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ELECTRIC MACHINES WITH NON-RADIALLY MOUNTED RECTANGULAR PERMANENT MAGNETS

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The authors analyze the advantages and disadvantages of brushless synchronous electric machines with radially and non-radially mounted rectangular permanent magnets. The results show that the proposed non-radial mounting of permanent magnets considered in the paper, in several cases (e.g. multi-pole brushless generators with tooth windings of the armature) allows achievement of the following advantages: better technology of manufacturing the electric machine owing to simple packing of the stator winding in the stator open slots, which also increases the copper slot fill-factor; reduction in the mass-and-size of permanent magnets at least twice; significantly lower cost of the electric machine; and, finally, its greater specific power.

Key words: *electric machine, permanent magnets, non-radial orientation.*

1. INTRODUCTION

The use of permanent magnets (PMs) in electric machines increases their reliability. Exploitation of the modern high-energy PMs in electric machines raises their output and efficiency, improves performance and opens new opportunities for such machines. At the same time, high-energy materials for PMs are still very expensive and sensitive to the influence of ambient conditions. In this connection, it is important to design magnetic systems with PMs so that the magnets create the maximum energy of magnetic field and are protected against the influence of ambient conditions.

As known, the operational principle of electric machines is entirely based on the conversion of the mechanical energy into electrical and vice versa. The air-gap plays an important role in the energy conversion, being the place of maximum concentration of the electromagnetic field energy. The more energy is concentrated in the air-gap, the more efficient the electric machines are [1–4].

The size and mass of an electric machine are dictated by the required electromagnetic torque M (or force F). These basic parameters featuring the electric machine performance can be defined by the following equations [4]:

$$M = -\frac{\partial}{\partial \alpha} 0.5 \sum_{i=1}^{n} \Psi_i i_i \quad (1)$$

or

$$F = -\frac{\partial}{\partial x} 0.5 \sum_{i=1}^{n} \Psi_i i_i \,, \quad (2)$$

where α and x are the rotation angle and moving coordinates;
Ψ_i is the magnetic flux linkage in the i-th contour;
i_i is the electric current in the i-th contour;
n is the number of the magnetically coupled contour.

The energy of the magnetic field in the air-gap is defined as

$$W_\delta = l \int_0^\tau \frac{B_\delta H_\delta dx}{2} = \frac{l}{\mu_0} \int_0^\tau \frac{B_\delta^2 dx}{2} \,, \quad (3)$$

where l is the active length of the electric machine (assuming that the magnetic field is plane-parallel), m;
B_δ, H_δ are the magnetic flux density and the magnetic field strength in the air-gap, T, A/m, correspondingly;
$\mu_0 = 4\pi \cdot 10^{-7}$ is the magnetic permeability of air, $\frac{\Omega \cdot \mathrm{s}}{\mathrm{m}}$;
τ is the pole pitch, m.

For approximate estimation of the considered process it is suggested that the magnetic flux density is constant under the entire surface of the pole, so the magnetic field energy under the surface of one pole is defined as

$$W_{P(t)} = \frac{B_\delta^2}{2\mu_0} l_m b_m \delta \,, \quad (4)$$

where δ is the air-gap of electric machine, m;
l_m is the length of the PM and is equal to the machine active length, m;
b_m is the width of the pole under which the magnetic field is considered, m.

If the overlapping of the pole and armature surfaces remains constant under the no-load operating condition of electric machine, the magnetic field energy will also be constant, with no electromagnetic torque generating.

In the case when the electric machine is loaded, the magnetic field intensity changes under the influence of armature reaction, i.e. the magnetic flux density is changed under the pole, so

$$W_{P(t+\Delta t)} = \frac{\left(B_\delta - \Delta B\right)^2}{2\mu_0} \cdot l_m b_m \delta \,. \quad (5)$$

The energy difference in relation to the rotation angle of the rotor, causing the change in the magnetic flux density, determines the electromagnetic torque:

$$M=\frac{W_{P(t+\Delta t)}-W_{P(t)}}{\Delta\alpha}=\frac{B_\delta^2}{2\mu_0}\cdot\frac{l_m b_m\delta}{\Delta\alpha}-\frac{\left(B_\delta-\Delta B\right)^2}{2\mu_0}\cdot\frac{l_m b_m\delta}{\Delta\alpha}= \\ =\frac{2B_\delta\Delta B-\Delta B^2}{2\mu_0\Delta\alpha}l_m b_m\delta, \tag{6}$$

where ΔB^2 is the second-order infinitesimal value.

Therefore, from Eq. (6) it follows that the generated electromagnetic torque is proportional not only to the magnetic flux density but also to its initial value, i.e. to the previously concentrated energy:

$$M=\frac{B_\delta}{\mu_0}l_m b_m\delta\cdot\frac{\Delta B}{\Delta\alpha}, \tag{7}$$

from where a very important inference could be drawn: if the magnetic field of excitation is evenly distributed under the poles with a large width, i.e. $b_m\to\tau$, the pole width decreasing (with the magnetic field of the pole kept constant) leads to increase in the electromagnetic torque and specific power of the electric machine.

2. THE USE OF PERMANENT MAGNET ENERGY

Figure 1 presents the demagnetization curve of a PM with the points characterizing the use of its energy during the electromechanical conversion [4]. Parameters plotted on the axes are: B_r – the remanent flux density, H_c – the coercive force. Point C on the demagnetization curve characterizes the maximum energy of the PM.

The mentioned figure shows that the magnetic flux density at the operating point A for a hard-magnetic material (e.g. Nd–Fe–B) is usually chosen close to its remanent value ($B_\delta=0.8\div1.0$ T). Such a point is chosen taking into account the value of magnetomotive force required for concentration of the magnetic flux in the magnetic circuit and the counteraction of armature reaction. However, as follows from Fig. 1, in this case the PM is not used at the maximum of its capabilities. The energy of magnetic field at point A (area S_A) is significantly smaller than possible for this magnet (point C, area S_C). The use of magnet energy is incomplete here – only ~ 50%. Thus, it is necessary to increase the PM size to provide the excitation performance, which would make the PMs – and, therefore, the electric machines containing them – too expensive.

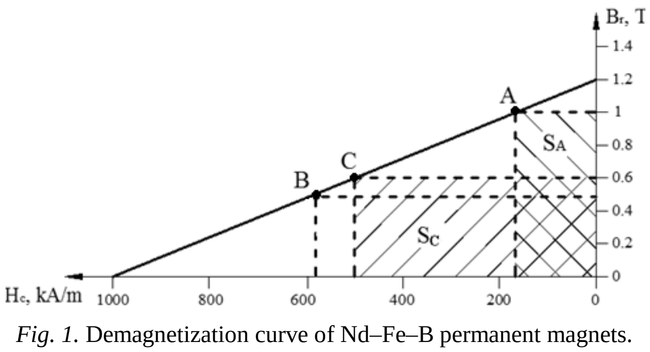

Fig. 1. Demagnetization curve of Nd–Fe–B permanent magnets.

From analysis of the results in the example under consideration it follows that a constructive solution with the 100% use of PM energy is needed in order to reduce significantly the cost of electric machine. So far, the most often employed constructive solution – that of mounting rectangular PMs with radial orientation – cannot ensure the complete use of magnet energy corresponding to point C (Fig. 1) because the magnetic flux density is very low at this point ($B_\delta = 0.6$ T). Therefore, this solution does not provide effective use of the magnetic circuit and of the electric machine in general.

3. RECTANGULAR NON-RADIAL PERMANENT MAGNETS AND ADVANTAGES OF THEIR USE

Figure 2 presents a fragment of the electric machine geometry where the mounting of rectangular PMs is illustrated for the case of tangential (non-radial) orientation instead of radial.

In this case, each pole of the rotor is formed by two PMs whose magnetic fluxes in the air-gap are summed up, i.e.

$$\Phi_\delta = 2\Phi_m \,. \tag{8}$$

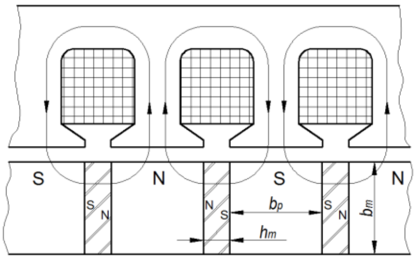

Fig.2. Fragment of the electric machine geometry with tangential orientation of PMs: b_m – PM width; b_p – pole width; h_m – PM thickness.

Assuming the PM width to be equal to that of pole and the magnetic flux density in the air-gap to be set e.g. as $B_\delta = 1$ T, then, taking into account Eq. (8), for each PM the magnetic flux density can be obtained as

$$B_\delta = 0.5 B_{\delta A} = 0.5 \text{ T}. \tag{9}$$

In this case the PM operating point should be chosen at point B on the demagnetization curve, which is not the point of maximum magnet energy (point C) but is close to it. Hence, according to Fig. 1, each PM creates a magnetic field with the intensity:

$$H_B \approx 600 \text{ kA/m}. \tag{10}$$

Considering that for concentration of the magnetic flux in the magnetic circuit (which, in this case, already includes two air-gaps) the magnetic field intensity created by each PM can be:

$$H_{2\delta} \approx 300 \text{ kA/m}, \tag{11}$$

i.e. half the existing value (600 kA/m). Thus, creating the conditions when the operating point on demagnetization curve (point B) approximately corresponds to those for deriving the maximum energy from a PM (point C), it is possible to reduce its thickness by half, and hence, reduce its cost.

The PM mass and cost reduction also allows reducing the cost of manufacturing the electric machine.

Referring to the features of the electric machine design (Fig. 2), it is specified that the rotor with the PMs mounted in its slots should have "open slots" in the direction to the machine shaft. This means that the rotor should be mounted on a non-magnetic sleeve as separated sectors, which are fixed with non-magnetic studs. This mounting complicates the design – though insignificantly, taking into account the cost reduction for a PM made of expensive hard-magnetic material.

To reduce the radial thickness of the sectors or increase the width of PMs they can be mounted skewed as shown in Fig. 3.

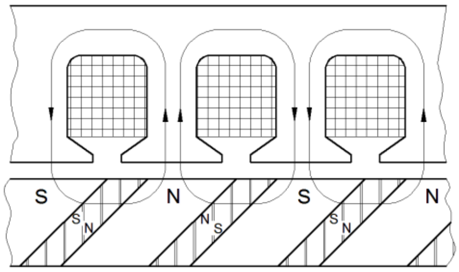

Fig. 3. Fragment of electric machine geometry with PMs skewed to the radius.

Increase in the width of PM (if necessary) allows decreasing its thickness or increasing the magnetic flux density in the air-gap up to 1.1÷1.2 T. At the same time, as shown above, this would increase the power of the electric machine.

Application of non-radially oriented PMs allows for the use of a stator with open slots, which not only simplifies the technology of manufacturing the electric machine but also makes it possible to increase significantly the specific power of electric machine due to better slot filling of the copper and increased magnetic flux density in the air-gap.

For instance, at the use of a stator with semi-closed slots the magnetic flux density is limited to 1 T, while a stator with open slots allows increasing the magnetic flux density in the air-gap, B_δ, up to 1.4 T due to decreasing the tooth tip width 1.4 times and keeping the magnetic field intensity the same. This solution can easily be achieved using non-radially oriented PMs. Then, according to Eq. (6), the torque (and the power) of the electric machine can be raised about 30–40% while reducing the cost of energy production without increasing its size and mass.

4. RESULTS AND DISCUSSION

Figure 4 shows the geometry of a generator's design with 20 poles on a rotor formed by conventional radially-oriented rectangular PMs and teeth [5, 6]. The concentrated three-phase armature winding is packed in 24 stator slots. The inside diameter of the stator is D = 196 mm, the length of stator and rotor packages is l = 50.4 mm. The rectangular Nd–Fe–B magnets with sizes 12.7×25.4×50.4 are mounted over one pole. The parameters of PM materials are: $B_r = 1.2$ T, and $H_c = 1000$ kA/m [7]. The total mass of the generator is 27 kg, and the power is $P_N = 1.4$ kW at the rotational speed $n_N = 250$ min^{-1}.

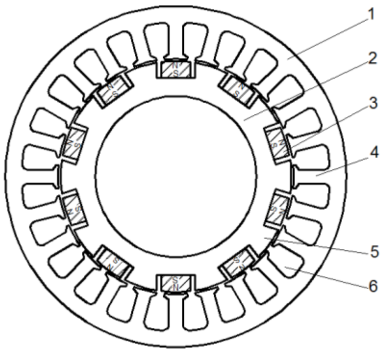

Fig. 4. Cross-sectional view of the generator with radially-oriented PMs: *1* – stator, *2* – rotor, *3* – permanent magnet, *4* – stator tooth, *5* – rotor tooth, *6* – stator slot with armature winding.

The magnetic field of the generator is calculated using the software "QuickField", which is based on the finite element method [8]. The numerical solution of the magnetic field shows that the maximum magnetic flux in the stator tooth is $\Phi_{z\max} = 0.001$ Wb. The calculated value of the magnetic flux has been confirmed by the results of experimental testing of the prototype generator. The calculated rated power has also been confirmed experimentally.

Figure 5 demonstrates the proposed design of the generator with tangentially oriented rectangular PMs. The PM mass and sizes (6.36×12.7×50.4 mm) are significantly reduced in this embodiment almost four times, at a double number of magnets. Other parameters are the same.

As shown by the magnetic field calculation, the magnetic flux in this generator coincides with the previous: $\Phi_{z\max} = 0.001$ Wb, while its power increases to 2 kW.

Thus, the use of PM non-radial orientation provides such advantages as high specific power, better manufacturing technology and low cost.

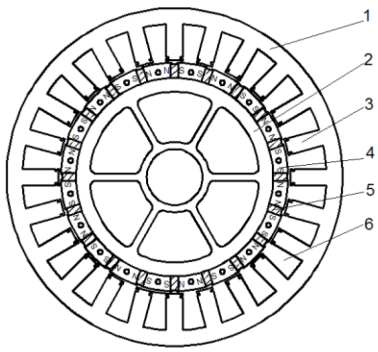

Fig. 5. Cross-sectional view of the generator with tangentially oriented PMs: *1* – stator, *2* – rotor, *3* – stator tooth, *4* – rotor tooth (rotor pole), *5* – permanent magnet, *6* – stator slot.

In the same way the PM non-radial orientation in electric motors could be considered for application, e.g., in hand electric tools [9].

4. CONCLUSIONS

Based on the results obtained in the work it could be stated that the use of non-radially oriented rectangular PMs in the multi-pole brushless generators with tooth windings of the armature allows the following to be achieved:

1) reduced size and mass of a PM made of hard magnetic materials, which allows for reduction in its cost twice;
2) better technology of electric machine manufacturing due to the use of open slots in the stator, which simplifies the winding packing and increases the copper slot fill-factor;
3) greater specific power of electric machine due to high copper slot fill-factor and high magnetic flux density in the air-gap, which reduces the steel saturation as well as eddy currents and hysteresis losses.

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ELEKTRISKĀS MAŠĪNAS AR PRIZMATISKIEM NERADIĀLI NOVIETOTIEM PASTĀVĪGAJIEM MAGNĒTIEM

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

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

Darbā tiek analizētas priekšrocības un trūkumi sinhronām bezkontaktu mašīnām ar radiāli un neradiāli novietotiem prizmatiskiem pastāvīgajiem magnē-tiem. Parādīts, ka vairākos gadījumos, piemēram, daudzpolu bezkontaktu sinhro-najos ģeneratoros ar zobu tinumiem, neradiāls pastāvīgo magnētu izvietojums nodrošina vairākas priekšrocības: uzlabojas mašīnas izgatavošanas tehnoloģija, jo statora atvērtajās rievās vieglāk novietot tinumus un iespējams sasniegt augstāku rievas aizpildījuma koeficientu; samazinās pastāvīgo magnētu masa un izmaksas; palielinās mašīnas īpatnēja jauda.

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