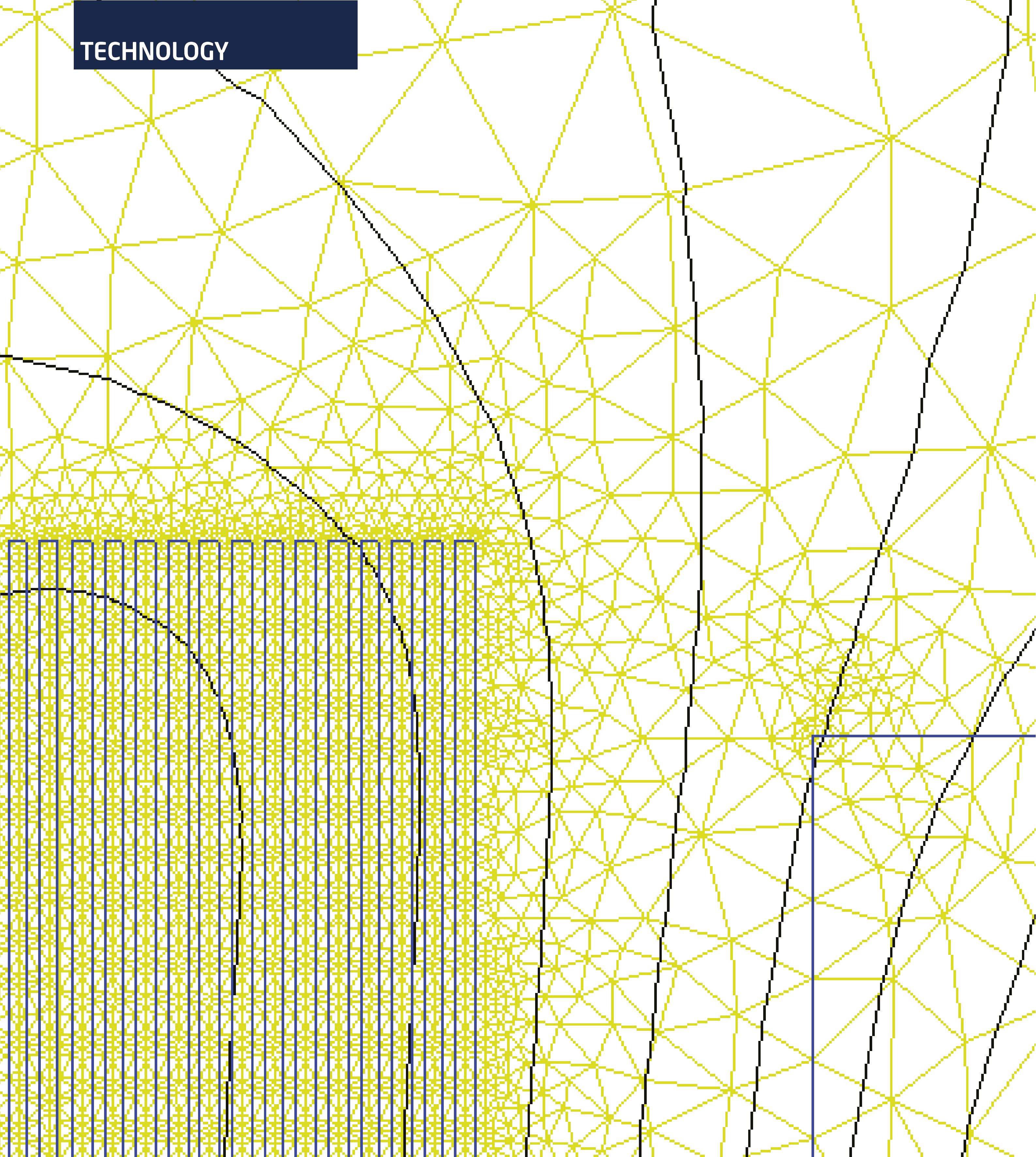

ABSTRACT

A semi-analytical method for calculating foil winding power losses is presented in the article. The short-circuit losses of foil type windings are somehow greater in comparison to the other types of windings consisting of rectangular conductors or magnet wires. The main reason for higher losses is related to eddy currents induced by the magnetic field passing through the foil surface. Namely, the eddy currents in the foil are developed through a large surface area, which gives rise to current density. However, the proposed method is based on the stray magnetic field distribution along the foil winding, from which the eddy currents are evaluated. The novelty of the method is introduced through a so-called "residual flux" which results from asymmetric field distribution along the foil and contributes strongly to power losses.

KEYWORDS

foil winding, loss calculation, rectifier transformer, FEM

Mislav TRBUŠIĆ, Igor LUGARIĆ

> **The short-circuit losses of foil type windings are somehow greater in comparison to the other types of windings**

Power losses model of a foil winding

1. Introduction

In transformer units with a nominal power rate up to a few MVA and relatively low voltage applications below 3 kV, the foil type of winding is generally applied to the low-voltage side. The typical applications for this type of winding are small distribution and rectifier transformers [1, 2]. The main advantage of the foil winding over the disc or a single layer type is its geometrical feature, since, usually, the height of the foil is much greater than its thickness, which gives a desirable conductor cross-section, as well as simplifies the winding process of the coil. On the other hand, due to the large surface area of the foil, the stray magnetic field induces eddy currents which produce significant additional losses, and can reach as much as 70 % of the winding DC losses. However, the addressed topic is, mathematically and computationally, a rather comprehensive task that requires a numerical approach, but still, even with the most extensively used method in the computational electromagnetics, the Finite Element Method (FEM), issues arise when the thick objects such as foil windings are involved in the analysis [3]. For this reason, the semi-analytical method of the additional losses' calculation is presented in the article. Here, the magnetic field in the transformer's window (the leakage or

Main reason for higher losses is related to eddy currents induced by the magnetic field passing through a large surface area of the foil, which gives rise to current density

stray field) is computed by the FEM, and the following losses related to the field are evaluated through the analytical expression.

2. The foil winding losses model

The losses in a transformer's windings are composed of the losses caused by the source current (load current) and of eddy currents induced in the winding by the stray magnetic field [4, 5]. In the case of a foil type winding, the ratio of thickness and height of the foil is much less than a unit, thus, the eddy currents are induced primarily by the radial component of the stray magnetic field. Therefore, it is somehow essential to have a picture of the spatial distribution of the magnetic field within the transformer's window, for which the numerical approach should be employed. In this study, 2D FEM based software has been used for the field computation. But still, the additional losses caused by the so-called residual flux are involved with the foil type of winding whenever the sum of a radial component of a stray magnetic field along the winding is different from zero. Namely, the residual flux appears as a result of asymmetry in the windings' arrangements, and, therefore, induces additional eddy currents in the foil. In conventional three-phase power transformers this effect is prevented mainly by the proper placement of the windings, while, in the specially designed transformers such as rectifier transformers, the residual flux exists by virtue of the windings' arrangement (Fig. 4). The proposed loss model of the foil winding is divided into three sections: The first is related to the source current (load current) with presumed constant current density through the foil cross-section; the second contribution takes into account the eddy currents which are developed at the foil edges due to the radial magnetic field distribution along the foil, and the last, third part of the load losses introduced here, is linked to the residual flux which is a consequence of magnetic field imbalance along the foil.

2.1. Losses caused by the load current in the foil

The three-phase foil winding losses correspond to the load current evenly distributed over a foil cross- section and they are simply obtained by Eq.(1) [4].

$$P_i = 3\int_V \frac{J_i^2}{\sigma}\, dV = 3\,\frac{J_i^2 a_0 b_g \pi d_{sr} N}{\sigma} \qquad (1)$$

Where:
J_i stands for the load current density (A/m^2),
σ is a specific foil material conductivity (Sm^{-1}),
a_0 is the foil thickness (m),
b_g is the foil (winding) height (m),
d_{sr} is a mean winding diameter (m), and
N is the number of turns in the winding.
It is noted that magnetic field distribution has no influence on this part of the losses.

2.2. Losses caused by the radial magnetic field distribution along the foil

The second contribution in the losses model of the foil winding is related to the induced eddy currents J_e caused by the radial magnetic field B_r in the foil, which is present mainly at the top and at the bottom of the foil, respectively. In this case, the evaluation of the aforementioned losses requires a picture of the spatial distribution of a radial magnetic field component along the foil (Fig. 2a, Fig. 2b). For convenience, determination of the eddy currents' distribution is given here for a single turn of the foil winding, where the turn is developed in the plane and divided into slices along its height, as is shown in Fig. 3. The eddy current $J_e(z)$, induced by spatially distributed magnetic field $B_r(z)$ along the winding, is determined by applying the Ampere's law, which yields the matrix equation (2) for the effective values of eddy currents' streamlines ($J_1, J_2, \dots J_n$), Fig. 2c [3].

$$\begin{bmatrix} J_1 \\ J_2 \\ \dots \\ J_n \end{bmatrix} = \frac{-\sigma\,\omega}{\sqrt{2}} \begin{bmatrix} -2 & -1 & \cdots & -1 \\ -1 & -2 & \cdots & \cdots \\ \cdots & \cdots & \cdots & -1 \\ -1 & \cdots & -1 & -2 \end{bmatrix}^{-1} \begin{bmatrix} \bar{B}_1 \\ \bar{B}_2 \\ \cdots \\ \bar{B}_n \end{bmatrix} \qquad (2)$$

Where:
ω (s^{-1}) is the angular frequency,
σ is the specific conductivity of the foil

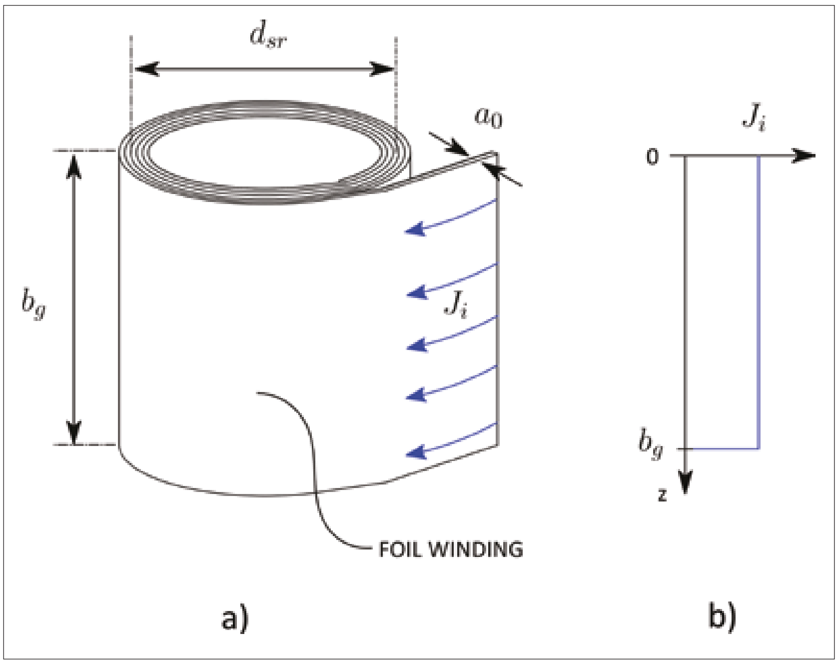

Figure 1: Depiction of foil-type winding
a) foil type winding
b) the load current density distribution along the foil

as discussed previously.
The expression for $B_1 \dots B_n$ is given with Eq.(3), where b is the height of the foil partition, defined as a quotient of the foil height b_g and the number of partitions n in which the foil has been virtually divided along the z-axis.

$$\bar{B}_k = \int_0^{kb} B_r(z)dz,\ k = 1,2,\dots n \left(b = \frac{b_g}{n}\right) \quad (3)$$

Once the eddy currents' streamlines are calculated by using Eq.(2), the referential eddy current streamline (J_0) is calculated as follows from Eq.(4), and, finally, the eddy currents' distribution is achieved along the winding, Eq.(5).

$$J_0 = -\sum_{k=1}^{n} J_k \quad (4)$$

$$J_e(z) = [J_0, J_1, J_2, \dots J_n]^T \quad (5)$$

In everyday design practice, the stray magnetic field within the transformer's window is evaluated numerically in discrete points, chiefly by using FEM or FDM (Finite Difference Method) based software, so the numerical methods are somehow desired to obtain the eddy current distribution $J_e(z)$ in the foil [3]. Further calculation of the losses is achieved by taking into account all contributions of the spatially distributed eddy currents $J_e(z)$, Eq.(6).

$$P_f = \int_{V_{foil}} \frac{J_e^2(z)}{\sigma} dV_{foil} = \frac{a_0 \pi d_{sr}}{\sigma} \int_0^{b_g} J_e^2(z)dz \quad (6)$$

At this point, it is particularly important to emphasise that Eq.(6) used here holds for a single turn of a foil winding, thus the evaluation of eddy currents' losses in the whole winding consisting of N turns is pursued by summing up the eddy currents' losses in the individual turn of all three phases, Eq.(7),

$$P_e = 3\sum_{q=1}^{N} P_{f,q} \quad (7)$$

where the subscript q indicates the turn in the foil winding.
The principal distribution of the radial magnetic field, as well as the eddy currents' density in the foil, is shown in Fig. 2b and Fig. 2c. As mentioned before, the radial component of the stray magnetic field is concentrated at the top and at the bottom of the foil, thus, the eddy currents' density, as follows from Eq.(2), is also intensified at the foil edges. In the case of symmetric field distribution, as is announced in Fig. 2b, the integral of $B_r(z)$ along the foil vanishes. On the other hand, when this is not the case, some residual magnetic field remains, thus inducing additional eddy currents which give rise to the total foil losses. The addressed topic is covered by the next paragraph.

The novelty of presented method is the introduction of so-called "residual flux" which results from asymmetric field distribution along the foil and contributes strongly to power losses

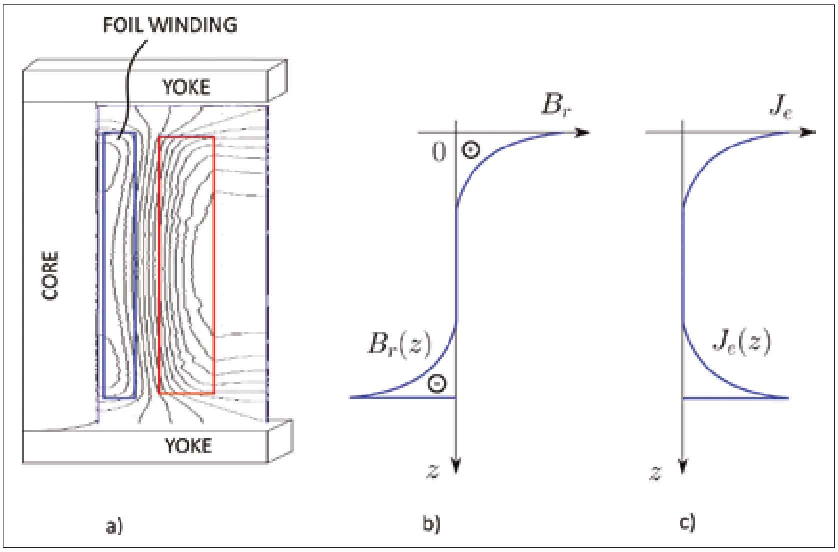

Figure 2: Magnetic field and current density distribution in the transformer window
a) symmetrical magnetic field distribution within the transformer window
b) radial magnetic field distribution along the foil winding
c) eddy current density in the foil

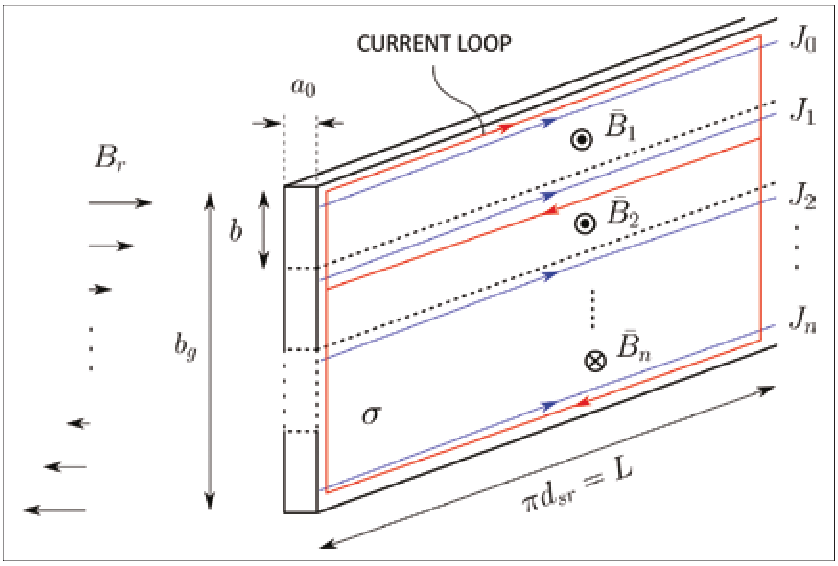

Figure 3: The foil winding (single turn) expended in the plane with indicated eddy currents' streamlines.

2.3. Losses caused by the residual flux – 'residual losses'

The asymmetry in the magnetic stray field distribution along the winding arises due to the winding constellation in the transformer window. In practice, especially with the special transformer

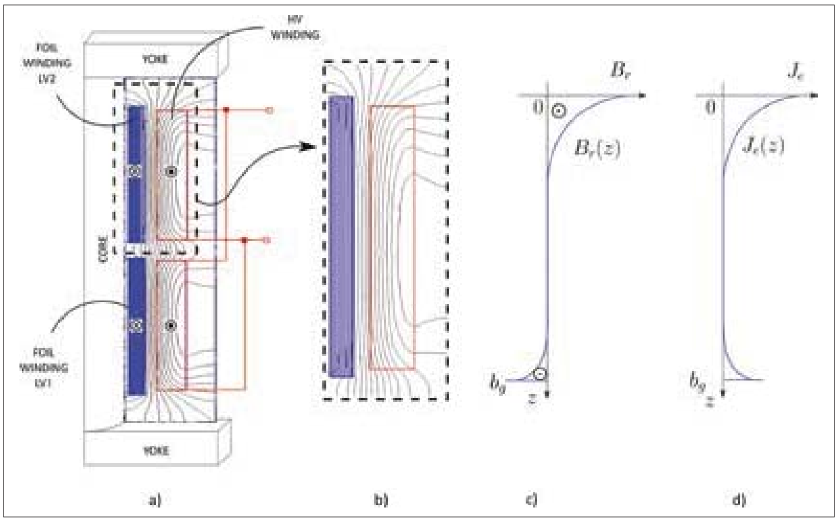

Figure 4: Overview of the rectifier transformer window
a) winding constellation of the rectifier transformer
b) stray magnetic field distribution in the upper section of the transformer
c) the spatial distribution of the radial magnetic field component along the foil winding
d) spatial eddy currents' distribution induced by the radial components of the magnetic field

The radial component of the stray magnetic field is concentrated at the top and at the bottom of the foil, thus the eddy currents' density is also intensified at the foil edges

design such as three-phase rectifier transformers, it is somehow desired to have two windings at the low voltage side (LV_1 and LV_2) placed one above the other; also, a high voltage winding requires division into two sections connected in parallel, as shown in Fig. 4a. Due to the magnetic field asymmetry (Fig. 4b), the surface integral $B_r(z)$ of along the foil height results in some residual flux (Fig. 4c).

Let us suppose for the moment that the magnetic field B_r related to the residual flux, is evenly distributed along the winding's height (B_0) as is illustrated with the dashed line in Fig. 5b. To abide by the actual field distribution, it is somehow sensible to expect that the field is going to be concentrated only at the limited portion of the foil marked by m in Fig. 5. In practical applications of the proposed method, the parameter m turns out to be in the range of $0{,}2b_g$ - $0{,}35b_g$, and has to be determined experimentally from the measured values of the short circuit losses. The losses' evaluation in the single turn of the foil due to the spatially distributed residual flux as is presented in Fig. 5b, follows from the loss expression which holds for the thin plates, and is given by Eq.(8) [4, 5].

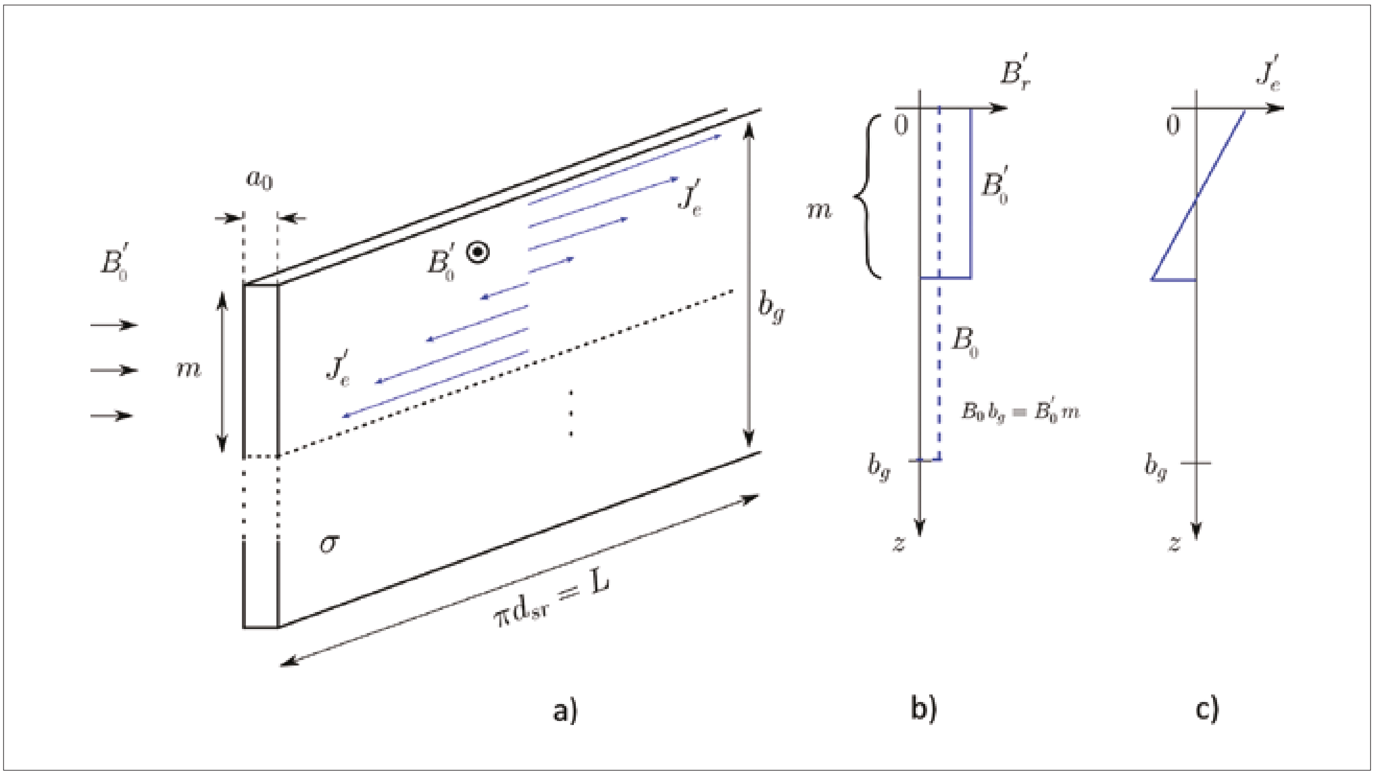

Figure 5: Eddy currents and 'residual flux' distribution across the foil sheet
a) the foil sheet (single turn) with eddy currents induced by the 'residual flux'
b) the spatial distribution of 'residual flux' along the foil
c) spatial distribution of the eddy current's density induced by the 'residual flux'

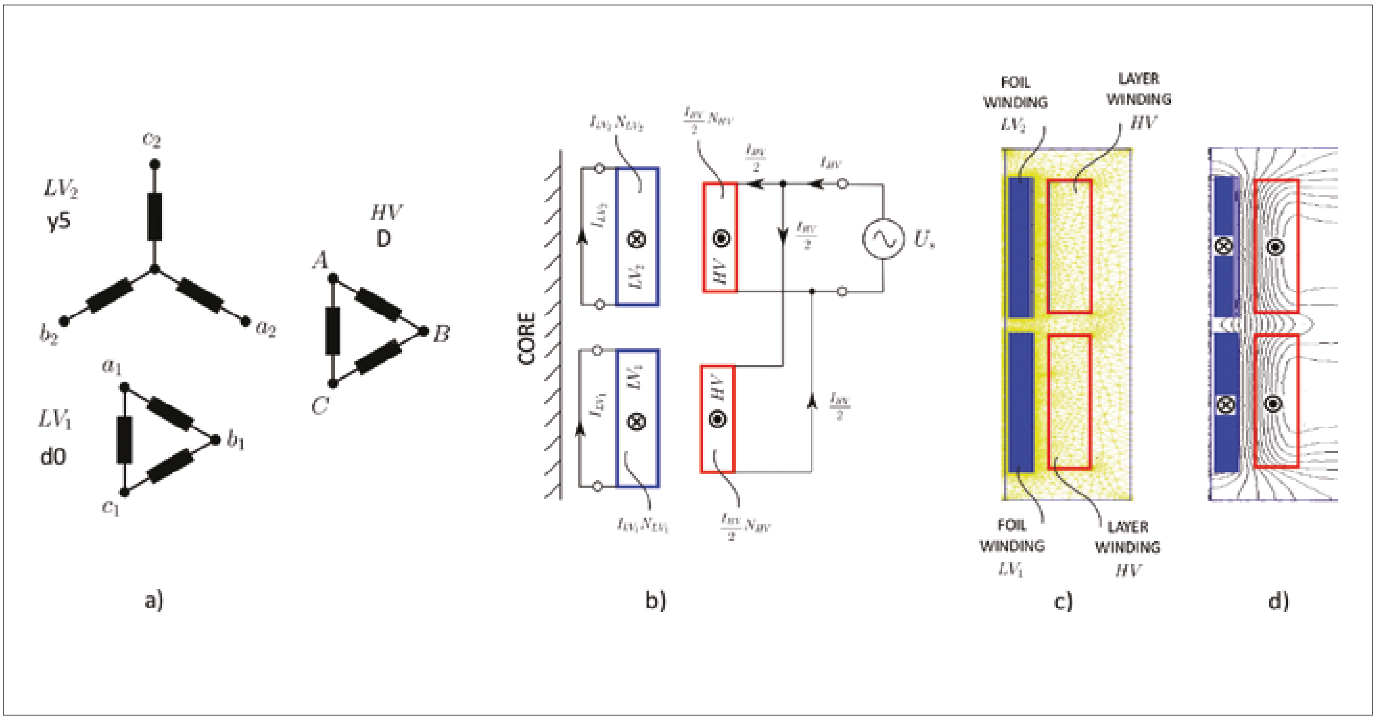

Figure 6: Three-phase rectifier transformer analyses
a) vector group and connection diagram of the rectifier transformer
b) winding connection during the short-circuit test
c) the transformer model in the FEMM 4.2 preprocessor mode
d) postprocessor mode

$$P'_{\mathrm{f}} = \frac{\omega^2 \sigma \pi d_{\mathrm{sr}} a_0 b_{\mathrm{g}}^2 B_0^2 m}{24} \qquad (8)$$

To take into account the residual losses of the whole winding in all three phases, a summation over winding's turns has to be performed, Eq.(9), where q indicates a turn in the foil winding.

$$P'_{\mathrm{e}} = 3 \sum_{q=1}^{N} P'_{\mathrm{f,q}} \qquad (9)$$

3. Results and Discussion

By means of the presented method, the losses in windings have been investigated numerically on a three-phase rectifier transformer, UT 3600 kVA – 35 / 2x0,7 kV Dy6d0 produced by Kolektor Etra, which serves as a power supply unit for the 12 pulse rectifier bridge used in metallurgical processes. Such transformer comprises of two low voltage windings (LV_1 and LV_2), placed one above the other, connected in delta and wye connections, respectively, where the high voltage winding is usually connected in delta and divided into two parallel sections, as presented in Fig. 6a. The losses have been evaluated in accordance with the standard loss procedure, where the HV winding is supplied, while the LV_1 and LV_2 windings are short-circuited, Fig. 6b. The field distribution within the transformer window during the short-circuit test is similar to the one shown in Fig. 6d, thus the losses caused by the residual flux have also been considered in the calculations. For the purpose of magnetic calculations, the 2D axisymmetric single phase model of the transformer was created in the software environment FEMM 4.2 [6]. The view of the model in preprocessor and postprocessor modes is shown in Fig. 6c and Fig. 6d respectively. The proposed method was used to obtain losses which arise in the foil windings only (i.e. LV_1 and LV_2 in Fig. 6b), while the determination of the HV losses was calculated by the method described in [4]. Additional losses that appear in other parts of the transformer's construction (eg. fitch plates, tank walls, leads, etc.) were not included in the model of the transformer, hence, the numerical results are somehow expected to be lower than the measured ones, which corresponded to the measurements (Table 1) [7]. Additionally, the numerical approach somehow gives a reasonable loss distribution among windings, from which the estimation of heat and temperature conditions within the winding could be discovered. Even though the additional losses have not been evaluated numerically, they are in the range between 3 % to 15 % of the total short circuit (SC) losses, depending mainly on the transformer design, power rating SC impedance, and voltage level [4]. We presumed that additional losses correspond to 11 % of the total SC losses just to compare the calculated and measured values.

The influence of the additional losses in the foil windings on the overall losses could be significant and reach up to 70 % of the winding's DC losses

Conclusion

The article deals with the losses model of a foil winding, including the load losses as well as the additional eddy currents' losses that appear due to the stray magnetic field distribution in the transformer window. In case of any

Table 1: Transformers' characteristics and short-circuit losses

Transformer characteristics				
Type		UT 3800		
No. Phases		3		
Frequency	Hz	50		
Rated Power	kVA	3600 / 2x1800		
Rated Voltage	kV	35 / 2x0,7		
Vector Group		Dy5d0		
Short circuit losses				
SC Losses		Calculated		Measured
		I^2R	eddy	
LV_1	kW	3,7	3,4	N.A.
LV_2	kW	3,8	3,5	N.A.
HV	kW	9,4	0,3	N.A.
Total SC losses in windings	kW	24,1.		N.A.
Additional losses	kW	~ 3*		N.A.
Total SC losses	kW	~ 27,1*		26,7
* The estimation of the additional losses has been evaluated as 11 % of the total SC losses.				

asymmetry of the magnetic field along the foil winding, the losses increase by virtue of the so-called residual flux introduced here; its influence on the overall losses could be significant and could reach up to 70 % of the losses caused by the load current in the winding. Even though the FEM based software was used in calculations, it is still necessary to carry out some extra computational efforts to obtain the 'residual losses', which are not reachable otherwise, but somehow occur in the foil windings. However, the numerical results gained by the method correspond to the measured ones; although the notable difference of near 10 % exists, it is mainly related to losses taking places in other constructional parts (eg. fitch plates, tank walls, cover, leads, etc.) which are not included in the proposed model.

Any asymmetry of the magnetic field along the foil winding increases the foil losses

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