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STUDY OF PHYSICAL PROCESSES IN LAMINATED MAGNETIC CORES OF ELECTRIC MACHINES

The aim of the work is to use fast-moving processes to detect defects in the interlayer insulation of laminated magnetic cores of electric machines. Damages of interlayer insulation causes increased eddy currents as a result of increased losses and integral local overheating in the magnetic core. The article develops a mathematical field model of induction distribution in a toroidal toothed magnetic core of a 0.37 kW 4AA63V4U3 asynchronous motor when superimposed on the back of the core of the power winding powered by a high frequency voltage source in the given range. An experimental study of losses in the magnetic core and the distribution of eddy current losses and magnetization reversal (hysteresis) were carried out.

When designing an electric machine, its performance, optimum operating conditions, thermal state and many other factors are calculated using the nominal values of the parameters of steel, windings and all materials used in the machine. However, these materials do not always have the declared characteristics and quality. For example, in the manufacture and stamping of electrical steel sheets, it experiences a significant level of influence, which in a certain way affects its characteristics. In addition, even if one assume that during production all the stages of manufacturing the material came flawlessly, the state and, as a result, the parameters of the materials and the electric machine as a whole change during operation as a result of emergencies or even simple aging and wear.

Therefore, given these facts, it becomes clear that during planned or unplanned repairs it makes sense to check the condition of materials, insulation, since the allowable loads, temperature conditions, etc. depend on their condition. In particular, the state of the magnetic core largely determines the temperature around the conductors in the grooves and, as a result, determines how long the winding will actually last, in contrast to the specified service life and the rated power at which this electric machine should be used.

The concept of the state of the magnetic core can be divided into the state of electrical steel and the state of its insulation. The first component changes rather little during operation and is generally caused by the "aging" of the steel, except for any serious damage as a result of faults, but it can be damaged during manufacture. But it is the second component that is significantly influenced during operation and significantly determines the quality of the magnetic core as a whole.

***Key words:** electric machine, magnetic cores, eddy current losses, magnetic flux*

Introduction

Laminated magnetic cores of electric machines are an active part, one of the most important components for carrying out a working magnetic flux, without which electromechanical energy conversion is impossible. During the operation of an electric machine in the magnetic core, the field is remagnetized in each sheet separately in the case when they are ideally isolated and in parasitic eddy current circuits in case of damage of the interlayer insulation. In this case, defects can be of a local nature if they are concentrated in a separate zone, and they can also be of a distributed nature if the defects are in the form of damages of interlayer insulation and are stochastically located in the core. The causes of defects are technological and operational in nature.

Causes of manufacturing defects

Electrical steel sheets are subjected to different manufacturing processes during the manufacture of magnetic cores for electric machines. Each of these manufacturing steps changes the physical and magnetic characteristics of the sheet material.

Cutting

To obtain the required shape of the magnetic core sheet, electrical steel sheets are stamped or cut, which causes deformation near the interaction line. These deformations worsen the permeability and degrade the performance of the electric machine, which negatively affects the distribution of the flux density and increases the losses.

The degree of deformation of the crystalline molecular structure depends on many factors of the cutting process and the properties of the sheet material.

Worn punching cutting tools, slow laser cutting speed, large grain size, and high silicon content increase the wear rate. In addition, the deformation of the material (burrs) right at the border of stamping or cutting creates additional short-circuited contours when assembling magnetic core packages, which increases eddy current losses.

Stamping

The stamping process also negatively affects the properties of the laminated magnetic core. In the article, the effect of stamping on the distribution of the magnetic field and the power loss in the region of the teeth was studied. The stamping effect was modeled as a continuous exponential decrease in permeability from the center of the tooth to its edges according to equations (1) and (2).

$$\mu_{Tooth} = \mu_{Sheet} e^{-\alpha x/d}, \tag{1}$$

$$\hat{B} = \mu_{Sheet} \hat{H}. \tag{2}$$

Despite the high flux density (at which the existence of the stamping effect stops) and the relatively small area affected by punching in the area of the teeth, an increase in the magnetization flux by about 5-10% is observed.

Force of pressing and fastening packages into a solid magnetic core

Ensuring sufficient interlayer insulation and increasing compaction density are two opposing current trends in the process.

With an increase in pressing pressure, simultaneously with an increase in the fill factor of the core with steel, the sheets are stressed, the electrical resistance between the sheets of the core decreases and, accordingly, eddy currents increase.

For cores stapled, welded, etc. after removing the effort, no noticeable deterioration in the parameters of the stators is observed even at pressures of 100-150 MPa.

The actual specific pressure of the sheets relative to each other in the finished core after bonding and release of the pressing pressure is significantly different from the specific pressure created during its pressing.

The maximum stresses in the core remain when it is bonded by pouring. In this case:

1) During the pouring process, the cores are subjected to a fairly significant pressing pressure (when pouring stators of asynchronous motors of low and medium power, the specific pressure reaches 550 MPa).

2) The maximum contact area of the fastening structure elements with the end and diametral surfaces of the core is ensured.

3) The core is subjected to additional pressures created during the cooling of the filled stators.

An increase in the specific pressing pressure leads to a significant deterioration in the characteristics of the cores. At pressures of about 550 MPa, the increase in specific losses in steel at induction B = 1.5 T at frequency f = 50 Hz was 46%; when the pressure decreases from 550 to 60 MPa, the specific losses decrease by 10% [3].

The two most common fastening methods are welding and stapling. Welding together with burrs creates additional short-circuited contours for eddy currents between steel sheets, which cause an increase in eddy current losses.

Annealing

Annealing is done to relieve residual stress caused by manufacturing processes.

Annealing involves uniform heating to a predetermined temperature, maintaining that temperature for a period of time, after which uniform cooling occurs.

Studies on the action of cutting [1] and [2] have also been experimented on annealed samples and found a marked reduction in loss compared to samples that did not go through it.

Local defects of magnetic cores

During the manufacture process, especially with the static pressing method, in certain zones of the core, most likely in the tooth zone, there is an increase in pressure due to the structure of the surface of the steel sheets, equal thickness and the presence of burrs. In such cases, insulation may be damaged. In damage zones, circulating currents create local flashes of increased heat release.

At a level with the value of specific losses in steel, the thermal resistance of the core and its individual parts characterizes the quality of its manufacture.

The main parasitic circuit of eddy currents in the magnetic core, due to the technological process, is closed as follows: a closed outer surface - a closed surface as a result of burrs (tooth zone) - the outer sheets of the stator. If the conductivity of burrs over the entire area of the bore is approximately the same, then this can be attributed to the integral deterioration of the state of the magnetic core.

If the conductivity of burrs in some zone significantly exceeds the average and the density of eddy currents increases during engine operation in this zone, then this is already a local defect, since there is a zone of increased heat generation.

Appearance of defects in interlayer insulation during repair work

Engines are often repaired, in which, as a result of a crash, the rotor barrel breaks off its axis and is pumped, leaving behind a strong defect in the tooth zone, the so-called “licking” of part of the bore surface, plastic deformation of the plates.

In many cases, the defect consists in the "tearing" of the plates from the tooth. The insulation between the sheets in this case may be broken along the entire height of the tooth.

In repair shops, torn and deformed tooth plates are straightened to their original position with special brackets.

In these cases, one can speak of a partial and even complete effect of a massive magnetic core in a separate area of the laminated magnetic core. All this leads to additional power losses.

But the danger of local defects lies elsewhere. A magnetic core having a local defect may well satisfy the integral level of quality, consisting in the given specific losses. At the same time, part of the winding adjacent to the defective teeth falls into the region of increased heat release, which drastically reduces the service life. In some cases, even thermal breakdown of the insulation is possible.

It should be noted that the necessity to take into account local defects is much higher for engines that are in operation and have been repaired than in the production process.

Materials and methods of research

The main task is the determination of specific losses in the magnetic core of an asynchronous motor with a power of 0.37 kW. The purpose of the experimental study was to evaluate the specific losses in the toothed toroidal magnetic core in the absence and presence of defects in the interlayer insulation.

Measurement of specific losses was carried out by conventional methods [4].

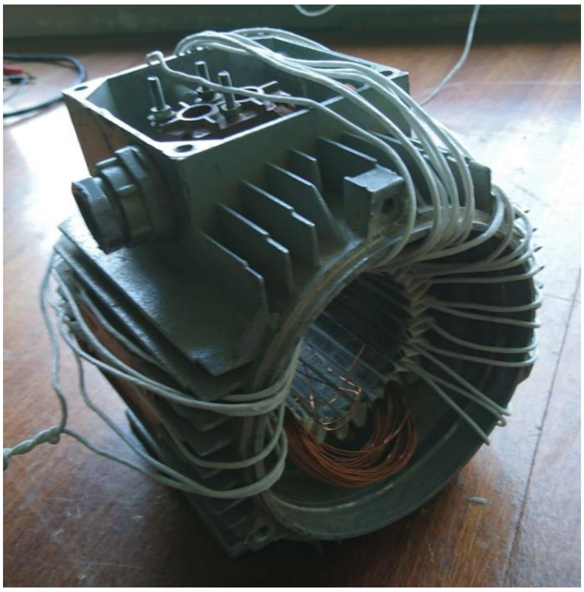

Fig. 1. The magnetic core of a 0.37 kW 4AA63V4U3 asynchronous motor in the housing

As a result of the experiment it can be noted that the losses in the specified magnetic core were determined at an induction $B = 1$ T and a power frequency of 50 Hz, which are approximately 16.8 watts.

To get the specific loss in steel, one first need to calculate the mass of steel, which is 3.48 kg.

A theoretical study was carried out by means of a field calculation of the quasi-static process of magnetization reversal in a toothed magnetic core in order to estimate the mass of that part of the magnetic core that takes part in the conduction of the magnetic flux.

With a help of applied software COMSOL Multiphysics, on the basis of a ready-made calculation model, the distribution of magnetic induction in one of the studied magnetic cores was calculated using the wattmeter method. Fig. 2 shows the distribution of magnetic induction in the magnetic core of a 0.37 kW 4AA63V4U3 asynchronous motor. The peak value of the induction corresponds to the position of the field winding.

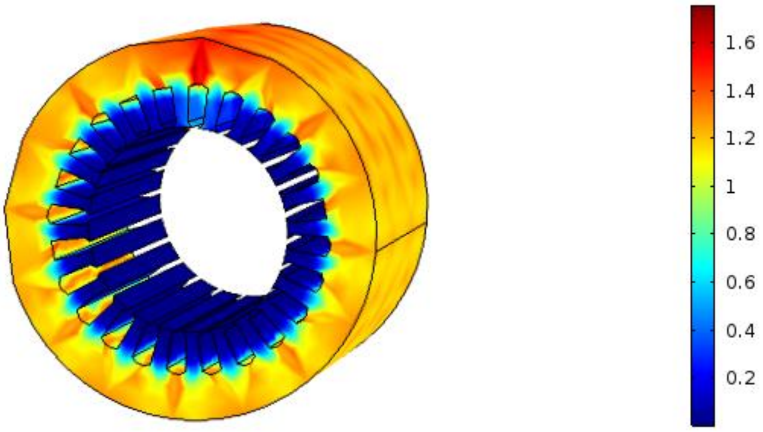

Fig. 2. Distribution of magnetic induction in the magnetic core of a 0.37 kW 4AA63V4U3 asynchronous motor

This calculation visually displays the flow paths of the magnetic flux and confirms the formulas that were used in the calculations, namely, the magnetic flux does not enter the teeth. Thus, the fact that only the height of the stator back was used to calculate the area of active steel and the fact that when calculating the mass of active steel only the mass of the back is calculated is theoretically and mathematically justified.

Since the magnetic flux almost does not enter the stator teeth when examining a disassembled motor and calculating specific losses, the mass of the teeth is not taken into account, since the losses in them are almost zero. And then the specific losses are:

$$\rho = \frac{P_{Steel}}{m_a} = \frac{10,97}{3,48} = 3,15\ \frac{W}{kg} \tag{3}$$

Also, on the basis of the complete mathematical model, the induction distribution over the sheet thickness was calculated at different remagnetization frequencies.

So, at a frequency of 50 Hz, which corresponds to the purple line, it can be seen that the induction is distributed evenly over the width of the sheet, that is, it completely penetrates it. And with increasing frequency, it can be seen that in the center of the sheet, the value of induction decreases and is almost equal to zero, which indicates that the magnetic flux penetrates the sheet only on the surface and does not penetrate into the depths.

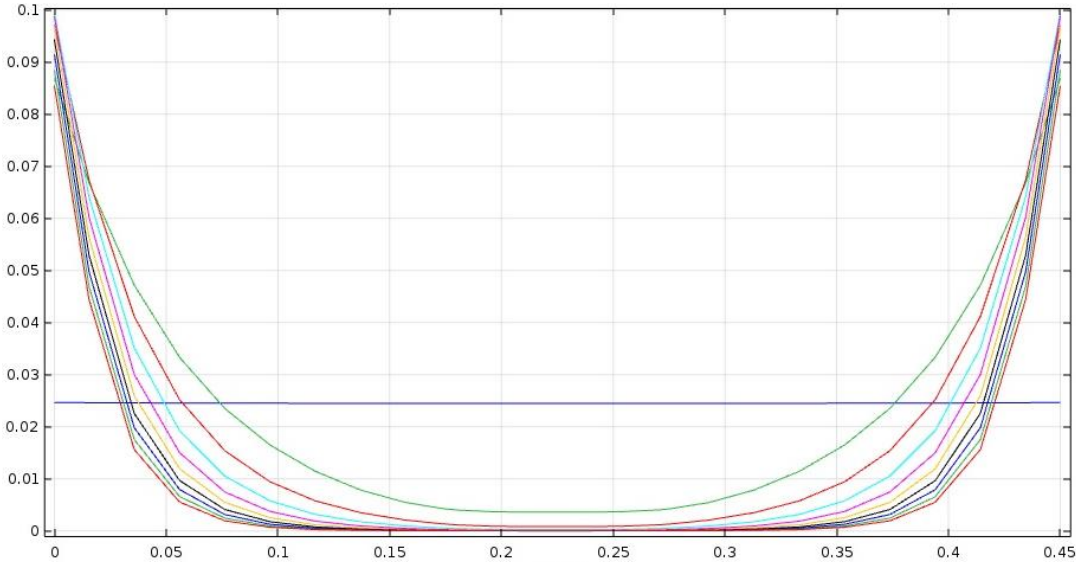

Fig. 3. Distribution of magnetic induction over the thickness of the sheet in the magnetic core of a 0.37 kW 4AA63V4U3 asynchronous motor at different frequencies

In a previous article by the authors [4], the measured losses were divided into hysteresis and eddy currents separately at frequencies in the frequency range close to the industrial frequency from 40 to 70 hertz using the Steinmetz method [9].

However, the most recent publications use a steel loss distribution model, also often referred to as the Bertotti model, which separates steel losses into hysteresis losses, eddy current losses, and sometimes excess losses.

More advanced steel loss models attempt to mathematically describe the physical properties of material hysteresis. However, such models require more input data and take much longer to calculate. Thus, there is a compromise between the effort involved and the time and accuracy of the results.

It should be kept in mind that the engineering approach of distributing losses in steel into different components and the calculation models associated with it is an empirical approach that tries to separate different physical effects, due to changes in frequency and induction in an electromagnetic system, into different components.

As a result of the analysis of various approaches, the Jordan method was chosen, the formula of which for the distribution of hysteresis losses is as follows:

$$p_{Steel} = p_h + p_e = C_h f \hat{B}^2 + C_e f^2 \hat{B}^2. \tag{4}$$

Based on the results of the studies, the dependences of losses in the magnetic core on hysteresis and eddy currents were plotted in the absence and presence of interlayer insulation defects, shown in Fig. 4.

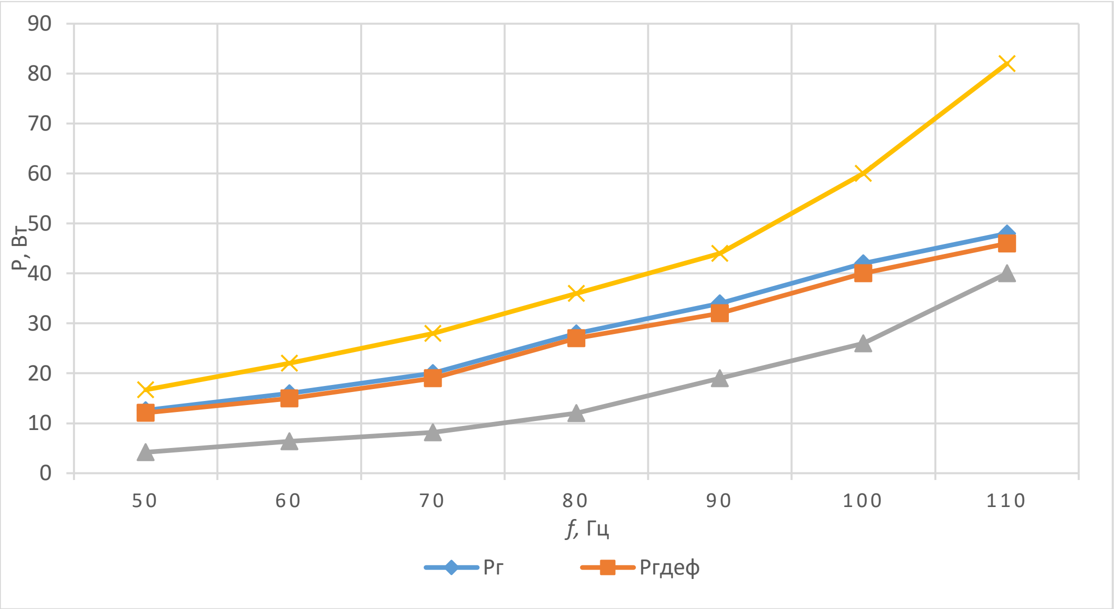

Fig. 4. Distribution of losses for eddy currents and hysteresis in the magnetic core with a defect in interlayer insulation and without a defect at different frequencies

Conclusions

As a result of the study on the distribution of losses, the following values were obtained: at a frequency of 50 Hz and an induction of 1 T, the total hysteresis loss is 12.6 W, the specific loss is 4.8 W/kg, and the eddy current loss is 4.2 W.

In the presence of defects, the hysteresis loss is 12.1 W, and the eddy current loss is 16.1 W.

The nature of the dependences obtained shows a significant increase in eddy current losses in the presence of interlayer insulation defects. The difference between eddy current losses and hysteresis on a defective magnetic core increases sharply with increasing frequency, which makes it possible to create the most sensitive methods for assessing the state of intersheet insulation in the high-frequency region (in the audio range).

The obtained dependence of the distribution of magnetic induction in specific sheets of the magnetic core at frequencies from 50 Hz to 50 kHz shows that at high frequencies the skin effect sharply increases, which manifests itself in the fact that the field does not penetrate into the depth of the sheet, but is concentrated on its side surfaces.

In the article, using a field mathematical model, the distribution of the magnetic field in the toroidal magnetic core was obtained at an industrial frequency and an induction of 1 T, which made it possible to reasonably determine that part of the magnetic core that is involved in the conduction of the magnetic flux, which allows one to reasonably calculate the specific losses in the magnetic cores, which, according to regulatory documents, indicate the quality of the magnetic core.

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ДОСЛІДЖЕННЯ ФІЗИЧНИХ ПРОЦЕСІВ В ШИХТОВАНИХ МАГНІТОПРОВОДАХ ЕЛЕКТРИЧНИХ МАШИН

Метою роботи є використання швидкоплинних процесів для виявлення дефектів міжлистової ізоляції шихтованих магнітопроводів електричних машин. Порушення міжлистової ізоляції викликає підвищені вихрові струми як наслідок підвищені втрати та інтегральні то локальні перегріви в тілі магнітопроводу. В статті розроблено математичну польову модель розподілу індукції в тороїдальному зубчастому магнітопроводі асинхронного двигуна серії 4АА63В4У3 0,37 кВт при накладенні на спинку осердя силової обмотки яка живиться від джерела напруги високої частоти в заданому діапазоні. Проведено експериментальне дослідження втрат в магнітопроводі і розподіл втрат на вихрові струми та на перемагнічування (гістерезис).

При проектуванні електричної машини її робочі характеристики, оптимальні режими роботи, тепловий стан та багато інших факторів розраховуються використовуючи номінальні значення параметрів сталі, обмоток та загалом усіх матеріалів, які використовуються у машині. Проте, ці матеріали не завжди мають заявлені характеристики і якість. Наприклад під час виготовленні та *штампування листів електротехнічної сталі вона зазнає значного рівня впливу, який певним чином впливає на її характеристики. До того ж, навіть якщо припустити, що під час виробництва всі етапи виготовлення матеріалу пройшли бездоганно, стан і як наслідок параметри матеріалів та електричної машини в цілому змінюються під час експлуатації в результаті аварійних ситуацій або навіть простого старіння і зносу.*

Тож зважаючи на ці факти, стає зрозуміло, що під час запланованих чи незапланованих ремонтних робіт має сенс перевіряти стан матеріалів, ізоляції, оскільки від їх стану залежить допустимі навантаження, температурний режим і т.п. Зокрема стан магнітопроводу значною мірою визначає температуру навколо провідників в пазах і як результат визначає скільки реально прослужить обмотки на відміну від зазначеного терміну експлуатації та номінальної потужності на якій варто використовувати цю електричну машину.

Поняття стан магнітопроводу можна розділити на стан електротехнічної сталі та стан її ізоляції. Перша складова досить слабо змінюється під час експлуатації та загалом викликана “старінням” сталі якщо не брати до уваги якісь серйозні пошкодження в результаті аварійних ситуацій, проте вона може бути порушена під час виготовлення. А ось саме друга складова зазнає значного впливу під час експлуатації і значним чином визначає якість магнітопроводу в цілому.

Ключові слова: *електрична машина, магнітопровід, втрати на вихрові струми, магнітний потік*

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