16th IMEKO TC10 Conference
"Testing, Diagnostics & Inspection as a comprehensive value chain for Quality & Safety
Berlin, Germany, on September 3-4, 2019

Metrological Performances of Current Transformers Under Amplitude Modulated Currents

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***Abstract* – All the measurement tasks, f.i. metering, protection and diagnostics, in electricity distribution and trasmission grids need instrument transformers (ITs) to scale voltage and current down to levels compatible with measuring instruments. Inductive voltage and current transformers (VTs and CTs) are still the most used ITs; however, their behaviour in presence of disturbances is not fully assessed. This paper analyses the behavior of CTs in presence of amplitude modulations, which is one of the disturbance under which the performance of Phasor Measurement Units (PMUs) has to be assessed. A measurement setup, able to test current transformers in accordance to the IEEE Std. C37.118.1 about the PMU performance testing, has been realized. Experimental tests on a commercial CT, changing the modulation frequency, are presented.**

Keywords* – *Current Transformer, Power System Diagnostics, Phasor Measurement Unit, Amplitude Modulations.

I. INTRODUCTION

All the measurement tasks, from metering to protection, from energy saving to diagnostics, that have to be performed in the electricity Transmission and Distribution Systems (TSs and DSs) need the measurement of grid voltage and current 1. Voltage and current levels spans from hundreds of volt and tens of ampere up to hundreds of kilovolt and tens of kiloampere [2]. This is the reason why all the measuring instruments for TSs and DSs need voltage and current instrument transformers (ITs) to make voltage and current levels compatible with their input range.

Although sensor technologies advance and new kind of voltage and current instrument transformers (active or passive, generally referred to as Low Power Instrument Transformers, LPIT) are available on the market [3,4], inductive voltage and current transformers (VTs and CTs) are still the most used ITs in TSs and DSs. Therefore, as the modern TSs and DSs experience a wide growth of conducted disturbances [5–9], (generally referred to as Power Quality, PQ), inductive ITs are used for PQ monitoring, as input stage of PQ measuring instruments [10].

Inductive ITs are designed to work at power frequency (i.e. 50/60 Hz) and, moreover, some recent literature [11, 12] show that inductive ITs suffer from an intrinsic non-linearity which is responsible for uncertainties up to some percent when measuring PQ phenomena. However, currently, the behavior of the inductive ITs in PQ measurement is not fully addressed.

The work presented in this paper is inserted in the framwork of the European project EMPIR 17IND06 Future Grid II: one of the objectives of this project is to define a set of test waveforms, representative of TSs and DSs real signals and that goes beyond the existing international standards, with which evaluate the performance of ITs in conditions similar to those that can be encountered in an actual power system.

In particular, one of the disturbance that can can be encountered in TSs and DSs are the amplitude modulation of voltage and current signals. Therefore, this paper is focused on the verification of the performance of CTs when their input currents are affected by undesired amplitude modulation.

Some paper in scientific literature face the issue of testing the performance of CT in non-sinusoidal conditions 13, 14. However, to the best of the author's knowledge, no paper reports experimental on CTs when its input is affected by amplitude modulation.

The international standard IEEE C37.118.1 [15] and its amendment [16], focused on synchrophasor measurement methods and performance verification of Phasor Measurement Units (PMUs), deals with amplitude modulations and proposes some tests to verify the performance of PMUs in their presence. PMUs have crucial role in modern TSs and DSs because they are used to implement remote diagnostic system of power grid by focusing on the synchronized phasor of fundamental component. In fact, the scope of a PMU is to measure the phasors of the voltage and current fundamental component, synchronized to the Universal Time Coordinated (UTC), even when they are affected by PQ disturbances. The same considerations made for PQ instruments are valid also for PMUs: inductive VTs and CTs are frequently used as input stage of PMUs for the measurement of TSs and DSs voltage and current fundamental synchrophasor. In this context, it would be very useful to know the additional uncertainty introduced by VTs and CTs to the fundamental synchrophasor, other than that of the PMU itself. Therefore, the approach followed in this paper is to evaluate the uncertainty contribution of CTs to the measurements performed by a PMU, when the currents are affected by amplitude modulation. The paper is organized as follows: Section II deals with the definitions and the testing procedure. Section III describes the measurement setup whereas Section IV presents the preliminary experimental results of the characterization of a commercial CT. Finally, Section V draws the conclusions.

II. DEFINITIONS AND TESTING PROCEDURE

A. *Definitions*

The current signals, $i(t)$, used for the scope of the paper are composed by a fundamental component (i.e. the carrier) at power frequency and a sinusoidal amplitude modulating component, which can be written as in equation (1):

$$i(t) = \sqrt{2}X_m(1 + k_a \cos(2\pi f_a t)) \cos(2\pi f t) \quad (1)$$

where X_m and f are, respectively, the root mean square (rms) amplitude and the frequency of the fundamental component, whereas k_a and f_a are, respectively, the amplitude modulation factor and the modulation frequency.

According to [17] the CT ratio and phase errors are evaluated as in equation (2) and (3).

$$\epsilon = \left(\frac{KI_2}{I_1} - 1\right) * 100 \quad (2)$$

$$\Delta\phi = \phi_2 - \phi_1 \quad (3)$$

where K is the rated ratio of the CT, I_1 (I_2) and ϕ_1 (ϕ_2) are the magnitude and phase angle of the fundamental primary (secondary) current phasor, respectively.

According to [15, 16], the Total Vector Error (TVE) is evaluated as in equation (4).

$$TVE = \sqrt{\frac{(\Re(K\boldsymbol{I_2}) - \Re(\boldsymbol{I_1}))^2 + (\Im(K\boldsymbol{I_2}) - \Im(\boldsymbol{I_1}))^2}{\Re(\boldsymbol{I_1})^2 + \Im(\boldsymbol{I_1})^2}} \quad (4)$$

where $\Re(\boldsymbol{I_1})$ ($\Re(K\boldsymbol{I_2})$) and $\Im(\boldsymbol{I_1})$ ($\Im(K\boldsymbol{I_2})$) are, respectively, the real and imaginary parts of the fundamental primary (secondary, multiplied by CT rated ratio) current phasor.

B. *CT Testing Procedures*

As it is written in the introduction, the aim of the paper is to evaluate the uncertainty contribution of CTs to the measurements performed by a PMU, when the currents are affected by amplitude modulation. Therefore, the aim of the paper is graphically represented in Fig. 1, where the functional block diagram of the measurements is depicted. The same current is sensed by a reference CT (CT$_{REF}$) and by the CT under test (CT$_{UT}$). Their outputs are acquired and processed by two identical PMUs (PMU$_1$ and PMU$_2$), which returns the fundamental synchrophasors of the outputs of CT$_{REF}$ and CT$_{UT}$, i.e. $\boldsymbol{I_{REF}}$ and $\boldsymbol{I_{UT}}$. After the calculation of $\boldsymbol{I_{REF}}$ and $\boldsymbol{I_{UT}}$, the quantities in equations (2) - (4) are evaluated: in fact, the equations (5) and (6) apply:

$$\boldsymbol{I_1} = K_{REF}\boldsymbol{I_{REF}} \quad (5)$$

$$\boldsymbol{I_2} = \boldsymbol{I_{UT}} \quad (6)$$

where K_{REF} is the ratio of the reference CT. In this way, since two identical PMUs measure the fundamental synchrophasor of the same current, but using two different CTs, the sole contribution of the CT under test to the uncertainty on ϵ, $\Delta\phi$ and TVE is evaluated. In particular, since in the realized setup (as it is explained in Section III) generation and acquisition are synchronized, the synchrophasors $\boldsymbol{I_1}$ and $\boldsymbol{I_2}$ are evaluated by performing the Discrete Fourier Transform (DFT) on the output samples of the CT$_{REF}$ and CT$_{UT}$. The DFT is executed on an observation window of four cycles of the fundamental frequency.

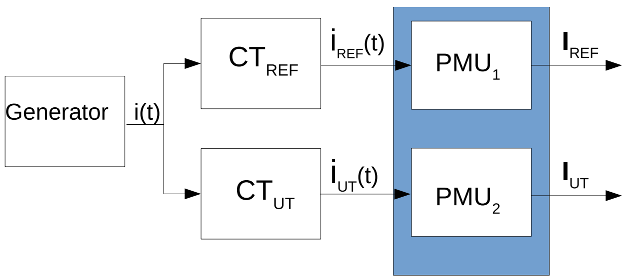

Fig. 1. Functional block diagram of the measurements

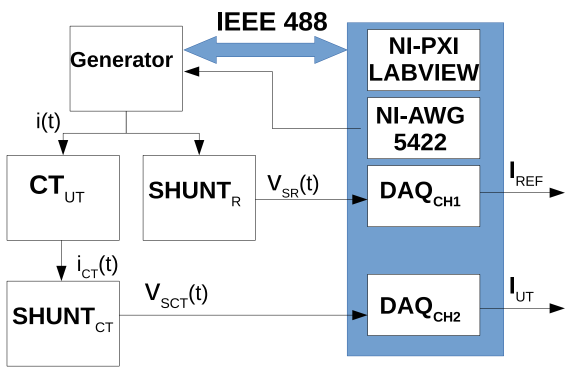

Fig. 2. Block diagram of the measurement setup

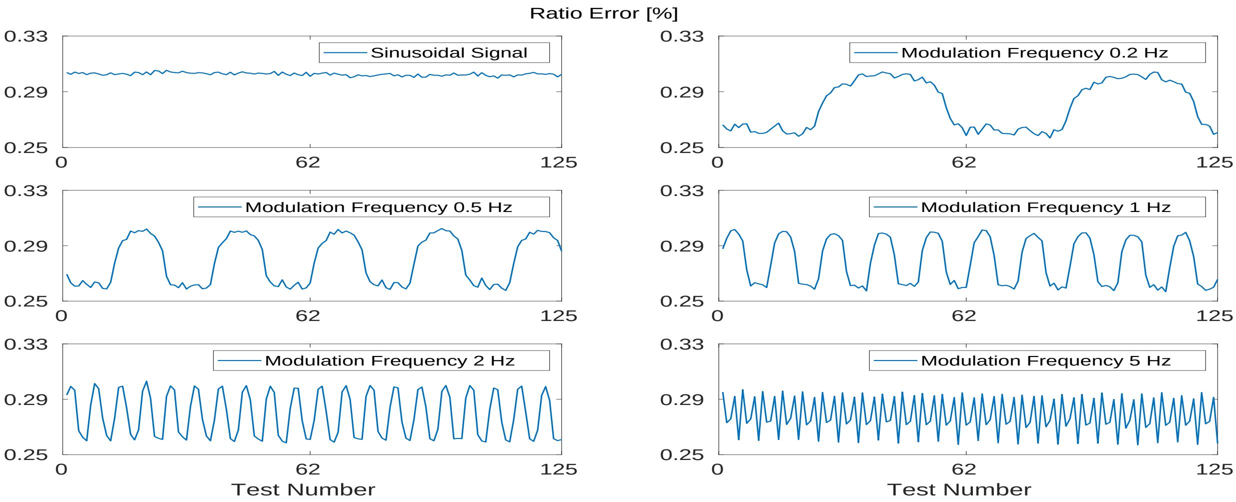

Fig. 3. Ratio Error, in sinusoidal conditions and with amplitude modulation

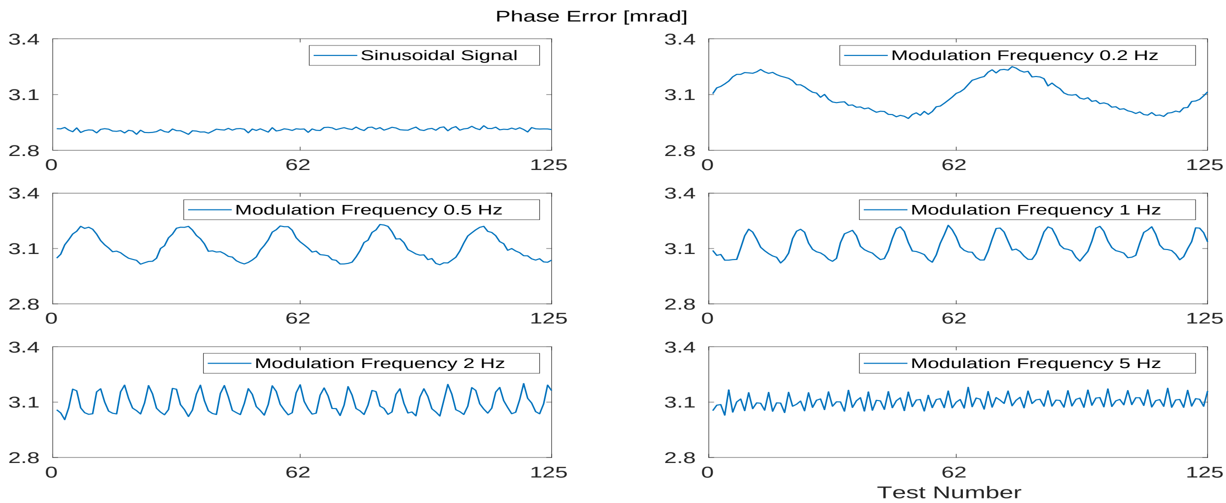

Fig. 4. Phase Error, in sinusoidal conditions and with amplitude modulation

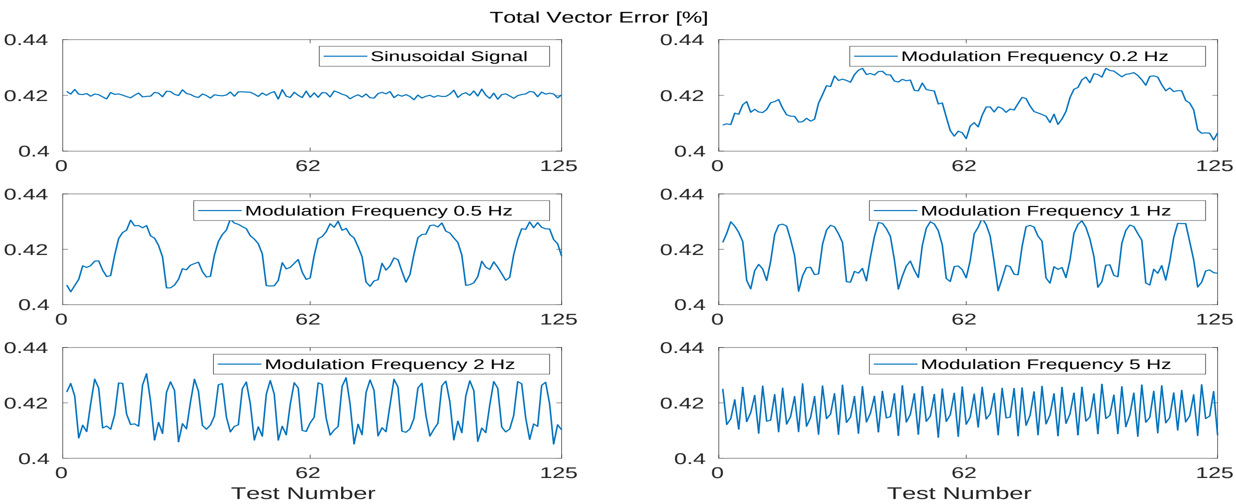

Fig. 5. Total Vector Error, in sinusoidal conditions and with amplitude modulation

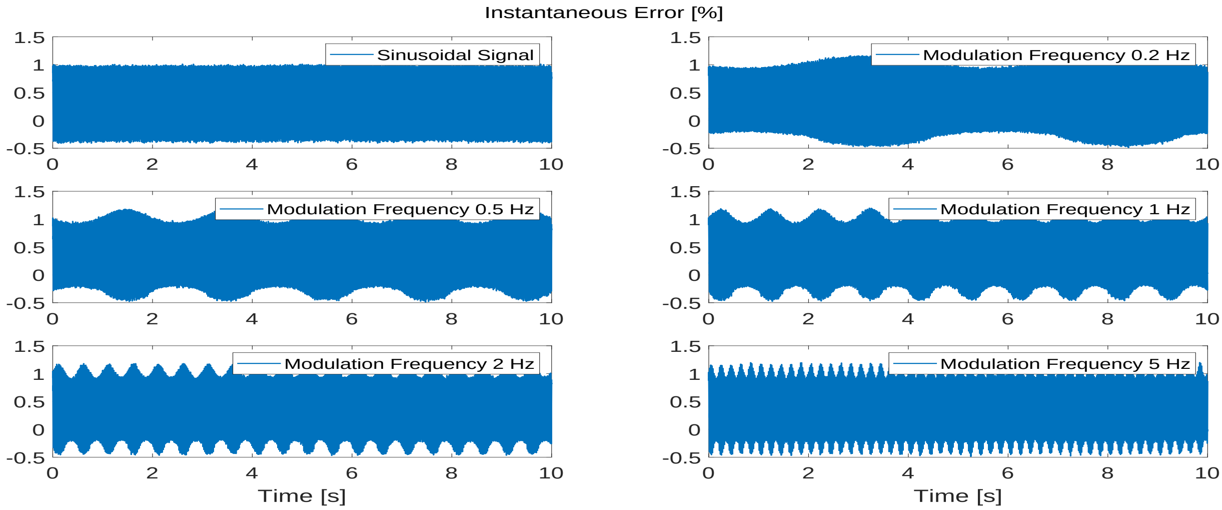

Fig. 6. Instantaneous Error, in sinusoidal conditions and with amplitude modulation

III. MEASUREMENT SETUP

The measurement setup is shown in Fig. 2. Current generation is obtained through the transconductance amplifier Fluke 52120 A (up to 120 A, up to 10 kHz). It is driven by the National Instrument (NI) PXI 5422 arbitrary waveform generator (AWG, ± 12 V, 200 MHz maximum sampling rate, 16 bit, onboard memory 256 MB).

The used data acquisition board (DAQ) is the NI PXI express (PXIe) 6124 (4 synchronous channels, 16 bit, 4 MHz maximum sampling rate). The DAQ and the AWG are housed in a NI PCI eXtension for Instrumentation (PXI) chassis which provides the same reference clocks to both of them: in such a way acquisition and generation are accurately synchronized. Current reference value is obtained by means of the current shunt FLUKE A40B 20/0.8 A/V (100 kHz, 30 μA/A). The CT under test is wound type and it has rated ratio of 10/5 A/A, rated burden of 5 VA and accuracy class of 0.5. Its output current is converted into a voltage by means of the current shunt LEM NORMA TRIAX Shunt 10/0.1 A/V (100 kHz, 0.03 %). The test bench is shown in Fig. 2. The software for data processing and instrument control was developed in Labview. A large choice of signal types can be generated, f.i. sinusoidal, fundamental plus a harmonic tone, fundamental with N harmonics, fundamental with an inter-harmonic, etc. Every signal generation is forerun and followed by a fade-in and a fade-out signal, in order to avoid generating large currents with a step variation. The samples at the output of the current shunts are acquired at a frequency of 10 kHz and stored into files. They are then processed in MatLab environment to extract the fundamental phasors and to evaluate ϵ, $\Delta\phi$ and TVE.

Table 1. Peak to peak values of the Ratio Error, Phase Error and TVE, in sinusoidal conditions and with amplitude modulation

Modulation Frequency $[Hz]$	Ratio Error [%]	Phase Error [mrad]	TVE [%]
Sine Wave	0.006	0.05	0.004
0.2	0.047	0.28	0.026
0.5	0.045	0.22	0.026
1	0.045	0.20	0.026
2	0.045	0.20	0.025
5	0.040	0.15	0.019

Table 2. Peak to peak values of the Instantaneous Error, in sinusoidal conditions and with amplitude modulation

Modulation Frequency $[Hz]$	Instantaneous Error [%]
Sine Wave	1.424
0.2	1.670
0.5	1.677
1	1.685
2	1.666
5	1.688

IV. EXPERIMENTAL RESULTS

The CT has been tested with currents having a fixed fundamental component, amplitude of 10 A, frequency of 50 Hz and zero phase, and an amplitude modulating component having fixed phase (0 rad) and amplitude (10 % of fundamental component) and variable frequency, from 0.2 Hz to 5 Hz. For each modulating frequency, 125 measurements have been performed. Fig. 3, Fig. 4 and Fig. 5 show, respectively, ϵ, $\Delta\phi$ and TVE in all the tests performed. Each figure shows six curves, referring, respectively, to sinusoidal conditions, amplitude modulation with frequency of 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz and 5 Hz. With respect to the sinusoidal case, the tests with amplitude modulation imply oscillations of the evaluated indexes, which probably, depend on the relative phase anlge between the fundamental and the modulating components within the observation window. Moreover, for ϵ and $\Delta\phi$, the averages of the oscillating values differ from the mean value observed for sinusoidal conditions, whereas for TVE the averages are more similar to the sinusoidal case. In all the cases, the peak to peak values of the oscillations decrease when the frequency increases. The peak-to-peak values of the evaluated indexes are reported in Table 1 and their maximum values are 0.047 % for ϵ, 0.28 mrad for $\Delta\phi$ and 0.026 % for TVE. It is worth to note that the oscillations, in presence of modulation, is about one order of magnitude higher than in sinusoidal case. The instantaneous error has also been evaluated and it is shown in Fig. 6: it is expressed in percentage of the fundamental amplitude. Table 2 shows the peak-to-peak values of the instantaneous error: it can be seen that, in presence of modulation, the istantaneous error is higher than in sinusoidal case of about 0.25 %.

V. CONCLUSION

This paper analyzes the uncertainty contribution of inductive current transformers to the synchrophasor measurement performed by a PMU, in the presence of amplitude modulated currents. A high-performance measurement configuration capable of generating up to 120 A was presented. Experimental tests, performed on a commercial CT, changing the frequency of the amplitude modulating component, showed that an additional error is introduced by the CT on the fundamental phasor, with respect to the sinusoidal case. However, other research activities, about the testing of different types of current transformers and with different types of input disturbances, are still in progress. The results of these activities, which are inserted in the framework of the research project EMPIR Future Grid II, will be also supplied to working group 47 "Evolution of Instrument transformer requirements for the modern market" of the IEC (International Electrotechnical Commission) Technical Committee 38 "Instrument Transformers". In fact, some of the authors participate to the standardization activity of this working group, which actually is dealing with the preparation of a document on the characterization of instrument transformers to be employed for power quality and synchrophasor measurements.

VI. ACKNOWLEDGEMENT

The work presented in this paper was funded by EMPIR, 17IND06 Future Grid II project, which is jointly funded by the EMPIR participating countries within EURAMET and the European Union.

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