This paper reports the model of a magnetic field of the synchronous reluctance motor with permanent magnets that was developed on the basis of a finite-element method. The model was implemented in the FEMM finite-element analysis programming environment involving the application of the Lua-based script. The model makes it possible to determine the dependence of the engine's electromagnetic moment on the rotor rotation angle.

Determining the level of a saw-shaped moment is important for assessing its harmful effect on the structural elements of the traction motor and the drive in general.

The results of digital modeling have established the dependences of the electromagnetic moment on the rotor rotation angle. The moment has a variable component – the saw-shaped moment, whose amplitude for open grooves under a rated load mode is 182 Nm, and for semi-open grooves – 90 Nm.

The use of semi-open grooves exerts a positive effect on eliminating the saw-shaped moment in a synchronous reluctance motor with permanent magnets and may be recommended for further application on engines of this type. Semi-open grooves reduce the opening of the stator groove by 2 times and lead to a smoother flux distribution under the gear division. That reduces the oscillations of the main magnetic flux. The proposed application of semi-open stator grooves makes it possible to reduce by more than 2 times the level of a saw-shaped moment of the synchronous reluctance motor with permanent magnets under a rated mode.

It has been determined that a rather positive factor is an increase of 4.8 % in the average motor moment value under a rated mode when using semi-open grooves. This is due to a decrease in the average value of magnetic resistance to the main magnetic flux. Therefore, with a simultaneous decrease in the moment's fluctuations, the transition to semi-open grooves makes it possible to improve the mass-dimensional indicators of the motor in general

Keywords: synchronous reluctance motor with permanent magnets, saw-shaped moment, finite-element method, stator groove

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DETERMINING THE EFFECT OF STATOR GROOVE GEOMETRY IN A TRACTION SYNCHRONOUS RELUCTANCE MOTOR WITH PERMANENT MAGNETS ON THE SAW-SHAPED ELECTROMAGNETIC MOMENT LEVEL

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1. Introduction

The application of traction electric drives with induction electric motors by the rolling stock of railroads, industrial and urban transport is currently a common worldwide practice [1–3]. Traction induction electric drives over the past 15 years have been most widely used by the rolling stock of urban electric transport – trolleybuses, manufactured by Solaris Bus & Coach S.A. (Poland), Škoda Transportation (the Czech Republic), Busscar Ônibus S.A. (Brazil), Bogdan (Ukraine), Elethrontrans (Ukraine), Etalon (Ukraine); trams, manufactured by Tatra-Yug (Ukraine) and Electrontrans (Ukraine), and others, as well as in the rolling stock being modernized by municipal enterprises of large cities [4]. Induction traction drive is used by the rolling stock on railroads in the locomotives, manufactured by LORIC (China), Alstom, ADtranz, Bombardier, Siemens AG (European Union); DS-3, manufactured by DEVZ

(Ukraine); the diesel trains DEL-02, manufactured by Luganskteplovoz (Ukraine); the high-speed electric train EKr-1, manufactured by PAO "KVZ" (Ukraine), as well as in the rolling stock by international manufacturers such as HRCS2 from Hyundai Rotem (South Korea) and EJ 675 Škoda Transportation (the Czech Republic), operated by Ukrzaliznytsia. The main advantages of traction induction electric drive are the high energy and mass-dimensional indicators, the high level of reliability, the simplicity of design, long term between service maintenance [5]. However, global trends in reducing energy and resource consumption by rolling stock pose a task for the scientific and technical community to further improve the AC traction electric drives towards new types of electromechanical converters [3]. One alternative approach is to use synchronous motors that are excited by permanent magnets [3]; however, a large weight of high-coercive permanent magnets significantly increases the cost of producing such electric motors. The need to maintain a wide range of adjustable rotation frequency and moment is a special requirement for traction drives. Therefore, maintaining energy indicators at a high level is necessary not only under a rated mode of operation but also under other operational regimes. According to the authors of work [6], such characteristics can be ensured by the permanent magnet-assisted synchronous reluctance motors (PMSynRM, PMA-SynRel). The analysis reported in [7] shows that the mass-dimensional and cost indicators of an engine of this type are comparable to the best induction ones. The PMSynRM-based drive is a "direct alternative" to the induction traction electric drive.

2. Literature review and problem statement

Work [8] examines the structural schemes and principles of PMSynRM operation. Paper [9] notes that this motor typically employs a distributed stator winding. The motor's rotor is divided into channels of flow barriers in the radial direction to increase the reactive torque. A feature of the rotor is the presence of permanent magnets (rare earth elements such as NdFeB, ferrite Y30), inserted into its flow barriers [10].

It has been shown that the motor's stator is typically made from rigid sections, which yields a high mechanical winding strength and the best conditions for its cooling [6]. The open grooves of the motor's stator in combination with an active clearly pole rotor predetermine the possibility of saw-shaped electromagnetic moments, which are considered in work [11]. The air gap between the PMSynRM stator and rotor is relatively small (1–2 mm). Its size is due to the attempt to improve the energy indicators of the motor. However, there unresolved issues related to the fact that reducing the gap leads to a growth of the saw-shaped moment of the motor. The negative impact of saw-shaped moments on the mechanical link of the drive is considered in work [11]. The authors of [11] noted that almost insignificant moments, in terms of their magnitude, could produce a significant impact on the mechanical part of the drive. The reason for this may be those objective difficulties that are associated with the fact that the grooves of the stator for such windings are typically made open, which is dictated by the technology of laying the rigid sections of the winding [6].

The saw-shaped moment of the motor is due to the uneven distribution of the magnetic induction of the motor in the air gap because of the different magnetic permeability of the tooth and the groove of the stator. This is based on the results of calculations reported in [6, 11], as well as a stepped form of distribution of the magneto-driving force of the stator winding [12].

To reduce a saw-shaped moment, it is possible to use semi-open grooves of the stator, which, on the one hand, reduce the uneven distribution of induction, and, on the other hand, provide an opportunity to comply with the conditions of technology for fabricating a stator winding. This approach is used in work [13], which examines the effect of the opening of the groove on the electromagnetic moment. The authors of the cited work note the significant impact of the groove shape on the energy indicators of the motor. However, the approach considered in [13] refers to motors of relatively low power, with a loose stator winding, for which it is possible to use closed slots. The effect of the stator gearing for the stator's explicit pole winding is considered in work [14]; its significant impact on the nature of the electromagnetic motor moment is noted [15].

The above suggests the expediency of conducting a study addressing the effect of the stator groove shape on the level of the traction PMSynRM saw-shaped moment.

3. The aim and objectives of the study

The aim of this study is to determine the effect of the groove geometry of traction PMSynRM on the level and nature of change in the saw-shaped moment.

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

– to build a model of the PMSynRM magnetic field with an open and semi-open stator groove;

– to determine the nature and magnitude of the saw-shaped moment of traction PMSynRM;

– to conduct a comparative analysis of the results of determining the saw-shaped moment of traction PMSynRM for various shapes of the groove.

4. The study materials and methods

For this study, we have chosen a traction PMSynRM for the drive of trolleybus wheels. The rated moment is 900 Nm at a phase current of 350 A. The main characteristics of which were found by the method [6]. The parameters of the motor stator are given in Table 1.

The geometry of the rotor was selected according to the procedure given in [6]; the parameters of the permanent magnet for it are shown in Table 2.

To study the saw-shaped moment, a finite-element method in a two-dimensional flat-parallel problem statement was chosen in this work. The method makes it possible to take into consideration the toothed nature of the motor stator and the local saturation of the elements of its design [11, 16–19].

Fig. 1, 2 show the estimation area, divided into the finite triangular elements, for the stator with open and semi-open grooves, implemented in the FEMM programming environment [19].

Table 1

Specifications of a traction PMSynRM stator for trolleybus wheels drive

Name	Value
Number of grooves	48
Number of effective conductors in a groove	4
Number of parallel branches	1
Number of elementary conductors in the effective	3 (for height)
Connection of phases – "star"	
Estimated outer diameter of the stator, m	0.46
Boring diameter, m	0.3
Axial length of the magnetic circuit, m	0.3
Air gap, m	0.0013
Dimensions of the stator winding conductor (without insulation)	1.6×12.5
Groove height, m	0.040
Groove width, m	0.0145

Table 2

Permanent magnet parameters

Name	Value
Material for magnets	Nd-Fe-B
Residual magnetic induction	1.0 Tl
Coercive force on magnetization	850 kA/m

We determined the electromagnetic moment on a PMSynRM using the FEMM postprocessor [19] by employing a standard moment detection function.

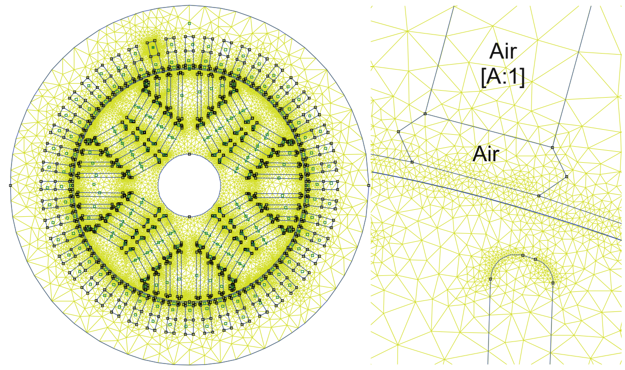

Fig. 1. A finite-element grid of the synchronous reluctance motor with permanent magnets with open grooves

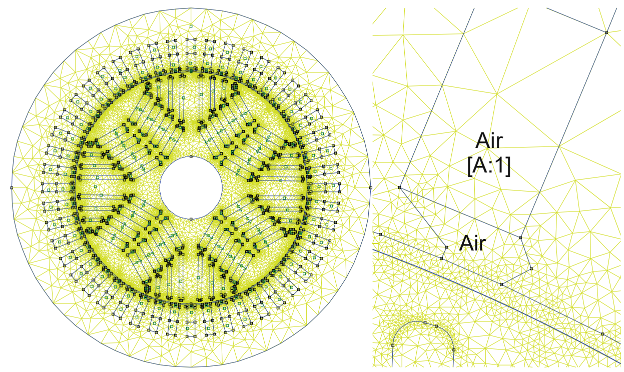

Fig. 2. A finite-element grid of the synchronous reluctance motor with permanent magnets with semi-open grooves

The reliability of our study is predetermined by the adequacy of the software packages used for the finite-element analysis of the magnetic field and determining the values of the electromagnetic moment, proved in works [16–19].

5. Results of studying the saw-shaped moments of a synchronous reluctance motor with permanent magnets

5. 1. A model of the magnetic field of a synchronous reluctance motor with permanent magnets with an open and semi-open groove stator

To determine the saw-shaped moment, the geometry of the estimation area may vary depending on the position of the rotor and the values of currents in the stator winding.

To calculate the field, a grid of finite elements was synthesized. We used finite triangular elements of the first order for the calculation, according to the recommendations from [18, 19]. The choice of this type of elements was justified in work [18] for rotary electric machines. For the air gap, a fixed radius of the circumference of the finite element synthesis was selected, equal to 0.0005 m, which makes it possible to build at least three layers of finite elements in the air gap. In other elements of the estimation area, the grid synthesis is carried out based on adaptive estimation geometry. The finite-element grid is shown in Fig. 1, 2.

For our digital experiments, a Lua-based macro [19] was developed, which makes it possible to automatically change the angle of rotor rotation and sets the stator current parameters that correspond to the rated angle of the motor load.

5. 2. Determining the saw-shaped moment of a traction synchronous reluctance motor with permanent magnets

Traction PMSynRMs are characterized by both thrust and electrical braking modes, as well as a run-out mode, under which the current in the stator winding is zero. However, under the run-out mode, the main magnetic flux is partially preserved, due to the action of permanent magnets. Thus, the traction PMSynRM retains the possibility of a saw-shaped moment under a run-out mode, which is especially harmful at high speeds (motor rotation frequency) of the vehicle.

Thus, we study here the saw-shaped moment for both the rated mode and the run-out mode.

The results of calculating the magnetic field under a rated mode and under a run-out mode are shown in Fig. 3, 4 for a stator with open grooves, and in Fig. 5, 6 for semi-open grooves.

The electromagnetic moment is determined using a script written in the Lua language for the FEMM postprocessor software [19]. Using the "groupselectblock" command, which makes it possible to simultaneously mark all the estimation areas of a PMSynRM rotor, indicates the rotating motor element. In the next step, using the command "blockintegral(23)", we determine the moment based on the procedure given in [18].

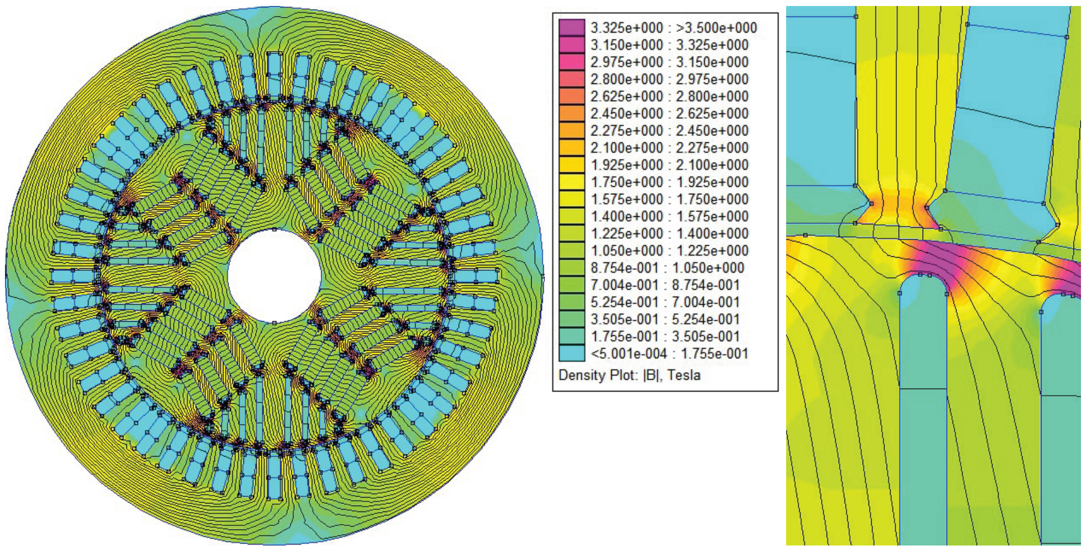

Fig. 3. Results of calculating the magnetic field of a synchronous reluctance motor with permanent magnets with open grooves under a rated mode

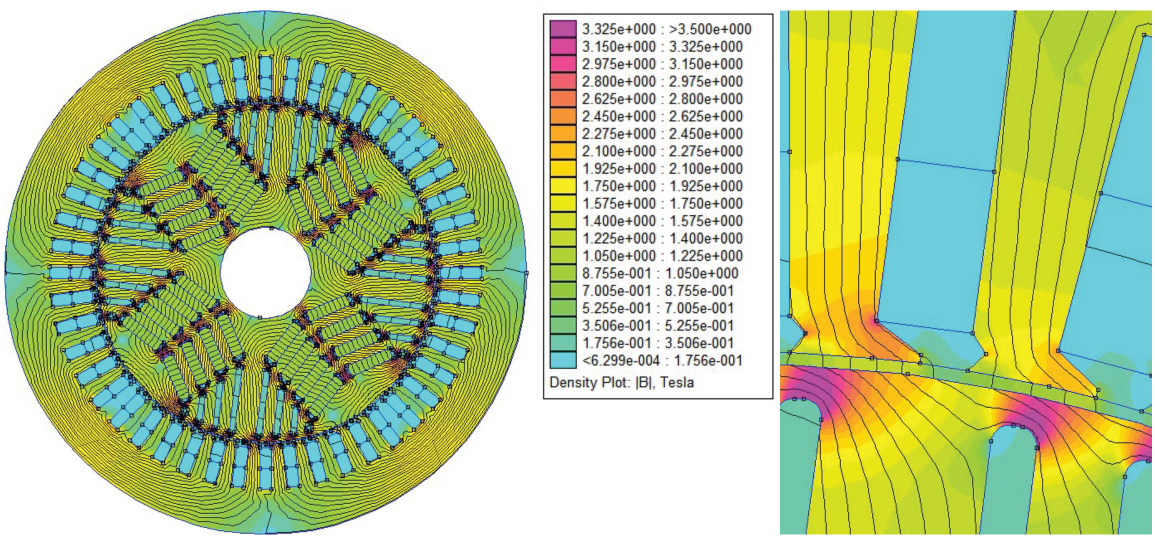

Fig. 4. Results of calculating the magnetic field of a synchronous reluctance motor with permanent magnets with semi-open grooves under a rated mode

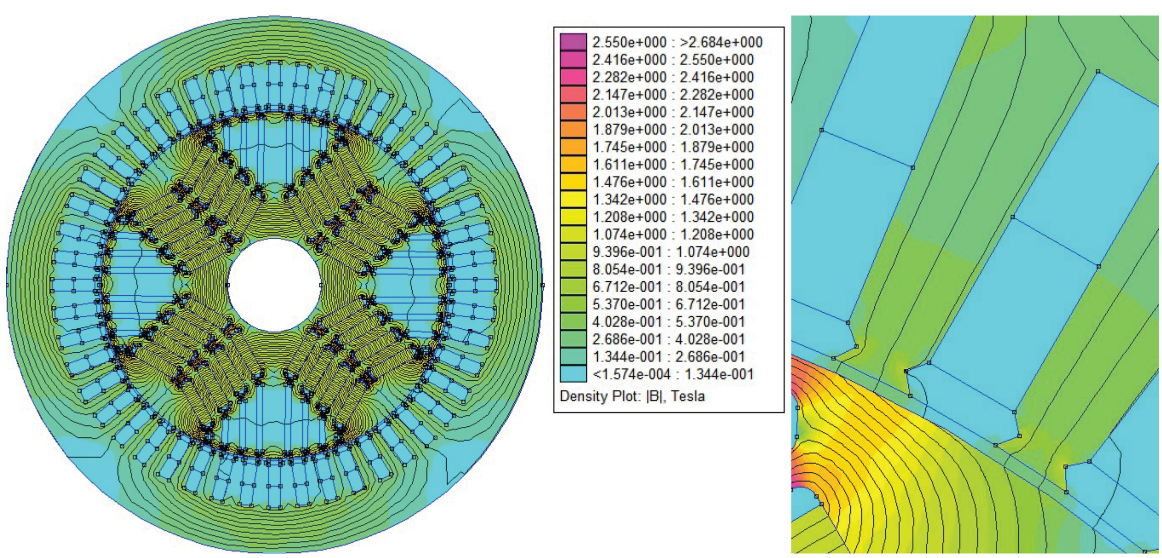

Fig. 5. Results of calculating the magnetic field of a synchronous reluctance motor with permanent magnets with open grooves under a run-out mode

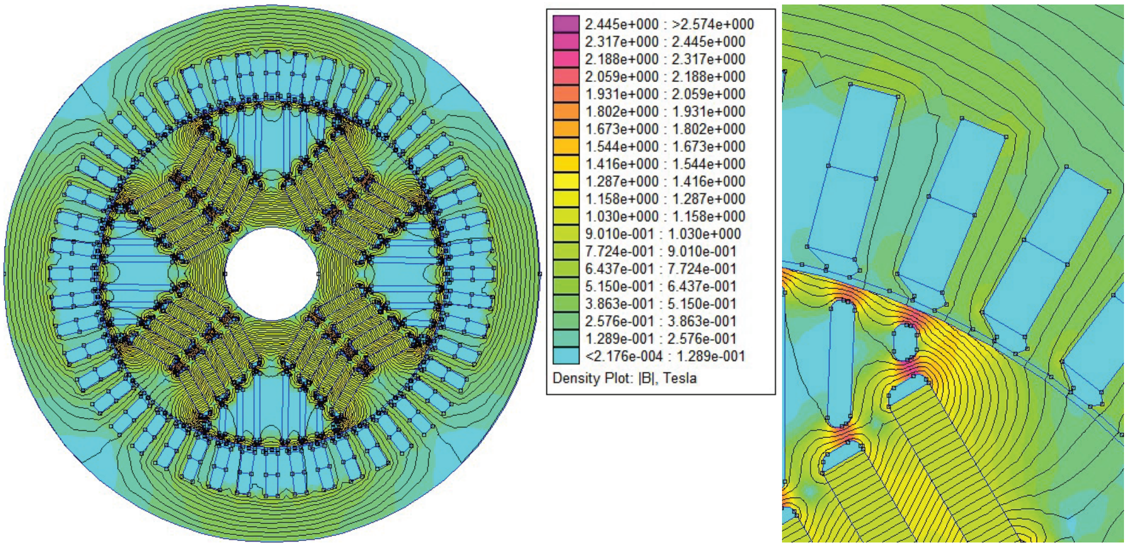

Fig. 6. Results of calculating the magnetic field of a synchronous reluctance motor with ermanent magnets with semi-open grooves under a run-out mode

5. 3. Comparative analysis of the saw-shaped moment of a traction synchronous reluctance motor with permanent magnets for various groove shapes

Based on the results from a set of digital experiments, we established the dependence of the PMSynRM saw-shaped moment on the angle of rotor rotation for one toothed unit. The dependence is illustrated in Fig. 7, for the rated mode, and in Fig. 8, for the run-out mode.

The charts of the dependence (Fig. 7, 8) of the electromagnetic moment on the angle of rotor rotation demonstrate that the moment has a variable component – a saw-shaped moment, whose amplitude for open grooves under a mode of the rated load is 182 Nm, and for semi-open grooves, 90 Nm. Under a run-out mode, the variable moment amplitude is 5.52 Nm for open grooves, 10.53 Nm for semi-open grooves.

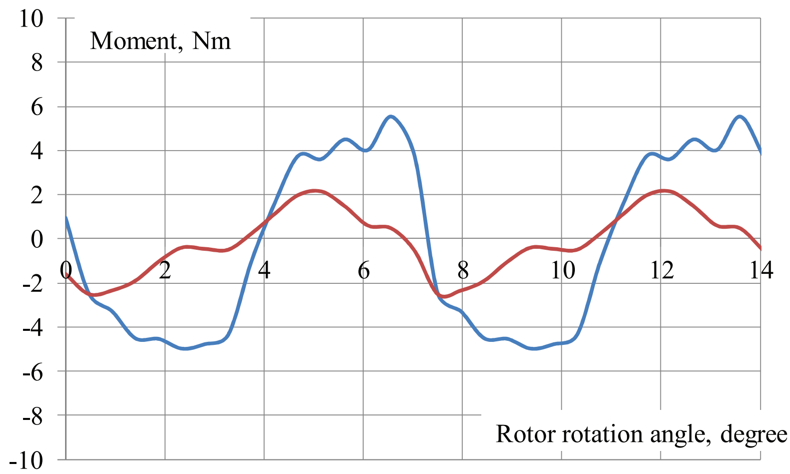

Fig. 8. Results for the electromagnetic moment of a synchronous reluctance motor with permanent magnets with semi-open grooves under a run-out mode

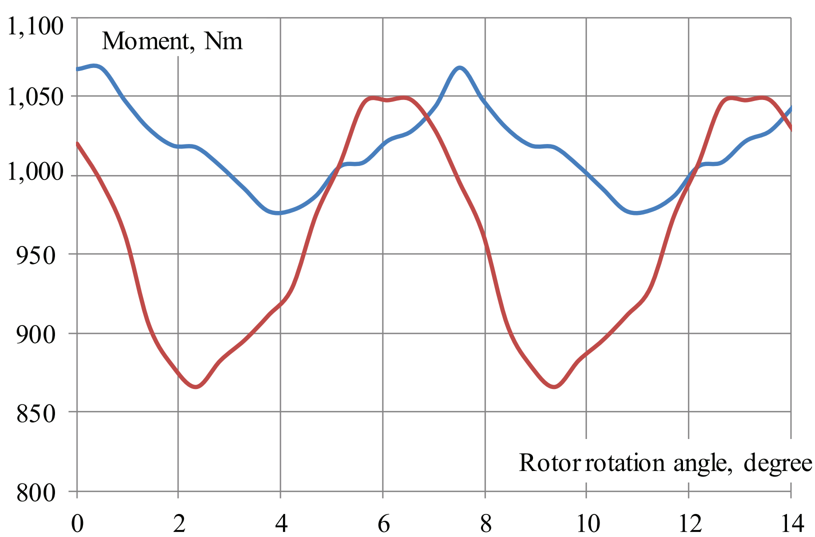

Fig. 7. Results for the electromagnetic moment of a synchronous reluctance motor with permanent magnets with semi-open grooves under a rated mode

6. Discussion of results of studying the level of the saw-shaped electromagnetic moment of a synchronous reluctance motor with permanent magnets

The pattern of the PMSynRM magnetic field in Fig. 3, 4 demonstrates that the main magnetic flux of the motor passes mostly through the stator tooth. This process is typical for most electric machines. However, when entering the rotor, its significant part passes through the magnetic shunts of the rotor (steel membranes), which have significant saturation. When the rotor rotates, the direction of the flux and its level change due to the passage of magnetic shunts under the groove or stator tooth. This process is associated with a significant change in the magnetic resistance to the main magnetic flux. At the same time, a very small air gap, relative to other types of synchrony of electric machines, affects the increase in the level of change in the flux. Its low level (almost 8–10 times lower than in conventional synchronous motors) predetermines the high energy characteristics of PMSynRM, on the one hand. On the other hand, it leads to an increase in the level of a saw-shaped moment, the reason for which is the change in the resistance of the main magnetic flux, in which a large proportion belongs to a flux passing through the stator tooth.

The use of semi-open grooves reduces the opening of the stator groove by 2 times and leads to a smoother distribution of the flux under the gear division. Such a technical solution leads to a decrease in the fluctuations in the main magnetic flux. The proposed use of semi-open stator grooves makes it possible to reduce the level of the PMSynRM saw-shaped moment under a rated mode by more than 2 times.

A motor's run-out mode (Fig. 5, 6) is characterized by a significant change in the pattern of the magnetic field. The principle of PMSynRM operation implies that it is primarily a reactive electric machine. It is characterized by correspondence of the main magnetic flux of the stator. A permanent magnet in PMSynRM performs an auxiliary function. Therefore, the flux under a run-out mode is significantly reduced, which leads to a significant (9–17 times) decrease in the saw-shaped moment (Fig. 7, 8). The direction of the main magnetic flux changes, which leads to an increase in the saw-shaped moment when using semi-open grooves, relative to open ones (Fig. 8). However, the level of a saw-shaped moment under a run-out mode is much lower than the traction mode. Therefore, the use of semi-open grooves has a positive effect on eliminating a saw-shaped moment of PMSynRM and may be recommended for further use on motors of a similar type.

It should be noted that a rather positive factor is an increase of 4.8 % in the average motor moment value under a rated mode when using semi-open grooves. This is due to a decrease in the average value of the magnetic resistance to the main magnetic flux. Therefore, with a simultaneous decrease in the fluctuations in the moment, the transition to semi-open grooves makes it possible to improve the mass-dimensional indicators of the motor in general.

The results of our study could be useful when designing synchronous electric machines and drives based on them with a sufficiently small air gap value. These types include synchronous motors that are excited by permanent magnets, synchronous reluctance (valve) motors, as well as generators of such types.

The current research may be advanced by using the results of calculating a magnetic field to assess the level of surface losses in the motor. The reason for these losses is the fluctuations in a magnetic flux because of the toothed structure of the stator.

7. Conclusions

1. Based on a finite-element method, we have built a model of the PMSynRM magnetic field. The model is implemented in the FEMM finite-element analysis programming environment involving a Lua-based script. The model makes it possible to determine the dependence of the electromagnetic moment of the motor on the angle of rotor rotation.

2. The results of digital modeling helped establish the dependences of electromagnetic moment on the angle of rotor rotation. The moment has a variable component, a saw-shaped moment, whose amplitude for open grooves under a mode of the rated load is 182 Nm, and for semi-open grooves – 90 Nm. Under a run-out mode, the variable moment amplitude is 5.52 Nm for open grooves, and 10.53 Nm for semi-open grooves.

3. Our comparative analysis of using the open and semi-open grooves in a PMSynRM stator has shown the expediency of using the latter for traction motors of this type. It has been demonstrated that the application of semi-open grooves makes it possible not only to significantly reduce a saw-shaped moment, more than by 2 times, but also to increase the average electromagnetic moment of the motor under a rated mode by 4.8 %.

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