Mathematical modeling of thermal processes in small-size DC electric machines

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Abstract. This article considers small-size electric machines used in various fields of technology, from medical electrical equipment to complex mechatronic systems as part of spacecraft. To obtain satisfactory weight and size parameters of electric machines, it is necessary to take into account many factors that limit the possibility of reduction the machine size. The high energy of modern permanent magnets (250 - 300 kJ/m³) makes it possible to obtain the best weight and dimensions indicators in the designs of brushless direct current machines with excitation from permanent magnets, taking into account the influence of thermal processes.

Keywords: mechatronic systems, permanent magnets, electric machines

1. Introduction
Electric motors with excitation from permanent magnets are characterized by high reliability, improved weight and dimensions, and autonomy. Due to the extension of applications of such electric motors, as well as the creation of promising robotized modules, the need for such machines increases. In general, we are dealing with related problems, when, as a result of electromagnetic calculation, the energy losses generated in the form of heat are determined. Heat flows warm the machine and electronic control units. As a result of modeling the temperature field, it becomes possible to determine the areas that overheat and redistribute the sources of losses and the heat sink system in order to remain in the zone of permissible temperatures.

2. Analysis of thermal processes in small electric machines with elements of mathematical modeling
For the considered machine, the anchor winding is placed in the grooves of the laminated core. In this case, the magnetic circuit is remagnetized by a rotating magnet with a frequency proportional to the frequency of rotor [1, 2]. The medium resistance to the rotor spinning causes additional heat generation and an increase in the idling moment. Friction loss of the rotor of the machine on the air can be determined approximately by the formula for a rotating cylinder [3, 4]:

\[ P = C_f \cdot \pi \cdot \rho \cdot \Omega^3 \cdot R^4 \cdot L_a, \]  \hspace{1cm} (1)

where \( C_f \) is reduced losses in the steel of the magnetic core. The core material must be of the high magnetic permeability, as that for electrical steel, and its electrical conductivity should be equal to zero.
The aerodynamics of the air gaps between the stator and the rotor significantly affect the two main processes in the machine: heat transfer between the anchor and the environment, as well as the resistance of the medium to the rotor spinning; \( \rho \) is the medium density, \( \text{kg/m}^3 \); \( \Omega \) is the rotor speed, \( \text{rad/s} \); \( R \) is the cylinder radius (armature core), \( \text{m} \); \( L_a \) is the cylinder length, \( \text{m} \).

The air flow in the air gap of an electric machine has a complex structure, determined by the Reynolds number:

\[
\text{Re}_\Omega = \frac{\Omega \cdot R \cdot \delta}{\nu},
\]

where \( \delta \) is the thickness of the air gap between the stator and the rotor, \( \text{m} \); \( \nu \) is the kinematic viscosity of the medium (for air \( \nu = 16.96 \cdot 10^{-6} \text{m}^2/\text{s} \)).

For the Reynolds number (2) with rotational motion, the double thickness of the one-sided gap (2\( \delta \)) is taken as the characteristic linear size at half of the rotor speed (\( \Omega \cdot R/2 \)) [5, 6].

Thus, we obtain friction losses in bearings in the following form: [7, 8, 9]

\[
P_f = 2 \cdot M_t \cdot \Omega,
\]

where \( M_t \) is the friction torque in bearings, \( \text{N-m} \); \( \Omega \) is the rotor speed, \( \text{rad/s} \);

\[
M_t = f \cdot P_r \cdot \frac{d_s}{2},
\]

where \( f \) is the friction coefficient (\( f = 0.004 \)); \( P_r \) is the rotor weight, \( \text{N} \); \( d_s \) is the shaft diameter, \( \text{mm} \).

\[P_r = m \cdot g,
\]

where \( m \) is the rotor mass, \( \text{kg} \); \( g \) is acceleration due to gravity, \( 9.81 \text{ m/s}^2 \).

Other types of losses and efficiency of the electric motor are the following:

Electrical loss in copper anchor winding

\[P_{em} = m \cdot I_p^2 \cdot R_p
\]

Magnetic loss are [11,12]:

\[P = \rho_{1.0/50} \left( \frac{f}{50} \right)^{\beta'} \cdot \left( k_a \cdot B_a^2 \cdot m_a + k_z \cdot B_z^2 \cdot m_z \right) W
\]

where \( \rho_{1.0/50} \) is specific losses in steel (\( \rho_{1.0/50} = 1.3 \)); \( k_a \) is the coefficient(\( k_a = 1.6 \)); \( B_a \) is the yoke induction \( B_a = 1.6 \); \( k_z \) is the coefficient (\( k_z = 1.8 \)); \( B_z \) is induction in the teeth of the anchor (\( B_z = 1.8 \)); \( \beta' \) is exponent (\( \beta' = 1.3 \)).

At present, in the practice of designing the mechatronic systems, both analytical and numerical models are used, which complement each other and make it possible to eliminate possible errors in the implementation of various models [13, 14].

The calculated patterns of the magnetic field and the distribution of induction are presented in figures 1-3.
Figure 1. The distribution of induction in the magnetic system.

Figure 2. The distribution of induction on the pole pitch at the center of the air gap in the magnetic system \( F = 7.387 \times 10^{-3} \text{ Wb/m} \).

Figure 3. The distribution of induction on the pole pitch on the body of an electric machine with a magnetic system.

Further we specify the features of the thermal calculation of the machine due to the fact that the electric machine in the mechatronic system can operate in different modes: S1, S2, etc. In general terms, the timeline load of the machine (Table 1) can be specified. It is obvious that in this case it is necessary to consider the transition thermal process. [15, 16]

Table 1 shows the modes of operation of the engine during one cycle of operation of the electric machine.
Table 1. Modes of operation of the electric machine during one cycle.

| Mode | Time interval of the cyclogram, s | Function for $M$, N-m | Function for $\Omega$, rad/s (in parentheses is the amplitude in rpm) |
|------|----------------------------------|-----------------------|---------------------------------------------------------------|
| 1    | 0..5                             | $M(t) = 0.213\sin(2\pi \cdot 0.5 t)$ | $\Omega(t) = 164.4\cos(2\pi \cdot 0.5 t)$ (1570) |
| 2    | 5..28                            | $M(t) = 0$            | $\Omega(t) = 219.2\cos(2\pi \cdot 5 t)$ (2094) |
| 3    | 28..60                           | $M(t) = -0.115$      | $\Omega(t) = 219.2\cos(2\pi \cdot 5 t)$ (2094) |
| 4    | 60..124                          | $M(t) = -0.287$      | $\Omega(t) = 219.2\cos(2\pi \cdot 5 t)$ (2094) |
| 5    | 124..140                         | $M(t) = -0.115$      | $\Omega(t) = 219.2\cos(2\pi \cdot 5 t)$ (2094) |
| 6    | 140..160                         | $M(t) = -0.023-0.09\sin(2\pi \cdot 5 t)$ | $\Omega(t) = 767.1\cos(2\pi \cdot 5 t)$ (7329) |
| 7    | 160..180                         | $M(t) = 0.335\sin(2\pi \cdot 2 t)$ | $\Omega(t) = 1228.5\cos(2\pi \cdot 2 t)$ (11734) |

The change in current in the phase of the engine over the three cycles of operation of the electric machine in accordance with the load according to table 1, is presented in figure 4.

Figure 4. Cyclogram of motor phase over triple load cycle.

3. The simulation results of a nonstationary temperature field

Images of the temperature distribution inside the machine at maximum load for 3 minutes of operation of a contactless DC motor and graphs of the temperature distribution inside the machine over the ambient temperature for different moments of the same time interval are shown in figures 5, 6 [17, 18].

Figure 5. Temperature distribution inside the machine at full load for 3 minutes of operation.
4. Conclusion
Thermal calculation of the developed electric motor shows that the winding temperature reaches an acceptable value after three minutes of operation in the nominal mode. The development of new materials for permanent magnets contributes to the extension of the field of application of electric motors both in terms of power and in the range of rotational speeds [20]. At the same time, the need for modern, more accurate methods for calculating and designing new machines is increasing, which makes it possible to shorten the time for designing of electric motors and reduce the amount of experimental research.
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