UDC 629.429.3:621.313
DOI: 10.15587/1729-4061.2022.254373

OPTIMIZING GEOMETRIC PARAMETERS FOR THE ROTOR OF A TRACTION SYNCHRONOUS RELUCTANCE MOTOR ASSISTED BY PARTITIONED PERMANENT MAGNETS

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This paper considers partitioning parameters and the mutual arrangement of magnets in the rotor of the traction synchronous-jet engine with permanent partitioned magnets. The synthesis of geometrical parameters for the rotor of a synchronous reluctance motor with partitioned permanent magnets was proposed on the basis of solving the problem of conditional optimization. To solve the synthesis problem, a mathematical model has been built to determine the electromagnetic momentum of a synchronous reluctance motor with partitioned permanent magnets. It is based on the calculation of the electromagnetic momentum of the engine employing the results of a finite-element analysis of the magnetic field in the flat-parallel statement of the problem. The model is implemented in the finite-element analysis FEMM environment and makes it possible to determine the electromagnetic momentum of the engine with a variety of partitioning of permanent magnets. As an analysis problem, it is proposed to use a mathematical model of the magnetic field of the engine. The problem of conditional optimization of the rotor of a synchronous reluctance motor was stated according to the geometric criteria of the rotor. Restrictions are set on geometric, strength indicators, as well as on the level of electromagnetic momentum. The chosen optimization method is the Nelder-Mead method.

Based on the results of solving the problem of synthesizing parameters for the partitioned rotor of the traction motor of trolleybus wheels, it was established that the volume of permanent magnets was reduced by 2.27 times compared to the base structure; their optimal geometric dimensions were determined (5 mm, 5.2 mm, and 5 mm), as well as the distance between them, 17.8 mm and 15.3 mm, and the engine load angle, which is 121.12 electrical degrees.

Based on the results of solving the problem of synthesizing parameters for the partitioned rotor of a trolleybus traction synchronous reluctance motor, its optimal geometric parameters have been determined

Keywords: synchronous reluctance motor, Nelder-Mead method, finite-element method, partitioned permanent magnets

Received date 19.03.2022
Accepted date 22.04.20222
Published date 29.04.2022

***How to Cite:** Liubarskyi, B., Iakunin, D., Nikonov, O., Liubarskyi, D., Yeritsyan, B. (2022). Optimizing geometric parameters for the rotor of a traction synchronous reluctance motor assisted by partitioned permanent magnets. Eastern-European Journal of Enterprise Technologies, 2 (8 (116)), 38–44. doi: https://doi.org/10.15587/1729-4061.2022.254373*

1. Introduction

The transition from a collector traction drive to AC drives is currently a global practice [1–3] on the wheeled rolling stock involved in main, urban, and industrial transportation.

Induction electric drives are most used in this area. Since the beginning of the XXI century, induction traction drives have been widely applied on trolleybuses manufactured in the European Union: “Solaris Bus & Coach” S. A. (Poland), Škoda Transportation (Czech Republic). The same is true for trolleybuses made in other countries: “Busscar Ônibus S.A.” (Brazil), “Bogdan” (Ukraine), “Eletrontrans” (Ukraine), “Etalon” (Ukraine), as well as for trams produced by “Tatra-Yug” (Ukraine) and “Electrontrans” (Ukraine), and others [4]. It is also commonly used in electric vehicles manufactured by Tesla [5]. As regards the rolling stock of railroads, induction traction drive is also the most common one. For example, electric locomotives DS-3 produced by DEVZ (Ukraine), diesel trains DEL-02 made by “Luganskteplovoz” (Ukraine), high-speed electric train EKr-1 manufactured by PAO “KVBZ” (Ukraine). It is also widely applied in the rolling stock of global manufacturers, such as HRCS2 produced by Hyundai Rotem (South Korea) and EJ 675 by Škoda Transportation (Czech Republic), operated by Ukrzaliznytsia. The situation is similar on such railroads as “LORIC” (China), “Alstom”, “ADtranz”, “Bombardier”, “Siemens AG” (European Union). The advantages of the traction drive based on induction motors include high energy and mass-dimensional indicators, the simplicity of design and increased reliability, as well as a long interservice interval [5].

Global energy saving trends include alternative approaches in traction drive. One of them is the use of synchronous traction engines [6]. Another approach to improve the efficiency of a traction electric drive with such engines is the use of synchronous motors excited by permanent magnets [6]; however, a significant mass of high-coercive permanent magnets considerably increases the cost of producing such electric motors.

An important requirement for traction electric drive is the need to provide a wide range of speed and torque, as well as high energy indicators necessary not only under a mode close to rated but also at low and maximum rotation speeds. It follows from the analysis carried out in [7] that such characteristics can be provided by permanent magnet-assisted synchronous reluctance motors – PMSynRM, PMA-SynRel). It is noted in [8] that the mass-dimensional and cost indicators of the engine of that type are comparable to the best induction ones. Thus, the drive based on permanent magnet-assisted synchronous reluctance motors is an alternative to an electric drive with induction traction engines. Therefore, studies aimed at improving the mass-size and energy indicators of permanent magnet-assisted synchronous reluctance motors are relevant.

2. Literature review and problem statement

Work [9] analyzed the structure and principle of operation of synchronous reluctance motors with permanent magnets installed in the rotor of both partitioned and non-partitioned type. The analysis of the structure of the stator of permanent magnet-assisted synchronous reluctance motors, which is given in [10], reveals the similarity of its design to the induction motor stator. The structures of the rotors of these engines have significant differences. A rotor of the synchronous motor in the radial direction to increase the reactive torque has the following features. First, it is divided into flow channels. The number of channels is determined by partitioning the engine rotor. Second, permanent magnets can be divided in a direction close to the direction of the armature reaction streaming barriers [11], in which permanent magnets made of rare earth elements such as NdFeB or ferrite Y30 are installed [12]. According to the classification proposed in [11], the number of lines of barriers (holes in the rotor core) may be different. From one line, which is perpendicular to the q axis of the engine, as indicated in [13], and along the d axis, as given in [14], and makes up one layer of magnet position, which has additional mechanical strength of the structure. However, the disadvantage of [14] is an increased level of scattering flows. It is not a partitioned type. Up to five lines that are located at an angle to the q axis, as given in [15], that is, a partitioned type.

The principle of engine rotor structure is based on the following. Permanent rotor magnets are evenly magnetized in the direction of the q axis. The permeability of permanent magnets is close to the air. Thus, the line of barriers (sections) forms a direction with high resistance and magnetic anisotropy in the direction of the q axis. The rotor's iron is segmented, which is necessary for the main magnetic flux proceeding along the d axis [7]. An additional function is to ensure the mechanical strength of the rotor structure.

As noted in work [12], determining the size and parameters of the rotors in a permanent magnet-assisted synchronous reluctance motor should be reasonably carried out based on a finite-element analysis in combination with multicriterial optimization, as highlighted in [16]. The design procedure considered in [7] provides an opportunity to determine only the main parameters for the engine stator, the thickness and width of permanent magnets. Paper [11] reports a similar analysis for rotors with non-partitioned magnets, which is only one of the structural varieties. All this suggests that it is expedient to conduct a study aimed at determining the optimal rotor geometry for a synchronous reluctance motor with permanent partitioned magnets.

3. The aim and objectives of the study

The aim of this study is to devise a procedure for determining the optimal geometrical parameters for the rotor of a synchronous reluctance motor with permanent partitioned magnets, which would make it possible to increase the electromagnetic momentum of the engine at the predefined stator size.

To accomplish the aim, the following tasks have been set:

– to build a finite-element model of the magnetic field in a synchronous reluctance motor with permanent partitioned magnets;

– to state the problem of conditional optimization of rotor parameters in a synchronous reluctance motor with permanent partitioned magnets for the drive of trolleybus wheels;

– to synthesize the trolleybus traction engine by solving the problem of optimizing the geometrical parameters of the rotor.

4. The study materials and methods

The object of our research is the process of searching for optimal geometrical parameters of the rotor in a traction synchronous reluctance motor with permanent partitioned magnets. After conducting an analytical review of the literary data on the structures of rotors of the type of engines under investigation, a hypothesis is proposed according to which the selection of optimal dimensions of the layers of partitioned magnets could reduce their total volume while maintaining the level of electromagnetic momentum of the engine.

In our study, we adopted the following simplifications. A structure of prismatic partitioned magnets with three layers and geometric cutouts is considered. When solving the analysis problem, we simplify the two-dimensional statement of the problem without taking into consideration the end scatterings. Accounting for these assumptions and simplifications allows us to proceed with further studies of traction engines of the examined type.

Based on the results of our consideration of earlier studies [11, 17, 18], it is proposed that optimal synthesis should underlie the methodology based on solving the problem of conditional optimization of the geometrical parameters of the engine. The analysis problem is based on the method of finite elements for calculating the magnetic field in a flat-parallel statement of the problem. According to the results of the calculation of the magnetic field of the engine, its electromagnetic momentum is determined. A similar approach was applied to the optimization of the parameters for the non-partitioned rotor in work [11], as well as induction motors in [19]. The adequacy of the results obtained was confirmed by using the tested magnetic field simulation software FEMM (USA) [20, 21] and optlab packages (Ukraine) [17, 18, 22].

5. Results of studying the geometrical parameters of the rotor in a synchronous reluctance motor with permanent partitioned magnets

5. 1. Mathematical model of the magnetic field in a synchronous reluctance motor with permanent partitioned magnets

Paper [7] provides the basics of designing permanent magnet-assisted synchronous reluctance motors, according to which it is possible to determine the approximate dimensions of permanent magnets. However, the parameters of partitioning and the mutual arrangement of magnets in the rotor significantly affect the level of electromagnetic momentum, as indicated in [7, 8]. In the work, the analysis problem was stated for the rotor with partitioned permanent magnets. Such a structure is an alternative approach to the design proposed in [11] for permanent magnet-assisted synchronous reluctance motors. As an example, the choice of rotor motor geometry for the drive of trolleybus wheels is considered. In accordance with preliminary calculations based on the procedure from [7], the estimated engine data were defined, given in Table 1. The estimated data on the permanent magnet and its material are given in Table 2.

Table 1

Estimated data on the trolleybus traction engine

Name	Value
Engine power, kW	180
Maximum electromagnetic momentum, Nm	970
Armature current at maximum torque, A	350
Number of grooves	48
The number of effective conductors in the groove	6
Number of parallel branches	1
Step reduction factor	0.778
The number of elementary conductors in the effective	3 (height)
Estimated outer diameter of the stator, m	0.46
Boring diameter, m	0.3
Axial length of the magnetic circuit, m	0.15
Unilateral air gap, m	0.003
Dimensions of the stator winding conductor (without insulation)	1.6×12.5
Groove height, m	0.040
Groove width, m	0.0145

The chosen basic structure of the engine rotor is partitioned permanent magnets, which are in the cutouts of the rotor package. Magnets of prismatic shape are in the holes of the rotor. To direct the magnetic flux, the rotor has air supports of magnetic flux. The basic geometry of the engine is shown in Fig. 1.

Based on the research conducted in [11], our further study employs a finite-element method for determining the electromagnetic momentum. The 2d problem of calculation of a flat-parallel magnetic field is stated. The use of this method makes it possible to take into consideration the distribution of magnetic flux between partitioned rotor magnets, the saturation of its parts depending on the location of the magnets. To solve the problem, the finite-element simulation software FEMM [6, 20, 22] was used. The cross-section of the engine in the calculated area is divided into finite elements. The type of elements is triangular. A finite-element grid of adaptive type is applied, which makes it possible to determine the geometry of the rotor and partitioned permanent magnets (Fig. 2). The armature current level corresponds to the rated mode of operation of the engine. The distribution of the magnetic field of the engine according to the results of the calculation at a load angle of 135 electrical degrees is shown in Fig. 3.

Table 2

Permanent magnet parameters

Name	Value
Number of pole magnets	1
The total thickness of the magnet, m	0.03
Number of partitioning layers	3
Magnet width, m	0.09
Material of magnets	Nd-Fe-B
Residual magnetic induction, Tl	1.0
Coercive force on magnetization, A/m	850,000

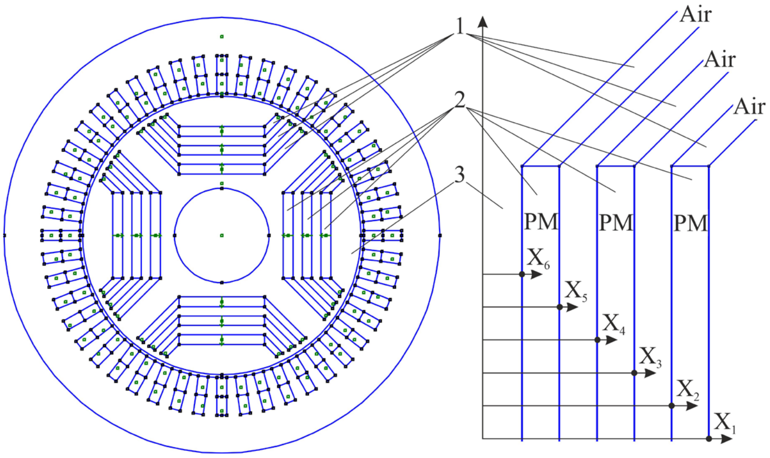
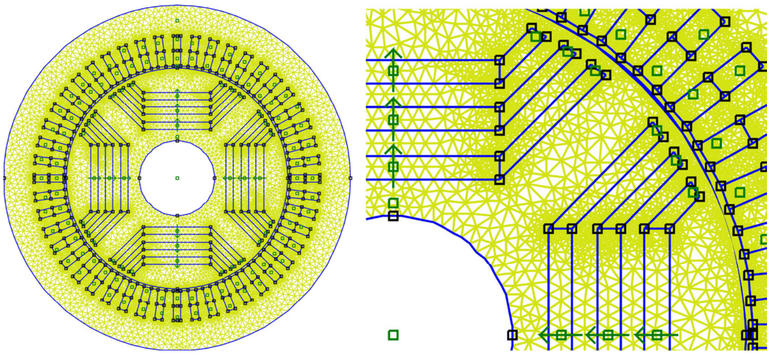
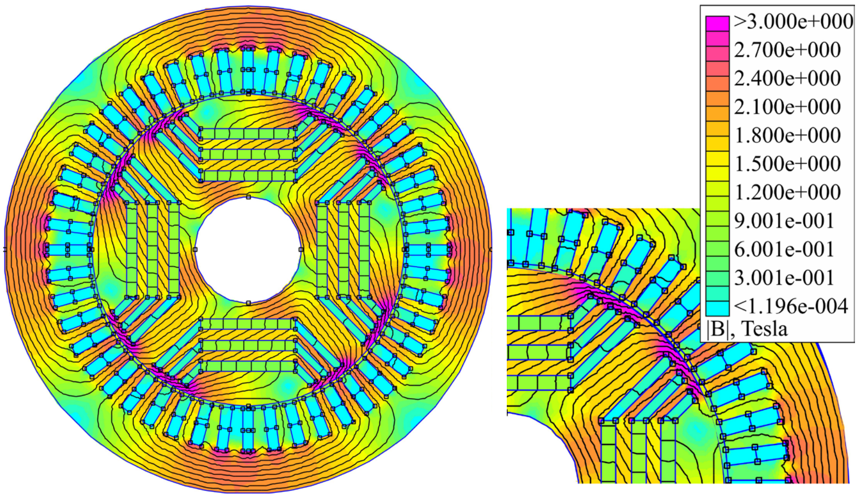


Fig. 1. Basic geometry of asynchronous reluctance motor with partitioned permanent magnets: 1 – cutouts in the core of the rotor; 2 – permanent magnets; 3 – the core of the rotor



a *b*

Fig. 2. A finite-element grid of the synchronous reluctance motor with partitioned permanent magnets: *a* – general view; *b* – zone of permanent magnets



a *b*

Fig. 3. The results of calculating a magnetic field of the synchronous reluctance motor with partitioned permanent magnets under a rate nominal mode: *a* – general view; *b* – zone of permanent magnets

Similar to [11], based on the results of the calculation of the magnetic field, the electromagnetic momentum of the engine is determined using standard FEMM functions [20].

5. 2. The problem of optimizing the parameters for the rotor with partitioned motor magnets for the drive of trolleybus wheels

Our work considers a rotor with the partitioning of permanent magnets into three parts. This is the most common technical solution. In the geometry under consideration, an increase in the number of partitioning layers is impossible because of technological signs. Due to a significant decrease in the thickness of permanent magnets, it is a problem to place them in the holes of the rotor.

Optimization problem parameters. As the problem's parameters, it is rational to choose the thickness of permanent partitioned magnets and the gaps between them. However, in order to simplify the formalization of the optimization problem, it is proposed to select the coordinates of permanent magnets along the q axis of the engine as parameters. These coordinates are denoted x_1, x_2, x_3, x_4, x_5, x_6 (Fig. 1). The parameters should also include a change in the load angle (θ) relative to the base structure in electrical degrees. The base load angle selected for the structure is 135 electrical degrees. The control of the trolleybus traction drive ensures the mode of maintaining the load angle during acceleration and reduces the load angle under the mode of increased speed [5, 7, 9, 11]. Determining the load angle identifies the parameters of the engine control system.

Set the restrictions imposed on optimization parameters:

1) Limitations on the strength of the rotor.

The mutual arrangement of the cutouts in the rotor core is subject to restrictions on the mechanical strength of the engine structure. Using the procedure given in [7], the minimum permissible thickness of the intersections between the layers of permanent magnets and the minimum thickness of permanent magnets were determined, which, for the problem under consideration, are $X_{d\min}=0.009$ m and $X_{\min}=0.005$ m, respectively.

The formulation of restrictions can be set out as follows for permanent magnets:

$$x_1-x_2<X_{\min};$$

$$x_3-x_4<X_{\min}; \tag{1}$$

$$x_5-x_6<X_{\min}.$$

And for the gaps between the layers:

$$x_2-x_3<X_{d\min};$$

$$x_4-x_5<X_{d\min}. \tag{2}$$

2) Geometric limitations of the optimization problem. The following geometric constraints are imposed on optimization parameters related to the size of the engine rotor

$$0\text{ m}<x_1, x_2, x_3, x_4, x_5, x_6<0{,}065\text{ m}. \tag{3}$$

3) The limitation on the load angle of the engine, due to the principle of its operation, is within the following range

$$-45\text{ electrical degrees}<\theta<45\text{ electrical degrees}. \tag{4}$$

4) Limitations on a given engine torque.

In practice, the task of designing a traction engine with a predetermined level of electromagnetic momentum often arises. Therefore, the level of the predefined electromagnetic momentum can be an additional limitation imposed on the problem

$$M_e>970\text{ Nm}, \tag{5}$$

where M_e is an electromagnetic momentum, which is determined from the results of the calculation of the magnetic field.

Given the different order of values for parameters x_1, x_2, x_3, x_4, x_5, x_6 and angle θ, further calculations are advisable to carry out in millimeters, which will greatly simplify the solution to the optimization problem.

As an objective function [11], it is rational to choose the total thickness of permanent motor magnets because this value is proportional to the volume and mass of permanent magnets, which have the highest cost in the structure

$$F=(x_1-x_2)+(x_3-x_4)+(x_5-x_6)\rightarrow\min. \tag{6}$$

Thus, the objective function F determines the cost of engine production.

5. 3. Solving the problem of optimizing the parameters of the partitioned engine rotor

In order to solve the problem of conditional optimization of the geometrical parameters of the partitioned rotor, the problem was stated in the optlab software package (Ukraine) [11, 17, 18, 21], developed at the National Technical University "Kharkiv Polytechnic Institute" (NTU "KhPI", Ukraine). A big advantage of optlab is the ability to use different methods of optimization and the selection of different starting points of the method. The problem of magnetic field analysis is solved using the FEMM 4.2 software suite (USA) [11, 20, 21].

A trial solution to the optimization problem from different starting points and by different methods showed that the result of the solution does not depend on the starting point, similar to the problem given in [11]. This indicates finding an unequivocal global minimum. Thus, the objective function is not multi-extreme. The similarity of physical processes in the problem under consideration and those given in [11] also indicates the problem's non-much extremeness. According to the research reported in [11, 17, 18], it is rational to use the Nelder-Mead method.

The course of solving the problem is shown in Fig. 4, based on x_1, x_2 coordinates and the objective function. Figure 5 indicates only the best points. The starting point 1 of the search is designated by a circle, and the end point 2 – by a diamond.

The selected starting point of the search algorithm was a point with coordinates x_1=50 mm, x_2=40 mm, x_3=30 mm, x_4=20 mm, x_5=10 mm, x_6=0 mm, and θ=0 electrical degrees.

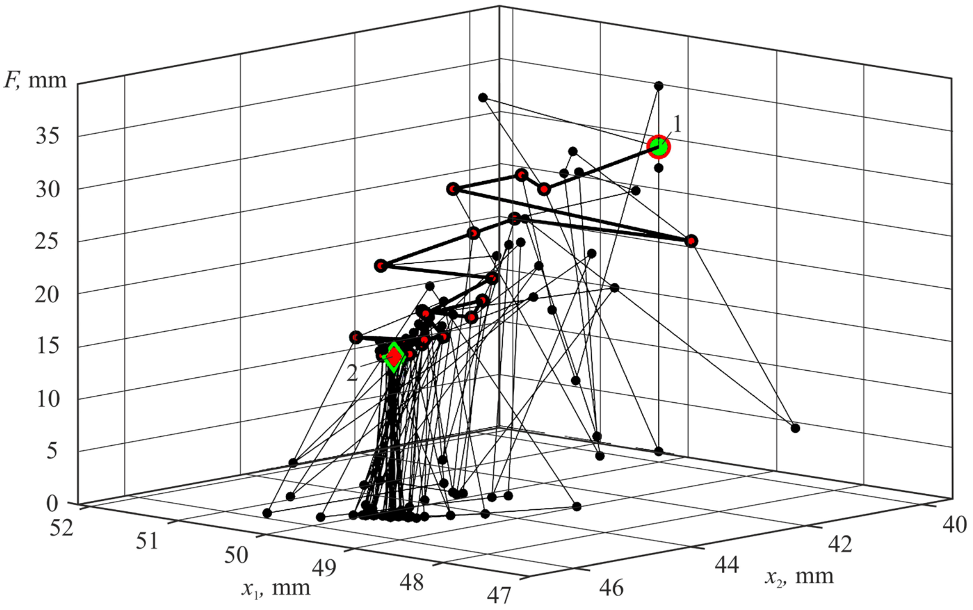


Fig. 4. The course of solving the problem of optimizing the parameters of the rotor in a synchronous reluctance motor with partitioned permanent magnets based on the objective function and x_1 and x_2 coordinates: 1 – the starting point of the search; 2 – the search endpoint

The results are given in Table 3.

Table 3

Results of optimization problem solving

Parameter	Value
x_1	49.8 mm
x_2	44.8 mm
x_3	29.5 mm
x_4	24.3 mm
x_5	6.5 mm
x_6	1.5 mm
θ	–13.88 electrical degrees
F	15.2 mm

According to the calculation results, the value of the objective function decreased by 2.27 times (from 30 mm to 13.2 mm), which makes it possible to significantly reduce the cost of engine design while maintaining the requirements for it.

6. Discussion of results of synthesizing the partitioned rotor for a synchronous reluctance motor

According to the results of our research, which are given in Table 3, it is shown that the thickness of permanent magnets in the optimal design is much lower than the base one, obtained on the basis of the procedure given in [7]. This can be explained by a much lower level of scattering flows than in a structure without partitioning. The resulting thickness of magnets is, respectively, 5 mm, 5.2 mm, and 5 mm. They are also close to limitations on mechanical strength. The gaps between permanent magnets are not uniform: the outer one is 15 % larger than the internal one and is 17.8 mm, which is due to the possibility of reducing saturation in the direction of the flow along the *d* axis of the engine. Similar to the problem involving non-partitioned magnets [11], the load angle decreased by 13.88 electrical degrees, which is due to the significant saturation of the elements of the engine rotor.

We have synthesized parameters for the partitioned rotor of a synchronous reluctance motor with permanent magnets based on solving the problem of conditional optimization. When solving the problem, the following restrictions were defined, imposed on the optimization parameters: restrictions on the strength of the rotor, geometric limitations of the optimization problem, restrictions on the engine load angle, and restrictions on the specified engine torque.

Our procedure could be used for the design of traction engines for electric transportation vehicles, such as individual electric transport means (gyro boards, electric bikes, etc.), trolleybuses, electric vehicles, electric trains, trams, and quadcopters. The range of engine capacity for which it is suitable is limited to capacities from 1 kW to 250 kW. With greater power, the use of unpartitioned permanent magnets is rational, and with less – it would be rational to switch to another type of electric motor. The procedure reported here is valid when using engines with high-coercive permanent magnets and at the number of partitioning layers of 3. According to the results of our calculations, the value of the objective function decreased by 2.27 times (from 30 mm to 13.2 mm), which makes it possible to significantly reduce the cost of engine production while maintaining its characteristics.

In several structures [13], magnets in the rotor are installed in arc-shaped holes, which reduces the concentration of saturation zones in the rotor and reduces the resistance of the main stream. Not taking into consideration the possibility of arc-shaped arrangement of magnets is a disadvantage of our work. The disadvantages also include its applicability only for three layers of magnet partitioning.

Further advancement of the devised procedure for determining the optimal rotor geometry may involve the optimization of rotor parameters with arc-shaped partitioned magnets.

7. Conclusions

1. A mathematical model has been built for determining the electromagnetic momentum of a synchronous reluctance motor with partitioned permanent magnets. The model is based on determining the electromagnetic momentum based on the calculation of the magnetic field of the engine by a finite-element method in the flat-parallel statement of the problem. When solving the problem, an adaptive finite-element grid was applied. For synchronous reluctance motors with permanent magnets, a procedure for synthesizing a partitioned rotor has been devised, based on solving the problem of conditional optimization. The following optimization criteria have been established: coordinates of permanent magnets along the *q* axis of the engine and a change in load angle relative to the base structure.

2. The problem of the conditional optimization of the rotor in a synchronous reluctance motor was stated according to the geometric criteria of the rotor. As an analysis problem, it is proposed to use a mathematical model of the magnetic field of the engine. Limits are set by geometric, strength parameters and the specified level of electromagnetic momentum. The chosen optimization method is the Nelder-Mead method.

3. According to the results of solving the problem of synthesis of parameters of the rotor of the trolleybus traction engine, it was established that the volume of permanent magnets was reduced by 2.27 times compared to the base structure; their optimal geometric dimensions (5 mm, 5.2 mm, and 5 mm) were determined; the distance between them is 17.8 mm and 15.3 mm, and the engine load angle is 121.12 electrical degrees.

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