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FEM package for iron loss evaluation and minimization of two grade lamination wound cores

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The iron loss and manufacturing cost of a strip-wound core can be reduced by constructing the wound core with a combination of average and high magnetization grade steel. The present paper introduces a two-dimensional finite element (2D FEM) package for the flux density distribution and iron loss computation of two grade lamination wound cores. The specific 2D FEM package is combined with deterministic and stochastic optimization algorithms in order to compute specific design variables of a two grade lamination wound core, that ensure the minimization of its iron loss and manufacturing cost.

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Keywords: Iron loss, Strip-wound core, Flux density distribution

1. Introduction

The purchasing decision for a typical wound core shell type distribution transformer depends not only on its first cost but also on the present value (PV) of its future losses. The PV of the future iron losses constitutes more than 60% of the PV of the transformer's total future losses [1]. Furthermore every 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 magnetic steel comprises the largest investment [2]. As a result the design of a transformer requires the right balance between first cost and cost of future losses.

By using wound cores constructed with a combination of average magnetization, standard loss, and high magnetization, low loss grade steel, the transformer manufacturer can effectively reduce the sum of first cost and PV of future iron losses [3]. However the computation of the flux density distribution and the iron loss of a two grade lamination wound core present difficulties that cannot be surpassed by simple analytical methods. Also specific design parameters of the two grade lamination wound core must be defined and computed in order to minimize the sum of manufacturing cost and PV of future iron losses [3]. For that purpose a two dimensional finite element (2D FEM) package is developed and is combined with a number of deterministic and stochastic optimization algorithms.

2. The multiple grade lamination wound core technique

The multiple grade lamination wound core technique presented in [3], is based on experimental evidence concerning the flux density distribution non-uniformity of strip wound cores [4]. According to [4] the flux density is low in the core's most inner steel sheets, then it increases to a value higher than the core mean flux density, and finally it decreases until the outer sheets. Thus, by using standard magnetization and loss grade steel for the inner and outer sheets of the wound core, and high magnetization, low loss grade steel for the rest part of the core, the transformer manufacturer may achieve a better tradeoff between first cost and PV of future iron losses. A two grade lamination wound core and its geometric parameters is depicted in Fig. 1. Fig. 2 illustrates the three parts comprising an actual two grade lamination wound core.

The evaluation of the optimum position and exact amount of the high magnetization grade steel, i.e. variables x_1 and x_2 of Fig. 1 respectively, that ensure the minimization of the sum of first cost and PV of future iron losses, is depended on several parameters that must be taken into consideration, like the core's working induction, the cost of the standard and high magnetization electrical steel, the electricity cost, the transformer's lifetime, and the discount rate. But most importantly an appropriate model is needed, that will compute accurately the iron losses of a multiple grade lamination wound core and simulate satisfactorily the core's flux density distribution, a key factor for evaluating the optimum position of the high magnetization grade steel inside the core.

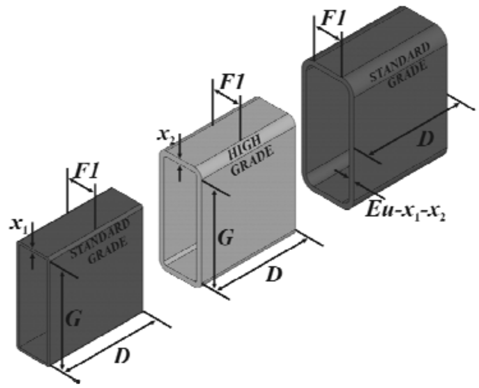

Fig. 1. Geometry of the two grade lamination wound core.

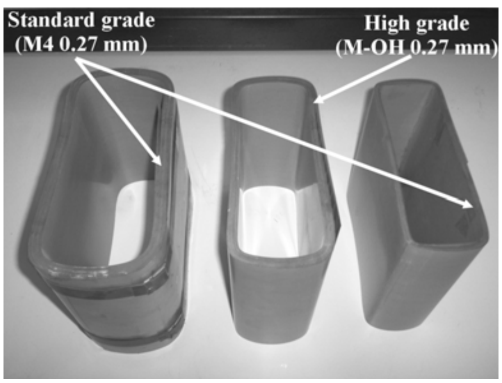

Fig. 2. A two grade lamination wound core.

3. Description of the 2D FEM package

For the accurate computation of the iron loss and the flux density distribution of a two grade lamination wound core, a 2D FEM package has been developed based on the computation of the magnetic vector potential A. The computation of the flux density distribution may be achieved by modeling every individual steel sheet as well as the air between two successive sheets. This however, is going to result to a FEM model of extreme computational cost, even in the case of a 2D model, as a typical wound core is made up from more than one hundred steel sheets. A FEM model such as this is not suitable for industry application.

An effective way to model iron-air lamination with a low computational cost is to consider the specific material as homogeneous and anisotropic at the level of finite elements [3]. This means that in the case of a 2D magnetostatic FEM analysis the reluctivity is treated as a tensor quantity. The reluctivity $\mathbf{v}$ is assumed to have two components as described by (1), one along the rolling direction v_p, and the other normal to the rolling direction v_q, within each element.

$$\mathbf{v} = \begin{bmatrix} v_p & 0 \\ 0 & v_q \end{bmatrix} \tag{1}$$

The directional dependence of the B - H characteristics is properly simulated by assuming that loci of constant magnetic field intensity H, or constant reluctivity, forms ellipses in the B_p - B_q plane. This assumption leads to a minor error in the case of the wound core in contrast with the stack core transformer [5], [6]. Based on this elliptic anisotropy model, the reluctivity in the orthogonal direction q can be written as follows, where r is the ratio of the ellipse semi-axes.

$$v_q = r\,v_p, \quad r > 1 \tag{2}$$

The reluctivity along the rolling direction v_p, and normal to the rolling direction v_q, for constant magnetic field intensity H is computed using (3) and (4) respectively

$$v_p = \left[\left(\left(1 - c_{sf}\right) + c_{sf}\,\mu_r\right)\mu_o\right]^{-1} \tag{3}$$

$$v_q = \frac{c_{sf} + \left(1 - c_{sf}\right)\mu_r}{\mu_r\,\mu_o} \tag{4}$$

where c_{sf} is the wound core empirical stacking factor, i.e. the relative quantity of iron, and μ_r is the relative permeability calculated by the B - H characteristic of the rolling direction for the constant value of field intensity H under consideration.

This simple anisotropy model was applied to a 2D variational finite element method using the magnetic vector potential A, [5] - [7]. The resulting 2D FEM technique is computationally cheap as a coarse mesh of a few thousands nodes is enough for the accurate evaluation of the flux density distribution and the iron losses. A macroscopic representation of the nonlinear characteristics of the core materials by cubic splines and a Newton-Raphson iterative scheme has also been adopted for the solution of the particular nonlinear problem.

Fig. 3 illustrates the areas with different material attributes comprising the 2D FEM model of a two grade lamination wound core. For the areas A1 to A5, and A11 to A15, the standard magnetization grade is assigned, and for the areas A6 to A10 the high magnetization grade steel is assigned. One half of the wound core geometry is modeled due to symmetry, and a Dirichlet boundary condition ($A = 0$) is imposed on the outer boundaries of the 2D model.

Due to the wound core's geometry the reluctivity tensor must be rotated to a different coordinate system in some of the areas of the 2D FEM model of Fig 3. The reluctivity tensor $\mathbf{v}$ in the global coordinate system is given by (5), where $\mathbf{R}$ is the rotation matrix, and $\mathbf{v}_F$ is the permeability tensor in the local coordinate system.

$$\mathbf{v} = \mathbf{R}^{-1}\,\mathbf{v}_F\,\mathbf{R} \tag{5}$$

Thus for the areas A1, A3, A6, A8, A11, and A13, a rotation to the cylindrical coordinate system is needed, whereas for the areas A4, A5, A9, A10, A14, and A15, a 90° rotation is applied. This means that in the latter case the rolling direction of the lamination (p axes) becomes parallel to the Y axis.

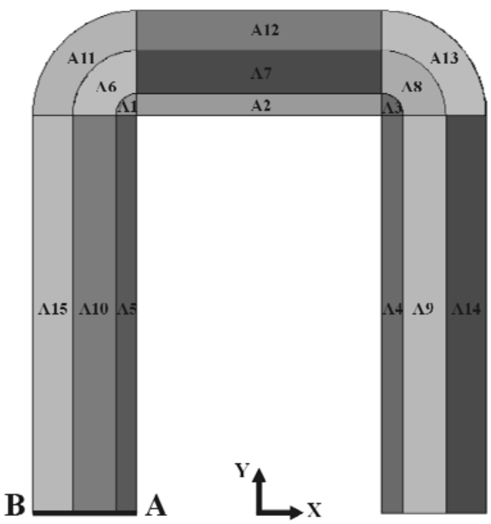

Fig. 3. Areas comprising the 2D FEM model of a two grade lamination wound core.

The accurate evaluation of the flux density distribution with the specific FE method is used in conjunction with the experimentally determined specific core losses of the standard and high magnetization grade steel, for the evaluation of the wound core iron loss. The specific core loss curves were approximated also by cubic splines.

Figs. 4 and 5 illustrate the flux density magnitude vector plot of a two grade lamination wound core for two different x_1, x_2 configurations (Fig. 4: x_1 = 5 mm, x_2 = 10 mm, and Fig. 5: x_1 = 0 mm, x_2 = 10 mm), and for the same mean flux density of 1.4 T. The FEM mesh is constituted by 8,110 first order triangular elements and 4,246 nodes. The wound core is constructed by the standard magnetization grade steel M4, and by the high magnetization grade steel M-OH, both by Nippon, and its geometry parameters are Eu = 24.3 mm, $F1$ = 57 mm, G = 183 mm, D = 190 mm.

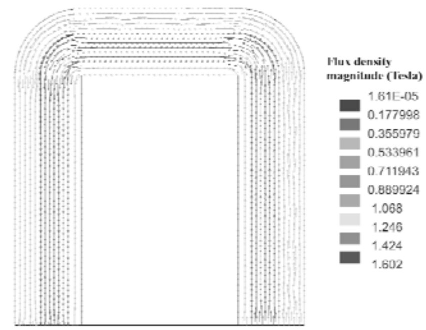

Fig. 4. Vector plot of the flux density of a two grade lamination wound core (B = 1.4 T, x_1 = 5 mm, x_2 =10 mm).

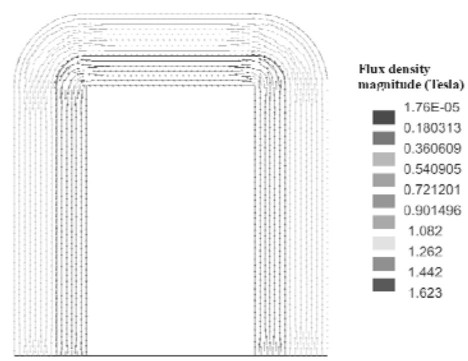

Fig. 5. Vector plot of the flux density of a two grade lamination wound core (B = 1.4 T, x_1 = 0 mm, x_2 =10 mm).

The computed flux density distribution across the core's limb, line AB of Fig. 3, for two different magnetization levels, 1.4 T and 1.5 T, and for the two aforementioned x_1, x_2 configurations are illustrated in Figs. 6, 7 and Figs. 8, 9 respectively. These distributions show clearly that the flux density is considerably higher in the high magnetization grade steel than that of the standard magnetization grade. Also, as the distance increases, the flux density decreases almost linearly both in the standard and high magnetization steel regions.

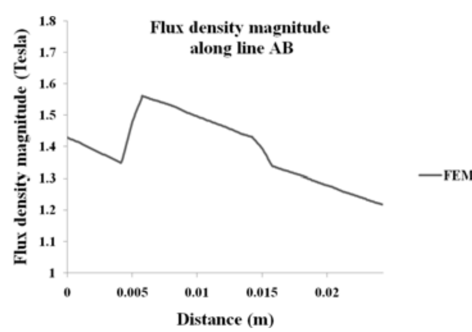

Fig. 6. Flux density magnitude distribution along line AB for B = 1.4 T and x_1 =5 mm, x_2 =10 mm.

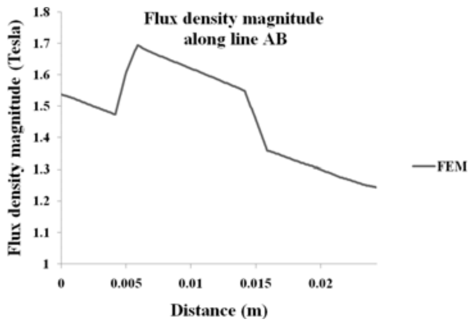

Fig. 7. Flux density magnitude distribution along line AB for B = 1.5 T and x_1 =5 mm, x_2 =10 mm.

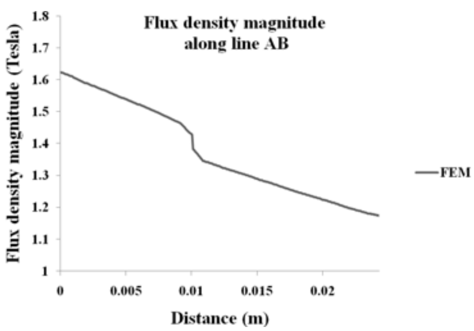

Fig. 8. Flux density magnitude distribution along line AB for B = 1.4 T and x_1 =0 mm, x_2 =10 mm.

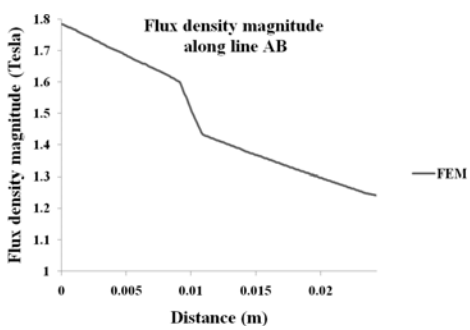

Fig. 9. Flux density magnitude distribution along line AB for B = 1.5 T and x_1 =0 mm, x_2 =10 mm.

4. Experimental setup for iron loss measurements of two grade lamination wound cores

The experimental setup used for the iron loss measurements of two grade lamination wound cores is illustrated in Fig. 10. It consists of a PC and a National Instruments (NI) 6143 data acquisition (DAQ) card (8 voltage differential inputs, 16 bit, 250 ksamples / s). The excitation coil terminals are connected to the input of the DAQ card via an active differential voltage probe (3 dB frequency of 18 MHz), and a current probe based on the Hall Effect (1 dB frequency of 150 kHz) is used for capturing the no load loss current. For the magnetization of the two grade lamination wound core, a 23 turn excitation coil is supplied by a one-phase 230 V, 50 Hz source through an autotransformer. The iron loss was evaluated by the acquired voltage and current data with appropriate virtual instruments (VI) created with the use of LabView.

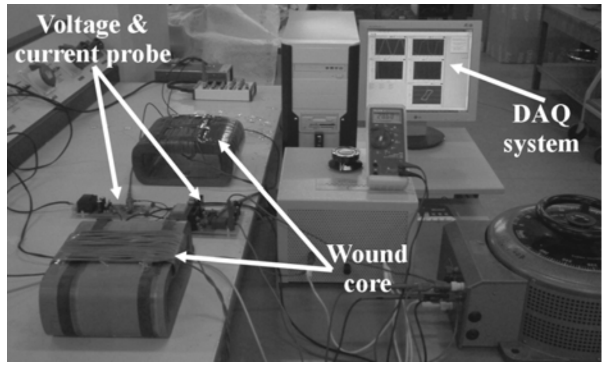

Fig. 10. Experimental setup.

Table 1 summarizes the calculated iron loss with the FEM package of Section 3 and the respective experimental values for various x_1, x_2 configurations. The considered wound core design parameters are Eu = 24.3 mm, $F1$ = 57 mm, G = 183 mm, D = 190 mm, and the mean flux density is B = 1.7 T. As can be seen from Table 1, the computed results are in good agreement with the measured ones and the error is less than 5% in all cases.

Table 1. Computed versus measured iron loss values (Eu = 24.3 mm).

x_1 (mm)	x_2 (mm)	Computed iron loss (W)	Measured iron loss (W)	Error (%)
24.3	0	22.7	23.1	1.73
0	24.3	18.5	19.4	4.64
3	9	21.9	22.4	2.23

5. Application of the multiple grade lamination technique

In the present section the multiple grade lamination technique is applied after the transformer's design optimization by conventional industrial methods [8], [9]. This means that the design variables Eu, $F1$, G, and D, shown in Fig. 1, the magnitude of the mean flux density B, and the number of turns of the primary winding N, are constants, predetermined by the typical industrial optimization procedure. The multiple grade lamination technique is applied in an attempt to reduce further the wound core's sum of first cost and PV of future iron losses.

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 variables (x_1, x_2) illustrated in Fig. 1. The design variables are subject to the following constraints

$$0 \le x_1 \le Eu, \quad 0 \le x_2 \le Eu, \quad 0 \le x_1 + x_2 \le Eu. \tag{6}$$

The objective function has to take into account the PV of the future iron losses and the cost of the standard and high magnetization grade steel. During the optimization process, the iron loss value is calculated with the use of the 2D FEM package described in Section 3. The mass of the high and standard magnetization material, M_{HM} and M_{SM}, are calculated by (7) and (8) respectively, where d_{ms} is the magnetic steel density (kg/m^3).

$$M_{HM} = d_{ms} c_{sf} \left\{ \pi x_2^2 D + 2 x_2 D (\pi x_1 + F1 + G) \right\} \tag{7}$$

$$M_{SM} = d_{ms} c_{sf} \left\{ \pi D (Eu^2 - x_2^2 - 2 x_1 x_2) + 2D (Eu - x_2)(F1 + G) \right\} \tag{8}$$

The objective function is given by (9), where C_{HM} and C_{SM} are the high and standard magnetization steel cost (\$/kg) respectively, SM is the sales margin and P_{IL} is the iron losses (W). A_{factor} (\$/W) is the PV of 1 W of no load losses over the life of the transformer and is given by (10), where PV is the present-value multiplier for selected life and discount rate, EL is the cost of electricity (\$/Wh), and HPY is the hours of operation per year ($HPY = 8{,}760$ for no load loss) [1].

$$f(\mathbf{x}) = (C_{HM} M_{HM} + C_{SM} M_{SM}) / SM + A_{factor} P_{IL} \tag{9}$$

$$A_{factor} = PV \cdot EL \cdot HPY \tag{10}$$

For the solution of the specific optimization problem, five deterministic and two stochastic optimization algorithms have been tested. This was done in order to verify if the specific optimization problem presents multiple optima in the feasible domain. The deterministic algorithms used are three gradient-based, the Broydon-Fletcher-Goldfarb-Shanno (BFGS), the Davidon-Fletcher-Powell (DFP), and the steepest descent, and two non-gradient methods, the downhill simplex method, and the pattern search. The two stochastic optimization algorithms used are the genetic algorithm (GA) [10], and the simulated annealing (SA).

The specific optimization procedure was applied to an outer wound core, of a 100 kVA, 20 kV / 0.4 kV, three-phase wound core distribution transformer. The standard and high magnetization materials used are M4 0.27 mm, and M-OH 0.27 mm respectively. The geometry parameters of the wound core are Eu = 51.3 mm, $F1$ = 57 mm, G = 183 mm, and D = 190 mm, and the mean flux density is B = 1.723 T. The specific design and operational parameters were calculated by a typical industrial design optimization procedure.

The deterministic algorithms failed to determine the global optimum in all cases and they converge to a local minimum near to the starting point. This implies that the multiple grade lamination wound core optimization problem presents several local minima, even in the simple case where there are only two unknown variables to be determined (x_1, x_2). Fig. 11 depicts the variation of the objective function with respect to the number of objective function calls by three of the five deterministic optimization algorithms tested, with a starting point very close to the global minimum.

The GA and the SA algorithm were successful in finding the global minimum and both of the stochastic algorithms converge to the same minimum. However the number of successes of the GA was lower than that of the SA, as the GA was trapped most of the times in local minima. The optimum distribution of the design parameters as calculated by the SA algorithm correspond to an objective function value of 677.5 \$, i.e. 3.2% reduction of the sum of magnetic steel cost and PV of future iron losses as it was pre-evaluated by a typical industrial design optimization scheme. Fig. 12 depicts the variation of the objective function with respect to the SA iterations.

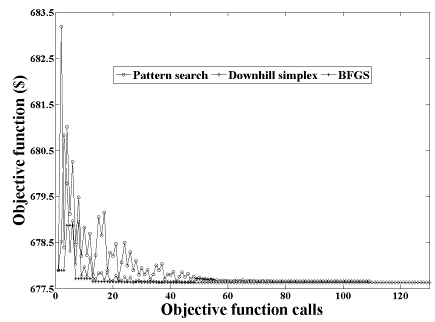

Fig. 11. Variation of the objective function with respect to the pattern search, downhill simplex, BFGS iterations.

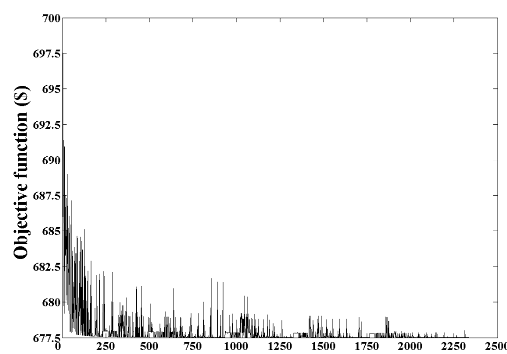

Fig. 12. Variation of the objective function with respect to the SA iterations.

6. Conclusion

The accurate computation of the iron loss and flux density distribution of a two grade lamination wound core is vital for determining the core's optimum geometric parameters that ensure the minimization of its first cost and PV of future iron losses. An optimization problem such as this presents multiple minima in the feasible domain and for its solution the use of stochastic algorithms is needed. For that purpose a 2D FEM package was developed that takes into account the anisotropy and the nonlinearity of the laminated material. The accuracy of the specific computational tool is verified by iron loss measurements. It is computationally efficient, it can be used effectively in conjunction with stochastic optimization algorithms and therefore it is ideal for transformer manufacturers and industry application.

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