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Large Power Transformers - Modern Trends in Application, Installation, Operation & Maintenance

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'Modern Trends in Design and Manufacturing Practices of the Core in Power Transformers'

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I. Introduction

The design of the magnetic circuit of a transformer mainly involves analysis of electromagnetic, thermal and acoustic engineering aspects. Advanced numerical computations need to be used for achieving its desired performance attributes, viz. losses, temperature rise and noise. However, in addition to sound design practices, state-of-the-art manufacturing tools and processes are essential to meet the objective [1]. The performance parameters of the core depend on both its material and design. The design of the core-joints and corners has a significant impact on its performance. The core losses are lower in step lap joints. Multi-step joints have been shown to give excellent performance [2]. A precise modeling of the core is always a challenge to its designers and researchers. The core performance is dependent on both its structure and magnetic characteristics. However, the difficulties in the core modeling arise due to its complex structure and material characteristics. Numerical techniques such as Finite Element Method (FEM) can be used for the purpose [1, 3]. Furthermore, a power transformer which operates at a low (power) frequency in a network is sometimes exposed to high frequency transients such as switching and lightening overvoltages. A few diagnostic techniques require an application of wideband frequency signals to the transformer under investigation [4]. Modeling of a transformer, for various ranges of frequencies, inevitably requires accurate representation of its core characteristics. Swept Frequency Response Analysis (SFRA) is a technique which can be used for the core diagnostics. The low frequency region of the frequency response can be used to diagnose the core condition.

This paper discusses recent trends in design and modeling of the magnetic circuit in a power transformer. A 2D FEM analysis with nonlinear, dynamic and hysteretic core characteristics is given in the paper. It is particularly useful for determination of performance characteristics of the core. The analysis is useful in determining local field distributions in joints. An alternative approach for the core modeling is also discussed; it is based on the complex permeability representation of the core characteristics. The approach can be useful for diagnostics purposes while assessing the response of a transformer over a wide frequency range. Effects of various manufacturing processes are also highlighted in the paper. Various quality checks that should be done during the core building process are elaborated.

II. Performance Parameters

No load current: The no-load current is an important parameter that is generally used to assess the condition of the core. It is usually less than 0.5% of the full load current in large power transformers. It depends on the characteristics and design of the core. For a sine wave flux density, the no load current will be distorted due to a nonlinear and hysteretic B-H curve of core materials used in transformers. The level of distortion and corresponding harmonics can be a good indicator of the quality of design and manufacturing practices of the core. The type of core-joints also affects the current magnitude. Since FEM based computations are quite cumbersome, designers usually calculate it using VA/kg versus flux density curves based on test data [1].

Core losses**:** The performance of the core of a transformer is usually assessed by the losses occurring in it. They depend on its design, material characteristics and manufacturing practices. The classical loss theory, which divides the losses into eddy and hysteresis components, generally underestimates them [1]. According to the Bertotti's approach, the losses are divided into static hysteresis loss, classical eddy current loss and anomalous loss [5]. The first two components are well-known; the anomalous losses result from domain wall motion during the magnetization process [6]. The static or DC hysteresis curve widens in the presence of the eddy and anomalous losses as evident in Fig. 1(a).

The core materials also exhibit strong anisotropic magnetic characteristics owing to their crystalline and textured structure. They generally show different magnetic characteristics in different directions. Typical rolling direction (RD) and transverse direction (TD) curves for grain-oriented (GO) laminations are shown in Fig. 1(b). Modeling of these characteristics using a modified Jiles-Atherton (JA) model is reported in [7].

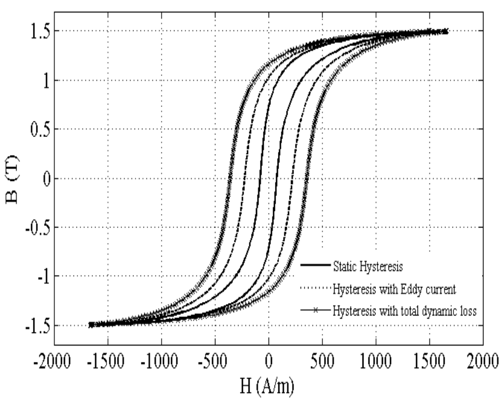


Fig. 1(a) Hysteresis loops

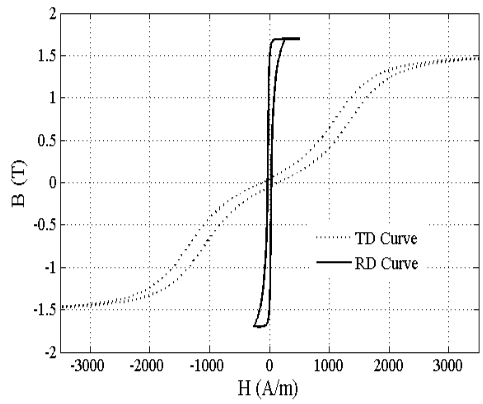


Fig. 1(b) Computed RD and TD hysteresis curves

Additional losses, called rotational core losses, occur in T-joints of the middle limb of a 3-phase 3-limb transformer construction [8, 9] due to rotation of B and H vectors in the plane of the laminations. Due to sequential magnetization of the three-phases, the vectors rotate in these regions. There is time-phase as well as space lag between the two vectors resulting in additional losses. The phenomenon is explained through a field plot in [1].

Core vibrations and noise: The two types of forces which can occur in the core of a transformer are magnetostriction and magnetization forces [10]. The core vibrates due to magnetizing forces that act between laminations and magnetostriction forces that result in changes in dimensions of laminations. The magnetostriction force is usually the main source of the core noise. Usually, the magnetization and magnetostrictive forces are determined using a virtual work approach and a Maxwell stress tensor approach, respectively [1]. The core noise prediction is a complex coupled problem involving four fields, viz. electromagnetic, fluid, structural and acoustic. However, the problem is usually simplified by analyzing the core in open air without the tank and estimating magnetostrictive displacements as a function of flux density using a numerical technique [1].

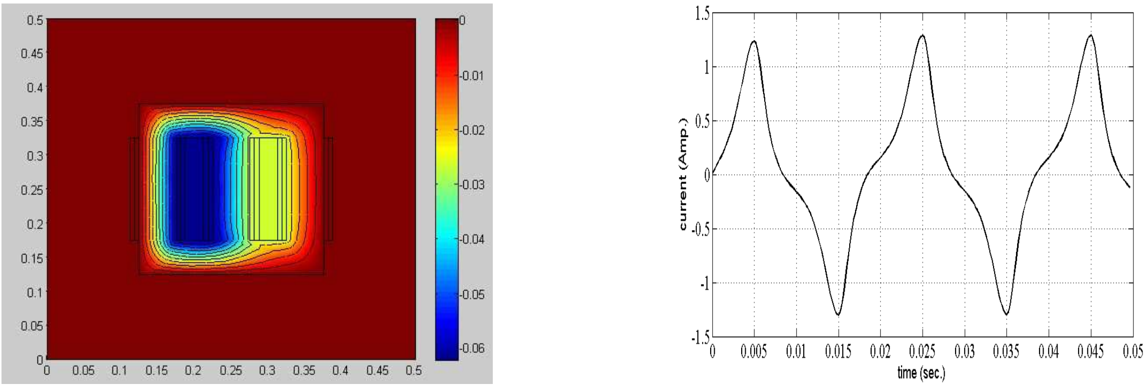
III. Modern Trends in Design, Modeling and Analysis of the Core

A. FEM modeling of the core with consideration of dynamic hysteresis

An accurate prediction of nonlinear, hysteretic, and dynamic core characteristics and their numerical implementation is still a challenging task to researchers. Various hysteresis models have been proposed in literature to characterize the core properties. Among the existing hysteresis models, the Jiles-Atherton (JA) model and the Preisach model are most widely used [11-12]. The Preisach model considers superposition of infinite hysteresis operators with rectangular characteristics corresponding to an assumed assembly of magnetic particles [11]. Although the Preisach model is accurate, its complex mathematical formulation is the main restriction in numerical implementations. On the other hand, the JA model is based on the physical process of magnetization through the domain wall motion with pinning effects [12]. The model can be represented by a first-order differential equation and is amenable to FEM implementation. The static JA hysteresis model is defined in terms of five parameters which can be determined from a measured curve using a hybrid identification technique [13]. The other two losses, the classical eddy current losses and anomalous losses can be taken into account by using dynamic hysteresis curves through the JA model [14]. The model can be coupled with Maxwell's equations and the resulting governing equation in terms of the magnetic vector potential (*A*) is [3, 15],

$$\nabla \times \frac{1}{\mu(B)} \nabla \times A = J \tag{1}$$

where, *J* is the source current density vector and μ is the flux density (*B*) dependent permeability variable. In a time-stepping FEM formulation, the above equation can be solved using a fixed-point iterative algorithm incorporating the dynamic JA model. Using the details of a transformer given in [15], analysis has been carried out for a single phase excitation condition. The field plot is shown in Fig. 2a. The computed no-load current, which accounts for dynamic hysteresis characteristics, is shown in Fig. 2b.



(a) (b)

Fig. 2 FEM analysis (a) Flux lines (b) Computed no-load current

B. Core modeling: Complex permeability approach

The complex permeability approach is basically an alternative way to represent magnetic properties which are usually expressed in terms of permeability and losses. The major advantages of this representation are viz. it is possible to represent the core by a simple equivalent electric circuit, the core losses are expressed as a function of frequency, and the problem becomes effectively linear.

The complex permeability approach can also include the eddy current losses. If hysteresis losses are not considered, the complex permeability can be represented as [1, 4],

$$\overline{\mu}^{eff} = \mu' - j\mu'' = \mu \frac{\tanh(\gamma b)}{\gamma b} \tag{2}$$

where, μ is the permeability of the lamination as measured using an Epstein tester and γ is the propagation constant, and 2*b* is the thickness of laminations. For a built core, the real and imaginary components of the relative complex permeability as a function of frequency are shown in Fig. 3.

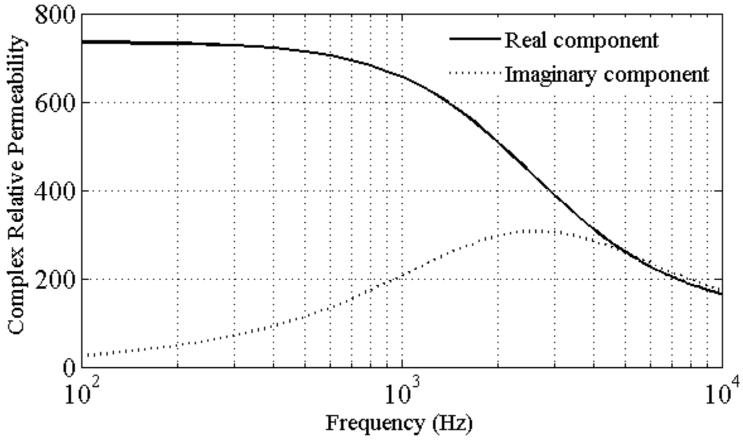


Fig. 3 Real and Imaginary components of complex relative permeability

Effects of the core joints with air gaps can be considered using this effective complex permeability based approach. Anisotropic properties and laminated structure of the core can also be taken into account by introducing its stacking factor [4]. The approach is useful for a correct modeling of the core while analysing frequency response of the transformer.

IV. Effects of Manufacturing Practices on the Core Performance

Core materials are very sensitive to manufacturing processes such as handling, cutting and slitting. They should be handled with care while storing and processing; otherwise elastic and plastic stresses can be induced in them and the losses will be higher [16, 17].

Fig. 4 (a) Improper storage/handling

Fig. 4 (b) A stack of laminations after cutting and slitting

Measured losses in the oval coil shown in Fig. 4 (a) may be about 3-5 % higher than a properly stored coil. Laminations are subjected to cutting and slitting operations (Fig. 4(b)) which produce stresses and burrs. Bending of CRGO steels also produces stresses that can affect magnetic properties. Prevention of stresses, due to either elastic or plastic deformations that might occur while handling CRGO sheets, is essential. The magnitude of clamping pressure has a significant impact on the core performance. Effects of the applied clamping pressure on the losses and sound level of a built core depend on several factors: its magnitude and distribution throughout the core, thickness and flatness of sheets, magnetostrictive strains, design of clamping structure, etc. Insulation layers may get detached during handling resulting in non-insulated surfaces; such surfaces can lead to short circuits and local heating. There should be no detachment of coatings; this aspect can be tested according to IEC60404-12. The surface insulation resistance of a lamination can be checked according to IEC60404-11 (Franklin test). A typical value of the minimum allowable surface insulation resistance (SIR) is 15 ohm-cm^2. Bolt-holes in yokes lead to local flux deviations which can be a cause of increased noise levels and losses. These unfavorable effects can be avoided by development of boltless yokes. The boltless yokes are generally held together by peripheral bands [18].

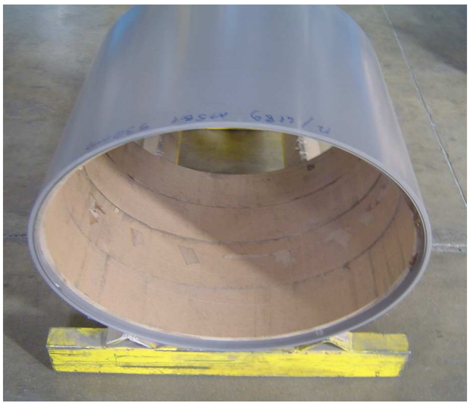
Burrs on sheared and punched laminations drastically reduce effectiveness of insulation coatings. During the assembly procedure, burrs can create short-circuits at lamination edges. Hence, it is necessary to ensure that burrs on laminations should be as small as possible. The measured burr height should not exceed 0.025 mm according to IEC 60404-8-7 and EN 10107. Burrs may also decrease the stacking factor; they can be more in case of manual production processes without tungsten carbide blades. Local overheating due to stray flux or main magnetic flux can occur due to burrs. Faults caused by closed loops, between adjacent laminations, linked by the main flux are dangerous.

V. Case Studies

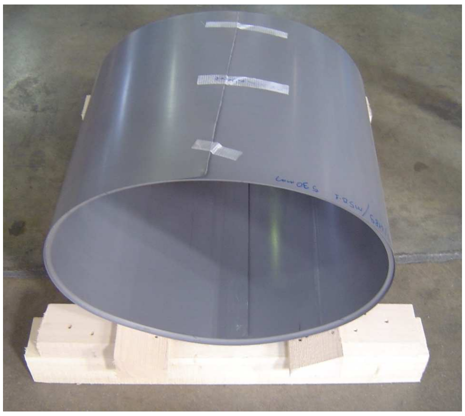
Two representative case studies are now reported, which clearly highlight the importance of having excellent processes and quality checks during the manufacture of the core in power transformers [16-17]. Specifically, the benevolent effect of using peripheral guard plate for stacking lamination rolls is discussed. Impact of bad quality of surface insulation resistance on core losses is also exemplified.

1. Use of inner peripheral guard plate

This case study shows the effect of handing processes on CRGO materials. The core loss increases when the inner peripheral guard plate is not used to keep coils of CRGO laminations.



(a)



(b)

Fig. 5 Coil handling (a) with an inner guard plate (b) without an inner guard plate

Losses are measured using Single Sheet Tester (SST) in two cases – one with an inner peripheral guard plate and the other without it, as shown in Figs. 5(a) and 5(b), respectively. The results are given in table I for the two cases for an M5 core material with 0.3 mm thickness. The performance figures are better with the guard plate.

TABLE I

Sr. No.	Max. Flux Density (T)	With guard plate			Without guard plate		
		Hmax (A/m)	Ss (VA/kg)	Ps (W/kg)	Hmax (A/m)	Ss (VA/kg)	Ps (W/kg)
1	1.5	41.12	1.11	0.8306	45.66	1.20	0.8678
2	1.7	128.49	2.56	1.1817	136.85	2.75	1.2352

2. *Effect of surface insulation on no-load losses*

Losses are higher in core materials with lower surface insulation resistance. Higher losses can be attributed to occurrences of short circuits on surfaces of sheets. Two core materials with low and high SIR values are shown in Figs. 6(a) and 6(b), respectively.

(a) (b)

Fig. 6 Core material (a) with a low SIR value (8 ohm-cm^2) (b) with a high SIR value (60 ohm-cm^2)

A no-load test is performed on two 400 kVA transformers built with these two types of materials. The transformer with better core material has about 10% lower loss as evident from table II.

TABLE II

Sr. No.	Max. Flux Density (T)	Surface Insulation Resistance (ohm-cm^2)	Power Loss (watt)
1	1.75	8	585
2	1.75	60	525

VI. Conclusions

Recent trends in design and manufacture of magnetic circuits in power transformers are discussed in this paper. It is a challenging task to model and analyse behaviour of the core in a transformer due to nonlinear, hysteretic and dynamic characteristics. Modeling of the characteristics using the JA approach and the corresponding numerical implementation has been enumerated. A 2D FEM analysis of a single-phase transformer with the above model is given. The approach can be used to analyze and design core joints that are confronted with local saturation problems. Another method based on a complex permeability approach is also elaborated, which can be used while assessing swept frequency response of transformers.

Effects of various manufacturing processes on the core performance are subsequently elaborated. Important quality checks such as *surface insulation test* and *adhesion test* should be performed. Core materials must be handled with care during storing and processing; elastic and plastic stresses can be induced, which can be detrimental. Two case studies are given at the end to demonstrate the importance of proper manufacturing practices. The first case study shows that approximately 5% higher losses occur without the use of an inner guard plate while storing a coil. In the second case, a higher surface insulation resistance value is shown to give 10% lower loss.

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