ELEKTROTEHNIŠKI VESTNIK 84(1-2): 56-60, 2017
ORIGINAL SCIENTIFIC PAPER

Minimization of Energy Losses in Ultra-High-Speed Electrical Rotating Machines

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Abstract. The paper presents an experimental and theoretical research of losses in magnetic cores of amorphous alloys of the high-speed and variations ultra-high-speed electrical rotating machines (ERM) caused by the temperature, frequency and magnetic induction variations. It is shown that for the amorphous alloys, the increase in the temperature leads to a significant decrease in the hysteresis losses, and the eddy-current losses weakly depend on the temperature variations. This proves that the ERM stator-core losses, in particular the ultra-high-speed micro-ERMs, should be calculated at their operating temperature, rather than at a room temperature, as being customary in the modern calculation methods. By using the analytical expressions to calculate the specific losses in the stator cores of the 5BDSR amorphous alloy in a wide temperature range, magnetization reversal frequency and magnetic induction are determined, too. The obtained results can be used in the ERM design, in particular in the ultra-high-speed micro-ERM.

Keywords: ultra-high-speed electrical rotating machines, amorphous alloys, specific losses.

Izgube v zelo hitrih električnih rotacijskih strojih

V prispevku so predstavljene teoretične in eksperimentalne raziskave izgub v magnetnih jedrih amorfnih zlitin pri zelo hitrih električnih rotacijskih strojih v odvisnosti od temperature, frekvence in magnetne indukcije. Dokazali smo, da povišanje temperature vodi k znatnemu zmanjšanju histereznih izgub, medtem ko so izgube zaradi vrtinčnih tokov v manjši meri odvisne od spremembe temperature. To pomeni, da moramo izgube v statorju, še zlasti pri zelo hitrih majhnih rotacijskih strojih, izračunati pri delovni temperaturi in ne pri sobni, kot je to v navadi. V prispevku so podani tudi analitični izrazi za izračun specifičnih izgub v statorju iz amorfne zlitine 5BDSR v širokem temperaturnem območju. Dobljeni rezultati so uporabni pri načrtovanju zelo hitrih in majhnih električnih rotacijskih strojev.

1 INTRODUCTION

Minimization of energy losses and heat generation in electrical rotating machines (ERM) are one of the main objectives of the electrical engineering industry. It is especially important to solve this problem for the ultra-high-speed micro-ERMs with a high-coercivity permanent magnet (HCPM). ERMs include electrical motors and generators with the rotor speed from 200,000 to 1,000,000 rpm, power up to 1 kW and rotor diameter up to 15 mm [1-7]. Their application area is in robotics, medicine, aerospace and military industry as well as in machinery and machine tools.

The ERM ultra-high frequency of the rotor rotation allows achieving a new functionality, i.e. the previously unachievable technical parameters for the industry application. For example, the ERM use allows drilling holes with a diameter of several micrometers which is especially necessary for the micro and nanoelectronics [1, 3, 4]. ERMs allow creation of miniature turbocompressors, including pumps for blood pumping with the possibility of installation in the human body [7, 8].

The ultra-high-speed rotor rotation underlies the development of electric power sources with minimal size / weight parameters for autonomous objects. In particular, the micro-generator and micro-motor manufacturing by the Celeroton company (CM-25-280) at a mass of 36 g and the rotor-rotating speed of 500,000 rpm allow producing up to 200 W of electric or mechanical power (depending on the mode, the specific gravity is 0.18 kg/kW). Due to the ultra-high rotor-rotation frequency, an especially promising ERM application is in high-speed actuators for optical and laser systems, where the system capabilities are determined by the mirror-rotation frequency. Moreover, ERMs can improve the efficiency and autonomy of spacecraft and unmanned aircraft systems [9-11].

The high frequency of the rotor rotation, in addition to significant benefits, can enable a significant ERM efficiency reduction. Almost all types of the ERM energy losses depend on the rotor-rotation frequency or the winding-current frequency. The stator-core losses for the hysteresis and eddy-currents are determined by

Received 24 January 2017
Accepted 15 March 2017

the first approximation by the square of the magnetization reversal frequency, and consequently, with an increasing frequency, the stator-core losses increase. The losses in the stator winding can be divided into the ohmic losses (not dependent on the frequency) and the losses due to eddy-currents and proximity effect (depending on the square of the frequency). In the ultra-high-speed ERM with an unappropriate wire diameter, the eddy-current losses and the proximity-effect losses can prevail over the ohmic losses.

The friction losses in bearings are determined by the rotor-rotation frequency and the rotor losses due to the friction with the air depend on the rotor-rotation frequency cubed.

Thus, the ERM efficiency can significantly decrease the useful effect achieved by the significant increase in the frequency. To minimize the losses in the ultra-high-speed ERMs, it is technically and economically feasible to apply innovative technical solutions.

It is reasonable to consider these solutions on an example of an ultra-high-speed ERM CM-AMB-400 manufactured by the Celeroton Company (Zurich, Switzerland).

In this ERM, to minimize the rotor losses due to the air friction and the friction losses in the bearings, electrostatic bearings and vacuumizing of the internal ERM volume are used. The active magnetic bearings or hybrid magnetic bearings are not used because at high speeds they significantly increase the eddy-current losses [1].

To minimize the energy losses in the windings, the high-frequency litz with a diameter core of 0.071 mm is used. Decreasing in the stator-core losses is achieved by manufacturing the core from an amorphous alloy.

Other technical solutions to decrease the losses in the ultra-high-speed ERMs can be used, for example, wires made of carbon nanotubes [12].

2 PROBLEM STATEMENT

To assess the effectiveness of using different technical solutions to increase the efficiency of the ultra-high-speed ERMs at the design stage, different calculation methods are developed.

In [1, 13], a computational method to estimate losses in the stator winding of the ultra-high-speed ERMs due to the proximity effect and eddy-currents is presented. In [1], empirical equations to determine losses in the stator core of electrical steel with a high frequency of the magnetization reversal are given. These equations cannot be used to calculate losses of the stator core of amorphous alloys used in the ultra-high-speed ERMs, because they are obtained for the electrical steels.

In [5, 13, 14], methods to determine aerodynamic losses in ultra-high-speed ERMs are described. In [14], a general method to calculate the stator-core losses of the ultra-high-speed ERMs is presented. This method uses three factors: the eddy-currents, hysteresis and excess-loss coefficients. However, for the amorphous alloys, these coefficients are not known.

In the literature there are no analytical loss calculations disclosed for the amorphous alloys. Moreover, the question of the change in the specific losses in the amorphous alloys by increasing their temperature remains unexplored. In [12], it is argued that by increasing the temperature, the stator-core losses decrease due to the increase in the steel resistivity.

The amorphous alloys are nanocrystalline iron alloys varies slightly with a low temperature coefficient, i.e. their resistivity with an increasing temperature. Therefore, it seems appropriate to study the temperature effect on the specific losses in the amorphous alloys.

The aim of this work is to research the temperature-dependence of specific losses in stator cores of the amorphous alloys and to develop analytical expressions for their calculation.

3 RESEARCH METHODS AND RESEARCH OBJECT

The experimental research of specific losses in slotless stator cores was performed for of three types of the 5BDSR amorphous alloy: T-type, E-type, B-type (manufactured by the Asha metallurgical plant). Their main parameters are presented in Table 1.

Table 1. Parameters of the 5BDSR amorphous alloys

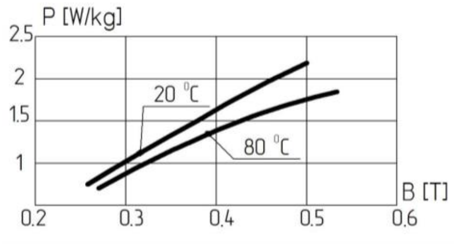
Parameter	Value
Saturation induction, [T]	1.3
Specific resistance, [μΩ/m] (or [S/m])	1.6 (or 62500)
Cores mass, [kg]	0.5
Active length, [mm]	50
Band thickness, [μm]	32
Curie temperature, [°C]	350

The experimental research was carried out on the MK–4E experimental unit with a sinusoidal magnetization reversal of the samples. The experiments were performed at inductions by 30% lower than the saturation induction, at 400 Hz, 1000 Hz and 2000 Hz frequencies. At a $20\,°C$ room temperature and the temperature after heating the sample with a measuring winding in a muffle furnace was $800\,°C$. The error due to increasing the resistance of the measuring coil was taken into account. The experimental method is presented in [15].

The experimental data was approximated by using the Ansoft Maxwell software package (a module to calculate the steel losses as a function of the frequency). The aim was to obtain empirical equations for loss calculation in amorphous alloys and to study them numerically.

4 Experimental research of the losses in the stator core of amorphous alloys

In the experimental research, the dependence was determined the specific losses in amorphous alloy samples on the magnetization reversal frequency,



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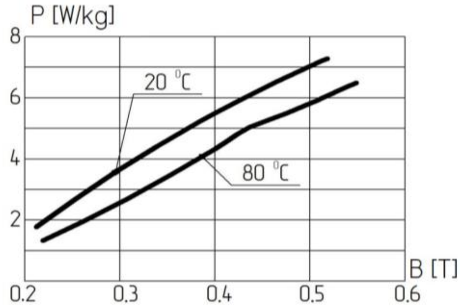

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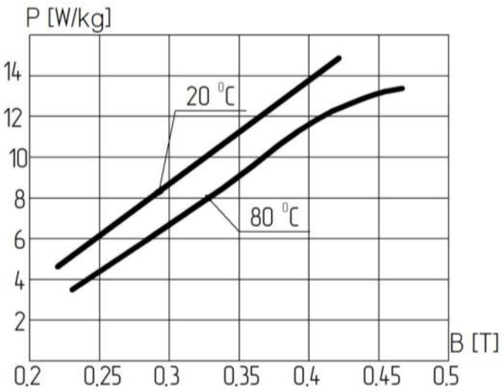


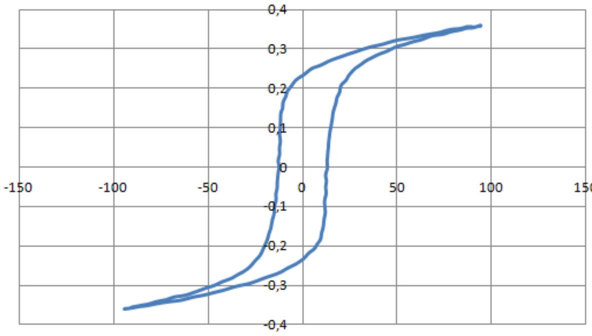
c

Figure 1. Loss dependence in the 5BDSR (E-type) stator core:
a) on the 400 Hz magnetization reversal frequency;
b) on the 1000 Hz magnetization reversal frequency;
c) on the 2000 Hz magnetization reversal frequency

magnetic induction and temperature.

For two temperatures (20 °C and 80 °C), the loss dependences of the stator core of 5BDSR (E-type) on the 400 Hz, 1000 Hz and 2000 Hz magnetization reversal frequencies are presented in Fig. 1a, 1b and 1c, respectively.

The obtained experimental data shows that the specific losses in the magnetic core decrease with an increase in the temperature. The specific losses are decreased by 15-17% by increasing the temperature from 20 °C to 80 °C at a 400 Hz magnetization reversal frequency and 0.5 T magnetic induction. For lower magnetic induction values (for example, a 0.25 T), there is only a 3-5% decrease, i.e. the decrease in the temperature-dependent specific losses significantly depends on the magnetic induction or the area of the hysteresis loop.



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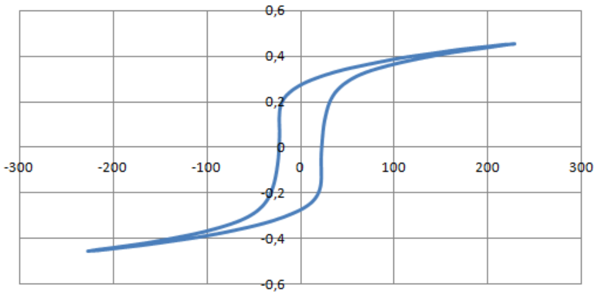

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Figure 2. Experimental hysteresis loop of the 5BDSR amorphous alloy (E-type) at the 80°C temperature:
a) on the 400 Hz frequency (0.3595 T induction);
б) on the 2000 Hz frequency (0.4561 T induction)

Thus, the eddy-current losses in the magnetic cores of the amorphous alloys are weakly temperature-dependent, while the magnetic-core hysteresis loss of amorphous alloys is much significant temperature-dependent. Similar conclusions can be drawn from the experimental curves (Fig. 1b, Fig. 1c).

Similar results were obtained for the T-type and V-type of the 5BDSR samples. By 2–3 % of the temperature-dependent for specific-loss decrease is here less than that of E-type. This is because the E-type has a rectangular hysteresis loop greater than the b-type and T-type.

In Fig. 2, the experimental hysteresis loop of the E-type is shown at the 80°C temperature and the 400 Hz (0.3595 T induction) and 2000 Hz (0.4561 T induction) frequencies.

An empirical model to determine the temperature-dependent stator-core losses.

To generalize the obtained results, an empirical model was developed to describe the temperature, frequency and magnetic induction dependence of specific losses in 5BDSR amorphous alloy.

A general model that describing the stator-core losses can be represented as follows [14]:

$$P = P_{hyst} + P_{eddy}, \tag{1}$$

$$P_{hyst} = k_{hyst} B^2 f, \tag{2}$$

$$P_{eddy} = k_{eddy}(Bf)^2 + k_{ex.eddy}(Bf)^{1.5}, \quad (3)$$

where P_{hyst} are the hysteresis losses; k_{hyst} is the coefficient characterizing the hysteresis losses; B is the magnetic induction; f is the magnetization reversal frequency; P_{eddy} are the eddy-current losses; k_{eddy} is the coefficient characterizing the eddy current losses; $k_{ex.eddy}$ is the coefficient characterizing excessive eddy-current losses.

In a general view, the eddy-current losses can be presented as:

$$P_{eddy} = \frac{E^2_{eddy}}{r(1+\alpha(T-20))}, \quad (4)$$

where r is the resistivity of the amorphous alloys; E_{eddy} is EMF of the eddy-current induced in the amorphous alloys; α is the temperature factor of the magnetic-material resistance; T is the core temperature.

Taking into account equation (4), equation (3) can be written as:

$$P_{eddy} = \frac{k_{eddy0}(Bf)^2 + k_{ex.eddy0}(Bf)^{1.5}}{r(1+\alpha(T-20))} = \frac{P_{eddy0}}{r(1+\alpha(T-20))}, \quad (5)$$

where k_{eddy0} is the coefficient characterizing the eddy-current losses at a 20 °C temperature; $k_{ex.eddy0}$ is the coefficient describing excessive eddy-current losses at a 20 °C temperature; P_{eddy0} are the specific eddy-current losses at a 20 °C temperature.

The hysteresis losses are characterized by the hysteresis loop area, which decreases with an increasing temperature, as shown above. Thereby, it seems appropriate to introduce a coefficient characterizing the decrease in the hysteresis-loop area as a function of the temperature increase (by analogy with the temperature resistance coefficient).

Therefore, for (2) the following is obtained:

$$P_{hyst} = k_{hyst0}\left(1-\beta(T-20)\right)B^2 f = P_{hyst0}\left(1-\beta(T-20)\right), \quad (6)$$

where k_{hyst0} is the coefficient characterizing the hysteresis losses at a 20 °C temperature; β is the temperature-hysteresis coefficient characterizing the decrease in the hysteresis loop area as the function of the temperature increase; P_{hyst0} are the specific hysteresis losses at a 20 °C temperature.

Based on the above, the empirical model characterizing the temperature-, frequency- and magnetic-flux density-dependent stator-core losses can be written as a sum of (5) and (6).

5 COEFFICIENT DETERMINATION FOR THE 5BDSR AMORPHOUS ALLOY FOR THE EMPIRICAL MODEL

For a practical application of the proposed model in the calculation and assessment of specific losses in the stator cores of amorphous alloys, the coefficients included in (5) and (6) should be determined. By approximating the experimental dependences by using the Ansoft Maxwell software package, the hysteresis and eddy-current losses were determined from the total experimental losses and this allowed determination of coefficients (2) and (3) at a 20 °C temperature:

$$P_{hyst} = 0.00975 \cdot B^2 f, \quad (7)$$

$$P_{eddy} = 3.83 \cdot 10^{-6} \cdot (Bf)^2 + 3.25 \cdot 10^{-4} \cdot (Bf)^{1.5}, \quad (8)$$

and at a 80°C temperature:

$$P_{hyst} = 0.004399 \cdot B^2 f, \quad (9)$$

$$P_{eddy} = 3.66 \cdot 10^{-6} \cdot (Bf)^2 + 2.9 \cdot 10^{-4} \cdot (Bf)^{1.5}. \quad (10)$$

From the approximation results of the numerical values of the coefficients of specific losses, it is seen that by increasing the temperature, the eddy-current losses do not change considerably, and the hysteresis losses are decreased by more than two times (Table 2).

Table 2. Losses at 0.45 T and at 2000 Hz magnetization reversal frequency

Losses	20 °C	80 °C
The eddy-current losses [W/kg]	11.87	11.35
The hysteresis losses [W/kg]	4.79	2.13

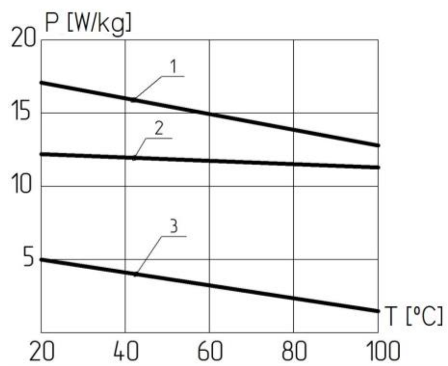

Figure 3. Temperature-dependencies of the hysteresis and eddy-current losses for the 5BDSR amorphous alloy (E-type) at a 0.45 T induction and a 2000 Hz magnetization reversal frequency:
curve 1 are the total losses,
curve 2 are the eddy-current losses,
curve 3 are the hysteresis losses

Based on these approximations, coefficients of equations (5) and (6) are determined and the general empirical model is set up to describe the stator-core specific losses as a function of the frequency, induction and temperature:

$$P_{hyst} = 9.75 \cdot 10^{-3} \cdot \left(1 - 9.21 \cdot 10^{-3} \cdot (T-20)\right)B^2 f, \quad (11)$$

$$P_{eddy} = \frac{3.83 \cdot 10^{-6} \cdot (Bf)^2 + 3.0 \cdot 10^{-4} \cdot (Bf)^{1.5}}{1 + 7.7 \cdot 10^{-4} \cdot (T - 20)}. \quad (12)$$

Fig. 3 shows temperature-dependencies of the hysteresis and eddy-current losses for the 5BDSR amorphous alloy (E-type) at a 0.45 T induction and a 2000 Hz magnetization reversal frequency.

To assess the accuracy of empirical determination of coefficients, the specific losses in the stator core of the observed amorphous alloy at a 120 °C temperature were experimentally researched. The discrepancy between the analytical calculations made according to expressions (11), (12) and experimental data at a 120 °C temperature was less than 5%.

6 Conclusion

For the amorphous alloys, the temperature increase gives rise to a significant decrease in the hysteresis losses, and the eddy-current losses weakly depend on the temperature variations. This proves that the ERM stator-core losses, in particular the ultra-high-speed micro-ERMs, should be calculated at their operating temperature rather than a room temperature, as being customary in modern calculation methods.

By using the analytical expressions to calculate the stator-core specific losses of the 5BDSR amorphous alloy in a wide temperature range, the magnetization reversal frequency and the magnetic induction are also obtained.

The results can be used in the ERM design, in particular in the ultra-high-speed micro-ERMs design.

Acknowledgement

This work was performed under a state support grant for leading scientific schools of the Russian Federation (the NSH-6858.2016.8 project “The fundamental study of electromagnetic and thermal fields of high-speed electromechanical energy converters with the requirements of strength, with a view to their multidimensional optimization”).

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