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ENERGETICS

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Problems of brushless motors applying in electric drives

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Abstract.
The development of technologies, corrosion resistance, mechanical properties and temperature range of magnetic materials have recently improved significantly. As a result, machines with permanent magnets find a wider distribution in industries with a heavy operating mode, in electric drives of ship mechanisms and devices, in the military field, etc. The cost of rare-earth permanent magnets has decreased by a factor of five over the past two decades, while the corresponding specific magnetizing force has increased by a factor of three, which represents a 15-fold improvement in cost-benefit ratio and is essential for affordability by price. The article is devoted to the study of an electric drive with a brushless motor, as well as the definition of problems that arise in this electric drive and ways to overcome them.

Keywords:
mathematical model
positional electric drive
collectorless engine
transient characteristic
simulation model
laboratory stand
current and moment pulsations

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I. Introduction

Collectorless motors with permanent magnets are by 1-2% more efficient than asynchronous motors and synchronous motors at full load and by 10-15% at partial load. Efficiency is ensured due to full excitation of the rotor without current and the absence of corresponding losses at all speeds . At the same time, the engine cooling is simplified, since the heat coming from the rotor is insignificant. Simplifying the cooling circuit also results in flexible engine geometry. Permanent magnet machines support a much wider range of aspect ratios than standard motors [1,2]. The brushless engine design allows it to be operated in water and aggressive environments, also they practically do not create radio interference [3]. At the same time, analysis of existing technical solutions for the implementation of brushless motors and their control systems shows that windings switching and form of the electrical signal applied to them have the greatest influence on the efficiency of their use and the efficiency factor [4]. This feature complicates the electric drive use and limits the scope of its use. Therefore, one of the most relevant directions of research in the field of such electric drive systems is solution of the issue of minimizing electromagnetic moment pulsations created by the electric motor. Another important direction in the development of this type of electric drive is solving the problem of ensuring operation reliability of the electric drive [5]. Thus, currently relevant areas of research and development of an electric drive based on a brushless motor indicates the need to establish the dependence of equalizing currents as well as pulsations of moments and currents on the electric drive load. To solve this problem, it is necessary to create a simulation model of a positional electric drive based on a brushless motor. To confirm its adequacy, it is needed to create a laboratory stand for researching working processes in an electric drive with a brushless motor.

II. analysis of the main achievements

Among electric motors with permanent magnets, systems based on electric machines with trapezoidal EMF (electromotive force) have become widespread. Such electric motors are called brushless DC motors or BLDC motor in the literature [6]. A brushless DC motor consists of a rotor with

permanent magnets and a stator with windings. There are two types of motors: "Inrunner ", in which rotor magnets are inside the stator with windings, and " Outrunner", in which magnets are located outside and rotate around a stationary stator with windings. The " Inrunner " scheme is usually used for high-speed motors with a small number of poles. "Outrunner "is used when it is necessary to get a high-torque engine with relatively low revolutions. Structurally, "Inrunners " are simpler due to the fact that the stationary stator can serve as a housing. It can have mounting devices installed. As for "Outrunners", the entire outer part rotates [3]. BLDC motors have many advantages, such as high efficiency, high specific power, high ratio of torque to moment of inertia, high speed, simple control algorithm, and low cost. Thus, nowadays they are widely used as a cost-effective solution in low and medium power drives. Rotor position sensors and special controllers are used for electronic switching of collectorless DC motor windings. Using the information about the rotor position, the speed and direction of rotation command signals, the controllers form control signals of the inverter keys.

III. Objective of the Study

Physical phenomena that occur in the working processes of electric drives with a brushless motor.

IV . Steady Method And Results

Voltage equation of a brushless DC motor

$$U_{as} = R_s i_{as} + (L_s - M)\frac{di_{as}}{dt} + e_{as}, \quad (1)$$

$$U_{bs} = R_s i_{bs} + (L_s - M)\frac{di_{bs}}{dt} + e_{bs}, \quad (2)$$

$$U_{cs} = R_s i_{cs} + (L_s - M)\frac{di_{cs}}{dt} + e_{cs}. \quad (3)$$

Where Rs - stator resistance; i_{as}, i_{bs}, i_{cs} - stator phase currents; L_s - self-inductances of the windings; M - mutual inductances of the windings; e_{as}, e_{bs}, e_{cs} - counter EMF of the stator phases.

Unlike AC motors, which use the d-q coordinate system to

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facilitate their control, DC motors directly use three-phase abc quantities for their control. The d-q transformation is necessary for sinusoidal quantities. Since the currents, flow and counter EMF of the BDPS are non-sinusoidal values, the d-q transformation for the BDPS does not make sense [7, 8]. Since phase current is in phase with counter EMF, the torque equation can be expressed as the multiplying of phase current and counter EMF

$$T_e = \frac{e_{as}i_{as}+e_{bs}i_{bs}+e_{cs}i_{cs}}{\omega_m} = 2\frac{EI}{\omega_m}. \quad (4)$$
$$i_{as} = I,\ i_{bs} = -I,\ i_{cs} = 0 \text{and } e_{as} = E,\ e_{bs} = -E.$$

If I and E are constant values, the output torque of equation (4) is a constant value. However, if the counter EMF waveform is not a perfect trapezoid, there is torque pulsation even though the BDPS stator currents are constant. For BDPS with arbitrary waveforms of counter EMF, the output torque equation (4) can be represented in the form

$$T_e = \psi_f[i_{as}f(\theta) + i_{as}f(\theta - 240°) + i_{as}f(\theta - 120°)]. \quad (5)$$

where $\psi_f = N\Phi_{f\_}$; Φ_f *- magnetic flux of the stator winding; N is the number of the stator winding turns, f - the unit function that plots the waveform counter EMF with a maximum amplitude of ±1;* Θ *- position of the rotor.*

In accordance with the system`s functional scheme [9], a simulation model for the MATLAB Simulink environment was built. The model is presented in Fig. 1. It includes: an ideal constant voltage source; semiconductor converter; brushless motor, control subsystem (Control) and measuring subsystem (Scopes).

The work uses the BDPS model as an electromechanical system taking into account the following assumptions [9-15]: the stator windings are located at an angle of 120 degrees relative to each other; their resistance and inductance of steel; saturation of the magnetic circuit, hysteresis and eddy currents are not taken into account; interaction of stator steel with permanent magnets is not taken into account; the gap of the electric machine is considered uniform; the

stator windings are considered symmetrical and star-connected.

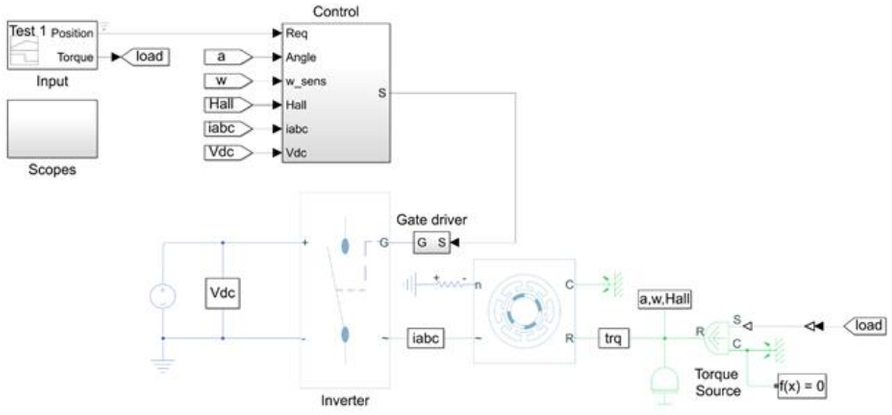

Figure 1

Simulation model of a positional electric drive in MATLAB Simulink

Input block is intended for setting the angle of rotation of the BDPS rotor (Position) and the moment of resistance (Torque) and is a standard Signal Builder block (Fig. 2).

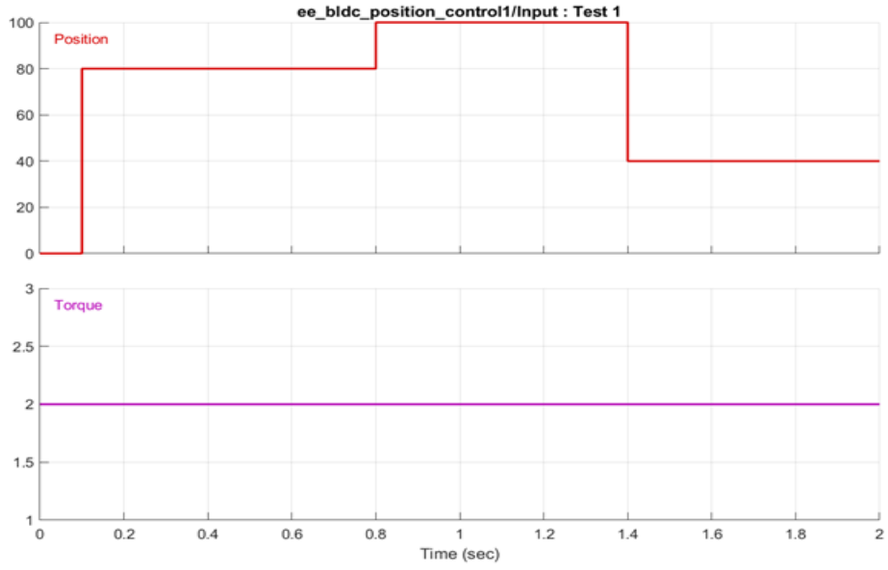

Figure 2

Signal Builder window

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Control subsystem uses a cascade control structure based on PI controllers with three control loops (Figure 3): an outer position control loop, a speed control loop, and an inner current control loop. In Fig. 3, the following designations are adopted: Position controller – regulator of position (angle of rotation), Speed controller – speed regulator, BLDC Current Controller – current regulator, PWM – PWM generator, Udc filter - a filter.

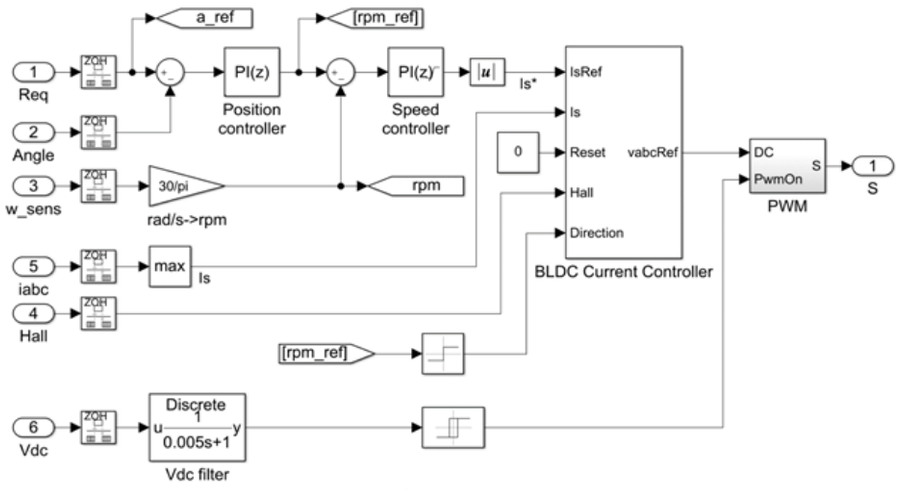

Figure 3

Control subsystem

BLDC Current Controller subsystem is presented in Fig. 4. The current regulator is marked as PI controller.

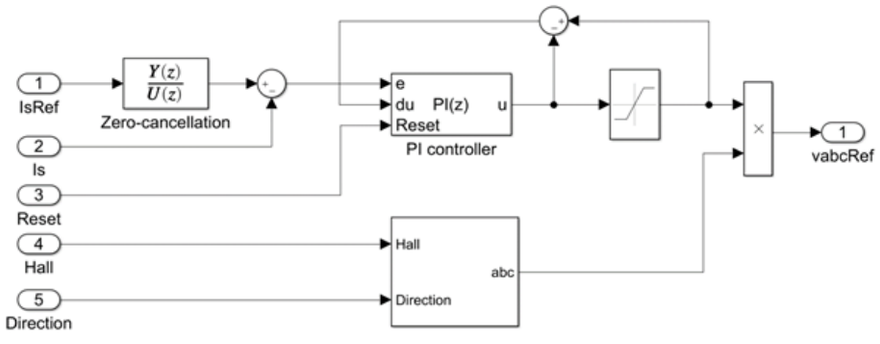

Figure 4

BLDC Current Controller subsystem

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The BDPS is powered by a controlled three-phase inverter (see Fig. 1). The block is a six- pulse three-phase controlled converter consisting of three bridge arms, each with two switching devices. Available in a selection of switching devices are: GTO, Ideal Semiconductor Switch, IGBT, MOSFET, thyristor or averaged switch. An averaging switch-based implementation uses gate signals from 0 to 1 that can be averaged over a period. This implementation allows you to subsample the model or use modulation signals instead of PWM signals. The only vector G needed to control the three-phase converter is formed using the Gate block driver. It is based on the standard Six-Pulse Gate Multiplexer. The brushless DC motor in the model is represented by a BLDC unit. This unit is a three-phase brushless direct current motor with a trapezoidal counter EMF waveform. At the same time, it remains possible to determine other variants of the counter EMF form using tabular values. The Scopes subsystem is presented in Fig. 5. It contains oscilloscopes that allow you to see the results of modeling: given (a _ ref) and actual (a) rotor rotation angles (Angle); angular velocity of the rotor rpm (RPM); moment Tq_meas (Tq); phase currents iabc (Iabc).

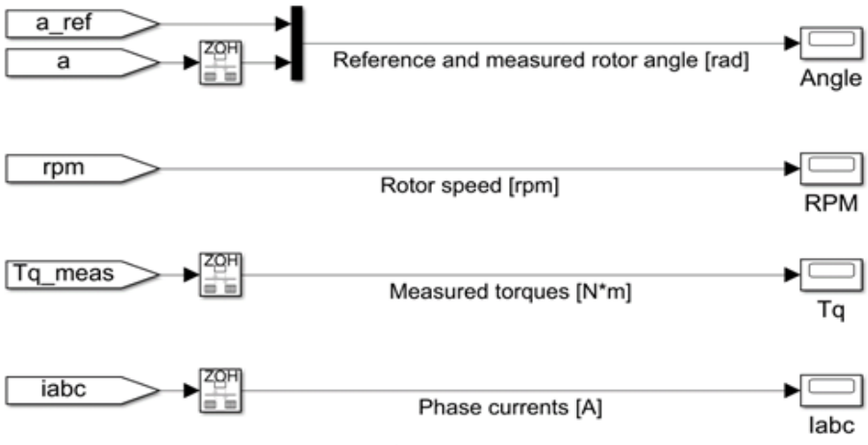

Figure 5

Scopes subsystem

Modeling of the positional electric drive based on the BDPS with the parameters listed in Table 1 and 2 was carried out.

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Table 1

Parameters of BDPS

Parameter	Value
The number of poles pairs p	4
Stator phase resistance R_s, Ohm	0.1
Stator phase inductance L_s, Hn	0.0001
Mutual stator inductance M, Hn	0.00001
Magnetic flux Φ_{max}, Vb	0.0175
Moment of inertia of the rotor J_m, kg m ^{2}	0.0005
Supply voltage U_{dc}, V	48

As a result of the BDPS control system simulation, it`s transient characteristics were obtained, which are presented in Tab. 3. In most drives, such a transient process of working out medium/large movements, when the speed of the engine in the process of working out a given angle changes according to a trapezoidal graph, is considered the best in most drives. That is because it allows to fully use the engine's overload capacity and excludes the occurrence of overregulation in the transient process.

Table 2

Regulator parameters

Parameter	Value		
	Current regulator	Speed controller	Position regulator
Gain coefficient of the proportional link k_P	0.01 _	0.1	250
Gain coefficient of the integrating link k_I	0.08	15	0.5

Table 3

Quality indicators

Parameter	Relative readjustment, %	Installation time t_i, s	The rise time t_r, s	Fixed error ε_{fix}
Angular velocity	0	0.,065	0,03	0
Angle of rotation	0,65	-	-	0,035 rad

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The analysis of transient processes showed that the system is operational and has relatively high-quality indicators. It was found that when working out medium/large rotation angles, the engine speed changes according to a trapezoidal graph, therefore, the overloading capacity of the engine is fully used. Torque pulsations are caused by current pulsations that occur during phase switching. Due to torque fluctuations, the characteristics of speed regulation deteriorate, especially at low speeds. There are two main causes of torque ripples caused directly by the brushless motor control system. The first is due to current pulsations caused by PWM in the period between phase commutations. The second is the processes that occur when the current is switched from one phase of the motor to another. To confirm the theoretical studies, a laboratory stand was developed and manufactured [10-18]. Conducting the experiment confirms the adequacy of the obtained calculations.

V. Conclusion

The study of an electric drive with a brushless motor allows us to draw the following conclusions:

1. Use of electric drives with a collector-less engine on ships is more advisable in contrast to asynchronous electric drives;

2. Problems of currents and moments pulsations in these electric drives are easily solved with the help of appropriate regulators;

3. The developed model allows analyzing static and dynamic modes of operation of electric drives of non-standard topologies based on brushless DC motors with permanent magnets;

4. For the use of collectorless motors in electric drives, you can use ready-made control systems of complete electric drives made by the companies Lenze, Siemens, Altivar etc.

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