Numerical simulation of electromagnetic and thermal processes in high-speed electric machines

Yu V Pisarevsky*, V L Burkovsky, A Yu Pisarevsky, V B Fursov, A I Borisova and K Yu Gusev
Voronezh State Technical University, 394026, Russia, Voronezh, Moskovsky prospekt, 14

* E-mail: 2732558@gmail.com

Abstract. In this paper high-speed electric motors are considered, allowing one to obtain the necessary weight and dimensions for modern equipment. The creation of high-speed machines is directly related to the study of factors limiting their range of rotational speeds with the choice of electrical steel with lower specific losses and sheets of smaller thickness and modeling the magnetic field in the magnetic system of the machine.

Keywords: high-speed electric motors, modeling, magnetic field.

1. Introduction
The development of new materials for permanent magnets contributes to the expansion of the field of application of brushless motors in terms of both power and range of rotational speed. At the same time, there is an increasing need for modern, more accurate methods for calculating and designing new machines, which can reduce the time needed to design new electric motors and reduce the amount of experimental research.

2. Study of direct current brushless machines
The best designs have brushless direct current machines with excitation from permanent magnets. Consider two designs of electric motors presented in figure 1 [1].

![Figure 1. Transverse geometry of the investigated machines (A is electric motor with a hollow anchor; B is electric motor with a smooth anchor).](image-url)
The main difference between the considered machines is that the motor with a hollow anchor has an inductor (a four-pole permanent magnet), which rotates with the magnetic circuit around the anchor having a single-sided support in the bearing shield. In this case, the magnetic core does not overmagnetize and has a non-laminated structure and allows an increase in the magnetic field induction up to 1.8-2.0 T, depending on the material which is used. In an electric motor with a smooth anchor, the anchor winding is attached to the magnetic conductor, which is stationary and has laminated structure. In this case, the magnetic circuit is reversed by a rotating magnet with a frequency proportional to the frequency of rotor [2,3]. Obviously, in case of option A, there was practically no loss, and in case of option B, the loss arose inevitably. To eliminate losses in the steel of the magnetic circuit (option B), the material of the magnetic circuit must have a high magnetic permeability such as that of electrical steel and electrical conductivity equal to zero. Currently there are no such materials [4,5].

However, there are varieties of electrical steel with lower specific losses and sheets of smaller thickness. In addition, for the option B design the thickness of the magnetic circuit is $\delta = 1\text{mm}$, which is twice more than in that for the option A. As a result, the maximum value of induction in the magnetic core decreases approximately twice and amounts to 1.0-1.2 T. The advantage of the machine of option B is in a more reliable fastening of the anchor winding to the steel core of the magnetic circuit [6-8].

It is obvious that these structures have both advantages and disadvantages, which must be compared according to the results of calculations in order to more accurately determine the scope of the structures under consideration [9, 10].

The maximum currently achieved speed of electric cars is 1000000 rpm. The research results presented in figure 2 show that an electric motor with a hollow anchor has an advantage. At a speed of 300000 rpm, the difference in efficiency decreases to 10%.

![Figure 2. Relationship between efficiency of the engine and rotational speed $n$ for a smooth and hollow anchor (basic values: $P_b = 300000$ rpm).](image)

Electric motors with a smooth anchor have a more rigid and durable construction, which expands the area of their application. The simulation of the magnetic field in the magnetic system of the machine is performed by the finite element method. The results of the magnetic field simulation are presented in figure 3 [11-13].
The electronic switch, which provides the operation of the electric motor, is controlled depending on the position of the rotor, by a sensorless system for the EMF transition through zero. Considering the dynamics of motor start-up, we use the well-known mathematical model of a permanent-magnet synchronous motor equation (1).

\[
\begin{align*}
    u_d &= R \cdot i_d + L \frac{di_d}{dt} - p \omega L \cdot i_q \\
    u_q &= R \cdot i_q + L \frac{di_q}{dt} + p \omega L i_d + p \omega \Psi_m \\
    J \cdot \frac{d\omega}{dt} &= M_{em} - M_l \\
    M_l &= \frac{3}{2} p \cdot \Psi_m \cdot i_q
\end{align*}
\]

where \(u_d, u_q\) is voltage on the stator windings along the d and q axes; \(i_d, i_q\) is current in the stator windings along the d and q axes; \(R\) is the active resistance of stator windings; \(L\) is the stator winding inductance; \(\Psi_m\) is the flux linkage of the stator winding from the field of a permanent magnet; \(M_{em}\) is electromagnetic moment of the electric motor; \(p\) is the number of pairs of poles; \(J\) is moment of inertia of the rotor; \(\omega\) is rotor angular speed; \(M_l\) is load moment.

The simulation results are presented in figures 4, 5, 6.
The performed calculations (figure 6) show that the electric motor reaches the set speed in 1.2 seconds. Obviously, the design of a smooth anchor provides a significant reduction in inductive resistance, in this regard, the mechanical characteristics of the machine are linear.

Comparison of the performance of electric motors with a hollow and smooth anchor shows that the main differences are related to the energy of the machines. The greatest differences are in relationships of efficiency on the power at the shaft of the machine [14-17].

Despite the fact that the efficiency of an electric motor with a hollow anchor is significantly higher than that of an electric motor with a smooth anchor, the maximum efficiency is achieved at loads significantly exceeding the nominal value. A comparison of the two designs of electric motors shows that a machine with a hollow anchor is more economically viable. At a rotation frequency of 300000 rpm, the efficiency is higher by 17% compared to that of a smooth-core electric motor [18-20].

The change in the motor temperature in time was calculated using the finite element method. The results of the study are presented in figures 7, 8, 9.

![Figure 7](image1.png)

**Figure 7.** The results of the study of the electric machine (heating time (t = 120 s)).

![Figure 8](image2.png)

**Figure 8.** The change in the machine body temperature (the machine operation time is 120 seconds or 2 minutes).

![Figure 9](image3.png)

**Figure 9.** The change in difference between the anchor winding temperature and the ambient temperature (the machine operation time is 120 seconds or 2 minutes).
3. Conclusion
As a result of the analysis, it was established that there are tendencies to expand the scope of application of high-speed electric motors (n ≤ 300000 rpm), which allow realizing the idea of an autonomous product of extremely small dimensions. In particular, these are devices for various purposes. However, the methods of calculating brushless direct current motors with a smooth and hollow anchor require further improvement.

References

[1] Pisarevsky Yu V 2013 Special electric motors for high-speed drilling machines 103-106.
[2] Sipailov G A, Sannikov D I, Zhadan V A 1989 Thermal, hydraulic and aerodynamic calculations in electric machines: Textbook for universities for the training program "Electromechanics". Moscow: Vyschaya Shkola 239.
[3] Borisenko A I, Kostikov O N, Yakovlev A I 1983 Cooling of industrial electric machines. Moscow: Energoatomizdat 296.
[4] Pisarevsky U V, Pisarevsky A Yu, Parkhomenko G A, Sergeev V A, Fursov V B, Nizovoy A N, Boychuk V S, Gene J A Patent 152267 Russian Federation. MKI NC 21/12, NC 16/02 Contactorless electric machine / -No. 2014133105/07; newsletter № 13.– 2 p.: II.
[5] Kenio T, Nagamori S 1989 Direct current motors with permanent magnets: Translation from English. Moscow: Energoatomizdat 184.
[6] GOST R 52956–2008 Materials magnetically hard sintered on the basis of an alloy of neodymium-iron-boron. Classification. Main settings.
[7] Pisarevsky Yu V, Fursov V B, Pisarevsky A Yu 2013 High-speed electric motors for dental drills. New technologies in research, design, management, production: the works of All-Russian conference. Voronezh: Voronezh State Technical University 212-4.
[8] Agapov A A 2018 A research of power characteristics of contactless electric motors of a direct current of slotless execution with various types of windings. The world of electromechanotronics 80-5.
[9] Borisova A I 2016 The heatrational modes of electromechanothrone propellers in unpackaged complexes of spacecrafts. The world of electromechanotronics 90-4.
[10] Khrushchev V V 1985 Electrotechnical machines of systems of automatic equipment. – Leningrad: Energoatomizdat 368.
[11] Agapov A A 2016 Issues of optimization of characteristics of contactless direct current motors with different types of windings of the stator. The world of electromechanotronics 119-26.
[12] Bogushev V I 2016 The analysis of a design of the electric motor analog at the solution of a problem of development of micro contactless direct current motors with a diameter no more than 22 mm on meringue of perspective domestic materials and element design base, The world of electromechanotronics 145-51.
[13] Chirkin V S 1959 Thermal and physical properties of materials 356.
[14] Goncharov A S, Mironov S.M. 2017 Mathematical description of the contactless direct current motor as object of management. The world of electromechanotronics 17-19.
[15] Annenkov A N 2017 Analytical description of electromagnetic processes in an inductive angle sensor code with increased resistance to external influences, The world of electromechanotronics 71-2.
[16] Bogushev V I 2017 A research of issues of improvement the quality of the electric motor of a direct current collector by increase in temperature stability, The world of electromechanotronics 112-5.
[17] Ovchinnikov I E 2006 Valve electric motors and the drive on their basis. St. Petersburg: KORONA-Vek 366
[18] Dulnev G N1963 Heat exchange in radio-electronic devices
[19] Pulyer Yu M 1964 Induction electromechanical elements of the computing and remote watching systems. Moscow: Mechanical engineering.
[20] Development of high-resource contactless electric motors of a direct current with the built-in controller of management for work in the conditions of a deep vacuum. – Scientific and technical report. Gosregistration № U93688, 2015.