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THREE-STATOR DISK SYNCHRONOUS MOTOR WITH PERMANENT MAGNETS

TRÓJSTOJANOWY, TARCZOWY SILNIK SYNCHRONICZNY Z MAGNESAMI TRWAŁYMI

Abstract: The paper deals with the disk synchronous motor with permanent magnets issue, as a possible design modification of this motor type. In the first part, the constructions of disk motors with double-sided thrust are described. The next sections are described the propose of the dimensions and design arrangement of the electromagnetic circuit of the disk synchronous motor, which respects its technical implementation in the three-stator design. The synchronous motor has three toroidal wound stators and four rotor discs with permanent magnets. Motor calculations were done in Matlab and the model was drawn in AutoCad.

Streszczenie: W artykule podjęto problematykę dyskowego silnika synchronicznego z magnesami trwałymi, jako możliwą modyfikację konstrukcyjną tego typu silnika. W pierwszej części opisano konstrukcje silników tarczowych o ciągu dwustronnym. W kolejnych rozdziałach opisano propozycję wymiarów i rozmieszczenia konstrukcyjnego obwodu elektromagnetycznego silnika synchronicznego tarczowego, uwzględniającą jego techniczną realizację w konstrukcji trójstojanowej. Silnik synchroniczny ma trzy stojany uzwojone toroidalnie i cztery tarcze wirnika z magnesami trwałymi. Obliczenia silnika wykonano w programie Matlab, a model narysowano w programie AutoCad.

Keywords: Synchronous motor, disk rotor, permanent magnet, electromagnetic circuit

Słowa kluczowe: silnik synchroniczny, wirnik tarczowy, magnes trwały, obwód elektromagnetyczny

1. Introduction

The development of motors and drives that is currently being realized and which are referred to as "modern", so their principle was discovered and used already in the 19th century. An example of one such motor is a synchronous machine. A synchronous machine is a rotating electrical machine that converts electrical energy into mechanical energy or in reverse. It is the most used machine in electrical energy production [1]. It is generally known that, from the point of view of energy conversion, a synchronous machine can work in two modes: generator mode and motor mode.

The construction of a synchronous machine is like an asynchronous motor. The stator winding is usually three-phase, but a different number of phases is currently being developed [2]. In the case of a rotor, there are two types: a smooth rotor and a rotor with expressed poles. The excitation winding on the rotor is powered by a DC voltage. DC excitation current is supplied to the rotor through two sliding contacts (carbons) that slide on brass rings located on the rotor shaft. In machines of smaller power, the excitation winding is replaced by a permanent magnet. In that case, they are permanent magnet synchronous machines and they have come to the fore in recent decades due to their advantages, which are also commonly described in older commonly available literature [3]. The design development and control research of multi-phase synchronous motors with permanent magnets (PMSM) up to 200 kW, which are mainly used for electric vehicle drives, are commonly presented [4, 5].

Modern control systems require fast, dynamic drives with a precisely defined position. For small power machines with high dynamics, it is possible to design motors with a disk rotor and magnetization in the axial direction. Currently, such DC and asynchronous motors, BLDC and BLAC motors, permanent magnet motors with a disk rotor are known, all of which have very good dynamic properties due to the small moment of inertia of the machine rotor. This also results in the design of a disk synchronous motor with permanent magnets with an axial air gap, which would combine the advantageous properties of a cylindrical permanent magnet synchronous motor with the dynamic properties of motors with a disk rotor [6].

For needs, e.g., integration of drive motors with planetary gears in modern electro-mechanical drive systems, disk synchronous motors with permanent magnets are often used. It follows from that the necessity of designing and researching these multi-rotor machines with permanent magnets.

2. Permanent magnets for brushless synchronous motors

Synchronous motors with excitation from permanent magnets have come to the fore in recent decades. The correct selection of permanent magnets is one of the requirements when designing a brushless motor. The basic criteria for selecting magnets are [7]:

- Simple construction, low price, which results from the fact that the rotor has no windings (electrical circuit) or magnets.
- The price. For drives that are produced as cheaply as possible, ferrites can be used if their properties are sufficient. The most expensive magnets are from rare earths (eg Sm-Co magnet). The price of permanent magnets has been constantly increasing in recent years and is influenced not only by business interests but also by the political situation. China is the dominant country in the export of rare earth magnets.
- Specific motor torque. Magnets can produce a limited amount of motor torque for a given motor type, and with some types of magnets that torque may not be sufficient.
- High coercivity. High coercivity (HC) means the magnet's resistance to demagnetization. Coercivity is the limit value of the intensity of the magnetic field, if will exceeded than demagnetizes the magnet.
- Operating temperature range. Rare earth magnets have a low Curie temperature, so the rotor cooling system is very important at higher motor loads.
- Remanence. The strongest magnets may not be a guarantee of simplicity and quality. Magnets with high remanence can create excessively high magnetic inductions in the motor, and high induction means saturation of critical parts of the magnetic circuit, which means higher losses.
- Dimensions of the magnet. Ferrites are sufficient to generate a small magnetic voltage on a certain surface. Theoretically, the same voltage can be achieved with neodymium magnets (NdFe). In practice, however, the width of the magnet can be so small that it would be difficult to make and use such a magnet. Also, the use of magnets of the AlNiCo group can be limited due to the demanding dimensions and shape of the magnet, because the magnets of this type are more difficult to processing (they are hard and brittle).

For practical use, the energy product BH_{max}, is given, which characterizes the quality of the permanent magnet and describes about the amount of energy stored in the magnet (Fig. 1).

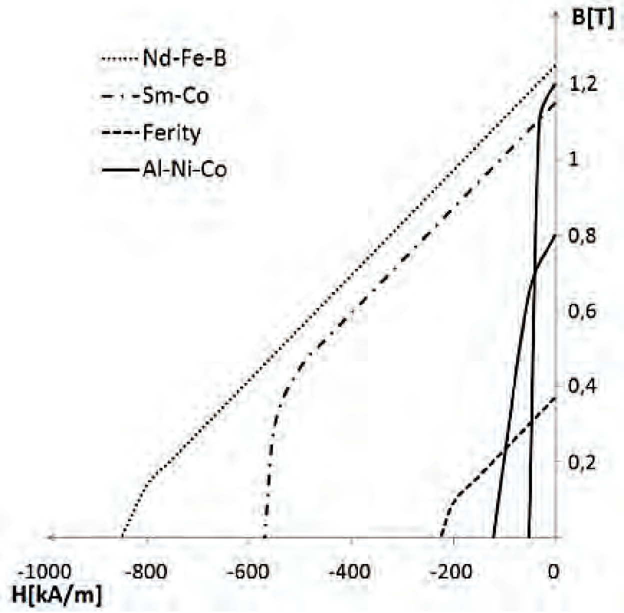

Fig. 1. BH curves of permanent magnets

3. Motors with a disc rotor

For the first time, disc motors with PM were constructed in the late 70s and early 80s of the last centuries [8, 9]. The constructors were Campbell (1975), Leung and Chan (1980), Weh et al. (1984). Interest in them has grown in recent decades mainly due to their high ratio of torque to motor weight and high efficiency [10]. Compared to radial flux motors, thinner magnets are used. Also, the noise and vibration that disc motors produce is less than conventional machines.

Advances in disc motors came with advances in power electronics. Disc motors can be produced with outputs of up to hundreds of kW. A disc motor can have up to 78% higher performance compared to a cylindrical motor of the same bulk and used material [11, 12]. Possible design solutions of disk motors are listed below.

3.1. Disc motor with one rotor and stator

This type of motor (Fig. 2) has a simple design. The rotor and stator are parallel to each other.

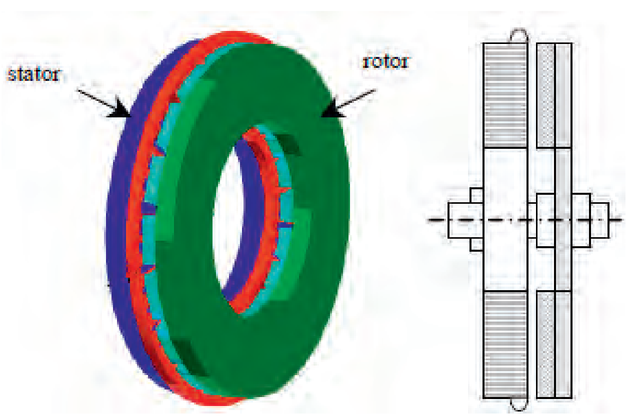

Fig. 2. Disc motor with one rotor and stator and axial winding of stator

There are permanent magnets on the inner side of the rotor, windings in the radial direction on the stator, and an air gap between the magnets and the poles of the stator.

3.2. Disc motor with one stator and two rotors

For the first time, this construction was made only at the end of the 80s. In the centre of construction is the stator and on the sides are the rotors. This design solves the problems of axial forces acting on the bearing, as they cancel out. According to the construction of the stator winding, the stator can be slotted (Fig. 3). or groove-less (Fig. 4). where the individual windings are separated by an air gap filled with epoxy resin, which dissipates heat well.

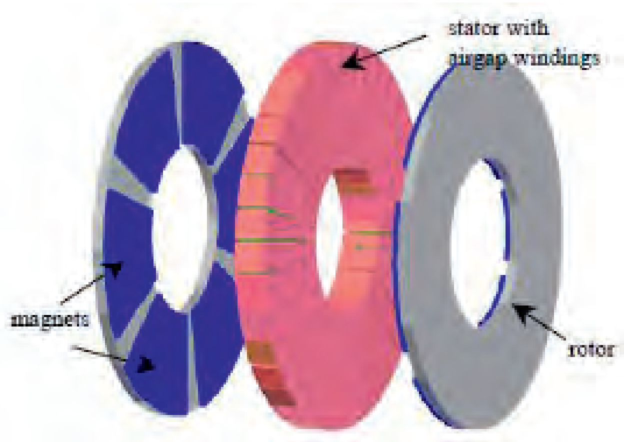

Fig. 3. TORUS-S disk motor with slotted stator

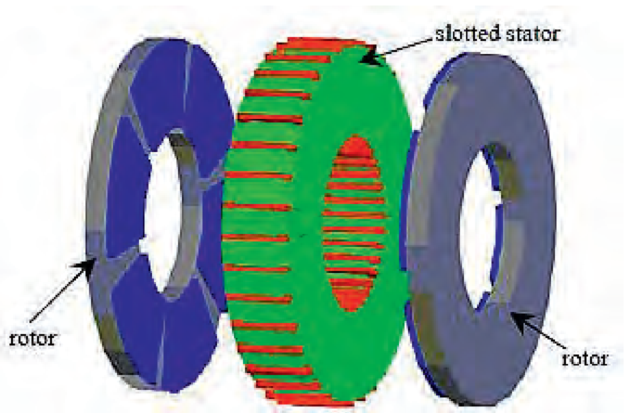

Fig. 4. TORUS-S disk motor with groove-less stator

The magnets on the opposite disks can be oppositely polarized (the same poles of the magnets are opposite each other – NN) or positively polarized (opposite poles are opposite each other – NS), as seen in Fig. 5.

When the LV (SS) magnets are arranged, the magnetic flux from one rotor does not pass to the second rotor but is closed through the stator yoke (Fig. 4 left). With the NS arrangement of the magnets, the

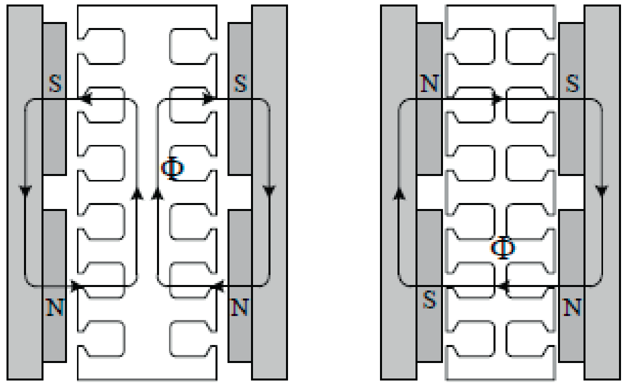

Fig. 5. Magnetic flux of TORUS motors with rotor types NN and NS

main magnetic flux is not closed by the action of the magnets through the stator yoke but passes through both rotors (Fig. 4 on the right). Thus, the stator can have a smaller thickness (we do not need a stator yoke), which leads to a higher efficiency of the motor and a reduction its weight. A significant difference between a slotted stator and a non-slotted stator is that in the case of a slot-less stator, less copper is used, resulting in lower losses. In addition, the heat from the stator is also better removed here.

Other advantages of the TORUS type motor are lower mutual inductance, elimination of higher harmonics from the course of the motor torque, lower high-frequency losses in the rotor and in the stator teeth.

3.3. Disc motor with two stators and one rotor (AFIR)

This type of motor solves the problem of axial forces acting on the rotor bearings, since the axial forces are distributed and act evenly against each other. The stator can be grooved or without grooves. The space between the grooves is filled with resin, which dissipates heat well. In this case, more copper is used for a slotted motor than for a non-slotted motor. The rotor is different from the TORUS type. Permanent magnets are on or in the rotor disc and fill the entire thickness. The magnetic flux must pass through the rotor only in the axial direction. This is achieved if the rotor disk is made of magnetically non-conductive material, which prevents the magnetic flux from flowing in the radial direction of the rotor and closing only through one stator and the rotor yoke. Since no magnetic flux passes radially through the rotor, a thinner disk can be used. Replacing steel with a lighter magnetically non-conductive material and at the same time a thinner rotor means a smaller moment of inertia and better dynamics. Therefore, they are suitable for use in applications where great motor dynamics are required. Even with this motor, according to the design of the stator winding, the stator can be with grooves (Fig. 6). or groove-less (Fig. 7).

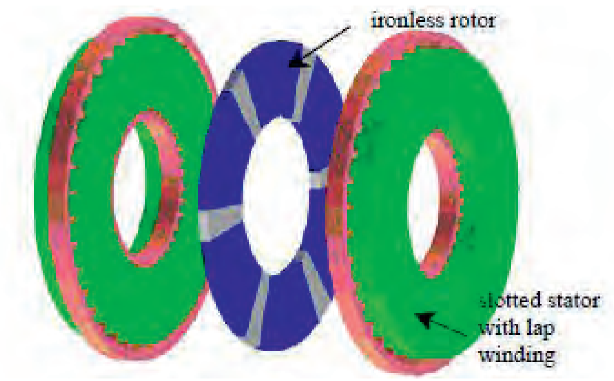

Fig. 6. AFIR disc motor with slotted stator

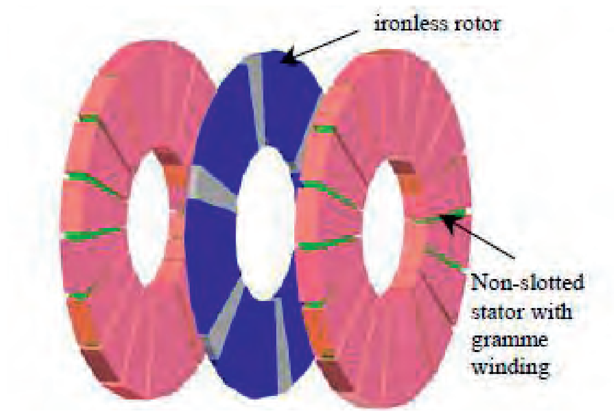

Fig. 7. AFIR disc motor with non-slotted stator

The advantages of a single-disk axial motor with a rotor in the middle:

- By using two air gaps, the forces between the rotor and the stator are balanced. The rotor is less affected by sudden pulling forces that destroy the bearings.
- The shape of the motor supports the stator cools better.
- The magnets have a flat shape they do not need to be ground like in the case of radial motors.
- The air gap is structurally adjustable, which is almost impossible in the case of radial motors.
- The stator is flat and open – easy to wind.

The disadvantages of a single-disk axial motor with a rotor in the middle:

- If there is a large difference between the outer and inner diameter of the stator or there is a large number of magnetic poles, it is necessary to use a longer wire for the winding and thus it is used inefficiently.
- Threads in the inner radius of the stator have a limited capacity.
- The torque is not sinusoidal but toothed.
- Stator lamellas must have a spiral shape [13].

3.4. Multi disc motor

In some applications, a small diameter disc motor is also required. The torque of a simple disc motor is a function of rotor diameter, and small diameter means small torque. If necessary, the torque can be increased with a multi-disc motor. A multi-disk motor is a disk motor extended by additional stages. The motors are placed next to each other on one shaft. As a rule, there should be one more stator or rotor disc, but the second option is usually used. Compared to multiple cylinder motors connected via a common shaft, disc motors are simpler to construct.

As in the previous motors, the multi-disk motor can have radial or axial stator windings, slotted or non-slotted, and the magnet placement can be NN or NS. The stator is usually made of steel sheets. The magnetic flux is closed depending on whether the rotors are of NN or NS type.

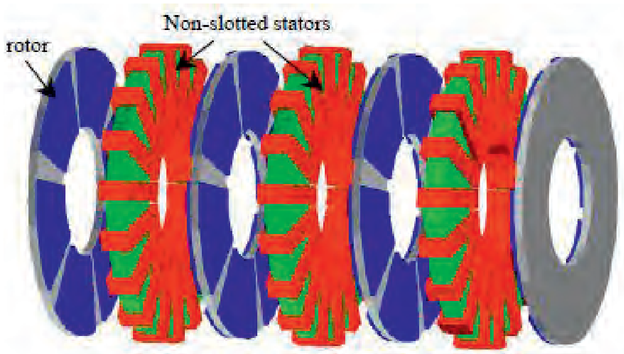

Fig. 8. Axial-wound MULTI-NS disc motor with slot-less stators

4. Design of a three-stator disk synchro-nous motor with permanent magnets

Designing disk motors with permanent magnets is a relatively difficult issue that is not comprehensively treated in the available literature. Most of the proposals are incomplete and only deal with a certain issue and part of the motor.

However, the three-stator motor was simply obtained by connecting three disk motors with one common shaft, while the motors are powered in parallel from one common source. It is important that the motors are rotated by 30° and are separated by non-magnetic steel so that the outer motors do not affect the middle motor with their magnetic flux. Next, the design of one motor is described. The motor is a TORUS type with a NN rotor type (Fig. 9).

The representation of the magnetic flux of the motor is shown in Fig. 10. The figure shows the moment of time at different magnitudes of the voltages in the phases. The fluxes have a symmetrical shape with respect to the stator axis.

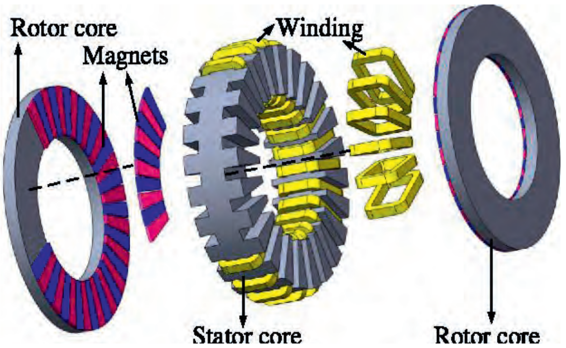

Fig. 9. 3D model of a TORUS type motor with magnets on the rotor

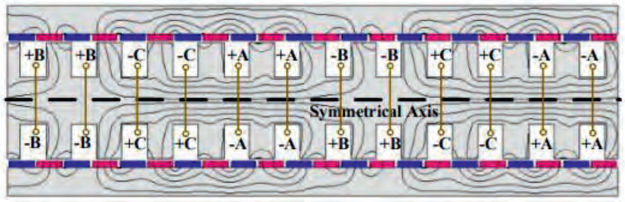

Fig. 10. Magnetic flux in TORUS motor with magnets on the NN rotor

4.1. Design of the basic motor parameters

A total apparent power of 3 kVA was chosen for the proposed three-stator synchronous motor. A third of the apparent power is the apparent power of one disk motor, i.e. 1 kVA. It was also determined that the motor would operate with a power factor of 0.8 and according to theory from scientific articles and comparisons with other permanent magnet motor designs, we would like to achieve a motor efficiency of $\eta = 0.87$. To determine the motor current, it is also necessary to know the size of the phase nominal supply voltage. According to the catalogue data of other disc motors, the nominal value of the phase voltage is 50 V.

Additional basic parameters of the proposed disk synchronous motor were determined by calculation, which are listed in Table 1.

Table 1. Construct parameters of magnetic circuit

Parameter	Sign	Value
Active power	P_{1N} [W]	800
Voltage between 2 phases	U_S [V]	86.6
Number of motor phases	m [-]	3
Number of motor poles	$2p$ [-]	4
Number of coils per phases	n_f [-]	2
Number of stator slots	n_d [-]	24
Number of magnets on rotor	n_m [-]	4

4.2. Design of the basic dimensions of the motor and parameters of the electro-magnetic circuit

Slotted stator disk model based on the parameters calculated so far and the studied scientific articles, the outer diameter of the stator disk was designed to be 0.3 m and the width of the disk annulus 0.05 m. The calculated internal diameter of the stator is 0.2 m. The rotor discs also have the same diameters. The total number of slots on the stator and therefore also the pole teeth is 24. The slots have a simple shape and the slots and therefore also the pole teeth have the same size of the angle in the ring, which is determined as 360º/24/2 = 7,5º. In Fig. 11 shows a 3D model of the slotted stator disk.

Fig. 11. 3D model of the slotted stator disk

The magnitude of the induction in the air gap is chosen to be 0.8 T, which is common for such types of motors. The size of the air gap is 0.3 mm. Using the equations that are used in designing and calculating the parameters of the electromagnetic circuit of the motor, the magnetic conductivity, magnetic field intensity, magnetic and magnetic flux in the air gap were successively calculated.

Electrotechnical steel was chosen for the magnetic circuit of the stator type M-4/120 Carlite. It has low hysteresis and eddy current losses. It is produced by cold rolling. Magnetic field intensity values were read from the magnetization characteristic [14]. for individual inductions in individual parts of the stator magnetic circuit, and from these the corresponding magnetic voltages were determined. Then the magnetic stresses in the yokes of both rotors and the magnetic stresses in the permanent magnets were calculated. The number of turns in a phase is determined from the total magnetic voltage required for excitation. In Fig. 12 shows a 3D model of the stator with a winding, and the calculated parameters of the electromagnetic circuit of the motor are listed in Table 2.

Since it is a synchronous motor, the number of rotor magnets is chosen so that the mechanical angular velocity of the rotor is the same as the electrical

Fig. 12. 3D model of disc stator with axial winding

Table 2. Parameters of the motor electromagnetic

Parameter	Value
Magnetic flux in the stator yoke	0.0026 Wb
Magnetic induction in the stator yoke	1.31 T
Magnetic voltage in the stator yoke	4.91 A
Magnetic induction in the stator tooth	1.61 T
Magnetic voltage in the stator tooth	4.52 A
Magnetic induction in the stator yoke	1.28 T
Magnetic voltage in the rotor yoke	3.98 A
Magnetic voltage in the rotor magnet	65.2 A
Total magnetic tension	1032.3 A
Phase current	7.65 A
Number of turns in a phase	67

angular velocity of the stator. For this reason, there are 4 magnets on the rotor, i.e., two positive magnet poles to the stator and two negative magnet poles. Since the stator has one pole formed by two coils, the magnet must cover both coils with its surface, but it must not overlap with other phases at the same time, so the angle of one magnet is 24º. The location of the magnets on the rotor and their polarization because the NN type configuration was chosen is shown in Fig. 13. The model of the electromagnetic circuit of the motor with a winding is shown in Fig. 14.

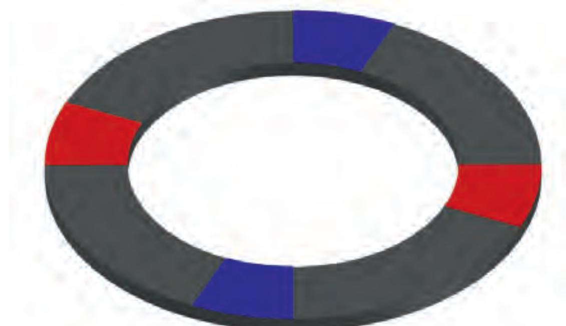

Fig. 13. Model of disc rotor with permanent magnet

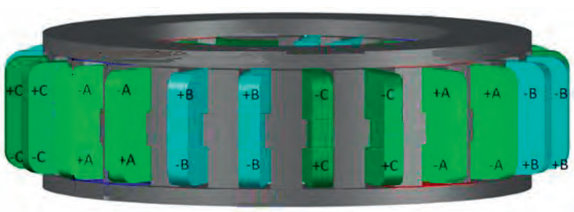

Fig. 14. Model of electromagnetic circuit of the motor with winding

A three-stator motor can be obtained by simply placing three single-disk motors on one common shaft. Individual motors will be powered in parallel. However, the motors are shifted relative to each other by 30°, which reduces the undulation of the total torque of the motor. Individual motors separated from each other by non-magnetic steel class 316. It is shown in Fig. 15 highlighted in yellow and has a thickness of 5 mm.

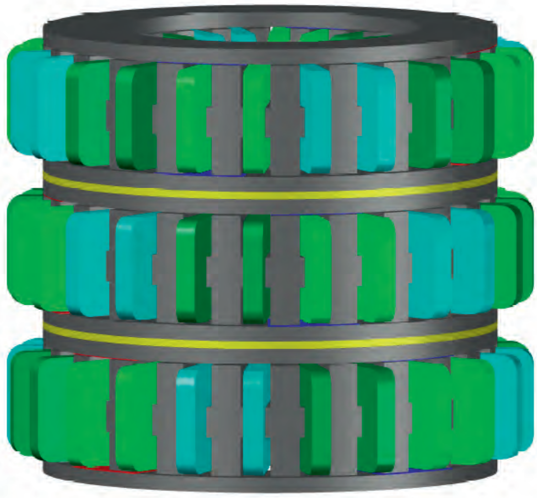

Fig. 15. Model of the three-stator electro-magnetic circuit of the motor

4.3. Calculation of the motor losses and efficiency

In the informative and simplified calculation of the total losses in the motor, Joule losses in the winding, losses in the electromagnetic circuit of the motor, mechanical losses and additional losses were calculated. The additional losses that arise when the motor is loaded and are caused by eddy currents with higher harmonics are relatively difficult to accurately calculate, so they are given as an estimate, which is approximately 0.5% of the nominal power of the motor. The calculated values of losses and efficiency are shown in Table 3.

Table 3. Losses and efficiency of the motor

Parameter	Value
Joule losses in the winding	18.43 W
Losses in the stator yoke	6.02 W
Losses in the stator teeth	12.61 W
Losses in the rotor yoke	3.01 W
Mechanical losses	17.42 W
Additional losses	4.01 W
Motor efficiency	0.91

The efficiency of the motor is quite high, but the overall efficiency of the drive with this motor will be lower, since the motor will need its own converter, the losses of which are not included here.

5. Conclusions

Designing of disc motors is a relatively difficult issue that is not comprehensively described in the available literature. Only incomplete proposals are available. In order to verify the correctness of the above proposal, it is planned to add the calculation of the torque characteristic of the motor and a simple thermal calculation in the future.

Based on the motor design presented in this article, it is possible to verify the analytical calculation and optimize the calculated dimensions and parameters of the motor using electromagnetic simulation in a suitable simulation program. After this optimization, it is also possible to process the overall construction technical documentation necessary for the production of the motor and after the successful production of the prototype, its functionality and parameters can be verified by measurement.

Acknowledgment

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