Multiple Grade Lamination Wound Core: A novel technique for Transformer Iron Loss Minimization using Simulated Annealing with Restarts and an Anisotropy Model

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Abstract — The paper introduces a novel technique for iron loss optimization of wound core shell type distribution transformers. Such a technique involves the evaluation of appropriate design variables of wound cores constructed by a combination of standard and high magnetization grade laminations. The evaluation of the optimum design variables of a multiple grade lamination wound core is achieved by combining a finite element model (FEM) considering tensor reluctivity and simulated annealing with restarts (SAR).

I. INTRODUCTION

The present value (PV) of the future iron losses of a typical wound core shell type distribution transformer constitute more than 60% of the PV of the transformer's total future losses [1]. Any attempt to reduce the iron losses results in a significant increase of the transformer's first cost as of the various materials required to manufacture a transformer, the electrical steel comprises the largest investment [2]. Therefore the design of a transformer requires the right balance between the first cost and the cost of future losses.

By using wound cores constructed with a combination of average and high magnetization grade steel, the transformer manufacturer can effectively minimize the sum of first cost and the PV of future iron losses. Therefore it is important to calculate the optimum design variables of a multiple grade lamination wound core that ensure a desired value of no load loss with the minimum weight of high magnetization material. The accurate evaluation of the no load loss and the accurate computation of the flux density distribution of the multiple grade steel wound core is needed in order to evaluate the exact position inside the core, of the high magnetization grade. For that purpose a finite element model (FEM) considering tensor reluctivity [3], [4] is proposed to be used. Such an optimization problem presents multiple optima in the feasible domain. Thus an appropriate improvement of the simulated annealing (SA) algorithm for continuous problems, the simulated annealing with restarts (SAR) [5], has been adopted.

II. RELUCTIVITY TENSOR FINITE ELEMENT MODEL

In this paper, it is proposed to use a FEM in order to compute the no load loss of multiple grade wound core. This FEM is based on a particular reduce scalar potential formulation [6]. However, adaptations are needed so as to improve the model performance. In particular, the detailed modeling of the core material is achieved 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 and the annealing process [3], [4]. The adoption of the considered reluctivity tensor enables the accurate calculation of the flux density distribution with the use of an intermediate mesh resulting in this way into further reduction of the computational effort and time making the specific FEM ideal for providing the solution to the SAR algorithm searching iteratively for the optimum design parameters. Fig. 1 illustrates the vector plot of the flux density magnitude distribution during open-circuit test for an outer wound core of a shell type 100 kVA, 20 kV / 0.4 kV transformer, constructed by using standard magnetization and loss grade, M4 0.27 mm laminations.

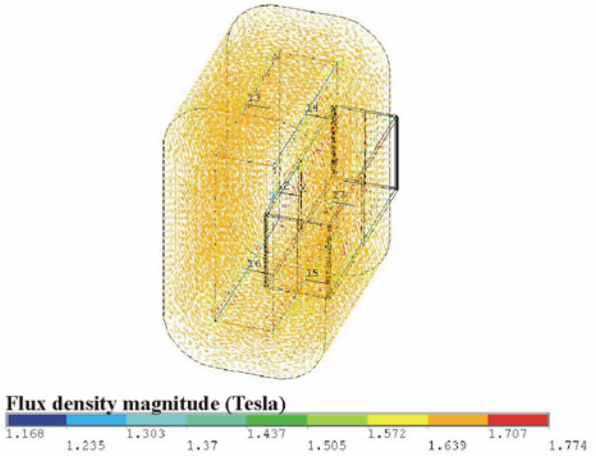

Fig. 1. Vector plot of the flux density distribution of an outer wound core of a 100 kVA, 20 kV / 0.4 kV shell type distribution transformer

III. OPTIMIZATION METHODOLOGY

The evaluation of the multiple grade lamination wound core design parameters consists in the minimization of an objective function $f(\mathbf{x})$, where $\mathbf{x}$ is the vector of the core design variables (x_1, x_2) illustrated in Fig. 2. The quantities a, b, c, and d depicted in Fig. 2 are constants. The design variables are subject to the following constraints :

$$0 \le x_1 \le a \,,\; 0 \le x_2 \le a \,,\; 0 \le x_1 + x_2 \le a \qquad (1)$$

The objective function must take into account the PV of the future iron losses and the cost of the standard and high magnetization grade laminations used for the construction of the wound core. During the optimization process, the no load loss value is calculated with the use of the FEM anisotropy model described in Section II. The mass of the high magnetization material, M_{HM}, and the mass of the standard magnetization material, M_{SM}, are calculated analytically by (2) and (3) respectively, where d_{ms} is the magnetic steel density (d_{ms} = 7,650 kg/m^3) and c_{sf} is the empirical core stacking factor ($c_{sf} = 0.965$).

$$M_{HM} = d_{ms} c_{sf} \left[\pi x_2^2 d + 2x_2 d\left(\pi x_1 + b + c\right)\right] \qquad (2)$$

$$M_{SM} = d_{ms} c_{sf} \left[\pi d\left(a^2 - x_2^2 - 2x_1 x_2\right) + 2d\left(a - x_2\right)\left(b + c\right)\right] \qquad (3)$$

The objective function is given by (4) where C_{HM} is the high magnetization steel cost (\$/kg), C_{SM} is the standard magnetization steel cost (\$/kg), SM is the sales margin and P_{IL} is the iron losses (W). The A factor (\$/W) is the PV of 1 W of no load loss over the life of the transformer. The A factor is given by (5) where PV is the present value multiplier for selected project life and discount rate, EL is the cost of electricity (\$/Wh) and HPY is the hours of operation per year (8,760 for no load loss).

$$f(\mathbf{x}) = \left(C_{HM} \cdot M_{HM} + C_{SM} \cdot M_{SM}\right) / \, SM + A \cdot P_{IL} \qquad (4)$$

$$A = PV \cdot EL \cdot HPY \qquad (5)$$

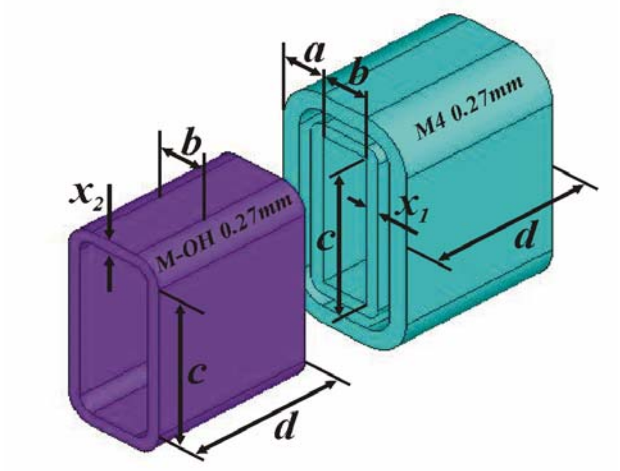

Fig. 2. Representation of the multiple grade wound core design variables

IV. RESULTS AND DISCUSSION

The method described in Section III is applied to an outer wound core of a 100 kVA, 20 kV / 0.4 kV shell type distribution transformer, constructed by a combination of standard magnetization and loss grade steel, M4 0.27 mm, and high magnetization low loss grade steel, M-OH 0.27 mm. The geometry parameters of the wound core are a = 51.3 mm, b = 57 mm, c = 183 mm and d = 190 mm. The excitation coil has 20 turns and the rms value of the applied voltage is 72 volts. The SAR algorithm was used and the optimum distribution of the design parameters is x_1 = 5.9 mm and x_2 = 6.7 mm which corresponds to an objective function value of 677.5 \$. Fig. 3 illustrates the vector plot of the flux density distribution of the upper left part of the wound core with the optimum design parameters. The SAR algorithm uses 2,080 evaluations and exhibits a 20% reduction in computing time comparing to the standard SA algorithm. Fig. 4 depicts the variation of the objective function with respect to the SAR iterations.

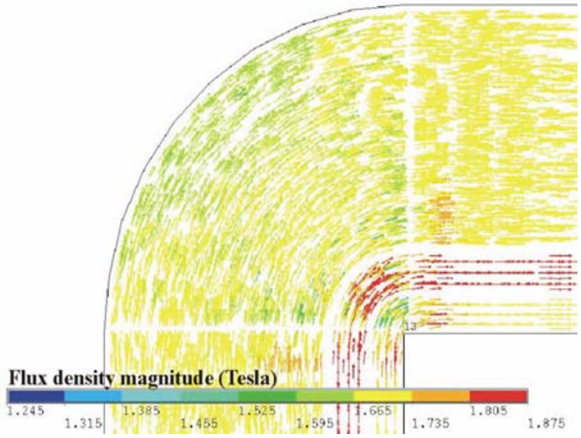

Fig. 3. Vector plot of the flux density distribution of the multiple grade wound core with optimum design variables x_1, x_2

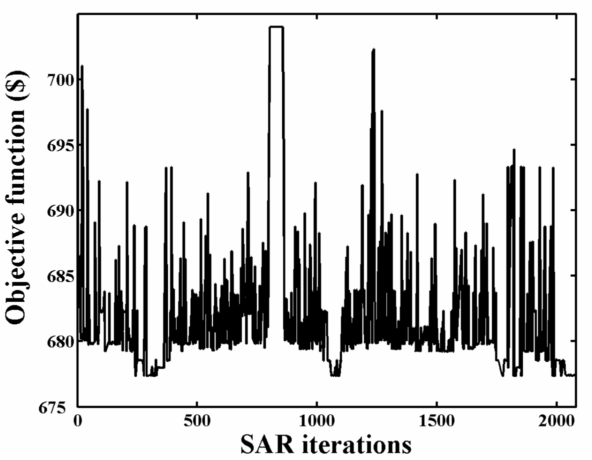

Fig. 4. Variation of the objective function with respect to SAR iterations

V. ACKNOWLEDGMENT

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VI. REFERENCES

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