A PORTABLE SYSTEM FOR PHASE MEASURMENT UNITS (PMU) CALIBRATION IN HIGH-VOLTAGE SUBSTATIONS

Daniel Slomovitz [a], *Leonardo Trigo* [b], *Agustin García* [c], *Daniel Izquierdo* [d], *Carlos Faverio* [e], *Rogelio Sandler* [f]

[a] UTE LABORATORY, Montevideo, Uruguay, email address: dslomovitz@ute.com.uy
[b] UTE LABORATORY, Montevideo, Uruguay, email address: ltrigo@ute.com.uy
[c] UTE LABORATORY, Montevideo, Uruguay, email address: agarcia@ute.com.uy
[d] UTE LABORATORY, Montevideo, Uruguay, email address: dizquierdo@ute.com.uy
[e] UTE LABORATORY, Montevideo, Uruguay, email address: cfaverio@ute.com.uy
[f] UTE LABORATORY, Montevideo, Uruguay, email address: rsandler@ute.com.uy

* Corresponding author. E-mail address: dslomovitz@ute.com.uy

Abstract – This paper presents the advances in the development of a portable PMU standard for online calibration of PMUs installed in high voltage substations. This system is intended to be connected in parallel with the PMU under test, without disconnecting it from the network. Current and voltage sensors do not need to interrupt the service. In this way, all the substation functions remain operational during the calibration process.

The time stamp is also checked by the proposed system, using a common-view GPS system traceable to the Coordinated Universal Time (UTC).

Keywords: Calibration, high voltage, power network, synchronism, uncertainty.

1. INTRODUCTION

Phasor Measurement Units (PMU) increase their use in power networks since 1988. They measure voltage and current phasors in real time, with time stamps. This allows to implement smart protection systems. They are regulated by different standard beginning in 1995 (IEEE 1344) [1], which was replaced in 2005 by IEEE 37.118.1 [2], the version of 2011 [3] and the amendment in 2014 [4]. In addition, the standard IEEE C37.242 [5] defines the requirements of synchronization, calibration, testing and installation.

These instruments combine two different metrological fields: Electricity and Magnetism, and Time and Frequency. Because of this, the calibration systems must be traceable to standards of voltage, current and time. There are some proposal to implement this. The North American Synchro Phasor Initiative (NASPI) and the National Institute of Standards and Technology (NIST) assist manufactures of commercial systems for different tests and calibrations under static and dynamic conditions. Some devices are based on a three-phase commercial calibrator which is commonly used in Power Quality measurements, plus a time reference based on GPS [6]. However, for calibrating it, complex equipment is required, which only few National Laboratories have.

On the other extreme of accuracy are the PMUs installed in substations, which also need periodical calibration. There are some proposals for this task [7] - [9], but all require interrupting the under-test PMU (UUT) operation, to connect it to the calibrator. During this period, there is no protection of the network, unless there is a back-up unit, which is not usual. The consequence of this problem is the refusal to calibrate, on the part of those in charge of the facilities, which increases the risk of malfunction of the unit.

To avoid all these drawbacks, this work presents a new system to attend on–line calibrations that do not interrupt the operation of the UUT. In the following sections the design, construction and test of this system will be shown. A preliminary report was presented in [10].

2. DESCRIPTION OF THE PROPOSAL

A standard PMU and a system to verify the time stamps were developed. Connections of this system to the current inputs of the UUT are made with clamp-on current sensor, so there is no need to interrupt the circuit. Voltage is sensed connecting the inputs of the standard PMU in parallel to the UUT. Again, no interruption is needed, so the protection system is always working. In this way, both PMUs measure and record the same electric variables during some hours or even days. Recorded data is compared to evaluate the errors.

Despite this advantage, the proposal has certain limitations. The values of the voltages, currents, phases and frequencies are imposed by the power network. This restricts the ranges of these parameters that can be tested. Static tests can be reasonably done, but dynamic conditions are difficult to test. The probability of occurrence of a rapid and large parameter variation is low during the testing period. Anyway, relevant deviations that exceed the accuracy limits of the UUT are detected.

A complementary testing system verifies the time stamp of the UUT, comparing it with the Coordinated Universal Time (UTC). It is based on a common view satellite system.

Fig. 1 shows the general diagram of the equipment. A GPS receiver generates the synchronism pulses of one pps and the signals required by other components. These pulses are applied to the FPGA (field-programmable gate array) and the A/D converter through a phase-locked oscillator. An in-house developed software calculates all static parameters. The analog signals of current and voltage are filtered and digitized by A/D converters.

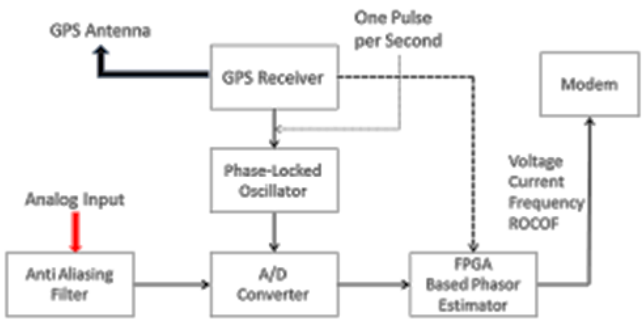

Fig. 1. General block diagram of the proposed system.

2.1. Hardware platform

The platform is an NI-CompactRio chassis [11] which has a dual-core 667 MHz CPU and a FPGA (Field-Programmable Gate Array) type Xilinx Zynq 7020, which allows to run two processes at the same time. Fig. 2 shows its block diagram.

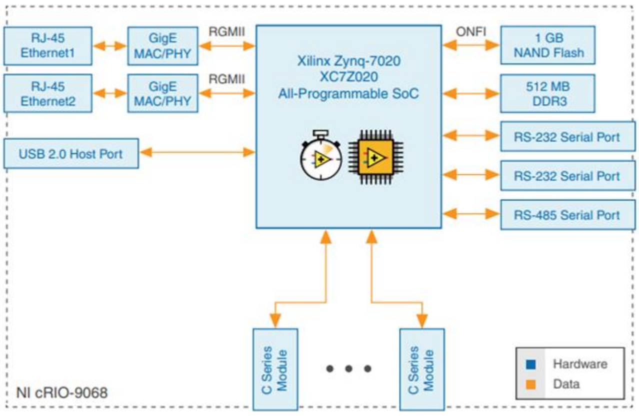

Fig. 2. Block diagram of the hardware platform [11].

This platform supports many models of digitizers with different input voltages, number of bits, accuracies and sampling frequencies.

24-bit Sigma-Delta digitizers, with simultaneous sampling, up to 50 kS/s of sampling frequency per channel were selected. For voltage measurements, the NI-9242 model [12] was chosen. It has four input channels (see Fig. 3). The maximum voltage is 250 V, enough for the output voltages of the voltage transformers, typically 100 V line to line. Its specifications state a gain error of 0.05% and very low nonlinearity (20 ppm).

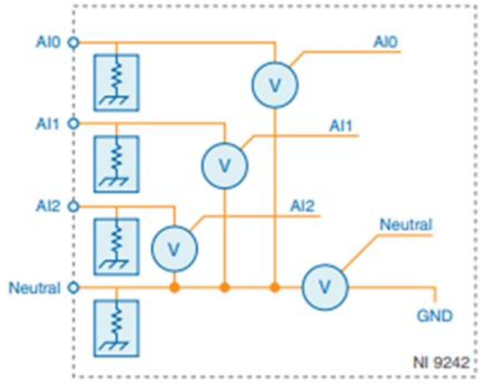

Fig. 3. Structure of the digitizer for voltage inputs [12].

For current measurement, the model NI-9239 [13] was selected. It is a voltage module, appropriate for the output voltage level of the current sensors. Its maximum input voltage is 10 V and the sampling frequency can be selected from 1.613 kS/s to 50 kS/s. The clock of this module is used to synchronize the other modules. Its specification state an uncalibrated accuracy of 0.3% that can be reduced to 0.03% by corrections with calibration constants.

Due of the lack of specific accuracy data at power frequency, both digitizers were tested to evaluate their amplitude and phase errors, and linearity in the ranges used in this work. As references, the standards for this test were a binary inductive divider [14] and a high accuracy DMM (Agilent 3458) running an external algorithm [15].

The error results for the both digitizers at rated voltages and 50 Hz were 250 ppm in amplitude and 400 µrad in phase. Additionally, a linearity test was done on the digitizer for the current sensor. Table I shows the results. They are appropriate for the project even at 0.01 A, that is 500 times lower than the rated value.

Table I. Amplitude errors of the digitizer used for current sensors at 50 Hz.

Voltage (V)	Error (ppm)
6	-83
1	-160
0.5	-200
0.1	-250
0.05	-300
0.01	-500

2.2 Current sensor

High precision clamp-on current sensors were developed as current transducers. They are composed by a commercial clamp-on current transformer (CCT), followed by an electronic device that reduces the errors and generates a voltage proportional to the current [16]. The rated current of the CCT is 100 A, although the rated current of the PMU is 5 A. This extra range allows to manage short circuit currents higher than the rated one. However, care must be taken to reduce errors that come from the position of the cable inside the hole of the CCT. The section of a 100-A cable is much larger than the section of the actual cables in the substation. To centre the cable, isolated supplements were installed, as show Fig. 4.

Fig. 4. Clamp-on transformer used in this project, with isolated supplements to centre the cable in its hole.

This compensator is based on reducing the magnetizing current of the current clamp-on transformer. Calibrations showed that ratio error and phase shift were reduced from original 1% and 3° to 0.06% and 0.15 crad at 50 Hz in the range 50 mA to 5 A (see Table II).

Table II. Errors of the current sensor.

I (A)	(%)	(crad)
5	0.06	0.13
4	0.06	0.13
3	0.06	0.13
2	0.06	0.14
1	0.06	0.14

I (mA)	(%)	(crad)
1000	0.06	0.14
500	0.06	0.13
100	0.06	0.14
50	0.06	0.15
10	0.03	0.26

Up to 4 kHz, the errors still are lower than 0.2%. This allows to evaluate harmonic content. Fig. 5 shows the electronic diagram of the compensator. This design has a total constant (including the CCT) of 1 V/1 A, but other values can be got changing the value of some resistors.

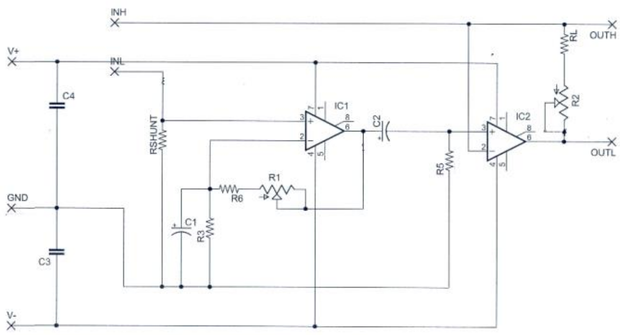

Fig. 5. Electronic diagram of the current sensor compensator.

The clamp-on transformer is connected to terminals INH and INL. IC1 generates a voltage proportional to the current, while IC2 and the other associate components are part of a feedback loop that imposes null voltage on the transformer-magnetizing arm. R1 adjust the feedback gain, which has main impact on phase error, and R2 the amplitude gain of the entire device.

2.3 Synchronization

For the time reference from a GPS signal, NI-9467 [17] and NI-9402 [18] modules were chosen. The first one provides the time stamp and a 1 PPS signal (Pulse Per Second) for the other modules. Its specification states an accuracy of ±100 ns in the generation of the 1-PPS. The second module has digital input/output ports that allows to access to the 1-PPS signal in one of its outputs. Its specification states a maximum propagation delay of 55 ns (18 ns typical). Calibrations were done with respect to the UTC, obtaining deviations less than 150 ns. The stability of these measurements in 7 days were ± 50 ns. Although, this variation is low enough, it is possible to implement a software correction to minimize this phase change.

Although the clock of the proposal as well as the substation clock are based on GPS signals, and the rated uncertainty of that systems in enough, several problems can introduce unanticipated delays. To test the absolute time errors of the synchronism signals, a technique based on Common View System was implemented. It is based on a Septentrio PolaRx5TR [19] equipment that has a 1 PPS input. It receives the substation synchronism signal and measures the delay between that signal and those from the viewed GPS satellites. A similar equipment is installed in our Laboratory, connected to the output of a caesium clock with traceability to the UTC. The difference between both systems allows to calculate the absolute error of the substation time clock, independently of the GPS system accuracy. Another calibration is performed on site on the proposed PMU to ensure that its time error is under specifications.

Fig. 6 shows a general view of the proposed standard. The front panel contains the three input jacks for the clamp-on transformers, access for adjusting the compensators, while the rear panel has the connection terminals of the voltage inputs. Inside, the cabinet contains all the electronic described devices, plus isolated power supplies.

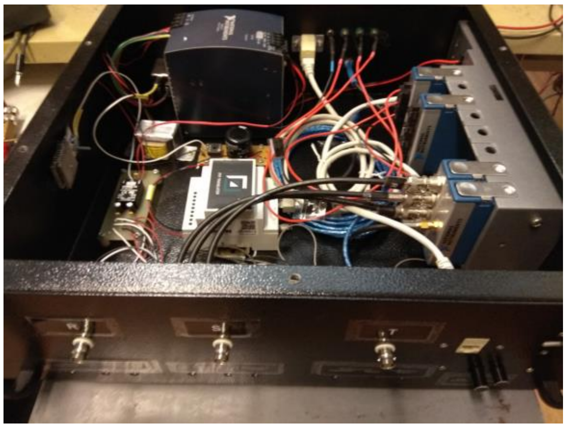

Fig. 6. General view of the proposed standard PMU.

2.4 Software

The FPGA program configures and drivers the GPS and digitizer modulus. The GPS 1-PPS signal starts all digitizers. It stores the sample values and other information in the FIFO memory. At the same time, the software in the CPU runs the mathematical algorithms for calculation PMU parameters. With Interpolated Discrete Fourier Transform (IDFT), the frequency, modulus and phase of voltages and currents are computed. Corrections are applied to take into account the system constants and if necessary to compensate deviations of the digitizers. The accuracy of the IDFT algorithm was evaluated from 49 Hz to 51 Hz (power frequency: 50 Hz), with sample frequency of 5 kS/s and additional noise of 0.1% of the peak voltage. Table III resumes the results. The data to evaluate the phasor was taken from three to five periods that slice cycle by cycle. In all cases, the errors are very low compared with the accuracy limit of the proposal (0.2%).

Table III. Evaluation of the accuracy of the IDFT algorithm.

Cycles	f (Hz)	Ratio error (ppm)	Phase error (µrad)
5	49	-150	-524
5	51	150	175
4	49	-300	-700
4	51	260	350
3	49	-530	-873
3	51	490	524

The Rate of Change of Frequency (ROCOF) calculation was implemented using the Fast Hilbert Transform, to obtain the phase change versus time. Tests on this parameter showed errors of 0.4%.

3. UNCERTAINTY

The precision target of the proposal is around 0.2% and 0.2 crad, which is five times lower than the error limits stated for PMUs. Tables IV and V show the expanded uncertainty budget estimation at rated conditions, in amplitude and phase, respectively. The main uncertainty sources come from the current sensors, the digitizes and the phasor calculations. The combined uncertainty results comply with the espectations.

Table IV. Uncertainty Budget for phasor amplitude.

Current			Voltage	
Uncertainty source	Standard uncertainty (%)		Uncertainty source	Standard uncertainty (%)
Current sensor	0,06		Voltage digitizer	0,05
Current digitizer	0,01		Voltage phasor calculation	0,01
Current phasor calculation	0,01		Combined uncertainty	0,06
Combined uncertainty	0,06			

Table V. Uncertainty Budget for phasor phase.

Current			Voltage	
Uncertainty source	Standard uncertainty (crad)		Uncertainty source	Standard uncertainty (crad)
Current sensor	0,15		Voltage digitizer	0,04
Current digitizer	0,04		Voltage phasor calculation	0,08
Current phasor calculation	0,08		Combined uncertainty	0,09
Combined uncertainty	0,17			

5. CONCLUSIONS

A proposal for PMU online calibration was described. It is based on the development of a standard PMU connected in parallel with the PMU under test. Results shows that traceability accuracy ratio of 4:1 was obtained, allowing the use as standard for calibration of commercial PMU with error limits of 1%.

Acknowledgement

This work was partially financed by ANII (Agencia Nacional de Innovación e Investigación) under the project FSE_1_2017_1_144198.

REFERENCES

[1] IEEE 1344-1995, “IEEE Standard for Synchrophasors for Power System”.

[2] IEEE 37.118.1-2005 “IEEE Standard for Synchrophasor Measurements for Power Systems”.

[3] IEEE 37.118.1-2011, “IEEE Standard Synchrophasor Measurements for Power Systems”.

[4] IEEE 37.118.1, Amendment, 2014.

[5] IEEE C37.242–2013, “IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power Systems Protection and Control”.

[6] FLUKE 6135, http://us.flukecal.com/products/electrical-calibration/electrical-calibrators/6135apmucal-phasor-measurement-unit-calibrati, accessed on 01-27-2020.

[7] J-P. Braun, S. Siegenthaler, “Calibration of PMUs with a reference grade calibrator,” CPEM, pp. 678-679, 2014.

[8] D Georgakopoulos, S Quigg, “Precision measurement system for the calibration of Phasor Measurement Units,” IEEE Transactions on Instrumentation and Measurement, Vol. 66, pp. 1441-1445, 2017.

[9] C. Qin, J. Greig-Prine, Z, Nie, P. Banerjee, A. K. Srivastava, “Remote PMU Testing using Low-cost FPGA Platform and PPA following IEEE TSS,” IEEE Industry Applications Society Annual Meeting, 2019.

[9] D. Slomovitz, D. Izquierdo, L. Trigo, A. García, C. Faverio and L. Astesiano, "Online Verification System for Phasor Measurement Units," 2020 Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, pp. 1-2, 2020.

[11] NI-CompactRio 9068 chassis, https://www.ni.com/es-cr/support/model.crio-9068.html, accessed on 04-26-2021.

[12] NI-9242, https://www.ni.com/es-cr/support/model.ni-9242.html, accessed on 04-26-2021.

[13] NI-9239

[14] D. Slomovitz, C. Faverio, D. Izquiedo, L. Trigo, C. Castet, “An electronically assisted binary inductive voltage divider,” CPEM Digest, pp. 274-275, Torino, Italy, Jul. 2006.

[15] D. Slomovitz and L. Trigo, "A power Standard System for calibration of power analyzers," IEEE ISGT LATAM, Montevideo, 2015, pp. 664-666.

[16] D. Slomovitz, “Electronic error reduction system for clamp-on probes and measuring current transformers,” IEEE Trans. on Instrum. and Meas. vol. 49, pp.1278-1281, 2000.

[17] NI-9467

[18] NI-9402

[19] Septentrio PolaRx5TR, https://www.septentrio.com/en/products/gnss-receivers/reference-receivers/polarx-5tr , accessed on 04-26-2021.