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Spatial distributions of magnetostriction, displacements and noise generation of model transformer cores

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ABSTRACT

Recently, the relevance of audible noise of power transformers tends to increase due to the growing environmental awareness. For sound assessment, two standardised methods reveal the global noise of the whole system, as resulting from the interaction of core, windings, oil and tank. But for a deeper understanding of noise generation, it would be advantageous to investigate also the individual roles of the single above components in closer ways. This paper summarizes attempts to study the first component, i.e. the soft magnetic core, by means of model cores. For the first time, we analysed local distributions of all three strain, displacement and audible noise, keeping in mind that these quantities depend on many parameters like material, stacking, clamping, induction, rotational magnetization, or additional DC-bias, in complex ways. In-plane strain proved to be dominated by magnetostriction, with maximum intensities in corners and T-joints. The interpretation of in-plane displacements proves to be complicated by the unknown resting point of the whole system. However, the results reflect contributions of both magnetostriction and magneto-static forces. Out-of plane displacements proved to be dominated by effects of magneto-static forces, in particular at overlaps of corners and T-joints, due to imperfect clamping. Regional measurements of audible noise were performed in the near-field mode by means of automatic scanning by microphone over free core regions within a noise-isolating scanning chamber. As to be expected, the results showed strongly inhomogeneous distributions with maxima at T-joints and corners. As a conclusion, model core results have very restricted relevance for full sized cores in quantitative ways. But they favour an understanding for crucial mechanisms and for core regions that play dominating roles.

1. Introduction

Recently, the relevance of audible noise of power transformers tends to increase due to growing environmental awareness. Nowadays, transformers are located closer to the urban areas. Thus, noise reduction may be more relevant than loss reduction. For the assessment of audible noise of industrial transformers, two standardized methods are generally used, i.e. Sound Pressure Measurement and Sound Intensity Measurement [1,2]. Both reveal the *global* noise of the whole system as resulting from the interaction of core, windings, oil and tank. However, it is evident that a deeper understanding of noise generation needs separate investigations of the roles of the single above components in closer ways.

This paper summarizes studies on the first component, i.e. the core. Apart from the windings, the core can be assumed as a primary source of audible noise [3]. It is well known, that the latter originates from both magnetostriction and magneto-static forces. However, a clear distinction between them is an almost impossible task, since both interact, apart from exhibiting the same spectral components. We assume that a split would need very specific experimental and/or analytical modelling.

As it is well known, the core's audible noise generation is a complex process depending on many parameters like material, stacking, clamping, induction, rotational magnetization, additional DC-bias, etc. Concerning the material, it is known, that compared to non-oriented SiFe, that of grain-oriented (GO[1]) SiFe is lower, due to weaker magnetostriction (MS[2]) as a result of a highly ordered texture. Even better performance can be expected from laser scribed materials (e.g. [4]). The core clamping influences local strains of both MS and magneto-static forces, as closer discussed in [3,5]. Also rotational

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[1] grain-oriented
[2] magnetostriction

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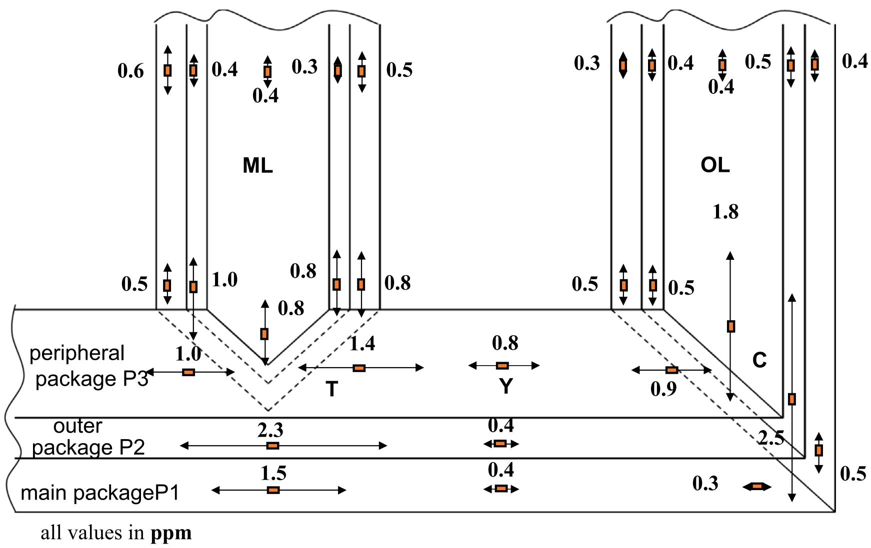

Fig. 1. Local distribution of peak-to-peak strain ε_{RD} in RD in a 3-phase, 3-package model transformer core, stacked from highly grain oriented material, for B_{NOM}=1.7 T. All values are given in ppm.

magnetization has a very significant impact on MS, causing increases up to a factor of 10, compared to mere alternating magnetization (see [6]). Finally, additional DC-bias, caused e.g. by geomagnetically induced currents, leads to general increases of local strains, especially in regions of mere alternating magnetization, audible noise being distinctly enhanced (e.g. [7]).

As already mentioned, most authors consider audible noise for the entirety of a transformer [1,2,8]. Only few ones concentrate on the magnetic core by numerical calculations, in particular of local distributions of core surface displacements, e.g. using FEM techniques [9,10] and by measurements of audible noise in single-phase cores [11] and in three-phase cores [12–14]. Most commonly, the numerical models are restricted to 2D calculations of core packages without considering the impact of the overlaps [10,15]. In [15], a coupled 2D magnetic and mechanical FEM-model for the investigations of the influence of magnetostriction and Maxwell (magneto-static) forces to the dynamic displacement of the inductor is presented. As an important result, the authors found that magnetostriction and Maxwell forces might even interfere destructively for a certain frequency range. In [16], the authors present a model for the prediction of the magnetostriction in several directions. However, the model is validated only for the case of non-oriented silicon steel, having a low relevance for modern transformer cores, stacked from grain oriented materials. In [17], a 3D model is used to calculate the magnetic field distribution and vibrations of a 3-phase transformer core and windings. Subsequently, the noise distribution is calculated based on achieved vibration data. The authors tried to verify the achieved distribution by standardized measurements of the noise at four local positions, 1 m away from the transformer tank.

The acoustic measurements show the high impact of the clamping [11], of the compressive stress [12] as well as of the design of the overlaps on the noise generation [13]. In a rather surprising way, in [12], the authors show that increase of the local noise does not necessary mean increase of the peak-to-peak magnetostriction.

In our own studies, we performed various experimental analyses on different 1-phase and 3-phase model cores. The latter prove to be very effective for basic studies on mechanisms of loss generation. On the other hand, studies on vibrations or even noise are problematical a priori, in particular due to the well known relevance of eigen-values [9,18]. However, keeping the latter in mind, experiences show that experimental modelling may yield basic conclusions, in particular if local investigations are performed in comparative ways.

The main target of the current paper is to summarize our experiences from regional measurements on magnetostriction, displacements and audible noise. A second aim is to discuss basic problems of such measurements, as well as restrictions of practical relevance. All in the work investigated cores were magnetized with sinusoidal excitation with 50 Hz for the practically relevant case of B_{NOM}=1.7 T, measured and controlled in the middle limb.

2. Local distributions of strain

As it is well known, measurements of magnetostriction (MS) are being performed in routine ways for all types of laminated soft magnetic materials as being applied for transformer cores. A material sample is magnetized in a so-called single sheet tester or rotational single sheet tester, and MS-caused strains are detected by means of strain gauges (e.g. [6,19]), or also by interferometers (e.g. [20,21]). The results proved to be affected by many impact factors, as summarized in [6].

In a rather surprising way, literature does not report any study of regional in-situ measurements, as performed directly on transformer cores, neither on core surfaces nor in the core interior. A possible reason may be that such measurements are highly problematical, as revealed by our own attempts of investigations. First, let us report results, then discuss the problems of measurement.

In a series of studies, we arranged strain gauges on the surface – and partly also within the stack – of model transformer cores. Considering the large grain size of modern core steel, we use about 50 mm long sensors for averaging. For temperature compensation, each gauge was placed in a quarter bridge circuit together with a top-on dummy gauge. It is well known, that the sensitivity of the strain gauges is worse than that of interferometers. However, both methods prove to yield quite similar results for transformer core materials and magnetization values above 1.3 T, as demonstrated in [20]. From our experience with measurements of magnetostriction of transformer cores, we found that the sensitivity of the strain gauges is roughly about 0.1 ppm. The main factor, influencing the sensitivity of the gauge is the complex process of fixing it to the core surface.

Fig. 1 shows typical results for a square 3-phase model transformer core with outer dimensions of 750 mm and a stacking height of 57 mm. The core was stacked from three packages of different width and height: main package P1 (width 150 mm, height 30 mm), outer package P2 (110 mm, 11 mm) and peripheral package P3 (100 mm,