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PECULIARITIES OF DESIGNING BRUSHLESS DIRECT CURRENT MOTORS FOR LIGHTWEIGHT MEANS OF TRANSPORT

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Abstract. In the article, the problem of improving the technique for the calculation of the geometry of a brushless direct current motor with U-shaped stator for lightweight means of transport and obtaining, at the project phase, relevant relations for its major quantitive characteristics is posed. The peculiarities of analysis of such motors, which are the fundamental part of the mathematical model for design calculation of the motor geometry, are discussed in the article. As a result, the technique for preliminary determination of the stator inner bore diameter of such a motor with permanent magnets on the rotor is proposed.

The relation for calculating optimal geometry of the tooth-slot zone, which is based on the determining the optimal dimensions of the stator lamination sheet and depends on the chosen criteria, is obtained.

The equation (13) enables the calculation of the dimensions of the stator lamination sheet at different limitations, for example, if it is necessary to ensure a given relative copper resistance. Applying the equation (13), it is possible to determine values of relative flux densities c_z and c_s in the teeth and in the frame yoke according to given constructional factors and check the observance of the condition $B_z < B_{\max}$.

Key words: brushless direct current motor, U-shaped ststor, mathematical model, permanent magnet, optimal dimensions, electric drive.

1. Introduction

One of the factors slowing down the domestic production of lightweight means of transport is the unavailability of a non-expensive and quality electric drive which could provide, along with sufficient capacity of controlled motors, high reliability, durability and controllability. In recent years, the efforts of foreign researchers in the field of car motor construction have been directed towards creating new kinds of electric motors as, for example, induction motors, brushless motors with permanent magnets (PM) characterized by enhanced specific flux (per mass unit) despite absence of mechanical gears, dual-rotor motors, motors with hybrid, magnetoelectric and electromagnetic excitation, dual-stator motors with magnetic gear system, electric machines integrated with magnetic gear system.

Based on these motors, compact and reliable direct drives for in-wheel motor systems for electric vehicles can be developed. For controlling these new kinds of electric motors modern methods of the control theory are applied: vector control with elements of adaptive control, sliding mode control, intellectual control (fuzzy control, application of artificial neural networks) [1].

Unlike induction motors, whose efficiency factor noticeably depends on changes in voltage and load, brushless direct current motors, in general, maintain their operation speed and power efficiency when mains voltage varies and their load changes; this fact attracts particularly the electric motor developers. Therefore, it seems to be logical to use brushless direct current motors in vehicle drives.

Nowadays, the analysis of the trends of development of electrical products production shows the significant success in the field of creating new generation of controlled electric drives with the use of brushless direct current motors. Electric drives based on such motors are produced by all leading electrical companies.

Particularly, more and more frequently, modern controlled low-powered and middle-powered electric drives contain brushless direct current motors (BLDCM).

2. Statement of the problem

BLDC motors are known to be electromechanical system containing electromechanical converter (EMC) shown in Fig. 1, electronic switch (ES) shown in Fig. 2, sensor of rotor position and control system [1]. Owing to their high reliability, comparatively simple design and production as well as microprocessor control, BLDC motors attract the developers of complex automated systems, robotic systems, electric drives of vehicles etc.

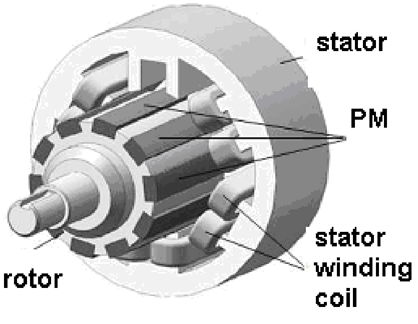

Fig. 1. EMC configuration with PMs on the rotor.

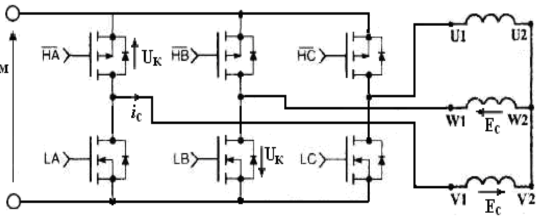

Fig. 2. Power circuit of BLDC motor with PM.

The sphere of applying BLDC motors with PM is predictably broadening which affirms the urgency of solving the task of the calculation of such motors. Since the characteristics and outer diameter of BLDC motor considerably depend on tooth-slot ratio, the method of optimization of this ratio is proposed. This method is based on the determining the optimal dimensions of machine for stator laminations of quasi-U form. Here the optimality criteria can be the efficiency factor, mass of the motor and active materials, useful power per mass or volume unit etc.

The aim of the paper is the improvement of the method of calculating the main dimensions of BLDC motor with U-shaped stator and obtaining relevant relations for its major quantitive characteristics at its design stage.

3. Development of mathematical model elements

The calculation of any electric machine in general and of the BLM in particular is subdivided into two parts: determining basic dimensions and checking calculation. Basic dimensions of the BLM depend, as a rule, on dimensions of its exciting system. The techniques for calculating basic dimensions of the known types of electric machines are based on the chosen values of electromagnetic load (inductions in certain parts of magnetic circuit, linear load, current density, etc), which are chosen on the basis of the experience in designing machines of general purpose. Nevertheless, there is no sufficient experience in BLDCM design.

Taking into account the peculiarities of BLDCM structure and the theory of electromechanical transformation of energy, let us justify some recommendations which will make up the basis of developing such motors and, in particular, the BLDCM with quasi-U-formed stator (Fig.1). EMCs with such a structure, as well as those of so called “classical” design, can be considered to be the most reasonable from the technological point of view [2]. Structures with quasi-U-formed stator provide better dynamic parameters at less leakage inductances and armature reaction caused by virtually total magnetic phase insulation, but the number of rotor teeth should be big enough which may be unacceptable while using them in BLDCM with high rotational speed. It should also be remarked that different types of structure and, accordingly, of organizing the paths of operating flux closure caused the necessity of developing different techniques of designing BLDCMs with specific features. Particularly, for the structure with quasi-U-formed stator the ratio between the number of stator teeth and rotor poles (permanent magnets) is:

$$Z_r = Z_s \cdot \frac{2 \cdot m \pm 1}{2 \cdot m}; \; \mathrm{Z_s} = m \cdot q; \quad q\text{=4, 6, 8...} \qquad (1)$$

where m is the number of BLDCM sections. That is, the number of poles at m=3 will be no less than 10, so a slightly bigger diameter of rotor should be chosen to place magnets while calculating BLDCM with relatively small torque.

As a rule, a BLM design specification contains preset values of supply voltage and torque, so determining the BLM geometry and the ratios between the dimensions is carried out basing on the torque values preset or calculated from other given values. However, it is worth reminding, that BLM electromagnetic torque could depend on different values according to a task being solved.

At the pre-design phase of the project, it is advisable to consider electromagnetic torque in the connection with BLM basic dimensions and electromagnetic load. At the phase of technical design, the relation between the electromagnetic torque, on the one hand, and dimensions and permanent magnet parameters, on the other hand, is needed. At this phase, the evaluation of torque stability over time and at environmental changes, as well as the evaluation of torque pulsations are required.

Having accepted several assumptions, the authors [2] obtained the general expression for the torque of the section of three-phase BLDCM with salient-pole stator and permanent magnets on the rotor, which, without considering armature reaction, can be written down as follows

$$M_c = c_M w_z \Phi_{\max} I_c \cdot 4p \sin q_c, \qquad (2)$$

where w_z is the number of turns in the stator tooth section; $\Phi_{\max}$ is the total magnetic flux; I_c is the section current; p is the number of poles (magnets);

$l_d = m_0 \dfrac{ab}{d} + m_0 a g_{pa} + m_0 b g_{pb} + m_0 (a g_a + b g_b)$ is air gap permeance; l_s is leakage permeance; $l_m = \dfrac{B_r S_m}{H_{cf} h_m}$ is inner permeance of the magnet; $c_M = \left(\dfrac{l_d}{l_m + l_d + l_s} \right)$ is a coefficient depending on BLDCM tooth-pole geometry and parameters of the chosen permanent magnet; q is an angle between the stator tooth axe and the magnet axe; a, b, d are width, length and height of the air gap; g_{pa}, $g_{p\mathrm{b}}$ are dimensionless quantities that correspond to derivatives of permeance between tooth and permanent magnet faces (that are adjacent to air gap) with respect to their width and length and depend on relative position of the stator tooth and rotor magnet; g_a, g_b are dimensionless quantities that correspond to derivatives of permeance between tooth and permanent magnet lateral faces with respect to their width and length and depend on relative position of the stator tooth and rotor magnet; $m_0 = 4p \cdot 10^{-7}$ H/m is vacuum permeability; $\Phi_{\max} = S_m B_r$; H_{cf} and B_r are the coercive force and residual flux density of the permanent magnet. These two values depend on the material and are provided in its technical data; h_m and $S_m = a_m \cdot b_m$ are the height and base area of the permanent magnet of the rotor pole where a_m, b_m are its width and length, respectively.

According to [1], the section current can be represented as a dependence on the nominal torque

$$I_c = \frac{p M_n}{\sqrt{3}\Phi_{d0} w_z pm}, \tag{3}$$

It follows from (2) that the necessary motor torque can be provided by different combinations of the values of maximum flux $\Phi_{\max}$ of the magnet, total current of the section $w_z I_c$ and factor c_M which depends on the tooth-pole geometry of the BLDCM (Fig.3) and the parameters of a chosen permanent magnet.

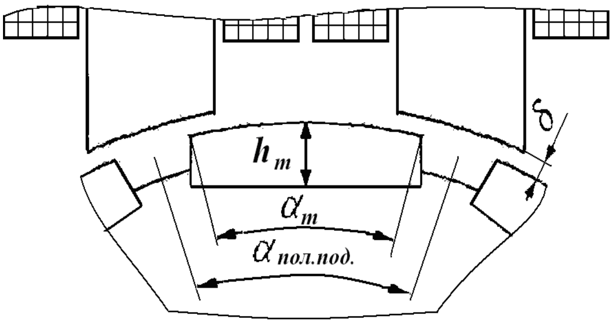

Fig. 3. Segment of BLDCM cross-section.

As theoretical and experimental investigations show, the correlation between the geometry of elements of the BLM tooth-pole zone lies within rather close limits. Particularly, the optimal values of stator pole overlapping factor are within a range $a_s = = a_r \cdot m/(m-1) = 0.6 \div 0.7$, and those of rotor pole overlapping factor are within a range $a_m = 0.75 \div 0.8$.

The magnet height, as a rule, is determined by the condition of achieving maximum of energy in the air gap and minimum of tooth torques. It is, on average, 2–3 times higher than the air gap which, in turn, is chosen quite big. Taking into account mentioned above, as well as low values of permeability of modern magnetic materials, c_M can be calculated in the preliminary stage.

Then, the values in (1) are chosen and the section current (3) is determined. Thus, to determine the diameter of the inductor, one has to choose first the value of flux density B_d (that is, a magnet type and a pole area S_m) in the air gap for the case, when the axis of the pole coinsides with the middle of the tooth. The preliminary evaluation of the initial value of flux density B_d is realized with the use of the diagram of the chosen type of magnet [1], following chosen optimality criteria and the analytical expression for calculating the useful flux Φ_d in the air gap [2]

$$\Phi_d = \frac{\Phi_{\max} l_d \pm w_z I_c l_d (l_m + l_s)}{l_m + l_d + l_s} \tag{4}$$

For making the values of leakage permeance more precise, the real distribution of magnetomotive force (MMF) along the magnet height is taken into consideration [7]. The distribution of the MMF in the PM, as well as its leakage flux can be calculated for the particular system structure by solving the differential equations for magnetic field with the use of computer numeric methods. In engineering calculations, it is often assumed that magnet MMF changes linearly.

For a prism-shaped magnet (Fig.4) whose MMF (counted from the magnet neutral cross-section S_m) varies linearly with the height ($h_M = h_m / 2$):

$$F_{my} = F_m / h_M \cdot y,$$

let us consider an infinitesimal element of the lateral surface area, dy in height, at a distance y from the neutral cross-section. As a result, the elementary flux from the infinitesimal lateral surface to the similar surface over the neutral cross-section can be written down as

$$d\Phi_{s\,y2} = F_{my} \cdot d\,l_{s\,y2}.$$

Permeance of the elementary magnetic field tube associated with the PM lateral surface (marked with number 2 in Fig. 4) is

$$d\,l_{s\,y2} = m_0 \left(l_m / l_{y2} \right) dy,$$

where l_{y2} is the length of the middle field line of the field tube for one pole.

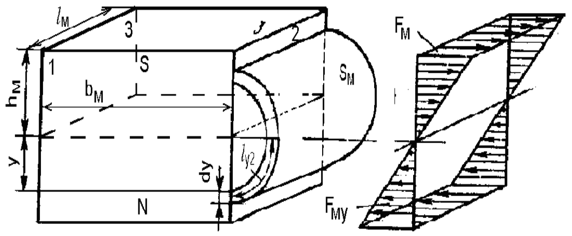

Fig. 4. Distribution of PM MMF and leakage flux.

The total leakage flux associated with the magnet lateral surface

$$\Phi_{s\,2} = \int_{o}^{h_m} \frac{F_m \cdot m_0 \cdot l_m y}{h_M \cdot l_{y2}} dy.$$

Therefiore, leakage permeance associated with the lateral surface is expressed by

$$l_{s\,2} = \frac{\Phi_{s\,2}}{F_m} = m_0 \frac{l_m}{h_M} \int_{0}^{h_M} \frac{y dy}{l_{y2}}.$$

Leakage permeance $l_{s\,1}$ associated with the magnet end surface is determined in the similar way.

Leakage permeance $l_{s\,3}$ between two effective pole facial surfaces is determined as the permeance between two equipotential surfaces.

Total leakage permeance of the magnet not attached to any armature is calculated as

$$l_s = 2 l_{s\,1} + 2 l_{s\,2} + l_{s\,3}.$$

The set forth considerations show that leakage flux of the permanent magnet can be determined with the accuracy satisfactory for engineering design.

After determining the desirable maximum flux $\Phi_{\max} = S_m B_r$, the width a_m and length b_m of the chosen permanent magnet, the rotor diameter is calculated according to the formula [2]

$$D = 2p \frac{b_m}{p\, a_m}, \qquad (5)$$

Then the obtained torque is refined and, if it diverges from the preset value considerably, the calculations are repeated with the use of the corrected data.

Then the dimensions of tooth-slot zone of stator are to be calculated. Necessary slot area is determined on the basis of chosen thermal load for given values of total section current $w_z I_c$. Such a multicriterion problem causes the optimization problem (task) ambiguity and requires a compromise. But, in many cases partial optimizations may work, for example, the optimization of the stator tooth-slot layer, the optimization of the dimensions of the inductor magnetic core, etc.

The task of optimization of the tooth-slot layer of the quasi-U-formed stator can be solved in the same way as for classical one. For the optimization of the dimensions of the EMC of BLDCM stator slot, it is assumed that a stator lamination sheet with the outer diameter d_3 and inner diameter d_b has Z_s teeth with parallel faces and permanent width b_z over their height h_z; the area of a diamond-shaped slot is denoted as S_{nm}; the area of a rectangular slot is denoted as S_{nn}.

For the connection of the area S_n of a real slot (Fig. 5) and its calculated area S_{np} we use the factor of slot imperfection

$$k_n = \frac{S_n}{S_{np}}, \qquad (6)$$

where $S_n = \frac{S_{nm} + S_{nn}}{2}$ is a real slot area for the quasi-U-formed stator.

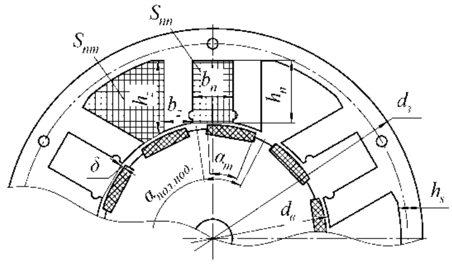

Fig. 5. Lamination segment of a quasi-U-formed stator.

Let us introduce constructional factors representing the ratio of stator bore diameter to the outer diameter

$$k_i = \frac{d_b}{d_3} \qquad (7)$$

and relative area of stator slots

$$k_{snb} = \frac{Z_s S_n}{\left(\frac{p\, d_b^2}{4}\right)\left(\frac{1}{k_i^2 - 1}\right)} \qquad (8)$$

The values determining the geometry of the stator lamination sheet can be connected together in the expression of the total stator slot area for the stator with constant tooth width

$$Z_s S_n = k_n \left\{ \begin{matrix} \left(\frac{p}{4}\right)\left[(d_3 - 2h_s)^2 - d_b^2\right] - \\ -\left(\frac{Z_s}{2}\right) b_z (d_3 - d_b - 2h_s) \end{matrix} \right\}, \qquad (9)$$

where h_s is the height of the frame yoke.

Magnetic flux in the tooth can be wtitten gown as

$$\Phi = \left(\frac{2}{p}\right) B_d \left(p \frac{d_b}{Z_s}\right) l_s = 2 h_s l_s k_c B_s, \qquad (10)$$

where l_s is the stator length; B_d, B_s are the values of flux density in the air gap and frame yoke respectively; k_c is a stator stacking factor.

From (10) the frame yoke height is

$$h_s = \frac{d_b}{Z_s k_c c_s}, \qquad (11)$$

and tooth width

$$b_z = \frac{p\,d_b}{Z_s k_c c_z}, \qquad (12)$$

where $c_s = \frac{B_s}{B_d}$ is relative flux density in the frame yoke; $c_z = \frac{B_z}{B_d}$ is relative flux density in the tooth; B_z is the flux density in the tooth.

Using the equations (8), (11), (12), the equation (9) can be rewritten in the form

$$k_{snb} = \frac{k_n}{1-k_i^2}\left\{\begin{array}{l}\left[\left(1-\frac{k_i}{2Z_s k_c c_s}\right)^2 - k_i^2\right] - \\ -\frac{2k_i}{k_c c_z}\left(1-k_i-\frac{k_i}{2Z_s k_c c_s}\right)\end{array}\right\}, \qquad (13)$$

which connects constructional factors k_i and k_{snb} with relative flux density values c_s and c_z in the teeth and in the frame yoke respectively.

The obtained expression lays the foundation for the design calculation of the basic dimensions of the BLDCM with the quasi-U-formed stator.

Using the proposed technique, the BLDCM with the following characteristics has been designed: output torque $M = 7.2$ Nm; nominal rotational speed $n = 750$ rpm; supply voltage $U = 120$ V.

The magnet SmCo5 with the following parameters has been chosen: $\Phi_{\max} = 250$ mWb; $B_r = 1.1$ T; H_{cf} = 600 kA/m. The designed motor has the following parameters: $U = 120$ V; stator bore diameter $D = 90$ mm; rotor axial length $L = 40$ mm; the number of magnets on the rotor $2p = 10$; magnet dimensions $h_m = 5$ mm, $b_m = 8$ mm, $a_m = 40$ mm; it provides the following characteristics: $M = 7.2$ Nm; $n = 780$ rpm.

4. Conclusions

The technique for the preliminary determination of the stator inner bore diameter of a brushless direct current motor with permanent magnets on the rotor has been proposed. The expression for calculating optimal geometry of the tooth-slot zone has been obtained, which is based on the determining the optimal dimensions of the stator lamination sheet and depends on the chosen criteria.

The results of the conducted calculations with the use of mathematical model developed on the basis of the proposed technique for calculating the bore diameter of BLDCM stator correspond with the experimental data which proves that the model is quite adequate. The equation (13) enables the calculation of the dimensions of the stator lamination sheet at different limitations, for example, if it is necessary to ensure a given relative copper resistance. Applying the equation (13), it is possible to determine values of relative flux densities c_z and c_s in the teeth and in the frame yoke according to given constructional factors and check the observance of the condition $B_z < B_{\max}$, where $B_{\max}$ is maximal flux density in the teeth for a chosen steel type.

It is also possible to solve the task of computing the relative slot area at given k_i and values of relative flux density, as well as the task of determining k_n and verifying the values of flux density c_z in the teeth for a chosen (according to the technological or other criteria) k_i, a chosen height of the frame yoke and a width of the tooth. If the relation between c_z and c_s is not known, it can be assumed that $c_z \approx c_s$.

References

[1] V. Tkachuk, *Electromechanotronics.* Lviv Polytechnic National University: Lviv, Ukraine, 2006. (Ukrainian)

[2] V. Tkachuk, “Switched reluctance motor with capacitive buffer of energy“, *Elektromazhynobuduvannia ta elektroobladnannia*, no. 52, p. 82–98. 1999. (Ukrainian)

[3] V. Tkachuk and Yu. Osidach, “Transistor commutator with capacitive buffer of energy”, *Elektroenerhetychni ta elektromekhanichni systemy*, no. 301, p. 115–122, Lviv Polytechnic National University: Lviv, Ukraine, 1996. (Ukrainian)

[4] V. Tkachuk, “Subsystem of computer dialog design of a switched reluctance motor” *Elektroenerhetychni ta elektromekhanichni systemy*, no. 340, p. 112–120, Lviv Polytechnic National University: Lviv, Ukraine, 1997. (Ukrainian)

[5] V. Tkachuk. “Mathematical model of a switched reluctance motor for mean values”, *Elektroenerhetychni ta elektromekhanichni systemy*, no. 301, p. 106–115, Lviv Polytechnic National University: Lviv, Ukraine, 1997. (Ukrainian)

[6] V. Tkachuk, L. Kasha, and I. Shapovalov, “Switched reluctance motor in a controlled electric drive”, in *Proc. VIIth International Conference “Perspective Technologies and Methods in MEMS Design” (MEMSTECH)*, p.120-123, Lviv-Polyana, Ukraine, 2011.

ОСОБЛИВОСТІ ПРОЕКТУВАННЯ ВЕНТИЛЬНИХ ДВИГУНІВ ДЛЯ ЛЕГКОВАГОВИХ ТРАНСПОРТНИХ ЗАСОБІВ

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Розглянуто проблему вдосконалення методики розрахунку основних геометричних розмірів безконтактних двигунів постійного струму з постійними магнітами та U-подібним статором для легковагових транспортних засобів і отримання відповідних співвідношень для основних його показників на етапі проектування. Наведено особливості розрахунку таких двигунів, які покладено в основу математичної моделі проектного розрахунку їхніх основних геометричних розмірів. У результаті запропоновано методику попереднього визначення внутрішнього діаметра розточки статора вентильного двигуна з постійними магнітами на роторі. Отримано співвідношення для розрахунку оптимальних, з погляду вибраних критеріїв, геометричних співвідношень між елементами зубцево-пазової зони, що основується на визначенні оптимальних розмірів штампованого листа статора. Рівняння (13) дає можливість розв'язувати задачі визначення розмірів штампованого листа статора за різних обмежень (зокрема, в разі необхідності отримати певний відносний активний опір обмотки) і за заданими конструкційними коефіцієнтами визначати відносні індукції c_z та c_s в зубцях і в спинці статора та перевіряти виконання умови $B_z < B_{\max}$.

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