Unification of Anisotropy and FEM-BE Models for Distribution Transformer Optimization

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Abstract. The paper presents a three-dimensional finite element anisotropy model, based on a particular reduced scalar potential formulation, for the evaluation of the no load loss of wound core shell type distribution transformers. The specific anisotropy model is combined with a hybrid finite element-boundary element model, used for the calculation of the transformer's short circuit impedance, and various optimization algorithms in order to minimize the total owing cost of a distribution transformer.

1. Introduction

The design optimization of a wound core shell type distribution transformer consists in minimizing the transformer's total owing cost (TOC), where TOC is defined as the first cost of the transformer plus the calculated present value (PV) of its future losses [1]. The transformer manufacturer must also take into account the transformer's ratings, design constraints and specifications imposed by the electric power supplier [2]. Key specification parameters that must be met by the manufacturer are the no load losses and the short circuit impedance. The evaluation of the aforementioned key parameters is based most of the times on analytical methods [2]. However a simple analytical method for the computation of the short circuit impedance and the iron losses does not suffice especially in the case of transformers that do not fit the standardized large-scale constructions [3]. As a result the manufacturer is forced to adopt a safety margin for the no load losses [4], and to install magnetic shunts in order to correct within the desired limits the short circuit impedance [5]. In turn those actions result in the increase of the manufacturing cost and the losses.

The paper addresses the latter problem by introducing an appropriate three-dimensional finite element (3D FEM) anisotropy model used for the accurate prediction of the wound core transformer's iron losses. The specific 3D FEM model is combined with a hybrid finite element-boundary element (FEM-BE) model [3], used for the evaluation of the short circuit impedance, through the process of minimization of the TOC.

2. Description of the 3D FEM anisotropy model and FEM-BE model

The 3D FEM anisotropy model is based on a particular reduced scalar potential formulation, developed in [6], by partitioning the magnetic field strength **H** to a rotational and an irrotational part [6], as follows:

$$\mathbf{H} = \mathbf{K} - \nabla \Phi \tag{1}$$

The detailed modeling of the nonlinear core material is achieved by an accurate macroscopic representation and by adopting a reluctivity tensor thus taking into account the different characteristics due to the iron laminations and the grain orientation of the material after the core formation. Fig. 1 illustrates the flux density magnitude distribution during open-circuit test for an outer wound core of a 100 kVA, 20kV/0.4kV shell type wound core distribution transformer. The flux density magnitude along lines AB and CD, depicted in Fig. 1, is illustrated in Fig. 2. The proposed model's accuracy is verified via no load loss measurements and local field measurements using search coils and a data acquisition card (DAQ) as illustrated in Fig. 3.

The hybrid FEM-BE model, portrayed in Fig. 4, is ideal for the accurate calculation of the transformer's short circuit impedance since the field is not confined only in the conductors but it expands over extensive parts of air where the use of a BE representation can significantly reduce the computational effort [3,5].

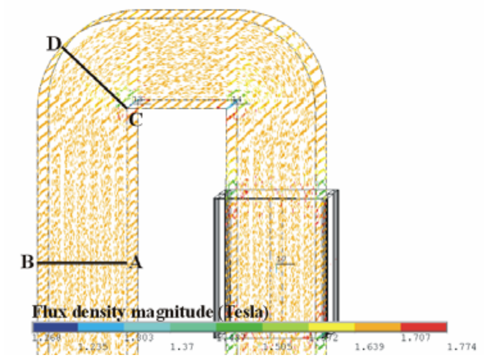

Fig. 1. Vector plot of the flux density magnitude distribution of a wound core during no load test

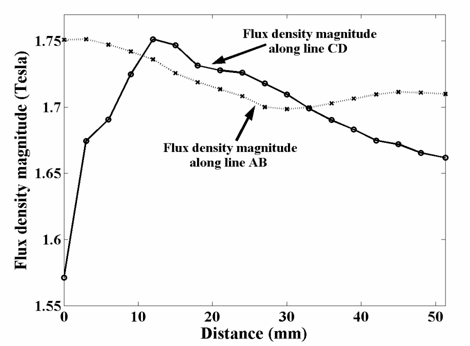

Fig. 2. Flux density magnitude distribution along lines AB and CD

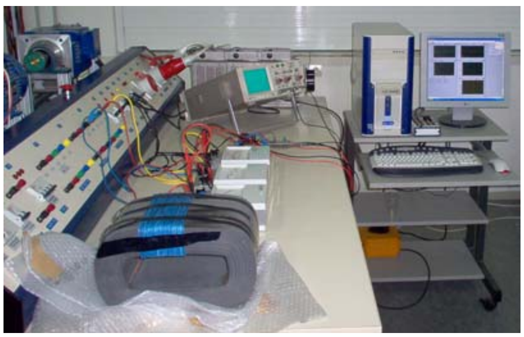

Fig. 3. Experimental apparatus

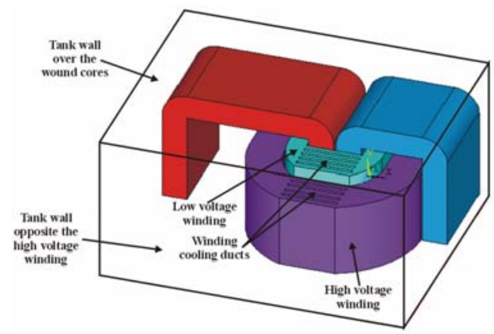

Fig. 4. Geometry of the FEM-BE model

The unification of the 3D FEM anisotropy and the FEM-BE models is achieved by the minimization of the TOC while satisfying the inequality and equality constraints, described by (2), where C_{Fe} and C_{Cu} are the magnetic steel and the winding material unit cost ($/Kg), M_{Fe} and M_{Cu} are the mass of the magnetic steel and the winding material (Kg), SM is the sales margin, P_{NLL} and P_{LL} are the no load and load losses (W) respectively, U_k is the short circuit impedance (%), P_{NLL}^{spec} and U_k^{spec} are the specified by the electric utility values of no load loss and short circuit impedance. The A and B factors ($/W) are the PV of 1 W of no load loss and load loss respectively, over the life of the transformer.

$$\mathrm{TOC} = \left(C_{Fe}M_{Fe} + C_{Cu}M_{Cu}\right)/\,SM + AP_{NLL} + BP_{LL}\,, \quad P_{NLL} \le P_{NLL}^{spec}, \quad U_k = U_k^{spec} \tag{2}$$

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