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ESTIMATION OF THE MAIN DIMENSIONS OF THE TRACTION PERMANENT MAGNET-ASSISTED SYNCHRONOUS RELUCTANCE MOTOR

Goal. The goal of the research is to develop an algorithm for selecting the main dimensions of a traction permanent magnet-assisted synchronous reluctance motor. **Methodology.** A method for determining the main dimensions of the motor, which combines the analytical selection of stator parameters and numerical field calculations for the selection of rotor parameters. The need to check the mechanical strength of a rotor with permanent NdFeB magnets in flux barriers is shown. **Results.** The article proposes an algorithm for selecting the main dimensions of a traction permanent magnet-assisted synchronous reluctance motor, which combines analytical expressions for selecting stator parameters and numerical field calculations for selecting rotor parameters. It is determined that analytical methods for calculating the magnetic circuit need to be developed in order to reduce the time to select the main dimensions of the motor. **Originality.** For the first time the sizes of active parts of the permanent magnet-assisted synchronous reluctance motor with power of 180 kW for the drive of wheels of the trolleybus are defined. **Practical significance.** As a result of research the sizes of active parts, stator winding data and a design of a rotor of the electric motor are defined. The obtained results can be applied when creating an electric motor for a trolleybus. References 17, tables 3, figures 5.

Key words: permanent magnet-assisted synchronous reluctance motor, traction electric drive, permanent magnet, energy efficiency.

У статті розглянуті питання проектування тягового синхронно-реактивного електродвигуна з постійними магнітами потужністю 180 кВт для приводу коліс тролейбуса. Запропоновано спосіб визначення головних розмірів електродвигуна, який поєднує аналітичний вибір параметрів статора та чисельно-польові розрахунки для вибору параметрів ротора. Показана необхідність перевірки механічної міцності ротора, в якому розташовано постійні магніти NdFeB у потокових бар'єрах. У результаті дослідження визначено розміри активних частин, обмоткові дані статора та конструктив ротора електродвигуна. Бібл. 17, табл. 3, рис. 5.

Ключові слова: синхронно-реактивний двигун з постійними магнітами, тяговий електропривод, постійний магніт, енергоефективність.

В статье рассмотрены вопросы проектирования тягового синхронно-реактивного электродвигателя с постоянными магнитами мощностью 180 кВт для привода колес троллейбуса. Предложен способ определения главных размеров электродвигателя, который сочетает аналитический выбор параметров статора и численно-полевые расчеты для выбора параметров ротора. Показана необходимость проверки механической прочности ротора, в котором расположено постоянные магниты NdFeB в потоковых барьерах. В результате исследования определены размеры активных частей, обмоточные данные статора и конструктив ротора электродвигателя. Библ. 17, табл. 3, рис. 5.

Ключевые слова: синхронно-реактивный двигатель с постоянными магнитами, тяговый электропривод, постоянный магнит, энергоэффективность.

Introduction. At present, the worldwide practice is the use of traction electric drives with induction electric motors on the rolling stock of railways, industrial and urban transport [1-3]. In Ukraine, large-scale traction induction electric drives are used in the rolling stock of urban electric transport and main railways [4]. The main advantages of the traction induction electric drive are high energy and mass-size indicators, high level of reliability, simplicity of design, long service life [5]. However, the requirements for reducing energy and resource consumption of rolling stock pose a task to the scientific and technical community both to the further improvement of traction induction electric drives, and the development and research of other types of electric drives [6]. An alternative approach to increase the efficiency of the traction electric drive is the use of synchronous motors with excitation from permanent magnets [7], but the large mass of high-coercive permanent magnets significantly increases the cost of production of such electric motors.

Analysis of literature data and problem definition. A specific feature of the traction drive is a wide range of speed and torque control, and therefore, it is important to ensure high energy performance of the traction drive in different operating modes. According to various authors, such characteristics are provided by permanent magnet-assisted synchronous reluctance motors (PMSynRM, PMA-SynRel) [8-12]. The weight and size of the motor of this type are comparable to an induction motor, and therefore the traction drive based on a permanent magnet-assisted synchronous reluctance motor is a «direct alternative» to the traction induction electric drive.

PMSynRM is a synchronous reluctance motor (SynRM) with permanent magnets inside the rotor. The configuration of a typical PMSynRM is shown in Fig. 1 [8-10].

In this motor, as a rule, a distributed stator winding is used [10, 11]. To increase the use of reactive torque, in

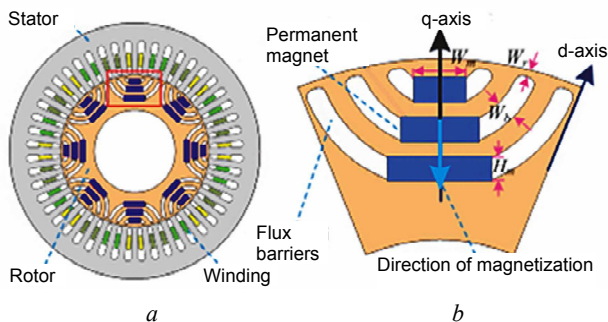


Fig. 1. PMSynRM configuration (a) and rotor section (b). Marked: W_r , W_b , W_m , H_m – tangential ribs, flux barriers, width and height of permanent rotor magnets, respectively

the radial direction of the rotor after another channels of flux barriers are placed one after another. A feature of the rotor is the presence of permanent magnets (rare earth magnets such as NdFeB, ferrite Y30) inserted into its flux barriers [11-13]. The permanent magnets are uniformly magnetized and form the q -axis of the rotor. Because permanent magnets have about the same permeability as air, they create a path with high resistance and magnetic anisotropy in the q -axis direction. The steel part of the rotor is formed by small segments isolated from each other by flux barriers. These segments provide a path with low flux resistance along the d -axis. To ensure the strength of the rotor structure, it is necessary that the ferromagnetic segments are internally connected to each other, so the rotor structure uses tangential ribs near the air gap with thickness W_r , [14]. Due to the installation of permanent magnets, the tangential ribs are saturated during normal operation of the motor and therefore magnetically insulate various steel segments [14]. From the point of view of creating torque, the scattering of the flux caused by tangential ribs should be minimal [11].

A review of publications [10-14] shows that the determination of the dimensions and parameters of electric motors is carried out by numerical field calculations in combination with multicriteria optimization. The varied parameters are usually the geometric dimensions of the elements of the magnetic core. At the same time, since the PMSynRM stator is similar to the stator of an AC motor, it is obvious that the optimization model can be simplified by applying classical methods for calculating the magnetic circuit of electric machines for the stator, and using numerical calculations only to determine the motor's rotor configuration. In addition, this decomposition allows to estimate the size of the active parts of the motor and its fit into the allotted mounting space without numerical calculations of the magnetic field, resulting in a set of allowable geometric stator parameters.

The goal of the work is the development of an algorithm for selecting the main dimensions of a traction permanent magnet-assisted synchronous reluctance motor.

The aim of the study is the adaptation of methods for selecting the main sizes of electric machines for their application to PMSynRM.

A technique for choosing the main dimensions of PMSynRM. The main dimensions of an electric machine are the diameter of the armature or the diameter of the stator bore and their axial length. These dimensions depend on the power, rotation speed and a number of indicators that characterize the use of active parts of electric machines [5]. Features of traction electric machines are, firstly, the regulation of rotation speed in a wide range (the ratio of maximum rotation speed to nominal one can be from 3 to 5 times, and the ratio of maximum torque to nominal one – up to 2 times), and, secondly, restrictions of overall dimensions associated with the placement of the electric machine on the vehicle and its arrangement in the transmission. This in most cases makes it impossible to use the Arnold constant to determine the main dimensions of traction electric machines, so there are special procedures developed for them [3, 5]. With this in mind, it is advisable to use this approach to select the main sizes of PMSynRM.

The number of pole pairs is determined from the condition of ensuring the maximum rotation speed at the highest frequency of the supply voltage:

$$p = \frac{60 f_{\max}}{n_{\max}}, \quad (1)$$

where f_{\max} is the highest supply frequency; n_{\max} is the highest rotation speed.

Since the traction motor must have a high degree of protection, which is adopted in order to prevent dirt from entering the air gap between the stator and the rotor, cooling of the electric motor is possible only through the axial ventilation ducts in the stator. In the caseless design, the axial channels are made directly in the stator sheet, for example, by stamping. In the case of the stator housing, the axial ventilation channels of the stator are formed by the motor housing, to which the ribs for laminating the stator core are welded, and the outer surface of the stator core. Regardless of the method of formation of axial ventilation ducts, their radial size (diameter or height) can be taken equal to 12–20 mm (smaller values – in the case of the housing). Adding to this size the thickness of the housing of 8–10 mm and technological reserves for the manufacture of holes, we obtain the outer diameter of the stator magnetic core (calculated diameter of the active part). This value is subject to specification based on the results of calculations and design processing of the electric motor.

The inner diameter of the stator D_i (diameter of the «bore») is determined by the expression

$$D_i = K \cdot D_a, \quad (2)$$

where K is the coefficient equal to, for example, 0.55–0.65 at $2p = 4$, p is the number of pole pairs, D_a is the calculated diameter.

To estimate the length of the stator magnetic core, calculate the departure of the front parts of the stator winding by expression

$$L_v = (0,12 + 0,15p) \cdot \tau_k + 10, \quad (3)$$

where τ_k is the average width of the stator coil.

Approximately the average width of the stator coil can be determined by expression

$$\tau_k = \beta \frac{Z}{2p} t_{av1}, \quad (4)$$

where β is the reduction of the winding step (approximately assumed to be equal to 0,8); Z is the number of slots in the stator; t_{av1} is the toothed step in the middle of the height of the slot.

The largest number of slots is determined from the expression

$$Z = \frac{(0,3 \dots 0,4)\pi D_i}{b_z}, \quad (5)$$

where b_z is the width of the stator tooth, which must be at least 5–7 mm;

$$t_{av1} = \frac{\pi(D_i + h_n)}{Z}, \quad (6)$$

where h_n is the height of the slot which is determined by the expression

$$h_n = (3 \dots 4)b_n, \quad (7)$$

where b_n is the width of the slot which is equal to

$$b_n = t_{z1} - b_z, \quad (8)$$

where t_{z1} is toothed step on the inner diameter of the stator

$$t_{z1} = \frac{\pi D_i}{Z}. \quad (9)$$

The size of the axial length of the stator on the front parts

$$L_l = (0,7 \dots 0,8)L_k, \quad (10)$$

where L_k is the body length (distance between the planes of bearing plates).

The axial length of the stator magnetic core is determined by the expression

$$L_i = L_l - L_v. \quad (11)$$

The phase current of the motor is predetermined by the expression

$$I_{ph} = \frac{P \cdot 10^3}{3 \cdot U_{ph} \cdot \eta \cdot \cos \varphi}, \quad (12)$$

where P is the nominal power; U_{ph} is the nominal phase voltage; η is efficiency (approximately 0.93–0.95); $\cos \varphi$ is the power factor (approximately 0.8–0.9).

The magnetic flux of the motor is pre-determined by the expression

$$\Phi = \alpha B_\delta \tau L_i, \quad (13)$$

where α is the coefficient of the pole arc (take equal to $2/\pi$); B_δ is the magnetic flux density in the air gap (take no more than 1 T); τ is the pole division.

The pole division is determined by the expression

$$\tau = \frac{\pi D_i}{2p}. \quad (14)$$

The number of turns in the phase of the stator winding is determined by the expression

$$w = \frac{(0,95 \dots 0,98)U_{ph}}{4,44\Phi f_{nom} k_{w1}}, \quad (15)$$

where U_{ph} is the phase voltage; k_{w1} is the winding coefficient (take equal to 0,9); f_{nom} is the nominal voltage frequency

$$f_{nom} = \frac{pn_{nom}}{60}, \quad (16)$$

where n_{nom} is the nominal rotation speed of the motor.

The number of effective conductors in the slot

$$s_n = \frac{2maw}{Z}, \quad (17)$$

where m is the number of phases of the motor (equal to 3); a is the number of parallel branches (the current of the parallel branch should not exceed 400 A).

It is advisable to choose the number of parallel branches from the condition of providing a whole number of slots per pole and phase

$$q = \frac{Z}{2pma}. \quad (18)$$

Preliminary assessment of the rotor configuration (number of flux barriers, geometric dimensions of permanent magnets) is performed by calculating the magnetic circuit of the motor using substitution circuits. The criterion for selecting a configuration option is to provide nominal torque at nominal phase current. The values of magnetic flux density in the parts of the magnetic core are analyzed and, if necessary, its geometric dimensions are adjusted.

When calculating the parameters of permanent magnets are taken according to the data given in Table 1.

Table 1

Parameters of permanent magnets

Name	Unit	Value
Material of magnets		NdFeB
Remanent flux density	T	1,0
Coercive force	kA/m	850

The next step is to calculate the magnetic field of the motor in the FEMM environment, which clarifies the results of the previous calculation [15–17].

Auxiliary criteria when choosing the configuration of the rotor are to ensure its mechanical strength, as well as satisfactory results of thermal calculation of the electric motor.

As an example, consider the procedure for selecting the main dimensions of PMSynRM to drive the wheels of a trolleybus with the technical parameters listed in Table 2. Technical parameters correspond to traction induction electric motors used in trolleybuses.

Table 2

Technical parameters of PMSynRM

Name	Unit	Value
Power	kW	180
Linear voltage	V	400
Phase current	A	350
Nominal rotation speed	Rpm	1500
Torque	Nm	1110
Maximum rotation speed	Rpm	4000
Maximum supply frequency	Hz	150

The selection criterion is to ensure the torque 1100 Nm at phase current of 350 A. From the analysis of designs of similar induction motors (AD903, DTA-1, 6DTA.002.1) we find that the external diameter of the electric motor should not exceed 500 mm, axial length on the case – 700 mm.

The procedure for determining the main dimensions of the traction PMSynRM is a series of calculations, which consist of calculations by analytical expressions (1) – (17), magnetic field calculations in FEMM environment (Fig. 2) and rotor strength calculations (Fig. 3). The calculations were performed for several values of the number of stator slots, after which the number of effective conductors in the slot was determined. After that, the calculations of the magnetic circuit of the stator were performed to assess the magnetic flux density in the teeth and the yoke (permissible values – not more than 1.7 T. In case of excess –the geometric dimensions of the slots were adjusted). Next, a sketch of the cross section of the motor was developed to calculate the magnetic field in the FEMM environment. Calculations were performed for rotor configuration options with two and three pairs of flux barriers. The thickness of the flux barrier was assumed to be 10 mm. The distance between the flux barriers in one layer is 5 mm. All flux barriers contain permanent magnets with parameters according to Table 1. The calculation of the magnetic field of the electric motor is performed for the stator current 350 A, according to which, taking into account the scheme of the stator winding, the magnetomotive force of the conductors of the stator winding is calculated. Calculations are performed for several positions of the rotor. For calculation options where the electromagnetic torque reaches more than 1100 Nm, calculations of a rotor on strength at frequency of rotation of 4800 rpm are carried out. If the mechanical strength of the rotor is provided (it is assumed that the safety factor should be greater than 2), the option is accepted as working.

After performing the above series of calculations, the configuration of PMSynRM was determined which satisfies the technical parameters specified in Table 2.

The stator data are given in Table 3, the results of the calculation of the magnetic field – in Fig. 2, the results

of the calculation of the rotor on strength – in Fig. 3. The sketch of the rotor is shown in Fig 4, the dependence of the torque of the motor on the angle of rotation of the rotor – in Fig. 5.

Table 3

Stator data

Name	Value
Number of slots	36
Number of effective conductors in the slot	6
Number of parallel branches	1
Step reduction ratio	0,778
Number of elementary conductors in the effective one	3 (in height)
Step on the slots	1-8-19
Connection of phases – «star»	
Calculated outer diameter of the stator, m	0,46
Boring diameter, m	0,3
Axial length of the magnetic core, m	0,3
One-side air gap, m	0,001
Dimensions of the stator winding conductor (without insulation), mm	1,6×12,5
Slot height, m	0,040
Slot width, m	0,0145

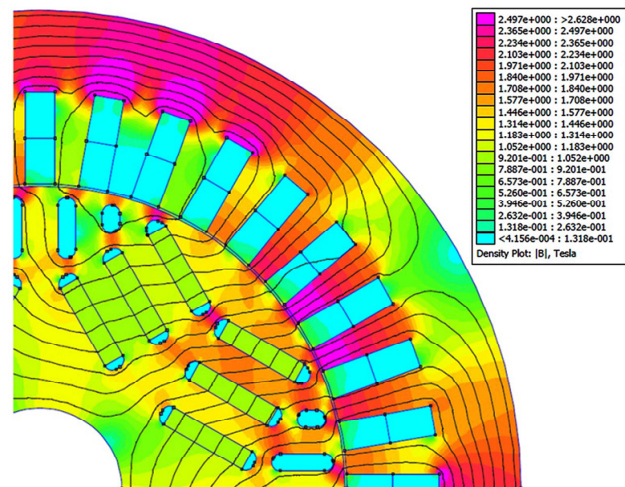


Fig. 2. Results of the calculation of the magnetic field in FEMM

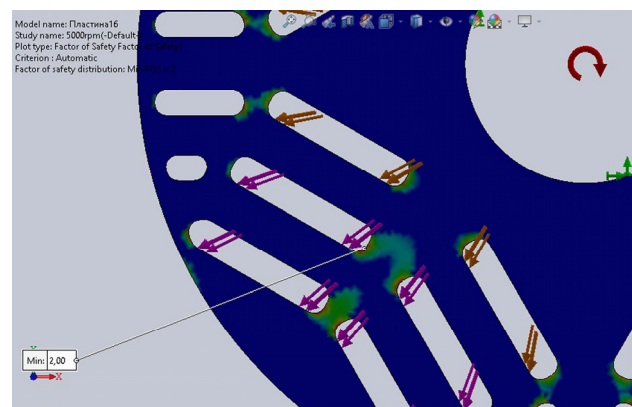


Fig. 3. Results of the calculation of the rotor on strength in SolidWorks Simulation

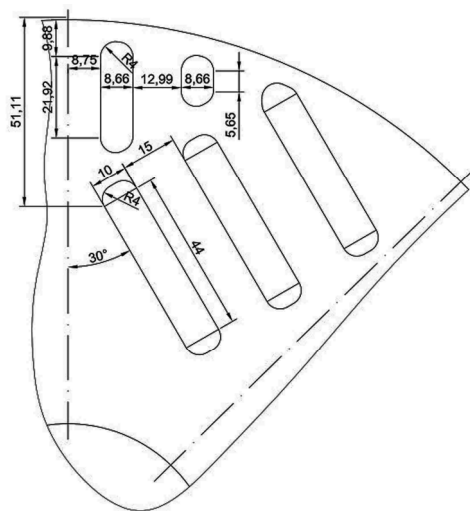


Fig. 4. Sketch of the PMSynRM rotor

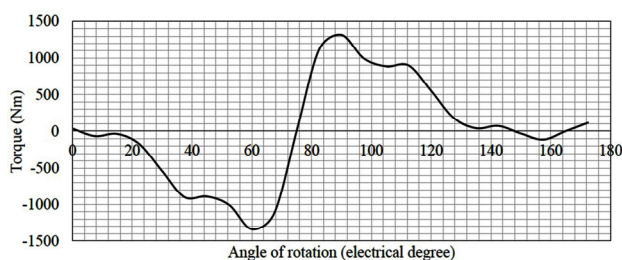


Fig. 5. Dependence of the torque on the angle of rotation of the rotor

As it can be seen from Fig. 5, the required torque equal to 1100 Nm is achieved by the calculated configuration of the active parts of the motor. However, it should be noted that in the given example of the PMSynRM configuration, the maximum torque of the electric motor does not significantly exceed the nominal torque, which can negatively affect the performance of the traction drive of the trolleybus.

Discussion of results. The proposed technique allowed to determine the parameters of the PMSynRM stator analytically, which reduced the number of options for numerical field calculations. The technique was tested in the calculation of PMSynRM with power of 180 kW for the drive of trolleybus wheels. In order to further reduce the numerical field calculations, it is advisable to analytically determine the parameters for assessing the performance of the electric motor. It is necessary to define and apply in the developed methodology criteria that take into account the frequency control of the motor.

Conclusions.

1. The paper proposes an algorithm for selecting the main dimensions of a traction permanent magnet-assisted synchronous reluctance motor which combines analytical expressions for selecting stator parameters and numerical field calculations for selecting rotor parameters. The technique was tested in determining the configuration of PMSynRM with power of 180 kW.

2. It is determined that analytical methods for calculating the magnetic circuit need to be developed in

order to reduce the time for choosing the main dimensions of the electric motor.

3. Techniques of heat-ventilation calculations of a traction permanent magnet-assisted synchronous reluctance electric motor and methods of calculation of its characteristics, based on the results of which a decision is made on the conformity of the electric motor to technical requirements, need to be developed.

Conflict of interest. The authors declare no conflict of interest.

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