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The magnetic flux density distribution in the anisotropic transformer core

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Abstract **The paper discusses the magnetic flux density distribution in medium power transformers core. Three-phase transformers are usually made of grain-oriented electrical steel characterized by anisotropy. Core losses, among other things, mainly depend on the grade of material. The selected results of calculation and measurement of no-load losses of medium power transformers have been shown.**

***Index Terms*—** **Three-phase transformer, Finite element method, Anisotropy.**

I. INTRODUCTION

An important issue in the design of the distribution transformer is the estimation of the no-load losses. Incorrect estimation of core losses during the design process can result in a financial penalty for the transformer manufacturer. The no-load losses are mainly influenced by the magnetic flux density, the excitation frequency, the mass and the grade of steel as well as other factors [1, 2, 3].

The transformer core is the element guiding the flux and is commonly constructed of rolled grain oriented (GO) electrical steel characterized by anisotropy. That means their magnetic properties differ depending on the examined direction [4, 5, 6]. In rolled material like GO steel, one reference axis corresponds to rolling direction (RD), one axis to lateral or transverse direction (TD), and the third axis is in the normal direction (ND).

This coordinate system for a rolled material is presented in Figure 1. The idea of orienting grains in a magnetically preferred direction was discovered by N. P. Goss. The corresponding texture (110), <001> is called the Goss texture, otherwise known as Cube-on-Edge (COE) see Fig. 1 a. The (110) plane lies in the sheet plane, and the [001] direction points approximately parallel to the rolling direction of the steel. The Goss texture has its highest magnetic permeability and a lower loss when magnetised in the rolling direction than that of other directions. Due to this texture, high values of the flux density can be obtained in the direction of rolling.

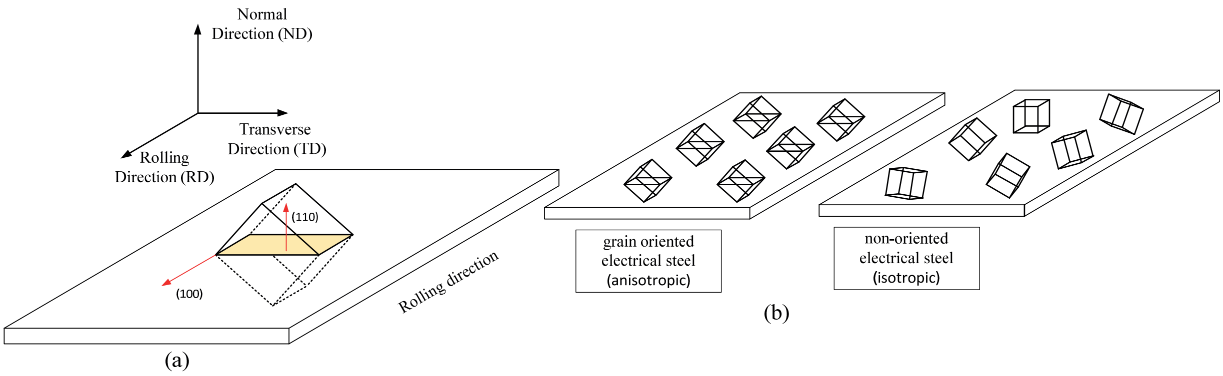

Figure 1. Reference coordinate system for a rolled material and crystal orientation relative to the rolled sheet reference axes for Goss (110)[001] cube-on-edge texture (a); grain-oriented and non-oriented electrical steel (b)

GO steel causes low core losses at high flux density levels when used as a core material in projects with a flux path parallel to the rolling direction, as in transformers. The direction of magnetic flux is consistent with the direction of rolling the sheet in a significant part (yokes and limbs). However, these directions don't overlap in the joints of the yokes and the limbs, as that is the region where the magnetic flux turns and changes the direction. At the corners of the transformer cores, the flux density is not parallel to the rolling direction. The flux in the corner flows from one lamination to another and also changes direction in space. The flux may lean towards to deflect away from the rolling direction of the lamination in the corner area. Owing to the presence of anisotropy in the material, the power losses will increase as the flux deflects from the rolling direction in the lamination plane.

Generally, the main labour in transformer modeling is concentrated especially on modeling the nonlinearities and the anisotropy of the core [8, 10, 14]. This paper deals with the modelling and analysis of a three-phase core-type transformer. The magnetic flux density distribution has been considered as well as the calculation and measurement of no-load losses of medium power transformers.

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II. THE CALCULATION AND MEASUREMENTS OF NO-LOAD LOSSES

On the whole, core losses (no-load losses) estimation methods in transformers can be classified into four main categories: measurement (empirical) methods [1,2,7,8], equivalent circuit methods [8,9,10], artificial intelligence methods [8,11,12] and numerical methods [8,13,14]. The measurement methods are determined by experimental measurements and the assessment of the building factor (*BF*). The building factor is defined as the ratio of measured no-load loss of a transformer (in watts per kg) to the estimated value based on nominal steel core loss (Epstein or Single Sheet Test loss in watts per kg) [1]. The building factor depends on several parameters, such as the air gap, areas of overlapping joints and the size of the stacking holes [1,2,7,8], therefore empirical methods require a huge number of measurements [8]. Additionally, due to the continuous optimization of the technical properties of both magnetic materials and the core structure, measurements of the core losses of these distribution transformers should be updated [8]. However, empirical techniques are characterized by fast calculations as well as taking into account all parts of the core losses.

Core losses can also be determined based on equivalent magnetic circuits using analytical methods [9, 10]. The analytical methods are built on a semiempirical description of the different components of core losses: hysteresis losses, eddy-current losses, and excess losses, which are functions of frequency and maximum flux density. The no-load losses are calculated by the introduction of resistance to the overall equivalent circuit model of the transformer [9]. Analytical methods are effectively used to study inrush current, ferroresonance, transients, etc., and are relatively simple [9,10]. Most often analytical methods are applied in real operation analysis. Nevertheless, these methods cannot accurately estimate core losses, and commercial transformer design programs that use numerical or empirical methods are typically used [8].

Artificial intelligence methods, which are often based on neural networks, are also used to determine core losses. Neural networks are applied to estimate core losses as a function of basic design parameters [8,11,12]. The accuracy of these methods is commonly dependent on the correctness of the training of neural network sets [8]. Generally, neural networks are effective in predicting no-load losses of power transformers, but in [8] shows that there are cases where the estimation error is unacceptable after the completion of transformer construction.

Then numerical methods calculate no-load losses by solving Maxwell Equations with numerical techniques such as Finite Element Methods (FEM) [8,13,14]. FEM is a highly successful numerical tool for verification and optimization of new transformer designs as well as used materials [14]. The main issues of these methods are time-consuming calculations.

One of the empirical methods described in a previous paper [3] takes into account the mass m, grade of steel as core losses p and the extra losses factor k_p estimated through analysis of transformers series. The formula may be presented as follows:

$$\Delta P_{Fe} = k_p \, m \, p, \tag{1}$$

There is considered that the main effect on the extra losses factor, and thereby on no-load losses, may have core's corners. This is the region, where the magnetic flux changes the direction. The flux goes through the corner from the limb to the yoke or inversely. In regard to this, the direction of the magnetization of the sheet doesn’t coincide with the rolling direction. The angle between these directions is named the anisotropy angle and its increase leads to a higher value of losses.

Table I shows data for selected transformers produced by Power Engineering Transformatory. It contains the power, the percent content of corners in the entire core mass and the extra losses factor. There are two values of k_p factor – first used for the calculation of losses and second recalculated from the no-load losses obtained in the test. The comparison of these two values is significant to develop a more accurate algorithm for the no-load losses calculations. The designer may modify the factor according to results from the analysis of measured losses.

The second purpose of the creation of the Table I was to check if there is a dependency between the content of corners and the extra losses factor. The dependency is not visible, hence the more complex analysis should be performed. That analysis should include e.g. the value of magnetic flux density, the grade of steel. Besides, more designs should be compared. Table I contains 19 units, though there are only three different designs. The dimensions of one of the cores from Table I are presented in Table II.

TABLE I. NO-LOAD LOSSES AND CORE EXTRA LOSSES FACTOR FOR DIFFERENT CONTENT OF CORNERS IN THE CORE

No.	Power	Content of corners in entire core mass	No-load losses calculated	No-load losses measured	Core extra losses factor calculated	Core extra losses factor measured
-	MVA	%	W	W	%	%
1	16	26,9	7886	7970	15	16,1
2	16	26,9	7886	7960	15	16,2
3	25	28,7	11730	11678	17	16,5
4	25	28,7	11730	11397	17	13,6
5	25	28,7	11730	11832	17	18
6	25	28,7	11730	11560	17	15,3

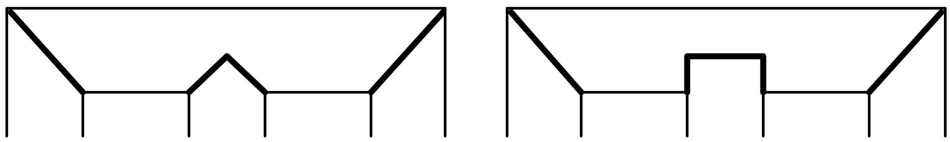
7	25	28,7	11730	11539	17	15,1
8	25	28,7	11730	11370	17	13,4
8	25	28,7	11730	11405	17	13,8
10	25	28,7	11730	11265	17	12,3
11	25	28,7	11730	11714	17	16,8
12	25	28,7	11730	11452	17	14,2
13	25	28,7	11730	11507	17	14,7
14	25	28,7	11730	11206	17	11,8
15	25	28,7	11730	11392	17	13,6
16	25	28,7	11730	11376	17	13,4
17	25	28,7	11730	11183	17	11,5
18	40	27,59	13216	12831	17	13,6
19	40	27,59	13216	12855	17	13,8

The measured values of the no-load losses are mostly lower from calculated ones. That implies the real core extra losses factor to be lower than taken into calculations. This is different only for 16 MVA transformers with assumed factor for calculations equal to 15% and the one 25 MVA transformer. For the factor 17%, the real value recalculated base on the measured losses ranges mainly from 13% to 16%.

The variation of measured losses for the same design might be affected by accuracy in the production of these cores. Even though the design is the same, produced cores may not be identical. Moreover, the disassembly of the upper yoke before placing the windings on limbs, then the reassembly, may have an impact on losses.

III. THREE PHASE TRANSFORMER CORE

The object of a survey was a transformer core (Fig. 3 and Table II). Generally, the transformer structures at the corner joint are made as a butt-lap joint either mitred overlap joint - see Fig. 2. In this paper, we considered mitred overlap joint.



(a) (b)

Figure 2. Different types of T-joins design: mitred 45°(a) and butt-lap 90° overlap joint (b)

Particularly, the corner of the core was the main concern as this is the area where the anisotropy occurs. The core lamination is made alternately. The layers of sheets are interlaced in the places where the columns are connected with the yokes, precisely in the corners and nodes. The most commonly used solution is the core's lamination with sheets cut angled at 45º. In such cores, the areas with different directions of rolling and magnetizing are smaller than in the case of cores laminated at the right angle. Hence the maximum anisotropy angle also equals 45º.

The examined core was made with lamination at 45º (Fig. 4). The chosen type of steel sheet was M080-23P5. The most significant parameters of this steel: the magnetic flux density at 800 A/m equals to 1,916 T and the typical core loss at 1,7 T (for 50 Hz) is 0,77 W/kg. All these parameters are catalog values specified for the direction of magnetization parallel to the direction of rolling. The values differ depending on the anisotropy angle. The impact of these variations on the magnetic flux density distribution was analysed in the paper.

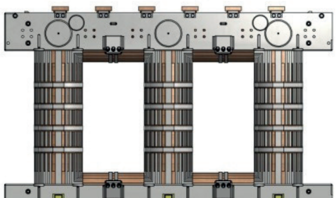


Figure 3. Assembly of the three-phase transformer core

TABLE II. DIMENSIONS OF THE EXEMPLARY CORE

Dimension	Value
Sheet thickness	0,23 mm
Core diameter	525 mm
Height	2456 mm
Width	2869 mm
Mass	15 200 kg

IV. SELECTED RESULTS

The distribution of the magnetic flux density in the core was modeled by the finite element method. The computation was performed in the Comsol Multiphysics software. Therefore to simplify the calculations, the 3D model contained a single limb and yoke (orange marking in Fig. 4). Moreover, there were only three steps in half of the core's cross-section. Although the real core contains typically more than 10 steps.

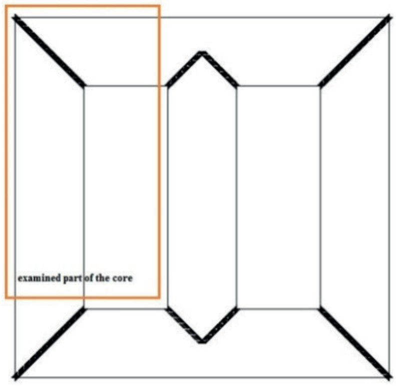
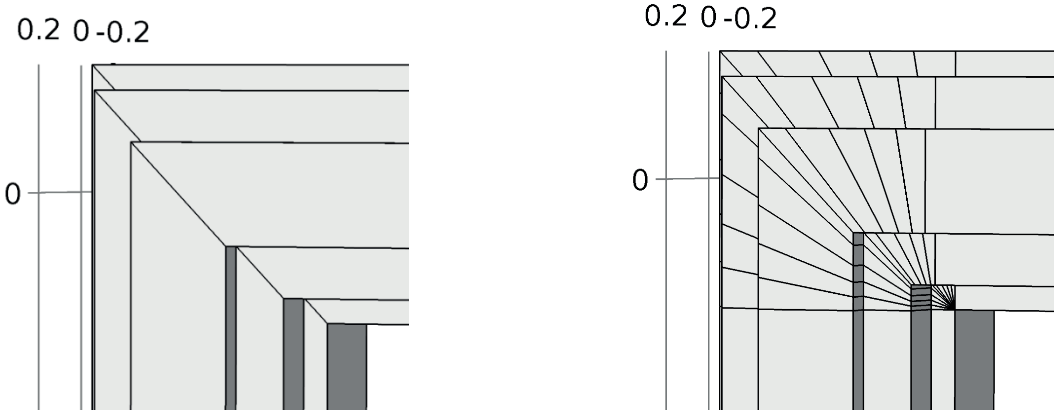


Figure 4. The view of the transformer's model

In the paper, two cases were examined. The first one didn't include different properties for different anisotropy angles (Fig. 5a). In the second case, the difference in properties was taken into account. The corner was divided into smaller elements, every 10º (Fig. 5b). This division enabled the implementation of the anisotropy in the model. The proper magnetization curve B(H) (Fig. 6) was applied to each part of the corner.



(a) (b)

Figure 5. Considered core models in FEM analysis: model 1(a), model 2 (b)

The curve for 0° corresponds with the one contained in the steel producer's catalogue. This curve was also implemented in case 1. The remaining curves were developed on the basis of the study included in [15]. The author of that paper describes the measurements of electrical steel. The results show dependency between the anisotropy angle and the magnetization curve, as well as core losses. According to this survey, the magnetic flux density decreases for a greater anisotropy angle (for the same value of the magnetic field).

The magnetic flux density and the magnetic field were calculated proportionally to values from the survey [15]. In order to measure parameters for different anisotropy angles, the sheet strips are cut at the proper angle relative to the rolling direction. On account of this survey, the authors made the assumption that as the anisotropy angle for M080-23P5 steel increases, the magnetic flux density will decrease by the same percentage as in the mentioned survey.

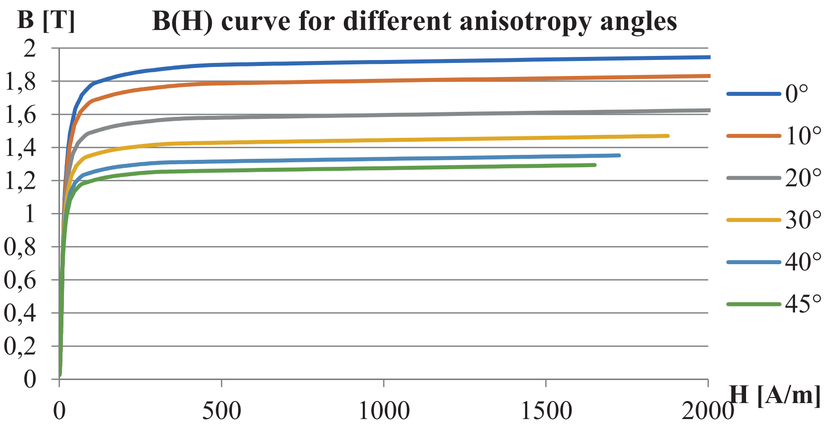


Figure 6. The magnetization curve for different anisotropy angle

In order to examine the distribution of the magnetic flux density, the constant value as a vector was applied to the ending surfaces of the yoke and the limb. The vector supplied to the yoke had a value of 1,7 T when to the limb it was -1,7 T. The condition is described by the formula:

$$-\boldsymbol{n} * \boldsymbol{B} = B_m, \tag{2}$$

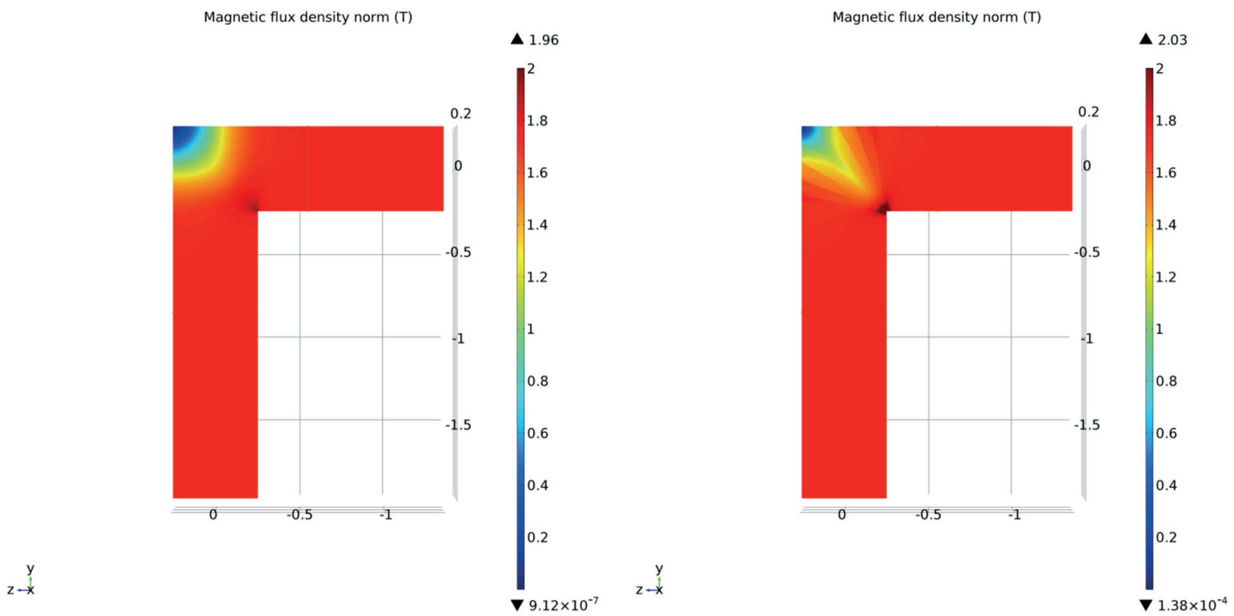
where:

n – directional vector (normal),

B – magnetic flux density vector,

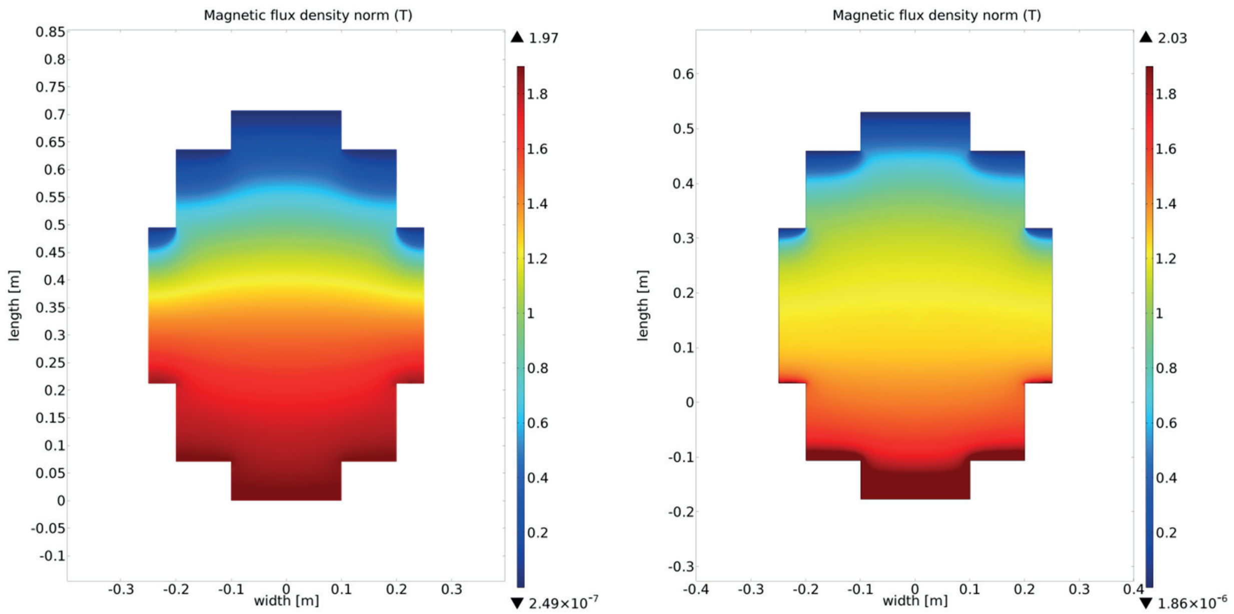
B_m – maximum magnetic flux density.

The results of the FEM calculations for both investigated cases are shown in Figure 7. In the yoke and the limb, where the direction of rolling is the same as the direction of magnetization, the magnetic flux density is constant and equal to 1,7 T. Instead, the value differs in the area of the corner. The more accurate distribution is presented in Figure 8. The surface showed in Fig. 8 is the diagonal cross-section of the corner. The magnetic flux density is greater closer to the inner part of the corner and lower closer to the outer part.



(a) (b)

Figure 7. The magnetic flux distribution for: model 1 (a), model 2 (b)



(a) (b)

Figure 8. The magnetic flux distribution in the corner: model 1 (a), model 2 (b)

Nonetheless, the distribution differs for two examined cases. In case 1 (Fig. 7a) the area of the lowest magnetic flux density is larger while the area of the highest is smaller. However, the minimum value is $9{,}12\cdot10^{-7}$ and the maximum value exceeding saturation is equal to 1,96 T. There should be emphasized that the increase of the magnetic flux density affects the increase of core losses and therefore no-load losses.

In view of this, the second case was analysed (Fig. 7b). Taking into account various magnetization curves for proper parts of the corner led to more precise results in the calculation. The difference between cases 1 and 2 is visible. The area of the magnetic flux up to 1 T is smaller while the region with the value above 1,8 T is wider. Furthermore, the range of approximately 1 T and 1,6 T is not placed around the outer corner as in case 1. That area extends through the diagonal of the corner. The extreme values are greater in this variant. The maximum value obtained in case 2 is 2,03 T and minimum $1{,}38\cdot10^{-4}$ T.

V. CONCLUSIONS

The aim of the paper was to observe the distribution of the magnetic flux density in the transformer's anisotropy core. Moreover, a short analysis of the no-load losses for different designs was performed. However, the analysis of calculated and measured values of the no-load losses allows assessing the correctness of the designing process. Obtaining comparable results is significant from the perspective of meeting the conditions set by the customer. Despite the fluctuation of the extra losses factor, all analysed transformers have losses below the required ones. Most measured values are lower about 1-5% than calculated. Observation of the relationship between the content of corners in the entire core mass and the extra losses factor should take into account more parameters. The magnetic flux density and the core loss for a particular grade of steel should be also considered.

Although there are several methods for calculating no-load losses, each requires a complex analysis of measured values. Real values should be taken into account during further development and improvement of algorithms.

The second part of the paper is dedicated to the distribution of magnetic flux density in the core. The results of the simulation show that in the corner the distribution is uneven. The implementation of different magnetization curves, resulting from the anisotropy angle, leads to obtaining a more accurate outcome. The distribution for model 2 is apparently different than for model 1. That knowledge is substantial for future studies.

The computations conducted in this paper will be developed in the future. It is planned to develop a method for calculating no-load losses using FEM. The impact of the varied distribution of the magnetic flux density will be included. Obtained results will show how much losses occur in the corner compared to other areas of the core. Moreover, the total no-load losses will be compared with the values calculated with formula 1. And also a comparison of this approach with that using an anisotropic magnetic permeability tensor will be carried out to determine the validity and accuracy of the proposed method.

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