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COMPARATIVE COMPARISON AND PHYSICAL AND MATHEMATICAL MODELLING OF MAGNETOELECTRIC BRUSHLESS DC MOTORS IN SLOTTING AND WITHOUT SLOTTING EXECUTIONS

ABSTRACT *On the basis of field calculation of a magnetic field in an active zone without grooving of the BLDC motor optimization of his cross-section geometry is offered with the purpose of increase in his electromagnetic torque. Characteristics serial slotting BLDC motor and a model sample without slotting BLDC motor, having identical cases are compared. The technique of definition of magnetic losses in the core and neodymium-iron-bor magnets is offered.*

The technique of analytical calculation (on the first harmonics of voltage and currents) performance data of salient pole BLDC motor with the inverter of a voltage and with magnetoelectric and electromagnetic excitation is offered.

Keywords: *PM Brushless DC motors, mathematical modelling, influence of slotting, comparative of torque*

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PROCEEDINGS OF ELECTROTECHNICAL INSTITUTE, Issue 229, 2006

1. STATEMENT OF A PROBLEM

Brushless permanent magnet DC motors (BLDC) in without slotting execution can have known advantages in comparison with classical BLDC motor likes this type with a winding of the stator, stacked in grooves. It, first of all, absence "pacing", small losses in steel, an opportunity of manufacturing of cores from the steel tape which have been reeled up on an edge. However rather low level of a magnetic induction in an air backlash can worsen use without slotting BLDC motor. Therefore their researches with the help of model samples and mathematical modelling are actual.

BLDC motor with constant magnets usually eat from transistor inverters of a voltage, therefore corners of installation of gauges of position of a rotor (obvious and implicit) coincide with corners of shift of the basic harmonics of phase voltage and EMF idling. The technique of analytical calculation of performance data such BLDC motor represents practical interest.

2. MATHEMATICAL MODELLING WITHOUT SLOTTING BLDC MOTOR. COMPARISON OF THE SETTLEMENT AND SKILLED DATA OF A MODEL SAMPLE

The basis of mathematical model was made with a method of interface of conformal representations [1]. His realization assumes the reference to the following procedures:

1) splitting initial settlement area into set of кусочно-homogeneous elementary sites (ES), magnetic permeability of which all points it is identical and varies jump on their borders;
2) conformal representations top of a half plane on specified ES;
3) use of integral of Schwarz for calculation of complex potential function top of a half plane;
4) data of vortical zones to potential;
5) deformation of anisotropic space with the purpose of his reduction to isotropic to a condition;
6) "sewing together" of borders conformal representations (material axes) next ES with the purpose of performance of boundary conditions of a magnetic field (MF) in settlement points.

On Chebocksary an electrohardware factory having the long moments from 0,23 to 70 H·m are issued magnetoelectric BLDC motor series 5ДВМ in slotting execution with diameters of connecting apertures on flanges 85, 115, 165 and 215 mm.

The model sample without slotting BLDC motor with a diameter of flange apertures of 115 mm to which there correspond serial BLDC motor with active length 140 mm, the long torque M_{d0} = 7 H·m, the maximal speed of rotation $n_{\max}$ = 6000 rpm has been made.

Specifications of the skilled engine the following: $n_{\max}$ = 6000 rpm; m = 3; 2p = 6; q = 1,5. A material of a magnet – neodymium-iron-bor with B_r = 1,12 T. Thickness of a magnet of 4,3 mm. Radial thickness of a two-layer winding makes 6,25 mm. The air backlash between a winding and a magnet is equal 1,5 mm. Cores are executed from steel 2013, a shaft - from steel 3. Settlement length l_δ = 0,14 m.

On Figure 1 the settlement area of this engine corresponding to the spatial period of MF is resulted. The area is broken on 47 ES, ring sectors having the form.

ES from 4-th on 21-st inclusive are vortical, in them the anchor conductors belonging to phases *A*, *B* and *C*. Steel sites are shaded (Fig. 1).

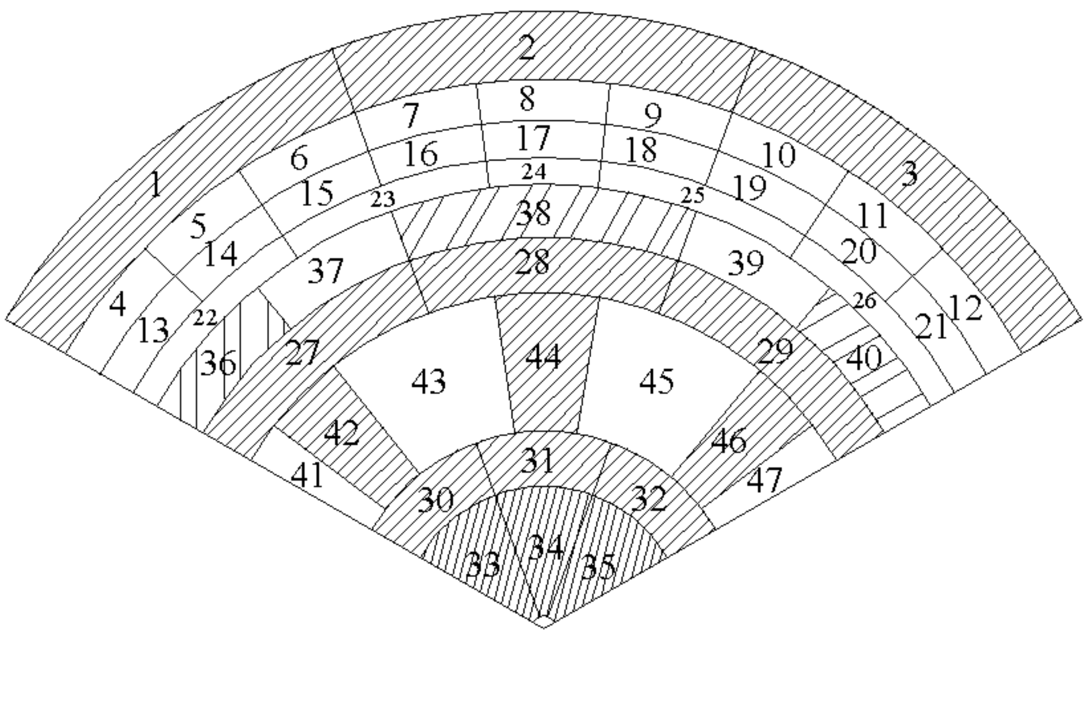

Fig. 1. Settlement area of the valve engine

For a point q, conterminous to points of supervision of two next ES with numbers i and k, fairly

$$ {}^{i}\mathbf{B}_{nq} = {}^{k}\mathbf{B}_{nq} \qquad (1)$$

Where

q – number of a point of supervision at their through indexation.

Having distributed equality (1) on all similar points of supervision, we shall receive system of the linear algebraic equations concerning a unknown vector of scalar magnetic potential (SMP) $\mathbf{u} = \left[u_1\, u_2 \ldots u_Q\right]^{\mathrm{T}}$ (here Q - full number of points of supervision), looking like

$$\mathbf{A}\,\mathbf{u} = \mathbf{F} \qquad (2)$$

Where

$\mathbf{A}$ - a square matrix of size Q (in given task Q = 1303).

Nonzero elements of a vector $\mathbf{F}$ are submitted by sources of MF.

At formation of the equations (1), (2) conditions on external borders of all settlement area were taken into account also: parameters of MF on the left and right radial borders are identical; the normal component of intensity of MF on the top border is equal to zero.

With the purpose of increase of accuracy of calculation of MF of a matrix $i_{\mathbf{g}}$ and $i_{\mathbf{h}}$, connecting vectors accordingly normal $i_{\mathbf{H}_n}$ and tangential $i_{\mathbf{H}_\tau}$ making MF with vector SMP $\mathbf{u}$ i-th ES, were exposed a normalization [1].

On Figure 2 settlement curve distributions of a normal making magnetic induction for position of a rotor on Fig. 1 on the circles which are taking place are resulted: on the bottom edge of a yoke anchors (a curve 1), on top (a curve 2) and bottom to edges of an air backlash (a curve 3), at the basis of a magnet (a curve 4) and on the bottom edge ES 27 (a curve 5).

From Fig. 2 it is visible, that the maximal value of an induction in an air backlash equally approximately 0,5 T.

Results of calculation show, that the maximal value of an induction in frame yoke and a rotor make accordingly 0,37 and 1,24 T, that allows to reduce section of the frame yoke in 3,7 times (the induction in this site increases up to 1,37 T) with the purpose of economy of a material and increase in the electromagnetic torque due to growth of external diameter of a rotor (at preservation of external diameter of the core of the stator).

Though the air backlash also is small, but levels of an induction at the top and bottom edges of an air backlash are various (see curves 2 and 3) (Fig. 2).

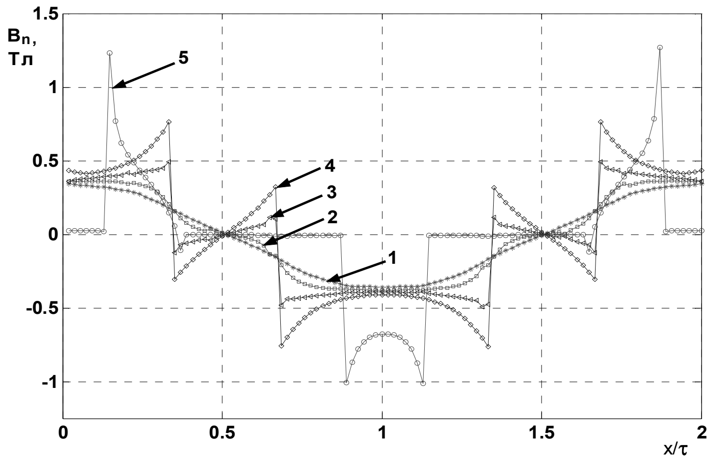

Fig. 2. Settlement curve distributions of a normal making magnetic induction on the circles which are taking place: on the bottom edge of a yoke anchors (a curve 1), on top (a curve 2) and to the bottom edge of an air backlash (a curve 3), at the basis of a magnet (a curve 4) and on the bottom edge ES 27 (a curve 5)

The Figure 3 contains settlement (curves 1, 2, 3) and skilled (curves 4, 5, 6) oscillograms EMF of idling for phases *A*, *B* and *C* accordingly (curves are constructed for speed of rotation of a rotor 1000 rpm).

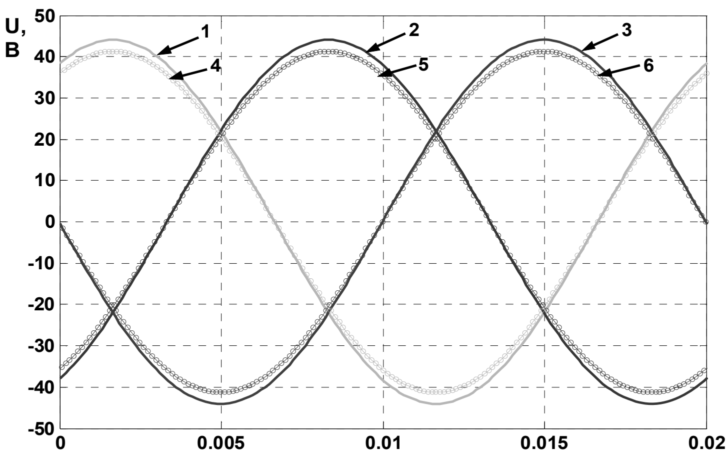

Fig. 3. Settlement (curves 1, 2, 3) and skilled (curves 4, 5, 6) oscillograms EMF of idling at rated speed of rotation of a rotor of the engine for phases A, B, C accordingly

Thermal tests of model sample BLDC motor have shown, that his winding of the stator with a class of thermal classification F has rated current 4,4 A (at this current excess of her temperature over an ambient temperature, measured by a method of resistance, has made 100°C).

To the specified current there corresponds skilled value of the maximal torque 3,6 H·m. The maximal, minimal and average values of the electromagnetic torque at a zero corner of installation of the gauge of position of a rotor have made, according to settlement curve Fig. 4, accordingly 5,0; 1,8 and 3,6 H·m.

Settlement instant value of the electromagnetic torque on Fig. 4 is received under the formula following from a method of tension [2]:

$$M = \frac{\pi}{2}\frac{l_\delta D_p^2}{N}\sum_{j=1}^{N} B_{nj} H_{\tau j}\ ,\ [\text{Н} \cdot \text{м}] \qquad (3)$$

Where

N - quantity of points of supervision on the arch of a circle of an air backlash adjoining to a rotor;

$B_{nj}, H_{\tau j}$ - normal components of vectors of a magnetic induction and intensity of MF in the given points;

D_p - Diameter of a rotor.

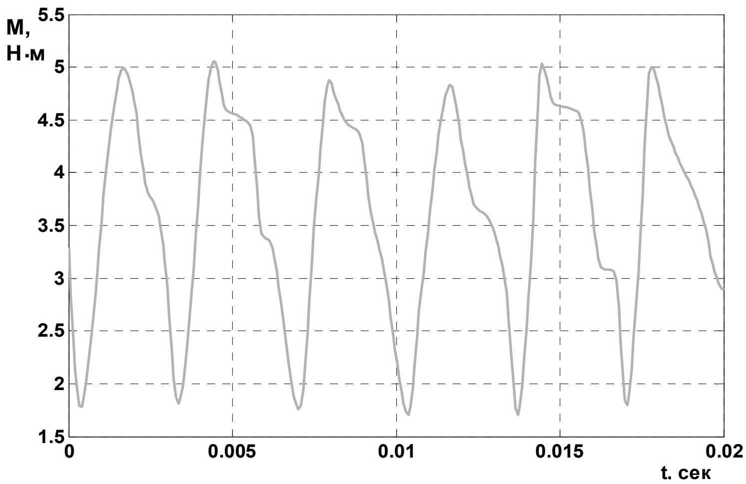

Fig. 4. Change of the torque of the engine at loading

The task of numerical modelling considered valve the engine has been realized in the programming language of high level C++ in Visual Studio 6.0 (SP6). The order of the received system - 1303. Number of discrete positions of a rotor on the period - 38. Time of calculation of characteristics for a mode of idling on the personal computer with processor AMD Athlon XP 2200 has made approximately 35 minutes.

3. THE COMPARATIVE ANALYSIS BLDC MOTOR IN SLOTTING AND WITHOUT SLOTTING EXECUTION. OPTIMUM CROSS-SECTION GEOMETRY WITHOUT SLOTTING BLDC MOTOR

Serial slotting BLDC motor with a diameter of flange apertures the long torque on a shaft M_{d0} = 7 H·m has of 115 mm (according to the standard such torque should be maintained in an interval of speeds from zero up to 0,25 $n_{\max}$; on the subsequent intervals (0,25 - 0,5) $n_{\max}$ and (0,5 - 1,0) $n_{\max}$ the torque can be no more accordingly 0,8 M_{d0} and 0,5 M_{d0}). Thermal tests serial BLDC motor have shown, that his moments at the end of three specified intervals do not exceed accordingly values: (0,54; 0,33; 0) M_{d0}, i.e. at the end of first interval BLDC motor can hold the torque a little more than half M_{d0} (instead of) M_{d0}, at the end of the second interval – third from M_{d0} (instead of 0,8 M_{d0}), at the end of the third interval – can work only idling.

At similar tests of a skilled breadboard model without slotting BLDC motor have received values: (0,86; 0,71; 0,43) M_{d0}, and at him M_{d0} = 3,6 H·m. These experimental data testify, that, since speed 2800 rpm, without slotting BLDC motor can develop is long the greater moment on a shaft, than his serial slotting analogue.

Results of thermal tests BLDC motor are resulted in below-mentioned tab. 1.

TABLE 1

	Slotting BLDC motor			Without slotting BLDC motor		
n, rpm	0	3000	4500	0	3400	10460
M, Н·м	7,0	2,33	0	3,6	2,43	0

In linear approximation the skilled data can be submitted as two crossed straight lines (Fig. 5) with coordinates of a point of crossing: M = 2,64 H·m; n = 2800 rpm.

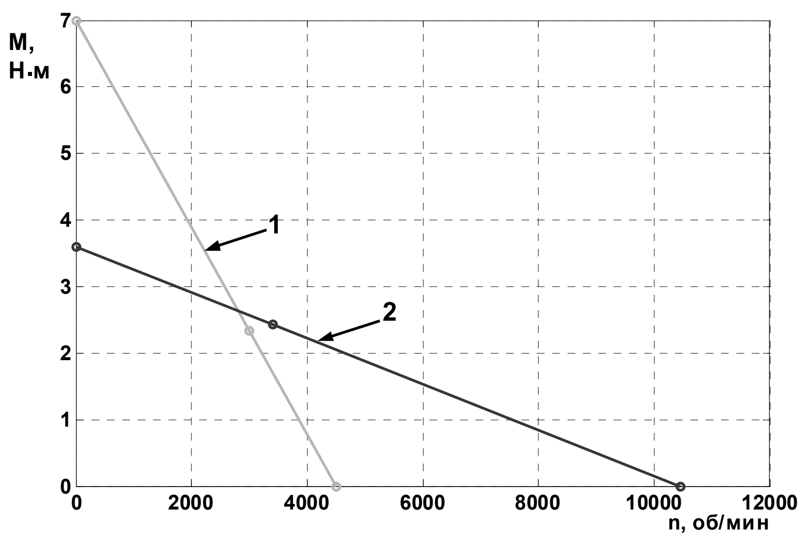

Fig. 5. Limiting on a thermal mode experimental mechanical characteristics slotting (a curve 1) and without slotting (a curve 2) BLDC motors

For improvement of use without slotting BLDC motor on his mathematical model the following actions have been realized.

1. Interpolar intervals on a rotor have been filled same magnetically hard with a material, as a inductor, but these sites have either radial, or tangential directions of magnetization [8]. Both these modernizations of a rotor increase his moment at rated current accordingly by 11,3 and 14,6 percent.
2. Increase in thickness of magnets with 4,3 up to 5 and 6 mm. In result the electromagnetic torque increases accordingly for 3,4 and 8,2 percent, accepting values 3,7 and 3,9 H·m.
3. Reduction of height back of the frame yoke with 5,5 up to 2 mm and corresponding increase in diameter of a rotor at constant external diameter stator the core. This action increases torque BLDC motor at rated current by 9,7 percent.

4. MAGNETIC LOSSES IN STATOR THE CORE AND MAGNETS

For calculation of thermal losses in magnets and the core of the stator settlement area of the engine (Fig. 6) has been broken on 69 ES instead of 47 ES into fig. 1.

The order of the received system has increased and has made - 1623. Number of discrete positions of a rotor on the period - 49. Time of calculation of characteristics for a mode of idling on the personal computer with processor AMD Athlon XP 2200 has made approximately 60 minutes.

For a presence of thermal losses in various elements of design BLDC motor have been entered into consideration virtual elementary contour (EC). Laminated stator the core and a magnet have been broken on 36 and 6 EC accordingly (Fig. 7).

The density of a current and magnetic permeability in everyone ES were accepted uniform.

Magnetic linkages EC Ψ_i^j (i = 1, 2... N, j = 1, 2... M, here N and M quantities accordingly layers and EC in one layer) stator the core were calculated as trellised functions which discrete argument υ_k was angular position of a rotor with constant magnets.

Discrete functions $\Psi_i^j(\upsilon_k)$ were exposed cubic spline to interpolation which allowed to find their first derivatives - EMF contours.

Resistance EC were defined under the formula

$$r_j^k = k_c \rho \frac{l_w}{S_j^k} \tag{4}$$

where

$k_c = 1 + \frac{2}{\pi}\left(\frac{\tau}{l}\right)$ - the factor which is taking into account resistance of frontal sites of contours;

S_j^k - the area of cross-section section EC;

ρ - specific resistance of a material of a contour, Ohm·m (for currents across interleaving the stator according to [5] ρ=1 Ohm·m; for a magnet from neodymium-iron-bor we have $\rho = 1{,}6 \cdot 10^{-6}$ Ohm·m [6]);

l_w - length EC.

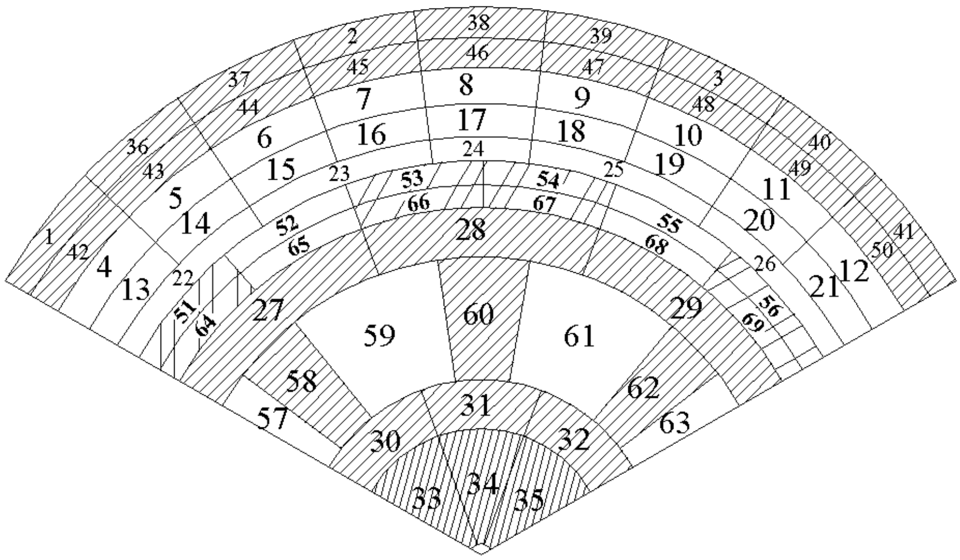

Fig. 6. Internal settlement area BLDC motor for definition thermal losses in steel of cores and magnets

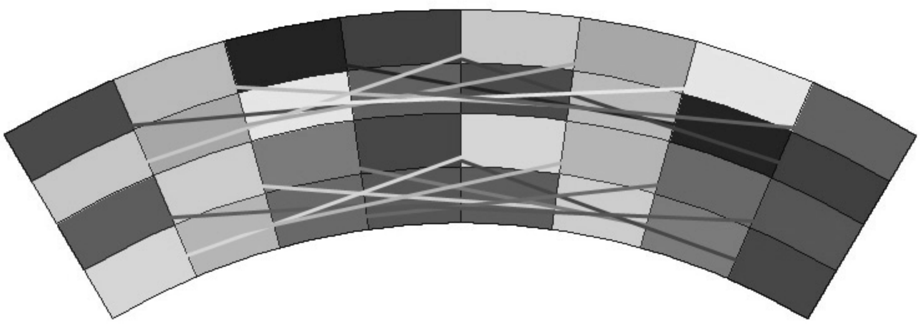

Fig. 7. Elementary contours of vortical currents in constant magnets

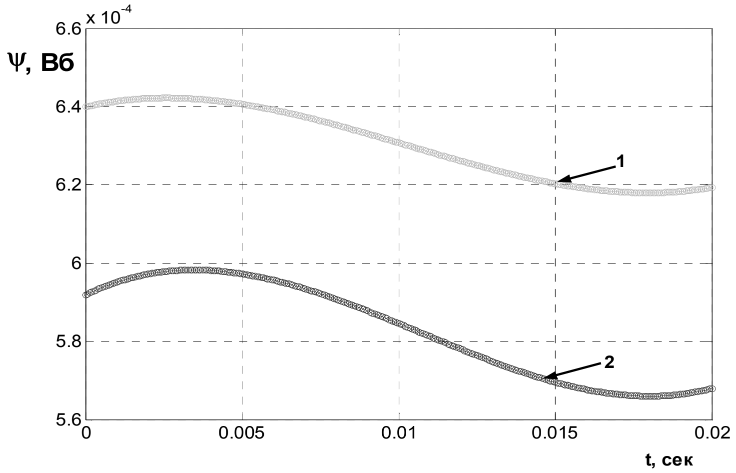

Fig. 8. Settlement curve changes magnetic linkages in the some EC magnet (1, 2) in a mode of idling

On Figure 8 settlement curve changes of a magnetic linkage the some EC a magnet for a mode of idling are resulted.

Number of a curve is meant corresponding virtual EC, with their numbering – on growing from left to right and from top to down. The Figure 8 shows, that at absence of grooves on the stator of magnetic linkage EC magnets in a mode of idling remain practically constant. In result vortical currents and losses from them in magnets will be underestimated.

Settlement curves of instant values of normal and tangential components of an induction of a magnetic field in laminated ES stator the core in a mode of a rated load were displayed in Fourier series (Fig. 9).

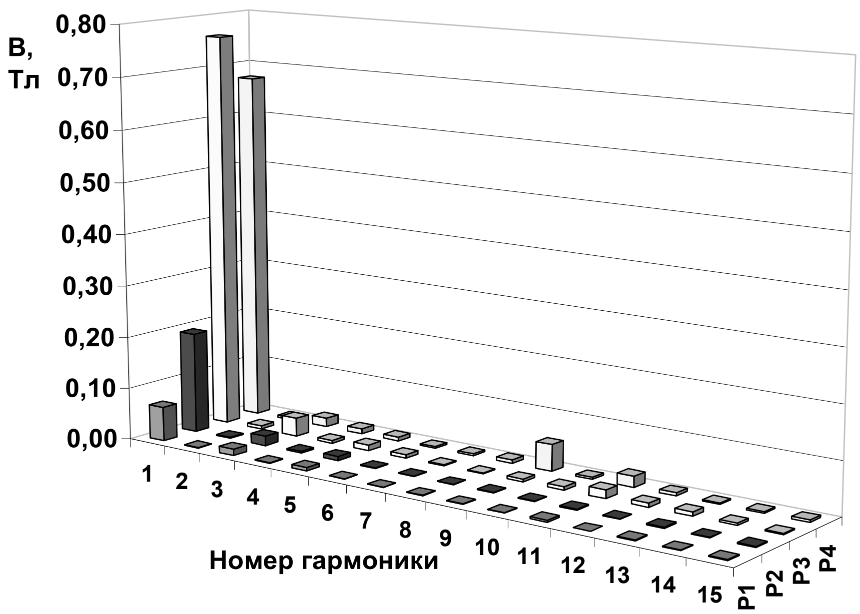

Fig. 9. Decomposition of normal and tangential components of an induction of a magnetic field in laminated ES stator the core in number Fourier on harmonious components. A number 1 (3) corresponds to decomposition of a normal (tangential) making induction in ES 1, 2, 3..., and a number 2 (4) – a normal (tangential) making induction in ES 42, 45, 48 …

A number 1 (3) Fig. 9 corresponds to decomposition of a normal (tangential) making induction in ES 1, 2, 3, ..., and a number 2 (4) - a normal (tangential) making induction in ES 42, 45, 48, …

Magnetic losses (from vortical currents and a hysteresis) in laminated stator the core from each of the induction designed harmonics can be determined separately under known formulas [7].

Total losses on vortical currents and a hysteresis in laminated stator the core from all harmonics of an induction of a magnetic field have made 0,172 W, and losses from the supreme harmonics of an induction have made 11 % of losses from the first harmonic.

The data of electromagnetic calculation allow to define also losses from the vortical currents which are becoming isolated on EC in magnets. Losses in them at rated speed of rotation of a rotor have made 0,11 W. Their low value is connected to absence of grooves on stator and presence enough the big air backlash. Electric losses in windings of phases have made 111,5 W.

5. ANALYTICAL CALCULATION OF PERFORMANCE DATA BLDC MOTOR

In the inverter of a voltage a source of a constant voltage (the storage battery, the rectifier with in parallel attached big capacity) is connected directly through keys to loading – to the synchronous electric motor.

As signals of management of keys will follow from the gauge of position of rotor (GPR) of the electric motor also the curve of a target voltage of the inverter will be rigidly synchronized with angular position ϑ of a longitudinal axis of a rotor concerning a magnetic axis of a phase *A* of stator. If we shall define EMF idling of a phase *A* the electric motor expression

$$e_{A0} = -E_m \sin \vartheta \tag{5}$$

That for the first harmonic of a phase voltage of a phase *A* of stator will be fair

$$U_A = U_m \sin(\vartheta + \theta_u) \tag{6}$$

Where the corner $\theta_u = \angle\, \dot{U}, -\dot{E}_0$ will be compulsorily set GPR and should be considered not as a measure of loading of the synchronous machine with a network feed, and as parameter of management valve the engine $(\theta_u = \mathrm{const})$.

Let's consider the basic electromechanical properties valve the engine with the inverter of a voltage, assuming, that voltage and currents of a winding of an anchor sinusoidal.

Expression for the mechanical characteristic valve the engine we can receive from the formula for the electromagnetic moment [3]

$$M = \frac{m U^2 \varepsilon}{\omega_c \left(r^2 + x_d x_q\right)^2} \left[\left(x_d x_q^2 - r^2 x_q + 2 r^2 x_d\right) \sin\theta_u + \right.$$
$$\left. + r\left(2 x_q^2 + r^2 - x_d x_q\right) \cos\theta_u - \varepsilon r \left(r^2 + x_q^2\right)\right] + \frac{m U^2}{2\omega_c} \frac{x_d - x_q}{\left(r^2 + x_d x_q\right)^2} \times \quad (7)$$
$$\times \left[\left(x_d x_q - r^2\right) \sin 2\theta_u + r\left(x_d + x_q\right) \cos 2\theta_u - r\left(x_d - x_q\right)\right]$$

Where

$\varepsilon = E_0 / U$ - a degree excited state a rotor;

$x_d = \omega L_d$, $x_q = \omega L_q$ - synchronous inductive resistance accordingly on longitudinal and cross-section axes of the machine;

$\omega = 2\pi f$ - angular frequency of a voltage of a feed stator;

θ_u - a corner between a vector of a phase voltage and a cross-section axis q a rotor;

$\omega_c = \frac{\omega}{p} = \frac{2\pi n_c}{60}$ - mechanical synchronous angular frequency;

n_c - synchronous speed of rotation, rpm;

p - number of pairs poles.

As EMF idling it is equal

$$E_0 = C \omega \Phi_0 \quad (8)$$

Where

$C = w k_{w1} / \sqrt{2}$; $\Phi_0 = \frac{2}{\pi} B_{m1} l \tau$ - a magnetic stream of excitation in an air backlash idling, That (7) is possible to give the formula such kind:

$$M = \frac{m\,p\,C\,\Phi_0\,U}{\left(r^2+\omega^2 L_d L_q\right)^2}\begin{Bmatrix}\left[\omega^3 L_d L_q^2+\omega\left(2\,r^2 L_d - r^2 L_q\right)\right]\sin\theta_u + \\ + r\left[\omega^2\left(-L_d L_q + 2L_q^2\right)+r^2\right]\cos\theta_u - \\ -\omega^3 C\,\Phi_0\, r\, L_q^2/u - \omega\, C\,\Phi_0\, r^3/u\end{Bmatrix} + \\ + \frac{mU^2}{2}\frac{p\left(L_d-L_q\right)}{\left(r^2+\omega^2 L_d L_q\right)^2}\begin{Bmatrix}\left(\omega^2 L_d L_q - r^2\right)\sin 2\theta_u + \\ \omega r\left[\left(L_d+L_q\right)\cos 2\theta_u - \left(L_d - L_q\right)\right]\end{Bmatrix} \quad (9)$$

It is remarkable that contains two composed from which the first depends on a magnetic stream of excitation Φ_0, and the second - from salient-pole of inductor.

Having accepted $\omega = 0$, we shall receive expression for the starting moment valve the engine

$$M_{\text{п}} = \frac{m\,p\,C\,\Phi_0 U}{r}\cos\theta_u - \frac{m\,p\,U^2}{2}\frac{L_d - L_q}{r^2}\sin 2\theta_u \quad (10)$$

We see, that at a corner $\theta_u = 0$ salient-pole does not influence the starting moment. At values of a corner $0 < \theta_u < 90^\circ$ salient-pole will reduce the starting moment at engines with electromagnetic excitation (at them $L_d > L_q$) and to increase - at engines with constant magnets (at them $L_d < L_q$).

Having increased the left and right parts of the formula (9) on size $\left(r^2 + \omega^2 L_d L_q\right)^2$, we shall receive a polynom of the fourth degree concerning electric speed of rotation of a rotor ω:

$$a_0\omega^4 + a_1\omega^3 + a_2\omega^2 + a_3\omega + a_4 = 0 \quad (11)$$

Where

$$a_0 = \left(L_d L_q\right)^2 M \quad (12)$$

$$a_1 = m\,p\,C\,U\,\Phi_0 L_q^2\left(C\,\Phi_0\, r/u - L_d\sin\theta_u\right) \quad (13)$$

$$a_2 = 2r^2 L_d L_q M - r\,m\,p\,C\,U\,\Phi_0 L_q\left(-L_d + 2L_q\right)\cos\theta_u - \\ - \frac{m\,p\,U^2}{2}\left(L_d - L_q\right)L_d L_q\sin 2\theta_u \quad (14)$$

$$a_3 = m p\, C U \Phi_0\, r^2 \left[\frac{C \Phi_0 r}{U} - \left(2 L_d - L_q\right) \sin\theta_u \right] - \frac{m\, U^2}{2} p\, r \left(L_d - L_q\right) \times \\ \times \left[\left(L_d + L_q\right) \cos 2\theta_u - \left(L_d - L_q\right)\right] \tag{15}$$

$$a_4 = r^4 M - r^3 m p C U \Phi_0 \cos\theta_u + \frac{mU^2}{2} p \left(L_d - L_q\right) r^2 \sin 2\theta_u . \tag{16}$$

The equation (11) in the implicit form defines the mechanical characteristic $\omega = f(M)$ valve the engine.

The electromagnetic moment can be found also under the formula

$$M = \frac{m U I \cos\varphi - m I^2 r}{\omega / p} \tag{17}$$

Where $\cos\varphi$ it is searched from the equation [4]

$$\operatorname{tg}\theta = \frac{I\left(\omega L_q \cos\varphi + r \sin\varphi\right)}{U + I\left(\omega L_q \sin\varphi - r \cos\varphi\right)} \tag{18}$$

Let's note some specific properties BLDC motor at a corner $\theta_u = 0$ - the most widespread corner of installation of the gauge of position of a rotor.

From (18) we have for $\theta_u = 0$

$$\omega L_q \cos\varphi + r \sin\varphi = 0$$

And, hence,

$$\operatorname{tg}\varphi = -\frac{\omega L_q}{r} \tag{19}$$

Where $\varphi < 0$ for a lagging behind current of stator.

This formula shows, that at constant speed of rotation of the engine his factor of capacity (on the first harmonic) is constant. This feature can serve as the test for adjustment of the gauge of position of a rotor for zero value of a corner θ_u.

At growth of speed of rotation the factor of capacity of the engine with $\theta_u = 0$ will be reduced.

Dependence (9) essentially becomes simpler at absence salient-pole at the engine

$$L_d = L_q = L_C \tag{20}$$

In this case from (9) we have

$$M = \frac{m\,p\,C\,\Phi_0}{r^2 + \omega^2 L_C^2}\left[\omega\left(L_C\,U\sin\theta_u - C\,\Phi_0\,r\right) + r\,U\cos\theta_u\right] \tag{21}$$

For $\theta_u = 0$ the formula (21) it is possible to give a kind

$$M = \frac{m\,p\,C\,\Phi_0 U\,r}{r^2 + \omega^2 L_C^2}\left(1 - \frac{C\,\omega\,\Phi_0}{U}\right) \tag{22}$$

The formula (21) allows to find expression for speed of idling of the engine ω_0. Having accepted $M = 0$, we have:

$$\omega_0 = \frac{r\,U\cos\theta_u}{C\,\Phi_0 r - L_C U\sin\theta_u} \tag{23}$$

At $\theta_u = 0$ we have

$$\omega_0 = \frac{U}{C\,\Phi_0} \tag{24}$$

At micromotors we can have

$$r >> \omega\,L_C = x_C \tag{25}$$

Then the mechanical characteristic becomes linear

$$\frac{\omega}{\omega_0} + \frac{M}{M_{\text{п}}} = 1 \tag{26}$$

Where

$$M_{\text{п}} = \frac{m p C \Phi_0 U}{r} \cos\theta_u \tag{27}$$

The starting moment, and speed of idling ω_0 is on (23).

At known speed of a rotor we can find a current and primary capacity of the engine:

$$I = \frac{U}{r^2 + \omega^2 L_d L_q} \sqrt{\frac{2 C \Phi_0 \omega}{U} \begin{bmatrix} r\omega\left(L_d - L_q\right)\sin\theta_u - \\ -\left(r^2 + \omega^2 L_q^2\right)\cos\theta_u \end{bmatrix} - \begin{bmatrix} \omega^2\left(L_d^2 - L_q^2\right)\sin^2\theta_u + \\ + r\omega\left(L_d - L_q\right)\sin 2\theta_u - \\ -\left(r^2 + \omega^2 L_q^2\right) \end{bmatrix} + \left(\frac{C\Phi_0\omega}{U}\right)^2\left(r^2 + \omega^2 L_q^2\right)} \tag{28}$$

$$P_1 = \frac{mU^2}{r^2 + \omega^2 L_d L_q}\left[\frac{C\Phi_0\omega}{U}\left(\omega L_q \sin\theta_u - r\cos\theta_u\right) + \frac{\omega}{2}\left(L_d - L_q\right)\sin 2\theta_u + r\right] \tag{29}$$

At absence salient-pole ($L_d = L_q = L_c$) and at $\theta_u = 0$ we have

$$I = \frac{U}{\sqrt{r^2 + \omega^2 L_c^2}}\left(1 - \frac{C\omega\Phi_0}{U}\right) \tag{30}$$

$$P_1 = \frac{mU^2 r}{r^2 + \omega^2 L_c^2}\left(1 - \frac{C\omega\Phi_0}{U}\right) \tag{31}$$

From last expression follows, that at $r = 0$ (we have powerful BLDC motor) and $\theta_u = 0$ BLDC motor it is disabled, since P_1 addresses in zero. In this case, apparently from the formula (19), the current of stator becomes jet (we have $\varphi = \frac{\pi}{2}, I_q = 0, I_d = I$).

At known value of active primary capacity we can find factor of capacity on the first harmonic of this circuit

$$\cos\varphi = P_1 / mUI$$

In below-mentioned tab. 2 performance data of a model sample considered above without slotting BLDC motor, having in lock mode $M_{н} = 3{,}6$ H·m, $I_{н} = 4{,}4$ A are submitted.

TABLE 2

n, rpm	1000						1500					
U_1,V	90	106	116	123	127	131	113	126	136	144	149	151
I, A	0,4	0,95	1,3	1,65	1,95	2,3	0,4	0,95	1,3	1,6	1,9	2,25
M, H·m	0,35	0,7	1,05	1,4	1,75	2,1	0,35	0,7	1,05	1,4	1,75	2,1
	0,28	0,78	1,17	1,56	1,90	2,29	0,24	0,62	0,90	1,18	1,42	1,69

Settlement values are specified in the bottom line of tab. 2 for the electromagnetic torque of the M, received under the formula (9). The first harmonic of a phase voltage of a winding has been involved in this formula of stator, determined under the formula

$$U_1 = U K_u$$

Where

U - working skilled value of a phase voltage,

K_u - Factor of distortion.

For speeds of rotation of rotor BLDC motor these factors have made 1000 and 1500 rpm accordingly 0,77 and 0,83.

For adjustable high-power engines and at enough big speeds of rotation of a rotor it is possible to neglect active resistance of a winding of an anchor. Let's accept

$$r = 0 \tag{32}$$

In this case from formulas (15) and (16) factors a_3 also a_4 become equal to zero, and the polynom (11) will be square

$$a_0\omega^2 + a_1\omega + a_2 = 0 \tag{33}$$

Where

$$a_0 = L_d^2 M \tag{34}$$

$$a_1 = -mpCU\Phi_0 L_d \sin\theta_u \tag{35}$$

$$a_2 = -\frac{mpU^2}{2}\frac{L_d}{L_q}\left(L_d - L_q\right)\sin 2\theta_u \tag{36}$$

The mechanical characteristic under condition of (32) can be received and from the well-known equation

$$M = \frac{mpC\Phi_0 U}{\omega L_d}\sin\theta_u + \frac{mpU^2}{2\omega^2}\left(\frac{1}{L_q} - \frac{1}{L_d}\right)\sin 2\theta_u \tag{37}$$

Under conditions

$$r = 0, \quad L_d = L_q = L_C \tag{38}$$

The factor (36) will be zero, and the equation (33) becomes linear

$$a_0\,\omega + a_1 = 0 \tag{39}$$

Where

$$a_0 = L_C M; \quad a_1 = -mpCU\Phi_0 \sin\theta_u$$

Hence, the mechanical characteristic BLDC motor at performance of conditions (38) will be a hyperbolic kind

$$\omega = \frac{mpCU\Phi_0 \sin\theta_u}{L_C M} \tag{40}$$

This dependence under condition of (38) is easy for receiving and from expression (37).

On Fig. 10 mechanical characteristics BLDC motor by capacity of 2,8 kW designed on the equation (7) for case, when $U = U_н$ are shown and $L_d = L_q$.

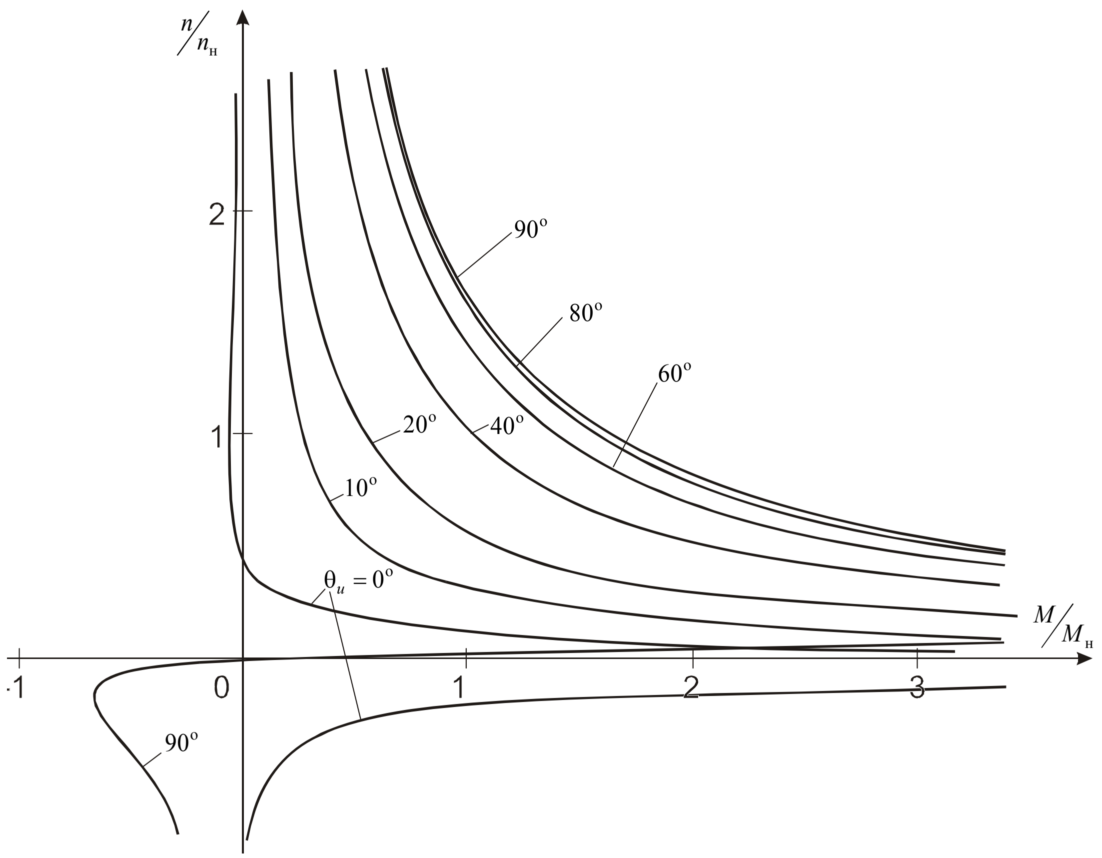

Fig. 10. Mechanical characteristics неявнополюсного valve the engine with the inverter of a voltage capacity of 2,8 kW at $U = U_н$

At a corner of management of the inverter $\theta_u = 0$ the significant part of the mechanical characteristic belongs to the second quadrant, and at a corner $\theta_u = 90^\circ$ - to the third quadrant and we have the starting moment equal to zero.[1]

The formula for the electromagnetic torque (7) generally will consist of two composed

$$M = M_1 + M_2 \tag{41}$$

[1] The analysis of the equation (7) is made, neglecting saturation of a magnetic circuit of the electric machine.

First of which it is proportional to a target voltage of the inverter in the first degree, the second is proportional to a voltage in the second degree. Therefore the second composed in a mode of formation of the natural mechanical characteristic when $U = U_{н} = \mathrm{const}$, renders essential influence on its kind.

Mechanical characteristics of the motor[2] on Fig. 10 are constructed with the account only the first composed in (41).

Mechanical characteristics of the same motor on Fig. 11 are constructed at $U = U_{н}$ on the equation (7) with the account and composed M_2, caused salient-pole a design of a rotor.

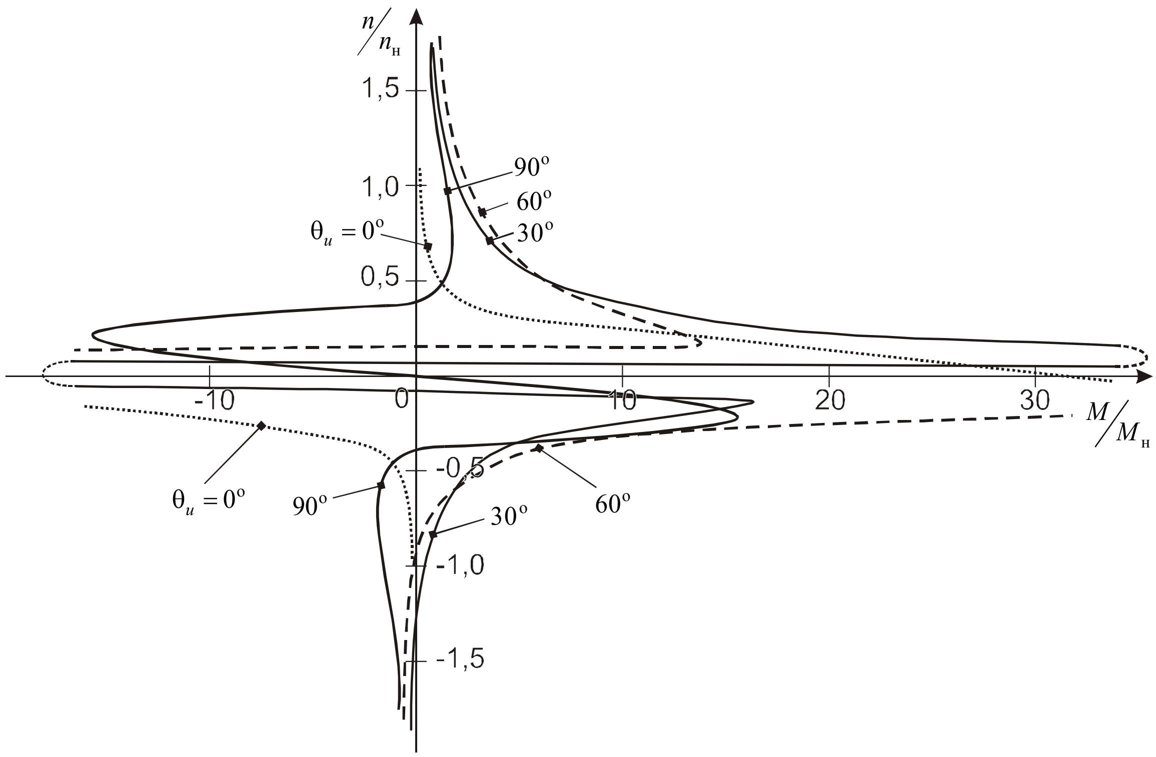

Fig. 11. Mechanical characteristics salient-pole BLDC motor with the inverter of a voltage capacity of 2,8 kW at $U = U_{н}$

From the formula (7) follows, that starting values $(\omega = 0)$ of the considered torques are equal

[2] The experimental synchronous salient pole motor has the following data: $P_{2н} = 2{,}8\ \mathrm{кW}$; $n_{н} = 1500\ \mathrm{rpm}$; $m = 3$; $U_{нф} = 150\ \mathrm{V}$; $I_{н} = 8{,}5\ \mathrm{A}$; $\Phi_0 = 4{,}88 \cdot 10^{-3}\ \mathrm{Wb}$; $C = 97{,}95$; $L_d = 0{,}092\ \mathrm{H}$; $L_q = 0{,}051\ \mathrm{H}$; $r = 0{,}715\ \Omega$.

$$M_{1п} = \frac{mpC\Phi_0 U}{r}\cos\theta_u = a\cos\theta_u \tag{42}$$

$$M_{2п} = -\frac{mU^2 p}{2}\frac{\left(L_d - L_q\right)}{r^2}\sin 2\theta_u = b\,\sin 2\theta_u \tag{43}$$

For the analyzed motor having $L_d > L_q$, these torques operate back-to-back. Therefore at corners of management

$$\theta_u > \theta_u^{крит} = \arcsin\frac{a}{2b} = \arcsin\frac{C\Phi_0 r}{U\left(L_d - L_q\right)} \tag{44}$$

The starting torque will be negative. At $\theta_u = \theta_u^{крит}$ we have $M_п = 0$. For the considered motor the critical corner of management will make 0,0560. For his increase it is required to lower a voltage of stator at start-up. Otherwise, as well as at collector motors of a direct current, we have excessively big starting currents and the torque. At $\theta_u = 0$, when $M_{2п} = 0$, it agrees Fig. 11 $M_п / M_н = M_{1п} / M_н = 33{,}8$.

At $\theta_u = 90^\circ$ from formulas (42), (43) follows: $M_{1п} = M_{2п} = 0$.

Permanent magnet BLDC motors have $L_d < L_q$, therefore at them at start-up the toque $M_{2п}$ will operate in one direction (positive) with the torque $M_{1п}$.

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Manuscript submitted 30.11.2006
Reviewed by Jarosław Zadrożny

PORÓWNANIE FIZYCZNE I MATEMATYCZNE MODELOWANIE MAGNETOELEKTRYCZNYCH SILNIKÓW BEZSZCZOTKOWYCH W WYKONANIU ZE ŻŁOBKAMI I BEZ ŻŁOBKÓW

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STRESZCZENIE *Na podstawie obliczenia pola magnetycznego w strefie czynnej ze żłobkami, proponuje się optymalizację geometrii jego przekroju w celu zwiększenia jego momentu elektromagnetycznego. Porównano charakterystyki seryjnego bezszczotkowego silnika prądu stałego następnie magnetoelektrycznego silnika bezszczotkowego i jego modelu bez żłobków. Podano definicję strat magnetycznych w rdzeniu i magnesach neodym-żelazo-bor.*

W artykule podano metodę analitycznego obliczania danych silnika bezszczotkowego z biegunami ukrytymi z przekształtnikiem napięcia ze wzbudzeniem magnetoelektrycznym i elektromagnetycznym z uwzględnieniem 1-szej harmonicznej napięcia i prądu.

IEl, Warszawa 2006. Nakład 110+10 egz. Ark.wyd. 19,12. Ark.druk. 14,12. Pap.off. Kl.III. 80 g.
Oddano do druku w grudniu 2006 r. Druk ukończono w styczniu 2007 r.
Redakcja – Dział Informacji Naukowo-Technicznej
Indeks nr 37656