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Real time compensation algorithm for air-gapped current transformers saturation effects

F.A. Pereira*, F.C.F. Guerra, B.A. Sousa, E.N.A. Santos, N.S.D. Brito, U.A. Carmo

Federal University of Campina Grande (UFCG) – Brazil, Post-Graduate Program in Electrical Engineering – PPgEE – COPELE, Brazil

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ABSTRACT

A platform implemented with digital signal controllers (DSCs) developed for real time studies of the dynamic behavior of the air-gapped current transformers (CTs) used in power grid protection and measurement systems is presented. The implemented algorithms simulate the fault current in an electric power system as well as the transient response of the current transformer. A method for correcting the CT secondary current distortion is presented in the case of gapped core where residual flux is negligible. To estimate the flux, a tertiary winding must be available. The ratio and phase errors, as well as the distortions in secondary current due the core saturation in fault situations are properly corrected by the method. Several cases were tested and the results indicate that the proposed method is very effective in improving the performance of protection schemes based on the current measurement.

1. Introduction

The fault currents in electric power systems present a sinusoidal component plus a dc decaying component. The first produces a sinusoidal magnetic flux in the current transformer (CT) core. The second produces an initially increasing flux which may lead to a high saturation level in the core. This may cause severe distortions in the secondary current supplied to protective relays. As consequences, some problems may arise [1]:

1. Relays can operate inadequately;
2. Relays may not be sensitive to the distortions that reduce the root-mean-square value of the secondary current;
3. Relay operation may be delayed, for the reason cited in the previous item;
4. Fault locators may not show the correct indication.

Those occurrences can cause thermal and electrodynamics damages, loss of coordination in the protection relays, difficulty of location of the faulted point and loss of system stability. Thus, it is necessary to develop techniques that provide the best accuracy in the secondary current estimation. This task has been accomplished by several methods and mathematical tools used in the area of digital signal processing, applicable to the field of power system protection.

The initial works about the mitigation of the distortions in secondary currents considered the problem by means of hardware [2,3]. With the development of microprocessors, numerical techniques for detection of the CT core saturation and correction of the secondary current waveform were developed. Conrad and Oeding [4] is the first reference about this matter. The authors proposed a method in which the magnetic flux is obtained by numerical integration of the secondary current. In addition, a function that describes the hysteresis loops in the iron core is used to obtain the excitation current. So, the correction is performed adding this current to the distorted secondary current.

The described method in [5] would work for gapped CTs. In [6], the distortion is detected by analyzing the secondary current using an algorithm that evaluates the first, second and third difference functions. The first difference contains points of inflection, which correspond to the start and end of each saturation period. The second and third differences convert the discontinuities at the points of inflection into pulses that can be used to detect saturation. For gapped CTs, the described method is not effective due to the smooth transition feature of the magnetization curve between the unsaturated and saturated regime. So, the third order difference functions provide pulses whose amplitudes do not differ so significantly in the transition between the CT operating regimes, making the saturation detection more difficult. The same problem occurs in [7]. In general, [5,7] could work for gapped CTs. However, the estimation of the initial flux and the detection of the start and end of saturation

* Corresponding author at: Rua João Batista Neves, 239, Santa Cruz, Campina Grande, PB 58417-070, Brazil. Tel.: +55 83988804450.
E-mail addresses: fagner.pereira@ee.ufcg.edu.br, fagnereng@gmail.com (F.A. Pereira).

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period would be unreliable. As we will see, the difference between these methods and the proposed in this work is the way of determining the initial flux: in [5,7], the initial flux is estimated from considerations related to the periodicity of the flux waveform. In this work, the initial flux is measured from the voltage integration in the tertiary winding.

The discrete wavelet transform was proposed by [8] to detect the CT saturation, in conjunction with a regression technique designed to correct the secondary current wave. Methodologies based on least squares curve fitting were presented by [9–11]. Despite the refined mathematical treatment, these methods impose an intense burden of computation to the relay. A simple method to reconstruct the primary current waveform is suggested in [12]. However, the accuracy might degrade if the primary fault current contains harmonics and noise.

Techniques based on artificial neural networks (ANNs) for detection and correction were proposed by [13–15]. These methods might require a substantial amount of network training.

The technique adopted in this work is the numerical correction of the distorted secondary current based on the estimation of the excitation current value, which, when added to the distorted secondary current, gives the value of the reflected primary current in the secondary winding. In conventional methods, using iron-cored CTs, the distorted secondary current is integrated to obtain the flux linkage imposed by the primary current. This flux is added to the residual flux and then, by using a model characterizing the magnetic core of the CT, the excitation current is estimated. So, the knowledge of the residual flux value in the core, CT load characteristics and secondary winding impedance, which in practice are not easy to be obtained with accuracy, are needed in this approach. In the proposed method, the flux linkage is obtained by integrating the voltage on a tertiary winding, typically available. Thus, knowledge of the secondary winding impedance is not necessary. Further, with a gapped core, the value of the residual flux can be ignored. Thus, the excitation current is determined directly by using the saturation curve of the core and added to the distorted secondary current to obtain an accurate reproduction of the primary current waveform.

In Section 2, the mathematical modeling of air-gapped CTs is presented. The proposed method is described in Section 3. The hardware platform for real time simulation of an electrical system used as a model to validate the proposed method is shown in Section 4. The hardware and software set of the correction platform is described in Section 5. Finally, in Section 6, analysis of the results from the real time implementation of the proposed method and its applicability are performed.

2. Current transformer model

A way to improve the transient performance of CT is to insert air gaps in the magnetic core to reduce the residual flux, as shown in the characteristics *B*–*H* (induction versus magnetic field) of Fig. 1.

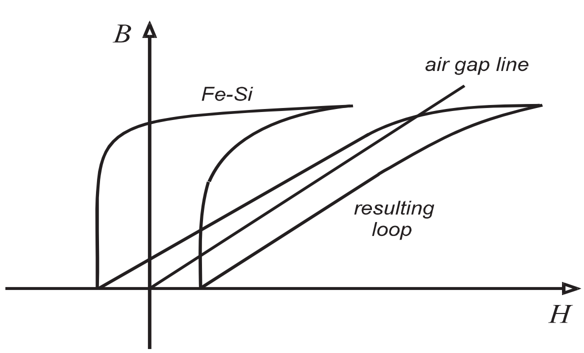

Fig. 1. Air gap effect in magnetic core of iron–silicon alloy (Fe–Si).

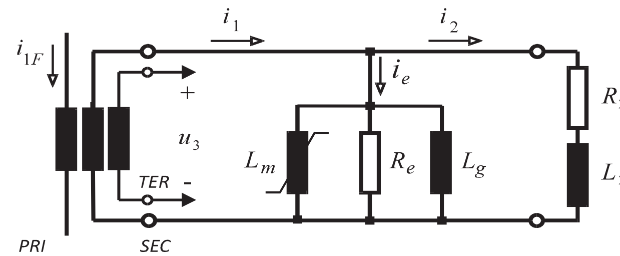

Fig. 2. The current transformer equivalent circuit.

This is an advantage compared to conventional CTs, because the *B*–*H* characteristic becomes close to a singular curve; so, this characteristic simplifies its mathematical modeling. In this approach, in algorithms based on excitation current estimation, it is unnecessary the determination of the residual flux.

Other advantages of inserting air gaps in magnetic cores are [16]: reduction of the CT secondary time constant, which implies a reduction of the core cross section area (smaller physical size) to the same operating conditions compared to the closed core CTs; less influence of load power factor in CT performance in transient regime and a lower voltage appearing at the secondary terminals when they are open. The disadvantages of air-gapped CTs are: increasing in excitation current, causing greater ratio and phase errors. Moreover, they are more costly.

The CT equivalent electric circuit is shown in Fig. 2. A third winding (tertiary), made of a thin wire is used to provide the voltage u_3 that will be integrated for determination of the magnetic flux in the CT core.

Fig. 2 shows the total resistance and inductance of the wiring and burden (R_2, L_2), as well as the nonlinear magnetizing inductance of the iron core (L_m), the linear inductance of the gap (L_g) and the resistance R_e related to the dynamic iron core losses.

In this figure, i_{1F} is the primary fault current, i_1 is the primary current reflected to the secondary, i_e is the excitation current, i_2 is the secondary current and u_3 is the induced voltage in the tertiary winding. The magnetic core properties are represented by the expression (1) below, where λ is the flux linkage in the secondary winding and $\sigma = 1/R_e$ is the electric conductance related to the dynamic iron core losses.

$$i_e(t) = f[\lambda(t)] + \sigma \frac{d\lambda(t)}{dt}. \quad (1)$$

The function $f[\lambda(t)]$ describes the CT saturation curve, represented by the points corresponding to the vertices of several hysteresis loops at 60 Hz, for different peak values of the flux. The parameter σ is calculated from magnetic total losses in 60 Hz of typical grain-oriented silicon–iron alloys manufactured in Brazil.

For the circuit of Fig. 2, where N_2 and N_3 are the number of turns in the secondary and tertiary windings, respectively, it follows that:

$$\lambda(t) = \lambda(t_0) + \frac{N_2}{N_3} \int_0^t u_3(t)dt. \quad (2)$$

$$i_e(t) = f[\lambda(t)] + \sigma \frac{N_2}{N_3} u_3(t). \quad (3)$$

$$i_1(t) = i_e(t) + i_2(t). \quad (4)$$

The term $\lambda(t_0)$ of (2) is the residual flux in the magnetic core, λ_R, plus the initial secondary flux linkage λ_0. The residual flux is reduced to a negligible value by the air gap (CT class TPZ). However, λ_0 cannot be neglected because small increases of λ cause large increases in i_e when the core saturates.