Behaviour of Current Transformers (CT's) under severe saturation conditions

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Abstract - **Modern protective systems require a faithful reproduction of primary short circuit current. Often, specially in high power installations, an important part of the current, during a few cycles at least, is the d.c. component, which causes severe saturation conditions, if the current transformer is not correctly selected and employed.**

Prediction of the behaviour of these devices during the first 20-40 ms, when d.c. component is higher, becomes a must.

Many models have been presented to simulate current transformers, but only some of them are well suited for transient conditions. This paper presents a comparison between predicted results, from accepted models, and real conditions ones, from high power laboratory tests. Significative differences, that tend to disappear with time, have been found in certain cases.

Keywords: Current transformer, saturation.

1. INTRODUCTION

It is important to be able to determine the behaviour of a CT within a certain range of accuracy when it is applied a primary current which contains a d.c. component that may cause its saturation, since this will allow to predict the behaviour of related equipment, such as that aimed at protecting power electric systems, which due to this situation might make an incorrect operation within the period involved.

This paper shows the theoretical and experimental results obtained from typical CT's, emphasising on the first cycles of the transient event, and states some considerations on their applicability.

2. EQUIVALENT CIRCUIT OF A CURRENT TRANSFORMER.

Fig. 1 shows the typical equivalent circuit of a transformer.

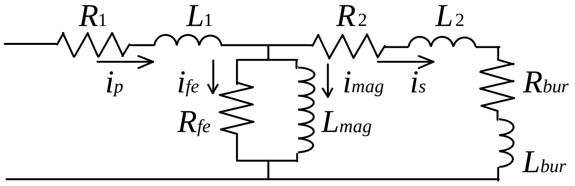

Fig. 1. Equivalent circuit of a transformer.

R_1, L_1 : primary leakage impedance.
R_2, L_2 : secondary leakage impedance.
R_{bur}, L_{bur} : burden impedance.
R_{fe}, L_{mag} : derivation branch.
i_p : primary current.
i_s : secondary current.
i_{fe} : current derived by the branch representing the core losses.
i_{mag} : current derived by the magnetising branch.

As usual, all magnitudes must be referred to one side of the transformer. In this work they are considered as referred to the secondary side.

2-1. Considerations on the equivalent circuit.

In order to incorporate the hysteresis loop into the suggested model, two alternative ways can be taken. On one hand, considering the iron core losses (by means of a variable resistance R_{fe}) separately from the magnetising current (by means of a variable inductance L_{mag}). On the other hand, introducing the iron core losses into the magnetising branch and considering the hysteresis loop dynamics in this branch. The latter has been chosen to perform the analysis hereby presented, since in this way the possibility to introduce the models which predict the hysteresis loop dynamics in the CT core during the transient situation is more straightforward ([1],[2],[3],[4],[5] or [6]).

According to usual considerations for these cases, it is assumed that $R_2 = constant$, and since the primary leakage impedance does not affect the behaviour of the CT, the following simplified equivalent circuit is obtained:

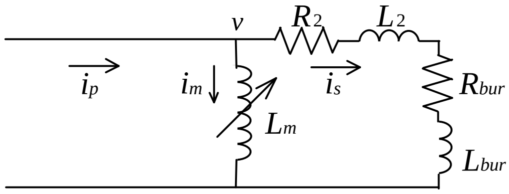

Fig. 2. Simplified equivalent circuit of the a current transformer.

2-2. Mathematical model representing the equivalent circuit of the CT.

Fig. 2, shows that the primary current is the sum of two components:

$$i_p = i_m + i_s \quad (1)$$

Based on [7] and considering that the path taken by flux l as a function of current i_m is available (by means of a test performed on the secondary side of the CT), and stating a linear trajectory between the points used as data, it is possible to posit (2).

$$i_{m_{new}} - i_{m_{data}} = \frac{1}{P}(l_{new} - l_{data}) \quad (2)$$

In equation (2) the subscript *data* is assigned to i_m and l values, which correspond to the start of the linear segment of the current-flux curve in which the simulation calculus is situated and *P* is the slope of such segment, which changes when flux value l exceeds either limit of such segment. Subscript *new* refers the values obtained at present simulation time (*t*).

$$i_{m_{new}} = \frac{1}{P} l_{new} + K_m \quad (3)$$

For which

$$K_m = -\frac{1}{P} l_{data} + i_{m_{data}}$$

Combining the secondary impedance of the CT with the burden we get:

$$R_s + j\,w\,L_s = (R_2 + R_{bur}) + j\,(w\,L_2 + w\,L_{bur}) \quad (4)$$

Taking into account the aforementioned, voltage *v* shown in Fig. 2, will be (5)

$$v = R_s\,i_s + L_s\frac{\partial i_s}{\partial t} \quad (5)$$

furthermore:

$$v = \frac{\partial l}{\partial t} \quad (6)$$

where $l = N f$, is the total linked flux, N being the number of turns and f the equivalent flux per turn, hence:

$$\frac{\partial l}{\partial t} = R_s\,i_s + L_s\frac{\partial i_s}{\partial t} \quad (7)$$

by approximating the derivatives by means of a difference quotient, where subscripts *new* and *old* refer to the values at the present time step (*t*) and the preceding time step $(t - \Delta t)$, (8) is obtained .

$$\frac{(l_{new} - l_{old})}{\Delta t} = R_s\frac{(i_{s_{new}} + i_{s_{old}})}{2} + L_s\frac{(i_{s_{new}} - i_{s_{old}})}{\Delta t} \quad (8)$$

from which we get (9) in which J_s is a constant value throughout simulation, and $h_{s_{old}}$ is a history variable, (where history variable is the one whose value for simulation corresponds to time step $t - \Delta t$).

$$i_{s_{new}} = J_s\,l_{new} + h_{s_{old}} \quad (9)$$

$$J_s = \frac{1}{\left(\frac{R_s\,\Delta t}{2} + L_s\right)}$$

$$h_{s_{old}} = -J_s\,l_{old} - d_s\,i_{s_{old}} \quad (10)$$

where d_s is another constant:

$$d_s = J_s\left(\frac{R_s\,\Delta t}{2} - L_s\right)$$

Considering the equations developed so far and relating (1), (3) and (9):

$$i_{p_{new}} = i_{m_{new}} + i_{s_{new}}$$

by substituting terms it is possible to relate the flux value to the primary current, which is data:

$$l_{new} = \frac{i_{p_{new}} - K_m - h_{s_{old}}}{\frac{1}{P} + J_s} \quad (11)$$

With the result from (11) and substituting in (9), secondary current $i_{s_{new}}$ is obtained. Once these values are obtained, variable h_s is updated, so that these variables are considered as old values for the next simulation time step. Thus, with calculated values l_{new} and $i_{s_{new}}$ the value of $h_{s_{new}}$ is obtained, which will be the $h_{s_{old}}$ for the next simulation step.

$$h_{s_{new}} = - J_s \; l_{new} - d_s \, i_{s_{new}}$$

Considering the aforementioned, variable K_m will be modified when slope P changes its value.

This algorithm permits a fast solution for the representation of a CT; it can therefore be used in real time applications to obtain the current signals to feed protection relays in order to analyse their behaviour.

3. MEASUREMENTS ON THE CURRENT TRANSFORMER.

The necessary data to be introduced in the mathematical model have been obtained from two CT's and they are:

Transformer 1:

Ratio: 400/5
Accuracy class: 10P
Rated burden: 10 VA
R_2 (secondary winding resistance): 0.187 Ω.
R_{bur} (burden resistance connected to secondary winding): 0.34 Ω
L_{bur} (burden inductance connected to secondary winding): $\rightarrow 0$.

Transformer 2:

Ratio: 1000/5
Accuracy class: 0.5
Rated burden: 30 VA
R_2 (secondary winding resistance): 0.183 Ω.
R_{bur} (burden resistance connected to secondary winding): 1.6 Ω
L_{bur} (burden inductance connected to secondary winding): $\rightarrow 0$.

3-1. Obtaining the hysteresis loop feeding the CT through the secondary winding.

The CT's have been fed from the secondary side, with the primary side open circuited. By integrating the voltage across secondary terminals, and considering the value of R_2, we get:

$$l = v_{\text{int}} - \int_0^t i_m R_2 \, dt$$

or:

$$l = \int_0^t (v_{\sec} - i_m R_2) \, dt$$

in both equations current i_m is the measured current, while v_{int} is the integral of the voltage in connection terminals $v_{\sec}$.

The curves obtained are those in Figs. 3 and 4, which show that for these transformers the hysteresis loop area is negligible for the current amounts involved.

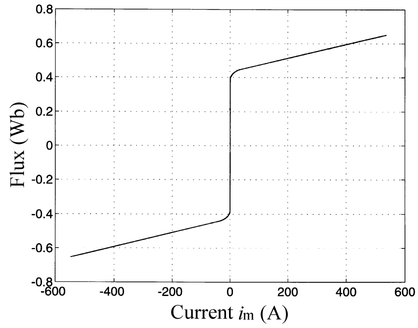

Fig. 3: Flux-current curve of transformer 1.

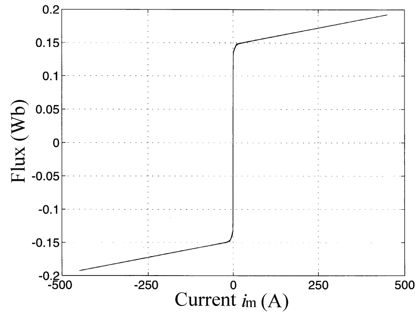

Fig. 4: Flux-current curve of transformer 2.

Fig. 5 shows the hysteresis loop obtained from another test performed on transformer 1, with current values about 100 times lower than those in Fig. 3.

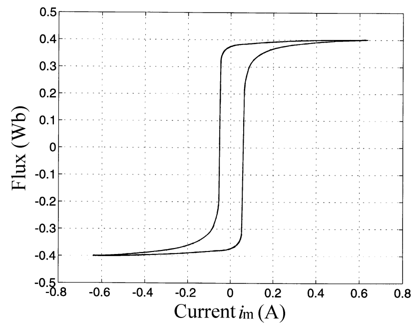

Fig. 5: Flux-current curve of transformer 1, low current applied.

Considering that the current and flux values involved in the test performed on the transformers are around the values shown in Figs. 3 and 4, the data to be used will be those shown in these figures. Therefore, we need not consider a model which predicts the flux path taking into account the hysteresis loop area.

4. RESULTS OBTAINED.

The currents applied to the primary sides of transformers 1 and 2, are respectively those shown in Figs. 6 and 7. The values of the secondary currents, measured and calculated by the methodology developed above are presented in Figs. 8 and 9.

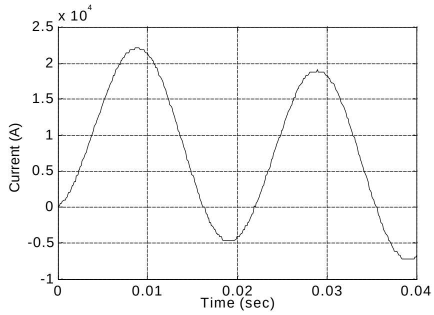

Fig. 6. Primary current measured in the test (CT 1).

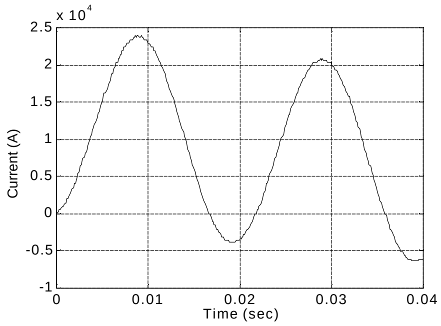

Fig. 7. Primary current measured in the test (CT 2).

It is observed from Figs. 8 and 9 that there are differences between measured and calculated values.

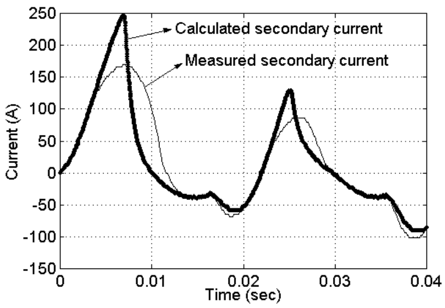

Fig. 8. Secondary current measured and calculated in CT 1.

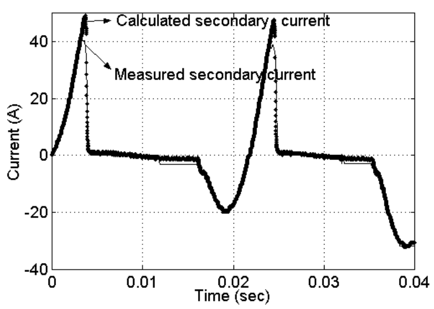

Fig. 9. Secondary current measured and calculated in CT 2.

In order to determine the effect produced by considering a constant value for inductance L_2, we have included in the model of transformer 1 a leakage reactance equal to 0.1 Ω at 50 Hz, (a much higher value than expected in this machine), and so obtaining the results shown in Fig. 10, appreciably similar to those in Fig. 8:

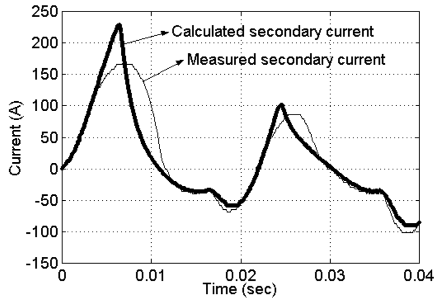

Fig. 10. CT 1 considering a leakage reactance of 0.1 Ω to 50 Hz

The differences between measured and calculated currents (Fig. 8) are attributed to the fact that in saturation conditions the leakage reactance does not have a constant value (usually negligible), as is generally considered in this type of CT model, but it adopts different values in function of the saturation degree. The methodology usually employed (item 3-1) to obtain the flux-current graphics (Figs. 3 and 4) does not consider the separation between the leakage flux and the flux that must be entered as data in the magnetising branch of the CT model (Fig. 2), which provides another source of error to the calculated values.

When leakage flux is negligible measured and calculated values tend to be similar, as shown in Fig. 9.

5. CONCLUSIONS.

From the analysis performed, and taking into account the considerations stated in 2-1, it is observed (Figs. 8, 9 and 10) that the values obtained by simulation sligthtly differ from the actual values in the cycles where magnetic saturation is more important. As follows from Fig. 10, a constant value for the leakage reactance, do not improve dramatically simulation results.

The differences between simulated and measured values are attributed to the fact that the leakage reactance value has not been considered as a variable, since the leaked flux varies taking different values in function of the core saturation degree. On the other hand, flux measurement (item 3-1), takes into account the value of such reactance.

In order to obtain a degree of approximation higher than the actual values, the leakage reactance variation pattern should be known throughout the development of simulation, and the leaked flux should be separated from the one introduced as data in the model by means of the curves shown in Figs. 3 and 4.

It is noteworthy that in those current transformers which in saturation conditions have a low flux leakage, the values obtained by this type of simulations, with the considerations stated above, will be closer to the actual values.

From the aforementioned, it must be taken into account that when a CT represented with a model as that of Fig. 2, is submitted to severe saturation conditions, failure to consider leakage flux variations can give rise to differences between the calculated and measured secondary currents at the first stage of the transient (Fig. 8), which may lead to error in the results of the simulations, and to wrong conclusions when these results are intended to determine the behaviour of the protection relays.

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