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Measurement of the leakage flux in the vicinity of a transformer core

Application to detection and localization of faults

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Abstract

Purpose – This study presents a new method for the detection of faults in large transformer cores. It is based on the analysis of leakage flux components in the vicinity of the sheet stack. The purpose of this study is to provide a nondestructive analysis tool for transformer cores during the assembly process to detect accidental defects such as inter-laminar short circuits.

Design/methodology/approach – The different components of the leakage flux allow localization of the fault in the stack and also permit to assess its severity. Out of the many kinds of defects which may appear in a transformer core, this method only detects those which actually cause an increase in the transformer's global iron losses, which are thus the most detrimental.

Findings – The proposed method allows a more efficient control of the quality of the cores during their manufacturing process. Until now, it was only possible to know the quality of the core when the transformer was fully assembled.

Research limitations/implications – The accuracy of the method depends on the size of the defect and may request many measurements to give usable information.

Practical implications – Controlling iron losses in a core during its construction avoids heavy dismantling operations, both financially and temporally.

Originality/value – This method can help transformer manufacturers optimize their building process. In addition, the method remains effective regardless of the size of the core considered.

Keywords Nondestructive testing, Electromagnetic fields, Transformers, Fault analysis, Iron losses, Leakage field

Paper type Research paper

1. Introduction

The transformer steel industry produces grain-oriented steel sheet with high efficiency whose properties are generally controlled by standardized measurements on an Epstein frame (EIC, 1996). The actual losses measured on the magnetic core are always higher than calculated by multiplying the core mass by the specific loss of the sheets given by the steel

manufacturer. This discrepancy is described by the so-called building factor, which is an empirical parameter taking into account different phenomena (Girgis *et al.*, 1998; Bielawski *et al.*, 2012; Anderson *et al.*, 2014a; Anderson *et al.*, 2014b). The occurrence of short circuits between sheets is one important component, which degrades the overall performance of a core (Aimoniotis and Moses, 1993; te Nyenhuis *et al.*, 2001; Moses and Aimoniotis, 1989; Beckley *et al.*, 1998). The insulating material separating the sheets is a very hard ceramic and consequently, short circuits in the interior of the core are rare. In fact, short circuits arise generally on the edges of the column or yoke (Schulz *et al.*, 2010b; Roger and Duchesne, 2012). They can be due to cutting burrs or accidental deformations caused by handling of the core elements. This study proposes a new method for the detection of accidental inter-laminar shorts by measuring the leakage flux in the vicinity of a transformer core. This is a very fast and adjustable way, which can be implemented on the core production line (Hamzehbahmani *et al.*, 2015). The method is presented in Section 2 to give the whole steps of the detection procedure. In Section 3, the experimental setup is detailed and two kinds of shorts are introduced. Section 4 will be devoted to the presentation of the results, and Section 5 will start a discussion on the physical interpretation of the given results.

2. Method

A schematic representation of a part of a transformer core is given in Figure 1. The core is made of a large number of thin magnetic sheets stacked in y -direction. Without any inter-laminar short circuits, the flux density inside the column is in x -direction and the leakage flux near the cutting edges of the magnetic sheets is also in x -direction, the z -component of the field is very low. When current flows in y -direction in inter-laminar short circuits, it creates a perturbation of the leakage flux in its vicinity. The detection principle consists in measuring the z -component of the leakage field near the cutting edges of the magnetic sheets. For measurements, the core is magnetized at low flux density and at an elevated frequency. With such a choice, the deviation of the eddy currents inside the sheets caused by the fault becomes more pronounced, which enables detecting the fault through the normal field component. The approach proposed here is macroscopic and considers currents flowing through the entire sheet section as would be the case for non-oriented grain sheets (Zirka *et al.*, 2008). In grain-oriented sheets, the phenomena are more complex and involve currents rotating in different magnetic domains. Nevertheless, this approach allows the

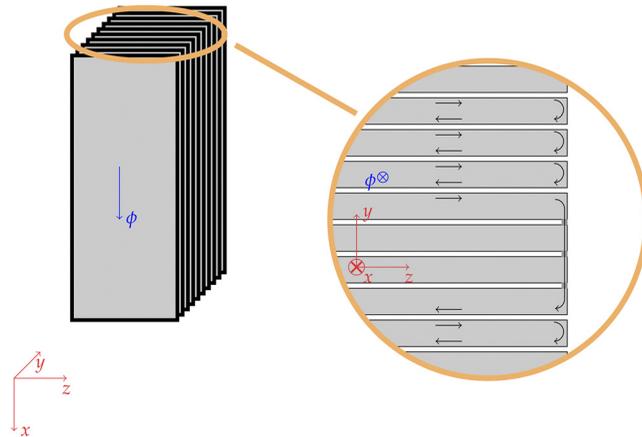


Figure 1.
Part of a transformer core leg

method to be highlighted in a qualitative way. A more quantitative approach, in particular, for the choice of the excitation frequency, will require more detailed attention to the specificities of grain-oriented sheets.

3. Experimental setup

To test the detection method, it is applied to a model transformer core featuring artificially introduced inter-laminar shorts. An elementary magnetic core, of square form, was built from Epstein strips. A view of the main parts of the experimental setup is presented in [Figure 2](#), showing the model transformer built horizontally and the robot with field probe mounted. The magnetic joints are interleaved at 90° . Each transformer leg consists of 208 grain-oriented Epstein strips with an individual cross section of 30×0.30 mm, thus resulting in an overall cross section of 30 mm width and 64.4 mm height. Excitation of the core is provided by a 400-turn coil placed on the leg opposite to the one under test. To strongly accentuate eddy currents, the excitation frequency was chosen at 4 kHz. Considering a relative permeability $\mu_r = 50,000$ and a conductivity $\sigma = 2.10^6 \text{ Sm}^{-1}$, this frequency corresponds to a skin depth $\delta = 25 \mu\text{m}$, as given by $\delta = \sqrt{\frac{2}{\sigma\mu_r\omega}}$.

As a first approximation, we can estimate that the skin depth is thus in the order of one-tenth of the sheet thickness. At such elevated frequency, relatively weak excitation levels are sufficient to obtain short-circuit currents strong enough to be detected. A global induction level of 25 mT has been chosen. This quantity is measured by means of a one-turn coil wound around the core. The normal component of the magnetic field near the leg under test is measured using a commercial field probe optimized for magnetic imaging applications (Micromagnetics STJ-020). This probe is mounted on a six-axis industrial robot (Denso VS-6577G), to allow precise positioning and automated recording of a field map along the sheet

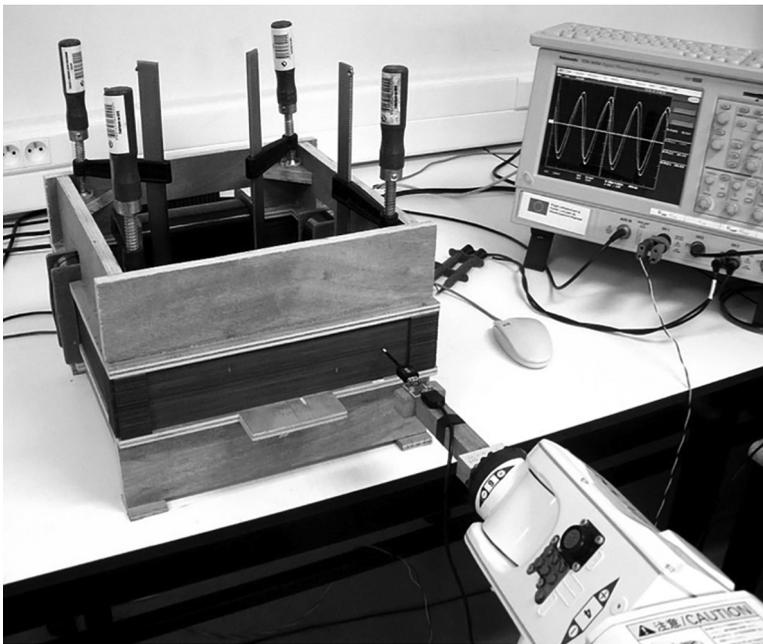


Figure 2.

View of the main part of the experimental setup showing model transformer, the industrial robot with field probe and signals acquired

stack. For each probe position, an oscilloscope is used to acquire, at the same time, the amplified probe signal and the global flux density waveform over two periods. A custom MATLAB application is used to synchronize probe positioning and signal acquisition. The measurement of the global flux density waveform in addition to the probe signal makes possible the exploitation of the phase of the signal with respect to the main flux.

Artificial faults have been created on the leg under test in form of vertical scratches over several laminations. These have been provoked by touching the stack gently with a small rotating disk made of weakly abrasive material. Rather than removing any material, this technique locally smears the sheets' edges, resulting in a realistic scratch as it could be caused by bumping the core during production. These faults are indicated in [Figure 3](#), showing their positions on the front side of the leg under test and the boundaries of the area scanned. The first fault, located top left in the area shown, has a counterpart on the backside on the leg: an identical scratch has been introduced at the same position on the other side of the leg. The second fault is located in the lower right of the sheet stack and has no counterpart on the backside. The faults have a length of 6 mm, thus affecting approximately 20 sheets.

4. Results

A complete field map for the normal component has been recorded at 2 mm distance from the core; it is presented in [Figure 4](#). The scanning resolution is likewise 2 mm in x - and y -direction. One can observe that fault no. 1 clearly causes a disturbance in the B_n component. Regarding in the first instance the amplitude, the presence of fault $n^{\circ}1$ leads to a slight increase on the right side of the fault; while on the left side, no influence is visible. Remarkably, the increase caused on the right side of the fault spreads over a considerable length and is still discernible at several centimeters distance from the fault. Regarding the

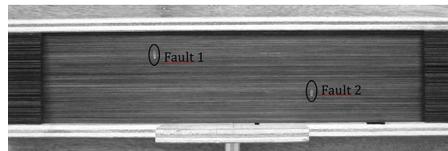


Figure 3. Picture of leg under test with artificial faults indicated

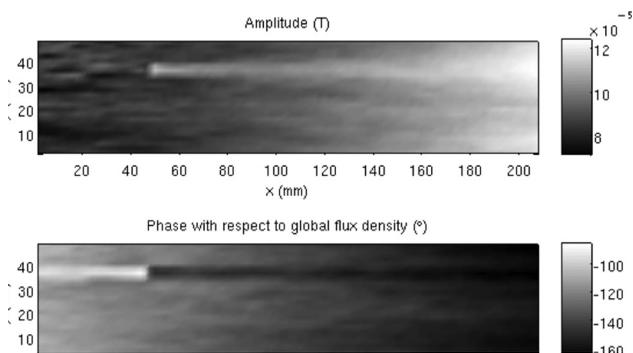


Figure 4. Distribution of B_n at 2 mm from the faulty transformer leg

phase, one can observe an even stronger influence of the fault. The position of the short circuit is marked by a clear phase change in B_n .

The disturbance seems to affect a number of sheets almost over the whole length of the transformer leg. There is no homogenization of the field map, even within considerable distance from the fault. This phenomenon clearly merits further discussion, as it opens interesting perspectives for simplified detection. On the other hand, fault no. 2 having no counterpart on the backside of the stack is not visible at all. The absence of any disturbance caused by fault no. 2 is in agreement with other studies, e.g. study by [Aimoniotis and Moses \(1993\)](#). Inter-laminar shorts on one side only of a stack are inoffensive for transformer operation, as they do not offer a closed electric path perpendicular to the magnetization vector, and thus, do not entail additional eddy currents.

5. Interpretation

It has been observed that the perturbation of the normal component is not strictly limited to the vicinity of the short circuit, but is also visible at a considerable distance from the fault. Evidently, the field emitted by the short-circuit current itself decreases very fast with increasing distance. It is thus safe to assume that the perturbation of B_n , measured at a considerable distance from the fault is not directly emitted by the short-circuit current, but is rather emitted by the sheets. A satisfactory explanation for this field component emitted by the sheets would require an exhaustive theoretic analysis, which is beyond the scope of a feasibility study. However, a general explanation can be offered for the fact that the perturbation caused by the short circuit spreads over a considerable length.

5.1 “Confinement” effect

The perturbation observed in B_n is certainly related to inhomogeneity of the main flux, as it propagates in direction of the main flux. The short circuit evidently causes a local decrease of the main flux density through its opposing field. This perturbation does not disappear within a short distance from the short circuit by flux exchange with neighboring sheets, but rather stays confined to the package of sheets containing the short circuit, and thus affects these sheets on a considerable length. This means that there is almost no exchange of flux between the sheets in vertical (y) direction. The explanation for this behavior can be found in the high excitation frequency of 4 kHz. Any exchange of flux between sheets in vertical direction leads to planar eddy currents. At normal operating frequency of 50 or 60 Hz, planar eddy currents can already cause considerable loss, which constitutes a problem, e.g. in single-step lap joints with uneven shift lengths ([Pfützner et al., 1994](#)). At 4 kHz, planar eddy currents associated with vertical flux exchange would be enormous. As a consequence, flux exchange between different layers of sheets does not constitute a good option anymore with respect to global energy minimization. Instead, the flux in each layer of the transformer leg stays largely independent of the neighboring layers, resulting in the confinement effect that was observed. The effect is particularly advantageous for the localization procedure. If the excitation frequency is chosen sufficiently high, inter-laminar shorts present in one layer of sheets will cause an inhomogeneity in the phase which is visible on the whole length of the transformer leg. This layer can thus be identified by scanning a single line in y -direction.

5.2 Sensitivity of the method

As the field inhomogeneity detected is directly due to the short-circuit current, the latter is the key quantity defining the method’s sensitivity. The short-circuit current depends on not only the frequency and the induction level but also the cross-section short-circuited. The model transformer used in the experiments has a width of 3 cm only, which is very narrow

compared to the core widths found in power transformers. To compensate the narrow core width, the artificial faults provoked on the model transformer had thus to be spread over 20 laminations to provoke a short-circuit current strong enough to allow detection. It is thus safe to assume that, if applied to a core of realistic width, the proposed method is much more sensitive and thus even capable to detect much smaller short circuits spreading over very few laminations only. Measurements show that short-circuit currents increase approximately proportionally to the core width (Schulz *et al.*, 2010a), promising high gains of sensitivity for larger cores. The demonstration has been made at low flux density; with a higher excitation it will be possible to detect smaller scratches. The main limit of the method is the precision of the robot, which defines the minimum distance between the sensor and the edge of the sheets.

6. Conclusions

The feasibility of short-circuit detection through leakage flux analysis has been demonstrated. Recording the normal component near a sheet stack magnetized at low amplitude and high frequency permits to clearly detect and localize inter-laminar shorts. Detection is most distinct by interpreting the phase of the normal component with respect to the main flux. The perturbation of the normal component observed even at a considerable distance of the short circuit is not easily explained and requires further analysis. However, this phenomenon opens interesting perspectives for simplified detection procedures. A single scan in the vertical direction can be sufficient to detect a layer of sheets, which is affected by inter-laminar shorts. The demonstration of the feasibility of inter-laminar short-circuits detection opens the way to further studies. The next step will be the correlation between the severities of the scratches with the additional core losses in accordance with the sheets behavior.

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