirements according to the standard[1]:

Table 1 Synchrophasor measurement requirements. Steady State

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		Performance – P class		Performance – M class	
		Range	Max. TVE %	Range	Max. TVE %
Signal frequency	Frequency = f_0 ($f_{nominal}$)	± 2,0 Hz	1	± 2,0 Hz for F_s < 10 ± F_s/5 for 10 ≤ F_s < 25 ± 5,0 Hz for F_s ≥ 25	1
Voltage signal magnitude	100 % rated	80 % to 120 % rated	1	10 % to 120 % rated	1
Current signal magnitude	100 % rated	10 % to 200 % rated	1	10 % to 200 % rated	1

Table 2 shows the steady state requirements for frequency and ROCOF measurements[1]:

Table 2 Frequency and ROCOF requirements. Steady State

Influence quantity	Reference condition	Error requirements for compliance			
		P class		M class	
Signal frequency	Frequency = f_0 ($f_{nominal}$) Phase angle constant	Range: f_0 ± 2,0 Hz		Range: f_0 ± 2,0 Hz for F_s ≤ 10 ± F_s/5 for 10 ≤ F_s < 25 ± 5,0 Hz for F_s ≥ 25	
		Max. |FE|	Max. |RFE|	Max. |FE|	Max. |RFE|
		0,005 Hz	0,4 Hz/s	0,005 Hz	0,1 Hz/s

B. *Dynamic Compliance testing*

A condition is considered dynamic when balanced three-phase input sine waves are modulated when being injected. Certain modulation factors are used separately with regards to amplitude modulation, phase angle modulation and frequency modulation. Table 3[1] shows the synchrophasor measurement bandwidth requirements using modulated test signals, where kx is the amplitude modulation factor and ka is the phase modulation factor.

Table 3 Bandwidth requirements using modulated test signals

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

Table 4 below shows the requirements for frequency and ROCOF tests when the frequency is modulated. Frequency and ROCOF follow the modulated input and measure the combined effects of the fundamental signal and the modulation. The errors in both measurements are a small fraction of the measured values, but since ROCOF (the second derivative of phase) becomes a large value, the expected error is also large [1].

Table 4 Frequency and ROCOF compliance limits

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

IV. TEST SETUP

We configured a Protective relay as a PMU generating data in C37.118 message format. It was set to produce 30 samples per second with a fast response digital filter with a higher cutoff frequency. This option was used to have high speed in tracing system parameters. PMU data configuration included settings to acquire specific data such as positive sequence as well as three phase voltage and current quantities to be recorded. The PMU frequency configuration was set to calculate rate of change of frequency for every 9 cycles of data. TCP transport scheme was configured for the PMU data transfer. The test setup that was used to perform PMU testing is shown in Figure 3.

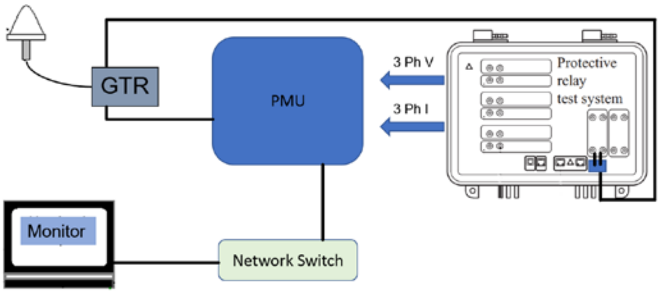


Figure 3 Test setup

A multi-phase test equipment with a test uncertainty ratio of 4:1 was used. The standard recommends that for any accuracy class rating, the test system should have at least a 4:1 test uncertainty ratio (TUR). Three phase currents and voltage connections were made to the respective current and voltage terminals of the PMU.

A GPS reference source is connected to the PMU and configured to receive the IRIG-B timing reference signal for synchronization. For synchronous injection, we decided to use the IRIG-B timing signal with the test set as well.

An ethernet connection is made between PMU and the switch using the TCP protocol to send the synchrophasor data over the network.

During the configuration and testing process the use of a network sniffer proved very useful to verify that the PMU was sending the synchrophasors data and configuration frames to the network as well as being sent to the proper server and using the proper protocol TCP or UDP (Figure 4):

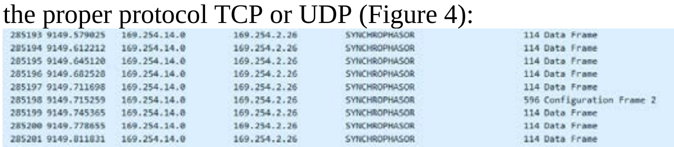


Figure 4 Synchrophasor packages on the network

It was also useful to check the quality of the timing signal (Figure 5),

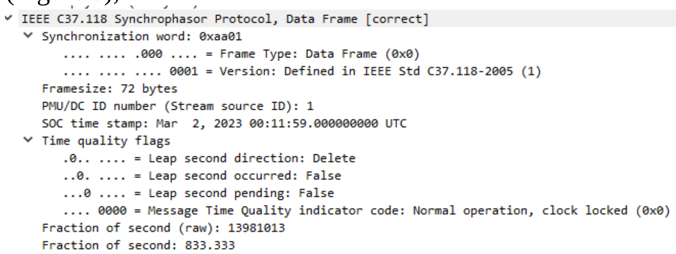
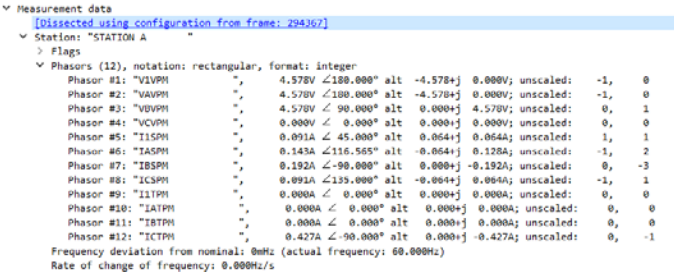


Figure 5 Synchrophasor package showing clock locked

To verify the payload information on the synchrophasor packages (Figure 6), etc.



```
Measurement data
  [Dissected using configuration from frame: 294367]
  Station: "STATION A       "
    Flags
    Phasors (12), notation: rectangular, format: integer
      Phasor #1: "V1VPM           ",    4.578V ∠180.000° alt  -4.578+j  0.000V; unscaled:   -1,    0
      Phasor #2: "VAVPM           ",    4.578V ∠180.000° alt  -4.578+j  0.000V; unscaled:   -1,    0
      Phasor #3: "VBVPM           ",    4.578V ∠ 90.000° alt   0.000+j  4.578V; unscaled:    0,    1
      Phasor #4: "VCVPM           ",    0.000V ∠  0.000° alt   0.000+j  0.000V; unscaled:    0,    0
      Phasor #5: "I1SPM           ",    0.091A ∠ 45.000° alt   0.064+j  0.064A; unscaled:    1,    1
      Phasor #6: "IASPM           ",    0.143A ∠116.565° alt  -0.064+j  0.128A; unscaled:   -1,    2
      Phasor #7: "IBSPM           ",    0.192A ∠-90.000° alt   0.000+j -0.192A; unscaled:    0,   -3
      Phasor #8: "ICSPM           ",    0.091A ∠135.000° alt  -0.064+j  0.064A; unscaled:   -1,    1
      Phasor #9: "I1TPM           ",    0.000A ∠  0.000° alt   0.000+j  0.000A; unscaled:    0,    0
      Phasor #10: "IATPM           ",    0.000A ∠  0.000° alt   0.000+j  0.000A; unscaled:    0,    0
      Phasor #11: "IBTPM           ",    0.000A ∠  0.000° alt   0.000+j  0.000A; unscaled:    0,    0
      Phasor #12: "ICTPM           ",    0.427A ∠-90.000° alt   0.000+j -0.427A; unscaled:    0,   -1
    Frequency deviation from nominal: 0mHz (actual frequency: 60.000Hz)
    Rate of change of frequency: 0.000Hz/s
```

Figure 6 Synchrophasor Measurement data

After the initial configuration and verifications, a commercially available monitoring software system that has the capability to decode, register and display the synchrophasor data is connected to the same network switch to receive the synchrophasor data that PMU is outputting.

V. RESULTS, COMPARISON & ANALYSIS

For steady state compliance testing, a constant set of nominal values (in secondary) were injected to the PMU. Balanced three phase current of 1 amp, balanced three phase voltage of 69V at 60 Hz were injected to the PMU for about 10 seconds. The standard recommends that injection of the constant input signals to the PMU for steady state testing should be no less than 5 seconds. Since, we chose to perform synchronized injection, the analogs were initiated at a certain set time based on the IRIG-B timing signal.

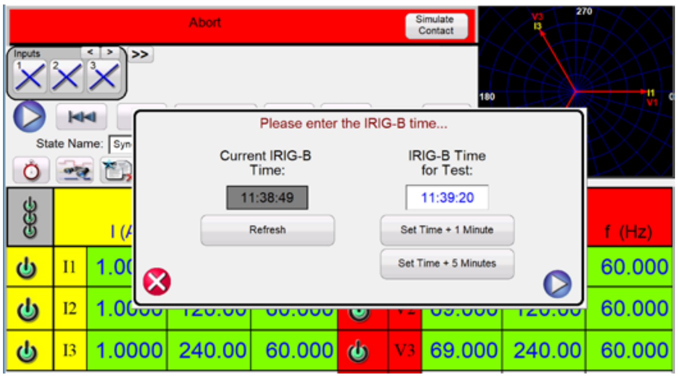


Figure 7 Synchronized injection.

Figure 5 shows the setup on the software test screen to setup the currents, voltages, and frequencies for the three-phase injection.

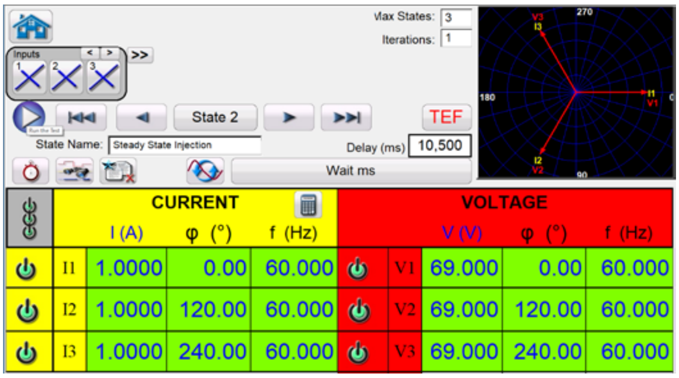


Figure 8 Signals injected into the PMU

The synchrophasor data was continuously monitored on the monitoring platform. The synchrophasor data which included, current magnitude, current phase angle, voltage magnitude, voltage phase angle, frequency, and rate of change of frequency were then exported, from the PMU monitoring software in the form of a COMTRADE file. This COMTRADE file does not contain the usual oscillographic records but rather the phasor profiles for magnitude, phase angle, frequency and rate of change of frequency. The PMU also had certain protection features enabled.

The PMU was alto setup to generate oscillographic records in the form of COMTRADE files which contained the original analog signals injected into the device. These COMTRADE files were then used to compare the injected signals and the output synchrophasor data (retrieved from monitoring platform) to validate the errors.

Figure 6 below shows the capture of current magnitude on the monitoring platform for a steady state test. The currents shown are in primary amps with respect to time.

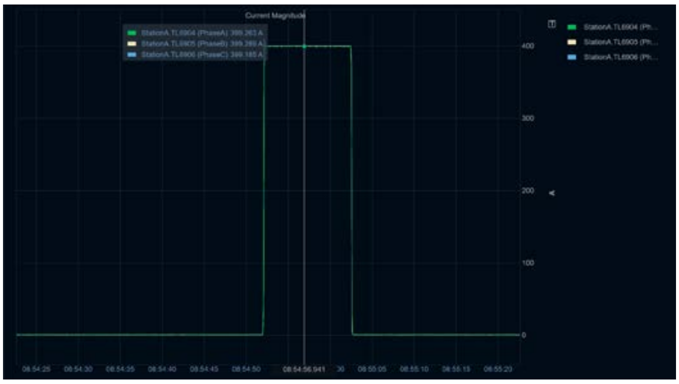


Figure 9 PMU Current profile capture

Figure 7 shows the panels used to capture all the data that was configured to be recorded on the monitoring platform.

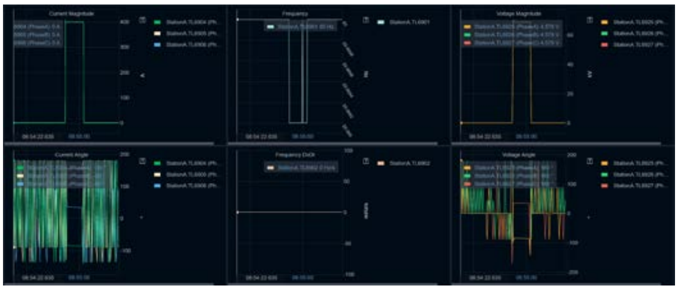


Figure 10 Capture panels

Each panel displays a particular dataset. Current magnitude, current phase angle, voltage magnitude, voltage phase angle, frequency, and rate of change of frequency panels were configured to be displayed on the monitoring dashboard.

Once the injection was stopped, the data was exported for the same 10 second timeframe in the form of COMTRADE. A COMTRADE file containing the original injected signal was exported from the PMU for comparison purposes. Figure 11 to Figure 14 show a comparison of the COMTRADE files produced from the PMU monitoring software and the original signal injected into the PMU for currents and voltages.

In Figure 11, the currents that the PMU read were about 400 amps primary. The synchrophasor data was sampled at about 30 samples per second. The synchrophasor data for current was included with the original signal COMTRADE file to compare the values.

The outputs from PMU were within the range somewhere between 398.7 Amps to 401.9 amps.

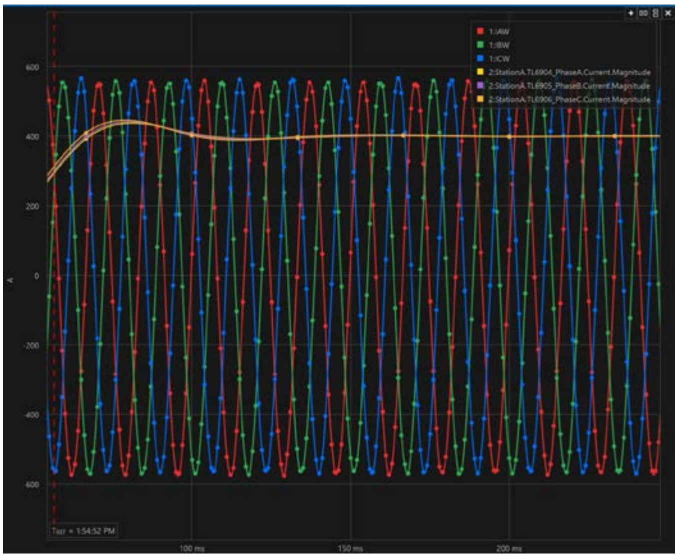


Figure 11 3 phase currents and PMU currents

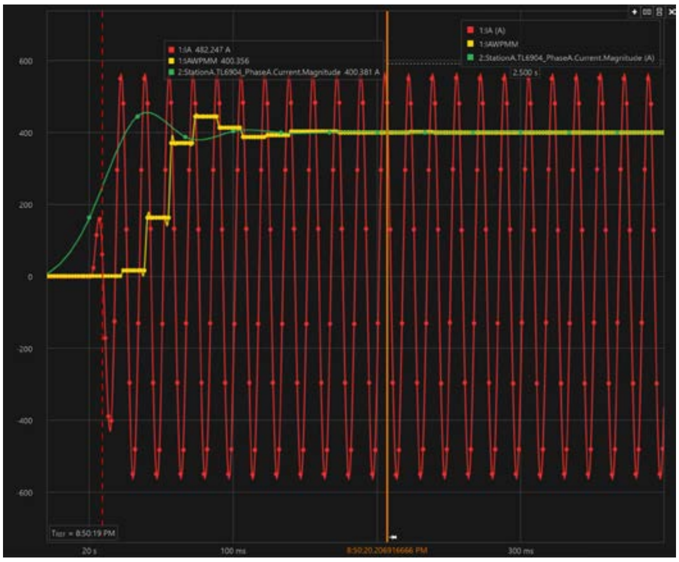


Figure 12 Single phase Current & PMU current

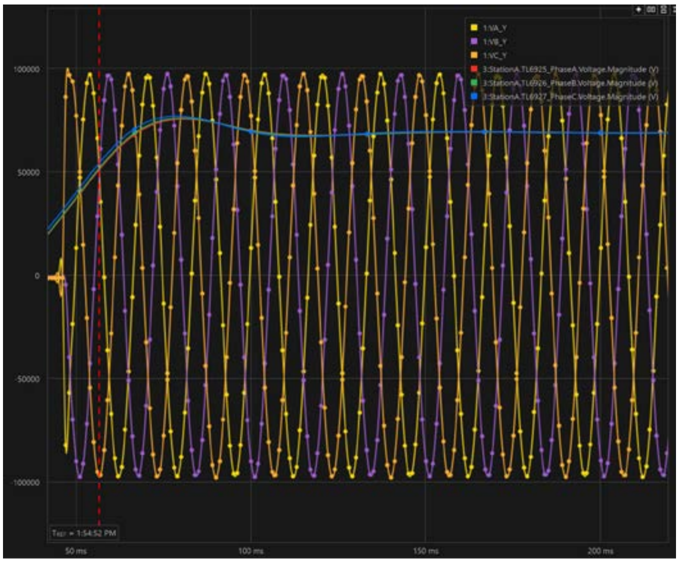


Figure 13 3 phase Voltages and PMU Voltages

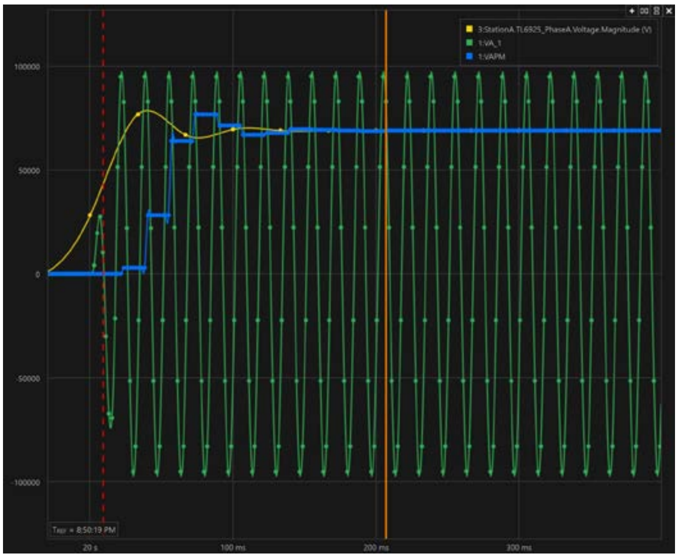


Figure 14 Single phase Voltage and PMU Voltage

Similarly, the voltage magnitude read by the PMU was 69kV at 60 Hz.
For both voltage and current magnitudes, the PMU measurements take about 7 cycles to stabilize and produce the proper RMS values. A certain offshoot of the expected value is produced. However, the applied steep change in current and voltage, applied to the PMU during this test, is not a typical condition in the power system. The purpose of the test was to verify the production of the steady state synchrophasor data. It is verified that after 6 power system cycles the PMU output corresponds to the injected signal. A different type of test should be used to verify the dynamic behavior of the PMU.
Figure 15 shows a comparison between the system frequency and the synchrophasor output which differs by about 0.001Hz.

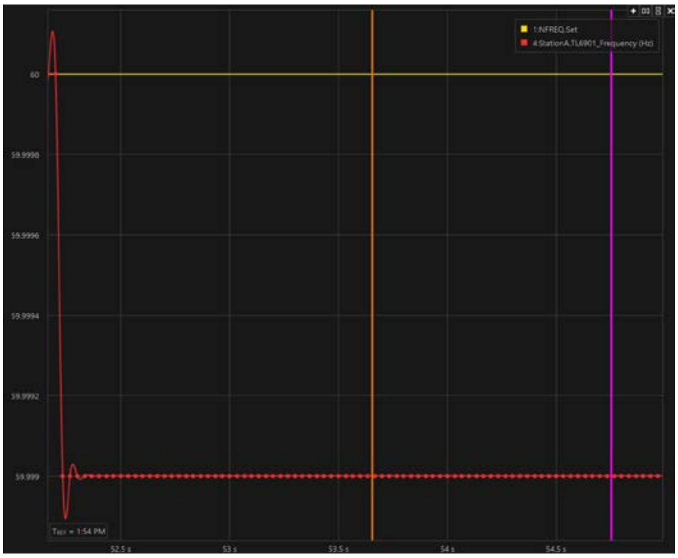


Figure 15 PMU frequency vs COMTRADE frequency

A second test that was performed was the rate-of-change-of-frequency test. A ROCOF test was setup with rate of change set to 0.5Hz/s from nominal. The test was run for more than 5 seconds. The figure below shows the test setup for ROCOF test.

Figure 16 ROCOF test configuration

For the ROCOF test, the prefault values were set to 1 amp and 69V at 60 Hz for two seconds, followed by which the frequency of the voltage was linearly ramped for about 0.5 Hz per second as can be seen in Figure 8.

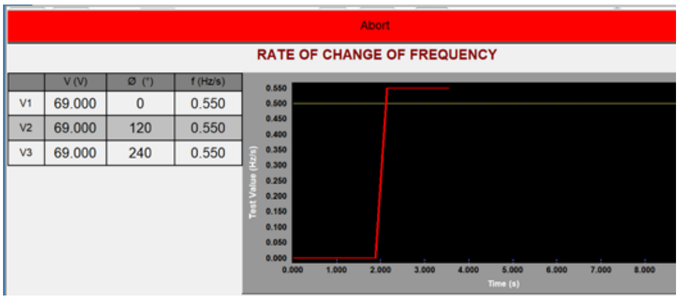


Figure 17 ROCOF test graph

The COMTRADE files show the captures from the monitoring platform for the ROCOF test. The figure shows the actual frequency changes as well as the phase angle response for the current and voltage signals. The figure shows the actual rate of change of frequency as per the test performed.

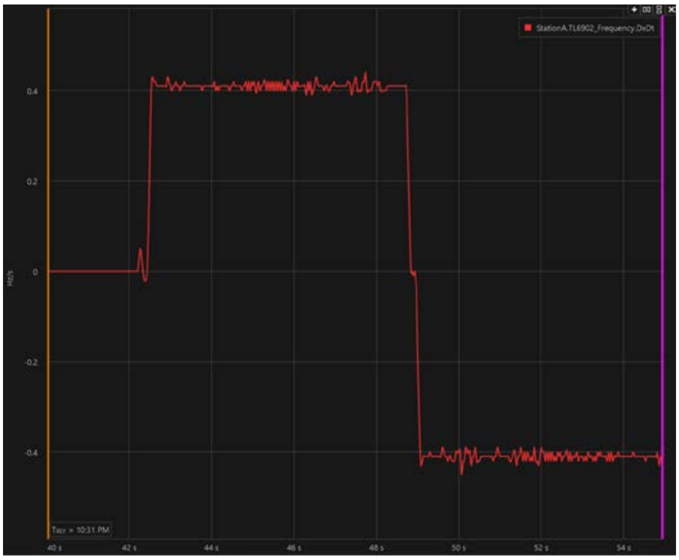


Figure 18 ROCOF PMU

The rate of change of frequency was kept constant during the test. A certain jitter can be seen in the rate of change frequency measurement in Figure 18 which may have something to do with the type of frequency variation applied. However, the frequency variation graph shown in Figure 19 is very clean. This could merit further investigation.

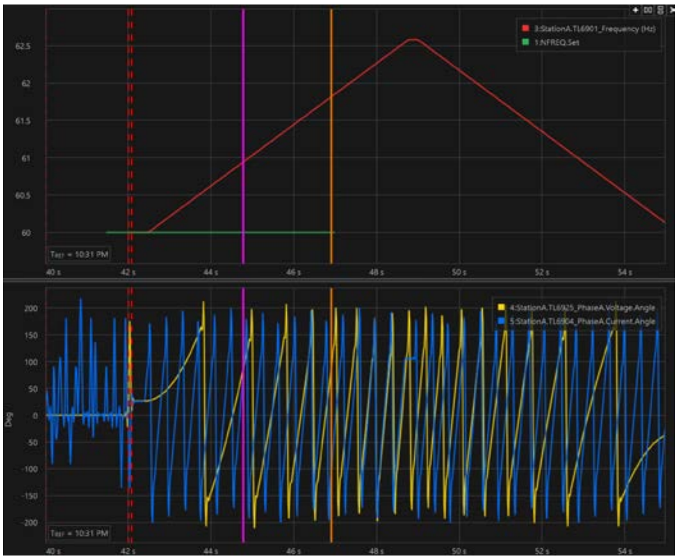


Figure 19 Frequency PMU

VI. CONCLUSION

Verifying PMU measurements in the field is similar to verifying metering functions on protection relays or other measurement equipment. PMU with analog inputs should be verified using test sets capable of injecting analog signals injection with a 4:1 TUR. This process of verification should include producing both steady state and dynamic signals. The PMU output can be captured using commercially available software tools which can produce them in the form of COMTRADE files. These PMU COMTRADE can be compared to the original signals injected into the PMU to verify their output. This simple process of verification was presented in the paper.

VII. REFERENCES

[1] IEC/IEEE 60255-118-1 Measuring relays and protective equipment-Synchrophasors for power systems – Measurements

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[3] Brett Cockerham, Andy Gould, Tim Grigg, and Jai Subbarayan. Visualize Synchrophasor Data in Real Time With an SEL-735 Meter and Synchrowave Monitoring. https://selinc.com/api/download/136446/

VIII. BIOGRAPHIES

Sughosh Kuber is a Relay & Protection Applications Engineer at Megger North America, where he provides technical support to service companies and utilities responsible for reliable operation of electrical networks. Sughosh brings over 10 years of field experience and academic research in power systems from protection schemes and testing to data analysis for energy efficiency and sustainability. Sughosh received his MS in Electrical Engineering from New Mexico State University. Sughosh earned his B.E in instrumentation technology from J.S.S Academy of Technical Education in Visvesvaraya Technological University. He worked at Sentinel Power Services as Project Engineer from 2013 to 2018 before joining Megger. He is currently a member of IEEE-PSRC.

Abel Gonzalez is a Senior Relay Applications Engineer with Megger. Received his bachelor's and his MSc in Electrical Engineering from the Universidad Central de Las Villas, Cuba in 1996 and 2000. From 1996 to 2000 Worked as an Assistant professor for the Faculty of Electrical Engineering at the Universidad Central de Las Villas, Cuba, where he taught courses in Electrical Drives and Power Electronics. From 2000 to 2010 worked as a Tele-traffic Engineer, Control Engineer and Head of the Marketing Department for the Cuban Telecommunications Company as well as a professor of Marketing and Electrical Engineering, for the Universidad Central de Las Villas, Cuba. From 2010 to 2013 worked as a Design Engineer for Arteche Medición y Tecnología in Zapopan, Jalisco, Mexico and Curitiba, Brazil. From 2013 works as an applications Engineer for Megger, LTD in Markham, Ontario. His research areas are the analysis operation, control, and protection of electric power systems. He is currently a member of IEEE-PSRC.