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PERMANENT-MAGNET BRUSHLESS DC ELECTROMOTOR WITH TOOTH COILS AND SELF-BRAKING

ABSTRACT *The electric drives with synchronous gearmotors are obtained generally in actuating constant velocity devices in electroenergetics, heat-power engineering, pipeline transportation today. But they have not only well-known advantages but also essential disadvantages.*

The permanent magnet brushless DC motor with weakening from rotor permanent magnets and staror tooth coils may be an alternative to this fixed electromotor.

The made optimization of cross geometry of PM brushlesh DC motor is based on the field mathematical model with Nd-Fe-B plastomagnets and six stator teeth. The rating value of moment is 1 Nm, of rotor speed is 750 rpm.

It was calculated the width of interpole nonmagnetic arcs which provides the desired value of cogging torque after the stator coils are currentless.

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It was appreciated the effect of the width of tangent-magneted interpole arcs to the maximum peaks of the cogging torque and the full load torque.

It was analysed the possibility to produce the rotor version of magnet ring without m-metal core.

Keywords: *permanent magnet (PM) brushless DC motors, influence of slotting, computing torque, cogging torque*

1. INTRODUCTION

At present in the actuating constant velocity devices it is prevailed the machines with synchronous gearmotors (GM) that they are obtained in electroenergetics, heat-power engineering, pipeline transfer. They have many well-known advantages as the simplicity of construction, the processibility, the reliability, the high specific torque at low speed of rotation under circumstances of AC line supply [1].

At the same time the synchronous gearmotors do not comply with up-to-date requirements of energy-saving through their sequent limitations as the lack or the complication of speed regulation, the low overload capacity, the possibility of self-moving at the supply absence, the high rotor inertness torque, the low starting torque-to-nominal torque ratio, the low radiant quantities such as the low coefficients of efficiency and ratings.

The possible alternative to synchronous velocity unregulable gearmotor is the following noncontact electomotors as the PM brushless DC electromotor with weakening from rotor permanent magnets, the asynchronous motor with frequency control, the gated inductor motor.

The most preferred alternative is the PM brushless DC electromotor with weakening from high-energy permanent magnets because it is exceeded in ratings and geometry of other electomotors [2].

The general advantages of PM brushless DC electromotors are the high overload capacity, the high starting torque-to-nominal torque ratio from 5 and higher (it is limited by peak currents of power transistor), the self-braking torque at currentless state that can reach from 25 to 30 percents of rated value and makes impossible of the self-moving, the low inertness torque and the fast response, the best ratings and geometry.

The basic lack of PM brushless DC electromotors with high-energy permanent magnets is the high price and laboriousness. But the price of these motors can be reduced appreciably by the simplification of the construction and a liitle deterioration of geometry. In this case the price become comparable to the price of induction motor.

The most acceptable consturuction for this type of GM is the construction with six stator tooth coils. It has the following advantages:

- demountable construction of coils allows to make and isolate exterior to stator iron;
- the high value of stator slot opening allows to get the sufficiently great value of cogging torque of self-braking; this is a clamping torque of rotor stop;
- the number of rotor poles with permanent magnets is chosen from 2 to 8 excepting 6 for stator with six teeth.

We chose the following Nd-Fe-B plastomagnets [3]. These are the quick hardened composite magnets that are fastened with polymers. Their flux density is B_r = 0,55 T, the coercive force along magnetized-axis is H_{cM} = 750 kA/m, the coercive force along flux-axis H_{cB} = 400 kA/m, the estimated cost is 40$/kg. These plastomagnets look as the toroidal rings with outer diameter of 40, 50 and 60 mm, with thickness of 4 and 5 mm, with length of 24 and 32 mm. We made a breadboard design of three-phase GM of rating moment M_L = 1 N·m, rotor speeds are 750 rpm and 1500 rpm. The model is the four-pole GM with rotor diameter D_r = 50 mm, with magnet height of 5mm, with rotor length (active length) of 48 mm, with number of turns in every coil of 232, with phase current of 1.0 A.

The cross geometry of this GM is shown in the Fig. 1.

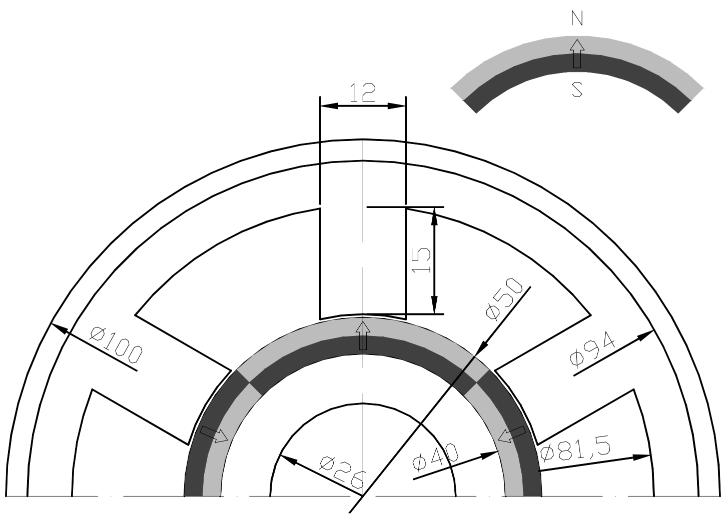


Fig. 1. The cross geometry of GM with D_r = 50 mm, the number of magnet poles 4

In compliance with conformal mapping union method [4] the active cross geometry was fragmented to elementary regions (ER) for the calculation of magnetic field and operating characteristics of this GM (see Fig. 2). The general number of ER is 119. The 74 of ER are in the stator, the 35 are in the rotor, the 4 are in the air gap.

The dimension of vector-matrix equation

$$\mathbf{A} \cdot \mathbf{u} = \mathbf{F} \quad (1)$$

is 1708. This equation defines the vector of scalar magnetic potentials $\mathbf{u}$ (SMP).

The output result of equation (1) is the vector of SMP for observed points in the bondaries of ER. After that it is calculated the vectors of magnetic strength and flux density in these points. From calculated magnetic field it is possible to calculate the internal torque and the EMF of stator coils.

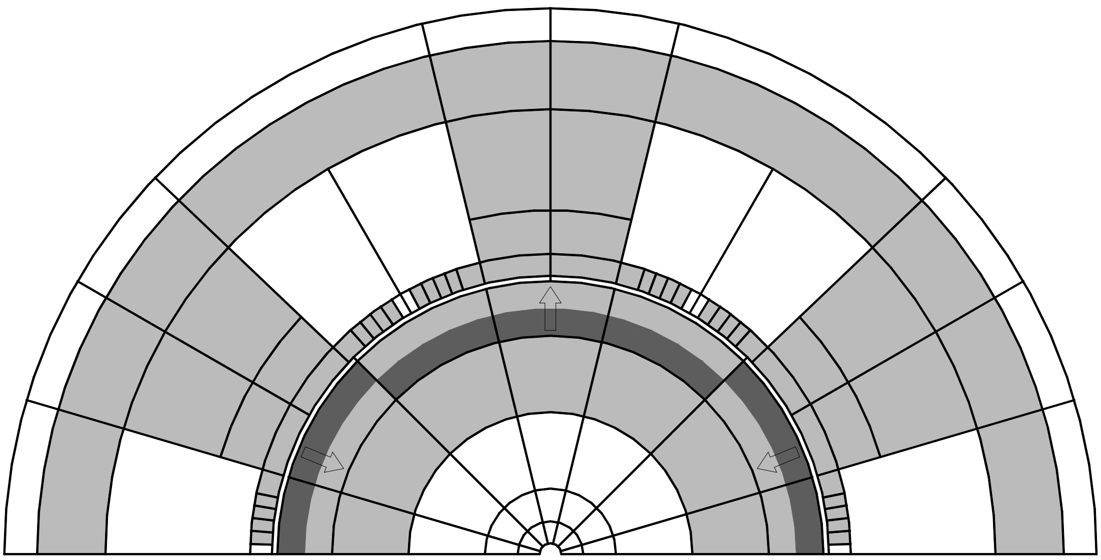


Fig. 2. The fragmentation of calculated area of GM to ER

In compliance with tension theory [5] the internal torque can be calculated in the following equation

$$M = \frac{\pi}{2} \frac{l_\delta D_r^2}{N} \sum_{j=1}^{N} B_{nj} \, H_{\tau j} \quad (2)$$

where

N – the number of observed points in the air gap arc that borders on rotor (or stator);

B_{nj}, $H_{\tau j}$ – correspondingly the normal components of flux density vector and magnetic strength vector in observed points;

D_r – the rotor outer diameter.

The curve of cogging torque of currentless GM is calculated from equation (2) and shown in the Fig. 3.a). This curve shows very high peak value of cogging torque that is very near to rating torque.

2. THE NUMERICAL ANALYSIS OF RELATIONSHIP BETWEEN THE LENGTH OF «SHOES» AND THE INTRENAL TORQUE OF GM

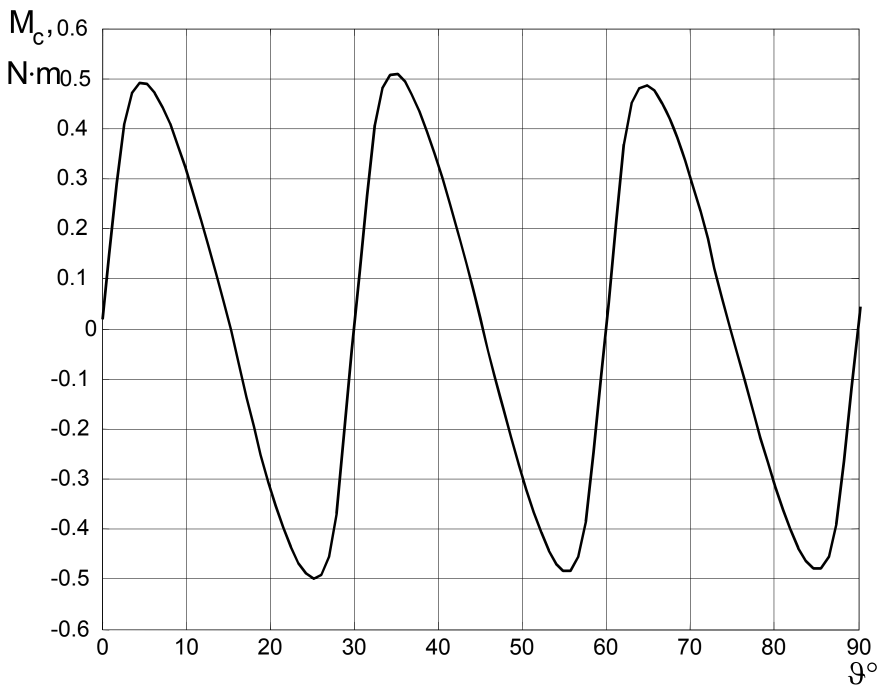
The one of the simpliest ways to reduce the cogging torque is to reduce the slot opening of stator using to make the stator slot with «shoes» (Fig. 2).

It was found at the length of 4 mm (the height of shoes is 2 mm) that the peak value of cogging torque is M_C = 0.26 N·m. This value complies with required value from 25 to 30 percents of full load torque M_L. But this length of shoes makes the stator slots nearly semi-closed and brings to loss the essential advantage of form-wound coils.

From the estimated calculation the ampere turns of phase winding of 232·1.0 = 232 A provide the desired value of full load torque of GM (1 N·m).

In the figure 5 it is shown the curves of EMF of stator phases with shoes of 4 mm under no-load conditions. The shapes of EMF shows the presence of essential triplen harmonics.

a)



b)

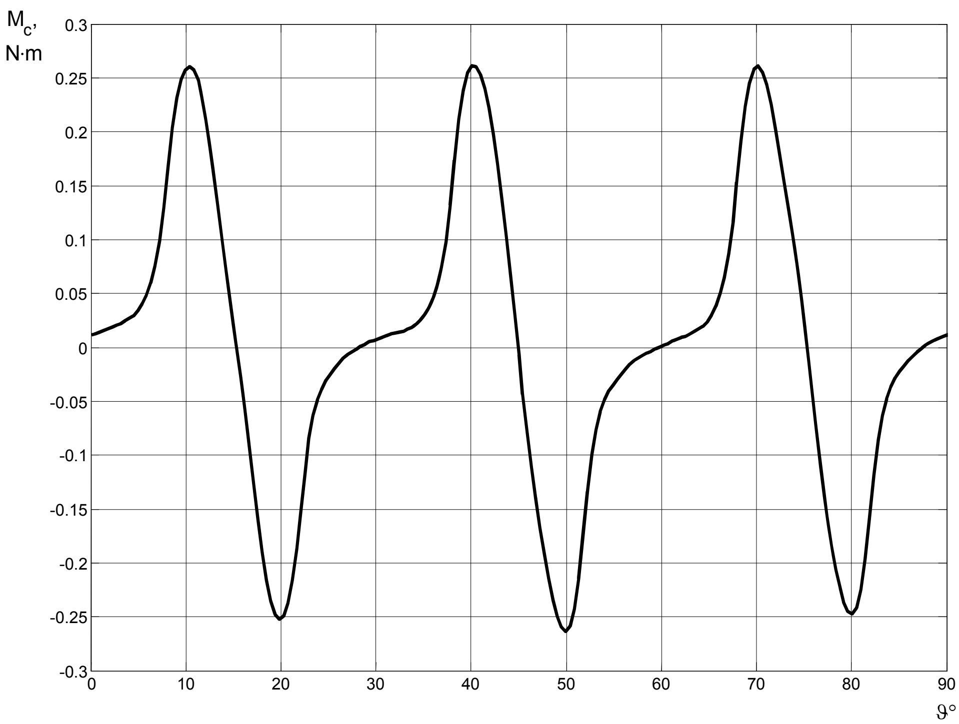


Fig. 3. The curves of cogging torque at the shoes length of:
a) 0 mm (w/o shoes), b) 4 mm

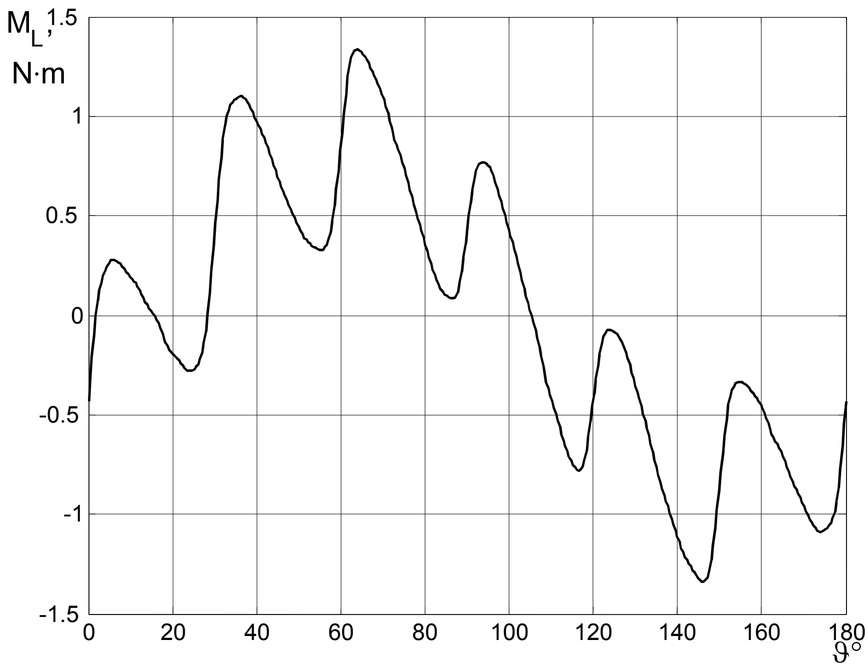


Fig. 4. The curve of full load torque of GM at rated current of 1.0 A in two stator phases

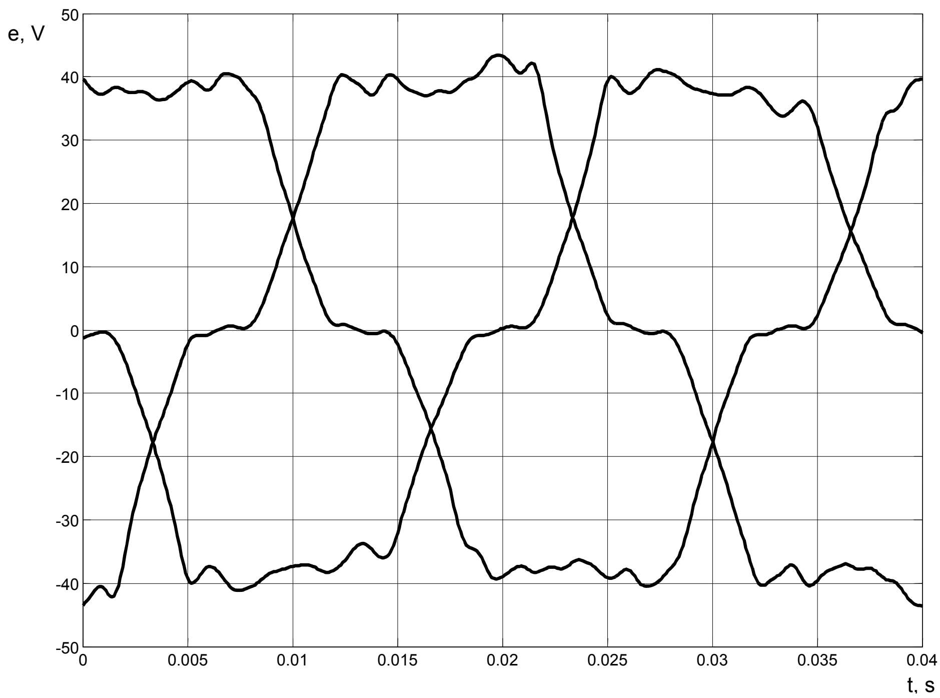


Fig. 5. The curves of EMF of stator phases under no-load conditions

3. THE NUMERICAL ANALYSIS OF RELATIONSHIP BETWEEN THE INTRENAL TORQUE OF GM AND THE WIDTH OF MAGNET POLE ARC

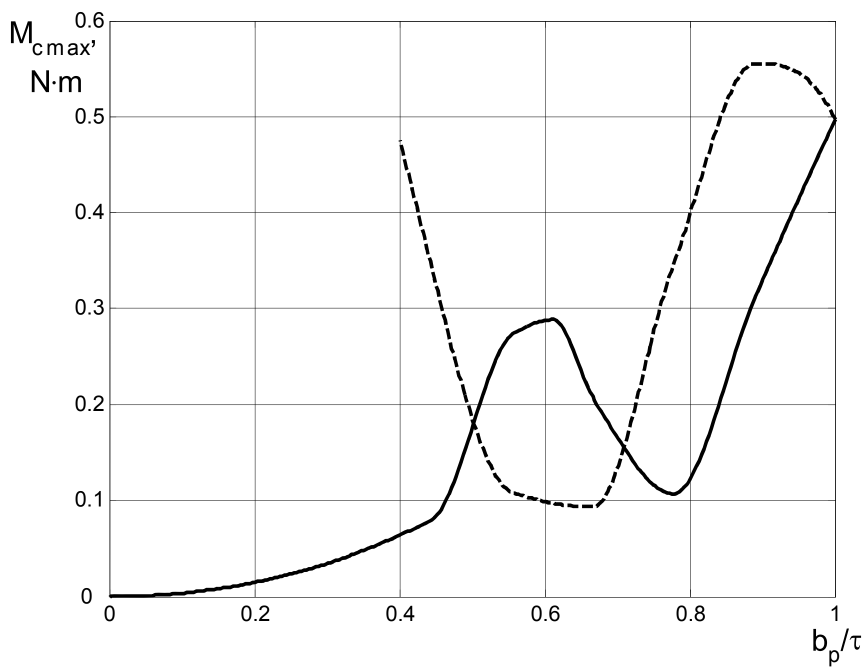
In this chapter it is shown the ability to necessary operating characteristics of GM without shoes with variation of magnet pole arc.

The calculated relationship between the peak value of cogging torque and the magnet pole arc is shown in the Fig. 6a). The necessary cogging torque of 0.25 N·m is at three values of relative width of magnet pole arc $\frac{b_p}{\tau}$ of 0.55, 0.64 and 0.85. The cogging torque is higher of 0.25 N·m than it's neccesary at the values $\frac{b_p}{\tau}$ being in intervals [0.55...0.64] or [0.85...1.00]. In the Fig. 6b) it is shown the full load torque of GM at rated current of 1.0A in two stator phases. The desired value of full load torque of 1 N·m are at the value $\frac{b_p}{\tau} \geq 0.82$.

The curves of the normal component of flux density in the rotor aig gap arc are shown in the Fig. 7 when the direct magnet pole axis is congruent to the middle of stator tooth.

In the all four figures the average value of flux density in air gap in the limits of one magnet pole arc is 0.3 T, the average value of flux density opposite the stator tooth is 0.5 T. The demagnetization from stator reaction is low from 6 to 7 percents.

a)



b)

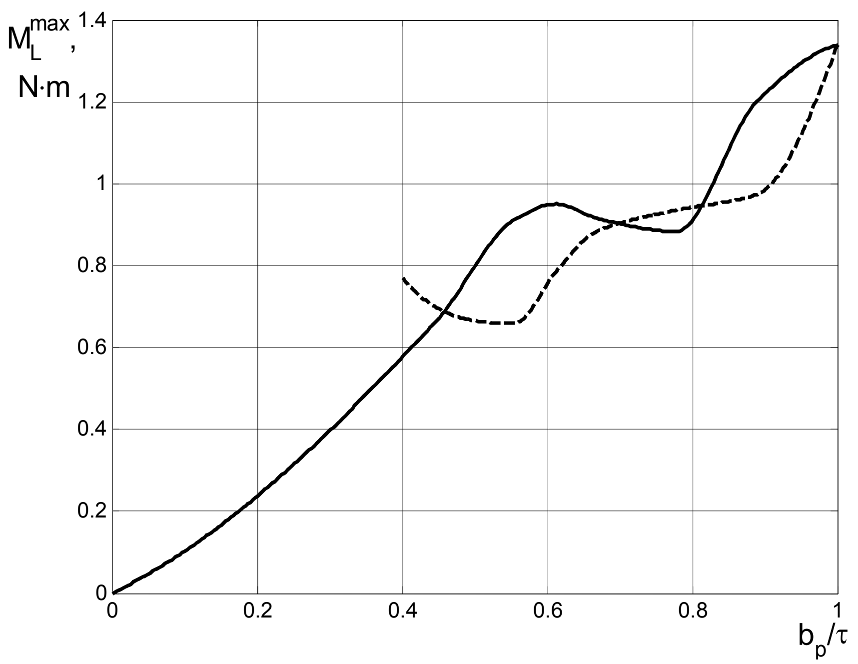
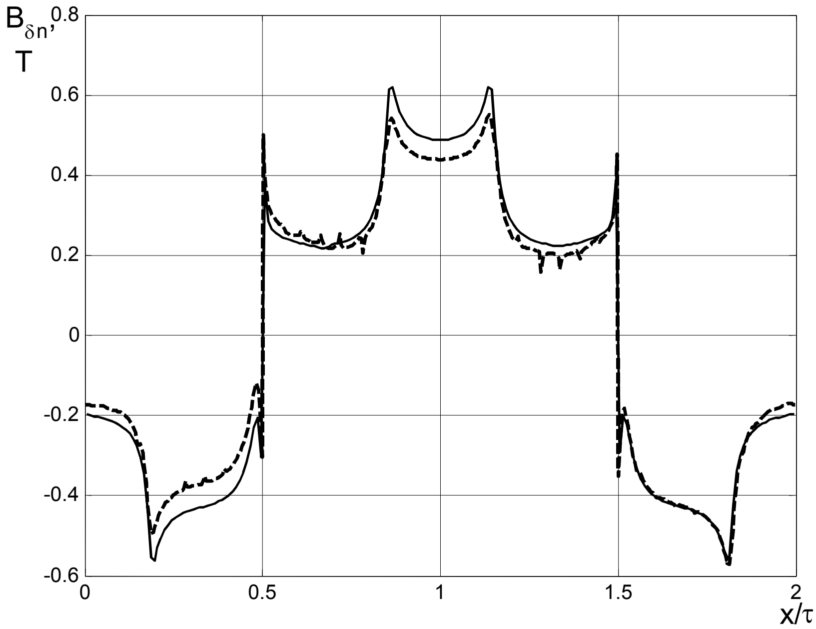
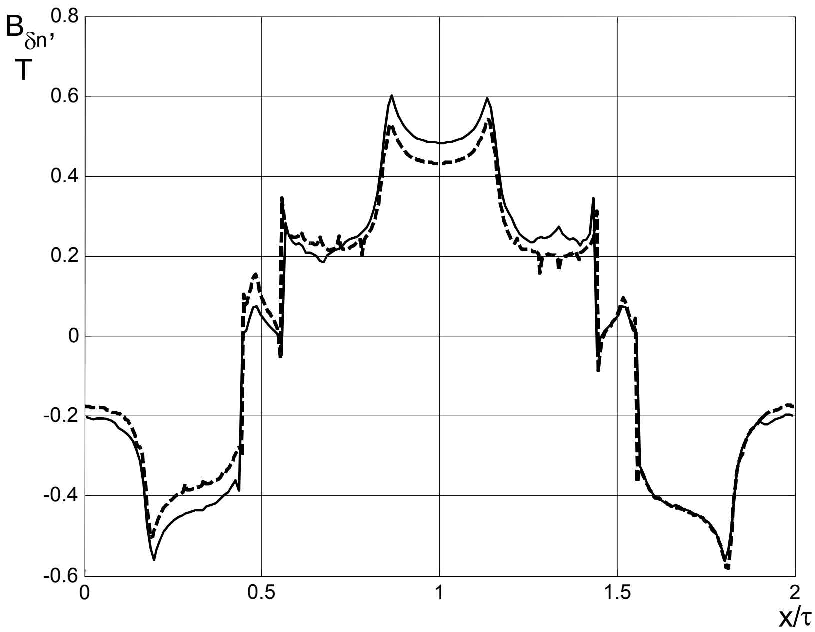


Fig. 6. The relationship beetween the internal torque of GM and the relative width of magnet pole arc: a) the cogging torque; b) the full load torque at $I_A = -I_B = 1.0\grave{A}$. The block block curve means the absence of tangent-magneted interpole arc, the broken curve means the presence of tangent-magneted interpole arc.

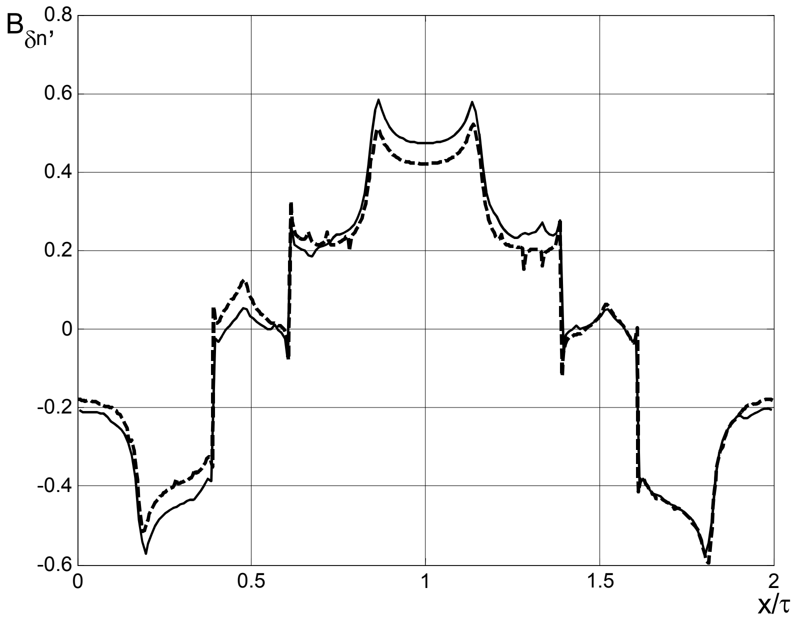
a)


$B_{\delta n}$, T
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
0.5
1
1.5
2
x/τ

b)


$B_{\delta n}$, T
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
0.5
1
1.5
2
x/τ

c)



d)

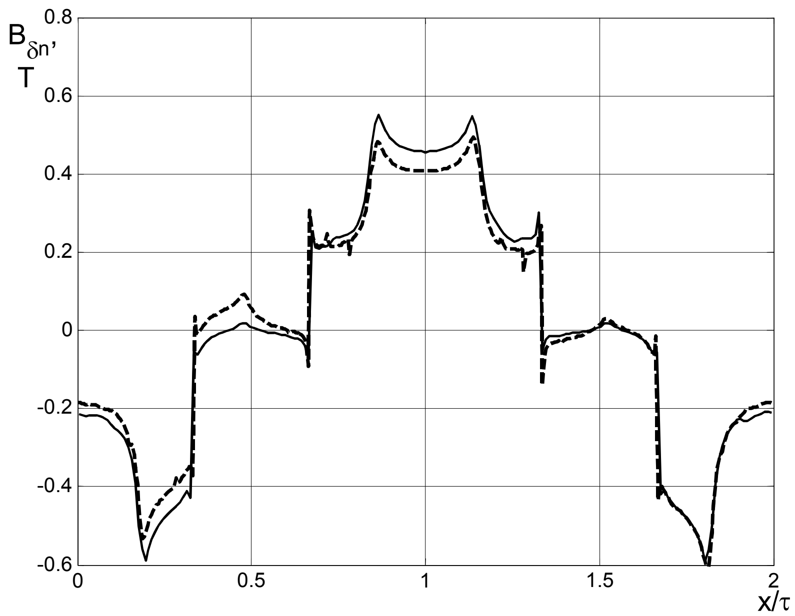


Fig. 7. The normal component of flux density in the rotor aig gap arc when the direct magnet pole axis is congruent to the middle of stator tooth. It is shown for relative width of magnet pole arc $\frac{b_p}{\tau}$ of a) 1.0; b) 0.887; c) 0.778; d) 0.667. ——— no-load operation; ----- $I_A = -I_B = 1.0\,\text{A}$**.**

4. THE RELATIONSHIP BETWEEN THE TANGENT-MAGNETED INTERPOLE ARC OF ROTOR AND THE INTERNAL TORQUE OF GM

The application of the tangent-magneted interpole arcs allows to increase the internal torque up to 10-15 % [6-8].

We suppose that the tangent direction of interpole arcs is congruent to the best magnetizing axis *α* for permanent magnets.

In the Fig. 6 from the numerical computation it is shown the curves of peak values of internal torque depend upon the width of the tangent-magneted interpole arc (see the broken curves).

The tangent-magneted interpole arcs increase the internal torque if the the relative width of radial magnet pole arc is between 0.7-1.0 for cogging torque and 0.7-0.8 for full load torque.

5. THE EFFECT OF THE TANGENT-MAGNETED INTERPOLE ARCS WITHOUT M-METAL ROTOR

In this case the rotor of GM is made from anisotropic hardmagnetic material (AHM) in ring shape without m-metal magnetic core (MMC) [9-11].

The authors [11] of this rotor construction name it ROMA (rotor is optimized, mosaic, assembly). From their information ROMA has the better characteristics by 15-50 % than the best analogs in Russia and abroad.

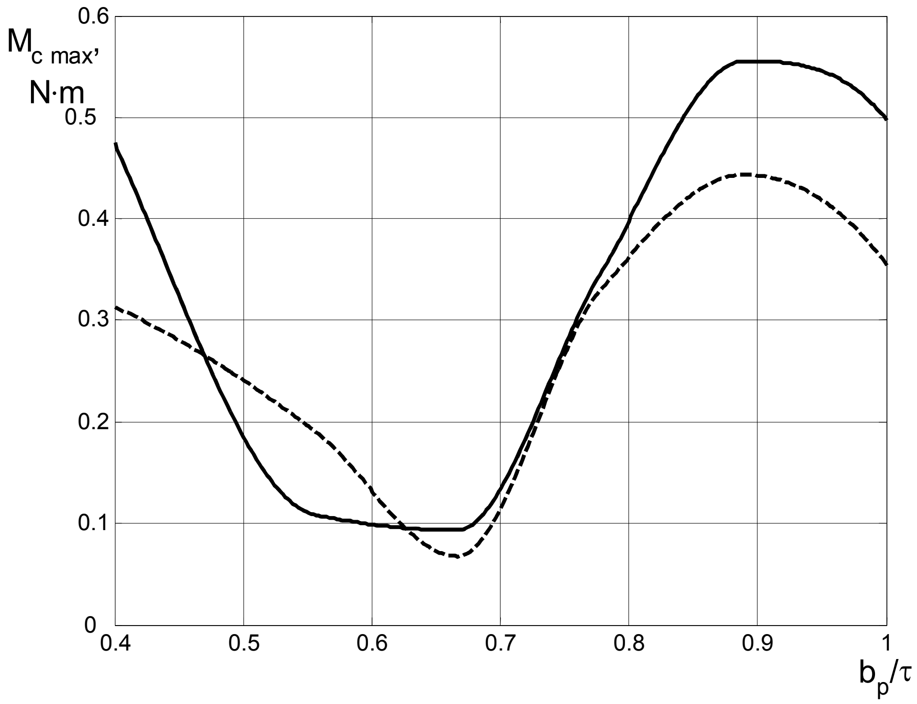
The traditional constructions of MMC rotors (for example sprocket, collector-type) have the following lacks [9]:

- The volume underapplication to insert the MMC that is used as magnetic field source;
- The combination MMC with high magnetic permeability and AHM with magnetic permeability of nearly to μ_0 brings to be generated the big leakage fluxes at big specific gaps;
- The loss presence is conditioned by the turbulent currents in the overfluxed MMC;
- The low stability against the demagnetization because of the small height of permanent magnets in magnetic direction.

The RAMA rotors can be made with the number pole pairs from 2 to 8 [9]. Because of it we made a calculated model of estimated four pole GM.

The calculated dependencies of the peak values of the cogging and full load torques at rated current on the relative width of radial magnet pole arc are shown in the Fig. 8.

a)



b)

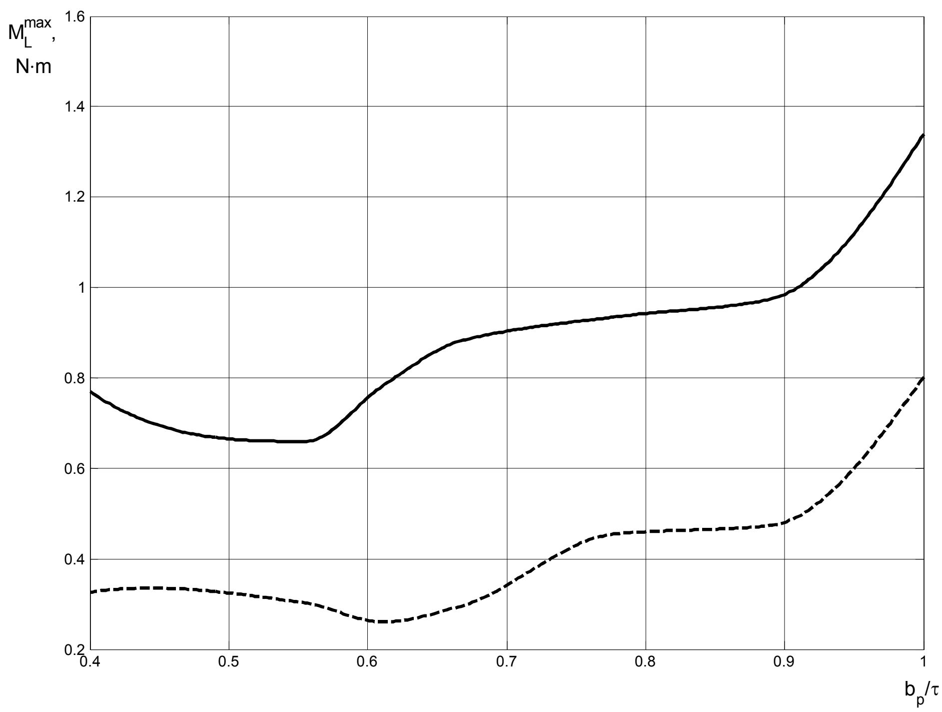


Fig. 8. The relationship beetween the internal torque of GM and the relative width of radial magnet pole arc: a) the cogging torque; b) the full load torque at $I_A = -I_B = 1.0\grave{A}$. The block curve is for MMC rotor, the broken curve is for AHM rotor.

As we can see, for this observed construction of GM the deletion of m-metal rotor brings to reduce of the cogging and full load torques.

The similar analysises were made for this GM with changing the number of pole pairs of rotor magnet ring at the same rotor speed and with the same turns of stator coils. The some of results is shown in the Fig. 9 and in the following tab. 1.

TABLE 1

Parameters Characteristics	$\frac{b_p}{\tau}$	$2p=4$	$2p=8$
$M_{c\max}$, N·m	1,0	0.4978	0.2616
	0,85	0.2245	0.0901
	0,7	0.1666	0.1264
$M_L^{\max}$, N·m	1,0	1.3390	0.9681
	0,85	1.0829	0.7988
	0,7	0.9024	0.7371
$E_{0\max}$, V	1,0	80.25	65.25
	0,85	56.64	62.38
	0,7	48.78	59.21

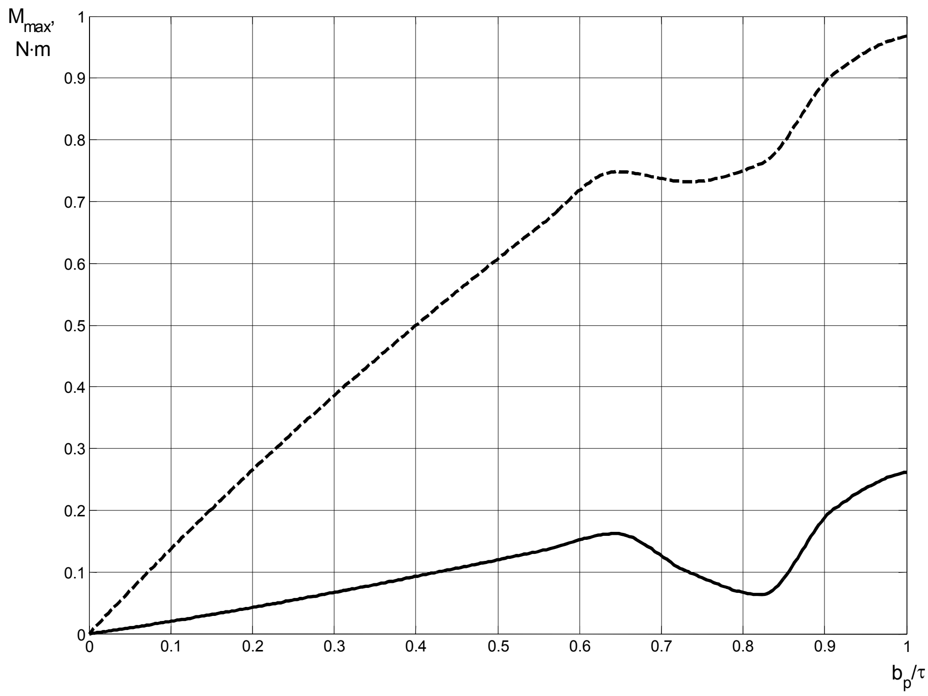


Fig. 9. The relationship beetween the internal torque of eight-pole GM and the relative width of radial magnet pole arc. The block curve is the cogging torque, the broken curve is the full load torque at $I_A = -I_B = 1.0\grave{A}$

6. CONCLUSIONS

- The required values of the full load torque of 1.0 N·m and the cogging torque of 0.25 N·m for given cross geometry of GM with $2p = 4$ can be reached at the relative width of radial magnet pole arc being more than $0{,}85\tau$.
- The tangent-magneted interpole arcs increase the cogging torque and reduce the full load torque. These torques will not be smaller than the required ones are with the relative width of radial magnet pole arc being more $0{,}9\,\tau$.

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BEZSZCZOTKOWY SILNIK PRĄDU STAŁEGO O MAGNESACH TRWAŁYCH, Z UZWOJENIAMI NA ZĘBACH I SAMOHAMOWANIEM

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STRESZCZENIE *Napędy elektryczne z synchronicznymi silnikami przekładniowymi są stosowane ogólnie w napędach o stałej prędkości w energetyce, elektrociepłowniach, transporcie rurociągami, ale mają one nie tylko ogólnie znane zalety lecz również istotne wady.*

Alternatywą może być bezszczotkowy silnik prądu stałego o magnesach trwałych z dodatkowymi uzwojeniami na zębach stojana.

Optymalizacja geometrii tego silnika jest oparta na matematycznym modelu pola z magnesami Nd-Fe-B i z sześcioma zębami stojana. Znamionowa wartość momentu wynosi 1 Nm, prędkości obrotowej 750 obr/min. Obliczono szerokość niemagnetycznego łuku między magnesami, która daje żądaną wartość momentu utknięcia, gdy w uzwojeniu statora nie ma prądu.

Oceniono wpływ szerokości łuków między biegunami na maksymalną wartość momentu utknięcia i na moment pełnego obciążenia.

Przeanalizowano możliwość wykonania wersji pierścienia magnetycznego wirnika bez rdzenia z metalu m.