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Determining Specific Power Loss in
Joint Area of Laminated Magnetic Core

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Abstract—**This paper discusses the method of analysis of specific power loss in the joint area of steel laminated core. The method is based on comparison of power loss data obtained from the tests of a circular shape magnetic core. Initially, the core build using uncut (solid) lamination sheets was tested to obtain the loss reference values. Then the laminations were cut onto four sections, and the core was tested again to obtain the loss increase associated with the implemented joint area. The test readings were processed to separate losses due to tangential and normal fluxes in the laminates. The processed data represented as relative p.u. values of increase in specific power loss have been extended to conduct an analysis of a rectangular magnetic core made using anisotropic, grain-oriented silicon electrical steel. The results demonstrated that the power loss produced by the normal magnetic flux dominates in the structure of total power loss in the rectangular core (approx. 85%). The proposed approach utilises the septation of losses produced by tangential and normal fluxes; it can be applied for the analysis of loss in the joint areas of magnetic cores of various power transformers.**

Keywords—specific power loss, eddy current loss, hysteresis loss, electrical steel, laminated core

I. INTRODUCTION

Power transformers are recognised as very efficient components of the electrical power system. A typical loss rate of power distribution transformers is about 1% [1]. However, the total power loss in the grid related to transformers' operation is comparably high due to a large number of transformer installations in the electricity path form generation side to consumer load. It has been reported that the total rated capacity of installed transformers is in 6-7 times higher than actually generated power whereas the energy loss in the transformers constitutes of 2% of the electricity produced by power plants. It is about 1/3 of total losses occurred in the power system due to transmission and distribution of electrical energy [2].

Improvement in magnetic properties of electrical steels used to manufacture power transformers is the main factor to reduce the losses produced by transformer operating under no-load condition. Testing, analysis and prediction of operational performance of existing and incoming electric steels become crucial for research, development, design, and industrial application of power transformers. A thorough analysis of electric steels requires the implementation of appropriate models and methods for detailed investigation of the magnetic phenomenon in the transformer core [3]-[7]. The major contributor to power loss of laminated transformer core is the joint area where the magnetic flux is redistributed and performed differently in comparison to uniform flowing. Understanding of the flux behaviour in the lamination joint area is a key requirement for a comprehensive analysis of the core magnetic properties [8].

This paper presents an approach to determine the increase in specific power loss associated with the joint area in the magnetic core of power transformers. It provides the method description and an example of its application for analysis of the relative increase in specific power loss in an anisotropic, grain-oriented silicon electrical steel core sample.

II. METHODOLOGY

The method of determining the power loss associated with joints in the laminated structure of the magnetic core is based on comparison of power losses obtained from tests of two magnetic cores having the same dimensions and material but different assembling structures. In fact, it is the same magnetic core assembled initially using the lamination sheets without joints and tested, whereafter the core laminations are cut onto several sections and the same tests are applied to investigate the difference in power losses.

At the first stage, the practical experiment is applied to the core built by laminations without joints to obtain the reference value of the power loss P in the magnetic core. At the next stage, the core was disassembled, and the laminations have been cut using an electrical discharge machining method. Then, the core has been reassembled and tested again using the same instrumentation set-up. The power loss readings P_J obtained from the second test include the additional power loss ΔP occurred in the joints area. Therefore, the power loss in the second core is defined as

$$P_J = P + \Delta P \qquad (1)$$

where P_J is the power loss in the magnetic core with joints (W); P is reference power loss for no joints magnetic core (W); ΔP is the power loss in the joints area (power loss increase due to joints) (W).

From (1) the increase in power loss is expressed as

$$\Delta P = P_J - P \qquad (2)$$

In terms of specific power loss, the above equation is rearranged as follows

$$\Delta P_S = P_{SJ} - P_S = \frac{P_J - P}{G} \tag{3}$$

where ΔP_S is the increase in specific power loss due to joints (W/kg); P_S is the specific power loss for no joints magnetic core (W/kg); P_{SJ} is the specific power loss in the core with joints (W/kg); G is the mass of the magnetic core (kg).

The magnetic core without joints has no normal flux in the laminations, and the power loss associated with this flux is negligible. Hence, the increase in the specific power loss associated with the joints is represented as follows

$$\Delta P_S = P_{SEn} + \Delta P_{SHE\tau} \tag{4}$$

where P_{SEn} is the specific eddy current power loss produced by the normal flux component (W/kg); $\Delta P_{SHE\tau}$ is the additional specific power loss due to hysteresis and tangential flux in the joint area (W/kg).

$$\Delta P_{SHE\tau} = \Delta P_{SH} + \Delta P_{SE\tau} \tag{5}$$

where ΔP_{SH} is the additional hysteresis specific power loss produced in the joints area (W/kg); $\Delta P_{SE\tau}$ is the additional eddy current power loss produced due to compression of tangential flux component in the joint area (W/kg).

A classical equation of eddy current loss is based on the assumptions that the magnetic permeability of the material is constant (μ = const) [9]. In order to omit this assumption, it is suggested to implement the dynamic coefficient, which reflects the change in magnetic flux penetration depth occurred under varying magnetisation and frequency [4], [9]. Therefore, the specific eddy current power loss P_{SE} is defined as follows:

$$P_{SE} = \frac{\pi^2 l^2}{6\gamma\rho} B_M^2 f^2 F(\xi) \tag{6}$$

where l is the smallest transverse dimension of the laminations; B_M is the magnitude of ac magnetic field density; f is the frequency; $F(\xi)$ is the dynamic coefficient which is the function of the dumping factor ξ; γ is the material mass density; ρ is the material resistivity.

The dynamic coefficient as a function of the dumping factor is defined as [9]

$$F(\xi) = \frac{3(\sinh\xi - \sin\xi)}{\xi(\cosh\xi - \cos\xi)} \tag{7}$$

where the damping factor $\xi = l\sqrt{\dfrac{\pi f \mu}{\rho}}$; μ is the magnetic permeability of the material.

The graph of dynamic coefficient vs damping factor is shown in Fig. 1. If the value of the dumping factor $\xi \leq 2$, then the function $F(\xi) \approx 1$, which means that the skin effect is negligible. This is corresponding to the magnetising mode by tangential flux Φ_τ. Therefore, the equation on specific eddy current loss is reduced to the classical form [9].

$$P_{SE\tau} = \frac{\pi^2 d^2}{6\gamma\rho} B_M^2 f^2 \tag{8}$$

where d is the lamination thickness (the smallest transverse dimension for the tangential magnetic flux).
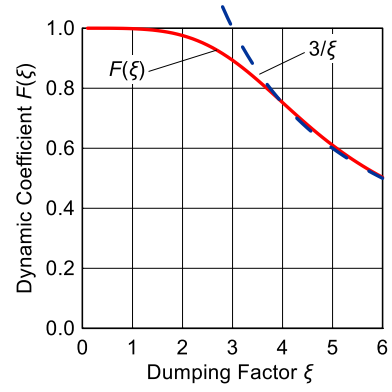

Fig. 1.   Dynamic coefficient vs. damping factor $F(\xi)$ [9].

However, with an increase in the magnetisation process dynamic the skin effect becomes stronger. As a consequence, the strong skin effect increases the dumping factor ($\xi \geq 4$) and reduces the dynamic coefficient to the following equation:

$$F(\xi) = \frac{3}{\xi} \tag{9}$$

Substituting (9) into (6) produces the equation of specific eddy current loss generated by the normal magnetic flux Φ_n

$$P_{SEn} = \frac{\pi^{1.5} b}{2\gamma\sqrt{\mu\rho}} B_M^2 f^{1.5} \tag{10}$$

where b is the lamination width (the smallest transverse dimension for the normal magnetic flux).

III. PRACTICAL EXPERIMENT

A. Steel Samples

Two samples of the magnetic core have been experimentally investigated. Both samples were made using cold-rolled electrical steel with a silicon content of approx. 3.3%Si. The dimensions of both samples are shown in Fig. 2.
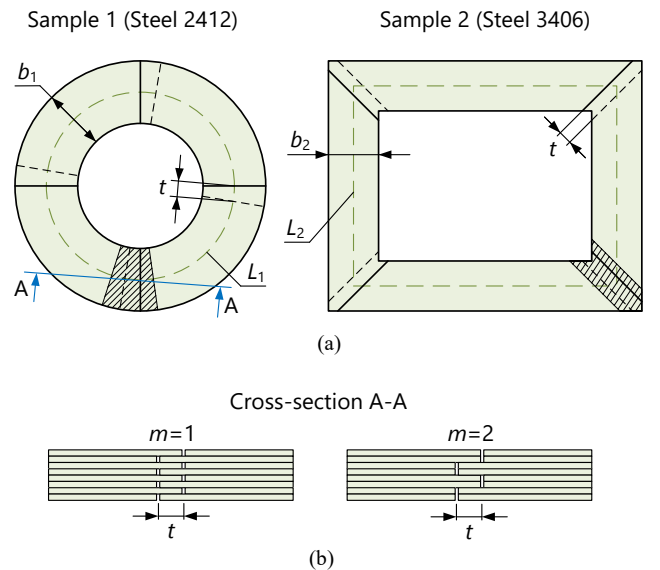

Fig. 2.   (a) dimensions of sample 1 (circle, steel 2412) and sample 2 (rectangular, steel 3406), where the lamination joint areas are cross-hatched; (b) cross-section of joint area, where t is the lamination sheet overlap, m is the number of laminations in a layer of the core sample.
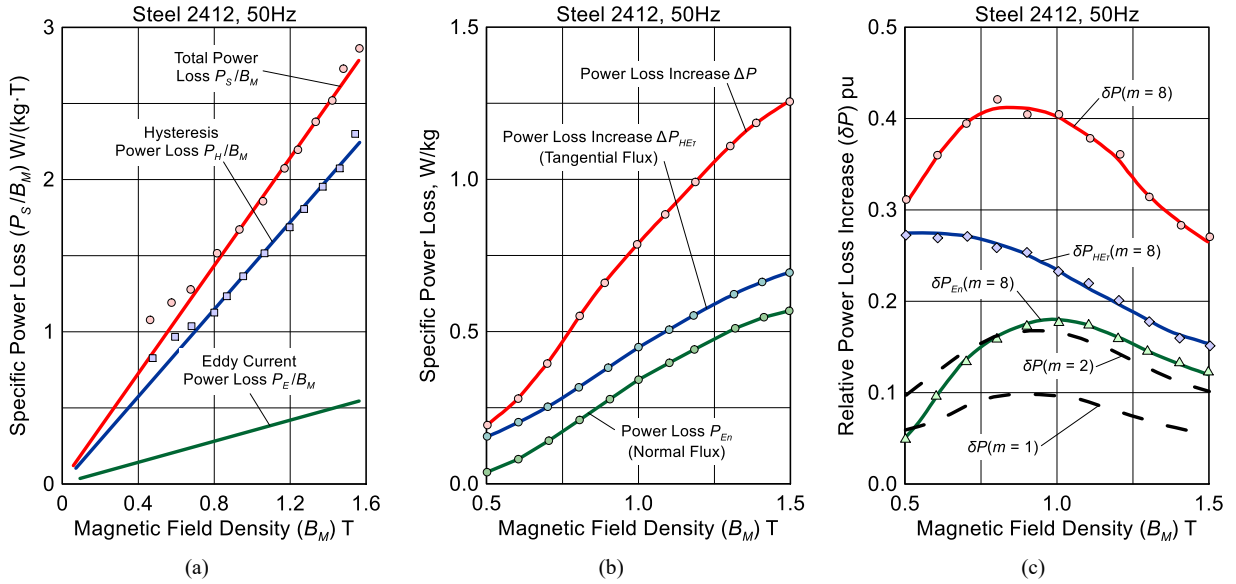
Fig. 3. (a) test results for the solid (uncut) sample 1; (b) test results for the cut sample 1 ($m = 8$); (c) relative increase in specific losses vs. magnetic field density B_M for sample 1.

Sample 1 is formed as a circle magnetic core with isotropic, non-grain-oriented electrical steel 2412 [10]. This steel has a fine-grain domain structure and a comparatively large level of specific loss of $P_S = 4.2$ W/kg (at frequency of 50 Hz and magnetic field density $B_M = 1.5$ T). Fig. 2a shows the dimensions of the sample, where the lamination thickness $d_1 = 0.5$ mm; the size $b_1 = 6.06$ cm; the mean length $L_1 = 0.536$ m; average lamination sheet overlap $t = 7.5$ mm; the weight of the sample $G_1 = 0.958$ kg; the ratio of the joint area volume to the sample volume $q = 0.45$.

Fig. 2a demonstrates that the sample core is assembled using layers of cut lamination sheets (four cuts). However, the number of cut laminations m in a layer can be varied. Fig. 2b shows the cross-section of the joint area for $m = 1$ and $m = 2$. The advantage of the circular shape core is that the same sample can be analysed at the different number of the cut laminations in a layer ($m = 1, 2, …, 8$). The number of laminations in a layer $m = 0$ corresponds to the uncut lamination sheets.

Sample 2 is a rectangular, U-shape magnetic core made of anisotropic, grain-oriented silicon electrical steel 3406 [11]. The steel has a stripe domain structure and the specific loss of $P_S = 1.33$ W/kg (at a frequency of 50 Hz and magnetic field density $B_M = 1.7$ T). The dimensions of the sample are as shown in Fig. 2a, where the lamination thickness $d_2 = 0.3$ mm; the width of the core laminations $b_2 = 0.12$ m; the mean length $L_2 = 2.505$ m; the weight of the sample $G_2 = 13.8$ kg; the ratio of the joint area volume to the total volume of the core sample $q = 0.27$.

Rectangular sample 2 is used to study how the joints overlap width t, and the number of laminations m affect the loss increase in the joints area. The sample 2 test readings are also used to verify the proposed approach.

B. Test Results of Sample 1

Sample 1 (steel 2412) was tested using the magnetic material measurement instrumentation ESS-2S to obtain the total power loss in the core under alternating sinusoidal magnetic field density at a frequency of 50 Hz. The readings of the total power loss were recorded for the magnetic field density magnitude varied in the rage of

$B_M = 0.4\text{-}1.6$ T. The hysteresis losses have experimentally determined by the hysteresisgraph BHS-40S as losses for dc hysteresis loops and then recalculated to adjust data to a frequency of 50 Hz.

Initially, the eddy current losses are determined in the solid (uncut) sample 1 (steel 2412) where $m = 0$. The test series conducted for various values of magnetic field density magnitude B_M to obtain the readings of total power loss and hysteresis power loss. The eddy current losses are calculated as the difference between total power loss and hysteresis loss. The results correspond to the classical approach (8) to determine eddy current loss. Hence

$$P_{SE} = P_S - P_{SH} \qquad (11)$$

Fig. 3a demonstrates the test results for the solid (uncut) sample 1 (steel 2412; $m = 0$). The results are shown as the ratio of specific power loss to magnetic field density: P_S/B_M (for total loss), P_{SH}/B_M (for hysteresis loss), and P_{SE}/B_M (for eddy current loss). It can be seen that, in the range of operating values of B_M, the results are well approximated by straight lines passing through the origin. It means that the specific losses for the steel 2412 P_S, P_{SH}, and P_{SE} are proportional to $(B_M)^2$, and the ratio P_{SH}/P_{SE} is approximately constant ($P_{SH}/P_{SE} \approx$ const.). The linear approximation of the losses confirms that the relative increase in the total loss, hysteresis loss and eddy current loss are the same

$$\delta P = \delta P_H = \delta P_E \qquad (12)$$

where $\delta P = \dfrac{\Delta P}{P}$; $\delta P_H = \dfrac{\Delta P_H}{P_H}$; $\delta P_E = \dfrac{\Delta P_E}{P_E}$.

The next test has been conducted using the same sample 1, which lamination sheets were cut onto four sections as shown in Fig. 2a. The laminations were cut using an electrical discharge machining method to avoid mechanical stress in the cut sheet edges. The test procedure applied for the cut sample 1 was the same as previously, and the readings of total power loss and hysteresis loss were obtained. The test results showed that the power loss in the magnetic core is increased due to additional loss produced in the joint area according (3). The test data for
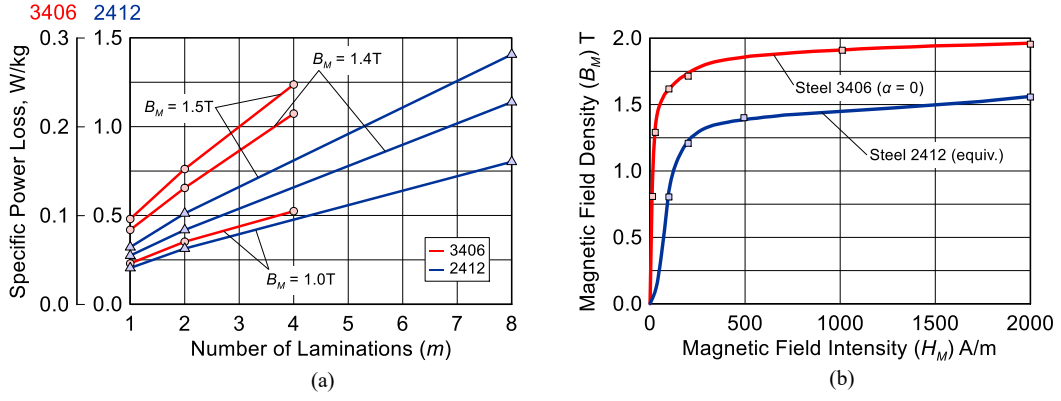
Fig. 4. (a) the increase in specific power loss vs. the number of laminations in a layer of the laminated magnetic core for sample 1 (steel 2412) and sample 2 (steel 3406); (b) the magnetising cures for sample 1 (steel 2412) and sample 2 (steel 3406) under tangential flux (alongside rolling direction).

the number of cut laminations in a layer $m = 8$ are displayed in Fig. 3b. It is assumed that the increase in eddy current loss is related to (1) the higher magnetic field density in the joint area of the core (tangential flux component Φ_τ) and (2) occurrence of normal flux component Φ_n which was non-existent in the uncut core sample. The specific eddy current power loss produced by the normal flux component in the joint area has been calculated as

$$P_{SEn} = \Delta P_S - \Delta P_{SHE\tau} \qquad (13)$$

The relative increase in specific power loss for the sample 1 can be found using (4) where all equation members are divided by P_S as follows to obtain p.u. values.

$$\frac{\Delta P_S}{P_S} = \frac{P_{SEn}}{P_S} + \frac{\Delta P_{SHE\tau}}{P_S} \qquad (14)$$

(13) is rearranged to represent it as

$$\delta P = \delta P_{En} + \delta P_{HE\tau} \qquad (15)$$

where $\delta P = \dfrac{\Delta P_S}{P_S} \times 100\% = \dfrac{\Delta P}{P} \times 100\%$;

$\delta P_{En} = \dfrac{P_{SEn}}{P_S} \times 100\%$; $\delta P_{HE\tau} = \dfrac{\Delta P_{SHE\tau}}{P_S} \times 100\%$

Therefore, the relative increase in specific eddy current power loss in p.u. produced by the normal flux component is calculated as follows

$$\delta P_{En} = \delta P - \delta P_{HE\tau} \qquad (16)$$

Fig. 3c shows curves of the relative increase in specific losses vs. magnetic field density B_M for the circle core sample 1 having eight laminations in a layer ($m = 8$). The dashed curves in Fig. 3c demonstrate the relative increase of power loss for the core with the number of lamination sheets in a layer of the laminated core $m = 1$ and $m = 2$. It can be seen that the curve $\delta P_{HE\tau}(B_M)$ has a maximum in the unsaturated area at low B_M and is reduced under core saturation, whereas the curve $\delta P_{En}(B_M)$ has a maximum at $B_M = 0.9$-1.2 T. The curve $\delta P(B_M)$ has the same shape at different values of m, while the components $\delta P_{En}(B_M)$ and $\delta P_{HE\tau}(B_M)$ are very different. Based on the similarity of the curves' shapes, it is assumed the structure of the components distribution $\delta P_{En}(B_M)$ and $\delta P_{HE\tau}(B_M)$ is similar for the different thicknesses of the layer of lamination sheets ($m \times d$).

At the final stage, sample 1 has been cut along the circle mean length L_1 (Fig. 3a) using also an electrical discharge machining method. Therefore, the width of the laminations in the core becomes half of the initial width ($0.5b_1$). The test results of the half-cut core having $m = 8$ showed that the loss component $\delta P_{En}(B_M)$ is reduced approx. in $\sqrt{2}$ (1.4) times. It means that the loss component related to the normal flux can be represented as $\delta P_{En} \sim (b_1)^{0.5}$. This fact concludes that the increase in the eddy current loss produced by a normal flux significantly depends on the width of the lamination sheet.

The described approach is based on the separation of eddy current losses produced by the tangential and normal fluxes. It has been shown that its application can successfully determine the distribution structure of power losses in the steel 2412 assembled as a sample core with joints. However, the steel 2412 is not applicable for power transformer manufacturing; it has a larger level of loss in comparison to isotropic steels usually used in the transformer industry. But, in contrast to the steel 2412, the proposed approach to determine the loss distribution structure can be extended to the analysis of the power losses in other types of electrical steels.

C. Test Results of Sample 2

This section discusses how the proposed method can be applied to determine the structure of power loss in the electrical steel 3406, which is the material of sample 2. The test measurements of sample 2 were conducted using a conventional wattmeter method [12] where the excitation winding was energised to provide an alternating sinusoidal magnetic field density in the range of $B_M = 0.5$-1.7 T at a frequency of 50 Hz. The power loss readings were obtained by a low power factor wattmeter D522. The test results showed that total power loss in the sample core significantly depends on the number of laminations in a layer m, whereas the lamination overlap t provides a very week affect on the value of power loss. When the number of lamination sheets in a layer of the sample core is $m = 1$ and the lamination sheet overlap in the joint area is varying in the range of $t = (4; 8; 10; 12; 20)$ mm, the largest relative increase in losses does not exceed $\delta P \leq 4.7\%$. However, when the number of lamination sheets in a layer is changed from $m = 1$ to $m = (2; 4)$ at a constant value of the overlap t, the increase in power loss is more significant: $\delta P = 8\%$ ($m = 2$) and $\delta P = 18\%$ ($m = 4$).
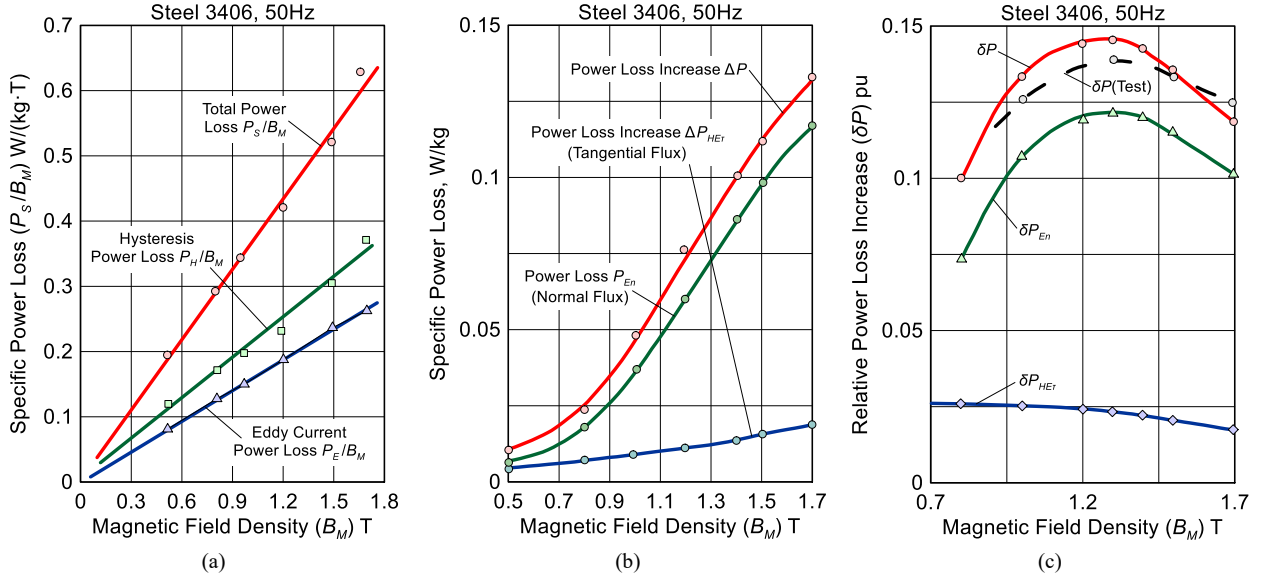
Fig. 5. (a) specific power loss for sample 2; (b) increase in specific power loss for sample 2; (c) relative increase in specific losses vs. magnetic field density B_M for sample 2 (the test data are obtained from an experiment where the magnetic flux flowed in the steel rolling direction).

Fig. 4a shows the increase in specific power loss vs. the number of lamination sheets in a layer of the laminated magnetic cores for sample 1 (steel 2412) and sample 2 (steel 3406). Fig. 4b demonstrates the magnetising curves for both samples. Analysis of the data represented in the graph (Fig. 4a) shows that the increase in power loss is approximated as follows

$$\Delta P_S \left(m \right) = \Delta P_S^{m=1} \times m^{0.72} \qquad (17)$$

where $\Delta P_S^{m=1}$ is the increase in specific power loss for a laminated sample core having a single lamination sheet in a layer ($m = 1$).

Extrapolation the increase in power loss (17) from the number of laminations in a layer m to the core layer thickness $m \times d$ shows that all components in (13) are proportional to $(m \times d)^{0.72}$.

IV. ADJUSTMENT OF LOSS STRUCTURE FOR SAMPLE 1 TO SAMPLE 2

In order to provide a correct extrapolation of the results obtained for sample 1 (steel 2412) to sample 2 (steel 3406), the data of sample 1 should be recalculated using a set of adjustment coefficients. The coefficients are defined in accordance to the following assumptions.

- Permeability μ in a perpendicular direction (under normal flux Φ_n) is similar for both samples.

- The distribution structure of the loss components $\delta P_{En}(B_M)$ and $\delta P_{HE\tau}(B_M)$ in terms of the relative increase in specific power loss is the same for both samples.

- The joint areas are different in the sample cores; hence, a parameter q is introduced as the ratio of the joint area volume to the sample volume to make possible a comparison of both samples.

- The relative increases in specific power losses are proportional to the core layer thickness as $\delta P_{En} \sim \delta P_{HE\tau} \sim (m \times d)^{0.72}$.

- The relative increase in the eddy current loss produced by a normal flux is proportional to the width of the lamination b as $\delta P_{En} \sim (b_1)^{0.5}$.

Based on the above assumptions, the set of adjustment coefficients (k_q; k_m; k_d; k_b; k_p) is defined as

$$k_q = \frac{q_1}{q_2}; k_m = \left(\frac{m_1}{m_2} \right)^{0.72}; k_d = \left(\frac{d_1}{d_2} \right)^{0.72};$$

$$k_b = \left(\frac{b_1}{b_2} \right)^{0.5}; k_p = \frac{P_{S1}^{m=1}}{P_{S2}^{m=1}} \qquad (18)$$

Therefore, the relative increases in specific power losses obtained for sample 1 can be recalculated to sample 2 using the adjustment coefficients as follows

$$\delta P_{En}^2 = \delta P_{En}^1 \times \frac{k_p}{k_q k_m k_d k_b}$$

$$\delta P_{HE\tau}^2 = \delta P_{HE\tau}^1 \times \frac{1}{k_q k_m k_d} \qquad (19)$$

where superscript index 1 designates sample 1; index 2 designates sample 2; $k_q = 1{,}67$; $k_m = 4.47$; $k_d = 1.44$; $k_b = 0.711$; $k_p = 5.11$; $m_1 = 8$; $m_2 = 1$.

The results obtained for sample 2 using (19) is shown in Fig. 5b. The relative increase in specific power loss for sample 2 and the distribution of components $\delta P_{En}(B_M)$ and $\delta P_{HE\tau}(B_M)$ are displayed in Fig. 5c. Fig. 5a demonstrates the specific power losses in the sample core without joints, which have been developed from the adjusted data in Fig. 5b.

V. CONCLUSION

It can be seen form analysis of the curves in Fig. 5b and Fig. 5c that the eddy current power loss produced by the normal magnetic flux Φ_n is dominating in the structure of total power loss in the magnetic core. The portion of the

relative increase in specific power loss due to normal flux is quite significant and constitutes approx. 85% of the total relative increase.

Fig. 5c demonstrates the results of the total relative power loss in sample 2 obtained experimentally (dashed line). It can be seen that the calculated data is satisfactory correlating with the test readings. This acceptable correlation verifies the proposed method.

The proposed approach is developed to determine the power loss distribution in the electrical steel cores and based on septation of losses produced by tangential and normal fluxes. It has been shown that the approach can be extended to an analysis of loss in the joint areas of other laminated magnetic cores including the cores of industrial-size power transformers.

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