

Comparative Testing of Synchronized Phasor Measurement Units

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Abstract

This work reports the result of a comparative testing done on four Phasor Measurement Units (PMU) from different manufacturers. Phase shift and attenuation at fundamental frequency, performance under system balanced and unbalanced conditions and performance under system variable frequency are the issues addressed for this comparative assessment. The results are presented in a comparative evaluation of features and performance of the PMU units. The results of this work reveal that data from the tested PMU units is of comparable accuracy only under nominal frequency operating conditions. At off-nominal frequency operation every tested PMU unit yielded a different phase and magnitude for the common measured voltage signal. The existing Synchrophasor standard does not specify phase or magnitude performance for off-nominal frequency operation. The standard is in the process of revision, and it is expected that the revised standard will specifically address performance requirements at off-nominal frequencies.

Introduction

Phasor Measurement Units (PMUs) are among the most interesting development in the field of real-time monitoring of power systems. PMU units provide real-time measurement of positive sequence voltages and currents at power system substations. Typically the measurement windows are 1 cycle of the fundamental frequency, and the measurements are time-stamped to a common GPS time synchronization signal. Data from substations are collected at a suitable site, and by aligning the time stamps of the measurements a coherent picture of the state of the power system is created. Many applications of these measurements have been described in the literature.

Several algorithms can be used to estimate the magnitude and phase of currents and voltages; however, one of the most extensively used by PMU manufacturers is the Fourier filter because of its harmonic rejection property and estimation speed, as well as its recursive formulation [1]. Although the basis of the Synchronized Phasor

Measurement may be the same for every PMU unit in the market, the implementation of the measurement algorithm may be rather different between PMU units. Manufactures are free to chose variables such as measurement window size, sampling rate, time stamping and phasor computation rate to suit the standard measurement algorithm to its particular hardware requirements and/or limitations in order to achieve maximum precision of measurement. These differences in the implementation of the phasor measurement algorithm may lead to differences among PMU units of different manufactures, which would jeopardize mix-and-match application of these PMU units. For instance, precision of measurement is enhanced by the use of true 16-bit A/D converters, and by using longer data windows. However, the longer the data window the greater the attenuation factor caused by off-nominal frequency operation [2]. Thus PMU units using different data window sizes may be expected to record different phasor magnitudes at off-nominal frequency operation.

Additionally, the phasor calculation process requires filtering of frequencies above half the sampling rate to prevent aliasing (Nyquist's criterion). Better filtering increases measurement precision but introduces delays, phase shifts and amplitude rolloffs [1]. Since manufacturers are adopting different sampling rates and filtering for their PMU units, identical performance of this units may not be automatically achieved under off-nominal frequency conditions.

The current Synchrophasor Standard, IEEE std. 1344-1995, establishes guidelines for assuring that PMU units can be readily interfaced with associated systems. As the scope of the standard states, only synchronization of data sampling and output formats are addressed leaving to the manufacturer's consideration aspects such as response time, accuracy, hardware, software and computing algorithms. Thus the compliance with the current Synchrophasor Standard does not guaranty that the performance of PMU units from different manufactures will be the same for all operating conditions.

This work reports the result of a comparative testing done on four PMU units built by different manufacturers. Phase shift and attenuation at fundamental frequency, performance under system balanced and unbalanced conditions and performance under system variable frequency are the issues addressed for

this comparative assessment. The results are presented in a comparative evaluation of features and performance of the PMU units. The ultimate objective of this comparative testing is to assess the feasibility of interchangeability for these four PMU units.

Test setup and results

Three tests were set up for this comparative assessment:

1. Balanced three phase voltages at nominal frequency.
2. Balanced three phase currents at nominal frequency.
3. Unbalanced (single phase) voltage at off-nominal frequencies

The four PMU units were mounted in a 19 inches rack and wired in a fashion such that all of them sense the same currents and voltages generated by a three phase variable source.

Test one: Balanced three phase voltages at nominal frequency.

Magnitude comparison:

Test one compares the performance of the PMU units under balanced three phase voltage conditions in a range from 10% to 120% of the nominal voltage rating in steps of 10% at nominal frequency. For every voltage step a three second window of data was aligned according to the time stamp provided by each PMU unit. The aligned phasor magnitudes were compared against a reference value measured at every voltage step using standard laboratory measuring instruments. Since no attempt to calibrate the laboratory instruments was made, the following results only measure accuracy with respect to the laboratory instruments used. The errors shown in

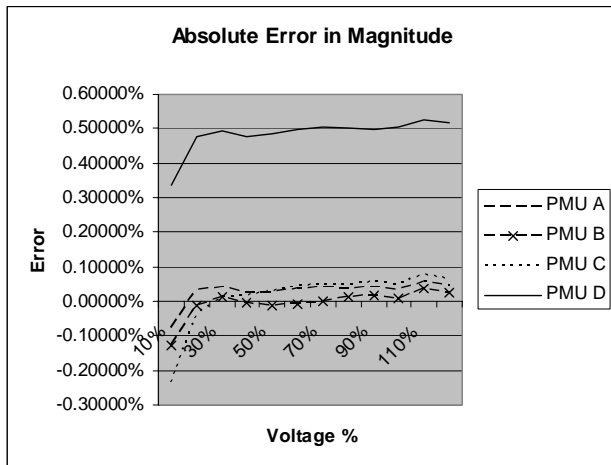


Figure 1 represent the deviation of the measured phasor magnitude with respect to the reference value.

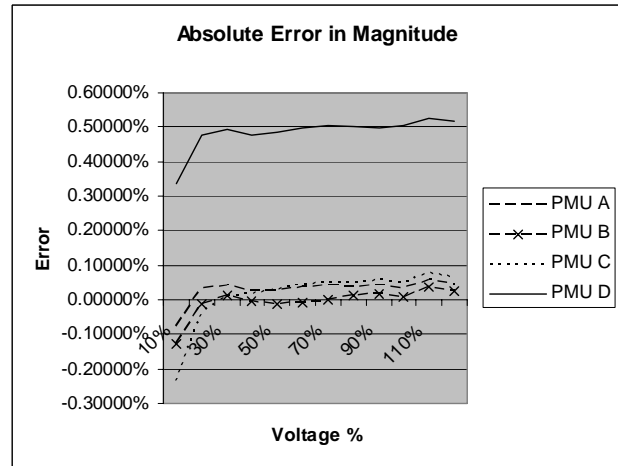


Figure 1: Magnitude errors for balanced three phase voltage at nominal frequency.

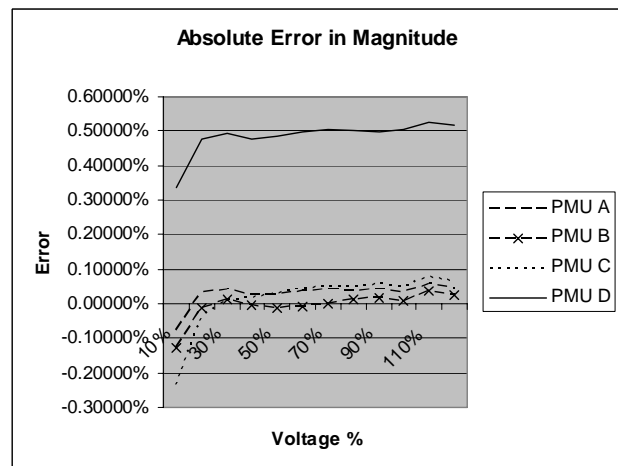


Figure 1 shows that the phasor magnitudes measured by PMUs A, B and C are very close to each other with errors less than 0.1 % with respect to the reference value. The Unit D’s phasor magnitude measurements show an unexpected offset of 0.5 % surely due to incorrect correction factor in its algorithm.

It is also clear from

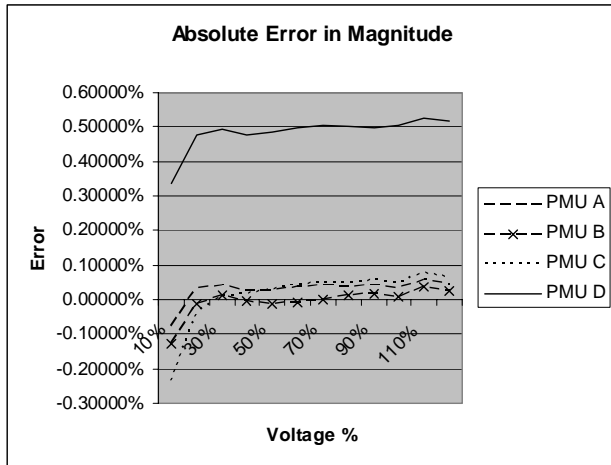


Figure 1 that for all four PMU units the error with respect to the reference changes significantly for voltages lower than 30% full scale (67 V).

Phase comparison:

The aligned phasor angles needed to be corrected into a more even baseline before being compared. To start with, a simple inspection of the available data revealed a fixed phase shift of 180 degrees for unit A and 17.31 degrees for unit D. The phase shift introduced by unit A is caused by an erroneous inversion of the signal during the measuring process. In the case of unit C the phase shift is due to the analog and digital filters. Once the data has been corrected for these biases it can be presented in a more meaningful way.

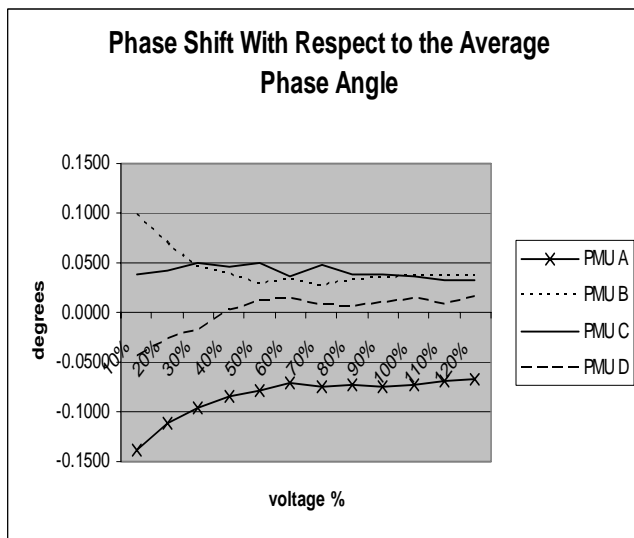


Figure 2 shows the phase difference between the corrected phase angle for every unit and the arithmetic average of the corrected phase angles for the four PMU units at each voltage step.

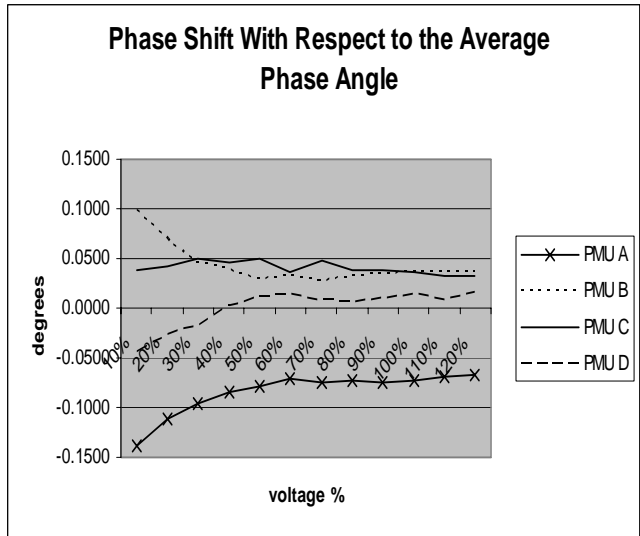


Figure 2: Phase shift with respect to the average phase for three phase voltage at nominal frequency.

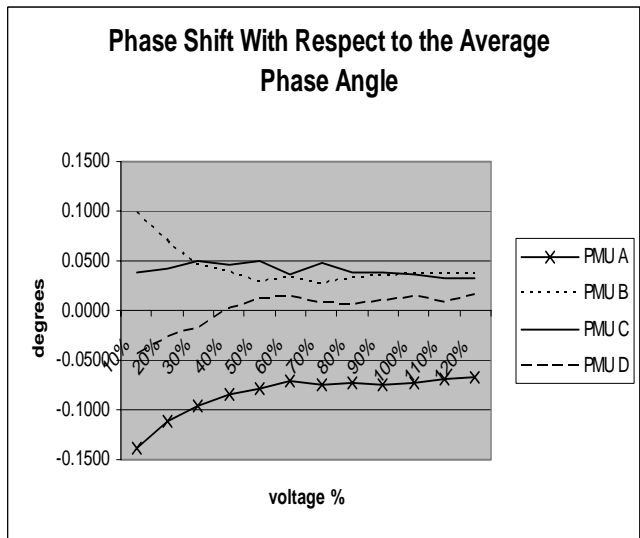


Figure 2 shows that the corrected phase angle measurements for every PMU unit are very close to each other having a maximum difference of around 0.125 degrees between units A and B for voltages greater than 40% of the full scale. For the cases where the voltage is below 40% full scale the phase difference between the measurements shows an increasing trend. A maximum difference of 0.25 degrees between units A and C is reached at 10% of the full-scale voltage.

Test two: Balanced three phase current at nominal frequency.

Magnitude comparison:

Test two aims to assess the performance of the four tested PMU under balanced three phase current at nominal frequency. The procedures adopted to carry out this test and evaluate its results are similar to the one followed for test one and describe in the previous section.

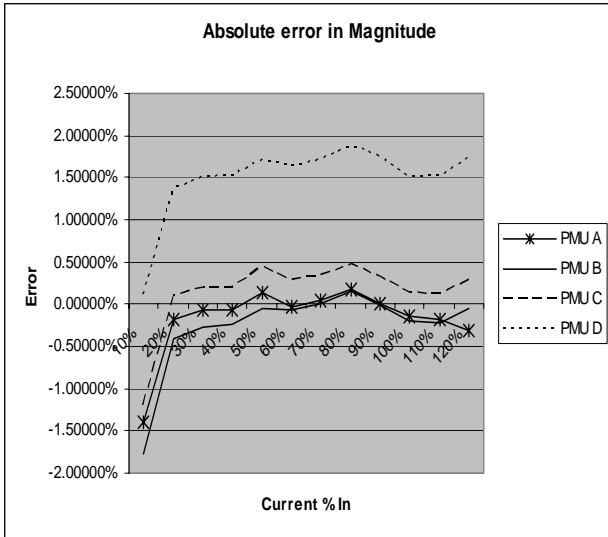


Figure 3 shows the errors of the current phasor magnitude recorded by the PMU units with respect to the reference value measured for every current magnitude step using laboratory instruments. Similarly to what was indicated in test one, no attempt was made to calibrated the laboratory instruments, thus the error presented in

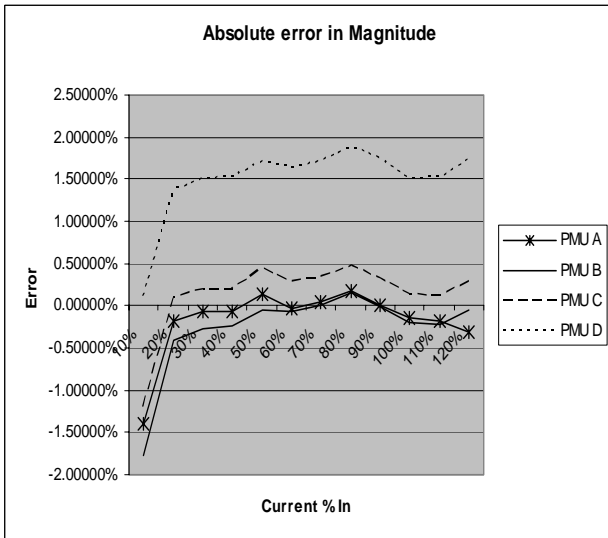


Figure 3 does not represent an absolute measure of the PMU's accuracy.

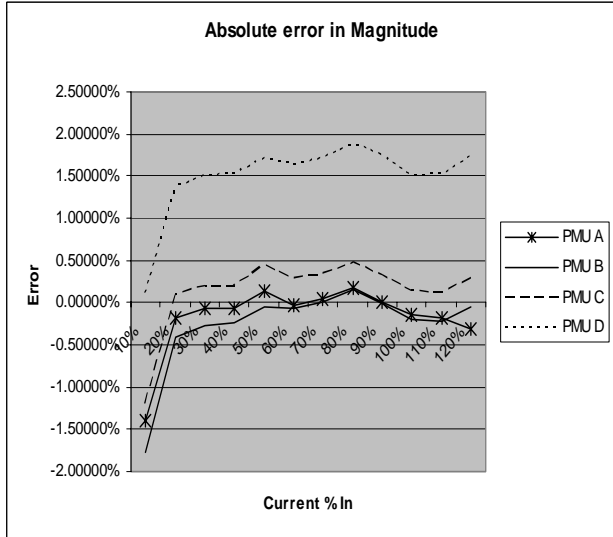


Figure 3: Magnitude's absolute error for balanced three phase current at nominal frequency.

From the results shown in

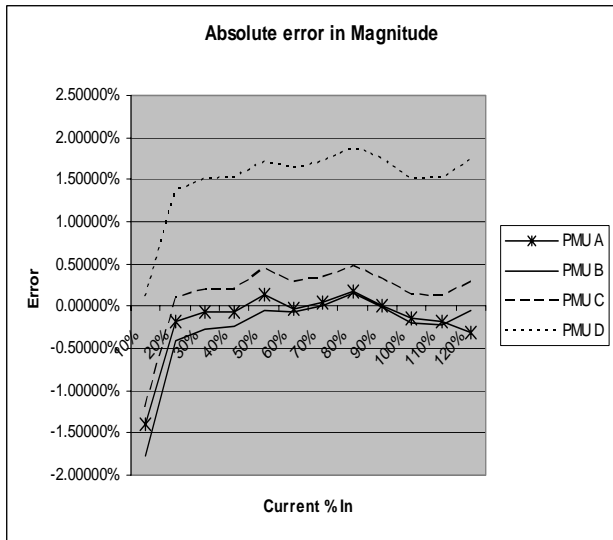


Figure 3 it can be concluded that the measurements made by PMUs A, B and C are very close to each other. The magnitude measured by PMU C shows a fairly constant 0.3% error with respect to PMU A and B. The measurements made by PMU A and B are coincident up to approximately 60% of the full scale current (5 Amp). Below this point the difference between these two measurements jumps to a value of approximately 0.3%. PMU D shows a fairly constant error of 1.5% with respect to the reference value. For currents below 20% full scale the current magnitude errors sharply increase for all four tested PMU units.

Phase comparison:

Similarly to the results of test one, the assessment of the phasor phase angle revealed a fixed phase angle shift of 180 degrees for PMU A and 17.31 degrees for PMU D. Figure 4 shows the phase difference between the corrected phase angle for every unit and the arithmetic average of the corrected phase angles for the four PMU units at each current step. It can be noticed from Figure 4 that the corrected phase angle measurements are very close to each other having a maximum difference of around 0.1 degrees between PMUs A and B for currents greater than 70% of the full scale. For the cases where the current is below 70% full scale an increasing trend is revealed in the phase difference between PMU B and the other three PMU units. A maximum difference of 0.5 degrees between PMUs A and B is reached at 10% of the full scale voltage.

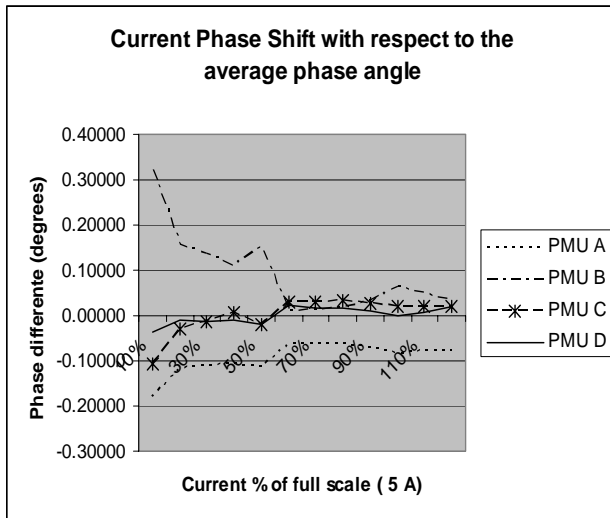


Figure 4: Current Phase Shift with respect to the average phase angle for balance three phase current at nominal frequency

Test three: Unbalanced (single phase) voltage at off-nominal frequency.

Test three is intended to evaluate the performance of the PMU units under unbalanced and off-nominal frequency operation. The unbalanced condition is simulated by applying a single phase voltage (phase A) to the PMU units. The frequency is varied in a range between 55 and 65 Hz. Using a sinusoidal function generator synchronized to the 1 PPS signal of a GPS clock it was possible to align the 1 PPS pulse with the zero crossing of the sinusoidal voltage applied to the PMUs (see Figure 5).

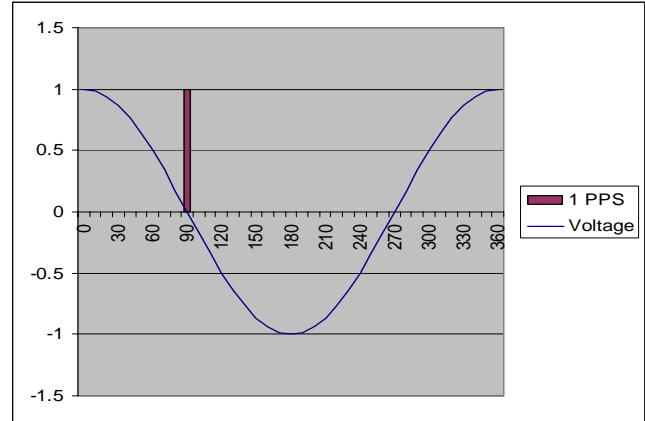


Figure 5: 1 PPS pulse and voltage Signal synchronization

Magnitude comparison:

Under the operating condition shown in Figure 5 the phase angle measurement shall be 90 degrees at nominal frequency. For off-nominal frequency signals a similar placement of the GPS pulse and the input signal will occur every

$$\left| \frac{1}{60 - f} \right| \text{ second,}$$

where f is the test frequency.

The variation of the phasor magnitude with respect to the off-nominal frequency is shown in

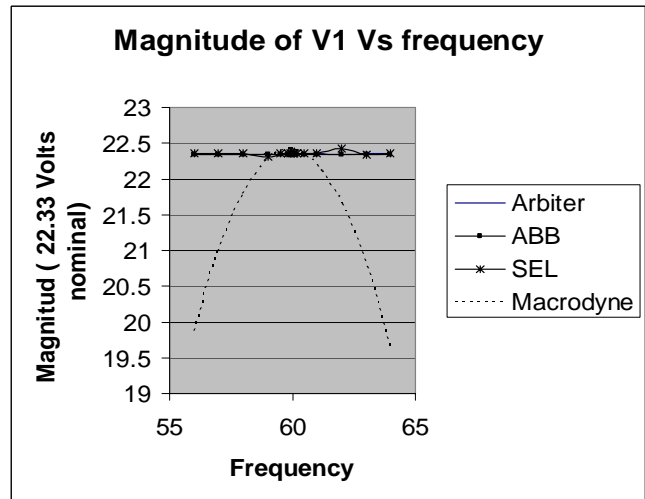


Figure 6. From this figure it can be concluded that the phasor magnitude measured by PMUs A, B and C is not affected by off-nominal frequencies in the range of 55 and 65 Hz. It is a clear indication that the measuring algorithms of these units

correct their final results for off-nominal frequency conditions. It can also be noticed from

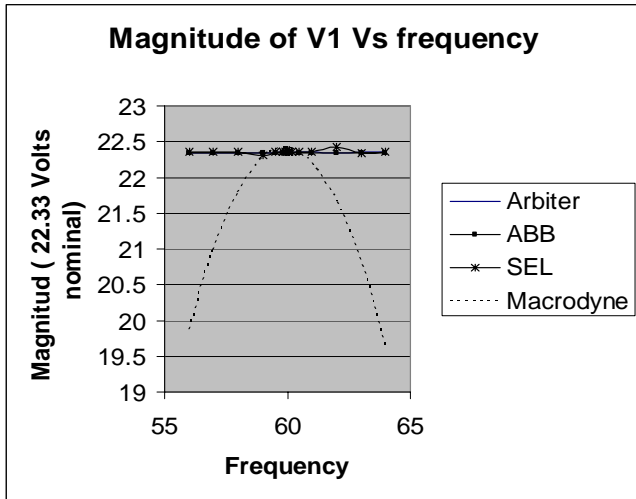


Figure 6 that the accuracy of the phasor magnitude recorded by PMU D is attenuated for the off-nominal frequency condition which is an expected behavior for uncompensated Fourier type Phasor Measurement algorithms.

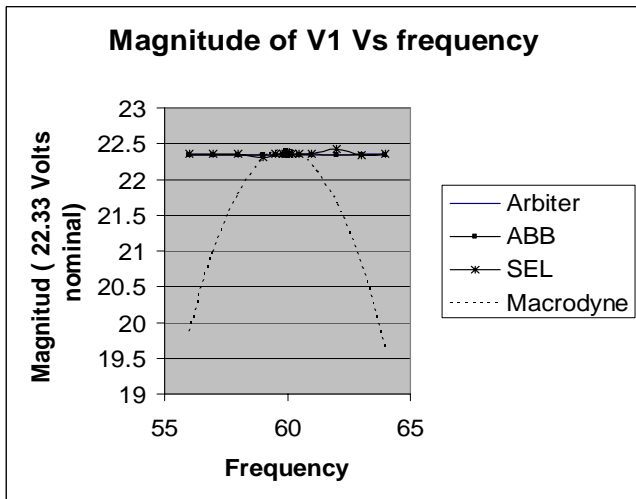


Figure 6: Positive sequence voltage variation with respect to the frequency.

Figure 7 shows the same information as in

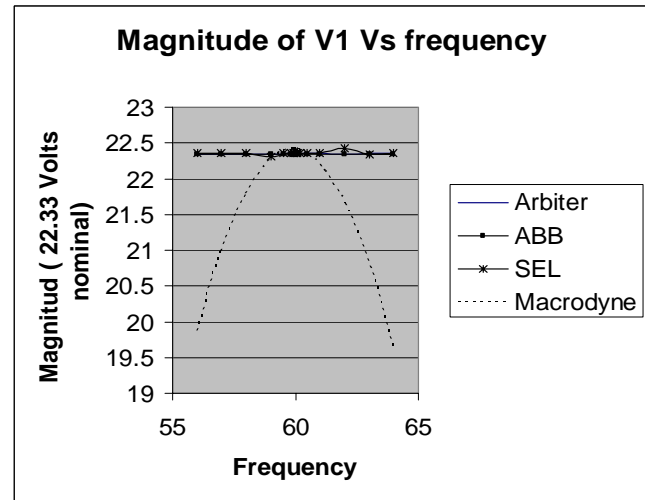


Figure 6 but in terms of absolute error with respect to the reference value of positive sequence voltage (22.33 V). Once again this test is not intended to measure the accuracy of the units; the result below should be used only for comparing PMU performances under similar system conditions.

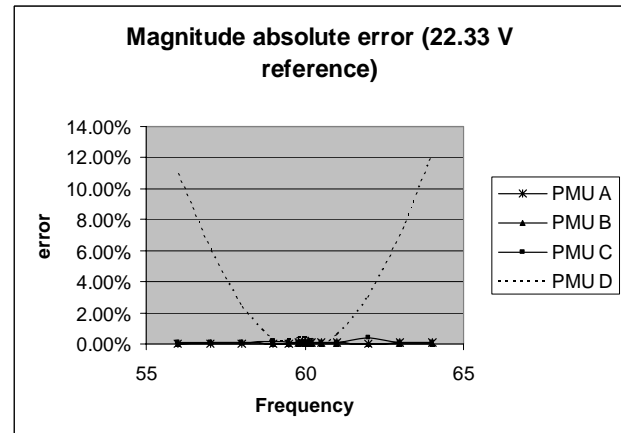


Figure 7: Magnitude absolute error with respect to a reference value of 22.33 V.

Phase comparison:

The variation of the phase angle measurements with respect to the frequency for every PMU unit is shown in Figure 8. The values shown correspond to the phasor with a time tap corresponding to the GPS 1 PPS signal where the 1 PPS pulse is aligned to the zero crossing of the voltage waveform as shown in Figure 5. Considering that the 1 PPS pulse is aligned with the zero-crossing of the sinusoidal voltage waveform the value recorded by the PMU units should theoretically be 90 degrees. Figure 8 shows a potential limitation for interchangeability of PMU units from different manufacturers

in power systems applications due to their dissimilar performances at off-nominal frequency conditions.

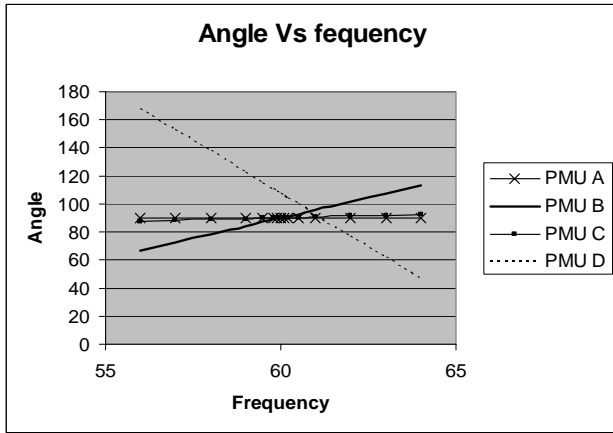


Figure 8: Phase angle variation with respect to the frequency.

Figure 9 shows the percentage deviation from 90 degrees of the phase angles measured by the tested PMU units at off-nominal frequencies within 55 and 65 Hz. From Figure 9 it can be concluded that the PMU A phase angle measurement is stable and very close to 90 degrees within the testing frequency range. Conversely, the phase angle measurements from the remaining three PMUS have errors which depend upon the frequency. The PMU C unit is less affected by the frequency showing a maximum deviation of +/-2.5 degrees at the boundary of the testing frequency interval (55 and 65 Hz). The PMUs B and D reach maximum deviation of +/-18.6 and +/-58.7 degrees respectively at the bounds of the testing interval.

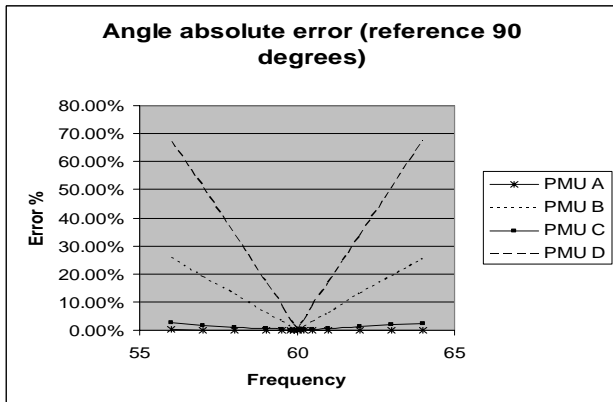


Figure 9: Variation of the Phase angle absolute error with respect to the frequency.

The above results reveal that even the units with proper magnitude correction algorithms yield different phase measurements at off-nominal frequencies. This situation makes unsuitable the combination of data from PMU

made by different manufacturers in their present form. Since the existing Synchrophasor standard [3] does not specify phase and magnitude performance requirements at off-nominal frequency operation, it is necessary to address this issue in the forthcoming revision of the standard. For off-nominal frequency operation the phase and angle should be corrected to their real values corresponding to the time stamp of the measurement. This requirement will assure similar performance for all PMU units at off-nominal frequency operation and will support interchangeability of PMUs.

Conclusions

The test results show that it is possible to combine these units in applications with a steady state and slowly varying dynamic conditions at the fundamental frequency. This will require that the measured magnitude and phase offsets be corrected in the units or be taken into account in the application program. The results also show that operation at 10% or less of the nominal value will greatly increase the magnitude and phase errors among the units.

Tests also revealed that data from PMUs of different manufacture cannot be combined for off-nominal frequency operation. Even for the units with correction algorithms, use of different correction algorithms yields different phase and magnitude offsets at different frequencies. The existing Synchrophasor standard does not require phase or magnitude correction for off-nominal frequency operation. The standard is in the process of revision, and it is expected that the revised standard will specifically address performance requirements at off-nominal frequencies.

References

- [1] Jose A. de la O Serna, Kenneth E. Martin. Improving Phasor Measurements Under Power System Oscillations. IEEE Transactions on Power Systems. Vol. 18, No. 1. February 2003.
- [2] A. G. Phadke. Time synchronization techniques, coupled with the computer-based measurements techniques, provide a novel opportunity to measure phasors and phase angle differences in real time. IEEE Computer Applications in Power. April 1993. 11-15
- [3] IEEE Standard for Synchrophasor for Power Systems. IEEE std. 1344-1995