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An Experiment-based Distribution Level Performance Comparison among PMUs

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***Abstract*—This paper presents a experiment-based distribution level performance comparison among three Phasor Measurement Units (PMUs). Several evaluation criteria, including the total vector error, the phase angle error, the frequency error, the rate of change of frequency, the response time, the settling time, the overshoot, and the algorithm window size, are selected to compare the static and dynamic performances of the PMUs under steady state and step response test conditions. In order to have a more realistic test environment, a test is setup in which PMUs under evaluation have exactly the same input signals. The quantitative experiment result analysis gives an end-user guideline to the PMU selection regarding distribution level applications.**

***Index Terms*—Phasor measurement units, test bench, μPMU applications**

I. INTRODUCTION

Thanks to the development of the synchronized phasor measurement technique, the phase angle and frequency estimations can be realized in distribution level Phasor Measurement Units (PMUs) through single phase measurement estimations [1]. Unlike conventional PMUs installed at the high voltage level, distribution level PMUs monitor a power grid at a much lower voltage level with reduced installation costs and improved accuracy [2]. The distribution level PMUs have been studied by several power system research groups, such as Frequency Monitoring Network (FNET/Grideye) and the Power Standards Lab. One of the successful examples is the Frequency Disturbance Recorders (FDRs) developed by FNET that have been widely deployed over the world. In addition to FDRs, Universal Grid Analyzers (UGAs) were developed at the University of Tennessee, Knoxville. With a basic synchrophasor estimation function similar to FDRs, UGAs have a higher reporting rate, better calculating ability, and the ability to estimate more power quality factors such as harmonics, signal to noise ratio (SNR), sags, and swells [3]. On the other hand, there are other distribution level PMUs such as micro PMUs (which are sometime referred to as μPMUs), and Field Programmable Gate Array (FPGA) PMUs [4]–[6].

The IEEE C37.118.1 standard for synchrophasor measurement provides the transmission level performance requirements for PMUs. Most of the popular PMUs can satisfy the requirements in this standard [7], [8]. However, there are still several different requirements between the transmission and the distribution level PMU applications, such as more harmonics, noises, and smaller phase angle difference. The phase angle and frequency estimation accuracy requirements of distribution level PMU applications are usually higher than the IEEE C37.118.1 standard, such as event location, oscillation detection, islanding detection, and dynamic line rating [9]. Different PMU applications may have special requirements on the estimated data that [10] utilize the distribution level PMUs to identify the inertia distribution change in high renewable systems. [9] discusses the PMU applications such as dynamic line rating, event, oscillation, and islanding detection. It also lists the related PMU estimated data as frequency and phase angle error. Again, [11] talks about other PMU applications such as transient detection, line parameter estimation, wide area control, and protection. In addition to frequency and phase angle error, these PMU applications have more requirements on the total vector error, the response time, the settling time, and the overshoot. Meanwhile, [12] utilizes the rate of change of frequency error and the phase angle error to detect the frequency disturbance events. In order to select a suitable PMU regarding different applications, this paper has designed an experiment-based distribution level performance comparison among three PMUs, including two distribution level PMUs and one commercial PMU. These two PMUs are all available on the market and can be deployed on both distribution and transmission levels. This comparison can be treated as a guideline for end users to select the best PMU for their unique requirements. Note that this is the first time to have an experiment-based comparison among PMUs for distribution level applications.

The contributions of this paper are summarized as follows,

- It is the first time to have an experiment-based distribution level performance comparison among PMUs.
- Through the test scenarios and criteria comparison, this paper provides a quantitative comparison among PMUs which gives an end-user guideline for the PMU selection regarding distribution level applications.

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II. TEST SCENARIOS

Generally speaking, there are five test scenarios (listed in the latest IEEE C37.118.1 standard named IEEE/IEC International Standard -measuring relays and protection equipment - part 118-1 [8]) to evaluate the performance of a PMU. They are steady state, step response, ramp response, modulation, and latency tests. However, for distribution level applications, there are several unique characteristics such as single-phase estimations, more harmonics, more noises, and smaller phase angle differences. Due to these unique characteristics of the distribution level power grid, distribution level applications usually have a higher requirement for phase angle, frequency estimation accuracy [9]. In addition, the Response Time (RT), Settling Time (ST), Overshoot (OS), and Estimation Algorithm Window Size (EAWS) are also important for applications such as wide area control and protection applications [11]. Since steady state tests have covered the phase angle/frequency accuracy, the phase angle/frequency step responses are utilized as test scenarios for the RT, and EAWS measurements. Note that the test profile fully satisfy the noise requirement mentioned in IEEE C37.118.1 standard.

To have a quantitative comparison, some criteria are utilized under different test scenarios. Under the steady state test, the Total Vector Error (TVE) and the Phase angle Error (PE) are utilized to compare the performances of the phase angle. TVE combines magnitude and phase angle error into a single criterion. Since the magnitude is not the target of this research, the TVE here focuses on the phase angle estimation quality. The PE represents the phase angle measurement accuracy in a more straight forward way. Similar to the TVE and PE, the critical criteria for frequency estimation are the Frequency Error (FE) and the Rate Of Change Of Frequency (ROCOF) Error (RFE) [8], [12]. Note that the input signal is defined as 60Hz and 120V. A simple summary for all test scenarios is given in Table I. The ST is calculated based on the method mentioned in [11] while other criteria are calculated based on IEEE C37.118.1.

The definition of the FE is straight forward, i.e., the absolute value of the difference between the measured frequency by the PMUs and the reference value. Similar to the FE, the PE is defined as absolute value of the difference between the measured phase angle and the reference value. Meanwhile the definition of the RFE is the absolute value of the difference between the measured ROCOF and the reference value. The TVE, FE, and RFE can be calculated as the following,

$$TVE_{PMU}(i) = |\frac{V(i) - V_{ref}(i)}{V_{ref}(i)}|, \tag{1}$$

$$FE_{PMU}(i) = |F(i) - F_{ref}(i)|, \tag{2}$$

$$RFE_{PMU}(i) = |\frac{dF(i)}{dt} - \frac{dF_{ref}(i)}{dt}|, \tag{3}$$

where $TVE_{PMU}(i)$ is the TVE for different time step, $FE_{PMU}(i)$ is the FE, $V(i)$ is the phase angle vector, $V_{ref}(i)$ is the reference phase angle, $F(i)$ is the frequency estimation for different time step, $F_{ref}(i)$ is the reference frequency, $RFE_{PMU}(i)$ is the RFE for different time step, $\frac{dF(i)}{dt}$ is the ROCOF, and $\frac{dF_{ref}(i)}{dt}$ is the reference ROCOF. Note that the experiment results listed in the experiment results section is the average of the criteria mentioned above.

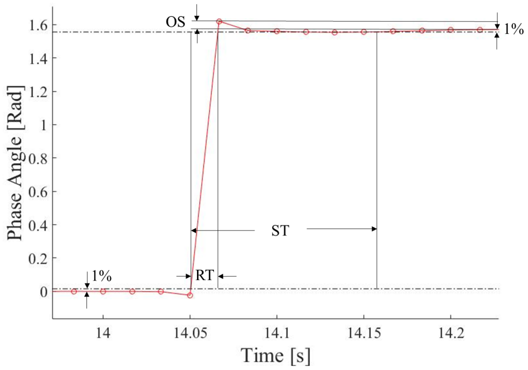

Fig. 1. The illustration for RT, ST, and OS.

Under phase angle and frequency step response tests, the RT, ST, and OS of the phase angle and frequency estimation are utilized as evaluation criteria. As shown in Fig. 1, the RT is the time to transition between two steady-state measurements before and after a step change is applied to the input. For the phase angle and frequency step response test, the RT is determined as the difference between the time that the phase angle/frequency measurement leaves a 1% TVE/0.005Hz and the time it goes back to that limit. Meanwhile, the OS is the maximum phase angle/frequency measurement during the step response. Similar to RT, the ST is the time that the phase angle/frequency measurement leaves a 1% step magnitude after the OS. In addition, the phase angle and frequency estimations usually utilize an interval or ”window” through which the estimations are made. Therefore, the estimations are averaged over that window. The length and weighting of the window would have influences on the estimation results. For example, a short window length would be sensitive to the dynamic response but increase the steady state interference. In this case, it would be valuable to compare the window length for both a phase angle and a frequency estimation algorithm. Fortunately, the phase angle and frequency EAWS can be easily estimated by the step response tests. In this case, the phase angle and frequency EAWS are taken as one of the criteria.

III. EXPERIMENT TEST BENCH

In order to have a fair comparison, an experiment test bench is setup to evaluate the performance of three PMUs. As shown in Fig. 2, the Omicron power source is utilized to generate the test profiles for three PMUs. The three PMUs tested in this paper are one UGA, one μPMU, and one commercial PMU (cPMU) which have been set with 60 frames per second (fps) reporting rate and M class PMU. The detailed setups for the cPMU can be found in Table II. The UGAs are the advanced version of FDRs which are capable of a higher

TABLE I
TEST SCENARIOS AND PARAMETERS

Test cases	Parameters
Frequency static state response	Nominal Frequency: 60Hz; Nominal Voltage: 120V; Nominal Phase Angle: 0°;
Phase angle static state response	Nominal Frequency: 60Hz; Nominal Voltage: 120V; Nominal Phase Angle: 0°;
Frequency step response	Frequency step: 60 to 61Hz; Nominal Voltage: 120V; Nominal Phase Angle: 0°;
Phase angle step response	Nominal Frequency: 60Hz; Nominal Voltage: 120V; Phase angle step: 0 to 90°.

reporting rate and real time power quality measurement [13]. The signal input plugs from the UGA, μPMU, and cPMU are directly connected to the Omicron power source. Note that Omicron 256 plus and a SEK-2488 satellites synchronized network clock are utilized to be the Omicron power source which is accurate enough to be utilized to calibrate PMUs [14]. On the other hand, the Ethernet cables of three PMUs and the Omicron are connected into one router together with a server computer. Through utilizing the Omicron test software, both the steady state and the step response tests can be generated through the stage sequence function. In addition, since three PMUs follow the IEEE C37.118.2 protocol, an Open-Historian is utilized as the server software installed in the server computer to receive all the data from three PMUs simultaneously. During the experiment, three PMUs will be tested simultaneously given the source signals from the Omicron 256 plus and stream data to the server simultaneously as well.

To have a better understanding of UGAs, the architectures of UGAs are briefly introduced. As shown in Fig. 3, the UGA hardware includes a GPS receiver, a Digital Signal Processor (DSP) board, a Micro Controller Unit (MCU) board, a data acquisition board, and an Ethernet module. Through receiving the signal from satellites, the GPS receiver generates the Pulse Per Second (PPS) signal to the DSP board. In addition, the data acquisition board provides 16 bits and 200k samples per each second of raw data to the DSP board. With these two inputs, the DSP board (the operating frequency is 225 MHz.) can calculate the synchrophasors through a 6-cycle recursive DFT algorithm designed for single synchrophasor estimations in distribution networks. The detailed algorithm can be found in [15]. On the other hand, the MCU board receives both the calculated synchrophasors from the DSP board and the GPS time information from the GPS receivers and then packages them into data frames following the IEEE C37.118.2 standard [16]. Finally, these data frames are sent to the server through the Ethernet module.

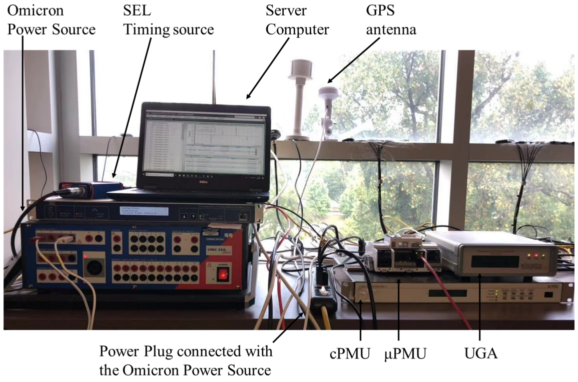

Fig. 2. Experiment test bench.

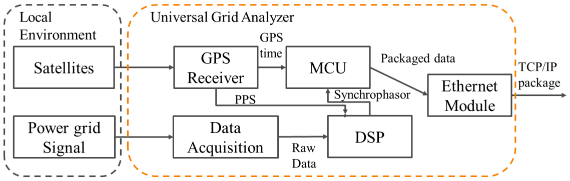

Fig. 3. The UGA architecture.

TABLE II
SETUPS FOR cPMU

Nominal Freq.	60 Hz	Window length in cycle	2 cycles
Adaptive Turning	+/- 5 Hz	Estimated Rate	60 Hz
Estimator Algorithm	Hann	Cycles Used	120 cycles

IV. EXPERIMENT RESULTS

A. Steady State Tests

The experiment results of two test cases are summarized and discussed in this section. The TVE, PE, FE and RFE under steady state test cases can be found in Table IV. It is obvious that three PMUs satisfy the requirements of the IEEE C37.118.1 standard as aspects of the TVE (1%), PE (0.57°), FE (0.005Hz), and RFE (0.1 Hz/s) under the steady state. However, since PMU applications in the distribution level have higher steady state accuracy requirement, it can be observed that the UGA has a relatively smaller TVE (0.0418% smaller than cPMU and 0.0428% smaller than μPMU), PE (0.024° smaller than cPMU and 0.0245° smaller than μPMU), FE (2.0872e-04 Hz smaller than cPMU and 2.6793e-04 Hz smaller than μPMU), and RFE (0.0201 Hz/s smaller than cPMU and 0.0278 Hz/s smaller than μPMU). The FE and TVE under steady state can be verified through the steady state given in Fig. 4 and Fig. 5.

B. Step Response Tests

As shown in Fig. 6, the phase angle step response among three PMUs are given. The phase step change is generated at 14 s with a step change from 0 to 90 degree. The reason for

TABLE III
PMU APPLICATION REQUIREMENT COMPARISON.

PMU Applications	FE (Hz)	RFE (Hz/s)	PE (°)	TVE (%)	RT (ms)	ST (ms)	OS (%)	EAWS	UGA	cPMU	μPMU
Event Location	-	-	± 0.1	-	-	-	-	-	√	√	√
Oscillation Detection	-	-	± 0.6	-	-	-	-	-	√	√	√
Islanding Detection	± 0.35	-	-	-	-	-	-	-	√	√	√
Dynamic Line Rating	-	-	± 0.1	-	-	-	-	-	√	√	√
Transient Detection and Analysis	-	-	-	-	40	60	5	-	√	×	√
Line Parameter Estimation	-	-	-	0.4	-	-	-	-	√	√	√
Wide Area Control and Protection Applications	-	-	-	-	200	-	-	1 - 3	√	√	×
Frequency Disturbance Event Detection	-	0.1	0.57	-	-	-	-	-	√	√	√

choosing a step change with a 90-degree change instead of a 10-degree change (mentioned in the IEEE C37.118.1 standard) is because that it would be easier to measure the phase angle EAWS utilizing a larger step change. Similar to the steady state test, the three PMUs satisfy the RT and OS given in the IEEE C37.118.1 standard, i.e., $7/F_s$ and 5%, where F_s is the reporting rate, i.e., 60 fps. However, as shown in Table IV, if the PMU application has a strict RT requirement, the UGA and μPMU would be a better choice (0.031 s and 0.047 s smaller than cPMU). On the other hand, if the PMU application has a strict ST or OS requirement, the UGA and cPMU would be better (0.118 s and 0.087s smaller than the μPMU for ST or 3.13 % and 3.06% smaller than the μPMU for OS). Meanwhile, as summarized in Table IV, according to the RT of the three units, the size of the phase angle EAWS for the UGA is roughly 2 cycles, while the other two PMUs are roughly 3 cycles and 4 cycles respectively.

In addition to the phase angle step response, the experiment result for the frequency step response is shown in Fig. 7. Again, as summarized in Table IV, three PMUs fully satisfy the frequency step response RT requirement in the IEEE C37.118.1 standard, i.e., $14/F_s$. However, compared with the frequency step response RT, the RT of the cPMU is 0.02 s and 0.04 s less than UGA and μPMU. In addition, the ST of the cPMU is also 0.014 s and 0.049 s less than UGA and μPMU. On the other hand, the OSs of the UGA and cPMU are almost the same and are much smaller than the μPMU (0.48% smaller). Based on the frequency RT, it can be observed that the size of the frequency EAWS of the UGA is 3 cycles, while the cPMU and the μPMU are 2 and 4 cycles respectively.

C. PMU Application Requirement Comparison

Eight PMU applications with their requirements are collected from [9], [11], and [12] in which [9] and [12] are distribution level PMU applications and [11] discusses both transmission and distribution level applications. Note that the frequency disturbance event detection has the exactly the same requirement for the RFE and PE listed in the IEEE C37.118.1. As summarized in Table III, the UGA can satisfy all the PMU applications. On the other hand, the cPMU cannot satisfy the transient detection and analysis requirement due to the stringent requirement on RT. Meanwhile, the μPMU cannot satisfy the wide area control and protection applications due to the EAWS requirement. It is interesting to note that these applications have higher requirements compared with the IEEE C37.118.1 standard. In this case, although a PMU has satisfied the requirements of the IEEE C37.118.1 standard, it may not satisfy the requirements of these PMU applications.

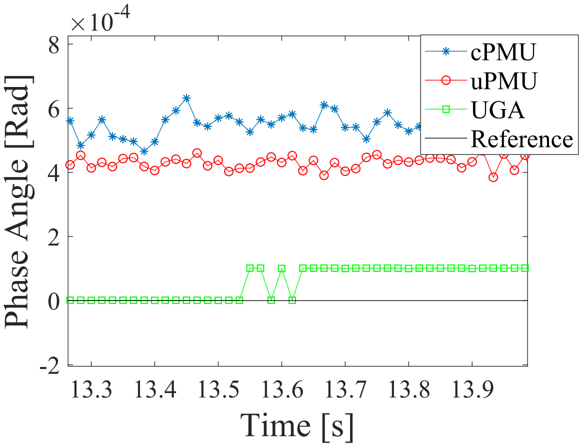

Fig. 4. The phase angle steady state response for Three PMUs.

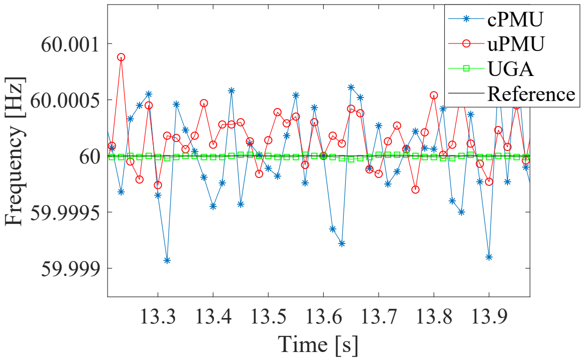

Fig. 5. The frequency steady state response for Three PMUs.

V. CONCLUSIONS

This paper discusses an experiment-based distribution level performance comparison among three PMUs. The universal grid analyzer, the μPMU, and one commercial PMU are tested under steady state and frequency/phase angle step response test conditions. The experiment results show that the three PMUs are largely different for the estimation accuracy, response

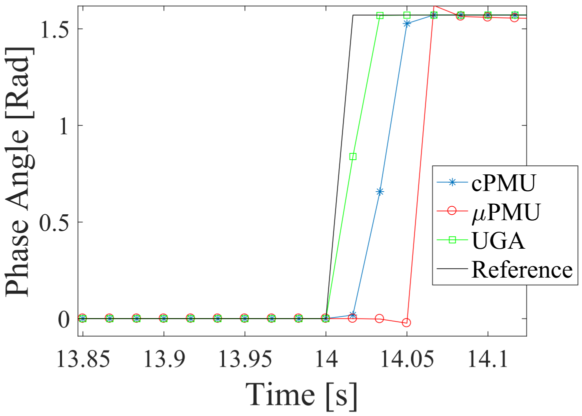

Fig. 6. The phase angle step response for Three PMUs.

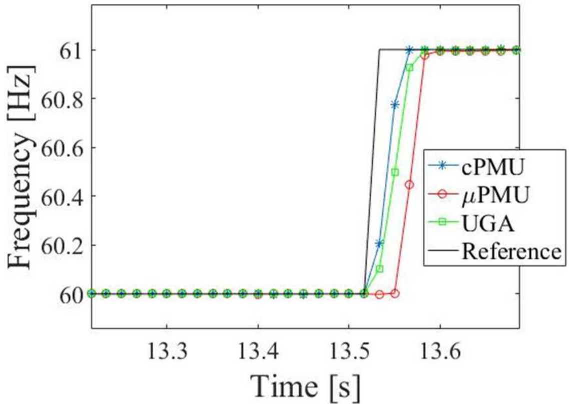

Fig. 7. The frequency step response for Three PMUs.

time, and algorithm window size. Through comparing with the PMU application requirements, this paper provides a guideline for the end-user to choose the suitable distribution level PMU regarding different application requirements instead of focusing on the IEEE C37.118.1 standard alone.

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TABLE IV
EVALUATION CRITERIA UNDER STEADY STATE AND STEP RESPONSE TESTS.

Steady State Test			
	UGA	cPMU	μPMU
TVE (%)	0.0079	0.0497	0.0507
PE (°)	0.0045	0.0285	0.0290
FE (Hz)	2.1455e-05	2.3018e-04	2.8939e-04
RFE (Hz/s)	0.0017	0.0218	0.0295
Step Response Test			
	UGA	cPMU	μPMU
Phase angle RT (s)	0.034	0.065	0.018
Frequency RT (s)	0.0700	0.0500	0.0900
Phase angle OS (%)	0.25	0.32	3.38
Frequency OS (%)	0.01	0.02	0.5
Phase angle ST (s)	0.035	0.066	0.153
Frequency ST (s)	0.063	0.049	0.098
Phase angle EAWS	1	2	4
Frequency EAWS	3	2	4

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