POWER LOSSES IN TYPICAL DYNAMO STEEL SHEETS DURING THE AXIAL MAGNETIZATION

Abstract: Magnetization processes in typical dynamo steel sheets can have different character. In parts of the dynamo sheets, which refer to the stator core of induction motors, the magnetization process has rotational character, first of all elliptical character. The second kind of magnetization processes, the axial magnetization occurs mainly in stator teeth. It is worth underlining that dynamo sheets are also applied in cores of small power transformers. The paper deals with power losses depending on the frequency and on the maximum value of the flux density in dynamo sheets. In the analysis, the anisotropic properties of these sheets were taken into consideration. Special attention was paid to the losses depending on the magnetization direction on the sheet plane. Measured power losses in selected dynamo sheets were compared with results obtained on the basis of analytical formulas.

Keywords: anisotropic properties, axial magnetization, dynamo steel sheets, power losses

1. Introduction
Dynamo steel sheets are mainly used in constructions of stators and rotors of induction and synchronous motors. In stators the magnetic field changes with the frequency of 50 Hz when the motors are powered directly by the one-phase or three-phase network. In cases, when motors are controlled by means of the voltage source inverters the frequency of the magnetic field in stator can vary its value in the range from several to several hundred Hz [2]. On the other hand, the frequency of rotor currents in induction motors has a value of several Hz. Therefore, it can be assumed that the iron power losses occur first of all in stator cores and stator teeth.

Magnetization processes in stators can have a different character. In stator cores the magnetization process has mainly elliptical character, but in stator teeth the axial magnetization occurs very often. When a dynamo sheet has isotropic properties then power losses in particular stator teeth are the same. However, most of dynamo sheets have certain anisotropic properties in terms of both the magnetic properties and power losses. It means that the amount of power losses depends on the direction of the magnetic field changes with respect to the rolling direction in the given dynamo sheet.

It is worth underlining that dynamo steel sheets are frequently used in constructions of cores of small power transformer. From these sheets, the E and U sheet shapes for transformer cores are cut out. Worse magnetic properties in directions other than the rolling direction of dynamo sheets cause to decrease the value of the resultant magnetic flux in a transformer core.

2. Calculation of power losses in magnetic circuits
Calculations of power losses in magnetic circuits of electrical machines and transformers are still an important task, which is usually an integral part in the analysis of the magnetization processes. It is well known that total power losses are treated as a sum of hysteresis losses, eddy current losses, and excess losses, which are caused by the occurrence of the so-called domain eddy currents in electrical steel sheets [4, 8, 10]:

\[ P_{\text{tot}} = P_h + P_{ed} + P_{ex} \]  \( (1) \)

where: \( P_h \) – hysteresis losses, \( P_{ed} \) – eddy current losses, \( P_{ex} \) – excess losses.

The reasons for power losses during the axial and rotational magnetization processes are similar, but their estimation varies considerably due to a different mechanism of each of these processes. In practice, losses occurring in steel sheets are given per mass unit and they are called as the specific power loss. Unlike losses in the rotational magnetization, power losses occurring during the axial magnetization can be estimated with the use some analytical formulas. The Steinmetz formula, determining the hysteresis losses, is well-known [5]:

\[ p_h = \eta f B^{1.6} \]  \( (2) \)
where: \( \eta = 3.9 \cdot 10^3 \), \( f \) – frequency, \( B \) – maximum value of the flux density in the sheet. Quite similar form, as previous relation, has the Richter formula:

\[
p_h = \varepsilon f B^2
\]

where: \( \varepsilon \) – constant depending on the kind of the given steel sheet. For electrical steel sheets this constant is equal to 0.038 m\(^4\)/H.

In some cases, concerning the calculation of the hysteresis losses, the following relation is used:

\[
p_h = \varepsilon f \left| B_{\text{om}} \right|^2 \frac{1}{k d} \left( \sin kd - \frac{kd}{chkd + \cos kd} \right)
\]

where: \( k \) – coefficient determined as

\[
k = \frac{\sqrt{\omega \mu \gamma}}{2}
\]

\( \gamma \) – conductivity of the given electrical sheet, \( d \) – thickness of the sheet.

The “classical” eddy currents are usually estimated with the use of the formula:

\[
P_{\text{ed}} = \frac{\gamma \pi^2 d^2 f^2 B_{\text{sm}}^2}{6}
\]

Parameters in the latter relation are defined in the previous formulas. The similar form has the relation, which is also frequently used:

\[
P_{\text{ed}} = \frac{1}{24} \gamma \omega x^2 \left| B_{\text{sm}} \right|^2 d.
\]

It should be remembered that the discussed formulas have been formulated assuming a constant value of the magnetic permeability. Moreover, the skin effect is omitted. However, for most of dynamo sheets, the magnetization characteristic has a curvature when flux densities are about 1 T. Due to this the magnetic permeability cannot be treated as a constant value. Additionally, in dynamo sheets with the thickness of 0.5 mm or thicker the distribution of the magnetic field is not homogeneous when the frequency is equal to 50 Hz or higher.

Many problems in estimation of power losses in electrical steel sheet occur during calculations of losses caused by the so-called domain eddy current. These micro currents appear around moving domain walls. The model of domain wall motion proposed by Pry and Bean allows us to estimate these losses but only in transformer sheets which usually have an ordered grain structure [9]. However, grains in typical dynamo sheets are arranged randomly, although, most of these sheets has certain anisotropic properties [7]. Presenting methods using for losses estimation we should also mention about the method worked out by G. Bertotti [3, 4], who has proposed statistical approach to estimate the eddy current losses. He assumed that the movement of domain walls during the magnetization process consists of random jumps in iron crystals of dynamo sheet. He treated fragments of these walls as certain magnetic objects.

It should be stressed that none of the above-mentioned formulas take into account the dependence of power losses on the magnetization direction.

Estimation of power losses arising during the rotational magnetization is qualitatively different problem. Determination of these losses is much more difficult than calculations of losses during the axial magnetization. Until now, analytical formulas allowing us to simply estimate power losses under rotational magnetization have not been formulated. These losses are determined with the use of the basic formula [1, 10]:

\[
P_h = \frac{1}{T} \int_0^T \left( H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt
\]

where: \( B_x, B_y \) – components of the flux density in a certain elementary segment of the given steel sheet, \( H_x, H_y \) – component of the magnetic strength.

However, application of this formula requires the calculation of the magnetic field distribution in the given electrical sheet for assumed conditions of the magnetization process. It is worth noting that a method of field determination of hysteresis power losses is presented in [6].

3. Dependence of power losses on magnetization direction

Dynamo steel sheets are produced as non-oriented sheets and therefore they should have isotropic properties. Different magnetic measurements show that most of dynamo sheets have certain anisotropy, both in terms of the magnetization curves and power losses. These anisotropic features have been confirmed by crystallographic studies on the possible occurrence of textures in dynamo sheets. On the one hand, the magnetization process occurs most easily along rolling direction in the given dynamo sheet, on the other hand, power losses...
are the biggest when the magnetization process takes place along the transverse direction with respect to the rolling direction. Studies were carried out for two selected dynamo sheets marked as M530-50A, one of which is produced in the Czech Republic and the other in South Korea. Figure 1 presents values of the specific power loss in the dynamo sheet produced in the Czech Republic as the dependence on the direction of the magnetic field strength changes. Measurements were performed for four frequencies 25, 50, 75, and 100 Hz. The specific power losses are presented for two typical values of the flux density: 1.0 T and 1.5 T, as it is usually determined in standards. The next figure (Fig. 2) refers to the dynamo sheet produced in South Korea. Higher values of the specific total power loss occur during the magnetization along directions on the sheet plane which significantly differ with respect to the rolling direction. Differences of the power losses may be higher than ten percent with respect to losses in the rolling direction. It can be assumed that bigger hysteresis losses in these directions are the direct cause of greater total losses. Figure 3 presents hysteresis loops of the Czech sheet for three magnetization direction. Due to magnetic anisotropy hysteresis loops measured along directions inclined 45, 60 or 90 degrees with respect to the rolling direction are wider than hysteresis loop in the rolling direction. Hysteresis loops measured for the flux density of 1.5 T along the direction of 45 and 90 degrees are almost the same. The Korean dynamo sheet has similar properties as the Czech sheet (Fig. 4). Table 1 presents, for example, hysteresis power losses per hysteresis cycle for the both tested dynamo sheets. These values were determined for seven magnetization direction wherein the maximum value of the flux density was equal to 1.5 T. Hysteresis losses in the transverse direction are about twenty percent higher than losses determined in the rolling direction. Both the magnetic anisotropy and the loss anisotropy are caused by the occurrence of certain textures, which is a characteristic property of the most dynamo steel sheets [7]. This means that a certain amount of grains have a privileged crystallographic orientation. It should be noted that the standards define the acceptable anisotropy of the power losses in the range from 10 to 14%. It is worth noting that the losses for directions higher than 45 degrees with respect to the rolling direction are practically the same.

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1 Magnetic measurements were carried out in Laboratory of Magnetic Measurements in Stalprodukt SA, Bochnia (Poland)

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Fig. 1. Core losses of the Czech dynamo sheet: a) for $B_{\text{max}}=1.0$ T, b) $B_{\text{max}}=1.5$ T

Fig. 2. Core losses of the Korea dynamo sheet for $B_{\text{max}}=1.5$ T
Fig. 3. Hysteresis loops of the Czech dynamo sheet: a) for $B_{\text{max}} = 1.0$ T, b) $B_{\text{max}} = 1.5$ T

Fig. 4. Hysteresis loops of the Korean dynamo sheet for $B_{\text{max}} = 1.5$ T

<table>
<thead>
<tr>
<th>Table 1: Hysteresis losses per magnetization cycle in W/kg</th>
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<tbody>
<tr>
<td><strong>Czech sheet</strong></td>
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<tr>
<td>1.0 T</td>
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<tr>
<td>$0^\circ$</td>
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4. Comparison between measured and calculated losses

In many papers, it is concluded that the measured losses are significantly bigger than the calculated losses. As it was mentioned in Chapter 2, reasons of these differences are the so-called domain micro eddy currents which occur around moving domain walls. However, these remarks refer first of all to the transformer steel sheets. Their grains and thus domains may have an area of several square centimeters. On the other hand, average size of grains in dynamo sheets is in the range from 60 to 100 $\mu$m, and grains, in the vast majority, are arranged randomly. The occurrence of the excess losses in the dynamo sheets is rather a controversial issue. Although G. Bertotti in his paper [4] showed that the measured losses in a certain dynamo sheet are bigger than calculated losses, the research carried out for some typical dynamo sheets does not generally confirm this fact. It is obvious that the value of the calculated losses depends on the applied formulas in estimation of the hysteresis and eddy current losses. Figure 5 presents comparison between measured losses and estimated losses during the axial magnetization along the rolling ($0^\circ$) and transverse direction ($90^\circ$). The latter losses are calculated for two cases. In the first one hysteresis losses were estimated with the use of the formula (3) and in the second case the relation (4) was applied. In both cases eddy current losses are estimated by means of the formula (5). It should be stressed once again that abovementioned formulas do not take into account the direction of magnetization process. The smallest errors between the values of the measured and estimated losses occur when the power losses are estimated with the use of the sum of the formulas (3) and (5). However, these errors amount to a dozen or even more than twenty percent. Similar differences between the losses are for the Korean dynamo sheet.
Fig. 5. Measured and calculated losses of the Czech dynamo sheet: a) for $B_{\text{max}} = 1.0$ T, b) $B_{\text{max}} = 1.5$ T

5. Conclusions

Determination of the total power losses in typical dynamo sheets with the use analytical formulas without taking into account the magnetization angle can cause errors even up to 20 percent. Differences of the total losses for individual magnetization directions are caused by presence of the anisotropy properties. It may be assumed that this is due to higher hysteresis losses for the magnetization directions other than the rolling direction. However, the formulation of more general conclusions requires studies of a larger number of dynamo sheets derived from different manufacturers.

Further research should aim at deriving such analytical formulas that could take into account the magnetization direction. Power losses obtained by means of different analytical relations should also be compared with the losses estimated with the use of the general formula.

References


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