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Inductive Current Transformer Core Parameters Behaviour vs. Temperature Under Different Working Conditions

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***Abstract* – This paper presents a study focused on the equivalent parameters of an inductive current transformer for medium voltage purposes. In particular, its equivalent parameters behaviour has been assessed by varying both the temperature and the working conditions (current and voltage). Preliminary results provide interesting "calibration" curves which may be used during the transformer modelling.**

Keywords – Inductive current transformer, core loss, shunt parameters, short circuit, open circuit, load current, temperature

I. INTRODUCTION

Despite the introduction of the new generation of Low-Power Instrument Transformer (LPIT) [1-3], the classical Inductive ones (ITs) are still wide adopted. As a matter of fact, both inductive current and voltage transformers (CTs and VTs) [4-6] are reliable measurement instrument, in particular for Distribution Networks (DNs). Distribution System Operators (DSOs) and electrical utilities are moving towards the adoption of LPIT but still they prefer the ITs for a delicate aspect as the metering for pricing. To guarantee a high accuracy for such a measurement, a transformer should be known and tested in all its peculiarities.

In light of this, a vivid literature can be found on the inductive ITs. In [7, 8] the accuracy vs temperature of both CT and VT is studied, while in [9, 10] they deal with their calibration. ITs performance concerning power quality aspects (i.e. harmonics, off-nominal conditions) are tackled in [11, 12].

As far as the internal behaviour of the ITs is concerned, their modelling has always been a paramount and critical topic. To this purpose, this paper aims at enhancing the knowledge of the core losses behaviour vs. two quantities: the load current and the temperature.

To the authors knowledge such behaviour has not been tackled in the literature yet; despite that several papers can be found on the ITs modelling. For example, core saturation has been studied in [13], whereas the typical linear-model approach is described in [14, 15]. In [16] and [17] new approaches for their modelling and their design are presented, respectively. As mentioned before, power quality is such an important topic that has been included in different ITs modelling studies [18-20]. Finally, another way to tackle the critical aspects of an IT model is to compensate all its non-linearities and losses with a posteriori analysis [21, 22].

Therefore, by using a developed test setup, different measurements have been performed on the CT under test (TUT) to calculate its series and parallel impedances. As it is well known, the main parameters of CTs, which affect its operation, are the series ones containing (i) primary and secondary equivalent leakage reactance X_{eq}, (ii) primary and secondary equivalent cooper loss resistances R_{eq}, and the shunt parameters (iii): magnetizing reactance X_m and core losses (eddy currents and hysteresis) resistance R_w.

Then, working conditions and temperature have been varied to assess the shunt impedance behaviour. This way, further studies could focus on their effect on the overall accuracy of the CTs.

The paper is structured as follows: Section II describes the setup adopted to test the Medium Voltage (MV) CT. The performed tests are detailed in Section III while their results are showed and discussed in Section IV. Finally, Section V presents some conclusions and future developments.

II. TEST SETUP

The circuit diagram shown in Fig. 1 schematises the general setup adopted for the measurements on the CT. It includes:

- a programmable power source Agilent 6813B,

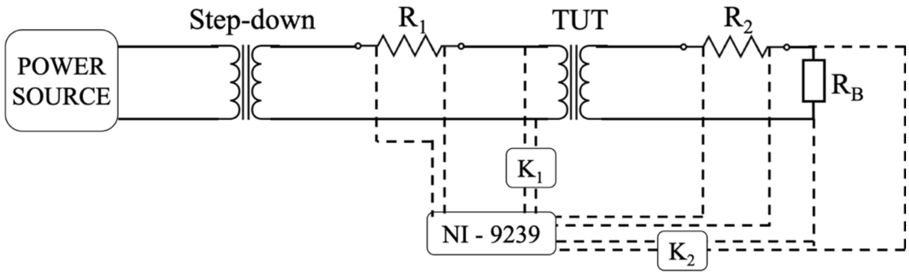

Fig. 1. Circuit diagram of the measurement setup adopted for the tests

Table I. NI-9239 main features

Architecture	24-bit	**Max input signal**	±10 V
Sample rate	50 kS/s/ch	**Simultaneous channels**	YES
ADC	Delta Sigma	**Temperature range**	-40 to +70 °C
Gain Error	0.03 %	**Offset Error**	0.008 %

Table II. Fluke 6105a main features

At power frequency conditions	
Range [V]	***Accuracy (ppm + mV)***
1 – 23	42 + 0.2
70 – 1008	60 + 10
Range [A]	***Accuracy (% of output + % of range)***
120	0.009 + 0.002
Frequency	***Accuracy (ppm)***
Full range	50

Table III. Components Characterization results

Item	Mean value	σ_m
R_1 [Ω]	0.0010250	$3\cdot 10^{-7}$
R_2 [Ω]	0.010035	$1\cdot 10^{-6}$
k_1 [-]	11.00215	$4\cdot 10^{-5}$
k_2 [-]	11.00110	$5\cdot 10^{-5}$
R_B [Ω]	0.52571	$7\cdot 10^{-5}$

which features up to 300 V RMS, 1750 VA from DC to 1 kHz. Which feeds:

- a 10-ratio step-down transformer used to isolate the source and to increase the current to the TUT rated value.
- The 0.5 accuracy class CT under test. It features: ratio of 20/5 A, 10 VA rated power and rated frequency of 50 Hz.
- Two shunt resistors to measure the primary and the secondary currents, $R_1 = 1\ m\Omega$ and $R_2 = 10\ m\Omega$, respectively.
- A pure resistive load used as rated burden R_B.
- Two accurate resistive dividers to measure the primary and secondary voltages, both with nominal ratio equals to 11 (k_1 and k_2 , respectively).
- The thermal chamber, it contains only the TUT and it allows to reach 60 °C.
- Data Acquisition Board (DAQ) NI-9239 equipped with 4 synchronized channels and which main characteristics are summarized in Table I.
- Personal Computer to analyze all the DAQ-acquired quantities.

III. EXPERIMENTAL TESTS

Before running the main tests aim of this work, the components of the proposed setup have been characterized. Hence, 1000 measurements have been acquired after injecting 20 A, 5 A, 5 A to R_1, R_2, and R_B, respectively. The injected values, by using the Fluke calibrator 6105a (Table II summarise its main features), represent the ones the components will be subjected to during the main tests. With the same criterion, 3 V has been applied to the two resistive dividers to compute their ratios (k_1 and k_2). Results of the characterization tests are reported in Table III in terms of mean value and standard deviation of the mean σ_m of resistance and of the dividers ratio. As it can be seen from the Table, all the components are known with a high accuracy level. As for R_B, the required value was 0.4 Ω according to the ratio rated voltage (2 V) over rated current (5 A). The measured one instead is slightly different, however, from [3] it is possible to extend the rated burden value if the CT remains in its accuracy class.

A. Rated Condition Test

The first test performed on the setup depicted in Fig. 1 has the aim of computing ratio and phase error at rated conditions of the TUT at 24°C and 60 °C. Hence, the power source was adjusted to provide an equivalent current of 20 A when the rated burden is connected. Then, 1000 values of primary and secondary quantities (current and voltages) have been acquired. Consequently, ratio and phase error (ε and φ) have been computed, for both the operating temperatures, as:

$$\varepsilon = \frac{kI_2 - I_1}{I_1} \quad (1)$$

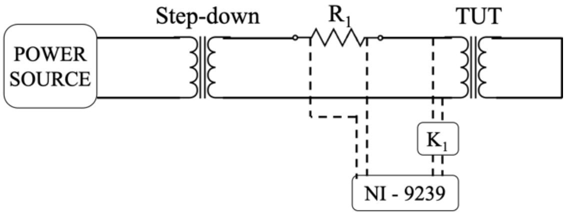

Fig. 2. Circuit diagram of the measurement setup adopted for the short circuit tests

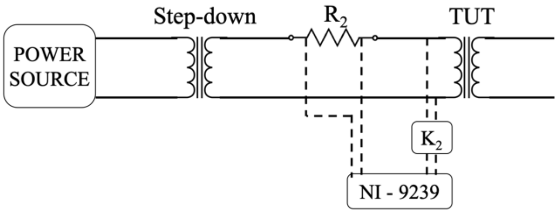

Fig. 3. Circuit diagram of the measurement setup adopted for the open circuit tests

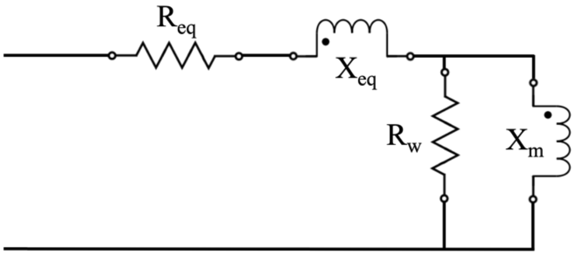

Fig. 4. Circuit diagram of the CT equivalent circuit considered

$$\varphi = \hat{I}_2 - \hat{I}_1 \tag{2}$$

where k is the nominal ratio of the CT, I_1 and I_2 are the RMS values of the primary and secondary currents, respectively. In (2), $\hat{I}_1$ and $\hat{I}_2$ are the phases of the primary and secondary current phasors.

B. Short Circuit Test

The Short Circuit (SC) test is done in the same way as for power transformers. Fig. 2 shows the adopted setup. While the secondary terminals are short circuited, on the primary side the voltage is increased and the current monitored till it reaches the test value (see below). For this test the measured quantities are: primary current phasor $\bar{I}_1$, primary voltage phasor $\bar{V}_1$ and phase displacement θ_1 between them. SC test has been performed at 24 °C and 60 °C under different primary current conditions (100 %, 75 %, 50 %, and 25 % of the rated current).

From such measurements the series equivalent parameters $R_{eq}{'}$ and $X_{eq}{'}$, referred to the primary side, can be calculated as:

$$R_{eq}{'} = \frac{V_1 * \cos(\theta_1)}{I_1} \tag{3}$$

$$X_{eq}{'} = \frac{V_1 * \sin(\theta_1)}{I_1} \tag{4}$$

where θ_1 is computed as the difference between the angles of the current and voltage phasors. These are obtained by applying the Fourier Transform (FT) to the sequences of samples acquired by the DAQ.

C. Open Circuit Test

The Open Circuit (OC) test has been performed on the secondary side of the TUT by using the setup depicted in Fig. 3. The test consisted of applying the secondary rated voltage (i.e. the ratio between rated power and rated secondary current, 2 V) and measuring its phasor ($\bar{V}_2$) along with the secondary current phasor $\bar{I}_2$ and the phase displacement θ_2 between voltage and current. The above phasors are obtained by applying the FT to the acquired samples. Then, the test has been repeated for the 75 %, 50 %, and 25 % of the rated voltage and for the two temperature of interest. Of course, the varied quantity is the voltage and not the current due to the peculiarities of the OC test. This way, it is possible to vary the operating conditions of the ferro-magnetic core. Thus, leading to different core-losses and magnetisation inductance.

By using the aforementioned acquired quantities, it is possible to calculate the parallel parameters of the CT as:

$$R_w{''} = \frac{V_2}{I_2 * \cos(\theta_2)} \tag{5}$$

$$X_m{''} = \frac{V_2}{I_2 * \sin(\theta_2)} \tag{6}$$

In light of the performed test, the equivalent model of the CT adopted is depicted in Fig. 4.

After the description of the OC and the SC test, it is worth to highlight an important aspect. Even if the former has been performed varying the applied voltage and the latter varying the injected current, both are varying the current flowing in the CT shunt impedance. Hence, in different ways, they are changing the CT working conditions.

IV. EXPERIMENTAL RESULTS

As previously mentioned, 1000 values for all the measured quantities have been collected.

A. Rated Condition Test Results

In Table IV, the measurement results from the test at rated conditions are presented. From the Table it can be seen that at room temperature the TUT works within its accuracy class (0.5) limits. Conversely, at 60 °C the TUT slightly overcome the 0.5 % limit value of the ratio error while the phase one is still within the 9 mrad limit.

Table VI. CT series parameters computation results, for different loads and two temperatures

Load [%]	24 °C				60 °C			
	$R_{eq}{}'$ [Ω]	σ_m [Ω]	$X_{eq}{}'$ [Ω]	σ_m [Ω]	$R_{eq}{}'$ [Ω]	σ_m [Ω]	$X_{eq}{}'$ [Ω]	σ_m [Ω]
100	0.008397	$2 \cdot 10^{-6}$	0.009863	$3 \cdot 10^{-6}$	0.008795	$5 \cdot 10^{-6}$	0.009921	$6 \cdot 10^{-6}$
75	0.008377	$4 \cdot 10^{-6}$	0.009860	$5 \cdot 10^{-6}$	0.008778	$3 \cdot 10^{-6}$	0.009919	$4 \cdot 10^{-6}$
50	0.008436	$3 \cdot 10^{-6}$	0.009858	$4 \cdot 10^{-6}$	0.008768	$4 \cdot 10^{-6}$	0.009916	$5 \cdot 10^{-6}$
25	0.008396	$1 \cdot 10^{-5}$	0.009859	$1 \cdot 10^{-5}$	0.008751	$9 \cdot 10^{-6}$	0.009914	$1 \cdot 10^{-6}$

Table IV. Rated conditions test results

Quantity	24 °C		60 °C	
	Mean Value	σ_m	*Mean Value*	σ_m
I_1 [A]	20.402	$6 \cdot 10^{-3}$	19.926	$2 \cdot 10^{-3}$
I_2 [A]	5.122	$2 \cdot 10^{-3}$	5.0081	$7 \cdot 10^{-4}$
V_1 [V]	0.87419	$5 \cdot 10^{-5}$	0.86705	$9 \cdot 10^{-5}$
V_2 [V]	2.9526	$3 \cdot 10^{-4}$	2.9078	$4 \cdot 10^{-4}$
θ_1 [rad]	0.23897	$9 \cdot 10^{-5}$	0.23639	$4 \cdot 10^{-5}$
ε [%]	-0.413	$2 \cdot 10^{-3}$	-0.532	$6 \cdot 10^{-3}$
φ[mrad]	5.54	$6 \cdot 10^{-2}$	5.50	$2 \cdot 10^{-2}$

Table V. Short Circuit test results for different load currents

Load [%]	*Quantity*	24 °C		60 °C	
		Mean Value	σ_m	*Mean Value*	σ_m
100	I_1 [A]	20.506	$3 \cdot 10^{-3}$	20.415	$7 \cdot 10^{-3}$
	V_1 [V]	0.26561	$4 \cdot 10^{-5}$	0.27067	$7 \cdot 10^{-5}$
	θ_1 [rad]	0.8655	$2 \cdot 10^{-4}$	0.8455	$2 \cdot 10^{-4}$
75	I_1 [A]	14.846	$4 \cdot 10^{-3}$	14.814	$3 \cdot 10^{-3}$
	V_1 [V]	0.19208	$4 \cdot 10^{-5}$	0.19622	$3 \cdot 10^{-5}$
	θ_1 [rad]	0.8665	$4 \cdot 10^{-4}$	0.8463	$3 \cdot 10^{-4}$
50	I_1 [A]	10.311	$2 \cdot 10^{-3}$	10.227	$3 \cdot 10^{-3}$
	V_1 [V]	0.13377	$3 \cdot 10^{-5}$	0.13537	$3 \cdot 10^{-5}$
	θ_1[rad]	0.863	$2 \cdot 10^{-3}$	0.8468	$4 \cdot 10^{-4}$
25	I_1 [A]	5.017	$3 \cdot 10^{-3}$	5.283	$3 \cdot 10^{-3}$
	V_1 [V]	0.06497	$4 \cdot 10^{-5}$	0.06986	$3 \cdot 10^{-5}$
	θ_1[rad]	0.8653	$7 \cdot 10^{-4}$	0.8476	$7 \cdot 10^{-4}$

The reason for that might be the high temperature, [2] states that the working conditions should not exceed the 50 °C. However, authors wanted to stress the TUT operating conditions to assess its behavior at higher temperatures.

B. Short Circuit Test Results

SC test results are listed in Table V. Primary voltage, current and phase displacement have been acquired at 4 different current conditions. Such results represent the base to compute $R_{eq}{}'$ and $X_{eq}{}'$ by applying (3) and (4). The series parameters results are summarized in Table VI. At a glance, from the Table it can be highlighted that both operating temperature of the TUT and the primary current are not affecting its series parameters. In other words, during the CT modeling, the series parameters can be treated as constants with respect to those two quantities. The results confirm what expected in terms of dependency on the applied primary current, given that the series parameters represent leakage inductance and resistance of the TUT windings. However, the behavior of the series parameters vs. temperature was not predictable as for the previous.

Table VII. Open Circuit test results for different load currents

Load [%]	*Quantity*	24 °C		60 °C	
		Mean Value	σ_m	*Mean Value*	σ_m
100	I_2 [A]	0.04423	$3 \cdot 10^{-5}$	0.04089	$7 \cdot 10^{-5}$
	V_2 [V]	2.05823	$9 \cdot 10^{-5}$	2.0625	$2 \cdot 10^{-4}$
	θ_2 [rad]	0.572	$1 \cdot 10^{-3}$	0.592	$2 \cdot 10^{-3}$
75	I_2 [A]	0.03341	$4 \cdot 10^{-5}$	0.03247	$7 \cdot 10^{-5}$
	V_2 [V]	1.47292	$8 \cdot 10^{-5}$	1.5591	$3 \cdot 10^{-4}$
	θ_2 [rad]	0.623	$2 \cdot 10^{-3}$	0.639	$3 \cdot 10^{-3}$
50	I_2 [A]	0.02536	$6 \cdot 10^{-5}$	0.0238	$1 \cdot 10^{-4}$
	V_2 [V]	1.05131	$9 \cdot 10^{-5}$	1.0526	$2 \cdot 10^{-4}$
	θ_2 [rad]	0.675	$3 \cdot 10^{-3}$	0.708	$5 \cdot 10^{-3}$
25	I_2 [A]	0.01575	$9 \cdot 10^{-5}$	0.0141	$1 \cdot 10^{-4}$
	V_2 [V]	0.54873	$9 \cdot 10^{-4}$	0.4657	$1 \cdot 10^{-4}$
	θ_2 [rad]	0.803	$5 \cdot 10^{-3}$	0.89947	$8 \cdot 10^{-3}$

C. Open Circuit Test Results

Table VII shows the OC test results performed on the secondary side of the TUT while the primary is open. As mentioned in the previous Section, the peculiarity of this test consists of varying the applied voltage from the rated to its 25 %. From the results such an approach is confirmed. As a matter of fact, the current flowing in the CT is very low (the magnetizing current), hence it is preferable to adopt the voltage as a reference quantity for the OC test.

By starting from the measurements results of Table VII, the shunt parameters referred to the secondary side ($R_m{}''$ and $X_m{}''$) can be computed by using (5) and (6). Their values include also $R_{eq}{}'$ and X'_{eq}; however, considering the latter negligibility (three orders of magnitude) compared to the former, the results of (5) and (6) can be directly treated as the shunt parameters of the CT. Obtained results are collected in Table VIII. From it, and with the help of the graph in Fig. 5, two interesting comments arise. Firstly, both the resistance

Table VIII. *CT shunt parameters computation results, for different loads and two temperatures*

Load [%]	**24 °C**				**60 °C**			
	R_w'' [Ω]	σ_m [Ω]	X_m'' [Ω]	σ_m [Ω]	R_w'' [Ω]	σ_m [Ω]	X_m'' [Ω]	σ_m [Ω]
100	55.34	0.02	85.96	0.06	60.8	0.1	90.4	0.2
75	54.28	0.07	75.56	0.09	59.8	0.1	80.5	0.2
50	53.1	0.1	66.3	0.2	58.2	0.3	68.0	0.3
25	50.2	0.4	48.4	0.4	53.1	0.4	42.2	0.3

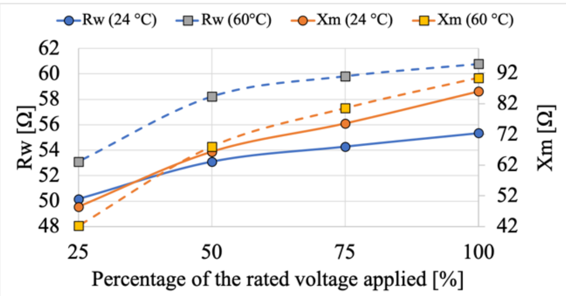

Fig. 5. Shunt parameters representation vs. temperature vs. applied voltage

and the reactance increase when the TUT is subjected to 60 °C. Secondly, by reducing the applied voltage, hence reducing the magnetizing current circulating in the CT, a decrease of both R_m'' and X_m'' is experienced.

In light of the obtained results, the "calibration" curves reported in Fig. 5 can be used for enhancing the inductive CT modelling. In particular, once the operating temperature and the working point are known, the proper values of the shunt parameters can be selected and implemented in every model.

V. CONCLUSIONS

In this paper, series and parallel parameters of a 20/5 current transformer are calculated by performing short circuit and open circuit test in different loading conditions at 24 °C and 60 °C. It has been shown that series parameters can be neglected if compared to parallel parameters. In particular, the former is not affected neither from the temperature nor from the core operating conditions. Instead, the latter resulted to be affected by both quantities. More in detail, an increase of temperature turns into an increase of the shunt parameters, while a decrease of the overall current flowing in the CT core results into their decrease. In the overall, the presented study results can be used to enhance the CT modeling. This, by providing calibration curves which give at a glance the shunt parameters values when temperature and load parameters are fixed.

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