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Comprehensive modelling of dynamic hysteresis loops in the rolling and transverse directions for transformer laminations

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ABSTRACT

Magnetic properties of grain-oriented materials are affected by hysteresis, anisotropy and dynamic effects. The attempts to describe dynamic hysteresis loops are usually limited to the rolling direction (RD). On the other hand, modelling of magnetic properties for the transverse direction (TD) is important for numerical analysis of core-joints and corner regions in transformers. For this direction, hysteresis loops reveal complex shapes particularly for dynamic magnetization conditions. This paper presents a comprehensive approach for modelling of dynamic hysteresis loops in RD and TD. This work uses the magnetic viscosity-based approach, which is able to describe irregular widening of dynamic loops. The loss separation scheme is also considered for both principal directions. Variations of loss components with frequency for both directions are discussed. The computed dynamic loops in RD and TD are in a close agreement with experimental ones.

1. Introduction

The magnetic properties of grain-oriented (GO) materials used in transformer laminations are affected by a number of phenomena, such as hysteresis, anisotropy, and eddy currents. The mechanisms underlying the physics of magnetization process are well described in the literature [1–4], yet the macroscopic behaviour of the material is still difficult to model. On the other hand, the development of an accurate model for predicting the gross behaviour of these materials is an important issue for the engineering community in order to design efficient electromagnetic devices [5–7]. Favourable crystallographic properties in the rolling direction (RD) of these materials make them ideal for power transformers and large rotating electrical machines. The properties along the directions other than RD are needed for more realistic field computation at joints/teeth regions [8]. For such an analysis, a precise vector hysteresis model is needed [7].

A number of significant attempts have been reported in the literature to characterize the hysteresis loops for the rolling and transverse (TD) directions [9–11]. One possible approach, based on some concepts from chemical/thermo-dynamical theories [9], has been presented in [10]. The latter paper has proven its usefulness for the description of quasi-static RD and TD magnetization curves. Another promising description which is based on the Jiles–Atherton (JA) approach, proposed recently in [11], has also been used for hysteresis loops in two principal directions. This model can also be used further for modelling of hysteresis loops in arbitrary directions, similarly to the description considered in [12], which uses the correlations of intrinsic RD and TD properties. The JA model can be a suitable candidate for hysteresis modelling due to its relative simplicity and ease in numerical implementation [13]. The original JA model is based on some physical premises concerning irreversible domain wall translation through pinning sites in isotropic materials [2]. Hence most of the existing dynamic JA models are focused on these materials [14–17]. Moreover, such model extensions are commonly based on Bertotti's approach [1], which under certain circumstances may fail to predict arbitrary loop shapes and loss vs. frequency dependencies [18,19]. In GO steels, the dynamic effects related to the existence of classical and excess field strengths [1] may be significant, which makes the analysis more difficult. The dynamic hysteresis loops of these materials may exhibit anomalous shapes [19]. The problem of modelling of dynamic hysteresis in TD is rarely addressed in the literature; this paper is aimed to fill the gap.

This paper presents a modelling approach for dynamic hysteresis loops in RD and TD using a viscosity-based extension of the modified quasi-static JA model which considers the crystallographic features of GO materials in order to predict accurately RD and TD static hysteresis loops [11]. The paper also elaborates loss separation using a three-component approach. A generalized approach based on the magnetic viscosity is used for modeling of excess losses in RD and TD. The approach offers flexibility to

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handle an arbitrary loss versus frequency dependence and to control anomalous loop shapes in both principal directions [20,21]. A magnetic viscosity based modified dynamic JA model has been proposed recently in [21]. Encouraging modelling results have been obtained for RD dynamic loops.

In the present paper, a comprehensive modeling approach for dynamic loops in RD and TD is described using the model. The approach is consistent with the classical theory of loss separation as the value of classical eddy current loss is kept constant disregarding the applied field direction. The hysteresis and excess losses vary with direction, and these loss components can be computed using the modified quasi-static JA model and the magnetic viscosity based approach, respectively. The arbitrary frequency-loss dependence and anomalies in loop shapes are attributed to the excess loss, which can be handled using the viscous approach.

2. Magnetic properties in the rolling and transverse directions

2.1. Measurement of dynamic hysteresis loops and losses

Measurements are carried out on two samples (Hi–B material; grade – 27M-OH) which are cut at angles of 0° and 90° with respect to RD. The thickness of samples is 0.27 mm, the length is 200 mm, and the width is 29.5 mm. The measurements are performed using a standard single sheet tester (Model: BROCKHAUS MPG 200D). Measurements of hysteresis loops and losses are carried out over a frequency range of 1–200 Hz. It is assumed that the effects of classical eddy currents and excess losses on the hysteresis loop can be neglected at 1 Hz. Hence the obtained hysteresis loops and losses at 1 Hz in are assumed to be static quantities. The peak flux densities are set to 1.7 T and 1.3 T for RD and TD, respectively. Measured hysteresis loops of the material for RD and TD at different frequencies are shown in Fig. 1(a) and (b). A lower value is chosen for TD since the curve saturates earlier in this direction as observed in Fig. 1(b).

As evident from the figures, GO steels show highly steep, gooseneck, and narrow waist hysteresis loops in RD and complex shaped curves in TD. Moreover, an irregular widening (as shown by line-L in the figures) in dynamic loops can also be observed for both directions in these materials. The irregular widening of dynamic loops can be attributed to the excess losses.

2.2. Corelosses

The separation of total core loss into three components viz., hysteretic, classic, and excess terms is a common practice for loss description in thin ferromagnetic laminations [22,23]. The total energy losses can be represented as the sum of the static hysteresis loss, the classical loss, and the excess loss using a thin sheet model (TSM). The loss equation for GO laminations can be written as [23]

$$W_{\text{tot}} = W_{\text{hyst}} + W_{\text{class}} + W_{\text{exc}}, \tag{1}$$

where W_{tot} is the total energy loss, W_{hyst} is the static hysteresis loss, and W_{class} and W_{exc} are the classical and excess losses, respectively. The hysteresis loss, W_{hyst}, was measured in a quasi-static field condition at 1 Hz as the dynamic effects are negligible at this frequency. The classical losses can be calculated using the following equation [1]:

$$W_{class} = k_e \int \left(\frac{dB}{dt}\right) dB \quad \text{where } k_e = \frac{d^2}{12\rho}. \tag{2}$$

Here d and ρ are the sheet thickness and resistivity. The classical losses can be calculated using Eq. (2). The parameter k_e (0.013 (m/Ω)) can also be calculated directly and it remains fixed in different directions (RD and TD) at all frequencies since it depends solely on thickness (d=0.27 mm) and resistivity (ρ=4.6 × 10^{-7} Ω m) of the material. The excess energy loss, W_{exc}, is computed as the difference between W_{tot} and the sum of W_{hyst} and W_{class}. These loss components are given in Table 1 for RD and TD for maximum induction of 1.1 T at 50 Hz.

The classical losses are calculated using Eq. (2) derived under the assumption of homogeneous material (devoid of domain structure) and hence it may be assumed that these losses do not vary with the direction of applied field [3]. Only two loss components (hysteresis and excess loss) will change with the direction. The difference in static hysteresis losses in two directions can be explained in terms of the different proportion of 180° and 90° domain walls in TD [3,12]. On the contrary, the excess losses depend on domain wall spacing and types of domain walls (90° and 180° walls) [3,24]. The domain wall spacing varies with crystalline orientation, and hence this anisotropy of the excess loss is not directly related to magnetocrystalline anisotropy [25]. Higher excess losses in TD can also be attributed to 90° wall processes and nucleation [26].

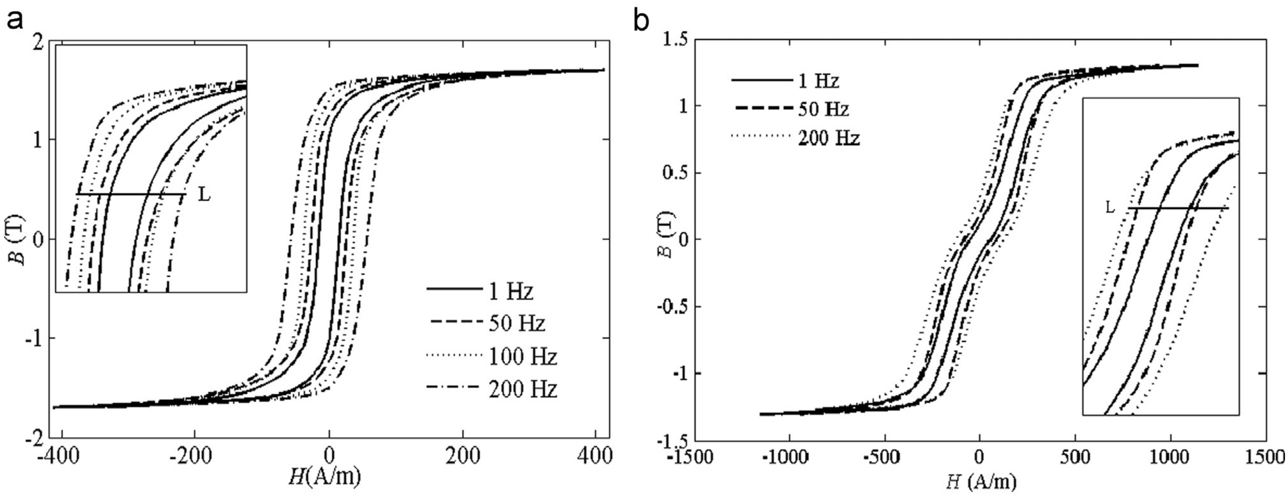

Fig. 1. Measured dynamic loops (Hi–B material, 27M-OH) (a) RD (b) TD.