Diagnoses of BLDC motor winding based on a model approach in the state space

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Abstract. To diagnose a brushless direct current motor, its nonlinear discrete control model is developed in a rotating coordinate system in the state space. The problem of determining the identifiability of this model with different values of the resistance of the motor winding and at different load moments has been solved. This model of controlling a brushless direct current motor can be used to build real-time diagnostic systems.

1. Introduction
There are various directions in the diagnosis of complex technical systems: diagnostics based on models, neural networks, fuzzy logic, recognition methods. Analysis of the object of diagnosis of brushless direct current (BLDC) motor—allows us to conclude that the most suitable type of diagnosis is a model-based approach.

In modern research, there is a tendency to abandon the use of rotor position sensors in the BLDC motor. An effective way of control is the use of systems with sliding modes (Sliding Mode Systems) [1-3]. The proposed model of an adaptive wavelet-neuro-fuzzy dynamic system with sliding modes for controlling brushless motors is more effective [4]. The system consists of neural controllers and switchable compensators. The neural controller uses a fuzzy wavelet-neural network, switching compensators are introduced to eliminate the approximation error of neural controllers. The laws of adaptive control of such a system are implemented in such a way that the system is guaranteed stability by the definition of Lyapunov stability.

In [5–7], a method for estimating the rotation angle using the Extended Kalman Filter is considered. To calculate the current state of the system, the results of the previous iteration of the filter (in the form of an assessment of the state of the system and an estimation of the error in determining this state) and current observations are necessary, thus, difficulties arise due to the large amount of calculations in real time and phase control delay.

Widespread use in the BLDC motor was found by observers [8]. The observer is used to diagnose and predict the value of currents 1 cycle ahead, which solves the problem of eliminating control delays. There are a large number of studies on the diagnosis of electric motors, including BDTT [9-23].

Direct torque control (Direct Torque Control) can be carried out by feeding a synchronous motor from a current inverter. Such systems have a number of advantages: robustness is achieved with respect to the spread of parameters, the control algorithm is simplified due to the absence of a current
control loop, and high system performance is ensured. However, the method is not free from a serious drawback: at small load angles, pulsations of the moment and rotor speed fluctuations occur.

The mathematical basis of vector control by a drive is differential equations that describe the drive equally correctly in both dynamics and statics. Due to the adequacy of control in dynamics, vector control, unlike scalar control, makes it possible to build highly dynamic and precision AC electric drives that provide the highest accuracy and speed of regulation. In addition, when vector control is used, the representation of three-phase quantities in the form of generalized vectors is used and control systems are constructed in rotating coordinates.

2. A dynamic BLDC motor model
To solve the diagnostic problem, we developed a dynamic model of BLDC in the state space in a rotating coordinate system (d, q), oriented along the magnetic axis of the rotor.

The novelty of the discrete model of BLDC is the presence of a variable load torque. The discrete model of the BLDC motor is presented in the form of a vector-matrix equation in the state space.

\[
\begin{bmatrix}
I_d(k+1) \\
I_q(k+1) \\
\omega(k+1) \\
\theta(k+1)
\end{bmatrix} = \begin{bmatrix}
1 - T \frac{R_s}{L_d} & Tp\omega(k) & 0 & 0 \\
-Tp\omega(k) & 1 - T \frac{R_s}{L_q} & T - \frac{\psi}{L_q} & 0 \\
0 & \frac{\psi}{L_q} & 1 - \frac{F}{J} & -\frac{M(k)}{J\omega(k)} \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
I_d(k) \\
I_q(k) \\
\omega(k) \\
\theta(k)
\end{bmatrix} + \begin{bmatrix}
\frac{T}{L_d} & 0 & 0 & 0 \\
0 & \frac{T}{L_q} & 0 & 0 \\
0 & 0 & T & 0 \\
0 & 0 & 0 & T
\end{bmatrix} \begin{bmatrix}
U_d(k) \\
U_q(k)
\end{bmatrix}
\]

(1)

where \( I_d(k+1) \) is the projection of the stator current onto the \( d \) axis at the time instant \( k + 1 \);
\( I_q(k+1) \) is the projection of the stator current onto the \( q \) axis at time moment \( k + 1 \);
\( \omega(k+1) \) is the angular velocity of the BLDC motor at time \( k + 1 \);
\( \theta(k+1) \) is the angular displacement of the BLDC motor at time \( k + 1 \);
\( T \) is the sampling interval, the time between \( k + 1 \) and \( k \) samples;
\( R_s \) is the active resistance of the stator winding BLDC motor;
\( L_q, L_d \) are the stator inductances of the BLDC motor along the \( q \) and \( d \) axes;
\( p \) is the number of pairs of the BLDC motor poles;
\( \psi \) is the magnetic flux induced by permanent magnets in the stator winding;
\( F \) is the coefficient of viscous friction in the supports of the BLDC motor;
\( J \) is the moment of inertia;
\( M \) is the electromagnetic moment of the BLDC motor;
\( I_d(k) \) is the projection of the stator current onto the \( d \) axis at time \( k \);
\( I_q(k) \) is the projection of the stator current onto the \( q \) axis at time \( k \);
\( \omega(k) \) is the angular velocity of the BLDC motor at time \( k \);
\( \theta(k) \) is the angular displacement of the BLDC motor at time \( k \);
\( U_q, U_d \) are the projections of the stator voltage on the \( q \) and \( d \) axes.

The equation at the output of the BLDC motor is written as:

\[
\begin{bmatrix}
\dot{I}_d \\
\dot{I}_q \\
\dot{\omega} \\
\dot{\theta}
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
I_d \\
I_q \\
\omega \\
\theta
\end{bmatrix} + \begin{bmatrix}
\xi_{I_d} \\
\xi_{I_q} \\
\xi_{\omega} \\
\xi_{\theta}
\end{bmatrix}
\]

(2)

where \([\xi_{I_d}, \xi_{I_q}, \xi_{\omega}, \xi_{\theta}]^T\) is the vector of measurement errors;
\([\dot{I}_d, \dot{I}_q, \dot{\omega}, \dot{\theta}]^T\) is the measured state vector.

The required torque is calculated by the formula (3):

\[
M(k) = \varepsilon(k) = \frac{\omega(k+1) - \bar{\omega}(k)}{T}
\]

(3)

The angular velocity of the BLDC motor is calculated by the formula (4):

\[
\bar{\omega}(k) = \frac{\dot{\theta}(k) - \dot{\theta}(k-1)}{T}
\]

(4)
The rotation frequency \( \omega(k + 1) \) denotes the target point on the trajectory, which allows at each control step to calculate the required moment using formula (3), which we substitute in the state matrix.

Diagnostics is performed on the basis of the identifiability criterion for this model of the BLDC motor. Identification criteria are determinants of the extended matrix:

\[
\det \left[ \begin{array}{cccc}
C_k^T & A_k^T & A_k^T & A_k^T
\end{array} \right] > \gamma
\]

where \( \gamma \) is the threshold value of the determinants determined by the identification object and close to zero.

The study of the influence on the identifiability of the control model, i.e. correspondence of the control model to the control object by setting path errors and state measurement errors. Given that the rank of the extended matrix determines identifiability in a theoretical sense

The BLDC motor was simulated in the program SimInTech. The discrete model of the BLDC motor for calculating determinants of state matrices was built in the software package “Environment for dynamic modeling of technical systems SimInTech” (No. 2379 in the Unified Register of Russian Programs) developed by 3V Service [24].

The BLDC motor parameters: stator winding resistance \( R_s = 1.9 \) Ohm, stator winding inductance along the \( d \) axis \( L_d = 0.0018 \) H, stator winding inductance along the \( q \) axis \( L_q = 0.0018 \) H, inertia moment \( J = 0.0000024 \), coefficient of viscous friction \( F = 0.001 \), number of pole pairs \( p = 8 \), magnetic flux \( \Phi = 0.001 \), angular velocity \( \omega_0 = 220 \) rad/s, sampling interval \( T = 0.005 \) s.

The scheme of the BLDC motor model for calculating the determinant of state matrices is shown in Fig. 1. Three program blocks PL calculate the determinants of the state matrices when the resistance moment changes linearly with different values of the resistance and inductance of the BJPT winding: at their nominal value (green color), with a decrease in their values by 10\% (red color), with an decrease in their values by 20\% (blue color).

![Diagram of the BLDC motor model for calculating the determinant.](image)

Figure 1. Diagram of the BLDC motor model for calculating the determinant.

The simulation results of the BLDC motor at different values of the resistance and inductance of the winding are shown in Figure 2.
Figure 2. The calculation results of the matrix determinant at $T = 0.005$ s., at the nominal value of the resistance and inductance of the BLDC motor winding (green color), when their values decrease by 10% (red color), when their values decrease by 20% (blue color).

3. Conclusion
To diagnose the motor, its nonlinear discrete control model is developed in a rotating coordinate system in the state space. The problem of determining the identifiability criterion for this model at different values of the resistance of the motor winding and at different load moments was solved.

With a 10% decrease in the resistance and inductance of the BLDC motor winding, the permissible moment decreases by 0.02 Nm, while a decrease in the resistance and inductance of the motor winding by 20%, the permissible moment decreases by 0.04 Nm.

This model of the BLDC motor can be used to build diagnostic systems that operate in real time.

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