Use of COMTRADE Fault Current Data to Test Inductive Current Transformers

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***Abstract*—This paper presents a study on the inductive current transformer behaviour when subjected to distorted actual waveforms. Typical tools adopted to deal with such a condition, as the well-known ratio error, phase error, frequency response, etc. not always provide satisfactory results in all the possible operating condition. In addition, Standards lack in detailing which actual distorted waveforms need to be used to test the transformers. To this purpose, the paper introduces both the use of particular actual fault current waveforms and a simple index for testing the performance of the transformer. Preliminary results show its helpfulness when applied to particular waveforms.**

Keywords—current transformers, fault current, distorted signals, measurement system, harmonics

I. Introduction

With the recent widespread dissemination of Distributed Energy Resources (DER) and electronic equipment among the power networks, different issues have arisen. In particular, such network elements introduce low/high frequency harmonic components, lowering the overall power quality of the network. To prevent the damage of the electrical assets among the grid and to guarantee a high quality of the supplied energy, Standards tried to define thresholds to comply with. In EN 50160 [1] limits for the harmonics value, compared to the power frequency one (50 Hz), are provided up to the 25th harmonic. Higher harmonics limits are not provided due to their typical small value and unpredictability. However, in [1] no indication on the harmonics phase or on their waveform shape is provided.

Considering that what previously mentioned holds for a general point of view on power quality, let us focus on the components which directly measure the electrical quantities of interest: Instrument Transformers (ITs). Despite of the introduction of the Low Power Instrument Transformers (LPITs) [2, 3] research on ITs are still multifold. In [4, 5] their accuracy vs. temperature is studied, while in [6] authors characterized them in a wide frequency range.

ITs measurements are the key element on which billing and active management of the grid are based. Hence, their accuracy must be guaranteed in all the operating conditions, including the presence of harmonics and interharmonics components. Referring to Standard IEC 61869-1, 2 and 3 [7-9], which defines all ITs requirements, it does not provide accurate guidelines on the ITs testing vs. frequency components.

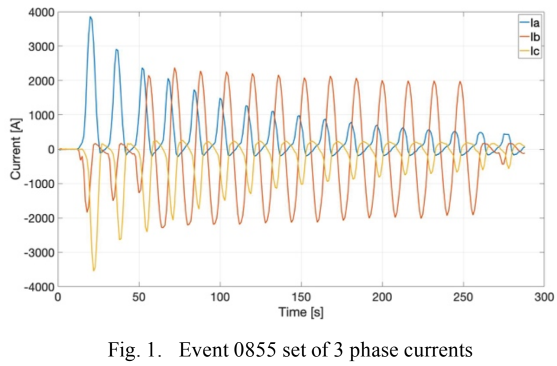

Fig. 1. Event 0855 set of 3 phase currents

In light of this, as far as the non-sinusoidal operation of the ITs is concerned, literature provides several approaches to understand the behaviour of transformers in such conditions. In [10] authors model the Current Transformer (CT) at high frequency, while [11, 12] analyse and characterize them when supplied with distorted waveforms.

In this paper, by starting from available fault current data, provided by the Electric Power research Institute (EPRI), the behaviour of a Medium Voltage (MV) inductive current transformer has been investigated. Such a study started from the literature, where the ITs accuracy performance is mainly tackled with two different techniques. The first one is the ratio and phase errors computation of the ITs [8]. Such errors are computed either for each single harmonic component or for the overall signal [13], hence the accuracy can be evaluated with different degrees of detail. The second paramount tool to approach ITs response is the Frequency Response (FR) [14, 15]. Its pro and cons are well-known in literature and in a nutshell, there is a wide consensus of its inapplicability as a unique method for the ITs evaluation [16]. To this purpose, new techniques have been developed [17] and this work wants to contribute in this way. In particular, the CT performance has been dealt with an index strictly related to composite error, a typical parameter used for protection ITs [18] which allows to approach the CTs in the time domain.

The paper is structured as follows: Section II briefly describes the current fault data and its common format. In Section III the measurement system developed and used in the work has been presented. Section IV lists all the tests performed with the developed system. In Section V all the results are collected and commented. Finally, some conclusions are drawn in Section VI.

II. COMTRADE Faults Data

To perform actual measurements on CTs, it is necessary to feed them with current which really flows in the power networks. Hence, EPRI database has been used. It contains voltage and current waveforms of 3-phase systems acquired during fault conditions of the grid. Faults are classified in terms of cause (lighting, animal, vegetation, etc.), and component that suffered from the fault. An example of data is shown in Fig. 1, which refers to a lighting on a power transformer. From the database, waveforms are available in the typical format used to share measurements collected or simulated by different devices, the COMTRADE (COMmon format for TRAnsient data Exchange) [19]. Each data file contains all the information necessary to the final user, such as measurements themselves, timestamp, type of fault and

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TABLE I. KEYSIGHT 33220A MAIN CHARACTERISTICS

Frequency Range	1 μHz to 6 MHz	**Sampling frequency**	50 MSa/s
Frequency resolution	1 μHz	**Frequency Accuracy**	±(20 ppm +3 pHz)
Architecture		14 bit	

TABLE II. FLUKE 52120A MAIN CHARACTERISTICS

Current range [A]	Frequency [Hz]	% of output	% of range
2	10 to 65	0.015	0.070
	65 to 300	0.030	0.070
20	10 to 65	0.015	0.060
	65 to 300	0.030	0.060

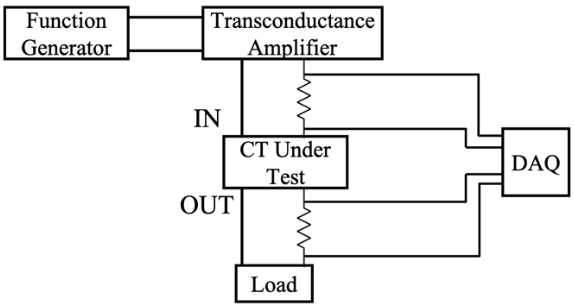

Fig. 2. Simple schematic of the measurement setup for the TUT testing

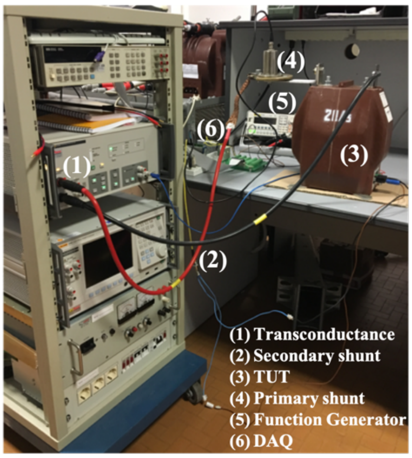

Fig. 3. Simple schematic of the measurement setup for shunt resistors characterization

sampling details. In the literature, it can be noted a massive use of this data format (due to its high utility). For example, in [20] it is used to test protective relays, while in [21] authors want to obtain power network models from their application. However, to the authors best knowledge, such transients data has not been used yet to test measurement inductive CTs.

III. MEASUREMENT SYSTEM

The measurement system developed to perform measurements on the transformer under test (TUT) consists of:

- Keysight Function/Arbitrary waveform generator 33220A. It allows to generate arbitrary waveforms defined by the user. Its general and arbitrary waveform main characteristics are summarised in Table I.
- Fluke Transconductance 52120A. It has been used as a master unit to transduce the voltage output of the function generator to a current in the range of 0 – 20 A. The transconductance accuracy specifications, at (5 to 35) °C ± 5 °C, are listed in Table II.
- The inductive CT under test. It is a 20/5 A transformer, used for MV measurement purposes (at 50 Hz) featuring: class 0.2 and rated power of 6 VA.
- Two shunt resistors to measure both the primary and the secondary current of the TUT. The first is a 1 mΩ shunt and it is installed in series to the primary current, the second one has 10 mΩ resistance and it is installed in series to the secondary current. In addition, a 220 mΩ resistor has been connected to the TUT output to guarantee its operation under rated burden conditions.
- NI 9239 Data Acquisition Board (DAQ). With its ±10 V peak to peak full range, it is used to acquire the voltages on the two resistors terminals. The DAQ features: 24-bit architecture, four simultaneous channels (50 kSa/s/ch), and accuracy parameters 0.03 % of the reading and 0.008 % of the range.
- A personal computer to control, via LabView software, both the arbitrary waveform generation and implementation on the function generator and the acquisition of the primary and secondary TUT currents via DAQ.

A simple schematic of the measurement setup is presented in Fig. 2. Instead, in Fig. 3 a picture of the actual laboratory setup is shown.

IV. TESTS & CHARACTERIZATIONS PROCEDURES

This Section presents all the tests performed with and for the measurement system.

A. Resistors Metrological Characterization

As previously mentioned, the system is composed by three different resistors. Two shunt resistors and the load. The first test consisted in the load characterization vs. time, to guarantee the resistor stability when subjected to the rated TUT current (5 A) for a long time-interval. To this purpose, 5 A were injected through the 220 $m\Omega$ resistor with the transconductance. Afterward, every 20 min 100 measurements of the voltage at the resistor terminals have been acquired by the NI9239 DAQ.

The second test aimed at characterizing the shunt resistors vs. frequency. This because the input signals may contain, as described in the following, several harmonics components different from the fundamental one. For these tests, the setup depicted in Fig. 4 has been used. It consists in the Fluke calibrator 6105A, which characteristics are listed in Table III, feeding one shunt resistor at the time. The voltage of the shunts is then collected by using the above described DAQ.

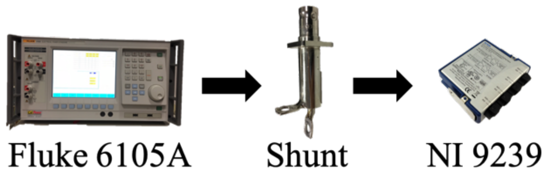

Fig. 4. Simple schematic of the measurement setup for shunt resistors characterization

TABLE III. FLUKE CALIBRATOR 6105A MAIN CHARACTERISTICS

Frequency Accuracy	±50 ppm	**Max current and voltage**	20 A, 1008 V
Range	**Frequency**	**ppm of output + μA**	
5 A	45 – 65 Hz	64	100
	up to 6kHz	400	400

TABLE IV. LIST OF FAULT EVENTS USED FOR THE TEST

Code	**Event**	**Component affected**
0855	Lighting on transformer	Fuse/Transformer
0963	Snake on recloser	Recloser
0965	Animal on recloser	Recloser
1111	Snake on lighting arrester	Transformer
2857	Multiple lighting on transformers	Breakers

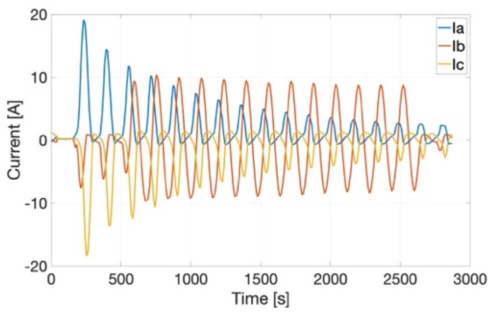

Fig. 5. Event 0855 set of 3 phase scaled currents

TABLE V. LOAD RESISTOR CHARACTERIZATION VS. TIME RESULTS

Time [min]	R_L [Ω]	σ_{RL} [Ω]	φ_{RL} [*rad*]	$\sigma_{\varphi_{RL}}$ [*rad*]
0	0.224269	$4 \cdot 10^{-6}$	$266 \cdot 10^{-6}$	$6 \cdot 10^{-6}$
20	0.229033	$4 \cdot 10^{-6}$	$266 \cdot 10^{-6}$	$6 \cdot 10^{-6}$
40	0.229106	$4 \cdot 10^{-6}$	$267 \cdot 10^{-6}$	$6 \cdot 10^{-6}$
60	0.229123	$4 \cdot 10^{-6}$	$266 \cdot 10^{-6}$	$6 \cdot 10^{-6}$
80	0.229155	$4 \cdot 10^{-6}$	$267 \cdot 10^{-6}$	$6 \cdot 10^{-6}$

B. TUT test procedure

Once all the system components have been characterized, the main tests can be performed. In particular, 5 different cases of 3-phase currents have been selected from the EPRI database. Table IV contains the reference code of the cases and their brief description. Absolute values of the adopted fault current have been scaled to the rated value of the TUT for two main reasons. Firstly, the purpose of the work is to assess the CT behavior when subjected to distorted waveforms (hence, not necessarily high fault currents). Secondly, working with currents ten times the rated one would have compromised the transformer itself. For the sake of brevity, in Fig. 5 the scaled waveforms of the 3 currents of Fig. 1 are showed. By referring to Fig. 2, the test consisted in the following steps:

- The arbitrary waveforms are created in accordance to the samples provided by the COMTRADE files.
- The function generator feed the transconductance amplifier with an input adapted to the range ±2 V_{PP}, the latter converts the input into a current within ±20 A.
- The current then flows inside the TUT and both primary and secondary are acquired using the shunt resistors. The DAQ is triggered by the function generator to start the acquisition only when the input current is provided. In particular, for each waveform provided by the COMTRADE files, the repetition period has been considered as the length of the waveforms data (as illustrated in Fig. 1).

By following the aforementioned procedure, 100 periods of the currents have been collected for both the primary and the secondary sides of the TUT.

C. Perfomance Index Definition

For an inductive CT, referring to [7], the composite error is defined as:

$$\varepsilon_C = \frac{\sqrt{\frac{1}{T}\int_0^T \left(k i_s(t) - i_p(t)\right)^2 dt}}{I_p} * 100, \qquad (1)$$

where, $i_p(t)$ and $i_s(t)$ are the instantaneous values of the primary and secondary currents, respectively. I_p is the rms value of the primary current and k is the rated transformation ratio. Finally, T is the period of the considered current. As previously mentioned ε_C limits are listed in [7] and used to evaluate protective CTs. In this work, by starting from (1), a related index has been adopted. It is defined as:

$$\varepsilon_D = \frac{\sqrt{\frac{1}{N}\sum_1^N \left(k i_s(n) - i_p(n)\right)^2}}{I_p} * 100, \qquad (2)$$

where N is the number of samples contained in each sequence $i_p(n)$ and $i_s(n)$ representing the primary and secondary currents acquired from the TUT. Such a parameter, which is a sort of normalized RMSE (Root Mean Square Error), has been applied to measurement CTs with the aim of evaluating their input/output response. The reason for that is supported by the fact that, during faults, grid operations and distorted working conditions, even measurement CTs are subjected to non-sinusoidal currents. Hence, their measurements might be highly inaccurate.

To this purpose, ε_D has been computed for all the cases of Table IV, one for each phase.

V. EXPERIMENTAL RESULTS

A. Resistors

Table V contains the characterizations results of the load resistor vs. time. From the Table it can be stated at a glance that the resistor reaches the thermal stability already after 20

TABLE VI. PRIMARY SHUNT CHARACTERIZATION VS. FREQUENCY RESULTS

Frequency [Hz]	R_{PS} [Ω]	σ_{PS} [Ω]	φ_{PS} [rad]	$\sigma_{\varphi_{PS}}$ [rad]
40	0.001021494	$6 \cdot 10^{-9}$	0.000447	$7 \cdot 10^{-6}$
50	0.001021496	$7 \cdot 10^{-9}$	0.000553	$8 \cdot 10^{-6}$
60	0.00102144	$2 \cdot 10^{-8}$	0.00066	$1 \cdot 10^{-5}$
100	0.00102117	$3 \cdot 10^{-8}$	0.00004	$3 \cdot 10^{-5}$
200	0.00102093	$4 \cdot 10^{-8}$	0.00010	$4 \cdot 10^{-5}$
300	0.00102096	$9 \cdot 10^{-8}$	0.00023	$4 \cdot 10^{-5}$
400	0.00102056	$5 \cdot 10^{-8}$	0.00031	$6 \cdot 10^{-5}$
500	0.00102035	$5 \cdot 10^{-8}$	0.00042	$6 \cdot 10^{-5}$
600	0.0010197	$2 \cdot 10^{-7}$	0.00049	$6 \cdot 10^{-5}$
700	0.0010196	$2 \cdot 10^{-7}$	0.00069	$6 \cdot 10^{-5}$
800	0.00101980	$8 \cdot 10^{-8}$	0.00085	$8 \cdot 10^{-5}$
900	0.0010203	$3 \cdot 10^{-7}$	0.00064	$7 \cdot 10^{-5}$
1000	0.00101946	$9 \cdot 10^{-8}$	0.00017	$9 \cdot 10^{-5}$

TABLE VII. SECONDARY SHUNT CHARACTERIZATION VS. FREQUENCY RESULTS

Frequency [Hz]	R_{PS} [Ω]	σ_{PS} [Ω]	φ_{PS} [rad]	$\sigma_{\varphi_{PS}}$ [rad]
40	0.0099994	$2 \cdot 10^{-7}$	0.00000	$1 \cdot 10^{-5}$
50	0.0100004	$2 \cdot 10^{-7}$	0.00000	$1 \cdot 10^{-5}$
60	0.0100028	$2 \cdot 10^{-7}$	0.00000	$2 \cdot 10^{-5}$
100	0.0100013	$3 \cdot 10^{-7}$	-0.00002	$3 \cdot 10^{-5}$
200	0.0100023	$3 \cdot 10^{-7}$	0.00000	$3 \cdot 10^{-5}$
300	0.0100042	$8 \cdot 10^{-7}$	-0.00001	$3 \cdot 10^{-5}$
400	0.0100023	$4 \cdot 10^{-7}$	0.00002	$4 \cdot 10^{-5}$
500	0.0100021	$4 \cdot 10^{-7}$	0.00005	$4 \cdot 10^{-5}$
600	0.009998	$1 \cdot 10^{-6}$	0.00003	$4 \cdot 10^{-5}$
700	0.009997	$1 \cdot 10^{-6}$	0.00004	$6 \cdot 10^{-5}$
800	0.0100015	$5 \cdot 10^{-7}$	0.00008	$5 \cdot 10^{-5}$
900	0.010009	$3 \cdot 10^{-6}$	-0.00018	$6 \cdot 10^{-5}$
1000	0.0100018	$5 \cdot 10^{-7}$	-0.00062	$6 \cdot 10^{-5}$

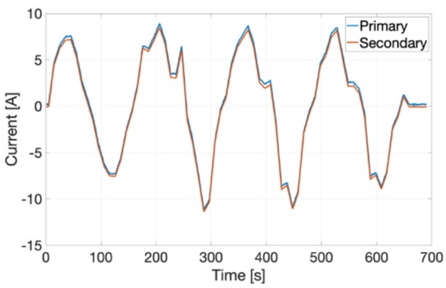

Fig. 6. Primary and secondary currents comparison for the case 0965, phase A.

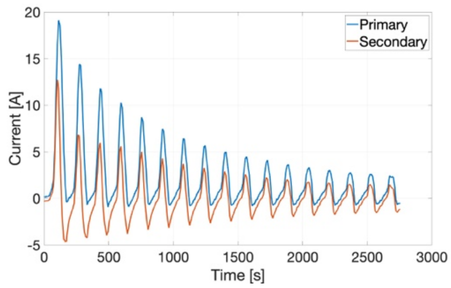

Fig. 7. Primary and secondary currents comparison for the case 0855, phase A.

TABLE VIII. COMPOSITE ERROR COMPUTED FOR THE 5 EVENTS OF INTEREST

Event Code	Phase	ε_D [%]
0855	A	76.12
	B	9.53
	C	61.02
0963	A	3.25
	B	3.89
	C	4.07
0965	A	6.03
	B	8.24
	C	42.65
1111	A	5.32
	B	54.83
	C	19.46
2857	A	47.79
	B	25.38
	C	51.71

min, maintaining a high stability for all the test duration. Moreover, the phase displacement introduced by the component is in the order of fractions of milliradians.

Results of the characterization vs. frequency of both the primary and the secondary shunt resistors are listed in Table VI and VII, respectively. From the two Tables same comments arise: both the resistors, in the range 40 – 1000 Hz, are not affected by the frequency. In other words, parasitic parameters do not influence the resistors behavior. Finally, in all Tables IV, V, and VI the measurement results are presented along with their associated uncertainty evaluated with the type A method (in accordance with the Guide of the expression of Uncertainty in Measurements [22]).

B. TUT Test Results

Five sets of three currents have been injected into the TUT. For the sake of brevity just two results are presented in Fig. 6 and Fig. 7. They both represent the comparison between the primary and secondary current (scaled by the transformer ratio) waveforms. In particular, Fig. 6 refers to the event 0965, while Fig. 7 refers to the event 0855 (phase A considered in both cases). In both figures it appears that the secondary current is (quite) different from the primary one.

C. Performance Index results

To better understand the results presented in previous subsection B, let us focus on the values taken by ε_D in the performed tests. All of them are listed in Table VIII. The Table contains the index ε_D in percentage, along with the event and the phase considered in each case. From the Table, it arises that the value of ε_D ranges from about 4 % to more than 70 % thus highlighting that the TUT is not able to correctly measure the input current. In light of the results, it can be stated that a 0.2 class CT does not work properly when subjected to distorted waveforms, even if their absolute value lays within the rated one.

VI. CONCLUSIONS

The paper has dealt with a significant issue concerning inductive instrument transformers: the behavior under non-sinusoidal conditions. In the literature several works approach the topic with many techniques such as frequency/time domain assessments as well as new techniques that include both of them. To this purpose, the work assesses the CT performance introducing the use of actual current waveforms taken from a database and by using a simple index derived from the composite error. Preliminary tests on a typical medium voltage current transformer confirm that, such a parameter, can be used as an additional parameter for the transformers analysis when subjected to distorted currents.

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