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CIGRE US National Committee
2015 Grid of the Future Symposium

Performance Evaluation of Phasor Measurement Units for Digital Substations (PMU with IEC 61850 sampled values)

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SUMMARY

IEEE C37.118.1 is a global standard which defines the requirements and specifications for Synchronized measurements under steady state and dynamic conditions. IEEE C37.118.2 defines the method to exchange the real-time Synchrophasors between various IEDs such as PMU, PDC, Super-PDC etc. IEC61850 process bus, besides providing various tangible and non-tangible benefits, leads the way to the realization of Digital Substations which in turn are the building blocks for smart grids. Most of the commercially available PMUs work with the conventional currents and voltages wired to it using copper wires. This paper approaches the application of sampled values, as defined in IEC 61850 9-2LE, as PMU inputs hereby enabling their use in Digital Substations/Smart Grids. The input SV are provided or streamed to the PMU by the Merging Units or Digital Instrument transformers, such as optical CTs for calculation of Synchrophasors, according to IEEE C37.118.1.
Various Field and Laboratory tests are performed to evaluate the performance of the "PMU with SV" against the performance of "PMU Conventional". The Total Vector errors (TVE), frequency (FE) and frequency variation (RFE) are calculated and compared with the limits proposed in the IEEE C37.118

KEYWORDS

PMU, Process Bus, Digital Substation, Merging unit, Synchronized Phasor Measurements, IEC 61850, IEEE C37.118.

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1.0 - INTRODUCTION

The Synchronized Phasor Measurements Systems (SPMS) have been recognized as a major technological means for the monitoring and real-time control of the Power System. The SPMS consists mainly of Phasor Measurement Units (PMU), which perform measurement of voltage and current phasors and sends those to a Phasor Data Concentrator (PDC). All the measurements are synchronized to a global time source reference, GPS. Thus, Synchrophasors can be compared with each other to record snapshots of operating points of the Power System. There has been significant worldwide investment to develop a robust Wide Area Monitoring and Protection Systems (WAMPS)/ Remedial Action Schemes (RAS) based on PMUs. With the advent of IEC61850 process bus, Substation Automation and control architectures are seeing a paradigm shift. The process data is digitized in the field at the primary source hereby the amount of copper cables needed from the switchyard to the substation IEDs, most of which is replaced by fiber cables. Of course, it demands a reliable and fast communication infrastructure but the numerous benefits of process bus outweigh the additional requirements.

This paper approaches the application of IEC 61850 Process Bus in Synchronized Phasor Measurements Systems. The PMU receives sampled values (SV) from a Merging Unit (MU), over Ethernet connection, referred to as "PMU with SV" in this study. The SV are used by the PMU to calculate Synchrophasors, according to the IEEE C37.118.1-2011 standard. Two sets of tests are conducted: measurement of real Power System in low voltage; and laboratory tests. In the first set of tests, the devices ("PMU with SV" and "PMU Conventional") are connected to the National System of Synchronized Phasor Measurements in Low Voltage of the MedFasee Project (01), at the same measurement point; the Synchrophasors measured by the "PMU with SV" are then compared with those measured by the "PMU Conventional". Situations where the Power System is found in normal operation conditions, as well as disturbance conditions are analyzed, with quantities electrically distant from the nominal conditions. The laboratory tests considered some of the tests proposed in the IEEE C37.118.1-2011 standard, both steady state and dynamic test conditions were considered. The Total Vector Error (TVE), the Frequency Error (FE) and the Frequency Range Error (RFE) are calculated and the results of the "PMU with SV" and "PMU Conventional" are compared with the limits proposed in the IEEE C37.118.1-2011 and its Addendum C37.118.1a IEEE-2014. MU was configured to stream both the protective profile (80 samples per cycle) and the measurement profile (256 samples per cycle) according to IEC 61850-9-2LE.

2.0 - TESTS AND PERFORMANCE REQUIREMENTS

2.1 TEST TYPES

The IEEE C37.118.1-2011 proposes two basic sets of tests to determine PMU compliance: steady state and dynamic tests. The steady state tests are based on the application of signals with different voltage levels, currents and frequencies including harmonics and interfering signals (sub-harmonics) and evaluating the performance of the PMU after the measurement has stabilized for each applied level. The dynamic tests are done by applying step changes to the magnitude, angle and frequency of the applied signals.

2.2 PERFORMANCE CLASSES

IEEE C37.118.1 defines two classes of performance for the PMU: P class and M class.
The PMUs used in this paper are of M type.
M class PMUs are generally used for monitoring, supervision systems and disturbances recording. The compliance verification of a PMU must be performed independently for each class, adopting the respective error limits and excursion ranges of the tests of each class.

2.3 EVALUATION PARAMETERS

The quality of the measured Synchrophasors is given by evaluating the Total Vector Error (TVE), defined in [01] given below:

$$TVE_{(n)} = \sqrt{\frac{\left(\hat{X}_{r\,(n)} - X_{r(n)}\right)^2 + \left(\hat{X}_{i\,(n)} - X_{i(n)}\right)^2}{X_{r(n)}{}^2 + X_{i(n)}{}^2}} \qquad [01]$$

Where:

$\hat{X}_{r\,(n)}$ e $\hat{X}_{i\,(n)}$ $\rightarrow$ real and imaginary values of the measured Synchrophasor, respectively;

$X_{r\,(n)}$ e $X_{i\,(n)}$ $\rightarrow$ real and imaginary values of the reference Synchrophasor, respectively.

The index (n) indicates that all values are instantaneous and there is a TVE value for every point in time.

The frequency error (FE) and the Rate of Change of Frequency (RFE) are defined in [02] and [03], respectively:

$$FE_{(n)} = \left| f_{medida(n)} - f_{ref\,(n)} \right| \qquad [02]$$

$$RFE_{(n)} = \left| ROCOF_{medida(n)} - ROCOF_{ref\,(n)} \right| \qquad [03]$$

For the evaluation of dynamic performance, the "response time" and "time delay" parameters are utilized. The response time is obtained by evaluating only TVE, FE and RFE, regardless of the instant of the step application. As for the time delay, it is necessary to know precisely the instant in which the step is applied to the input signal of the PMU, and compare that instant with the time stamps of the measured Synchrophasors. The time delays for magnitude and angles can be determined. There may be positive or negative delay times depending on the labeling compensation algorithm of the Synchrophasors used in each PMU.

2.4 TEST ARCHITECTURES

The “PMU with SV” consists of a Multifunction Digital Fault Recorder, RPV311, connected to a merging unit, MU320, via a process bus. In field tests, the “PMU with SV” was connected to the same measurement point as PMU UFSC (conventional PMU), measuring the three-phase voltages of the low voltage network, as part of the MedFasee Project facilities. The Synchrophasors of both PMUs were compared in several electric system operation situations. Separate GPS clocks for synchronization of each device were utilized - One for “PMU with SV” and One for “PMU Conventional”. The architecture used is shown in Figure 2.a. For lab tests, the architecture included an Omicron test set synchronized via the GPS and IRIG-B modules. This architecture allows the generation of sync signals without the need for a reference PMU. The architecture is shown in Figure 2.b. The generation of graphics was performed by the "MedPlot" software developed in MedFasee Project (UFSC).

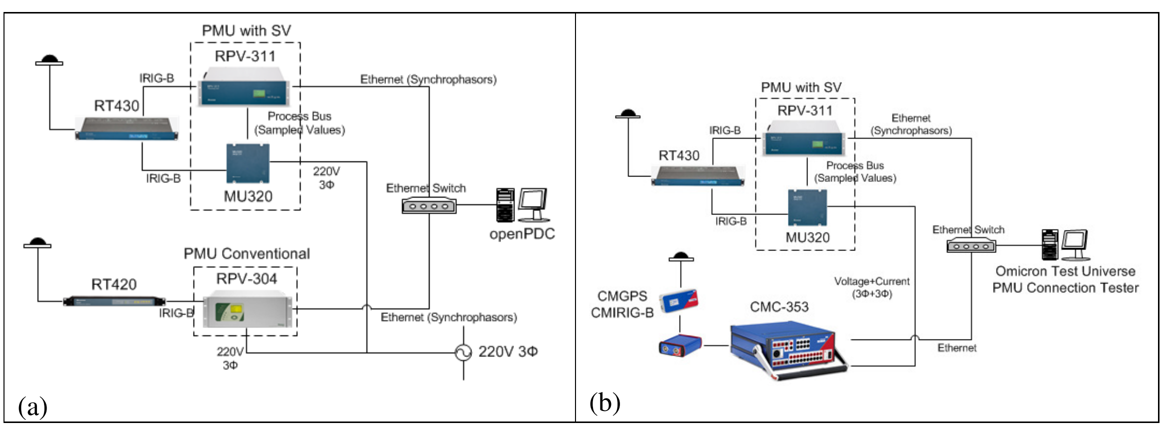
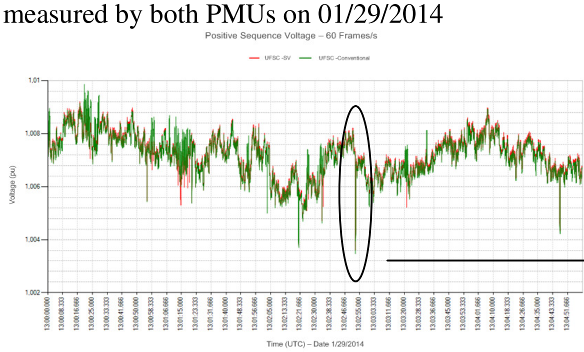


FIGURE 1 – Test Architectures

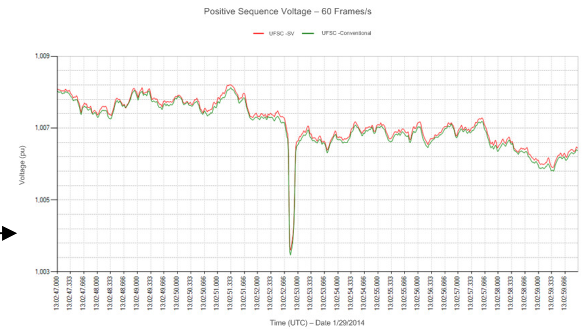
3.0 - RESULTS

3.1 MEASUREMENTS OF THE NATIONAL INTERCONNECTED SYSTEM (NIS) IN NORMAL OPERATION

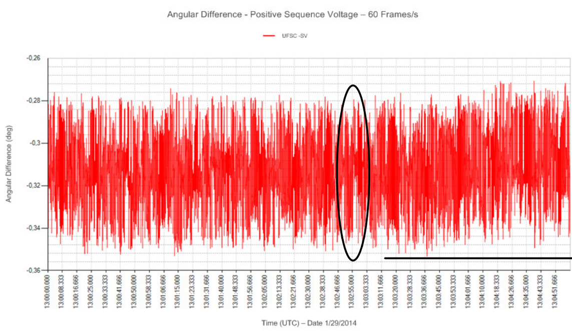
This test compares the Synchrophasors measured by the "PMU with SV" and the "PMU Conventional" in normal electric system operation. The following graphs show the Phasor magnitudes measured by both PMUs on 01/29/2014



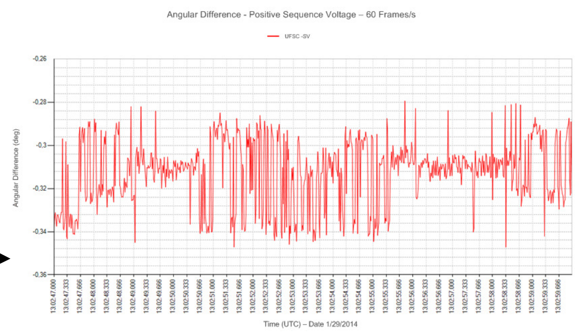
(a) – Voltage Magnitude



(b) – Voltage Magnitude zoom of (a)

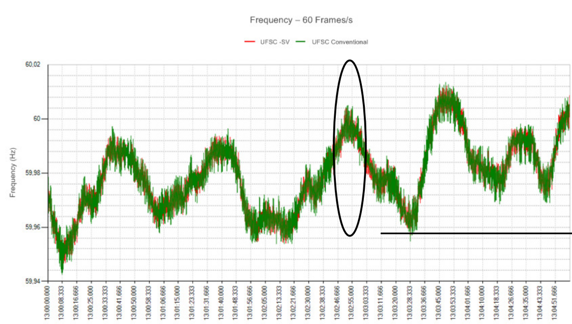


(c) – Voltage angle difference

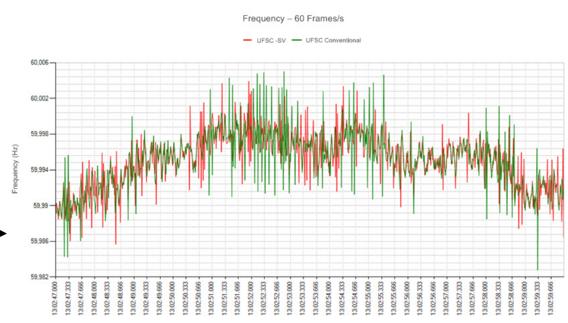


(d) – Voltage angle difference zoom of (c)

The Figure 3.c and 3.d show a fixed mean difference of 0.31 degrees between the analyzed devices, which is because of the fact that the "PMU Conventional" that belongs to the university (UFSC) was not calibrated and there was an offset of 0.31degrees (a constant phase difference. Voltage and frequency absolute values displayed negligible differences in the order of 0.011% & 1,7mHz respectively.



(e) – Frequency



(f) – Frequency zoom of (e)

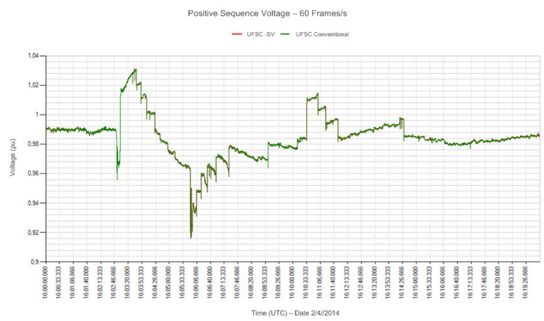
FIGURE 2 – Comparison between PMUs - NIS in normal operation conditions

3.2 Measurements of the National Interconnected System (NIS) under disturbance

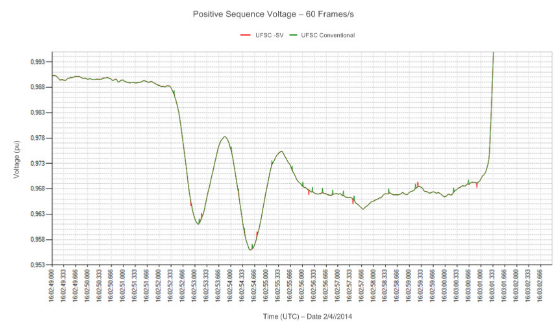
This test compares the Synchrophasors measured by both PMUs in a condition where the Power System is under disturbance. As reported in the "Daily Operation Preliminary Reports" (IPDO) on 02/04/2014 (06):

> *"At 14:03 there was the automatic shutdown of 12 transmission lines 500 kV that constitute the N / SE interconnection, causing its opening .... "*

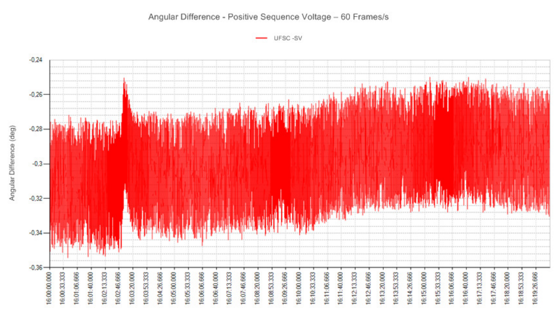
Comparison charts between Synchrophasors measured by both PMUs during the aforementioned disturbance in the NIS are shown below. It is noteworthy that the aim of this study is to compare the Phasor measurements of PMUs without commitment to the analysis of the disturbance itself.



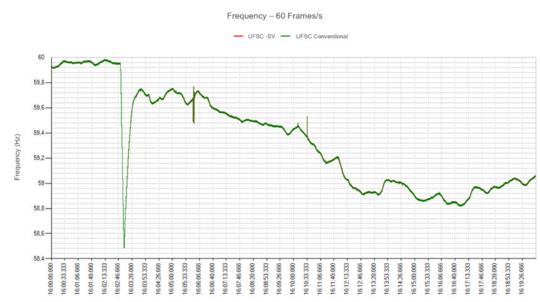
(a) – Voltage Magnitude



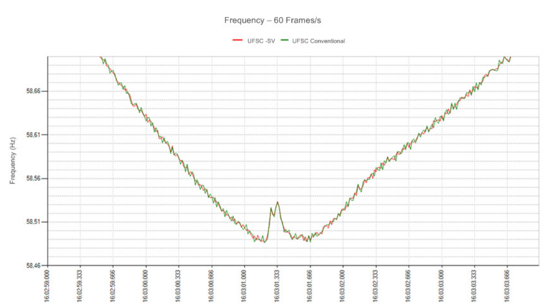
(b) –Voltage Magnitude zoom of (a)



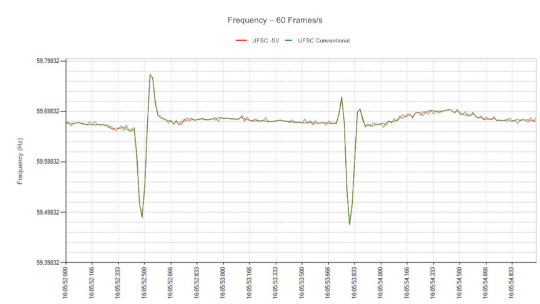
(c) – Voltage angle difference



(d) – Frequency



(e) – Frequency zoom-1



(f) – Frequency zoom-2

FIGURE 3 – Comparison between PMUs - NIS under disturbance

The Synchrophasors measured by both the PMUs have the same behavior, and the Synchrophasors measured by the "PMU with SV" reproduced the Synchrophasors of the "PMU Conventional". Consistency is maintained even in situations with significant variations of electrical quantities, and under oscillations.

3.3 Vectorial and Frequency Errors

The TVE and the FE between the two PMUs were calculated. To do so, the conventional PMU was considered as a reference. Different periods were used over a few typical days of the Power Systems operation, with 5s windows of data each. The average errors were: TVE = 0.55% and FE = 1.7 mHz. These values show the coherence between the two PMUs, considered appropriate. It is not possible to directly compare these errors with the limits defined in IEEE C37.118, since the reference PMU used in these tests was not properly calibrated.

3.4 Laboratory Test

Some of the tests proposed in the IEEE C37.118.1-2011 were performed, such as the frequency variation, magnitude and angle variations in the case of steady state and magnitude and angle steps in case of dynamic state. The tests were performed at rates of 20 frames/s and 60 frames/s. The limits proposed in addendum C37.118.1a IEEE-2014 for all PMUs class M were considered. In the steady state tests, each level of varying magnitudes lasted 10s, with errors evaluated during 5s, between instants 4s and 9s in each level, guaranteeing the stability of the measurements. The errors of the three phases and the voltage and current positive sequence, calculating the maximum error value among all values evaluated. All other quantities, excluding the varied magnitude in each test were maintained in nominal conditions and balanced system. The State Sequencer function of the Omicron test set, which allows programming a sequence of states with predefined quantities.
The results presented for the “PMU Conventional” were obtained from reference (07). In the tables below, “PP” means “Protection Profile (80 samples/cycle)” and “MM” means “Measurement Profile (256 samples per cycle)”.

3.4.1 Frequency Variation Tests

In this test, the frequency of the input signal varies between 55 Hz and 65 Hz, in steps of 1 Hz, totalizing 11 levels. The same range of variation in both Phasor sending rates was used. The frequency of all voltage and current channels were varied simultaneously. The results are shown in Table 1.

	20 frames/s Rate			60 frames/s Rate		
	TVE (%)	FE (mHz)	RFE (mHz/s)	TVE (%)	FE (mHz)	RFE (mHz/s)
Maximum Limits	1,00	5,00	100,0	1,00	5,00	100,0
PMU with SV (PP)	0,26	0,57	14,65	0,20	1,29	108,49
PMU with SV (MP)	0,35	0,71	16,57	0,28	0,84	60,20
PMU Conventional	0,20	0,48	14,88	0,21	0,89	56,99

TABLE 1 – Frequency Variation Tests

3.4.2 Magnitude Variation Tests

In this test the voltage magnitude of the input signals ranges from 10% to 120% of Vnom, in steps of 10%; and current magnitude between 10% and 200% of I_{nom}, in steps of 17.27% with a total of 12 levels. The steps of variation of voltage and current modules are performed simultaneously, since the operation of the voltage and current channels is independent in both the test set and the tested PMUs. The results are shown in Table 2.

3.4.3 Angle Variation Tests

In this test, the angles of the input signals ranges from -180° and +180° continuously. A single state was programmed in the test set with the frequency at 60.12 Hz. The total test time was 34s, sufficient time so that the angles varied throughout all the excursion range more than four complete cycles. The variation of voltage and current angles was performed simultaneously. The results are shown in Table 2.

Limit	$TVE_{máx} = 1\%$			
	Magnitude Variation Test		Anlge Variation Test	
	20 frames/s Rate	60 frames/s Rate	20 frames/s Rate	60 frames/s Rate
PMU with SV (PP)	0,35	0,90	0,08	0,09
PMU with SV (MP)	0,39	0,36	0,13	0,06
PMU Conventional	0,47	0,46	0,10	0,07

TABLE 2 – Magnitude and Angle Steps Tests

3.4.4 Magnitude and Angle Steps Tests

The response times and typical delay of a PMU are smaller than the sampling period of Synchrophasors (inverse of Synchrophasors sending rate). So, for the precise determination of these times, a sending rate considerably higher than the nominal rates would be required. One way to achieve an increase of resolution of measured points is to perform "n" repetitions of each test application of the same step, spacing the step application in "T/n" for each repetition, where "T" Synchrophasors the sampling period. At the end of the repetitive process, a detailed curve can be mounted from the "n" repetition interspersing the points of each repetition. The resulting data curve amounts to the same PMU operating with a sending rate "n" times the nominal rate. Further details of this procedure can be found in references (03) and (07).

Using the above procedure, the TVE, FE & RFE errors were calculated in each test, determining the delay and response times and the overshoot. The results are shown in Table 3 and Table 4.

Delay Time		
Equipment	Magnitude	Angle
Limit	12,50ms	12,50ms
PMU with SV (PP)	5,00ms	5,00ms
PMU with SV (MP)	5,00ms	5,00ms
PMU Conventional	5,00ms	5,00ms

Overshoot		
Equipment	Magnitude	Angle
Limit	10%	10%
PMU with SV (PP)	0,20%	0,60%
PMU with SV (MP)	0,36%	0,60%
PMU Conventional	0,17%	0,72%

Response Time						
Equipment	Magnitude Step			Angle Step		
	TVE (1%)	FE (5mHz)	RFE (100mHz/s)	TVE (1%)	FE (5mHz)	RFE (100mHz/s)
Limit	0,35s	0,70s	0,70s	0,350s	0,70s	0,70s
PMU with SV (PP)	0,10s	0s	0s	0,12s	0,21s	0,25s
PMU with SV (MP)	0,10s	0s	0s	0,12s	0,21s	0,26s
PMU Conventional	0,10s	0s	0s	0,12s	0,08s	0,38s

TABLE 3 – Magnitude and Angle Steps Tests – 20 frames/s

Delay Time		
Equipment	Magnitude	Angle
Limit	4,17ms	4,17ms
PMU with SV (PP)	1,67ms	1,67ms
PMU with SV (MP)	1,67ms	1,67ms
PMU Conventional	1,67ms	1,67ms

Overshoot		
Equipment	Magnitude	Angle
Limit	10%	10%
PMU with SV (PP)	0,56%	0,37%
PMU with SV (MP)	0,35%	0,41%
PMU Conventional	0,52%	0,34%

Response Time						
Equipment	Magnitude Step			Angle Step		
	TVE (1%)	FE (5mHz)	RFE (100mHz/s)	TVE (1%)	FE (5mHz)	RFE (100mHz/s)
Limit	0,117s	0,233s	0,233s	0,117s	0,233s	0,233s
PMU with SV (PP)	0,032s	0s	0s	0,038s	0,085s	0,115s
PMU with SV (MP)	0,032s	0s	0s	0,038s	0,082s	0,115s
PMU Conventional	0,032s	0,002s	0,035s	0,038s	0,112s	0,128s

TABLE 4 – Magnitude and Angle Steps Tests – 60 frames/s

Note:
1) "0s" response times indicate that the error did not actually leave its limit during the step applied.
2) PP → protection profile (80 Samples/Cycle)
3) MP → measurement profile (256 Samples/Cycle)

4.0 - CONCLUSION

This paper approaches the application of Sampled Values (SV) in Synchronized Phasor Measurements Systems (SPMS). The “PMU with SV” reproduced faithfully the Synchrophasors measured by “PMU Conventional” in various Power System operating conditions, demonstrating the feasibility of its use in SPMS.

Some results of laboratory tests for SV streaming with the protection profile (PP) were close to or above the limit, such as the RFE frequency range test at 60 FPS (TABLE 1). It is noteworthy, however, that the limits considered in this study were applied to the PMUs M class. If the limits of P class were considered instead, the “PMU with SV” meets the requirements. In the case of TVE close to the limit in the magnitude variation test at 60 FPS (Table 2), the larger TVEs occur in 10% of the nominal current level.

The tests with the measurement profile (MP) were conducted measuring directly at 256 samples per cycle, without interpolation. It is concluded in this study that this is the ideal profile for the use of SVs in SPMS. When configured with this profile, the errors of the “PMU with SV” are almost equal to those of conventional PMU. This paper shows the PP results for comparison purposes, because the MUs commercially available usually operate at this rate, requiring an additional interpolation process in order to achieve more samples per cycle.

The possibility of PMUs using sampled values over Ethernet (IEC 61850-9-2) also allows, Synchrophasors to be calculated directly from optical Instrument Transformers.

The application of the concepts of the IEC 61850, particularly regarding the effective use of SV in Electrical Power Substations is still in development. The use of modern equipment that meets the most current versions of the standard in relation to performance, precision and accuracy, reflects directly to obtain satisfactory results.

Finally, for the record: since 02/2014, the Synchrophasors of the measuring point "UFSC" in SPMS Low Voltage of the MedFasee Project are being measured by a “PMU with SV”, as reported in this paper.

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