MAGNETOSTRICTION DISTRIBUTION IN A MODEL TRANSFORMER CORE

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The primary aim of this work is to study the distribution of magnetostriction-caused strain in different regions of a model transformer core. A technique of measuring the peak-to-peak strain ε with a high number of well averaging strain-gauges is presented. The results indicate very high variations of ε. In rolling direction, limbs and yokes show values of ε below 1 ppm, close to catalogue values of magnetostriction (MS). Corners exhibit values up to 2.5 ppm, probably with strong contributions of magnetostatic forces. T-joints show values up to 3 ppm due to high MS as being typical for rotational magnetization apart from contributions from forces. Generally, much lower values were found for the transverse direction. As a main conclusion, a major contribution for vibrations can be expected for the axial direction of yokes.

Keywords: magnetostriction, core vibration, transformer noise, magnetostatic forces

1 INTRODUCTION

Recent attempts to improve transformer cores are not restricted to lower loss but also are focussed on lower noise. The increasing energy demand brings transformers closer to the population which makes the noise problem more and more important. Generally, it is accepted that transformer noise results from two basic contributions:

(i) core noise from the magnetization of the core, and
(ii) winding noise from forces due to load currents.

The present study was restricted to strain of the core as a primary source of vibrations which finally result in core noise. One of the sources of strain is given by magneto-static forces as closer discussed in [1]. However, for a well-clamped core, the more important source may be given by strain resulting from magnetostriction (MS). The magnitude of the magnetostrictive strain depends on the type of material, the applied magnetic field, the type of the magnetization, i.e. alternating magnetization (AM) or rotational magnetization (RM) of an axis ratio $a = B_{TD} / B_{RD}$ (with B_{TD} the induction peak value in transverse direction and B_{RD} in rolling direction, respectively).

This paper reports measurements of strain in RD and TD in different regions of a 3-phase model transformer core. A distinction between four major regions (limbs, yokes, corners and T-joint) was made, and a comparison between them was performed. The interpretation of results was based on simulations of magnetostriction by means of a rotational single sheet tester (RSST; [2]). The problem for 50Hz magnetization is that, both strain components, from magnetostriction and forces have their basic components at 100Hz thus making their separation difficult or even impossible.

2 EXPERIMENTAL

Experiments were accomplished on a 3-limb model transformer core magnetized with 1.7 T (50 Hz). According to Fig. 1, core size was 1 m × 1 m with window dimensions of 0.6 m × 0.2 m. The lamination width was 200 mm. The core was stacked from 56 layers of conventional grain oriented SiFe-sheets (CGO, 30M5).

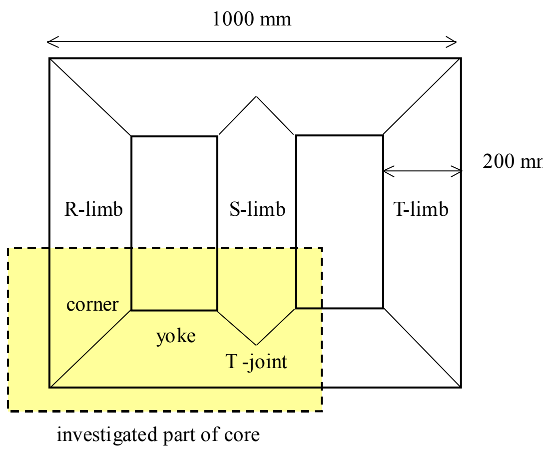

Fig. 1. Investigated model transformer core assembled from grain oriented SiFe

An option for strain measurements would be the application of laser interference sensors [3, 4]. However, earlier experience has shown that more stable results can be obtained from strain gauges provided that an average is obtained over the large grains of the core material. Considering a grain sizes close to 10 mm, 64 mm long

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gauges were used in the present work. 20 gauges were placed in different important regions of the core surface as illustrated by Fig. 2; twelve gauges in RD, eight in TD. For temperature compensation, a dummy-gauge was placed in loose contact on top of each measurement-gauge enclosed into a quarter bridge circuit.

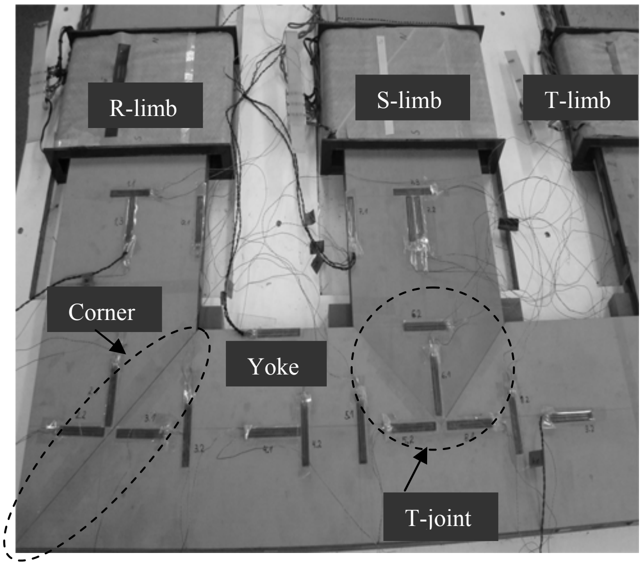

Fig. 2. Arrangement of 20 strain gauges placed in the rolling and transverse direction in different regions of the model core.

For a full description, the time waveform $\varepsilon(t)$ of strain would be relevant. But as a major problem, magnetostriction of modern core steel involves very low values - much below 1 ppm - for alternating magnetization in RD which yields very low signal to noise ratios. As a compromise, the present study was restricted to the peak-to-peak value ε_{pp} of strain. For each gauge, a harmonic signal analysis was performed. The spectral lines for 100 Hz, 200 Hz and 300 Hz were determined and applied for the determination of ε_{pp}. Since this synthetic procedure could not consider the angles of phase, the resulting value ε_{pp} represents an approximation. Finally, an average was taken from ten consecutive measurements.

3 RESULTS

Figure 3 shows a typical result of measurement for the harmonic content of strain ε_{RD} in RD in the middle S-limb. The three main spectral lines are given after mathematical elimination of noise. The spectrum indicates significant intensity of the 2nd and the 3rd harmonic. It can be assumed to have high relevance for effects of audible noise if we consider physiological characteristics of the human ear, compare [5].

Figure 4 shows the local distribution of peak-to-peak values for the total of 20 strain gauges for 1.7 T. In the limbs, $\varepsilon_{pp,RD}$ proves to be between 0.5 and 0.8 ppm which is consistent with magnetostriction catalogue data for 30M5 steel and also consistent with simulation performed on the RSST (Rotational Single Sheet Tester). $\varepsilon_{pp,TD}$ is close to 0.5 ppm.

This rather high value indicates very low $\varepsilon_{pp,ND}$ for the normal direction, if we assume zero volume MS. As a conclusion, strain of the limbs seems to be restricted to magnetostriction as resulting from alternating magnetization.

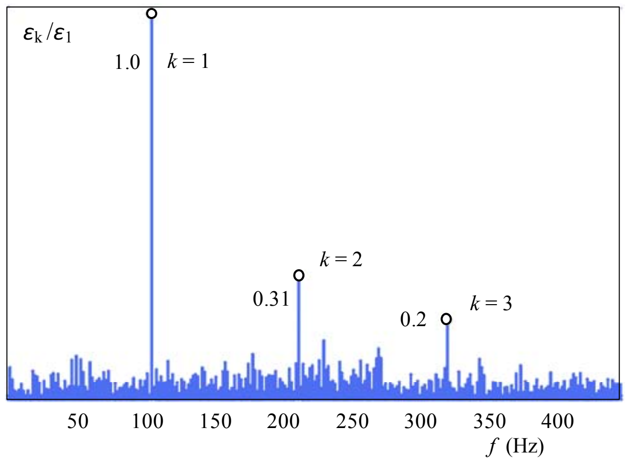

Fig 3. Typical example of an amplitude spectrum of ε_{RD} in the T-joint region for 1.7 T. The spectral lines of 100, 200 and 300 Hz components are given in filtered state, related to the 1st harmonic.

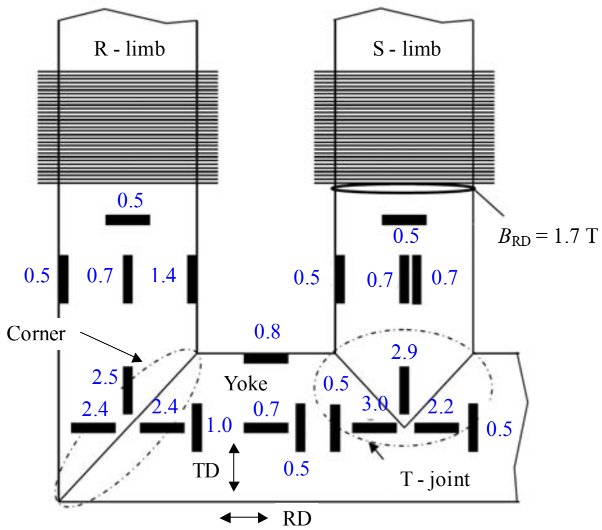

Fig. 4. Measured peak-to-peak values εpp,RD and εpp,TD of local strain in RD or TD, respectively in ppm

Compared to limbs, the yoke shows slightly higher values which can be attributed to weak rotational magnetization (*a* up to 0.1). On the other hand, the corner exhibits very high strain close to 2.5 ppm in both RD and TD. This cannot be explained by effects of magnetostriction. Rather, distinct magneto-static forces are given between the laminations of limb and yoke. According to earlier work [1], attractive forces are not restricted to the lamination area. But inter-laminar off-plane flux close to air gaps will exist as well, as a source of local, cyclic bending of lamination ends.

Finally, highest strain values $\varepsilon_{pp,RD}$ up to 3 ppm were found in the T-joint. This coincides with the tendency of values *a* up to 0.3 for this region. As demonstrated by RSST measurements [2], rotational magnetization (RM) may yield drastically increased MS compared to alternating magnetization (AM). However, in analogy to corners, it can be assumed that some contribution of forces is given also here.

4 DISCUSSION

As closer discussed in [1, 6], strain components due to forces depend on many parameters which cannot be modelled in effective ways. As a general rule, force effects tend to be over-estimated by model core experiments due to insufficient clamping. On the other hand, effects of magnetostriction (MS) can be modelled in a better way, according to the following.

MS-caused strain of modern core material is mainly determined by the volume portion ρ of oblique domains, i.e. domains oriented in [010] or [100] in about 45° to the sheet plane. For alternating magnetization as arising in the limbs, increasing induction B in RD yields an increased number of lancet structures which include a small tunnel-like oblique domain. Rising ρ reduces the volume portion of moments in [001] (close to the RD). Due to positive saturation magnetostriction of SiFe, this yields a weak shrinking of material in RD. It is reflected by small values $\varepsilon_{pp,RD}$ close to 0.5 ppm as measured in limbs.

For rotational magnetization (RM) as arising in the T-joints, a high amount of oblique domains is needed to carry flux in TD in large intervals of the period. In principle, this flux transfer is taken over by tunnel-like domains which merge to a plate-like oblique domains corresponding to high values of ρ. On the other hand, ρ is small in instants when induction is given in RD. The high change of ρ as arising during the period explains that $\varepsilon_{pp,RD}$ may rise to the order of 2 ppm, or even more, for a = 0,3.

For practice, it should be considered that RM is restricted to the rather small T-joint regions. However, large strain $\varepsilon_{pp,RD}$ seems to arise also in the corners. This means that maximum global strain should result for the axial direction of yokes. Maxima of strain from magnetostriction due to RM and from forces will not arise at identical instants of time. However, a restricted summing-up effect can be expected, apart from the fact that the course of time $\varepsilon(t)$ will show distinct distortions.

The above considerations mean that it is difficult to transfer the results of the present model core study to full-size cores of industrial relevance. It will be the task of further experiments to attain a more effective separation of effects due to forces and magnetostriction, respectively.

5 CONCLUSIONS

As a main conclusion, the results of this study indicate low strain values in limbs, due to mere magnetostriction which is weak for alternating magnetization. All other regions - including limb ends - exhibit distinctly increased strain values which partly can be attributed to rotational magnetization (RM; in T-joints and yokes) and partly to forces (in corners and T-joints). In all cases, the main direction of strain is given in RD. Maximum strain values arise close to overlaps, in agreement to the finding that maximum vibrations - as detected by accelerometers - are given in this region [1]. As a summing-up effect, maximum over-all strain can be expected for the axial direction of the yokes.

The involved effects of forces can be assumed to depend on many constructional factors. On the other hand side, the effects of magnetostriction can be interpreted on the basis of periodical changes of the volume concentration of domains which are magnetized in oblique directions, *ie* out of the plane of material.

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