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ELEMENTS OF THERMAL CALCULUS OF COMPONENTS IN ELECTROMECHANICAL BRUSHLESS CONVERTER WITH OPEN-POLE STATOR AND EXTERNAL ROTOR WITH PERMANENT MAGNETS

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Brushless motor with open-pole stator and permanent magnet rotor characterized by sufficient simplicity of design and manufacturing techniques. It is also relatively economical for asynchronous electric machines. At the same time, it provides much higher quality consumer characteristics. According to the widespread use of traditional designs with internal rotor gearless drive for a number of mechanisms is often necessary to use a design with external rotor. This design is simple, reliable, technological and economical. Methods of synthesis, optimization and research brushless motor with external rotor and permanent magnets require a simple and reliable method of the thermal state calculation of the main components, as it affects energy performance and reliability of this machine.

Estimation features of a thermal condition of the main components of the brushless electromechanical converter with an open-pole stator and an external rotor with permanent magnets are considered in the article. Particular attention is paid to the importance of such an assessment for electromechanical brushless converters with permanent magnets on the rotor, the maximum allowable operating temperature for which is limited to low values. Such magnetic materials are known to be significantly cheaper at high-energy values, but lose, often irreversibly, the magnetic properties when the temperature of the allowable heating is

exceeded. On the other hand, for a number of applications of such an electromechanical converters. For example, in motor-wheel in vehicles, the cooling surface of the rotor with permanent magnets is closed-type, which gives grounds to consider the need to assess the thermal state of the main components of the electromechanical converter of brushless motor, especially external rotor with permanent magnets, in all stages of its design - synthesis, optimization of geometric dimensions and research.

The proposed method of a thermal calculus of brushless electromechanical converter elements, such with permanent magnets on the rotor, allows with sufficient accuracy for engineering practice to perform appropriate calculations of these motors, in particular, for direct drive of mechanisms.

Key words: permanent magnets; brushless motor; thermal condition; open-pole stator; external rotor.

Problem statement

Brushless direct current machine (BLDCM) is a DC electric machines in which the brush-collector unit replaced on the inverter, which is controlled by signals from the rotor position sensor (RPS), located on the same shaft of the rotor of the electromechanical converter (EMC) [1–4]. BLDCMs are increasingly used in electric vehicles in world practice. One of the factors slowing down the domestic production of electric vehicles, including electric cars, is the availability of inexpensive and high-quality electric drive, which could provide, along with sufficient power of controlled motors, high reliability, durability and controllability. In recent years, the efforts of foreign researchers in the field of electric cars were aimed at creating new types of motors such as, for example, induction motors [5], brushless motors (BLDCM) with permanent magnets (PM), characterized by a high specific magnetic flux without mechanical transmissions [6]. Different study are developed in field of motors with two rotors [7], machines with hybrid, magnetic and electromagnetic excitation, motors with two stator windings, electric machines integrated with magnetic transmission system [8], etc.

Based on these motors, compact and reliable direct drives can be created for wheeled motors systems, for vehicles, including electric vehicles. To control these types of electric motors, modern methods of control theory are used: vector control with elements of adaptive control, sliding mode control, intelligent control (fuzzy control, use of artificial neural networks) [6–8]. Unlike induction motors, the efficiency of which significantly depends on changes in voltage and load, BLDCM with PM generally maintain their speed and energy efficiency when the mains voltage and load change and therefore are particularly attractive to motor developers [9–11].

Relevance of the study

Today, there is often a need for gearless drive, in particular, in transport, and therefore the use in BLDCM of EMC with PM and an external rotor. Synthesis and analysis of BLDCM with PM on the outer rotor requires a simple and reliable method of calculating the thermal state of important motor or converter units, because it depends on the performance of such a motor. The open-pole internal stator, concentrated coils of its winding and PM on the external rotor determine the difference between the methods of calculating the thermal state of the EMC of BLDCM with PM on the external rotor from those known in the literature [1–5, 8]. This calculation of EMC with an open-pole stator and an external rotor with permanent magnets has a number of differences compared to the BLDCM of traditional design and is especially important for EMC of BLDCM with magnets on the rotor, the maximum allowable temperature for which is low [12]. Magnetic materials with high-energy performance and low allowable operating temperature are significantly cheaper, but can irreversibly lose their magnetic properties in excess of the allowable value of the heating temperature [12]. Important task is checkout calculating of thermal condition of BLDCM with PM and external rotor on design and synthesis stages, on stage of geometric dimensions optimization, and especially in the case when the surface of the rotor cooling is also limited, such as in-wheel motor.

Purpose and objectives of research

The aim of the article is to develop the method of thermal state calculating of elements in electromechanical converter of BLDCM with PM. The last one would allow with sufficient accuracy for engineering practice to estimate the heat load of the main EMC components of such motors, in particular those application of magnetic materials critical to overheating both at the stages of design and optimization of geometric dimensions and during research.

Actual scientific researches analysis

To the problem of calculating the thermal state in EMC, include the calculus of the average temperature of the EMC active parts [16], determining maximum temperature of elements and components depending on the profile loading, calculating heat flow between adjacent elements of design and so on. The initial data are the distribution of energy losses over the volume of the machine [14], the values of physical quantities [8], primarily thermal conductivity and heat capacity, and cooling conditions at the boundary surfaces. In passive rotor BLDCM [14] heat sources are losses in the copper of the stator winding – ΔP_m, stator steel loses – ΔP_{sts} and rotor loses – ΔP_{str} and mechanical loses, which consist of friction losses in bearings and friction of rotor teeth to air – ΔP_{mech}. Since the designs of EMC of BLDCM with a passive external rotor and EMC with PM on the explicit rotor are largely similar, as a basis for calculating the thermal state of the latter we use the method described in [14].

The main material presenting

Among the significant structural differences between the EMC of BLDCM with PM on the outer rotor and the BLDCM with a passive rotor (Fig. 1 [14]) is absence of laminated core of the rotor and, accordingly, losses in the rotor steel. Instead, the frame of the external rotor with PM serves as a magnetic conductor to close the flow of magnets, which provides for the feasibility of developing elements of the method of the thermal state calculating of BLDCM components [14] for application to EMC with PM on the external rotor.

To do this, as in [14], we accept the following assumptions. At first, losses in copper are concentrated in the central part of the coils of the internal stator winding; losses in the stator steel are concentrated in the central axial lines of the teeth and the central cylinder of the frame. The next assumption – the coefficients of thermal conductivity of materials and air are constant and equal to their value at the accepted design temperature. And, at last, the stator and rotor cores conduct heat only in the radial direction.

In addition, suppose that heat fluxes propagate in the following directions. At first - from the stator winding to the teeth and the stator back, the next - from the teeth of the stator through the air gap to the rotor. So, the inverse direction – from the rotor to the indoor air and from the stator winding through the interturn insulation to the indoor air; from the indoor air to the end surfaces of the rotor, which give off heat to the outside air.

That is, as in [14], the thermal replacement circuit (Fig. 2 [14]) will consist of five elements: the stator winding (M) with losses ΔP_m and average temperature θ_m; stator (*S*) with loses ΔP_{sts} and average temperature θ_s; rotor (*R*), with the zero loses $\Delta P_{str}=0$ and average temperature θ_r; internal air (*P*) with loses ΔP_{mech} and average temperature θ_p; rotor body K_r with average temperature θ_{kr}. Temperature of external air θ_{air}.

Elements of the substitute thermal circuit are connected by thermal conductivities (see fig. 2). We write a system of linear algebraic equations like in

$$\Lambda \times \Theta = \Delta \mathrm{P}. \tag{1}$$

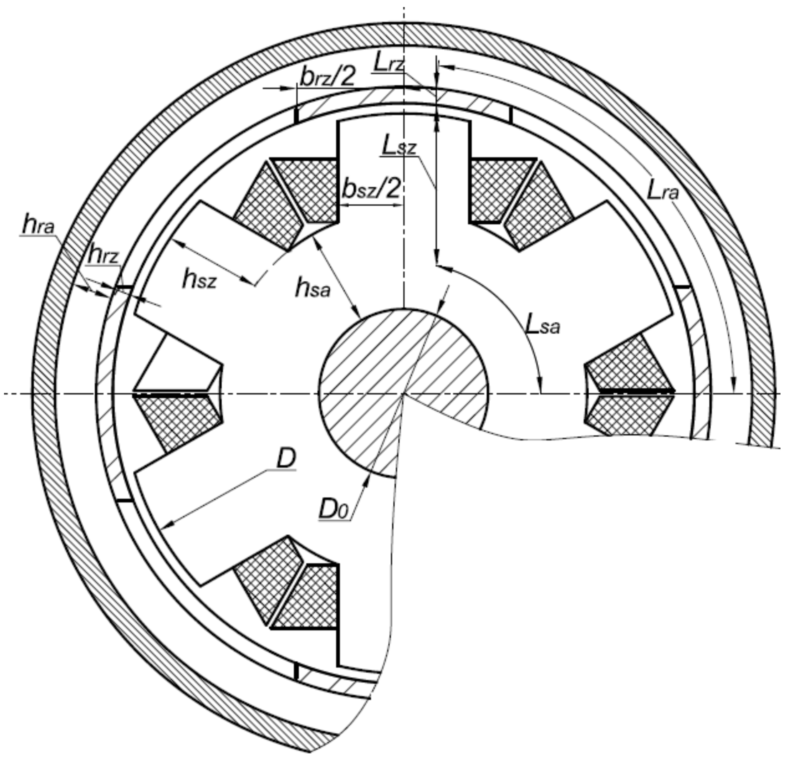

Fig. 1. Cross section of BLDC motor with external rotor

Matrix in (1) we can write as $\Lambda = \begin{Vmatrix} \Lambda_{11} & -\Lambda_{ms} & 0 & -\Lambda_{mp} & 0 \\ -\Lambda_{ms} & \Lambda_{22} & -\Lambda_{sr} & 0 & 0 \\ 0 & -\Lambda_{sr} & \Lambda_{33} & -\Lambda_{pr} & -\Lambda_{rkr} \\ -\Lambda_{mp} & 0 & -\Lambda_{pr} & \Lambda_{44} & -\Lambda_{pkr} \\ 0 & 0 & -\Lambda_{kr} & -\Lambda_{pkr} & \Lambda_{55} \end{Vmatrix}; \ \Theta = \begin{Vmatrix} \theta_m \\ \theta_s \\ \theta_r \\ \theta_p \\ \theta_{kr} \end{Vmatrix}; \ \Delta\mathrm{P} = \begin{Vmatrix} \Delta P_m \\ \Delta P_{sts} \\ \Delta P_{str} \\ \Delta P_{mach} \\ \theta_{air} \times \Lambda_{air} \end{Vmatrix},$

where $\Lambda_{11} = \Lambda_{mp} + \Lambda_{ms}$; $\Lambda_{22} = \Lambda_{ms} + \Lambda_{sr} + \Lambda_{air}$; $\Lambda_{33} = \Lambda_{sr} + \Lambda_{pr} + \Lambda_{rkr}$; $\Lambda_{44} = \Lambda_{mp} + \Lambda_{pr} + \Lambda_{pkr}$; $\Lambda_{55} = \Lambda_{rkr} + \Lambda_{pkr}$, where Λ_{ms}, Λ_{mp} – heat conductivity from the stator winding to the teeth and the stator back and from the stator winding through the interturn insulation to the indoor air; Λ_{sr}, Λ_{pr} – heat conductivity from the stator teeth through the air gap to the rotor and from the rotor to the indoor air; Λ_{rkr}, Λ_{pkr} – heat conductivity from the rotor to the rotor housing and from the indoor air to the bearing plates and the rotor housing; Λ_{kr}, Λ_{air} – heat conductivity from the rotor housing to the outside air and from the stator to the outside air [14].

To find the unknown temperatures, it is necessary to pre-calculate the heat conductivities included in (1) according to [14].

Since the structural stators of the BLDCM with PM and with a passive rotor are similar, the ratios for determining the thermal conductivities included in (1) are determined from the geometric dimensions of the stator components of the EMC. Similar to [14], we write equation (2):

$$S_1 = \left(2 \cdot b_{sz} + 2 \cdot L\right) \cdot h_k \cdot Z_s; \quad S_2 = \left(2 \cdot b_{sz} + 2 \cdot L + 2 \cdot \pi \cdot b_{ks}\right) \cdot h_k \cdot Z_s;$$
$$S_3 = \left[2 \cdot \left(b_{sz} + L\right) \cdot b_{k1} + \pi \cdot b_{k1}^2\right] \cdot Z_s; \quad S_4 = \left(2 \cdot b_{k1} \cdot L\right) \cdot Z_s; \quad S_5 = S_3 - S_4, \tag{2}$$

where S_1, S_2, S_3, S_4 – the contact area of the stator winding coils with the teeth, the contact area of the stator winding coils with the internal air, the ends of the coils in contact with the stator frame, the same ends that are in contact with the internal air, respectively [14]; b_{sz} – width of stator teeth; h_k – height of winding; b_k, b_{k1} – one-sided width of the coil (up and low); b_{ks} – the average value of the one-sided width of the coil;

$$b_{k1} = \sqrt{\frac{D_0^2}{4} + D_0 \cdot h_{sa} + h_{sa}^2 - \frac{D^2}{4} - D \cdot h_{sz} + h_{sz}^2} - \frac{b_{sz}}{2};$$

$$b_{ks} = \frac{1}{2} \cdot (b_k + b_{k1}).$$

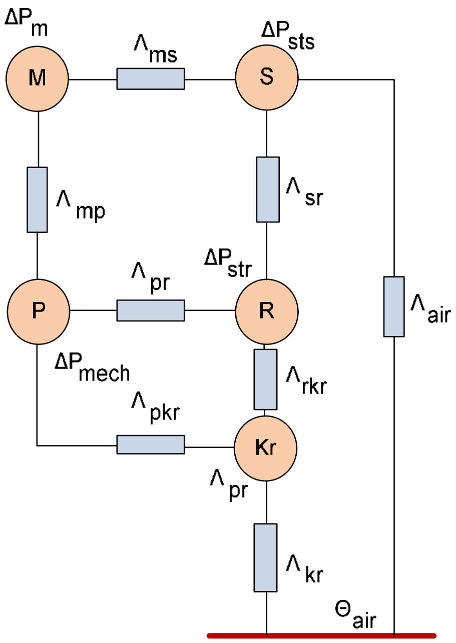

Fig. 2. Scheme for heat calculus of motor with external rotor [14]

Then, according to [14], the heat flux from copper to the teeth and the frame overcomes the thermal resistance of the winding insulation of the conductors, enamel insulation and air gaps between the conductors, the thermal resistance of the air gap between the frame and the tooth, the thermal resistance of the tooth. Therefore, the heat conductivity from copper to teeth [14]:

$$\Lambda_{m.z} = \frac{1}{\frac{1}{\Lambda_{e\_m.z}} + \frac{1}{\Lambda_{k\_m.z}} + \frac{1}{\Lambda_{\delta\_m.z}} + \frac{1}{\Lambda_{z\_m.z}}}, \tag{3}$$

where $\Lambda_{e\_m.z}$ – equivalent heat conductivity of coil insulation, varnish and air gaps; $\Lambda_{k\_m.z}$ – heat conductivity of the frame; $\Lambda_{\delta\_m.z}$ – heat conductivity of the air gap between the frame and the tooth; $\Lambda_{z\_m.z}$ – heat conductivity of the stator tooth [14]. Similarly, the thermal conductivity from copper to the stator frame

$$\Lambda_{m.a} = \frac{1}{\frac{1}{\Lambda_{e\_m.a}} + \frac{1}{\Lambda_{k\_m.a}} + \frac{1}{\Lambda_{\delta\_m.a}} + \frac{1}{\Lambda_{a\_m.a}}}, \tag{4}$$

where $\Lambda_{e\_m.a}$ is the equivalent heat conductivity of the coil insulation, varnish and air gaps; $\Lambda_{k\_m.a}$ – heat conductivity of the frame; $\Lambda_{\delta\_m.a}$ – heat conductivity of the air gap between the frame and yoke; $\Lambda_{a\_m.a}$ – heat conductivity of the stator yoke.

The heat conductivity of copper to indoor air

$$\Lambda_{mp} = \frac{\Lambda_{m\_m\delta} \cdot \Lambda_{\delta\_m\delta}}{\Lambda_{m\_m\delta} + \Lambda_{\delta\_m\delta}}, \tag{5}$$

where $\Lambda_{m\_m\delta}$ – heat conductivity from the center to the outer surface of the coil; $\Lambda_{\delta\_m\delta}$ – the heat conductivity of the surface of the coil adjacent to the internal air.

Heat conductivity from the stator yoke to the outside air

$$\Lambda_{air} = \frac{1}{\frac{1}{\Lambda_a} + \frac{1}{\Lambda_b}}, \tag{6}$$

where де Λ_a – heat conductivity from the steel of the stator; Λ_b – heat conductivity from the stator steel to the outside air.

Structurally, external rotor with PM is different from passive rotor because teeth and the core are absent. And the frame of such EMC is the core for magnetic flux circuit, we can determine the appropriate ratio and heat conductivity by different method than listed in [14].

Heat conductivity from the rotor to the stator teeth we can calculated as

$$.\Lambda_{sr} = \frac{\Lambda_{z\_r.s}\cdot\Lambda_{\delta\_r.s}}{\Lambda_{z\_r.s}+\Lambda_{\delta\_r.s}}., \tag{7}$$

where $\Lambda_{z\_r.s}$ – heat conductivity of the PM in the external rotor; $\Lambda_{\delta\_r.s}$ – heat conductivity of the PM in the external rotor to the outer air.

The conductivity of the side surface of the rotor to the indoor air

$$\Lambda_{pr} = \left[\pi\left(\frac{D}{2}+\delta+h_{rz}\right)^2 - \pi\left(\frac{D}{2}+\delta\right)^2 - (b_{rz}\cdot h_{rz}Z_r\right]\cdot 2\cdot\lambda_{\delta}\cdot \tag{8}$$

Conductivity from indoor air to the end surfaces of the rotor

$$\Lambda_{\delta.tp} = \alpha_{rtp}\cdot S_{rtp}, \tag{9}$$

where $S_{rtp} = 2\cdot\left(\frac{\pi\cdot D_z^2}{4} - \frac{\pi\cdot D_z^2}{4}\right)$ – heat area; D_r – internal diameter of the rotor;

Conductivity from internal air to the rotor frame

$$\Lambda_{pkr} = \alpha_k\cdot S_{ikr}, \tag{10}$$

where $S_{ikr} = \pi\cdot D_z\cdot\left(2\cdot\left(L_{ra}-L_{sa}\right)10^{-2}\right)$. Heat conductivity from the surface of the rotor housing to the outside air

$$\Lambda_{kr3} = \alpha_{k\Sigma}\cdot\pi\cdot\left(D_z+2\cdot\Delta_{korp}\right)\cdot k_p\ , \tag{11}$$

where $k_p = \frac{1}{\rho_m\cdot h_p}\left[th\left(\rho_m\cdot h_p\right)\cdot\frac{2\cdot h_p}{t_p}\cdot\left(1-\frac{\alpha_i}{\alpha_{k\Sigma}}\right)+\rho_m\cdot h_p\cdot\Delta k_p\right]$; $\rho_m = \sqrt{\frac{2\cdot\alpha_k}{\lambda_p\cdot b_p}}$; $\alpha_{k\Sigma} = \alpha_k+\alpha_i$; $\Delta k_p = \frac{N_p\cdot\left(t_p-b_p\right)}{\pi\cdot\left(D_z+2\cdot\Delta_p\right)}$; $\alpha_m = 6.8\ \left[\frac{Bm}{M\cdot{}^{\circ}C}\right]$ – heat transfer coefficient by radiation from the housing surface; h_p, b_p, t_p, N_p – height, width, step and number of fins, if its presence on the surface of the rotor housing; $\alpha_k = 0.0056\frac{1}{d_{ek}}Re^{0.66}\left(\frac{d_{ek}}{l_p}\right)^{0.88}$; $d_{ek} = \frac{4\cdot h_p\cdot\left(t_p-b_p\right)}{2\cdot h_p+t_p-b_p}$; $Re = \frac{V\cdot d_{ek}}{18.9\cdot 10^{-6}}$ - Reynold's constant.

Conductivity from the end surfaces of the rotor to the outside air

$$\Lambda_{k.23} = \alpha_{rtp}\cdot\pi\cdot\left(D_z+2\cdot\Delta_p\right), \tag{12}$$

where $\alpha_{rtp} = 20+2.6\left(0.5\cdot V\right)^{0.9}$ – heat transfer coefficient of the end surfaces of the rotor; V – effective linear cooling air velocity. Heat conductivity from copper to stator steel was calculated as $\Lambda_{m.s} = \Lambda_{m.z}+\Lambda_{m.a}$. Heat conductivity from indoor air to the rotor housing can be find as $\Lambda_{pkr} = \Lambda_{\delta.tp}+\Lambda_{\delta.k}$.

Conclusions

To calculate the stability-heating mode of EMC with open-pole stator and PM on the rotor on the basis of the described above method and formulas we developed computer program, which is part of the design subsystem of such motors and allows to determine the average temperatures of its main components. The proposed method of heat calculation of elements of BLDCM with PM allows to perform appropriate calculations of these motors with adequate for engineering practice accuracy, in particular, for direct drive of the mechanisms. The elements of the methodology presented in the materials of the article serve as a basis for calculating the heat state of the main components of an electromechanical converter with an open-pole stator and an external rotor with PM at the stages of its design synthesis, optimization and research.

In the future, the authors will planning to investigate the demagnetization resistance of PM in BLDCM using a mathematical model of this type of motor based on the theory of electric and magnetic circuits. This will further give the ability to refine the model of the total heat calculation.

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ЕЛЕМЕНТИ МЕТОДИКИ ОЦІНКИ ТЕПЛОВОГО СТАНУ КОМПОНЕНТІВ ЕЛЕКТРОМЕХАНІЧНОГО ПЕРЕТВОРЮВАЧА ВЕНТИЛЬНОГО ДВИГУНА З ЯВНОПОЛЮСНИМ СТАТОРОМ І ПОСТІЙНИМИ МАГНІТАМИ НА ЗОВНІШНЬОМУ РОТОРІ

Вентильний двигун з явнополюсним статором і постійними магнітами на роторі характеризується достатньою простотою конструкції та технологією виготовлення і є порівняно економічнішим за асинхронні електричні машини. Водночас він забезпечує значно якісніші споживчі характеристики. За широкого використання традиційних конструктивних схем із внутрішнім ротором для безредукторного приводу низки механізмів часто виникає необхідність застосування конструкції із зовнішнім ротором. Така конструкція проста, надійна, технологічна, економічна. Методики синтезу, оптимізації та дослідження вентильних двигунів із зовнішнім ротором і постійними магнітами потребують простого і надійного методу розрахунку теплового стану основних вузлів, оскільки від цього залежать енергетичні показники та надійність такої машини.

У статті розглянуто особливості оцінювання теплового стану основних компонентів електромеханічного перетворювача вентильного двигуна з явнополюсним статором і зовнішнім ротором із постійними магнітами. Особливу увагу зосереджено на важливості такої оцінки для електромеханічних перетворювачів вентильних двигунів з постійними магнітами на роторі, максимально допустима робоча температура для яких обмежена невисокими значеннями. Такі магнітні матеріали, як відомо, за високих енергетичних показників істотно дешевші, однак втрачають, часто незворотно, магнітні властивості у разі перевищення температури допустимого нагрівання. З іншого боку, для цілої низки застосувань такого електромеханічного перетворювача, наприклад, мотор-колесо, поверхня охолодження ротора з постійними магнітами обмежена, що дає підстави зважати на необхідність оцінювання теплового стану основних компонентів електромеханічного перетворювача вентильного двигуна, особливо зовнішнього ротора з постійними магнітами, на всіх етапах його проєктного синтезу, оптимізації геометричних розмірів та дослідження.

Запропоновані елементи методики теплового розрахунку вентильних двигунів оберненої конструкції з постійними магнітами на роторі дають змогу із достатньою для інженерної практики точністю виконувати відповідні розрахунки цих двигунів, зокрема, для прямих приводів механізмів. Наведені в матеріалах статті елементи методики слугують базою для розрахунку теплового стану основних компонентів електромеханічного перетворювача із явнополюсним статором та зовнішнім ротором із постійними магнітами на етапах його проєктного синтезу, оптимізації та дослідження.

Ключові слова: постійні магніти; вентильний двигун; тепловий розрахунок; явнополюсний статор; зовнішній ротор.