

ERRORS IN CURRENT TRANSFORMERS SUBMITTED TO NONSINUSOIDAL CONDITIONS

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Abstract: This paper describes methods and criterions for errors determination of current transformers (CT). It is shown that there is need for technical standards modifications, because traditional governmental standards tests are based on purely sinusoidal conditions. Based on sampling and composite errors, which can be used for the errors determination in non-sinusoidal system, experimental results are presented, comparing two toroidal CT, one with nanocrystalline alloy core and another with FeSi core both submitted to sinusoidal regime.

Key words: Measurement error; Current transformer; Non-sinusoidal conditions.

1. INTRODUCTION

Current transformer (CT) is a transformer specially designed and assembled to be used in measurement, control, and protection circuits. In CT cores can be employed materials as: grain oriented (GO) silicon-iron, permalloy alloys, amorphous or nanocrystalline alloys, wrapped in a toroidal shape [1].

In terms of electrical circuit, the primary winding of the CT is composed by only few turns, with diameter compatible with the current that you want to evaluate, while its secondary winding has a high number of turns. Generally, these windings are made of copper wires.

In relation to the magnetic circuit, the toroidal shape is particularly recommended because with this geometry the magnetic flux will propagate in a high permeability direction, without the presence of transversal air gaps. The core magnetic material characteristics is of great importance, because with higher permeability and lower coercive force, a low excitation current is required to establish the magnetic flux density for the proper functioning of the CT within the accuracy class limits.

The CT measurements quality is directly related to the equipment accuracy class, they must operate with low error ratio and phase errors. The accuracy class depends on the quality of the electrical circuit (low leakage inductance) and the quality of magnetic material (high permeability and low losses) that forms the CT core.

In this paper is presented a comparative study, analytical and experimental, about the applications of two ferromagnetic materials in the toroidal CT composition:

nanocrystalline alloy $\text{Fe}_{73,5}\text{Cu}_1\text{Nb}_3\text{Si}_{13,5}\text{B}_9$ and Fe-3,2% Si GO alloy.

2. ANALITICAL AND EXPERIMENTAL STUDIES

2.1. Errors in sinusoidal regime

Current transformers are characterized by some relationships. The first is the marked ratio of the primary current to the secondary current ($K_c = I_{pn} / I_{sn}$), and it is indicated by the manufacturer. This ratio is a fixed value for a given current transformer. The second is the true ratio of the rms primary current to the rms secondary current ($K_r = I_p / I_s$) under specified conditions. The true ratio of a current transformer is not a single fixed value, since it depends on the specified conditions of use, such as secondary burden (Z_c), primary current (I_p), frequency (f), and wave form. The third is the ratio correction factor (RCF). It is the factor by which the marked ratio must be multiplied to obtain the true ratio ($RCF = K_r / K_c$).

The CT errors exist due to the exciting current I_e at the magnetizing branch Z_m . The primary impedance does not affect the CT errors and it is represented by a low-impedance in series with the system circuit where the CT is installed, which value can be neglected. After these considerations, the CT electrical model can be represented in Fig. 1, where Z_s is the secondary impedance.

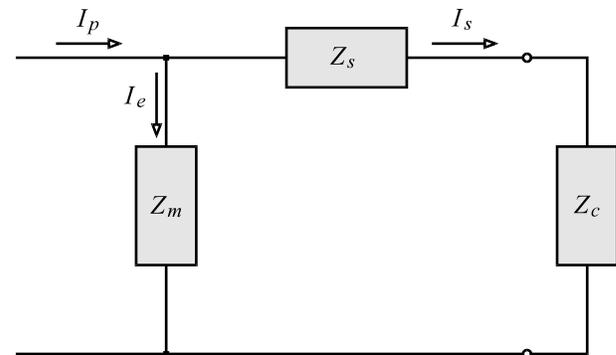


Fig. 1 – Equivalent electric circuit of a current transformer

Numerical field solutions may be used to determine the electrical equivalent circuit parameters of toroidal core current transformers. The lumped elements of equivalent

circuits correspond very closely to the various physical phenomena in the transformer. Calculation of the magnetizing inductance and minimization of the transformer magnetizing current render considerable interest for designers attempting to reduce the errors in the ratio of turns and phase angle of transformers feeding current-measuring instruments.

The phase angle of a current transformer, designated by the β , is the angle between the current leaving the identified secondary terminal and the current entering the identified primary terminal, under specified conditions [2].

It is apparent from Fig. 2 that the reversed secondary current I_2 is not in phase with the impressed primary current I_1 , there is an angle between them, the phase angle β , equation 1. This angle is considered positive when the secondary current leads the primary current and it is usually expressed in minutes.

$$\beta = \frac{|\vec{I}_0|}{|\vec{I}_1|} \cdot \cos(\alpha + \beta) \quad (1)$$

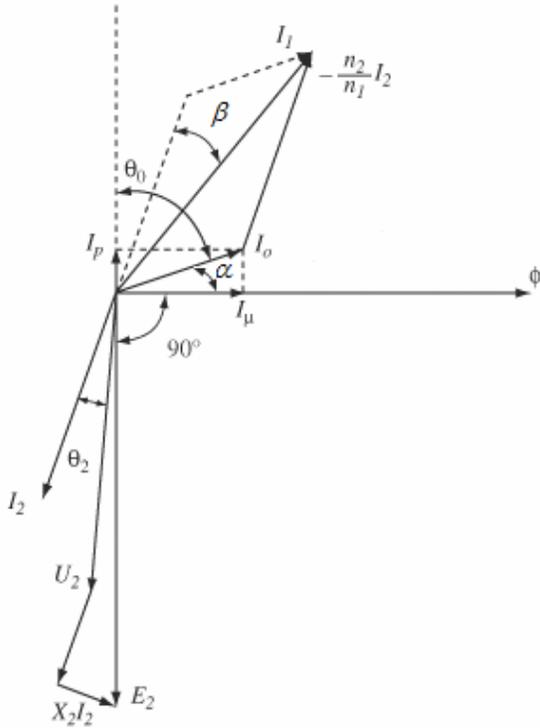


Fig. 2 – Phasor diagram of a current transformer

In this Fig. 2, Φ is the magnetizing flux and I_0 is the exciting current with its two components: I_μ , the magnetizing current, and I_p , the active losses current. In the secondary circuit: E_2 is the induced electromotive force, r_2 is the winding resistance, x_2 is the leakage reactance, U_2 is the terminal voltage, I_2 is the secondary current, and θ_2 is the angle between U_2 and I_2 . In addition, it can be seen that the primary current I_1 is obtained by phasor sum of I_0 and $(-n_2/n_1) \cdot I_2$, where n_2 and n_1 are the number of turns of the secondary and primary windings, respectively.

The ratio error ε is defined as the percent relative difference between the measured value of the primary current and its exact value, as expressed by the equation 2.

$$\varepsilon = \frac{K_r \cdot I_2 - |\vec{I}_1|}{|\vec{I}_1|} \cdot 100\% \quad (2)$$

2.2. Errors in non-sinusoidal regime

In measurement applications, the accuracy degree of CT is traditionally based on specified operating under purely sinusoidal, in terms of ratio errors and phase errors. However, these errors refer to phasor quantities, which makes no sense when considered waveforms with significant harmonic content. This is due to increasing use of electronic equipment of high power ratings in electric networks with strongly nonlinear characteristics (rectifiers, inverters, no-breaks, soft-starters, etc.). The harmonic components are also caused by poor design and inappropriate forms of operation of equipment with saturable cores, mainly transformers.

Another problem is that the voltages provided by power grids are strongly non-sinusoidal. This complicates the testing, since it takes power supplies with low total harmonic distortion (THD) and high power, and CT pattern, used as reference. These items are expensive, being available only in some specialized laboratories.

One way to eliminate the above problems is to adopt rules for evaluating error and test methods based on resources provided by the digital data acquisition systems. The virtual instrument is a tool to bring greater simplicity, speed and accuracy testing, and cost reduction.

Using digitized signals from the primary and secondary current, it is possible to define the sampling error and the error made. For a current sampled at regular intervals, define "sampling error" as the expression 3 [3-5].

$$\varepsilon_k = 100 \cdot \frac{\frac{i_{1k}}{K_N} - i_{2k}}{I_{2N}} \quad , \quad k = 1, 2, \dots, N_a \quad (3)$$

In which i_{1k} and i_{2k} are the values of primary and secondary currents at every moment of acquisition; K_N is the CT nominal ratio; I_{2N} is the nominal current; N_a is the number of samples considered.

The composite error to assess the accuracy of CT is presented in expression 4.

$$\varepsilon_c = 100 \cdot \frac{\sqrt{\frac{1}{N_a} \sum_{k=1}^{N_a} \left(\frac{i_{1k}}{K_N} - i_{2k} \right)^2}}{I_{2N}} \quad (4)$$

The use of composite sampling errors and enables the testing of CT both in sinusoidal and non-sinusoidal regime.

2.3. Manufacture of prototypes

The toroidal cores that were used in the current transformers are based on commercial nanocrystalline alloys with trade name FINEMET® FT-3KM F6045G with chemical composition: $\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$ and conventional Cold-Rolled Grain-Oriented Fe-3.2% Si.

The nanocrystalline alloy core dimensions are:

- Inner diameter: 38.5 mm
- Outer diameter: 63.5 mm
- Height: 23 mm.

The FeSi core dimensions are:

- Inner diameter: 43 mm
- Outer diameter: 59 mm
- Height: 24 mm.

The TC will be destined for use in measurement services and will be rolled-type, as presented in Fig. 3, and have the following rated values:

- Current in the primary: 5 A
- Current in the secondary: 5 A
- Number of primary turns: 72
- Number of secondary turns: 72
- Conductor cross area (primary and secondary windings): 1.28 mm² (16 AWG wire)
- Apparent power: 5 VA
- Thermal Factor: 1.2.



Fig. 3 – Prototype of current transformer

The soft magnetic materials characteristics used in the current transformers cores are presented in Table 1. The nanocrystalline alloy [6] is manufactured by Japanese company Hitachi Metals Ltd. and the steel grain oriented silicon is manufactured by Brazilian company Acesita.

Table 1. Comparative data of magnetic materials under study

Composition	B_s (T) (60 Hz)	μ_{rmax}	ρ ($\mu\Omega\cdot m$)
$\text{Fe}_{73.5}\text{Cu}_1\text{Nb}_3\text{Si}_{13.5}\text{B}_9$	0.90	185,000 ($3.0 \text{ A}\cdot\text{m}^{-1}$)	1.20
Fe-3.2% Si	1.85	40,154 ($23.0 \text{ A}\cdot\text{m}^{-1}$)	0.47

2.3. Experimental test

Aiming to investigate the behavior of TC with different magnetic materials used in the core, experimental tests were performed at the Laboratory of Industrial Electronics and Drive Machines, Federal University of Campina Grande, Brazil. The standard technique used as reference is NBR-6821 [7].

The circuit used for the experiments is shown in the diagram in Figure 4. The instruments that were used are the following:

- Voltage source: California Instruments, model 3001 iX
- Current sensors: Agilent 1146A
- Oscilloscope: Agilent DSO7014A
- Impedance R: 4 resistors, 50 Ω / 200 W.

How both CT were projected for a power of 5 VA, the NBR 6821 standardizes the impedance Z as: resistance of 0.18 Ω and inductance of 0.232 mH, 60 Hz. However, due to absent of standard load in laboratory, were used two inductors in parallel of 0.5 mH each, resulting in a total inductance of 0.25 mH and nine resistors of 1.5 Ω connected in parallel, resulting in a total resistance of 0.195 Ω . The value of the total resistance was obtained using a digital multimeter.

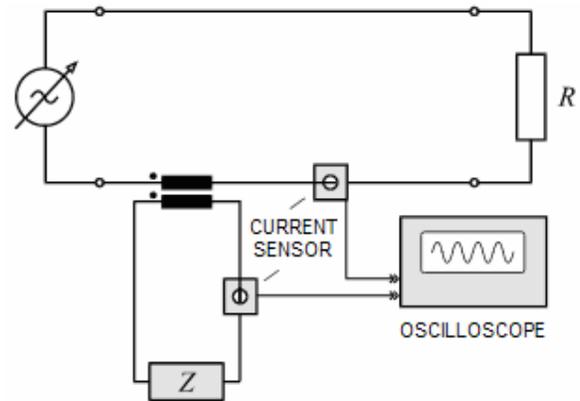


Fig. 4 - Diagram for realization of experimental tests

Defining the nominal current for the tests as 5 A, the tests were performed on the rated current of 10% and 100%. The tests were performed applying a purely 60 Hz sinusoidal signal, in order to validate the proposed error, sampling error and composite error. Similar tests were performed by other researchers following the standards (comparison of two CT, one with nanocrystalline alloy core and another with FeSi alloy core) [8].

3. RESULTS

Sampling errors for CT with FeSi and nanocrystalline alloy core under test to 100% of rated current are presented in Fig. 5 and 6.

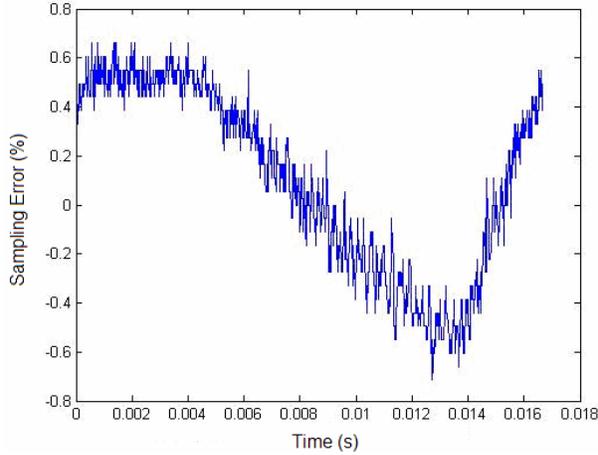


Fig. 5 – Sampling error of the CT core FeSi under 100% of rated

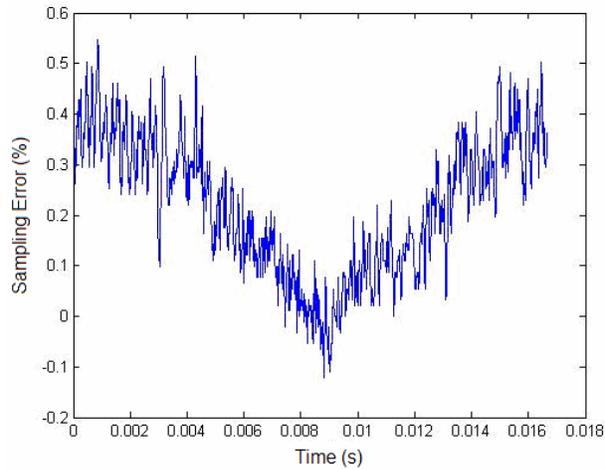


Fig. 6 – Sampling error of the CT core nanocrystalline alloy under 100% of rated

Composite errors obtained from (4) are presented in Table 2.

Table 2. Composite errors of the CT under test

Material	10% I_n	100% I_n
Nanocrystalline Alloy	0.5815%	0.2363%
FeSi - GO	1.2046%	0.3552%

It is possible to observe that the CT composite errors with nanocrystalline alloys core are smaller than the errors for the CT with FeSi GO alloys core. This is because the magnetic permeability of nanocrystalline alloy is higher than the FeSi alloy.

4. CONCLUSION

From experimental results, it can be observed that the TC with nanocrystalline alloy toroidal core presents lower values of phase angle (phase error) when compared with CT with the toroidal core of FeSi, used with the same rated characteristics, which confirms the presented in analytical study.

Through the current signal digitalization using digital instruments and adopting the sampling error and composite error concepts is possible evaluate measurement error imposed by CT, either in sinusoidal regime or in non-sinusoidal regime. This is important, because nowadays, due the presence of harmonics in the electrical systems, the majority of the measurement CT does not operates in sinusoidal regime. Based on these characteristics, additional studies become important for know the influence of harmonic contents level in the CT errors.

Thus, the main contribution of this paper is to compare results that can be purchased for new experiments, especially in evaluations with non-sinusoidal excitation.

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