ЕЛЕКТРИЧНІ МАШИНИ ТА АПАРАТИ

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FEATURES OF THE DEVELOPMENT OF SLOTLESS BRUSHLESS MAGNETOELECTRIC TORQUE MOTORS

V.G. Kireyev*, K.P. Akinin**
Institute of Electrodynamics of the National Academy of Sciences of Ukraine,
pr. Peremohy , 56, Kyiv, 03057, Ukraine
e-mail: kvg2016@ukr.net

The structure of a brushless magnetoelectric torque motor with a slotless stator with a surface installation of permanent magnets on the rotor is considered. A motor model has been developed to calculate its characteristics in the COMSOL Multiphysics 6.0 software environment. The optimization of its structure was carried out, as a result of which the optimal number of pole pairs and such a ratio between the dimensions of the elements of the electromagnetic core of the motor were determined, at which the maximum electromagnetic torque per unit of power consumption is achieved. The paper also touches upon the problem of achieving the minimum value of the torque ripple factor in motors of a similar design. Ways of its solution are proposed both due to constructive changes in the magnetic system, and due to the synthesis of reference signals for the formation of such forms of currents in the stator phases, as a result of the interaction of which with the rotating magnetic field of the rotor, the motor torque characteristic the with a minimum value of the ripple factor can be obtained. Ref. 6, fig. 11.
Key words: brushless magnetoelectric torque motor, slotless stator, torque factor, torque ripple factor.

Introduction. A torque motor (TM) is an electromechanical converter of an input electrical signal of direct or alternating current into an electromagnetic torque, while the rotor rotates at low speed or is stationary. TM are used in cases where it is necessary to ensure the rotation of the payload with high torque with minimal torque ripple throughout the entire rotation range, as well as ensuring high dynamics in transients and accuracy in positioning mode. These motors are widely used as actuating elements in gyroscopic systems, antennas drives, telescopes, solar batteries, robots, machine tools, medical equipment, etc.

When developing control systems and choosing an actuating motor, ordinary electric motors with a gearbox can compete with TM, since they have less weight, energy consumption, and an electromechanical time constant. However, the presence of a gearbox implies the introduction of errors into the control system loop due to the inevitable presence of backlash and friction in them, thermal instability of mechanical properties, and low reliability of the drive, which makes it preferable to use TM. The main distinguishing features of TM in comparison with conventional electric motors are the relatively low angular speed of rotation of the rotor and the frameless design, that is, the absence of a housing, shaft and bearings [1]. The task of designing an TM is not only to ensure the characteristics of the motor in accordance with the terms of reference, but also to create a design that is best integrated into the system being developed. This explains the wide variety of TM designs and the need for optimal design of an electromechanical converter to achieve the desired characteristics.

The purpose of the paper is to develop approaches to designing slotless brushless magnetoelectric TM that have a maximum electromagnetic torque per unit of power consumption, as well as ways to reduce the torque ripple factor.

The main material and study results. The main characteristic of the TM, which determines the very name of the motor, is the dependence of the magnitude of the electromagnetic torque on the consumed current, which can be expressed through the ratio of the starting torque M_s to the current I_s in the stator winding in the starting mode, called the torque constant C_m

ORCID ID: *https://orcid.org/0000-0002-9407-1074, **https://orcid.org/0000-0002-7830-2311

$$C_m = M_s / I_s \, . \qquad (1)$$

Since TM operate in the mode of positioning or slow rotation of the rotor, the main energy losses are dissipated in the stator winding, and the efficiency of converting electrical energy into mechanical energy depends on how well its parameters are chosen. Thus, the optimization task is to establish such a ratio between the sizes of the elements of the electromagnetic core of the motor, in which the maximum torque per unit of power consumption will be obtained. Previously, in [2, 3], a method for optimizing brushless motors with permanent magnets has already been described, and we can apply it to calculate the TM.

As an example, from the whole variety of TM designs, consider a brushless slotless magnetoelectric motor (Fig. 1), which consists of external 1 and internal 2 magnetic circuits, a three-phase stator winding 3 and permanent magnets of the rotor 4. Solving the problem of optimizing the configuration of the electromagnetic cores of the machine will be carried out taking into account a number of restrictions and assumptions, namely: the power dissipated in the winding $P = 18W$ and the power supply voltage $U = 36V$ are constant, the outer diameter of the stator D and the length of the active zone of the motor L_a are unchanged and equal to $88mm$ and $45mm$, respectively, there is no saturation of the stator and rotor magnetic circuits and the maximum induction value in them remains constant for all variations in the size of the motor elements, the air gap between the stator and the rotor is $0.5mm$, the length of the brand H42SH magnet h_m along the magnetization axis is 5mm. The target optimization function is the maximum starting electromagnetic torque M_s, and the arguments are the number of pairs of poles of the magnets p and the radial thickness of the winding b.

Since the power and supply voltage are constants, and all the consumed power is dissipated in the winding, the current I and the resistance of the winding will also be constant. The fulfillment of the condition of constant resistance when changing the cross-sectional area of the active part of the stator coils is achieved by simultaneously changing the number of turns of the coils and the copper section of the winding wire. We assume that a simple loop three-phase winding is installed on the stator, connected to a star with an isolated zero. Then the formula for calculating the length of the average turn of the coil can be written as

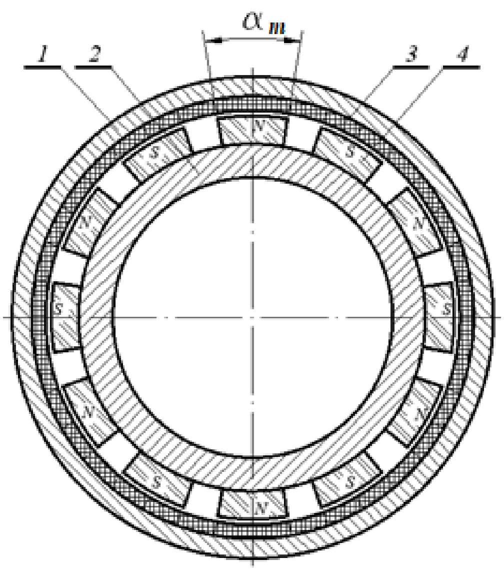

Fig. 1

$$L_{av} = 2\left(L_a + 3{,}5b + \left(R_{st} + \frac{b}{2} \right) \frac{\pi}{p} \right), \qquad (2)$$

where R_{st} is the inner radius of the stator winding. We express the number of turns of the coil through its geometric dimensions

$$W = \frac{\pi \left(2R_{st} + b \right) b k_r}{6 p S_w} \, , \qquad (3)$$

where k_r is the fill factor of the cross section of the coil with copper, S_w is the cross section of the winding conductor. Since, according to the accepted conditions, the current and the power dissipated in the winding are constants, the winding resistance can be expressed through these parameters

$$R_a = \frac{P}{I^2} = \frac{2p\rho L_{av} W}{S_w} \, , \qquad (4)$$

where

$$W = \frac{P S_w}{2 I^2 p \rho L_{av}} \, , \qquad (5)$$

where ρ is the resistivity of the winding wire material. Equating the two expressions obtained for the number of turns of the coil W, we obtain the value of the cross section of the winding wire S_w, at which the condition of constancy of the dissipated power will be satisfied.

$$S_w = \sqrt{\frac{\pi\left(2R_{st}+b\right)b\,k_r I^2 \rho L_{av}}{3P}}\,. \tag{6}$$

We will calculate the electromagnetic torque developed by the motor rotor using the Arcchio method implemented in the COMSOL Multiphysics 6.0 software package. Finding the torque value is possible both in two-dimensional and three-dimensional formulations, and the choice of one or another option depends on how much edge effects affect obtaining a reliable result, on the complexity of creating a model and setting up a solver, on calculation time, etc. The purpose of this article is to demonstrate an approach to designing an TM with optimal characteristics, as well as to demonstrate the influence of certain parameters on achieving the desired results, therefore, two-dimensional modeling is best suited for multivariate calculations, since this significantly reduces the calculation time. This reduction in time becomes especially noticeable when the vector magnetic potential is used in the problem, the necessity of using which is due to the choice of the Arcchio method. To verify the results obtained on a two-dimensional model, the values of magnetic induction in the motor gap were calculated with a change in its length, the number of poles and the length of the magnet in the environment of two-dimensional and three-dimensional modeling. The calculation error of the average value of induction in the working gap in the two-dimensional model ΔB is determined in comparison with the three-dimensional one. Fig. 2 shows the dependence of the error ΔB in percent when varying the number of motor poles and the length of the active part of the machine, expressed in relative units L_a/D_r, where D_r is the rotor diameter. Obviously, the main influence on the error in calculating the induction is the length of the active part of the machine, and the smaller it is, the higher the error.

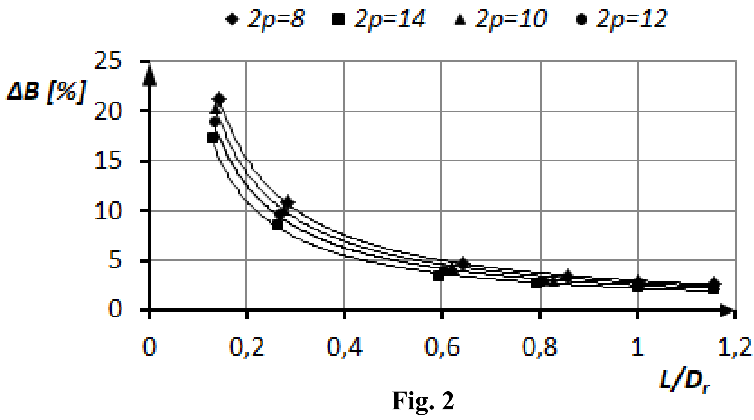

Fig. 2

The characteristics family of obtained graphs of the function $\Delta B(2p,\ L/D_r)$ is described by the empirical expression

$$\Delta B = \left(-0{,}22p + 3{,}65\right)\left(L/D_r\right)^{-1{,}05}, \tag{7}$$

that allows you to calculate the error in calculating the value of the average induction in the working gap when modeling in two-dimensional space, as well as to correct the calculation of the magnetic induction and thereby take into account the leakage fluxes from the end parts of the machine

As already noted, the optimization of the TM magnetic system with the above initial data will be carried out in the environment of the COMSOL Multiphysics software package in a two-dimensional formulation with the connection of the optimization module. The search for the maximum value of the torque was carried out under the condition (6) of the constancy of the power dissipated in the winding and the fixed outer diameter of the stator magnetic circuit, and the adjustment of the induction value (7) was also used.

To generalize the results obtained in the simulation, we introduce the concept of the relative values of the length of the magnet h_m/D and the thickness of the winding b/D, which determine the geometric relationships between the elements of the magnetic system. This will make it possible to extend the results of calculations to geometrically similar machines in accordance with the provisions of the theory of similarity of magnetic systems [5]. The simulation results are presented in fig. 3 as a family of performance characteristics $M_{max}(b/D)$ obtained for different values of the number of poles $2p$. Analysis of the simulation results shows that for a given configuration of the magnetic system and with a relative length of the magnet equal to 0.0568 units, the largest torque is achieved in the motor with the number of pole pairs p=7 and the relative thickness of the winding b=0.0284. Then, in accordance with the theory of similarity, with an increase in all geometric dimensions by n

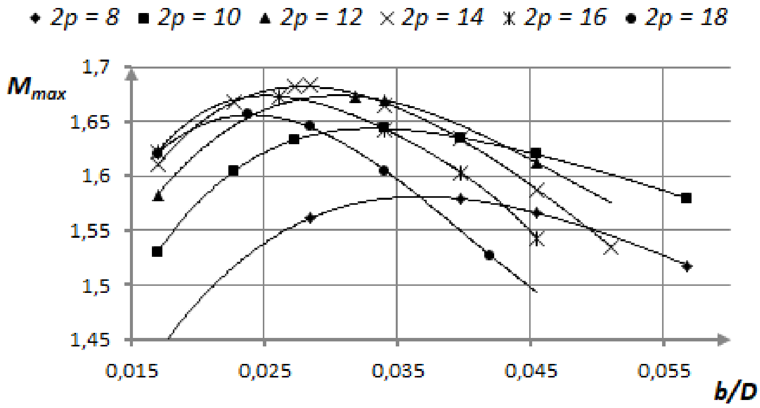

Fig. 3

times, the magnetic induction at all points of the magnetic system remains unchanged, and the magnetic flux increases by n^2 times. Similarly, the current in the stator winding increases by n^2 times. Accordingly, the electromagnetic torque will increase by n^4 times.

The given example of calculation demonstrates the method for optimizing the TM magnetic system in order to achieve the maximum of the electromagnetic torque at a fixed value of the energy consumed. Similarly, TM of any other design with different winding manufacturing methods can be calculated.

Achieving the maximum starting torque for TM is one of the main tasks of their development. At the same time, an equally important task is also to achieve a minimum change in the motor torque relative to the set value when the rotor rotates. To compare torque motors by this indicator, it is customary to use the torque ripple factor, determined by the formula

$$K_r = \frac{M_{\max} - M_{\min}}{2M_{av}} 100\% , \tag{8}$$

where M_{max}, M_{min}, M_{av} are the maximum, minimum and average torque values, respectively. Figure 4 shows the calculated dependences of the values of the average value of the torque M_{av} and the torque ripple factor K_r of the optimized TM for a different number of pairs of poles p. There is an obvious tendency to reduce ripples as the number of motor poles increases, however, after reaching its maximum at $2p = 14$, the torque begins to decrease and the developer must make a decision on choosing the number of poles based on the requirements for TM.

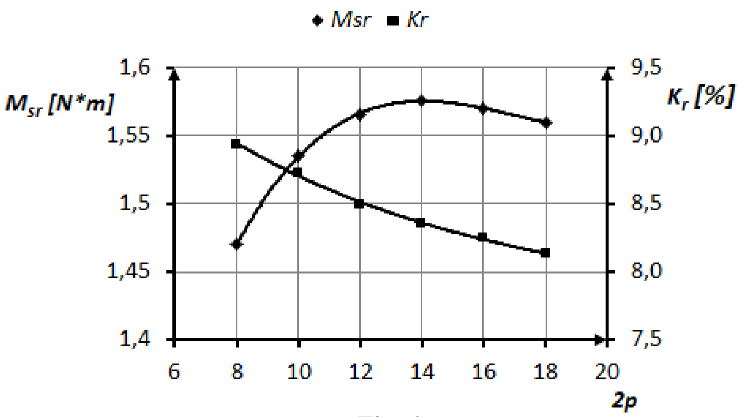

Fig. 4

In modern TM, torque ripples do not exceed 6÷10 %, therefore, we will further consider possible ways to reduce the torque ripple factor for brushless magnetoelectric motors with a slotless stator. One of the possible ways to reduce the ripple is the profiling of the pole or the pole piece [4], but in this case, as in the previous case the goal is achieved by reducing the torque. Quite effectively you can reduce the ripple by increasing the number of motor phases. Such a solution can be resorted to in special cases, when the additional number of conductors connecting the motor to the control system and the cost of the TM with the control scheme are not decisive.

Let's consider one more possible approach to TM optimization. In the example considered in the paper, the angular size of the magnet is α_m=2π/3p. The same angular size is occupied by two sections of the stator windings (Fig. 1). When the rotor rotates, the windings are switched every 120 electrical degrees, which corresponds to the physical rotation of the rotor at an angle φ=π/3p. At each switching period, the pattern of the change in the magnitude of the moment is repeated, therefore, we restrict ourselves to calculating the moment only in the range from 0 to π / 3p. Fig. 5 shows a family of graphs of the value of the motor torque with the number of poles $2p$=14 when the angular size of the magnet αm changes from 2π/3p to 11π/12p with a step of π/12p.

The nature of the change in the moment M_{av} and the torque ripple factor K_r depending on the angular size of the magnet α_m is shown in fig. 6. It can be seen from the graphs that an increase in the angle α_m leads to a decrease in pulsation from 8.4 % to 5.6 % if the angular size of the magnet is equal to the value of the pole division. In this case, the average torque value increases by 11 %. An increase in the moment value is due to both a change in the geometry of the magnet and an increase in the volume of the magnetic material. To numerically estimate the influence of each of the factors on the torque value, the motor was calculated with the number of poles 2p = 14 and the angular size of the magnet 11π/12p, provided that the volume of the magnet remained the same as at the angle α_m=2π/3*p*. The calculation showed an increase in the magnitude of the moment by 3.1 %, and the torque ripple factor was 5.9 %.

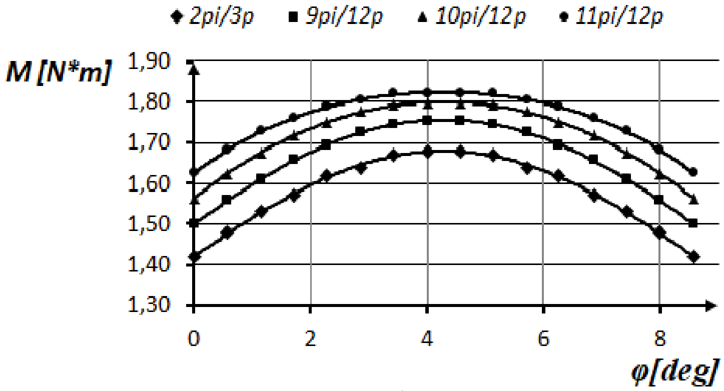

Fig. 5

In brushless TM, the windings are switched using a voltage inverter according to the signals of the rotor position sensors. If you pay attention to the nature of the change in the magnitude of the torque during the switching period (Fig. 5), then the motor develops the smallest torque at the edges of the presented angular interval, in which case an additional way to reduce ripples in the torque curve can be the formation of stator currents in a certain way. Next, consider the mode of slow rotation of the simulated motor and possible ways of generating currents in the winding. For definiteness, it can be noted that the operating angular speed of the considered TM has a value of 2 *rad/s*.

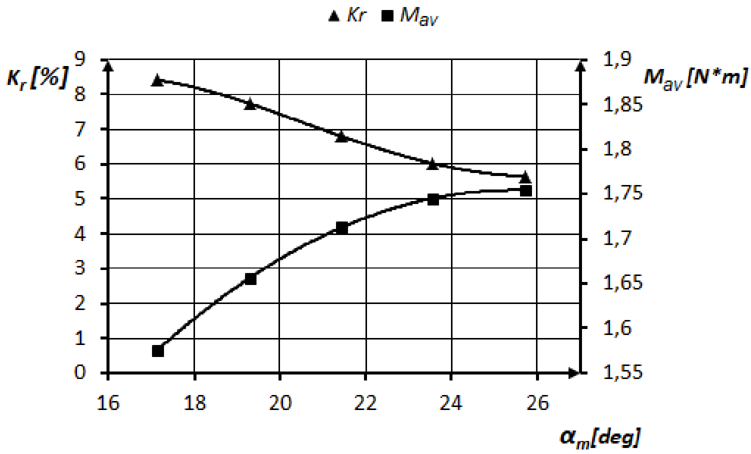

Fig. 6

Since for the TM, a special condition for their operation is the absence of any variable component in the curve of their torque characteristic, we will consider various variants for the formation of torque characteristics of TM to select the optimal solution.

The idea of forming the stator currents in a certain way to reduce torque ripples is known, and one of the particular cases of current formation is described in [6]. In this article, the authors, if possible, generalized possible approaches to solving this problem.

Further, we will consider the forms of writing equations in relative units. For a three-phase brushless magnetoelectric motor, its torque characteristic is the sum of three terms of the phase torque characteristics, which are determined as the result of the interaction of the rotating magnetic field of the rotor with the system of alternating currents in the stator windings

$$M^*(\alpha) = M_A^*(\alpha) + M_B^*(\alpha) + M_C^*(\alpha); \tag{9}$$

$$M_A^*(\alpha) = i_A^*(\alpha) b_A^*(\alpha);\ M_B^*(\alpha) = i_B^*(\alpha) b_B^*(\alpha);\ M_C^*(\alpha) = i_C^*(\alpha) b_C^*(\alpha), \tag{10-12}$$

where $M_A^*(\alpha)$, $M_B^*(\alpha)$, $M_C^*(\alpha)$ are the phase torque characteristics of the motor, which are functions of the electric angle α of rotor rotation; $i_A^*(\alpha)$, $i_B^*(\alpha)$, $i_C^*(\alpha)$ and $b_A^*(\alpha)$, $b_B^*(\alpha)$, $b_C^*(\alpha)$ are three-phase systems of stator currents and rotor field induction in relative units.

Further, we will give expressions for phase variables only for phase A, assuming the considered motor is symmetrical.

To fulfill the condition for the absence of a variable component in the torque characteristic curve, it is necessary to select such types of functions to describe the phase torque characteristics of the motor (10-12) so that their sum is always equal to a constant value. The same condition must be met for the rotor field induction curve $b_A^*(\alpha)$ obtained as a result of the optimization, shown in Fig. 7. It can be seen that this curve is quite different from the sinusoidal form.

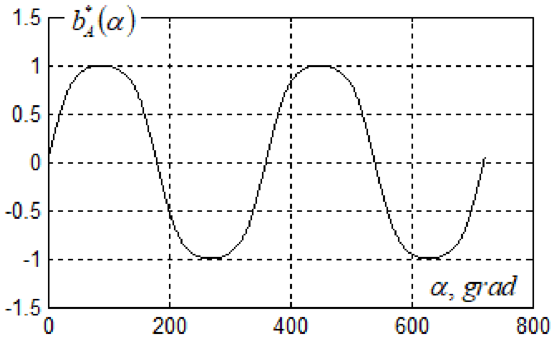

Fig. 7

It is known that the absence of a variable component in the curve of the moment characteristic of the motor is achieved by the interaction of the sinusoidal phase curves of the stator currents and the induction of the rotor field. In this case, the torque characteristic for phase A and the torque characteristic of the moto (9) in relative units have the form

$$M_A^*(\alpha) = \sin^2 \alpha \text{ and } M_S^*(\alpha) = 1{,}5. \qquad (13, 14)$$

Fig. 8a shows these characteristics.

This article does not consider the formation of motor stator currents with the help of semiconductor frequency converters. We are only talking about the synthesis of reference signals of currents for their further formation, that is, we will assume that the relative variables of the reference signals and the currents themselves coincide and, at the same time, have the same designations $i_A^*(\alpha)$, $i_B^*(\alpha)$ and $i_C^*(\alpha)$.

The idea of synthesizing the forms of the stator phase current curves $i_A^*(\alpha)$, $i_B^*(\alpha)$ and $i_C^*(\alpha)$ is that when they interact with the given angular distributions of induction $b_A^*(\alpha)$, $b_B^*(\alpha)$ and $b_C^*(\alpha)$ such phase torque characteristics of the motor (10-12) are formed, by summing which the desired torque characteristic of a three-phase motor can be obtained in form (14).

In this case, we obtain a formula for determining the phase A stator current curve

$$i_A^*(\alpha) = \frac{M_A^*(\alpha)}{b_A^*(\alpha)}. \qquad (15)$$

Fig. 8b shows the resulting stator phase current curve. In this case, we have the effective value of the stator current $I = 0{,}6491\ A$.

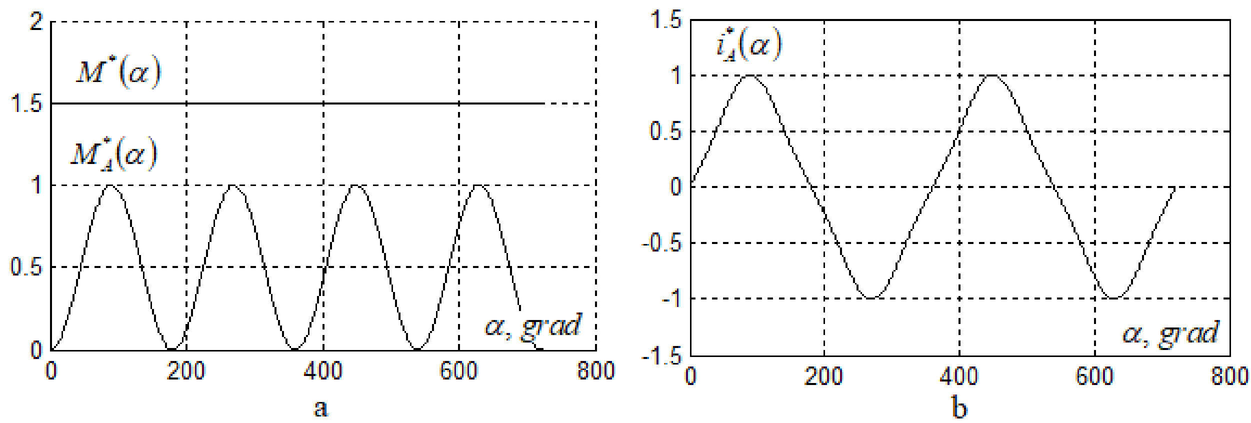

Fig. 8

The fulfillment of condition (14) is possible not only when the phase torque characteristic of the form (13) is realized, but also for some other forms. For example, Fig. 9 shows two variants similar to those described above for given forms of trapezoidal (a, b) and rectangular (c, d) phase torque characteristics $M_A^*(\alpha)$. The current forms were obtained in accordance with (15). In this case, the stator current effective values for these two variants are equal $I = 0{,}6501\ A$ and $I = 0{,}682\ A$, respectively.

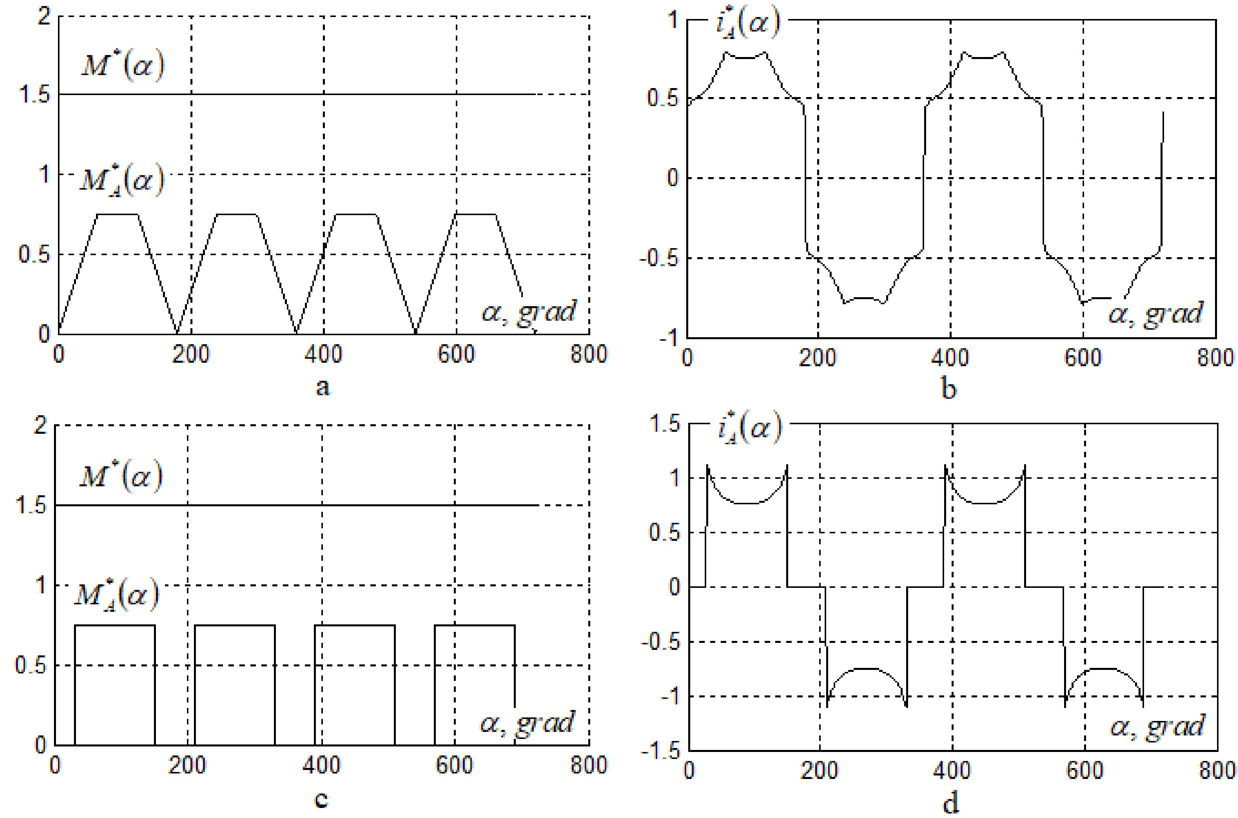

Fig. 9

A simpler way to obtain the torque characteristic of the motor of the form (14) is possible when the stator currents are formed, provided that the current flows in each half-cycle for only 120 electrical degrees. For phase A, we write the angular function, which is determined on one period of the electric angle of rotation $0 < \alpha < 360$,

$$\begin{aligned} &y_A^*(\alpha) = 0 \text{ at } \alpha < 30; \\ &y_A^*(\alpha) = 1 \text{ at } 30 < \alpha < 150; \\ &y_A^*(\alpha) = 0 \text{ at } 150 < \alpha < 210; \\ &y_A^*(\alpha) = -1 \text{ at } 210 < \alpha < 330; \\ &y_A^*(\alpha) = 0 \text{ at } 330 < \alpha < 360. \end{aligned} \tag{16}$$

We write an intermediate function for a three-phase symmetrical system

$$y^*(\alpha) = y_A^*(\alpha) b_A^*(\alpha) + y_B^*(\alpha) b_B^*(\alpha) + y_C^*(\alpha) b_C^*(\alpha), \tag{17}$$

as well as its inverse function

$$x^*(\alpha) = \frac{1{,}5}{y^*(\alpha)}. \tag{18}$$

Finally, we define the desired current in phase A as

$$i_{AR}^*(\alpha) = x^*(\alpha) y_A^*(\alpha). \tag{19}$$

The curves of the phase and total torque characteristics of the motor, as well as the current curve, are shown in Fig. 10, and its effective value is $I = 0{,}6721\ A$. The substitution of three phase currents in formula (9) made it possible to implement the torque characteristic of the motor of the form (14).

In addition to the considered cases in which condition (14) is satisfied, we will also consider simpler variants from the point of view of their implementation. Fig. 11 shows the curves of the variants for forming the torque characteristics of the motor for sinusoidal (a, b), rectangular (c, d) and trapezoidal (e, f) currents. In this case, the stator current effective values and the values of the

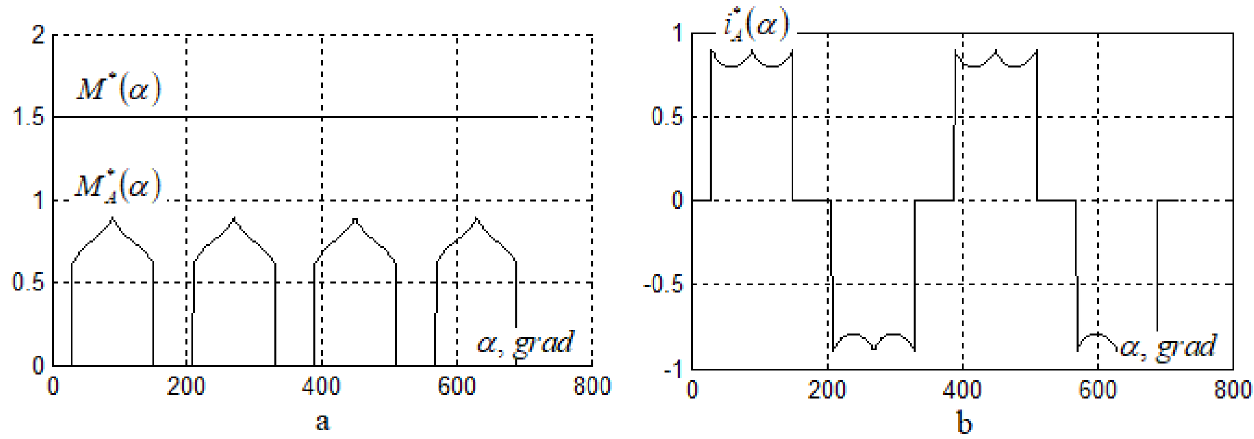

Fig. 10

torque ripple factor (8) for these three variants, respectively $I = 0{,}6395\ A$, $I = 0{,}671\ A$, $I = 0{,}6405\ A$ and $K_r = 1{,}326\%$, $K_r = 5{,}47\%$, $K_r = 6{,}02\%$.

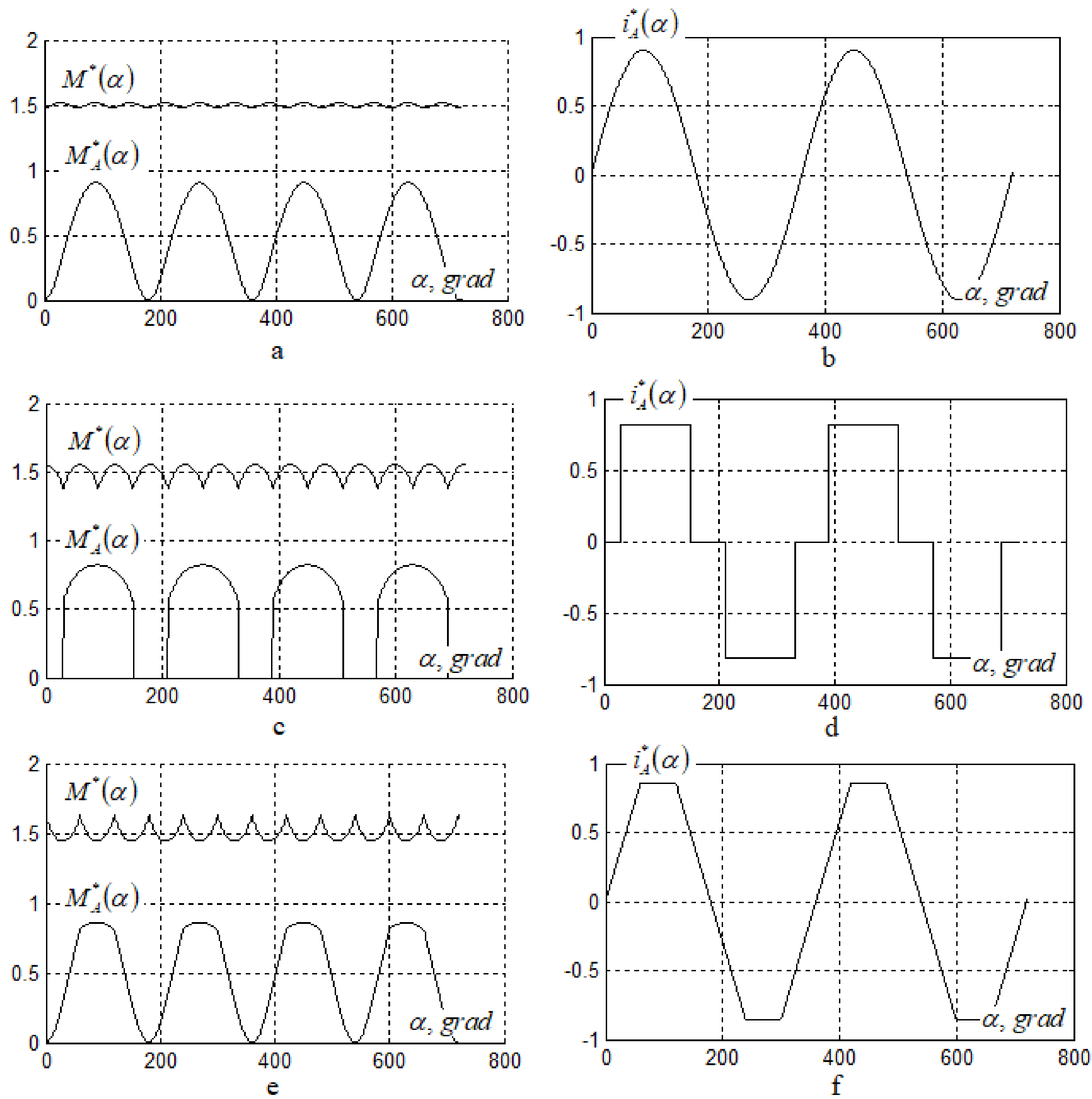

Fig. 11

Conclusions. As a result of modeling the brushless magnetoelectric TM with a slotless stator with a surface installation of permanent magnets on the rotor, it was found that for a given configuration of the magnetic system and the length of the magnet, the largest torque per unit of expended power is achieved with the number of pole pairs equal to 7. A further increase in the number of poles does not lead to an increase in the electromagnetic torque, however, in this case, there is a tendency to reduce its ripple, which in some cases can be a decisive factor in choosing an TM. The considered method of reducing the torque ripple by increasing the angular size of the pole made it possible to reduce the ripple factor by 1.5 times and at the same time increase the magnitude of the electromagnetic torque by 11 %, provided that the length of the magnet is constant along the magnetization axis and, respectively, by 1,4 times and by 3,1% subject to the constancy of the volume of the magnetic material. It is shown that a further reduction in the ripple factor can be most effectively implemented by generating such a form of currents in the motor phases, as a result of the interaction of which with the rotating magnetic field of the rotor, the torque characteristic of the motor with a minimum value of the ripple factor will be obtained.

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ОСОБЛИВОСТІ РОЗРОБКИ БЕЗПАЗОВИХ БЕЗКОНТАКТНИХ МАГНІТОЕЛЕКТРИЧНИХ МОМЕНТНИХ ДВИГУНІВ

В.Г. Кіреєв, канд. техн. наук, **К.П. Акинін,** докт. техн. наук
Інститут електродинаміки НАН України,
пр. Перемоги, 56, Київ, 03057, Україна
e-mail: kvg2016@ukr.net

Розглянуто структуру безконтактного магнітоелектричного моментного двигуна з безпазовим статором при поверхневій установці постійних магнітів на роторі. Розроблено модель двигуна для розрахунку його характеристик у середовищі програмного комплексу COMSOL Multiphysics 6.0. Проведено оптимізацію його структури, в результаті якої було визначено оптимальну кількість пар полюсів і таке співвідношення між розмірами елементів електромагнітного ядра двигуна, за якого досягається максимальний електромагнітний момент на одиницю споживаної потужності. Стаття торкається також проблеми досягнення мінімального значення коефіцієнта пульсацій моменту в двигунах подібної конструкції. Запропоновано шляхи її вирішення як завдяки конструктивним змінам магнітної системи, так і через синтез сигналів завдання для формування таких форм струмів у фазах двигуна, у результаті взаємодії яких з обертовим магнітним полем ротора формується моментна характеристика двигуна з мінімальним значенням коефіцієнта пульсацій. Бібл. 6, рис. 11.
Ключові слова: безконтактний магнітоелектричний моментний двигун, безпазовий статор, коефіцієнт моменту, коефіцієнт пульсацій.

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