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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

HIGH-RELIABILITY BRUSHLESS SYNCHRONOUS MOTORS FOR HAND TOOLS AND HOUSEHOLD APPLIANCES

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The paper presents an overview of brushless electric motors used in hand electric tools and household appliances. Analysis of the motor types has shown that synchronous reluctance motors are the most reliable for low-power drives of such tools and appliances due to their simple design, long service life and low cost of production. Solutions are proposed for significant decrease in the quadrature-axis magnetic flux of the synchronous reluctance motor. The motors are shown to develop the specific electromagnetic torque up to 0.35÷0.4 Nm/kg.

Key words: *brushless synchronous motor, electromagnetic torque, household appliances, hand tools*

1. INTRODUCTION

Electric motor is one of the most common types of power converters used in household appliances, hand electric tools as well as in other devices and systems owing to its high reliability, energy efficiency, low production cost, small sizes, and easy servicing.

As known, the electric motor is a complex element that combines its mechanical performance with electric and magnetic characteristics, and often operates under difficult conditions. Therefore, it is not always possible to meet all the mentioned requirements.

Brushless electric motors are relatively simple and cheap. They do not have sliding contacts and brushes that quickly wear out, even under easy operating conditions; neither have they additional loss by friction and contact voltage drop. Thus, these motors are considered as highly efficient and reliable [1, 2].

To brushless motors we relate the cage induction motors, permanent-magnet synchronous motors, hysteresis motors, and reluctance synchronous motors [3, 4]. Each type motor has its own advantages and disadvantages.

Induction motors possess easy and quick starting, stable operation under varying load conditions, being also easy to make. However, these motors, especially with a hollow rotor, have low power factor and efficiency. They cannot be designed with a high number of poles, and are therefore unsuitable for direct drive of low-speed devices.

Permanent-magnet synchronous motors have better performance. They are easy to produce and operate, being also highly efficient. Their disadvantages are: more difficult start-up (if no special starting elements are provided), unstable operation, and rather a high cost for the use in household appliances and hand tools. This last factor is caused by the high cost of permanent magnets for which expensive high-energy magnetically hard materials are used.

Hysteresis motors have the same disadvantages. In addition, their rotors are made of a special magnetically hard material (vicalloy), which has a low specific energy. Therefore, such motors have low specific torque and efficiency.

As concerns synchronous reluctance motors, they are simple in design, cheap and reliable. Still, they have a low specific electromagnetic torque, and are therefore of limited utility for the use in modern household appliances and hand electric tools.

2. CONFIGURATIONS OF SYNCHRONOUS RELUCTANCE MOTOR AND WAYS TO INCREASE SPECIFIC ELECTROMAGNETIC TORQUE

Synchronous motors with different reluctance along the direct and quadrature axes (d- and q-axis) without special excitation are called reluctance motors. The main rotor configurations of reluctance motors are presented in Fig. 1 [3]. For the improvement of starting characteristics they can be built with a squirrel-cage winding.

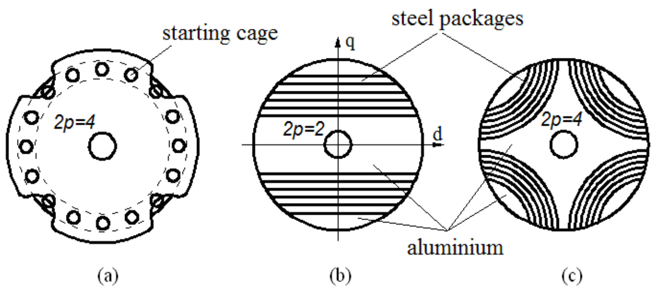

Fig.1. The main rotor configurations of a synchronous reluctance motor: (*a*) simple salient-pole rotor; (*b*) two-pole flux-guided rotor; (*c*) four-pole flux-guided rotor.

Electromagnetic torque in a synchronous reluctance motor is generated due to difference in reluctance along the *d*- and *q*-axes of the motor [5, 6]. Even at the d-axis component of magnetomotive force (MMF) being equal to the q-axis MMF component ($F_{aq} = F_{ad}$), the magnetic fluxes along these axes will not be the same – the d-axis magnetic flux will be higher than that along q-axis ($\Phi_d > \Phi_q$). Thus, the interaction of the magnetic fluxes with corresponding MMF components will result in the following electromagnetic torque:

$$M = p\left(\Phi_d F_{aq} - \Phi_q F_{ad}\right), \quad (1)$$

where p is the number of pole pairs;

Φ_d, Φ_q are the fundamental harmonics of the d- and q-axis magnetic fluxes;

F_{aq}, F_{ad} are the fundamental harmonics of the q- and d-axis magnetomotive force components.

From Eq. (1) it follows that for increasing the electromagnetic torque (specific torque included) the d-axis magnetic flux should also be increased, with reducing at the same time the q-axis magnetic flux thus maintaining the maximum possible values of MMF components.

The most widely used rotor configuration of synchronous reluctance motor is shown in Fig. 1*a*. This type of rotor has a simple and rigid structure, however with the difference of reluctances along the rotor d- and q-axes being relatively low, which means its poor performance. Higher difference of reluctances can be achieved with a flux-guided type rotor (Fig. 1*b,c*). Such rotor is made as a cylinder with steel packages surrounded with non-magnetic material (aluminium).

Another way to increase the electromagnetic torque is decreasing the number of motor poles to $2p = 2$. With the pole magnetic flux of a two-pole synchronous reluctance motor taken as a basis, the pole magnetic flux will be decreased at the pole number increasing. At the same time, the resultant MMF per pole pair will also be reduced due to the decrease in the number of current conductors under each pole. Therefore, in a first approximation, Eq. (1) can be rewritten as

$$M_p = p\left(\frac{\Phi_{d1}}{p}\frac{F_{aq1}}{p} - \frac{\Phi_{q1}}{p}\frac{F_{ad1}}{p}\right) = \frac{1}{p}\left(\Phi_{d1}F_{aq1} - \Phi_{q1}F_{ad1}\right), \quad (2)$$

where M_p is the electromagnetic torque per pole pair;

Φ_{d1}, Φ_{q1} are the fundamental harmonics of the d- and q-axis pole magnetic fluxes of a two-pole motor;

F_{aq1}, F_{ad1} are the fundamental harmonics of the q- and d-axis MMF components of a two-pole motor.

To reduce the electromagnetic torque is more significant under real conditions, since with the MMF per pole pair decreasing the magnetic flux density also decreases. This means that there are two ways for reducing the pole magnetic flux: through a smaller pole surface area, and through a lower magnetic flux density in the air-gap under the pole. Thus, to determine the electromagnetic torque under real conditions the following approximate equation can be used:

$$M_p = \frac{1}{p^k}\left(\Phi_{d1}F_{aq1} - \Phi_{q1}F_{ad1}\right), \quad (3)$$

where $1<k<2$ is the factor of electromagnetic torque reduction due to increase in the number of poles.

Finally, the third way of increasing the specific electromagnetic torque is minimization of the magnetic circuit mass by improving configuration of the massive elements of the motor.

The aim of this paper is to provide a detailed analysis of design solutions for increasing the specific electromagnetic torque of a synchronous reluctance motor.

3. SYNCHRONOUS RELUCTANCE MOTOR WITH INCREASED SPECIFIC ELECTROMAGNETIC TORQUE

Most researchers, when studying and optimizing the design of synchronous reluctance motor, make efforts to reducing the q-axis magnetic flux only. In many cases, the d-axis magnetic flux turns out to be too much reduced, which results in a lower electromagnetic torque of the motor.

For instance, the q-axis magnetic flux of a synchronous reluctance motor with the rotor configurations shown in Fig. 1*b,c* is significantly reduced due to non-magnetic layers of aluminium. However, the cross-section of steel packages in the rotor is also reduced, which means a decrease in the d-axis magnetic flux. In this case, the decrease is greater than that in the q-axis magnetic flux, which leads to a decrease in the electromagnetic torque.

To find an optimal solution at designing the synchronous reluctance motor with reduced q-axis magnetic flux and as high electromagnetic torque as possible, a careful analysis is needed.

Figure 2 presents the cross-section of a two-pole synchronous reluctance motor with the outer rotor. The figure also shows current distribution in the stator, the vectors of created MMF and magnetic flux components. The reluctance motor has a standard design with inner stator *1* and outer rotor *2*. To reduce the q-axis magnetic flux, the rotor is built with salient poles *5*, *6* separated from each other by non-magnetic spaces *3* and *4*. The optimal configuration of rotor elements will be considered below.

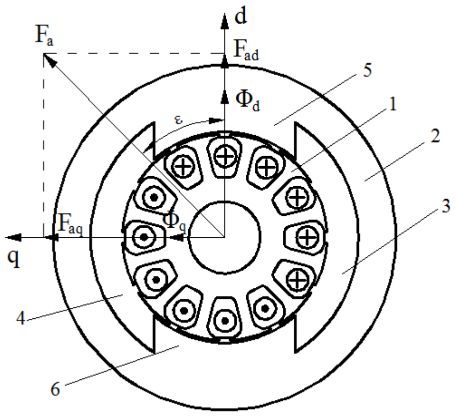

Fig.2. A two-pole synchronous reluctance motor with the number of pole pairs per phase q = 2: *1* – stator with armature winding; *2* – rotor; *3, 4* – non-magnetic spaces; *5, 6* – rotor poles.

First, it is important to find the optimal value of angle ε between the vector of resultant MMF (F_a) and the motor d-axis (Fig. 2).

The equation for the electromagnetic torque of a synchronous reluctance motor can be written as

$$M = \Phi_d F_{aq} - \Phi_q F_{ad} = G_d F_{aq} F_{ad} - G_q F_{aq} F_{ad} = F_{aq} F_{ad} (G_d - G_q) , \qquad (4)$$

where G_d, G_q are the permeances along the d- and q-axis, respectively.

The MMF components F_{aq}, F_{ad} can be obtained through the resultant MMF F_a and angle ε as $F_{aq} = F_a \sin\varepsilon$, $F_{ad} = F_a \cos\varepsilon$. Therefore, Eq. (4) can be transformed to the following:

$$M = F_a^2 \sin\varepsilon \cdot \cos\varepsilon \cdot (G_d - G_q)\,. \tag{5}$$

Without considering the values of permeances, analysis of Eq. (5) shows that the optimal value of angle ε for the maximum electromagnetic torque should be 45^o. In this case, the motor operation at angle $\varepsilon = 45^o$ can be provided by electronic commutation. Equation (5) for the maximum value of electromagnetic torque can be rewritten as

$$M = 0.5 F_a^2 (G_d - G_q)\,. \tag{6}$$

Next, optimal configuration of the rotor elements of a synchronous reluctance motor can be considered as associated with minimization of permeance G_q along the q-axis and maximization of permeance G_d along the d-axis. The task of the optimization is to find the effective values for the pole arc coefficient and for the non-magnetic space h_q between the rotor poles.

In the first approximation, pole-arc coefficient $\alpha_\delta = 0.5$ is taken as the initial value for the analysis. This means that pole width b_p is equal to the half of pole division τ, and, as shown in Fig. 2, the slots placed under one pole have conductors that carry current in the same direction. If the pole-arc coefficient is increased, there will be two more slots under the pole (one at each pole side), which have the conductors carrying current in different directions with respect to each other. In this case, permeance G_d will be 5/3 higher than the initial; however, the excitation MMF F_{ad} will be reduced in the air-gap under the pole, which would lead to decrease in the d-axis magnetic flux to 5/9 of the initial value. At the same time, permeance G_q will increase due to the reduced width of the non-magnetic space between poles. As a result, the difference of permeances along the motor axes $(G_d - G_q)$ will diminish, which means that it is of no use to increase the initial pole-arc coefficient. At the same time, decreasing this coefficient would also be inexpedient, since the d-axis magnetic flux will be significantly reduced, with corresponding increase in the q-axis magnetic flux. Thus, from this analysis it follows that the optimal pole-arc coefficient is $\alpha_\delta = 0.5$.

In order to increase the reluctance to the q-axis magnetic flux, e.g. to make it $10 \div 15$ times higher than permeance G_d, the thickness of non-magnetic space h_q should also be 10÷15 times greater than air-gap δ of the motor. However, it is not enough to reduce the braking electromagnetic torque. The analysis of the q-axis magnetic flux arising in a synchronous reluctance motor has shown that this flux, in turn, has two components: magnetic flux Φ_q' (closed through the non-magnetic spaces 3, 4), and magnetic flux Φ_q'' induced by current of the q-axis MMF under the middle of each pole (Fig. 3). In this case, electromagnetic torque generated by interaction of currents in two zones (A_q and A_d) holds the rotor poles in a symmetric position with respect to these zones.

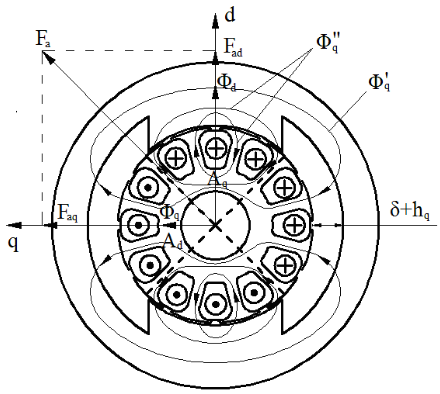

Fig.3. Visualization of the achieved q-axis magnetic flux.

To avoid interaction of current zones each pole should contain non-magnetic gaps *7, 8* (Fig. 4) [7]. In turn, this would lead to a weaker effect of currents in zone A_q, at the same time reducing the q-axis magnetic flux component Φ_q'' which interacts with zone A_d defining the d-axis MMF component.

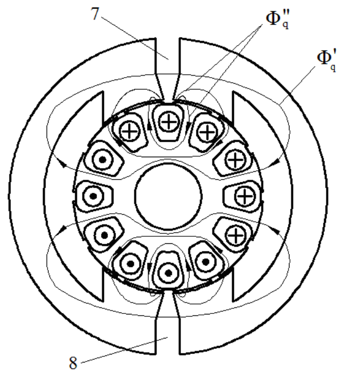

Fig. 4. Synchronous reluctance motor with non-magnetic gaps in the rotor poles: *7, 8* – non-magnetic gaps in the middle of each pole.

4. CONFIGURATION OF NON-MAGNETIC GAPS IN THE ROTOR POLES OF SYNCHRONOUS RELUCTANCE MOTOR

To increase the reluctance to the q-axis magnetic flux $\Phi_q = \Phi_q' + \Phi_q''$ in the synchronous reluctance motor a non-magnetic gap in its rotor poles is proposed. A fragment of the rotor pole with a non-magnetic gap is shown in Fig. 5.

In the mentioned figure it could be seen that the minimum width of non-magnetic gap *7* is at the air gap of motor Δ_{min}, and its maximum width – at the outer diameter of rotor Δ_{max}. In order not to decrease the d-axis magnetic flux, the width Δ_{min} of non-magnetic gap should not diminish much the pole surface at the air gap of motor.

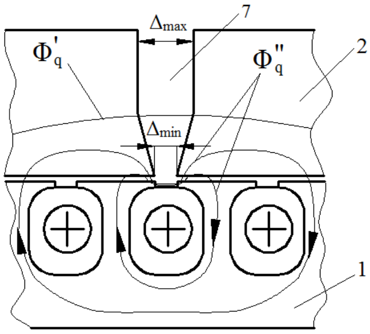

Fig.5. A fragment of the rotor pole of synchronous reluctance motor:
1 – stator; *2* – rotor; *7* – non-magnetic gap in the middle of pole.

At the Δ_{min} value chosen equal to tooth width b_z, the value of d-axis magnetic flux decreases by 30%; at the same time, the q-axis magnetic flux remains almost unchanged since the main reluctance to the q-axis magnetic flux is created by non-magnetic spaces 3, 4 between the rotor poles (see Fig. 4). In this case, the decrease in the q-axis magnetic flux component Φ_q'' will not compensate the decrease in the d-axis magnetic flux. Thus, it is not necessary to increase the value of Δ_{min} but it is important to improve its configuration.

Figure 6 presents the configuration proposed for the non-magnetic gap made non-parallel to the motor axis along its length *l* and having an arrow shape. The value of non-magnetic gap width Δ_{min} can be equal to the stator slot opening b_o. In this case, the non-magnetic gap does not raise the reluctance to the d-axis magnetic flux but significantly reduces the q-axis magnetic flux component Φ_q''.

The non-magnetic gap in the rotor pole creates a barrier for the q-axis magnetic flux; as shown in Fig. 5, magnetic flux Φ_q'', which is closed through a rotor pole, passes the air-gap of the motor four times, which significantly reduces the flux value.

The arrow shape of non-magnetic gap has an additional decreasing effect on the magnetic flux Φ_q''. This can be explained by the fact that each sheet of the laminated pole has different surfaces ($S_1 \neq S_2$) on both sides separated by the non-magnetic gap. Therefore, the reluctances to the magnetic flux on both sides are also different (Fig. 6).

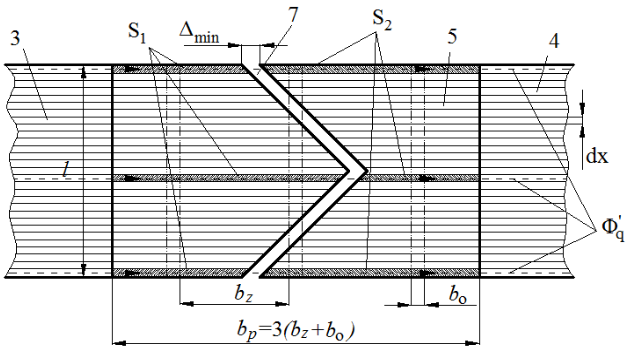

Fig. 6. A fragment of the rotor pole of synchronous reluctance motor: *3, 4* – non-magnetic spaces between poles; *5* – rotor pole; *7* – non-magnetic gap in the middle of pole; dx is the sheet width.

5. MAGNETIC FIELD SIMULATION OF SYNCHRONOUS RELUCTANCE MOTOR

Figure 7 shows the magnetic field simulated by QuickField computer software [8, 9] for modelling a synchronous reluctance motor with the following parameters:

– outer diameter of the stator	D = 54 mm;
– outer diameter of the motor	D_a = 100 mm;
– active length of the motor	l = 100 mm;
– width of the non-magnetic space between poles	h_q = 8 mm;
– pole overlapping coefficient	α_δ = 0.5;
– armature MMF	F_a = 840 A;
– number of conductors per slot	N_r = 50;
– amplitude of the 3-phase current	I_m = 4.2 A
– current density in the armature winding	j = 5.8 A/mm;
– minimal width of the non-magnetic gap in the pole	Δ_{min} = 2 mm;
– rated electromagnetic torque	M_N = 1.8 Nm;
– specific electromagnetic torque	M_s = 0.36 Nm/kg.

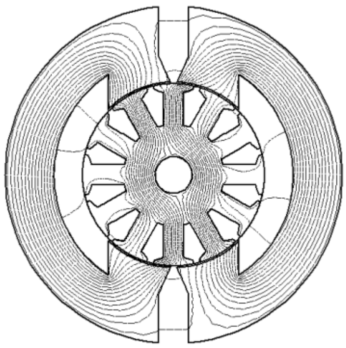

Fig. 7. Magnetic field of synchronous reluctance motor at $\varepsilon = 45^o$.

Analysis of the magnetic field of the synchronous reluctance motor under consideration evidences that the non-magnetic gap in its pole does not create a barrier for the d-axis magnetic flux but significantly reduces the q-axis magnetic flux. The results obtained in the magnetic field simulation show that the d-axis magnetic flux exceeds the q-axis magnetic flux almost 8 times.

6. CONCLUSIONS

Based on the results obtained in the work, the following conclusions can be drawn:

1. The analysis of brushless synchronous motor types has shown that a synchronous reluctance motor is the most reliable for low-power drives of power tools and household appliances.
2. High-speed synchronous reluctance motors have high efficiency and power factor, which is important at long operation under hard conditions.
3. The two-pole synchronous reluctance motor with non-magnetic gap in each pole is the most effective design solution for increasing the specific electromagnetic torque (up to 0.35÷0.4 Nm/kg).

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BEZKONTAKTU SINHRONIE DZINĒJI AR PAAUGSTINĀTU DROŠUMU IZMANTOŠANAI ELEKTROINSTRUMENTOS UN SADZĪVES TEHNIKĀ

N. Levins, V. Pugačevs, J. Dirba, L. Lavrinoviča

K o p s a v i l k u m s

Darbā veikta sadzīves tehnikā un elektroinstrumentos izmantojamo bez-kontaktu elektrodzinēju analīze. Parādīts, ka sinhronie reaktīvie dzinēji, pateicoties konstrukcijas vienkāršumam, drošumam un izturībai ilgstošā darbībā, kā arī mazām izmaksām, ir piemērotākie izmantošanai mazjaudas sadzīves tehnikā un elektro-instrumentu piedziņai. Piedāvāti sinhrono reaktīvo dzinēju konstruktīvie risinājumi magnētiskā lauka šķērskomponentes samazināšanai. Šādi dzinēji spēj nodrošināt īpatnējā momenta vērtības līdz 0.35÷0.4. Nm/kg.

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