Phase error in current transformers with nanocrystalline alloys core

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*Abstract-*Based on the electromagnetic properties of nanocrystalline alloys, such as high relative magnetic permeability, low coercive force and low hysteresis losses, in this paper are presented some considerations about the application of these materials in toroidal cores used as current transformers. Also, are discussed how the ferromagnetic core characteristics affect the current transformer performance. From the experimental results, it can be concluded that the use of nanocrystalline alloys in the current transformer cores can contribute to the reduction of phase errors, improving thus the accuracy class.

Keywords: current transformer, nanocrystalline alloys, toroidal cores.

I. Introduction

Current transformer (CT) is a transformer designed and assembled to be used in measurement, control, and protection circuits. Its primary winding consists of a few turns, sometimes even a single bar, and it is connected in series with the circuit whose electrical current is desired to be measured. The secondary winding is connected to the current-measuring instruments.

In CT cores conception, normally are employed grain oriented (GO) silicon-iron, wrapped in a toroidal shape. Nowadays with the development of new magnetic materials, several studies are been conducted to provide the feasibility of the use of these materials in the design of new current transformers. Among these new magnetic materials it is to highlight the use of nanocrystalline alloys.

The interest in nanocrystalline alloys in CT cores is based on their magnetic characteristics, e.g., high relative magnetic permeability, low coercive force, and low losses [1]-[3]. The grain size reduction to the nanometer scale is the key to the characteristics of magnetically soft nanocrystalline alloys [4].

The core material magnetic 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 CT functioning within a desired accuracy class limits.

This paper presents comparative analytical and experimental studies about the applications of four ferromagnetic materials in the toroidal CT: three nanocrystalline alloys (whose trade names are: N3E1, N3E2 e N3E3) and the steel grain oriented silicon. These studies aim to examine the influence of magnetic core material in relation to the angle phase error.

II. Analitical and experimental studies

A. Analitical studies

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_L), 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. Thus, the values of the exciting current decrease results in the reduction of the phase angle error.

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 Figure 1, where Z_s is the secondary impedance.
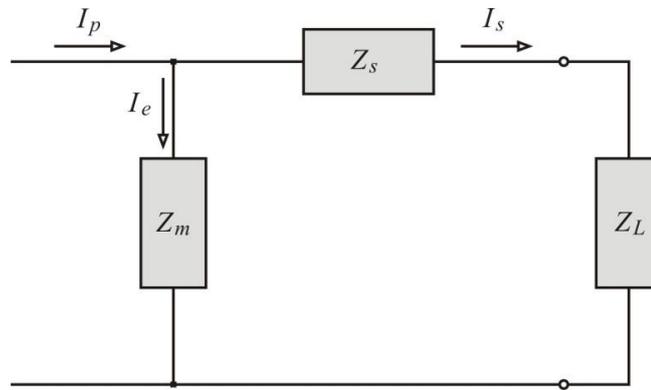
Figure 1. Equivalent electric circuit of a current transformer

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 [5].

It is apparent from Figure 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.

$$\beta = \frac{\left|\vec{I}_0\right|}{\left|\vec{I}_1\right|} . \cos(\theta + \varphi) \qquad (1)$$
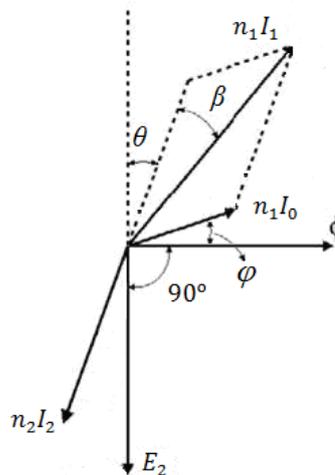

Figure 2. Phasor diagram of a current transformer

In this Figure 2, Φ is the magnetizing flux and I_0 is the exciting current, I_1 is the primary current. In the secondary circuit: E_2 is the induced electromotive force and I_2 is the secondary current. In addition, n_1 and n_2 are the number of turns of the primary and secondary windings, respectively.

In turn, the secondary current of a CT is extremely dependent on its primary current, and it is not influenced by the impedance of the element connected to the secondary terminals of the CT. However, if this impedance exceeds some limit values, determined by the maximum power with which the accuracy class of the CT was obtained, the errors can be much greater than those obtained with the tests.

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.

$$\varepsilon = \frac{K_r . I_2 - \left|\vec{I}_1\right|}{\left|\vec{I}_1\right|} . 100\% \qquad (2)$$

B. Experimental tests

To verify the influence of the magnetic permeability in the phase error, several experiments were performed using different CT ferromagnetic cores.

The toroidal cores that were used in the current transformers are based on commercial nanocrystalline alloys with trade names: N3E1, N3E2, N3E3 and the Fe-3,2%Si GO core. The dimensions of the nanocrystalline alloys core are: inner diameter = 25 mm, outer diameter = 40 mm and height = 15 mm. The core dimensions of FeSi are: internal diameter = 33 mm, outer diameter = 48 mm and height = 15 mm.

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

- Current in the primary: 100 mA
- Current in the secondary: 100 mA
- Number of primary turns: 150
- Number of secondary turns: 150
- Conductor cross area (primary and secondary windings): 0.13 mm^2 (26 AWG wire);

Figure 3. Prototypes of current transformers

The four materials characteristics used in the current transformers magnetic cores under study are presented in Table I, i.e., the nanocrystalline alloys and the steel grain oriented silicon.

Table 1: Comparative data of magnetic materials under study

Core alloy	B_s (T) 60 Hz	$\mu_{r\,max}$
FeSi	1.75	30950
Nanocrystalline alloy N3E1	1.03	39500
Nanocrystalline alloy N3E2	0.9	100000
Nanocrystalline alloy N3E3	1.04	147000

Experimental tests were performed at the Laboratory of Instrumentation and Scientific Metrology, Federal University of Campina Grande, Brazil. The standard technique used as reference is NBR-6821 [6]. The circuit used for the experiments is shown in the diagram in Figure 4.
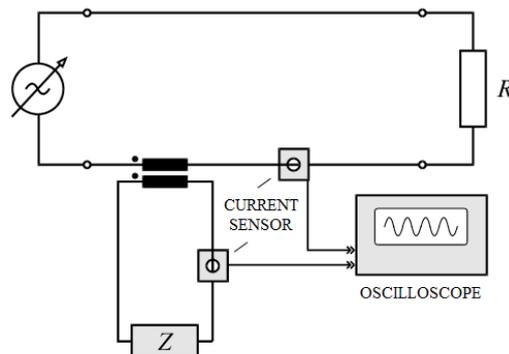

Figure 4. Diagram for realization of experimental tests

III. Results

In comparative tests, were determined the phase angles error of the CT under study, and the obtained results are presented in Table 2. In Figure 5 is shown a photograph of the experimental setup.

Table 2: Comparative phase angles error of the current transformers under study

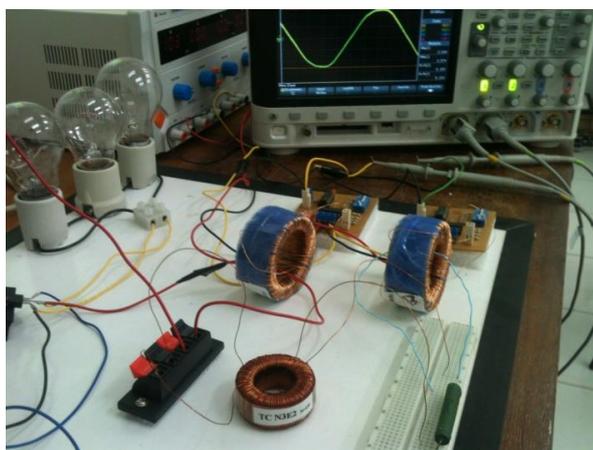| Core alloy	Phase Angles Error
FeSi	57.48'
Nanocrystalline alloy N3E1	30.69'
Nanocrystalline alloy N3E2	8.87'
Nanocrystalline alloy N3E3	3.83'

Figure 5. Photograph of the Experimental Setup

It can be observed from Tables 1 and 2 that when the magnetic permeability of alloys under study increases, the phase error decreases. The results variations found between the nanocrystalline alloys cores are caused by the different chemical composition of nanocrystalline alloys.

IV. Conclusions

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

The better performance of CT with nanocrystalline toroidal core alloy is due to the high magnetic permeability of nanocrystalline alloy, that is superior than the FeSi GO magnetic alloy permeability. The higher magnetic permeability results in the reduction of the magnetizing current and core loss values. The nanocrystalline alloy N3E3 presented a lower phase error among the nanocrystalline alloys under study, and it is due to its high magnetic permeability.

Acknowledgements

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