A new method to evaluate residual flux thanks to leakage flux. Application to a transformer

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Abstract —**This paper presents a new method to estimate the residual flux in the magnetic circuit of a transformer. The methodology is based on the measure of the magnetic field induced by the leakage flux around a single-phase transformer with adequate fluxgate sensors. The purpose of this paper is to present a new method to estimate the residual flux which are key data allowing determining the ideal closing time for the re-energization of a transformer.**

Index Terms—**Magnetic flux leakage, magnetic field measurement, remanence, transformers.**

I. INTRODUCTION

During the re-energization of unloaded power transformers, undesirable effects (inrush currents, overvoltages, …) can appear and may cause many problems in power system, mainly to the transformers. The determination of residual flux allows us to calculate the best closing time for the re-energization of a power transformer. The systems of controlled switching applied to transformers are used for reducing the magnitude of the inrush currents [1]. However, the determination of the residual flux isn't accurate. Indeed, the measurement of the residual flux is uncertain due to low voltage signal including DC component and noise. Furthermore the influence of system transients near transformer on the residual flux has been recently underlined [2]. This paper proposes a new method to calculate the residual flux from near magnetic field measurements. Part II presents the link between the leakage flux measured near a transformer and the residual flux in the magnetic circuit. Part III explains the new method for estimating the residual flux.

II. LINK BETWEEN THE LEAKAGE FLUX MEASURED NEAR A TRANSFORMER AND RESIDUAL FLUX OF A MAGNETIC CIRCUIT

A single-phase transformer (400V/4V, 32 kVA, 2 limbs) is chosen for this study. Some magnetic sensors are placed outside the magnetic circuit of the transformer (without tank). In Fig. 1, a schematic view of the transformer and some of the sensors positions are exposed. The measurement range of the sensor (fluxgate) is ±100 µT and the bandwidth is DC up to 3 kHz. For each sensors, the component of the magnetic field, tangential to the magnetic circuit is taken into account.
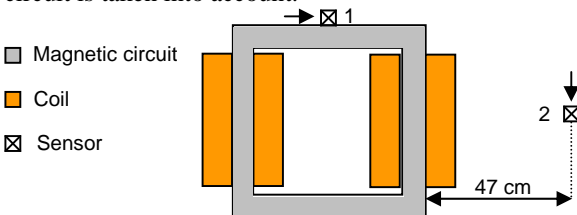

Fig. 1. Schematic view of the device

A. The leakage flux measured near a transformer

The test system consists in re-energizing an unloaded transformer. In a precedent paper [3], we realized some finite element calculations that proved the existence of a leakage flux around the transformer when it is off line. The leakage flux is measured by sensors. The electric measurements done, including the current in the primary winding allows to prove that the residual flux has changed during the test measurements, the graph will be exposed in the final paper.

B. Distinction of residual flux thanks to the leakage flux

When the transformer is unloaded at nominal voltage (400 V_{RMS}), the measured field by a sensor is the sum of the magnetic fields induced from: magnetic circuit leakage, coil field and the Earth's magnetic field. The main issue is to extract the field created by the magnetic circuit leakage from the total field. In order to extract this field, an algorithm has been developed. For zero current values, the field induced by the coil is zero, at these instants, the total induction measured by a sensor is interpolated. An example of this method is presented on the Fig. 2 and Fig. 3.

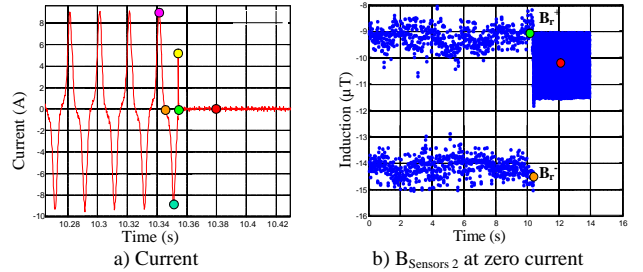a) Current   b) $B_{Sensors\ 2}$ at zero current

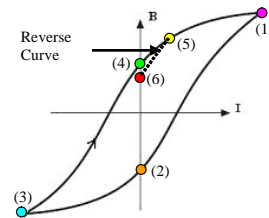Fig. 2. Current measured and induction interpolated during test

Fig. 3. Schematic view of a curve B(I)

The curve B(I), Fig. 3, has not a conventional rotation sense, because it is not the induction measured inside the magnetic material but an induction measure in the area. We will explain these measurements thanks to numerical field computations. In Fig. 3, two steps corresponding respectively to the points: B_r^+ (point (4) or green) and B_r^- (point (2) or orange) (Fig. 2.b). When the de-energization occurs, the current goes to a maximum negative value

(point (3) or blue on the Fig. 2.a) and then realizes a short incursion in the positive part (point (5) or yellow). Then, the residual flux takes a value between B_r^+ and B_r^- (point (6) or red) following what is classically called a *"reverse curve"*. The current measurement is noisy, by consequence the determination of the induction at zero current is difficult (especially the determination of the red point on Fig. 2.b). Recent developments have improved this determination and will be presented in the final paper. The final value of the induction is -10 µT. The ambient induction value measured is near -12 µT (mean value between the green and orange points). The residual flux creates on this sensor a field of +2 µT. We succeed in characterising the different field effects and we isolate the residual flux effect thanks to one field measurement.

III. METHODS TO EVALUATE RESIDUAL FLUX IN A TRANSFORMER

There are several ways to calculate the residual flux. Nowadays, the most used method is the voltage integration; however, it can present many uncertainties regarding with voltage measurement quality. Another method consists in using the *"maximal current"* value, the principle is to calculate the residual flux from inrush current obtained when the transformer is re-energized [4]. This method is unappropriate for industrial applications, because we will know the value of the residual flux only after the re-energization of the transformer. On the other hand, it is an excellent method to check the value of residual flux.

A. A new method to estimate the residual flux

The method proposed consists in estimating the residual flux from a magnetic field measurement sensor (fluxgate). In order to do this, two steps must to be respected.

The first step is to establish the transfer function between induction and flux when the transformer is at its nominal voltage in steady state. The induction is measured by magnetic field sensor and the flux is obtained from the voltage integration, measured on the secondary winding of the transformer. Once we have these parameters (flux and induction) it is necessary to obtain the two values of the flux, and of the induction, when the current is zero. After that, it is necessary to do the subtraction of each pair of values (flux and induction), with this operation we will obtain delta flux ($\Delta\Phi$) and delta induction (ΔB), the division between ($\Delta\Phi$) and (ΔB) is the transfer function.

The second step is to measure the induction when the transformer is off line. With this signal, we will obtain a new value, delta residual induction (ΔB_r). In order to do this, it is necessary to do the subtraction between the induction and the mean value of induction, measured when the transformer is off line and on line, respectively. This new value (ΔB_r) matches the residual flux in the transformer. Finally, to get the residual flux ($\Delta\Phi_r$), we simply multiply the residual induction by the transfer function. This equation is shown hereafter (1) and it will be illustrated in the final paper.

$$\Delta\phi_r = \Delta B_r \times \frac{\Delta\phi}{\Delta B} \qquad (1)$$

B. Application with a sensor on the magnetic circuit

In this part, we present the results obtained for the single-phase transformer chosen. It is necessary to remember that the magnetic field sensor (sensor 1) is located on the magnetic circuit. The results are expressed in percentage of the nominal flux in the transformer (1.8 Wb). The results shown in the table 1 represent the results for the residual fluxes calculated for a sequence of eight energizations.

Before Energization	Maximal Current Method (%)	Voltage Integration Method (%)	New Method (%)
1	-18	-18	-18
2	-18	-15	-13
3	17	19	26
4	-18	-18	-17
5	8	15	8
6	17	18	18
7	17	20	16
8	-18	-16	-27

TABLE 1: RESIDUAL FLUX CALCULATED BY DIFFERENT METHODS

The new method is consistent with the maximal current method in five of eight cases of energization. The new method presents wrong results regarding with integration voltage method for the cases 2, 3 and 8. The reason for this is the noise present in the current measurement by consequence the determination of the transfer function is difficult. On the other hand, the new method is more performing than voltage integration method for the case number five. The reason for this is that the new method takes into account all possible changes of the residual flux, because the delta residual induction (ΔB_r) is obtained in real-time just before the energization of the transformer.

IV. CONCLUSION

In this paper, a new method to estimate the residual flux in the magnetic circuit of a transformer is presented. Magnetic field measurements are done near the transformer with magnetic field sensors. We do the calculation of the residual flux value by isolating the magnetic field induced by the leakage flux. The new method of residual flux calculation gives coherent results and its major advantage is that it takes into account all possible changes of the residual flux, however, it can presents inaccurate results regarding with current measurement quality. Concluding, this method is straightforward and presents a good agreement with the existing methods.

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