MERGING UNIT APPLICATION FOR SYNCHRONIZED PHASOR MEASUREMENTS

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ABSTRACT

This paper approaches the application of Merging Unit in Synchronized Phasor Measurements Systems . A Digital Fault Recorder (DFR) receives sampled values (SV) from a Merging Unit (MU) via the process bus, forming a "PMU with MU". The SV messages are used by RDP for calculating Synchrophasors, according to IEEE Std. C37.118.1-2011. Real power system measurement tests and laboratory tests are performed. The Total Vector errors (TVE), frequency (FE) and frequency variation (RFE) are calculated, the results are compared with the limits proposed in the IEEE C37.118 standard.

KEYWORDS

Merging Unit, PMU, Synchronized Phasor Measurements, IEC 61850, IEEE C37.118.

1.0 - INTRODUCTION

The expansion of Power Systems has resulted in the proliferation of various manufacturers' equipment on the same power plant. The IEC 61850 standard introduced the concept of process bus, which allows standardized communication between devices such as instrument transformers, circuit breakers, disconnectors, and protection and control equipment. In this scenario, the Merging Unit (MU) is presented as an essential device for the operation of automated substations, and the equipment responsible for the interface between the analog and digital world. The voltage and current measurements of instrument transformers are digitized and encapsulated in Sampled Values (SV) protocol, and the states of the equipment in GOOSE messages.

At the same time, the Synchronized Phasor Measurements Systems (SPMS) have been recognized as a major technology means for the improvement of monitoring and real-time control of the Power Systems. The SPMS consists mainly of Phasor Measurement Units (PMU), which perform measurement of voltage and current phasors and sends them to a Phasor Data Concentrator System (PDCS). The PMU measurements are performed using a single time reference for all the devices: the GPS (Global Positioning System). Thus, Synchrophasors are obtained and can be compared with each other to record snapshots of operating points of the Power System. The SPMS constitutes a new paradigm, especially for making feasible the monitoring and control of the dynamics of the Power System by measuring voltages and currents directly in the form of synchronized phasor at sample rates of the same order of magnitude as the frequency of system electric.

This paper approaches the application of Merging Unit in Synchronized Measurement Systems phasors. A Digital Recorder Multifunction disorders (RDP) receives measurement data (SV) of a MU, using Ethernet connection (process bus), composing a PMU with acquisition via MU, named "PMU with MU" in this study. The SV are used by the DFR to calculate Synchrophasors, according to IEEE C37.118.1-2011standard. 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 are connected to the National System of Synchronized Phasor Measurements in Low Voltage of the MedFasee Project (01), in the same measuring point, and Synchrophasors measured by the PMU with MU are compared with those measured by a 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 consider some of the tests proposed in the IEEE C37.118.1-2011 standard, both at steady and dynamic state. The Total Vector Error (TVE), the Frequency Error (FE) and the Frequency Range Error (RFE) are calculated and the results of the PMU with MU and conventional PMU are compared with the limits proposed in the IEEE C37.118.1-2011 standard and its Addendum C37.118.1a IEEE-2014. MU is operated both using the protective profile (80 points per cycle) as using the measurement profile (256 points per cycle) according to IEC 61850-9-2LE.

2.0 - IEC 61850 STANDARD

The IEC 61850 (02) describes the characteristics of a system comprising a communication infrastructure, data model, packet format and characteristics of Intelligent Electronic Devices (IEDs) in a substation (SE), so as to achieve the interoperability and interchangeability objectives. Elements virtualization (object oriented modeling) is considered, regulating the naming of each element of the system and determining the decomposition of functions in logical nodes, which provides a well-defined data-oriented model. This data model is formatted in a specific language for the description of substations and IEDs.

In this new concept, the communication structures in the SE are separated into station bus and process bus. In simple terms, the bus station consists of the interconnection among devices inside the control room, allowing the replacement of cables for signaling and interlocks. The process bus, in turn, enables the communication via logical network of the equipment installed in the SE yard (switches, circuit breakers, instrument transformers, etc.) with the control room. The main interface device in this environment is the Merging Unit, which digitalize the measurement of analog values and the states of the binary signals and sends them to the network using standardized protocol. In FIGURE 1 illustrates the architecture.

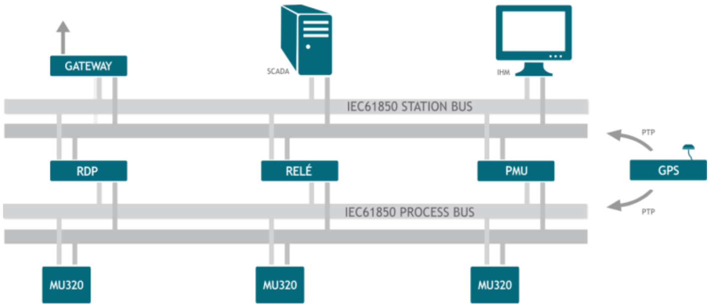


FIGURE 1 – Process Bus and Station Bus

The process bus is more critical as the data stream is quite significant and the information is critical to system operation. Information such as operation and state of circuit breakers and measures the voltage transformers (VT) and current (CT) are sent to the devices in the control room through a logical network, a number of aspects related to the performance of this shall be considered to ensure that the system is operated with robustness.

3.0 - TESTS AND PERFORMANCE REQUIREMENTS

3.1 Test Types

The IEEE C37.118.1-2011 standard proposes two basic sets of tests to determine PMUs compliance: steady state and dynamic regimes tests. The steady state tests are based on the application of signals with different voltage levels, current and frequency, as well as harmonics and interfering signals (sub-harmonics), evaluating the performance of the PMU after the measurement has stabilized in each level. The dynamic tests are made by the application steps of magnitude and angle, frequency ramp, and modulation of magnitude and angle.

3.2 Performance Classes

Two PMU classes are defined: P class and M class. The P class is related to faster responses, without a greater commitment to detailed filtering of the measured and / or calculated signals. Class P PMUs may be used in applications that operate in real time, for protection and control of the Power Systems, for example. The M class is related to measurements with more accuracy than the P class, but assuming that these characteristics can result in slower response times. M class PMUs can be used for the monitoring and supervision systems and for 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. The PMUs used in this paper are M type.

3.3 Evaluation Parameters

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

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

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] e [03], respectively:

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

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

wherein the measured frequency by the PMU is defined as the derivative of the voltage positive sequence angle, measured in Hz, and the frequency variation rate is defined as the derivative of the frequency or the second derivative of the positive sequence voltage angle measured in Hz / s (03).

For the evaluation of dynamic performance, the "response time" and "time delay" parameters are utilized. The response time is defined as the transition time of a certain error between two stable values after application of a step in the magnitude or angle of the signal measured by the PMU. It is determined as the time difference between the instant at which the error value leaves a certain limit and the instant that it returns to this limit. The limits are the maximum errors of TVE, FE and RFE, with specific numerical values for each test type. The delay time is defined as the time interval between the instant at which the step is applied to the magnitude or the angle and the instant in which the respective quantity (magnitude or angle) reaches half the numerical value between its initial state (before the step) and its final state (after step).

The response time is obtained by evaluating only TVE, FE and RFE, regardless of the instant of the step application. The response times of the TVE, FE and RFE from steps of magnitudes or angles. 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.

3.4 Tests Architecture

The PMU with MU consists of a RPV311 Multifunction Digital Fault Recorder connected to a merging unit MU320 via a process bus. In field tests, the PMU with MU was connected to the same measurement point as PMU UFSC (conventional PMU based on DFR model RPV-304), 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 RT430 for PMU with MU and RT420 for conventional PMU. The architecture used is shown in Figure 2.a. For lab tests, the architecture included a Omicron CMC353 test set synchronized via CMGPS and CMIRIG-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).

4.0 - RESULTS

4.1 Measurements of the National Interconnected System (NIS) in Normal Operation

This test compares the Synchrophasors measured by the PMU with MU ("UFSC-MU") and the conventional PMU ("UFSC") in normal electric system operation. The following graphs show the phasor magnitudes measured by both PMUs on 29/01/2014.

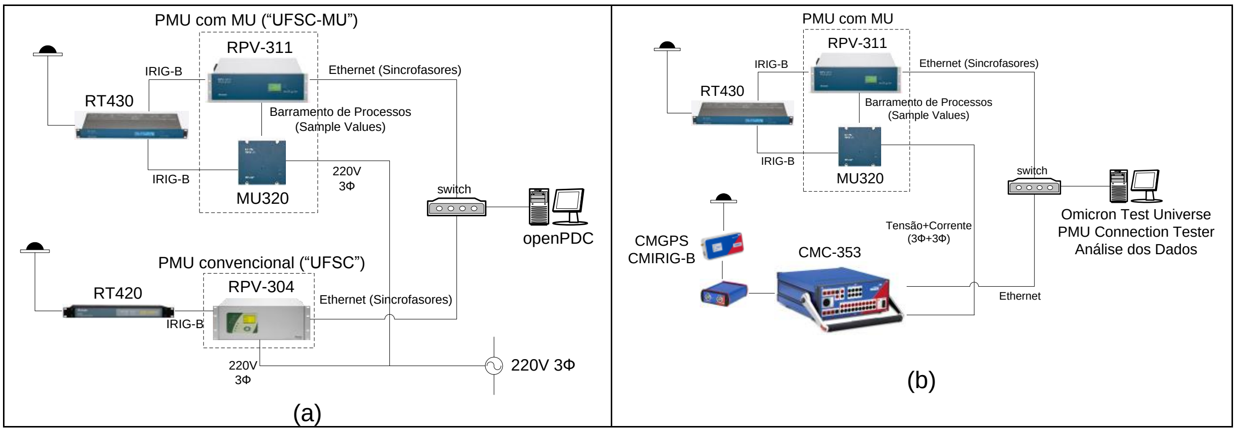
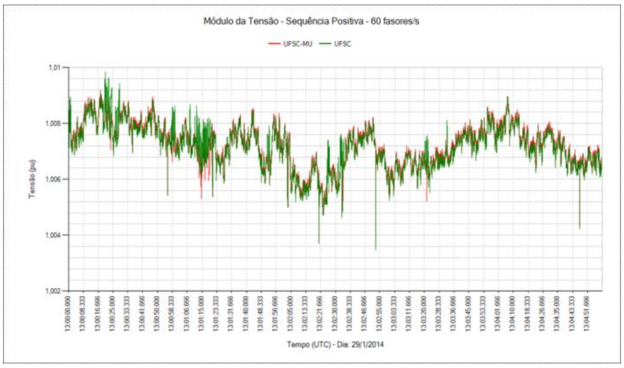
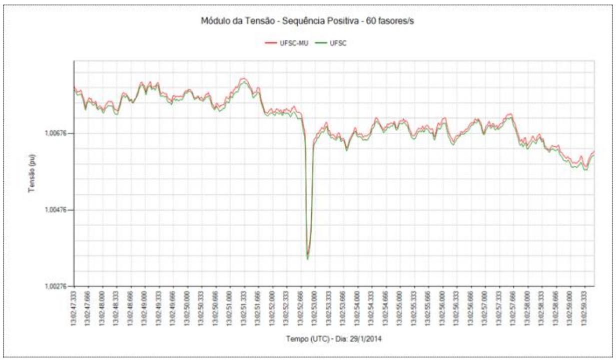


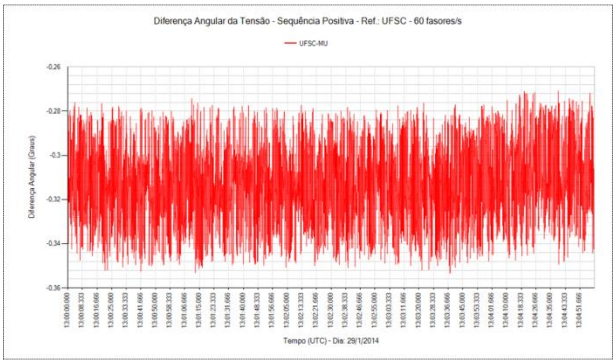
FIGURE 2 – Tests Architecture



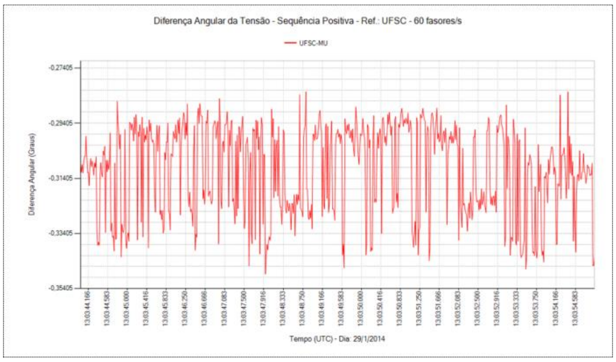
(a) – Voltage Magnitude



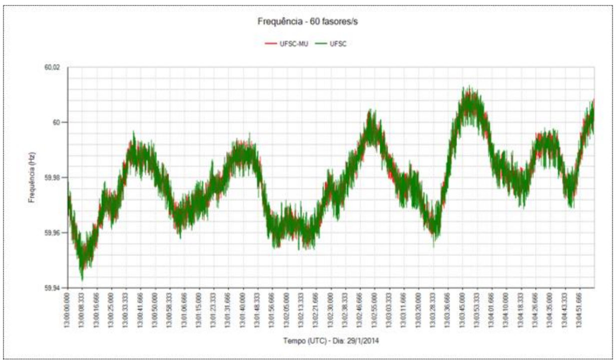
(b) – Voltage Magnitude (approximation)



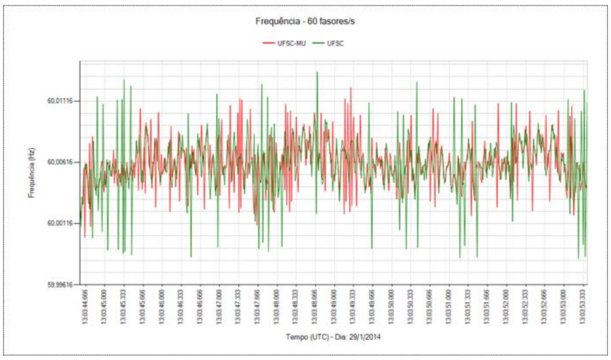
(c) – Voltage angle difference



(d) – Voltage angle difference (approximation)



(e) – Frequency



(f) – Frequency (approximation)

FIGURE 3 – Comparison between PMUs: NIS in normal operation conditions

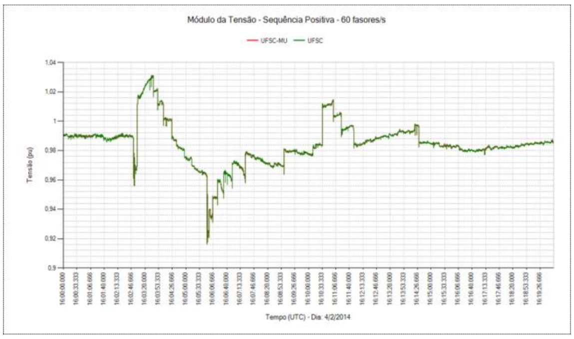
The Figure 3.c and 3.d show a fixed mean difference of 0.31 degrees between the analyzed devices, probably due to a different calibration tuning. Voltage and frequency absolute values displayed negligible differences in the order of 0.011% to 1,7mHz respectively.

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

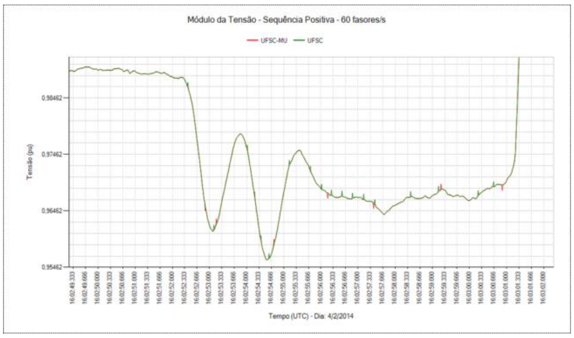
This test compares the Synchrophasors measured by both PMUs in a condition where the Power System is under disturbance. As reported in the "Daily Operation Preliminary Reports " (IPDO) on 04/02/2014 (06):

> *"At 14:03 there was the automatic shutdown of 12 transmission lines 500 kV that constitute the N / SE interconnection, causing its opening .... Consequences: this opening provoked generation deficit in the regions S-SE / CO causing the performance of the first stage of the Regional load Relief Scheme (RLRS), interrupting approximately 5,000 MW of load of states TO, AC, RO, MT, MS, GO, DF, MG, ES, SP, RJ, PR, SC and RS. To enable the recovery of the frequency and the consequent reconnection of the two subsystems North-Northeast and South / Southeast / Midwest was necessary additional load-shedding of 1.800MW in the South subsystem / Southeast / Midwest in order to allow the conditions burst. "*

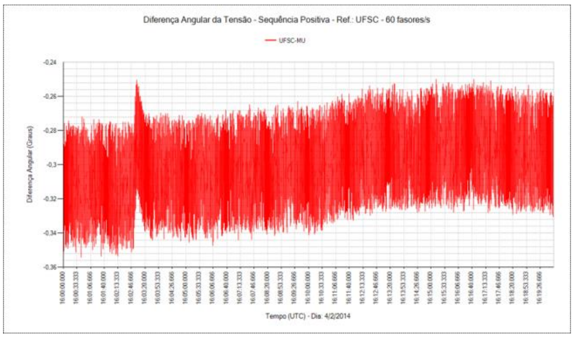
Below are shown comparison charts between synchrophasors measured by both PMUs during the aforementioned disturbance in the NIS. It is noteworthy that the aim of this study is to compare the phasor measurements of PMUs without commitment to the analysis of the disturbance itself.



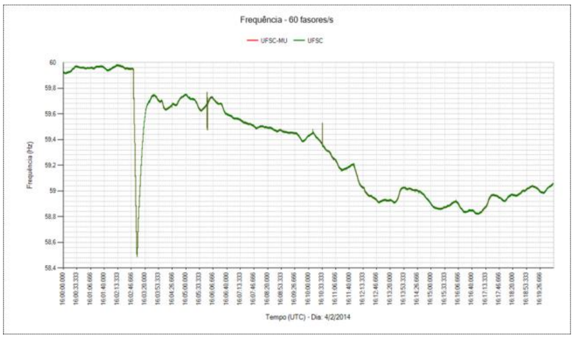
(a) – Voltage Magnitude



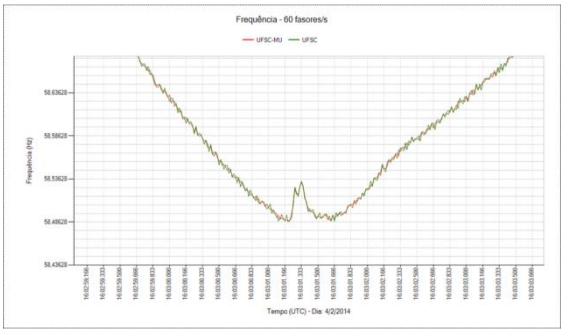
(b) – Voltage Magnitude (approximation)



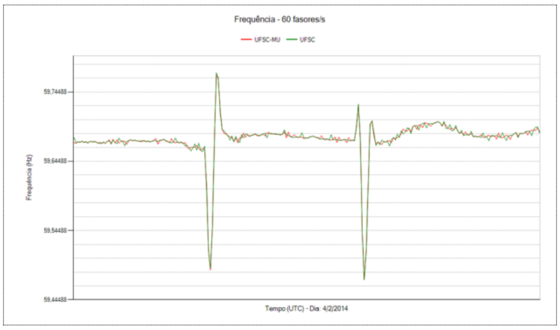
(c) – Voltage angle difference



(d) – Frequency



(e) – Frequency (approximation 1)



(f) – Frequency (approximation 2)

FIGURE 4 – Comparison between PMUs: NIS under disturbance

The synchrophasors measured by both PMUs have the same behavior, and the synchrophasors measured by the PMU with MU reproduce the synchrophasors of theconventional PMU. Consistency is maintained even in situations with significant variations of electrical quantities, and under oscillations.

4.3 Vectorial and Frequency Errors

The TVE and the FE between the two PMUs were calculated. To do so, the conventional PMU was considered as reference, calculating the errors of PMU with the MU. Different periods were used over a few typical days os 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 a reference PMU properly calibrated was not used in these tests.

4.4 Laboratory Test

Some of the tests proposed in the IEEE C37.118.1-2011 standard 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 conventional PMU were obtained from reference (07), considering the PMU function of the DFR RPV-311 with a conventional acquisition module RA332.

4.4.1 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.

4.4.2 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.

4.4.3 Angle Variation Tests

In this test the angles of the input signals ranges from -180^o and $+180^o$ 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.

4.4.4 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 e 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.

TABLE 1 – Frequency Variation Tests

	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 MU (PP)	0,26	0,57	14,65	0,20	1,29	108,49
PMU with MU (MP)	0,35	0,71	16,57	0,28	0,84	60,20
Conventional PMU	0,20	0,48	14,88	0,21	0,89	56,99

Note: PP → protection profile (80 ppc)
MP → measurement profile (256 ppc)

TABLE 2 – Magnitude and Angle Steps Tests

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 MU (PP)	0,35	0,90	0,08	0,09
PMU with MU (MP)	0,39	0,36	0,13	0,06
Conventional PMU	0,47	0,46	0,10	0,07

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

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

Overshoot		
Equipment	Magnitude	Angle
Limit	10%	10%
PMU with MU (PP)	0,20%	0,60%
PMU with MU (MP)	0,36%	0,60%
Conventional PMU	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 MU (PP)	0,10s	0s	0s	0,12s	0,21s	0,25s
PMU with MU (MP)	0,10s	0s	0s	0,12s	0,21s	0,26s
Conventional PMU	0,10s	0s	0s	0,12s	0,08s	0,38s

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

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

Overshoot		
Equipment	Magnitude	Angle
Limit	10%	10%
PMU with MU (PP)	0,56%	0,37%
PMU with MU (MP)	0,35%	0,41%
Conventional PMU	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 MU (PP)	0,032s	0s	0s	0,038s	0,085s	0,115s
PMU with MU (MP)	0,032s	0s	0s	0,038s	0,082s	0,115s
Conventional PMU	0,032s	0,002s	0,035s	0,038s	0,112s	0,128s

Note:
1) "0s" response times indicate that the error did not actually leave its limit during the step applied.

5.0 - CONCLUSION

This paper approaches the application of Merging Unit (MU) in Synchronized Phasor Measurements Systems

(SPMS). The PMU with MU reproduced faithfully the Synchrophasors measured by conventional PMU in various Power System operating conditions, demonstrating the feasibility of its use in SPMS.

Some results of laboratory tests for MU operating 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. Case the limits of P class are considered instead,the PMU with MU meets the requirement. 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 run with the measurement profile (MP) were conducted measuring directly at 256 points per cycle, without interpolation. It is concluded in this study that this is the right profile for the use of MUs in SPMS. When configured in this profile, the errors of the PMU with MU 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 points per cycle.

The possibility of PMUs using sampled values over Ethernet (IEC 61850-9-2) allows, additionally, synchrophasors to be calculated from optical Its. Unprecedented fact, since the conventional PMUs have only conventional voltage current inputs.

The application of the concepts of the IEC 61850, particularly regarding the effective use of MU in Electrical Power Substations is still an issue 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 02/2014the synchrophasors of the measuring point "UFSC" in SPMS Low Voltage of the MedFasee Project are being measured by a PMU with MU, as reported in this paper.

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