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DECREASING TORQUE RIPPLE OF A SLOTLESS PERMANENT MAGNET TORQUE MOTOR USING A DOUBLE-LAYER WINDING

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The torque of a magnetoelectric torque motor with surface-mounted permanent magnets on the rotor was studied. The sinusoidal current supply mode is considered. The torque was calculated according to the static model of the magnetic field. It was determined that the sixth harmonic makes a significant contribution to the torque ripple. To reduce the sixth harmonic it is proposed to use a winding with a shortened pitch, for which it is necessary to make this winding in two layers. The optimal values of the number of pole pairs, the angular width of the magnets of the magnetic field excitation system, and the shortening of the winding pitch were determined. It was found that shortening of the winding pitch decreases the torque ripple by 2 ... 2.5 times. References 7, figures 6, tables 3.
Keywords: torque motor, permanent magnets, torque ripple, shortened pitch.

Introduction. Some applications need a specific rotational movement for executive tools. These movements are low rotation speed or rotation from time to time at an arbitrary angle and then fix this position, provided definite torque. The electric machines that are used to realize such a case of movement, in fact, angular position control, are called torque motors (TM) [1,2]. Thus, the main feature of a TM is angle position control. The area of TM's application spreads from submarines to space apparatus. Mainly, TM's are used in the control, observation, and tracking systems. In the areas under consideration, using permanent magnet (PM) motors has virtually no alternative due to their high specific performance.

In many cases, high positioning precision is demanded from TMs. This precision in a great part is defined by the constancy of motor torque characteristics. Therefore, the ripples of the torque in the process of controlling the rotational angle are very harmful. The torque ripple of a slotted electrical machine is due to the structure of the magnetic core. In slotless machines, this phenomenon is absent, but the problems of torque ripple from the nonuniform winding layer remain.

The methods of decreasing torque ripples include applying special winding [3,4] and a special configuration of a magnetic system [5] or/and a special waveform of power supply [2]. But in a problem to obtain the constant rotational torque versus the rotation angle, the motor itself remains a crucial component. The most simple type of winding is the full pitch type. However, it is well known that such a type of winding has quite a notable MMF spectrum, and the magnitude of the high harmonics is significant. It is quite natural, that the MMF spectrum mentioned above causes the torque ripple. To eliminate this deficiency a short-pitched winding, which has a more suitable spectrum, may be proposed. Using short-pitched winding reduces the amplitude of an MMF wave, resulting in lower maximum torque.

Thus, **the paper's purpose is to study the influence of a two-layer short-pitch span winding structure on the torque ripple and the torque amplitude of the slotless PM motor**.

Structure of the machine's active volume. Due to the low rotation speed, it is reasonable to use the surface-mounted PM structure of the machine rotor. Fig. 1 shows the cross-section of the machine normal to the rotation axis (*1* is the stator yoke, *2* is the rotor yoke, *3* is the winding layer, *4* is the magnet).

The magnets have an angular size (width) of α_m and neighboring magnets are magnetized radially in opposite directions. The main dimensions of the machine are shown in Table. 1. The value of the angular width

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of magnets α_m (see Fig. 1) is the subject of optimization and below will be expressed in electrical degrees because their geometrical dimension depends on the number of pole pairs p.

Table 1

Parameter	Variable	Value (mm)
Outer stator diameter	D_a	88
The axial length of the motor	L_a	45
Height of stator yoke	h_{ys}	2,5
Height of winding layer	h_w	2,5
Technological air gap	δ	0,5
Height of magnet	h_{mag}	5,0
Height of rotor yoke	h_{yr}	6,0

The yoke of the stator is assumed laminated or made from a non-conducting ferromagnetic structure, for example, a powder material. In addition, the rotation frequency is low (up to 10 … 20 rpm), and therefore the frequency of the magnetic field is low. Thus, the influence of eddy currents and losses caused by them in rotor yoke and permanent magnets can be neglected. All mentioned above permit one to consider the magnetic field to be stationary.

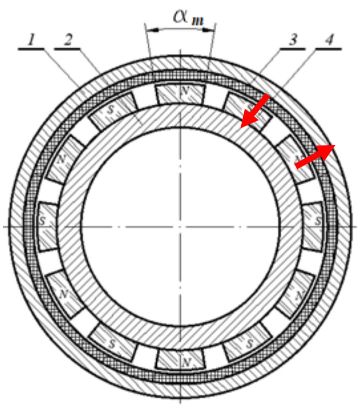

Fig. 1

The simple lap winding was considered. The TM manufactured with 3-phase full-pitch winding was studied in [2]. To make a short-pitched winding and save a filled winding space of height h_w (see Table 1) two layers are required to accommodate the winding coils. The schema of the cross-section of two pole pitches of the ten-pole machine is shown in Fig. 2. Bar shape magnets were used. The overhang part and active parts lying in different layers of one of two short-pitched coils of phase A are shown schematically. The coils sections are colored with correspondent colors: phase A – green, dark green; phase B – yellow, dark yellow; phase C – red, dark red. The angular width of coil α_{coil} is 60 electrical degrees. One should know, that here and below only electrical degrees will be used. It is worth noting that the total air gap through which the main magnetic flux passes is the sum of the technological gap δ and the layer of winding h_w (see Table 1). When modeling, the current density in the conductors was assumed to be 5 A/mm^2 with a fill factor of 0,6; the laminated stator yoke was assumed to be made of NOG 2211 steel; the rotor yoke was made of structural steel 20; the permanent magnet neodymium-ferrum-boron BMN-42EN with the remanent magnetic flux density of 1,33 T.

The pitch factor is not a suitable variable for the visual presentation of coil shortening (but it is an important variable to determine machine parameters). We will specify the coil shortening as the ratio of its angular dimension c to the angle dimension of a coil side α_{coil} (see Fig. 2), namely

$$\Delta\alpha_{coil} = \Delta\alpha / \alpha_{coil}. \quad (1)$$

Let us in the further presentation call this relative shortening $\Delta\alpha_{coil}$ simply by the term "shortening" (see Fig. 2). Then the expression for the pitch factor will be [1]

$$k_p = \cos\left(\Delta\alpha_{coil} \cdot 60^\circ / 2\right). \quad (2)$$

Consequently, when the coil side shifted by half the section width, a pitch factor of 0,87 is obtained. To make a two-layer winding, one layer corresponding to the machine's dimensions (see Table 1) should have a thickness of about 1,25 mm. One should note, that such thin coils

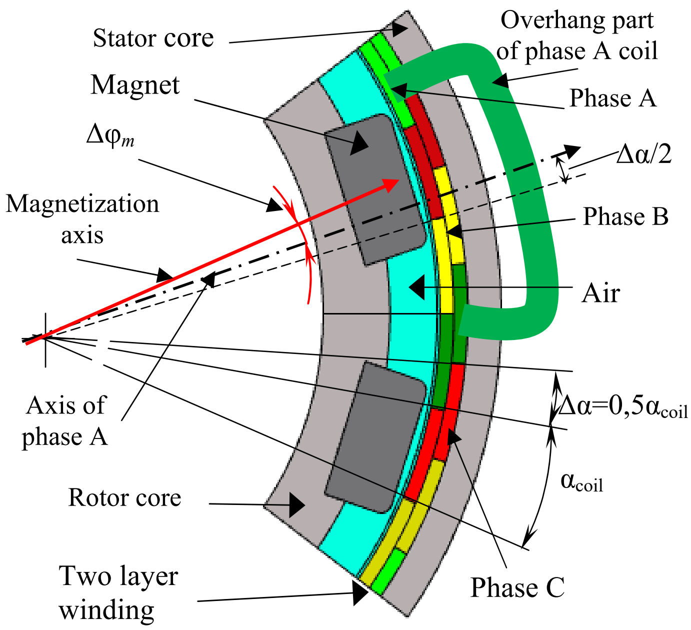

Fig. 2. Two pole pitch of TM (p = 5)

may be manufactured only in a soft version.

To achieve the maximum torque, the MMF vector of the stator winding must lead to the rotor field vector by 90 degrees, provided by a control system. As the coil parts are shortened by Δα, the angular shift of the phase A axis will be Δα/2 (as is shown in Fig. 2). Thus, the system of stator current is to have a phase

$$\psi_{A0} = \Delta\alpha / 2 + \Delta\varphi_m + 90^\circ . \quad (3)$$

The rotor angle position (direction of the magnetization axis, see Fig. 2) is defined by the Hall-sensor system.

Mathematical model and software. First of all, there is an important limitation to mention. This study considers the power supply by a sinusoidal current.

The 2-D modeling of the static magnetic field was done by using **"**COMSOL Multiphysics**"** software. The influence of the machine end parts effect can be taken into account by empirical expression, obtained in [2] after comparative three- and two-dimensional solutions. The fulfilled study took into account the nonlinearity of the magnetization characteristics of the magnetic cores. The magnetic characteristic of the permanent magnet was assumed to be linear with the remanent magnetic flux density and magnetic permeability specified.

As stated above, a static magnetic field model can be used. In two-dimensional formulation, the magnetic field problem is governed by equations in terms of magnetic vector potential **A**, which plays the role of the dependent variable [6]. The expression for the magnetic flux density vector **B** derived from magnetic vector potential is

$$\mathbf{B} = \nabla \times \mathbf{A} \, . \quad (4)$$

For torque calculation, the Arkkio method was used which is implemented in the interface "Rotating Machinery" of "COMSOL Multiphysics" software [6]. One can note, that in slotless machines one can calculate electromagnetic torque by integration of the expression for Lorentz force vector $\mathbf{F}_{Ltz}$ over the cross-section of winding [6]

$$\mathbf{F}_{Ltz} = \mathbf{J} \times \mathbf{B} \, , \quad (5)$$

where the $\mathbf{J} = (0, 0, J_{z,ex})$ is the current density vector having the only z-component. Both methods were tested and they gave identical results. The external current density is the homogenized variable in the cross-section of the winding layers. The determination of it is described in [7].

Results and discussion. The geometric parameters, excluding those pointed out in Table 1, which influence torque magnitude are the number of poles, the angular width of the magnet α_m, and the parameter Δα which determines the coil span factor. The influence of the two first parameters on the average magnitude of torque was studied for full-pitch winding. The corresponding dependencies are shown in Fig. 3, where angular width is expressed in electrical degrees. The presented data show that there is a maximum of torque magnitude. The maximum corresponds to six pole pairs under the condition of a magnet angular width of about 120 electrical degrees and more. On the contrary, smaller width values shift the maximum to the region of five pole pairs. The value of torque maximum monotonously increases with the increase of the magnet width α_m. The value of α_m about 140 electrical degrees can not be exceeded technologically due to the chosen magnet shape. Also, the cases of two and three number of pole pairs have no significant value as they can't be optimally constructed without geometry modification of the magnet shape.

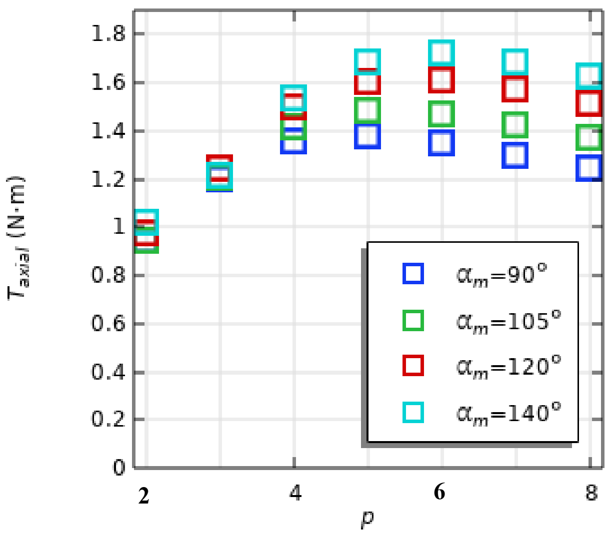

Fig. 3. Torque versus the number of pole

In slotless electrical machines, the torque ripples can only be caused by the high harmonics of the winding's MMF. An application in such a machine's single-layer full-pitch windings is justified by their simplicity and technological accessibility [2]. However, full-pitch coils have a significant contribution of higher harmonics to the MMF. To eliminate it, higher harmonic coils are manufactured with a reduced pitch. But this leads to a decrease in the fundamental harmonic of the MMF, magnetic induction, and, finally, the torque. Since a significant loss of productivity is undesirable, it is necessary to try not to allow a significant shortening of the winding.

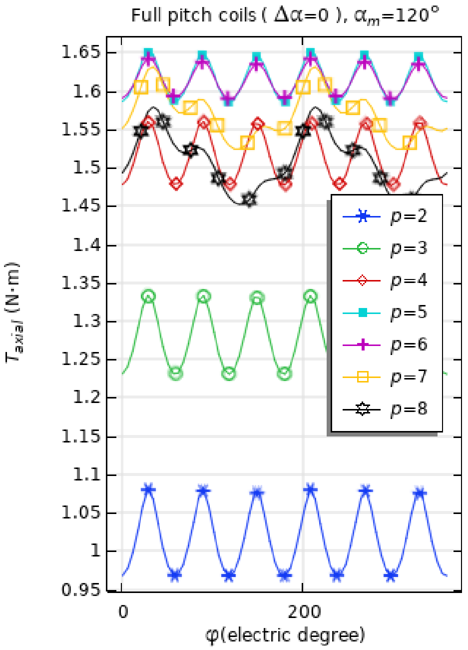

Fig. 4. Torque for different numbers of pole pairs

The second parameter to be optimized is the angular width of the magnet α_m. The angular width of the magnet leads to the fact that the magnetic flux is greater, the greater this width. In this case, it is also necessary to obtain a minimum of higher harmonics in the spectrum of the radial component of the magnetic induction in the air gap. A magnet with an angular width of 120 degrees creates a "pulse" of coercive force that does not contain the third harmonic. Due to the leakage of the flux, the magnetic induction wave is not a rectangular pulse. However, it can be assumed that such a "pulse" of coercive force creates an acceptable spectrum of magnetic induction in the air gap. Therefore, this pulse width was taken as the starting point in the study. Thus, the problem is to reduce torque ripples by optimizing the winding pitch, and magnet width.

Fig. 4 shows the angle dependence of the torque for a machine with full-pitch windings, with different pole numbers, under the condition of magnet width α_m=120°. In all curves, the sixth harmonic is presented. The maximum of the average torque corresponds to the minimum ripple and this feature is detected at five and six pole pairs. Consequently, the choice of such a quantity of poles is no alternative.

The influence of short-pitched winding under conditions of pole pairs of six and angular magnet width of 120 electrical degrees is illustrated in Fig. 5, where the value of the span factor k_p (see (2)) is also indicated. The sixth harmonic is still presented in all curves but at some values of the "shortening" $\Delta\alpha_{coil}$ in the range of 0,5 … 0,7 the torque ripples are decreased. And this decline is about 3 times. When the span factor value reaches 0,6 and more, the amplitude of the ripples increases again.

The numerical summary of torque ripple parameters (the mid value of torque and ripple swing ΔT) corresponding to Fig. 5 (p = 6, α_m = 90°, 120°) is presented in Table 2. From this table, it can be seen that the ripple with a magnet width of 90 degrees is less than that with a width of 120 degrees. However, the average amplitude of the torque in the first case is less.

The last column of Table 2 shows the relative ripple values ΔT normalized to the average torque of value. For example, in the first line, the relative decrease in ripple is

$$\Delta T(T_{avg\,90}/T_{avg\,120}) = 3,03\cdot 1,40/1,62 = 2,62 \qquad (6)$$

The expression (6) means that even if one reduces the average torque in the case of a magnet width α_m of 120°, the ripples will still be greater than with a magnet width of 90 degrees.

In general, one can say that a short-pitched winding makes it possible to reduce ripples by 2 ... 3 times. The table also shows that the relative values of the average torque T_{av90} and T_{av120} correspond to the value of the coil span factor k_p, which agrees with the theory of electric machines.

The presented results also indicate that the torque ripple for two angular sizes of magnets varies within the

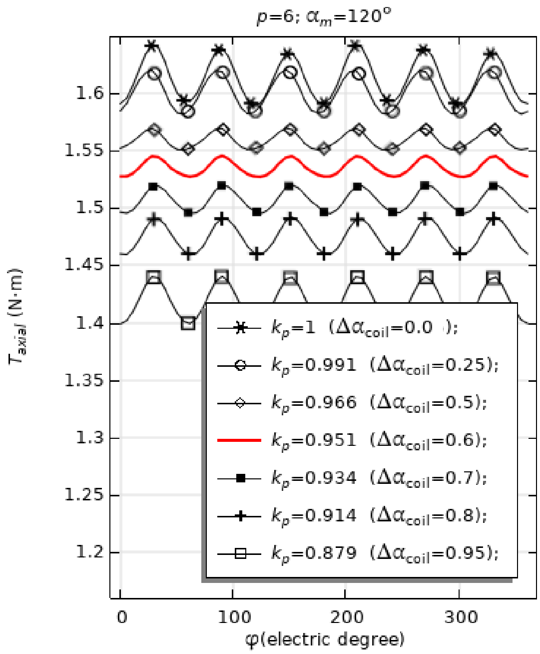

Fig. 5. Torque for different values of pitch factor

Table 2

Δα	k_p	$\alpha_m = 90°$, ($p = 6$)			$\alpha_m = 120°$, ($p = 6$)			
		T_{avg90} (N·m)	T_{avg} (ratio)	ΔT (%)	T_{avg120} (N·m)	T_{avg} (ratio)	ΔT (%)	$\Delta T \frac{T_{avg90}}{T_{avg120}}$
0.0	1.00	1.40	1.000	2.37	1.62	1.000	3.03	2.62
0.25	0.991	1.39	0.992	1.97	1.60	0.989	2.50	2.17
0.50	0.966	1.35	0.967	1.23	1.56	0.964	1.28	1.11
0.60	0.951	1.33	0.952	0.86	1.54	0.950	1.17	1.02
0.70	0.934	1.31	0.934	0.62	1.51	0.932	1.66	1.44
0.80	0.914	1.28	0.914	0.97	1.48	0.912	2.03	1.76
0.95	0.879	1.23	0.879	2.01	1.42	0.875	3.53	3.07

possible limits of winding span shortening by more than three times. In addition, as mentioned earlier, in such small machines (see Table 1), the winding is made of soft coils, making it difficult to accurately ensure a coil span value. Hence, we need to evaluate the effects of the magnet's width and the coil's shortening over a wide range. In studying the influence of these parameters, one can limit to a design with six pairs of poles, since even in the case of the angular width of the magnet 90...105 degrees, the value of the average torque is close to its maximum and the torque ripple in both case are equal (see Fig. 2).

The deviation of torque values over period 2π for magnet angular widths of 80, 90, 105, 120, and 140 electrical degrees are shown in Fig. 6. Their common feature is the presence of a clearly defined sixth harmonic in the torque curve. Based on the data in the graphs, it is evident that a magnet width of 120 degrees is far from the best option. Additionally, this particular one results in the highest torque ripple among all the calculated parameter combinations. The only positive property of this variant is the high torque value.

However, with a magnet angular width of 140 electrical degrees, the ripple is less and the average torque is greater. Thus, it should be noted that cases with an angular width of the magnet of less than 120 degrees are considered here only for completeness. Such options can be of practical importance only when, for technological or other reasons, the width of the magnet cannot be made larger. It also follows from the graphs that in the studied range of winding pitch span, the increase in ripple differs slightly from its minimum value. As mentioned, this is a favorable circumstance when manufacturing winding from soft coils.

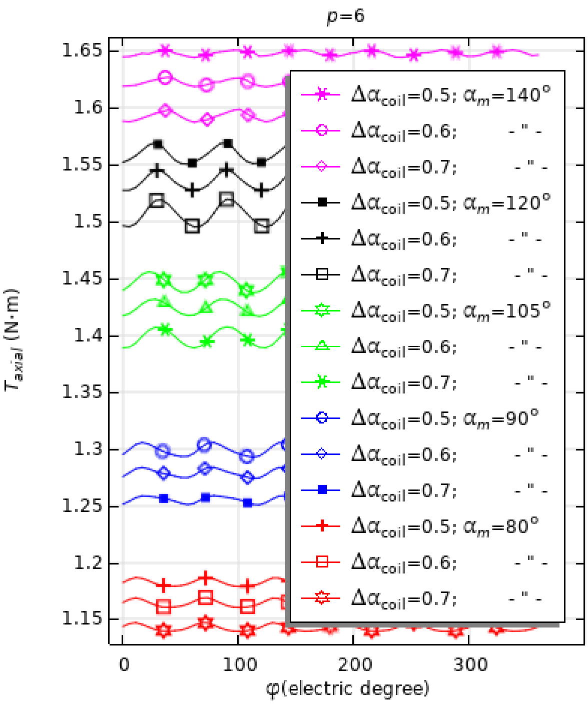

Fig. 6. Torque for different values of pitch factor and angular magnet width

Table 3.

	$\Delta\alpha_{coil}$ = 0.5 … 0.7 (two-layer winding)		$\Delta\alpha_{coil} = 0$ (k_p=1)	
α_m	T_{avg}(N·m)	ΔT %	T_{avg}(N·m)	ΔT %
140°	1.62	0.62	1.71	1.17
120°	1.53	1.22	1.62	3.60
105°	1.42	1.23	1.5	3.34
90°	1.27	0.98	1.34	1.49
80°	1.16	0.86	1.23	0.82

The generalized results of modeling the instantaneous torque for the numbers of pole pairs 5, 6, including those shown in Fig. 6, summarized in Table 3, where the average values of the ripple swing for short-pitched windings and full-pitch one are given for structures with six pole pairs. It follows from the table that shortening the winding pitch makes it possible to reduce the amplitude of the torque ripple by about 2,5 … 3,5 times.

Subject to the optimal pole pair number, angular magnet width ranging between 80 ... 120 electrical degrees, full-pitch winding, and a sinusoidal supply current, the range of torque ripple is 1.2 ... 3.6%. The maximum torque ripple occurs when the magnet width is between 110 and 120 electrical degrees. Both when the magnet width increases above 120 degrees and when it decreases below 110 degrees, the relative amplitude of the ripple decreases. Moreover, when this width increases above 120 degrees, the amplitude of the ripple decreases abruptly.

As a result, about the effect of pitch shortening, one can say that using a short pitch for values with magnet angular widths of 90, 120, and 140 electrical degrees reduces torque ripple by an average of 2.5, 3, and 2 times respectively. It should be taken into account too that reducing the magnet width by 10 degrees decreases average torque by 3 ... 5%.

Conclusions. In slotless magnetoelectric TMs, torque ripple can be reduced by manufacturing the short-pitch winding. The result of this reduction is influenced by two main geometric factors, namely the angular width of the magnet and the shortened coil pitch.

Provided that the number of pole pairs is optimal according to the criterion of the maximum torque, which can be 5 or 6 depending on the angular width of the magnets in the range of 80 ... 140 electrical degrees, the full pitch of the winding and the sinusoidal power supply current, the range of torque ripples is 1 ... 3 .6%.

When using a two-layer three-phase short-pitch winding, it is possible to reduce torque ripples by 2,5 … 3 times. For larger magnets angular widths (120...140 electrical degrees), the optimal value of the pitch shortening is from 0.5 to 0.6 of the phase zone, while for smaller magnet angular widths, it is from 0,6 to 0.7 of the phase zone. When the pole pitch of the winding is reduced, the decrease of the average TM torque exactly corresponds to the value of the coil span factor.

The smallest relative amplitude of torque ripples is 0,6% and it is observed in the design with an angular width of the magnet of about 140 electrical degrees with optimal coil shortening.

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ЗНИЖЕННЯ ПУЛЬСАЦІЙ ОБЕРТОВОГО МОМЕНТУ БЕЗПАЗОВОГО МОМЕНТНОГО ДВИГУНА З ПОСТІЙНИМИ МАГНІТАМИ ШЛЯХОМ ВИКОРИСТАННЯ ДВОШАРОВОЇ ОБМОТКИ

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Досліджено обертальний момент магнітоелектричного моментнолго двигуна з постійними магнітами, розташованими на поверхні ротора. Розглянуто режим живлення синусоїдальним струмом. Обертальний момент обчислювався за статичною моделлю магнітного поля. Визначено, що в пульсаціях значний внесок робить шоста гармоніка. Для зниження шостої гармоніки запропоновано застосувати обмотку зі скороченим шагом, для чого необхідно виконати цю обмотку двошаровою. Обчислено оптимальні значення кількості пар полюсів, кутової ширини магнітів системи збудження магнітного поля, та скорочення кроку обмотки. Винайдено, що скорочення кроку обмотки дає можливість знизити пульсацію обертального моменту у 2 ... 2.5 рази. Бібл. 7, рис. 6., табл. 3.

Ключові слова: моментний двигун, постійні магніти, пульсації обертального моменту, скорочений крок.

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