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Abstract—**Even if their deployment in electrical medium voltage networks was not as extensive as could be expected at the beginning, Phasor Measurement Units are key elements for Smart Grid operation. An impressive amount of papers discusses their implementation and usefulness in medium voltage network and almost as many deals with their metrological characterization. Although it is well known that instrument transformers are the main source of uncertainty in PMU-based synchronized measurements, this topic is not sufficiently tackled in the scientific literature. In this paper, the attention is focused on the calibration of a measurement system made by a PMU and a low-power instrument transformer commonly employed in the Italian distribution network.**

Keywords—*Phasor Measurement Unit, Smart Termination, Instrument Transformers, LPIT, Metrological characterization*

I. INTRODUCTION

In order to accomplish the goals of modern distribution grids, such as automatic control of Distributed Energy Resources (DERs), upgrades in the current monitoring systems have to be undertaken. In particular, it is required to extend diffusely sensors over Medium Voltage (MV) and Low Voltage (LV) networks. This requires the installation of measurement devices with a trade-off among cost, considering the huge number of nodes and lines, and performance.

Recently, the Phasor Measurement Unit (PMU), is considered a key technology to enable advanced monitoring of distribution systems [1]. It measures the synchrophasor, which is of great support for accuracy and update rate of Distributed System State Estimation (DSSE) [2], frequency and Rate Of Change of Frequency (ROCOF) which can be exploited in Microgrid applications [3]. These measurements must be performed respecting the real time and accuracy requirements specified in the standard IEEE c37.118.1-2011 and its amendment IEEE c37.118.1a-2014 [4]. Moreover, they should also require low costs for installation in a rising number of distribution Medium and Low Voltage (MV and LV) buses. To this purpose, a LOw COst (LOCO) PMU may be integral part of a distribution automation system, therefore communicating via recognized standards for communication, such as IEC 61850 [5] and include cybersecurity measures. Under these specifications, the LOw COst (LOCO) PMU solution was developed [6] and used in this work.

MV/LV sensors have to evolve and provide outputs directly connectable to acquisition systems. With this aim, [7] describes the so called "Smart Termination" (ST) installed in many secondary substations by Italian electrical utilities and described in the following chapters. Therefore, this paper aims at characterizing a novel measurement chain composed by: Low Power Instrument Transformer (LPIT), or ST, plus the LOCO PMU. In the literature there are some examples of metrological characterizations of the system PMU + instrument transformers such as [8] - [10]. No other work, to

the knowledge of the authors, tackled a measurement chain containing this new kind of transformers, the LPITs [11-13]. Such measurement system will be then deployed, in the near future, in several Italian and European secondary substations.

The paper is structured as follows: Section II briefly describes the PMU and its features. In Section III the novel LPITs are described, while in Section IV the proposed setup for the characterization of the novel measurement chain is presented. Section V contains all the tests run for the metrological characterization of the setup, while Section VI lists all the tests results. Finally, in Section VII some comments and conclusions are presented.

II. PHASOR MEASUREMENT UNIT

A. Hardware Description

The LOCO PMU is made of three main components. The first is the data acquisition board, the MCC USB 201, which converts the analogue input (in a range ± 10 V) to digital sampled values. Such board is set in order to acquire samples with a given sampling frequency, up to 12.5 kHz, when a specified trigger is received. In particular, by using the Pulse Per Second (PPS) signal, received from the GPS unit, it is assured that the sampling window starts at regular intervals. The second important component is the measurement computation unit, the Raspberry Pi 3. It receives the samples via USB interface from the MCC USB 201 and process them via C++ algorithms which extract synchrophasors, frequency and ROCOF. By exploiting the open-source libiec61850 libraries, the measurements are encapsulated in Sampled Value (SV) protocol and in UDP-IP packets, as required in the standard IEC 61850-90-5 [5] for PMU measurement exchange in Wide Area Networks (WAN). The messages are exchanged between the PMUs and the Phasor Data Concentrator (PDC) via an encrypted tunnel, via the open-source openVPN software. The third component is the GPS module, providing the PPS to the data acquisition board and the digital time information via Universal Asynchronous Receiver/Transmitter (UART) interface to the Raspberry PI. Considering other secondary components, the total hardware cost of the device is approximately 250 euros. This is why is considered low cost, compared to typical PMUs which cost more than thousand euro.

B. The Algorithm

The algorithm that runs regularly in the Raspberry Pi, permits to extract the measurements on a specified window, which is normally set to 1 second. When the PPS signal is received, the samples are acquired for an observation window shorter than 1 second. This is done in order to leave some time for the measurement computation and restart the acquisition before the next PPS is received. The samples are processed by a low pass filter, in this case a 3rd order Butterworth filter with cut frequency equal to 70 Hz, in order to remove high

TABLE I.   MECHANICAL AND ELECTRICAL SPECIFICATION OF THE
COMBINED CURRENT AND VOLTAGE SENSOR

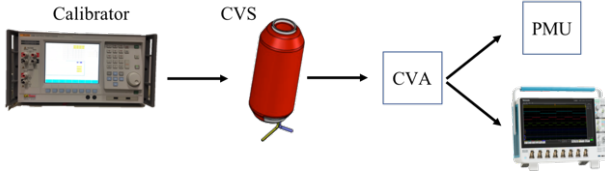| Rated frequency	50-60 Hz	Rated primary current	300 A
Rated Primary Voltage	20/√3 kV	Weight	1.5 kg
Nominal Voltage ratio in/out	10000:1	Accuracy class	0.5
Nominal current ratio		1000 A/ 31 mV	

Fig. 1   Schematic representation of the proposed setup
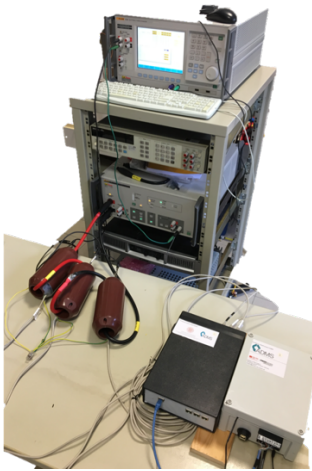

Fig. 2   Picture of the proposed setup during the measurements in the laboratory

Fig. 3 Picture of the PMU highlighting the 3 main components

harmonics and noise content. The filtered samples are processed with a zero-crossing algorithm to extract the signal frequency. The ROCOF is obtained as difference between frequency measured at first and last cycle of the observation window. If the measured frequency is distant from the nominal ($f_n \pm 0.2$ Hz) the Discrete Fourier Transform is calculated based on a reduced set of samples (only the first 6 cycles are selected). The DFT is applied on the original signal samples (not the ones filtered for the frequency calculation) multiplied by the flat top window. The phase angle is compensated considering the actual measured frequency in order to time tag the synchrophasor at the occurrence of the UTC second.

The described hardware and software were tested for compliance of steady state accuracy and requirements. As shown in [6], the Total Vector Error (TVE) in steady state conditions shows to be always below 0.3 %. Similar results were obtained for frequency and ROCOF errors.

III. Low Power Instrument Transformer

A new kind of Instrument Transformers (ITs) is replacing the legacy inductive ones: the LPITs. Therefore, new Standards were required to fully describe these new components, the low-power current and voltage transformers described in [11] and [12], respectively. LPITs features include lower weight and dimensions with respect to the inductive ones. Moreover, the novelty they introduce is the low-power output, ready for being connected, in most of the cases, to generic acquisition systems. Such characteristics make LPITs suitable for being spread and installed in many secondary substations, to acquire and have a better knowledge of the MV power network.

Authors' experience on LPITs have been consolidated with [14-15] and, with this work, a further step towards Smart Grids' implementation is done. The LPIT used in the following setup is a combined voltage and current sensor (CVS), suitable for MV indoor applications, which electrical and mechanical characteristics are summarized in Table I. The voltage is provided to the sensor through the high voltage electrode (top of the sensor) and the ground potential electrode (wire electrode). Concerning the current, the sensor is a trough-hole type; hence, the power cable is to be inserted into it. The output of the sensor is transmitted through RJ45 connector after the scaling procedure via the voltage and current transformers embedded in the sensor.

IV. Measurement Setup

A schematic representation of the proposed measurement setup is shown in Fig. 1. Fig. 2 instead, presents a picture of the measurement setup when tests have been performed. The setup consists of a 3-phase system with:

- Calibrator Fluke 6105A (maximum outputs: 1000 V, 120 A) under metrological confirmation, it provides 50 Hz sinusoidal voltage and current to feed the sensors.

- LPIT (Current and Voltage Sensor, CVS). Its characteristics are listed in Table I. The actual in/out ratios of the LPIT used to run tests are 8720 and 34598.5 for the voltage and the current, respectively.

- LOCO PMU: this low-cost version of the instrument allows to acquire phasors from a 3-phase system. It requires a time-reference signal to attach a time-stamp to the measurements. The inputs accepted are contained in the ±10 V range. It is shown in Fig. 3.

- Current and Voltage Adapter (CVA): this device, prototype developed in the lab, was necessary to adapt the output of the CVS, very low in particular for the current, to the input of the PMU. Its in/out ratios for both current and voltage correction are 240 and 4,

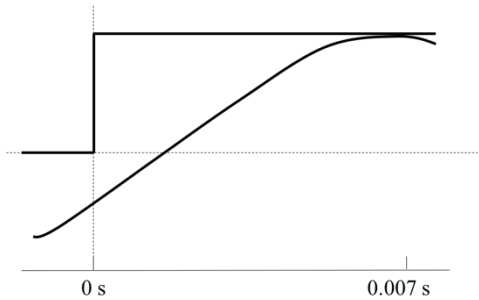| #test	Applied RMS Voltage [V]	V_M [V]	σ_{V_M} [V]
1	200	198.97	0.04
2	600	600.62	0.04
3	800	799.44	0.05
4	1000	999.42	0.05

Fig. 4 Snapshot of the two waveforms acquired by the Oscilloscope for the phase measurement

respectively. The CVA has been characterized using the Fluke calibrator in terms of both, amplitude and phase. The results are not presented for the sake of brevity, however the phase angle deviations obtained are negligible.

- Oscilloscope Tektronix MSO5 series (see Fig. 1). Used to evaluate the phase delay between the pulse per second and the sine wave maxima. It features an accuracy of $2.5 \cdot 10^{-6}$ for time measurements. The mentioned test will be described in the following section.

In a nutshell, the calibrator fluke provides the input voltage and current signals to the sensors. Their output is provided to the CVA, which, in the field, feed the signal to the RGDM (Rilevatore di Guasto Direzionale e Misura) and LOCO PMU. The PMU publishes its results via IEC 61850, which are collected by a cloud phasor data concentrator. Finally, the PMU data are downloaded regularly, to compare them with the input data produced by the calibrator. The oscilloscope is used as additional reference for the knowledge of the phase angle of the waveforms.

V. Tests Description

A. Introduction

In this Section, all the tests performed on the measurement chain (Fig. 1) are described. The intent is to evaluate the accuracy of magnitude, phase angle, frequency and ROCOF quantities measured by the system sensor + PMU. As already described, the system is to be applied in distribution systems, therefore the tests on frequency and ROCOF are limited in range and number with respect of the indications of the IEEE Std. C37.118.1-2011 and C37.118.1a-2014. Furthermore, in distribution grids, current and voltage phasors are elaborated to obtain power flow and injection measurements, therefore it is included in the tests the accuracy of the phase angle

difference between voltage and current. Phase angle measurements have to be repeated several times during the lab testing sessions. Such procedures require having a fixed phase angle to ensure the repeatability of the test over time. This however clashes with the rotation of the phase angle when the frequency generated by the calibrator is not exactly 50 Hz. Such effects are negligible when the test are run over short period of times, e.g. few seconds, but become preeminent when the test run for hours. Therefore this test are conducting adjusting the time reference that is sent to the PMU to trigger the acquisition to be a multiple of the signal frequency and not necessary a multiple of 50 Hz. For instance, if the generated signal matches nominal frequency is 50 Hz the time pulse is refreshed every 1 second (this will match the PPS signal), if instead the generated signal is 49.995 Hz, the time pulse is refreshed every 0.99999 seconds. This method allows the PMU to generate a phasor that rotates in the same domain of the current system frequency.

It is worth noticing that the Total Vector Error (TVE), as defined in the IEEE Std. C37.118.1-2011 is also not commonly applied in distribution network monitoring applications. Therefore, the errors are always split in terms of magnitude and phase angle error and quantified statistically as average + standard deviation.

B. Tests

First of all, the amplitude of the quantities acquired by the PMU was verified. To do so, different values of voltage were set by the calibrator (200, 600, 800, 1000 V), which feature, for the most interesting range (1000 V), an accuracy of 60 ppm + 10 mV. For each input value of the voltage and current 1000 values are acquired from the PMU.

The second and third tests regard the phase of the acquired quantities. The former consisted in the absolute phase measurement of a voltage, with respect to the cosine waveform with positive peak aligned with the PPS signal (see Fig. 4). The phase was measured 1000 times with both the PMU and the Oscilloscope, and the results compared. This test aimed at verifying the quality of the time measurement of the PMU, using the Oscilloscope as a reference. The latter test dealt with the evaluation of the phase difference between the voltage and current. Three different phases were set for the current by the calibrator (0, $\pi/4$, $\pi/2$ rad). As mentioned in the introduction, phase measurement test requires fixed values of phase over time. However, to avoid phase drifts, the aforementioned procedure has been applied, providing to the PMU a stable phase reference.

Finally, given that PMU allows frequency measurements, tests on frequency and ROCOF measurement have been performed. For three days, 1000 samples of both frequency and ROCOF have been acquired by the PMU. For all the aforementioned tests, the calibrator maintains the input signal for a fixed time window of 1 h. In this way, it is possible to be confident that, even if the input signal of the calibrator is not timestamped, both calibrator and PMU are referring to the same signal.

VI. Results

In Tables II to V all measurement results are presented. In Table II four voltage RMS magnitudes measured by the PMU are compared with the calibrator input. The Table list the mean value V_M of 1000 measurements together with the standard deviation of the mean σ_{V_M}. Assuming the magnitude error as unique contributor to the for the system sensor + PMU system, we would have a TVE ranging from 0.5 % (for 200V

TABLE III.   PHASE MEASUREMENT RESULTS: ABSOLUTE PHASE COMPARISON BETWEEN OSCILLOSCOPE AND PMU

#day	φ_{Os} [rad]	$\sigma_{\varphi_{Os}}$ [rad]	φ_{PMU} [rad]	σ_{PMU} [rad]	$\Delta\varphi$ [rad]
1	0.7627787	$3\cdot10^{-7}$	0.7504	$2\cdot10^{-4}$	-0.0124
2	2.1472786	$2\cdot10^{-7}$	2.1366	$2\cdot10^{-4}$	-0.0107
3	3.8798041	$1\cdot10^{-7}$	3.8622	$1\cdot10^{-4}$	-0.0176

TABLE IV.   PHASE MEASUREMENT RESULTS: PHASE DIRRENCE BETWEEN THE VOLTAGE AND CURRENT PHASORS

#test	Applied Shift [rad]	φ_M [rad]	σ_{φ_M} [rad]
1	1.571 ($\pi/2$)	1.589	0.002
2	0.785 ($\pi/4$)	0.749	0.006
3	0.0000	0.023	0.0008

TABLE V.   FREQUENCY MEASUREMENT RESULTS: FREQUENCY AND ROCOF EVALUATION

#day	Applied Frequency [Hz]	f_M [Hz]	σ_{f_M} [Hz]	ROCOF [HZ/s]	σ_{ROC} [Hz/s]
1	50	50.001209	$3\cdot10^{-6}$	0.0034	$4\cdot10^{-4}$
2	50	50.001200	$6\cdot10^{-5}$	0.000200	$4\cdot10^{-6}$
3	50	50.001225	$7\cdot10^{-5}$	0.058	$2\cdot10^{-3}$

Fig. 5   Pdf of the voltage phase acquired with the oscilloscope

input) to 0.06 % (for 1000V), thus being in line with the requisite for accuracy of synchrophasors (even in presence of the sensor uncertainty).

Table III list the 3 days measurements values of: the absolute phase angle measured with the oscilloscope φ_{Os} and the one measured by the PMU φ_{PMU}. Both values are reported with their mean standard deviation $\sigma_{\varphi_{Os}}$ and σ_{PMU}, respectively. Moreover, in the Table the difference between the two mean values $\Delta\varphi$ is reported to improve the results comprehension. The corresponding TVE, assuming the phase angle error as only contributor to the TVE, for the sensor + PMU system, would be between 0.12 % and 0.1 %.

The results of the phase difference between the voltage and current phasors measurements are listed in Table IV. The figures are the results of 1000 acquisitions, as for all the tests performed. φ_M is the phase difference acquired by the PMU and σ_{φ_M} its mean standard deviation. The results confirm what has been already stated in the previous phase measurement test. In Fig. 5 the probability density function of a phase measurement has been reported to confirm its normality distribution.

Finally, in Table V the frequency measurements are reported: aside from the applied frequency, the Table reports 3 days of measurement for the frequency f_M acquired by the PMU and its ROCOF. All results are provided with their mean standard uncertainty σ_{f_M} and σ_{f_M}, respectively. The frequency error is in the range of 1 mHz, in line with the conventional limits specified for frequency measurements for synchrophasors.

VII. CONCLUSIONS

The system proposed for monitoring distribution grids shows accurate results, in line with common sensor and synchrophasor standards. In fact, the system sensor + PMU would satisfy both an accuracy class 0.5 for sensor standard and the 1% TVE for PMU standard. However, it is required to advance the definition of the standard testing procedure and requirements for combined chain sensor plus devices. The test procedure should also take into account the peculiar features of distribution grids and not just extend the same rules applied to transmission. In this sense, this paper proposes a first set of tests that could become a benchmark for the LPIT + PMU chain characterization. In particular the phase angle is tested as absolute and relative information (phase angle of voltage minus current) by fixing the time reference to the signal frequency and not the nominal frequency.

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