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DETERMINING THE INFLUENCE OF STRUCTURAL AND ELECTROMAGNETIC PARAMETERS ON ACTIVE LOSSES IN AN ELECTRIC MOTOR WITH PERMANENT MAGNETS FOR UNMANNED AERIAL VEHICLES

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This study investigates a small-sized high-speed permanent magnet motor used in the drive of unmanned aerial vehicles.

As part of this study, a numerical simulation field mathematical model of a high-speed permanent magnet motor has been built, implemented by the finite element method. That made it possible to obtain the distribution of the electromagnetic field and forces, to estimate the total losses in all conductive and magnetically conductive media in individual structural elements of the permanent magnet motor under study. Unlike existing ones, the model built enables deriving the total losses in the calculation area; in permanent magnets, structural conductive elements, the armature winding, and in the magnetic core with hysteresis losses, eddy currents and additional losses caused by higher harmonics.

The task addressed is predetermined by the pressing scientific-practical issue related to increasing the energy efficiency of a high-speed permanent magnet motor used for electric transport systems and unmanned aerial vehicles. The use of a simplified, more technological rectangular shape of permanent magnets has been proposed. Applying permanent magnets of this configuration makes it possible to reduce the total losses in the motor by 23…41% depending on the type of power supply – sinusoidal or when powered by an inverter with PWM.

The use of a more technological form of permanent magnets leads to a decrease in the electromagnetic torque of the motor by approximately 18…30%, which is attributed to a decrease in the volume of active materials and an increase in the value of the equivalent air gap. At the same time, applying a modified form of permanent magnets makes it possible to reduce pulsations of the electromagnetic torque by 12%

Keywords: high-speed motor, losses in the magnetic core, permanent magnet motor

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1. Introduction

Electromechanical converters with permanent magnets (PMs) for unmanned aerial vehicles (UAVs) and transportation means must have high energy efficiency, compact dimensions, have high thermal stability and reliability. When powering such PM motors from an inverter with pulse-width modulation (PWM), the main criterion affecting the magnitude of losses is the losses in the magnetic core, which determines energy efficiency and temperature regimes in general. High-speed motors are powered from sources with a high frequency of supply voltage > 400 Hz, where the manifestation of higher harmonics from an inverter with PWM is significant and leads to a significant increase in losses and heating.

Structurally, UAVs must have the minimum possible dimensions and weight since these are significant factors affecting the load capacity and duration of flight and autonomous operation. These parameters are significantly affected by the parameters of the drive electric motor: specific power, overall dimensions, and energy efficiency. For hybrid UAV designs, in which vertical take-off and horizontal flight technologies are used, the requirements for the drive electric motor increase significantly. Such motors must operate stably in a wide range of rotation speeds and under dynamic operating modes, which can be achieved by reducing losses in the magnetic core. The study of losses in the magnetic core of high-speed motors with different techniques for controlling the stator winding is relevant and has important practical significance for UAV systems.

The electric motor studied in this work is, in most cases, used to drive UAVs. The peculiarities of operation under such conditions include cooling limitations, frequent alternating loads, and high specific power. Under such operating modes, classical methods for estimating losses in the magnetic core (Steinmetz equation [1]) are not accurate enough. Therefore, to estimate losses in the magnetic core of high-speed motors with PMs, it is necessary to construct multiphysical models that take into account both the shape of the supply voltage and the influence of the temperature field.

Our work investigates losses in the magnetic core, PMs, and in the structural elements of the motor for two techniques of powering the armature winding in a small-sized high-speed motor: with a sinusoidal supply voltage and when powered from an inverter with PWM. The study is carried out for different motor speeds.

Another area of our study is to estimate the magnitude of losses and electromagnetic torque of the motor when using a simplified, more technological form of PM, which makes it possible to reduce the cost of manufacturing the motor under consideration.

Summarizing the results of reviewing the operating modes of contactless high-speed motors with PMs makes it clear that the main goal of scientific research in this field is to study the parameters and characteristics of motors. The power supply of these motors comes from an inverter with PWM, as an affordable and common driver for motors of this type used in UAVs.

Quantitative assessment of losses in the magnetic core of an electric motor intended for UAVs, taking into account current scientific approaches and practical limitations, is a relevant scientific and practical task. In addition, the issue of reducing losses in the stator, rotor, and permanent magnets, optimizing thermal regimes in the core and cooling systems is relevant.

2. Literature review and problem statement

A study on a synchronous motor with permanent magnets in a flywheel energy storage system is reported in [2]. The authors calculated losses in the motor and generator modes, including losses in the windings, core, rotor, and mechanical losses. The optimized design makes it possible to reduce idling losses at high speeds and increase the efficiency of energy conversion. However, the paper does not provide data on the impact of temperature conditions on the reliability and durability of the system.

Another approach is outlined in [3], in which emphasis is on calculating losses in the stator of a high-speed motor. Using the example of a 120 kW motor, the finite element method determined that more than 70% of the losses under the idling mode and more than 50% under the rated mode are concentrated in the yoke of the stator magnetic core. This indicates the influence of the stator yoke configuration to reduce losses and enable effective cooling. The disadvantage is the lack of analysis of the impact of the winding parameters and rotor material.

In study [4], the influence of power supply harmonics and spatial harmonics on eddy current losses in the rotor is considered. A model based on an equivalent current layer is proposed, the calculation results of which are compared with the results obtained by the finite element method. It was found that the introduction of a graphite layer between the permanent magnet and the housing significantly reduces losses and overheating of the rotor. However, the authors did not study the durability of the graphite layer and its cost-effectiveness under industrial conditions.

The principles of complex analysis of high-speed engines are described in [5]. Losses, temperature fields were calculated using the computational hydrodynamics method and mechanical stresses in the rotor at extreme speeds and temperatures. Experimental studies on the designed prototype with a capacity of 25 kW at 95,000 rpm confirmed the accuracy of the obtained data during modeling within 5%. The disadvantage is the lack of research on dynamics under long load cycles and the influence of vibrations.

In [6], a model for the separation of eddy current losses in permanent magnets was proposed. Calculations were performed on a 50 kW motor at 30,000 rpm. The data obtained showed that taking into account the non-uniformity of losses makes it possible to increase the accuracy of temperature calculation and bring the modeling results closer to actual conditions. At the same time, the authors did not study the influence of such a technique on the design solutions of the cooling system.

The practical application of high-speed motors is illustrated in [7], in which their use is shown on the example of cordless vacuum cleaners. The authors estimated the losses in steel and windings since those have the greatest impact on the efficiency, energy efficiency, and duration of autonomous operation from the battery. However, the paper does not consider thermal calculation and methods for reducing engine noise, which are important for household appliances.

In [8], high-speed motors with permanent magnets and the influence of the ratio of the number of poles to the number of slots on their parameters and characteristics are considered. The authors applied optimization methods and designed a prototype of 37 kW, 36000 rpm, the test results of which coincided with numerical calculations. At the same time, the issues of durability and economic feasibility of the selected schemes remain open.

In work [9], the influence of mechanical tension and temperature on the rotor of a high-speed motor used to drive a compressor was investigated. Using the finite element method, it was shown that insufficient tension leads to rotor failure at speeds above 137 thousand rpm, while modification of the end caps reduces the maximum stresses by 3 times. However, the authors did not consider the influence of cyclic temperature loads that may occur during real operation.

In [10], a study of high-speed motors with a capacity of 30 kW with a low operating temperature is reported. The authors proposed three options for stator cooling and a methodology for calculating losses from viscous friction in the air gap. The effectiveness of the combined approach, which involves a multiphysics statement of the problem in the form of “thermal-fluid” modeling, is shown. The disadvantage is the lack of experimental test results.

In study [11], an ultra-high-speed engine for fuel systems with a rotation speed of 90,000 rpm was considered. A thermal model with magneto-thermal coupling was built, which takes into account losses in all engine elements. It was shown that multiphysics modeling of thermal and magnetic fields more accurately corresponds to experimental data (error 2–3°C). At the same time, the issue of reliability of the cooling system under variable operating conditions was left out of consideration.

Current studies confirm the need for a comprehensive approach to the analysis of losses in the magnetic core, which includes adapted mathematical models, accurate measurement methods, and the selection of the optimal material.

Our summary of related studies shows that modern work is focused on increasing the efficiency and reliability of high-speed engines with permanent magnets. Most of the works use the finite element method and analytical approaches, the calculation results of which are confirmed by experimental experiments. At the same time, in most papers, the issues of reliability, cyclic thermal and mechanical loads, as well as the economic feasibility of the implemented solutions remain open. This indicates the need for comprehensive interdisciplinary research that combines electromagnetic, thermal, mechanical, and economic aspects of the design of modern electric machines.

All this allows us to assert that the issue of studying the active losses of a small-sized high-speed permanent magnet motor when powered by a frequency converter and with a sinusoidal supply voltage has not been considered in the literature. In addition, the problem of taking into account hysteresis losses in modeling and optimizing the design to reduce losses in the magnetic core, increase manufacturability and reduce the cost of manufacturing a separate sample has not been solved. This necessitates the need for such a study.

3. The aim and objectives of the study

The aim of our work is to estimate the magnitude of losses in a high-speed permanent magnet motor with different techniques of armature winding power supply. This will make it possible to design structural solutions and optimal motor control systems that will provide for the increased operational reliability, reduced heating, and increased duration of autonomous operation.

To achieve the goal, it was necessary to solve the following tasks:

– to construct a numerical simulation model of a high-speed permanent magnet motor;

– to estimate losses in the magnetic core and structural elements when powered from a sinusoidal voltage source and a PWM inverter;

– to estimate losses and electromagnetic torque of the studied motor when using a simplified, more technological form of PM.

4. The study materials and methods

The object of our study is a small-sized high-speed permanent magnet motor used in the drive of unmanned aerial vehicles.

A numerical simulation model of a high-speed permanent magnet motor was built in the COMSOL Multiphysics software environment. A simulation mathematical model is used to solve the task of estimating the magnitude of losses in the magnetic core and other structural elements of the motor. This model takes into account the physical change in the frequency of internal processes when the rotation speed changes and the shape and composition of the supply voltage of the permanent magnet motor.

A prototype of a small-sized high-speed permanent magnet motor is used to calculate the electromagnetic field; it is shown in Fig. 1.

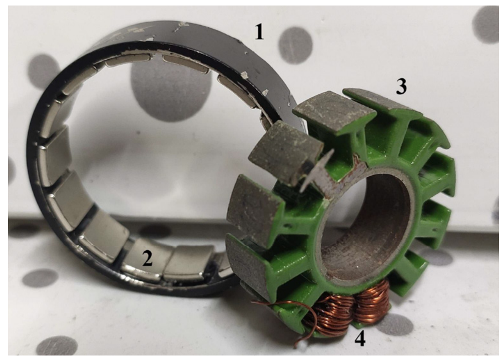


Fig. 1. General view of the engine under study: 1 – rotor sleeve (rotor magnetic core); 2 – radially magnetized permanent magnets; 3 – stator magnetic core; 4 – fragment of the stator winding

The basic design and geometric parameters of the prototype under study are given in Table 1.

Table 1

Basic parameters of the engine prototype under study

No.	Parameter	Value
1	Maximum motor power, W	1500.0
2	Rated supply voltage, V	25.0
3	Maximum current, A	110.0
4	Efficiency, %	0.89
5	Number of poles on the rotor	14
8	Axial length, mm	15.0
9	B_r, Tl	1.30
10	Outer diameter of the motor, mm	43.0
11	Magnetic core material	M530-50A
12	Maximum rotation speed, rpm	25000
13	Air gap, mm	0.2
14	Diameter of the elementary conductor, mm	0.30

The principal hypothesis of our study assumes that active losses in permanent magnet electric motors depend on the load modes, rotation speed, and design features.

Assumptions adopted in the study:

1. A permanent magnet electric motor is considered as a perfectly symmetrical machine without structural defects of the windings and magnetic system.

2. The influence of higher harmonics of the supply current is taken into account only within the limits that significantly affect power losses, other asymmetric modes (for example, phase asymmetry) are not taken into account.

Simplifications accepted in the study:

1) the influence of vibrations and mechanical deformations of the structure is not taken into account since our study focuses on electromagnetic processes;

2) the calculation of losses is carried out under steady-state operating modes, transient processes are not considered;

3) losses in bearings and other structural elements are not taken into account.

The research was conducted on the basis of a numerical simulation computer model of a high-speed permanent magnet motor, during which the distribution of the electromagnetic field in the calculation area was obtained. The calculation was carried out for different rotation speeds in the range of 5000 rpm to 25000 rpm.

5. Results of research on active losses in a small-sized high-speed permanent magnet electric motor

5. 1. Numerical simulation model of a high-speed permanent magnet motor

In the calculation domain of the studied motor, the electromagnetic field is determined by well-known equations for the vector magnetic potential given in [12], while the corresponding homogeneous boundary conditions are added to the model [13].

The losses in the stacked magnetic core of the stator were determined based on the modified Bertotti equation [14] by analyzing the magnetic field in the calculation of domain of the motor for each harmonic component. The value of losses in the magnetic core is calculated according to the expression below

$$Q_c = k_h \nu f \left(|B|\right)^{\beta} + k_c \sigma \nu f^2 |B|^2 + 8\sqrt{\sigma G S V_0} \left(\nu f\right)^{1,5}, \quad (1)$$

where Q_c – total losses in the calculation area of the studied motor; $G = 0.1356$ – given empirical constant [15]; V_0 – additional coefficient [16]; σ – electrical conductivity of the magnetic core; S – area of the calculation area in the two-dimensional statement of the problem; β – coefficient for induction; k_c – coefficient of eddy current losses, which depends on the sheet thickness of a separate sheet of the magnetic core; ν – harmonic number; f – harmonic frequency; k_h – coefficient of hysteresis losses.

The first component in equation (1) is responsible for hysteresis losses, the second component – for losses on Foucault currents, and the third component – additional losses.

Depending on the thickness of a separate sheet of the stacked magnetic core, the value of eddy currents and losses changes, which is taken into account by coefficient k_c

$$k_c = \pi^2 d^2 / 6, \quad (2)$$

where d is the width of a separate sheet of the stacked magnetic core of the stator or rotor of the motor.

The magnitude of the current in the armature windings, the induced EMF, and other winding parameters are determined from the following system of equations:

$$J_e = \frac{N\left(V_e + V_{ind}\right)}{S_c \cdot R_c}, \quad R_c = \int\limits_A \frac{N \cdot L}{\sigma_c \cdot a_c \cdot S_c} \mathrm{d}A, \quad (3)$$

$$V_{ind} = N \cdot \sum \frac{L}{S_c} \cdot \left(\int\limits_{S_c} E_{zA} \mathrm{d}s - \int\limits_{S_c} E_{zx} \mathrm{d}s \right),$$

where J_e is the value of current density in the armature winding, which depends on the load and the nature of the generator; N is the number of turns in the armature winding; S_c is the cross-sectional area occupied by the winding with conductors; R_c is the active resistance of the stator winding phase; L is the average length of the stator winding phase turn; σ_c, a_c is the electrical conductivity of the stator winding material and the cross-sectional area of the elementary conductor; V_{ind} is the value of the induced EMF in the generator stator winding; V_e is the voltage characterizing the generator load; E_{zA}, E_{zX} is the electric field strength in the locations of the phase zones "***A***" and "***x***".

The result of calculating the electromagnetic field and vector magnetic potential in the calculation area of the engine under study is shown in Fig. 2.

When powered by a PWM inverter, the shape of the output voltage curve supplied to the drive motor differs from the sinusoidal one. To calculate the losses in the motor under study when powered by a PWM inverter, the shape of the voltage curve shown in Fig. 3 is used.

The numerical simulation model built takes into account the change in the electromagnetic parameters of the engine under study when the rotation speed and load change, which significantly distinguishes it from existing analogs.

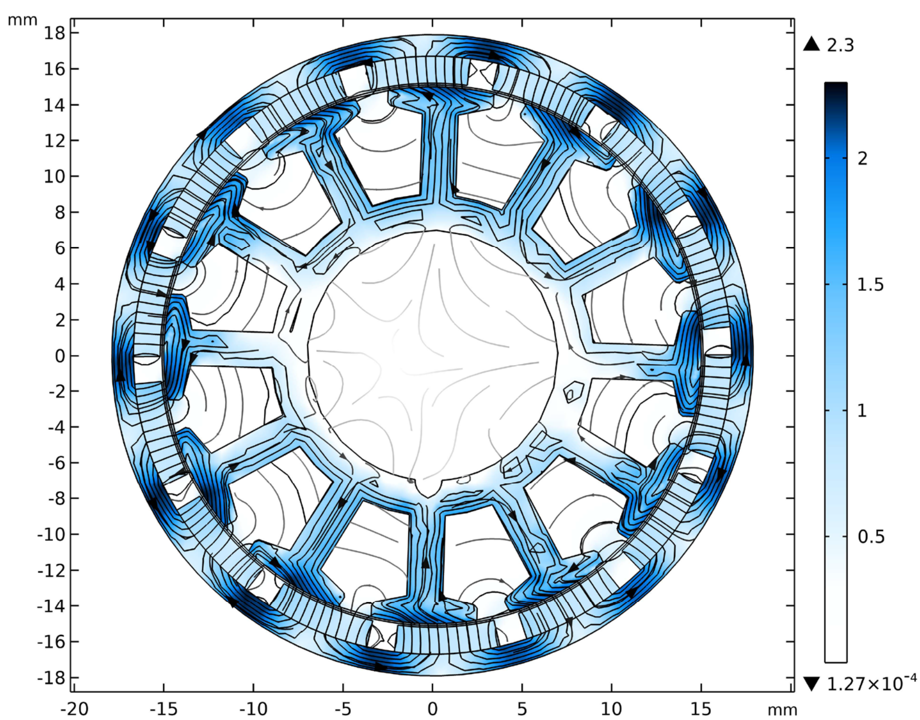


Fig. 2. Distribution of the electromagnetic field and vector magnetic potential of the studied motor

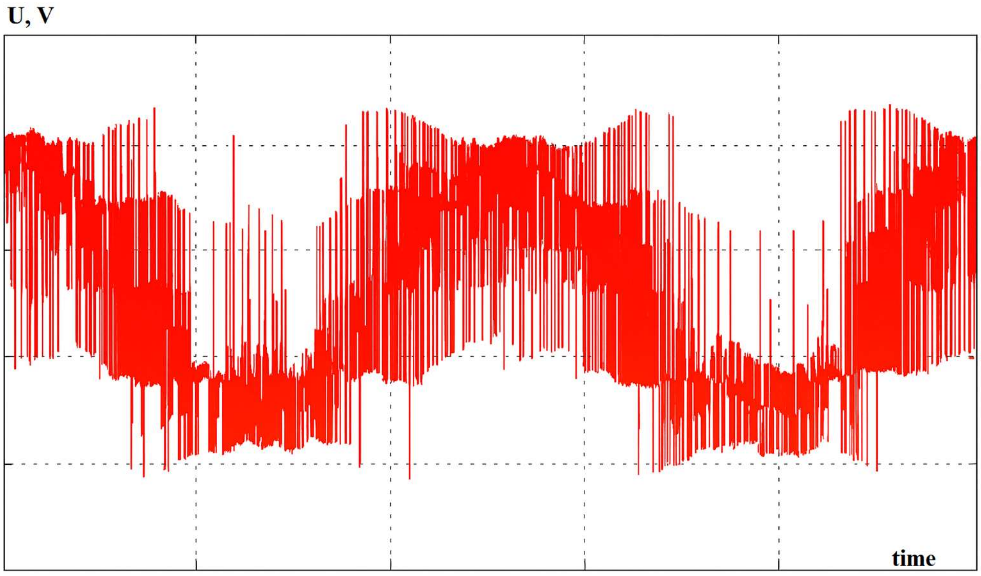


Fig. 3. Voltage curve shape when powered by a pulse-width modulated inverter

5. 2. Estimation of losses when powered from a sinusoidal voltage source and a semiconductor inverter

Harmonic components of current and voltage in electric motors powered by PWM arise due to the discrete nature of switching of the inverter's semiconductor keys. They cause additional losses in the magnetic core and windings, and also lead to increased noise, vibration of the motor and a decrease in its reliability. There are three main methods for combating excess losses when powered from a PWM inverter: optimization of PWM algorithms, use of filter elements, and optimization of the drive motor design.

The nature of the distribution of specific losses in the calculation area of the studied motor when powered from a PWM converter is shown in Fig. 4.

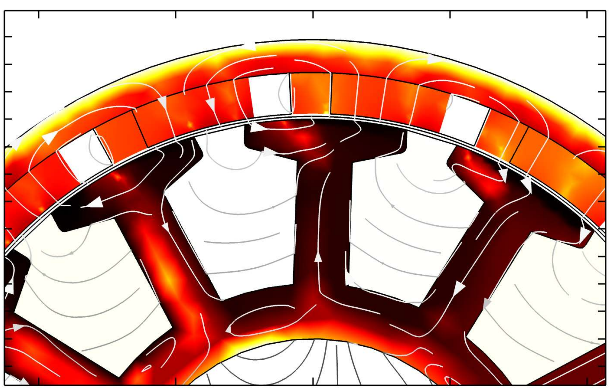


Fig. 4. Distribution of specific losses when powered by a converter

By changing the speed of rotation of the studied motor, a series of calculations is performed to determine the total losses. The results of calculating the motor losses when powered from a sinusoidal voltage source and when powered from a PWM inverter are given in Table 2.

When the rotation speed and power supply technique change, the electromagnetic torque also changes – an important operational indicator of any electric motor. The results of calculating the electromagnetic torque when the rotation speed of the studied motor changes and with different power supply techniques are given in Table 3.

Table 2

Result of calculating motor losses for different power supply techniques

Rotation speed, (rpm)	Harmonic power supply	PWM power supply
	Losses, (W)	Losses, (W)
5000	27.521	44.628
7000	36.132	59.246
10000	48.781	83.414
15000	71.628	129.88
20000	94.615	176.47
25000	136.11	232.13

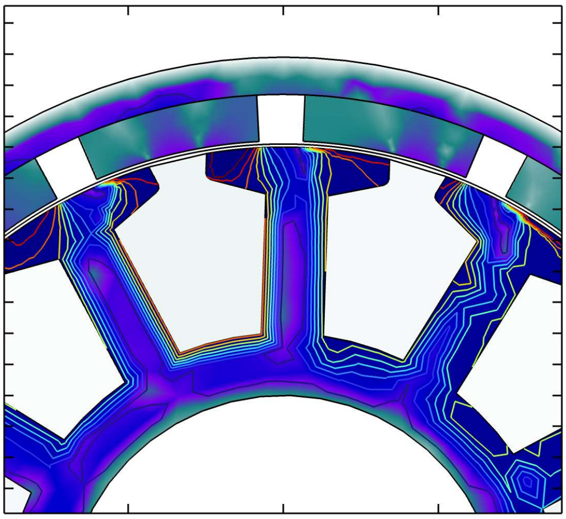
Table 3

Results of calculating the electromagnetic torque of the motor

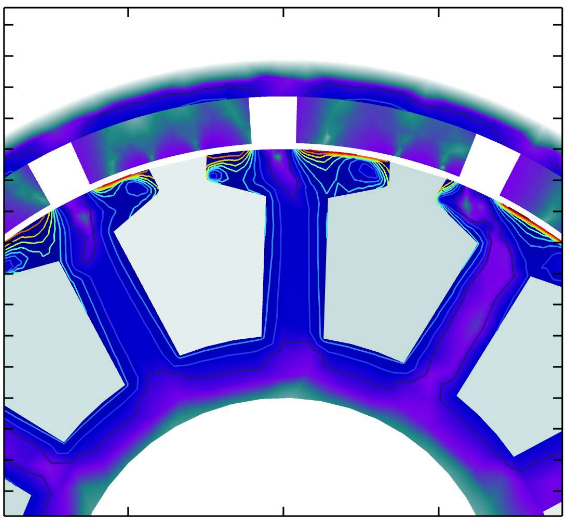
Rotation speed, (rpm)	Electromagnetic torque, (N·m)		Change in torque relative to the prototype, *Δ* %
	Harmonic power supply	PWM power supply	
5000	0.661	0.643	–3.03
7000	0.963	0.946	–2.083
10000	1.264	1.246	–0.79
15000	1.66	1.649	–0.60
20000	1.948	1.929	–1.025
25000	2.23	2.215	–0.672

When changing the power supply technique of the studied motor, the distribution of eddy currents in the structural elements of the studied motor changes: the magnetic core, rotor, permanent magnets, and armature winding. The distribution of eddy currents for different power supply techniques is shown in Fig. 5.

The most noticeable increase in currents and losses occurs in the tooth part of the stator magnetic core, where magnetic induction and magnetic flux are of greatest importance. In addition, there is a significant influence of higher harmonics from the PWM power supply.



a



b

Fig. 5. Distribution of currents in the structural elements of the engine: *a* — when powered by an inverter; *b* — when powered by a sinusoidal power supply

5. 3. Estimation of losses and torque when using a more technological form of magnets

In the considered prototype of the engine, the most rational solution is to use permanent magnets of a radial configuration, the contours of which ensure uniformity of the air gap. Such geometry contributes to a uniform distribution of the air gap and ensures the most efficient use of the volume of the active part of the machine for placing magnets. Due to this, improved operating characteristics of the engine are achieved – the electromagnetic torque and power increase.

At the same time, such a design solution also has significant drawbacks. The manufacture of permanent magnets of a complex rounded shape is technologically more complicated and much more expensive. The radius of curvature of such elements is determined by the individual dimensions and geometry of a particular engine, which makes it impossible to standardize the production process on a large scale. For each new size, it is necessary to design separate technological devices and reconfigure specialized equipment, which significantly increases the cost of manufacturing the engine as a whole.

The use of a more technological form of permanent magnets, namely, rectangular PMs, has a number of significant advantages. PMs of this form are more technological in manufacture, their production has less waste, and the simplicity of mechanical processing accelerates serial production and reduces labor costs. This leads to a decrease in the final cost of a serial sample.

It is obvious that when changing the configuration of PM, the characteristics of the engine under study will change with unchanged general geometric and structural dimensions.

The distribution of the electromagnetic field and vector magnetic potential for the prototype and the engine with a rectangular PM shape is shown in Fig. 6.

To estimate the magnitude of losses, a series of calculations was performed using the constructed numerical mathematical model for an engine with a modified PM form under different power supply techniques. The results of the calculation and comparison of losses in the prototype engine and the engine with modified PM are given in Table 4.

Table 4

Results of loss calculation for different shapes of permanent magnets

		n, (rpm)					
Losses, W		5000	7000	10000	15000	20000	25000
Prototype	Harmonic power supply	27.5	36.1	48.7	71.6	94.6	136.1
	PWM power supply	44.6	59.2	83.4	129.8	176.4	232.1
	Δ, %	62.1	63.9	70.99	81.3	86.5	70.5
Rectangular PMs	Harmonic power supply	20.2	25.5	32.1	48.8	57.5	80.2
	PWM power supply	33.9	43.3	56.7	91.6	111.7	141.5
	Δ, %	67.7	69.5	76.8	87.5	94.3	76.3
Change in losses relative to the prototype, *Δ* %	Harmonic power supply	–26.4	–29.2	–34.2	–31.8	–39.2	–41.1
	PWM power supply	–23.9	–26.8	31.9	–29.5	–36.6	–39.01

When changing the PM configuration to rectangular magnets, the magnitude of the electromagnetic torque will also change. The result of the calculation of the electromagnetic moment is given in Table 5.

Table 5

Results of calculating electromagnetic torque for different PM shapes

Rotation speed, (rpm)	Electromagnetic torque, (N·m)				Change in torque relative to the prototype, *Δ* %	
	Prototype		Rectangular PMs			
	Harmonic power supply	PWM	Harmonic power supply	PWM	Harmonic power supply	PWM
5000	0.66	0.64	0.51	0.52	–21.6	–18.3
7000	0.96	0.94	0.74	0.74	–22.9	–20.7
10000	1.26	1.24	0.96	0.98	–23.6	–21.6
15000	1.66	1.64	1.24	1.27	–24.8	–22.6
20000	1.94	1.92	1.43	1.45	–26.3	–24.7
25000	2.23	2.21	1.56	1.63	–29.8	–26.2

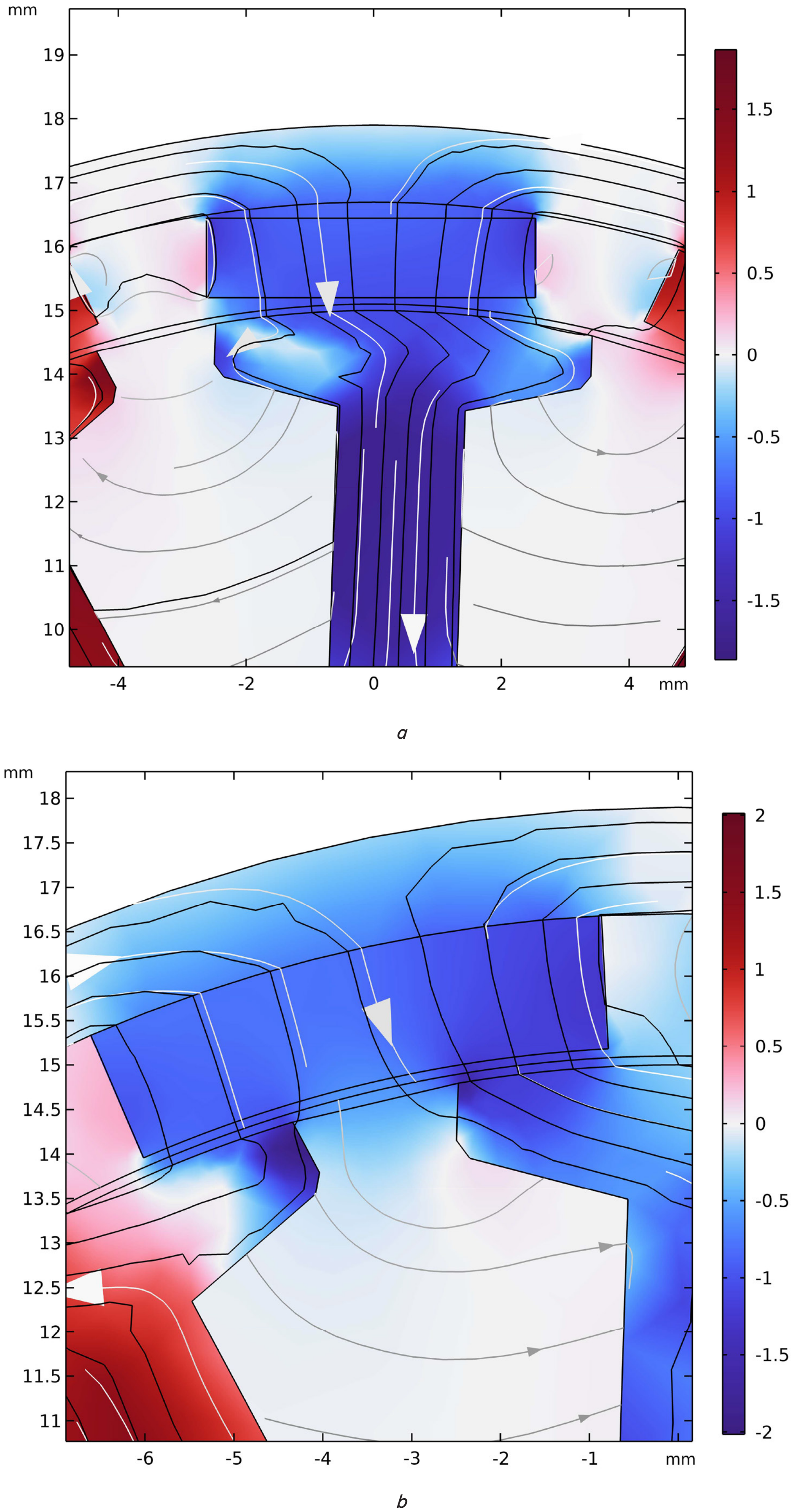


Fig. 6. Result from calculating the electromagnetic field for: *a* – engine with modified magnets; *b* – for the prototype

It is worth noting that the calculation of losses in the prototype and the engine with a rectangular PM shape was performed during idle operation.

6. Results of analyzing active losses in an electric motor with permanent magnets: discussion and summary

Our study of the distribution of magnetic induction in the cross section (Fig. 2) of the motor showed that the magnitude of magnetic induction in individual sections of the magnetic core does not exceed the uncommented values. This confirms the correctness of the choice of geometric parameters, characteristics of permanent magnets and load currents of the armature winding. Thus, in the stator yoke the average induction is about 1.01 T, in the stator teeth – 1.67 T, in the air gap – 0.793 T, in the permanent magnet area – 0.91 T, and in the rotor yoke – approximately 1.39 T.

The output voltage spectrum of the converter (Fig. 3) with a PWM inverter provides the motor with the first harmonic of the operating frequency, and it also contains higher harmonics on the order of 24, 32, 56, 58.

Based on the analysis of Fig. 4, it can be concluded that the largest specific losses are observed in the area of the teeth of the magnetic core of the stator of the electric motor. At the edges of the teeth, the value of the specific losses reaches $(2.7–2.8)·10^8$ W/m^3, which is due to the peculiarities of the closure of the main magnetic flux. In the middle part of the teeth, these losses are about $6.05·10^7$ W/m^3, while in the stator yoke they decrease to $2.24·10^7$ W/m^3. In the permanent magnets of the rotor, the average value of the specific losses is approximately $4.79·10^4$ W/m^3, and in the yoke of the rotor sleeve – $1.71·10^5$ W/m^3. The losses in the rotor and permanent magnets are approximately 1.5–2.5 orders of magnitude lower than in the stator. This is explained by the fact that in the studied motor the outer rotor rotates synchronously with the fundamental harmonic of the stator magnetic field, therefore there are no losses from the fundamental harmonic in the rotor; the main losses are caused by higher harmonics.

In addition, the electrical conductivity of the permanent magnet material is significantly lower than that of electrical steel, which also reduces losses. Losses in the rotor are also explained by the influence of higher harmonics, in particular tooth harmonics. When the motor is powered by a PWM inverter, these losses increase due to the appearance of additional harmonic components introduced by the power source itself.

As the speed of the electric motor increases, losses increase, which is due to an increase in the frequency of magnetization reversal of the magnetic system and, accordingly, an increase in losses due to hysteresis and eddy currents. In other parts of the structure, such as the magnetic core of the rotor and the stator winding, an additional increase in losses is associated with an increase in the current displacement effect. It becomes more pronounced with increasing supply voltage frequency and rotation speed.

When powered by a PWM inverter (Table 2), the total losses increase by 62–86% depending on the speed, which is explained by the influence of higher harmonics characteristic of the PWM signal. In this case, the increase in losses is nonlinear: when the speed is doubled, they increase by approximately 77%, when tripled – by 260%, and when quadrupled – by 340%. At a maximum speed of 25,000 rpm, the losses exceed the initial (at 5,000 rpm) by 4.9 times. This effect is due not only to an increase in the frequency of magnetization reversal but also to an increase in active resistance due to an increase in the effect of current displacement in the conductive elements of the motor. With an increase in the speed of rotation (Table 3), the magnitude of the electromagnetic torque increases. This is explained by a change in the control mode (in the case of a PWM inverter) and a significant increase in the armature current. When powered by a PWM inverter, a decrease of ≈ 3% is observed, which is explained by increased losses and heating.

When the motor is powered by PWM (Fig. 5, *a*), compared to power from a source with sinusoidal voltage (Fig. 5, *b*), eddy currents in the stator magnetic core increase. The greatest increase in currents, and accordingly losses, occurs in the tooth zone, where the concentration of the magnetic flux is the greatest and, accordingly, the manifestation of higher harmonics.

The dimensions of the rectangular PMs (Fig. 6, *a*), compared to the shape of the PM of the prototype motor (Fig. 6, *b*) are determined in such a way that the minimum air gap remains constant at ≈ 0.2 mm. The use of rectangular magnets reduces their total volume by approximately 20%. As a result, there is a decrease in magnetic induction, electromagnetic moment, power, and the level of magnetic induction in individual parts of the magnetic system. At the same time, a decrease in the volume of magnets leads to a decrease in losses, which has a positive effect on the thermal regime of the motor, reducing its heating.

Depending on the rotation speed, when using a rectangular PM shape and powered by a source with sinusoidal voltage (Table 4), losses are reduced by ≈ 26...41%. When powered by an inverter with PWM and using a rectangular PM shape, losses are reduced by 23...39%.

However, when using a rectangular PM shape (Table 5), the electromagnetic torque value decreases with harmonic power supply by 21...30% and with PWM power supply by 18...26%. The reduction in torque value is also due to an increase in the equivalent air gap value. In addition, with a modified PM shape, electromagnetic torque pulsations are reduced by ≈ 12%, which leads to a decrease in the noise and vibration level and has a positive effect on the service life of the mechanical components of the engine.

Compared with similar studies [2, 5], our results take into account the design and electromagnetic features of the engine under study during its modification.

Based on the results of our study, the values of losses and electromagnetic forces when using permanent magnets of a more technological form were obtained. This makes it possible to reduce the cost of its manufacture, improve manufacturability, reduce the amount of losses, heating, and improve its energy performance.

The limitations of this study are due only to electromagnetic losses without taking into account the mutual influence of thermal deformations, vibrations, imbalance or mechanical losses in bearings. In addition, when modeling power from a PWM inverter, simplifications were adopted regarding the harmonic spectrum, which does not fully correspond to the real operating conditions of motors from PWM inverters of various types and qualities.

The disadvantages of our work include the lack of complex interaction between electromagnetic, thermal, and mechanical processes, which determine the real level of energy losses and temperature regimes of the engine.

Future studies might construct a complex multiphysics model of the engine, which would simultaneously take into account electromagnetic, thermal, and mechanical processes. This could make it possible to assess the mutual influence of heating, vibrations, and mechanical deformations on the loss distribution and stability of the magnetic characteristics of permanent magnets.

7. Conclusions

1. To assess the influence of the structural and electromagnetic parameters of a permanent magnet motor, a numerical mathematical model implemented by the finite element method has been constructed. The model built makes it possible to obtain the distribution of the electromagnetic field, forces, and determine the integral values of losses in its individual structural elements. A feature of our model is that it makes it possible to calculate the total losses in the magnetic core: eddy currents, hysteresis, and additional losses from higher harmonics. Eddy current losses, depending on the rotation speed, are from 19 to 26%, hysteresis – from 47 to 62%, and additional losses – from 12 to 34%.

2. Analysis of losses in the magnetic core and structural elements of the studied motor revealed that losses significantly depend on the type of power supply. When powered by a PWM inverter, there is an increase in losses in the motor, compared to sinusoidal power supply, by 62–86%, depending on the rotation speed. This is explained by the influence of higher harmonics of the supply voltage, which lead to increased losses on hysteresis and eddy currents. When the motor rotation speed increases, the losses increase disproportionately, from 77% to 340%, at a speed of 20,000 rpm. At a maximum rotation speed of 25,000 rpm, the total losses exceed the losses at 5,000 rpm by 4.9 times. This is explained by an increase in the fundamental frequency of the magnetic core reversal and an increase in losses arising from an increase in active resistance due to an increase in the effect of current displacement in the conductive elements of the structure.

3. The use of a simplified, more technological form of permanent magnets is advisable since such a design solution makes it possible to reduce losses and heating of the studied engine. In addition, it makes it possible to increase energy efficiency and manufacturability of series of such engines. When powered from a source with sinusoidal voltage, losses are reduced by 26–41%, and when powered from an inverter with PWM – by 23–39%. The reduction in losses is explained by the reduction of the main magnetic flux due to the reduction of the volume of permanent magnets. The use of a rectangular shape of the PM leads to a reduction of the electromagnetic moment by 21–30% with sinusoidal power supply and by 18–26% when powered from an inverter with PWM. This is due to an increase in the value of the equivalent air gap. The use of a simplified shape of the PM makes it possible to reduce the magnitude of pulsations in the electromagnetic moment by 12%, which contributes to a reduction in the level of noise and vibrations and an increase in the reliability of its mechanical components. The use of this form of PM is a compromise solution between the reliability of high-speed electric motors, their manufacturability, and level of losses and operational characteristics.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript under full human control.

Artificial intelligence was not used to generate, process, or interpret scientific data, form conclusions, or other elements of the scientific results in the paper.

Tool used: ChatGPT (OpenAI GPT-5, version 2025).

The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

Authors' contributions

Mykhailo Kovalenko: Writing – original draft, Writing – review & editing, Investigation, Project administration; **Vadim Chumack:** Conceptualization, Supervision; **Viktor Grebenikov:** Validation; **Leonid Mazurenko:** Methodology; **Ihor Tkachuk:** Resources; **Oleh Bazarov:** Software; **Yehor Titov:** Funding acquisition.

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