Numerical simulation of the process of sensorless determination of the mechanical power developed by a torque motor

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Abstract. The proposed algorithm for calculating the mechanical power makes it possible to determine the value of the mechanical power developed by each separately considered winding of the electromechanical converter. The developed mechanical power of an electric motor is one of the main parameters that determine the efficiency of its functioning. It allows you to form special operating modes of the electric drive, for example, shockless, with a constant motor speed. The monitoring of the mechanical power of the electric motor reveals the pre-emergency and emergency state of the electric drive. The relevance of the work is due to the need to develop methods for determining the instantaneous values of mechanical power. The proposed algorithm for determining the mechanical power developed by an electromechanical converter does not require the use of mechanical torque sensors, which reduces the cost of monitoring systems for the load of electric drive equipment. The reliability of the proposed algorithm is confirmed by the results of numerical simulation of the dynamic dependence of the mechanical power developed by the 6DBM40 series torque motor.

1. Introduction
One of the main parameters that determine the efficiency of an electric motor is the mechanical power it develops on the output shaft. In modern electric drive systems, mechanical power control makes it possible to form special operating modes of the electric drive, including: shockless, with a constant movement speed. Analysis of the mechanical load of the electric drive system allows to automatically identify the facts of the pre-emergency and emergency state of the electric drive. Thus, the development of methods for determining the mechanical power developed by an electric drive is an urgent scientific and technical problem.

In this work the results of numerical simulation of the process determining of the mechanical power developed by the electric motor without the use of mechanical torque sensors on the electric motor shaft are presented.
2. Materials and methods

The well-known expression of the mechanical power developed by an electric drive is as follows [1]:

\[
P_{\text{mech},1} = \omega (M - M_{\text{resis}}),
\]

(1)

where \( \omega \) – angular speed of rotation of the motor shaft; \( M \) is the electromagnetic moment developed by the electric motor; \( M_{\text{resis}} \) – moment of resistance to rotation of the motor shaft.

Determination of the mechanical power (actual load) of the electric motor according to expression (1) requires the measurement of the mechanical values of the rotation speed \( \omega \) and the resulting torque on the shaft of the electric drive. For this, relatively expensive sensors are used, the collection and processing of information from which increases the response time of the electric motor control system, for example, to the fact of an accident, complicates the control system and reduces the reliability of its operation. To eliminate these shortcomings, on the basis of works [2, 3], it is proposed to calculate the mechanical power according to the following expression:

\[
P_{\text{mech}} = \sum_{j=1}^{N} \left( \frac{u_j - i_j R_j}{L_j} \right) \left( \frac{di_j}{dt} \right),
\]

(2)

where \( i_j, j = 1, 2, ..., N \) – the instantaneous value of the current flowing in the \( j \)-th winding of the electric motor; \( N \) is the number of phases of the motor windings; \( L_j, j = 1, 2, ..., N \) – instantaneous value of self-inductance of the corresponding phase winding of the electric motor; \( u_j, j = 1, 2, ..., N \) – is the instantaneous value of the supply voltage applied to the \( j \)-th (\( j = 1, 2, ..., N \)) winding of the electric motor; \( R_j \) – is the active resistance of the \( j \)-th power loop (\( j = 1, 2, ..., N \)) of the motor winding.

It should be noted that when determining the mechanical power according to the second method (based on expression (2)), it is not required to use data on the value of the total mechanical moment applied to the electric motor shaft \((M - M_{\text{resis}})\), implement this method, the sensor does not need to be installed mechanical moment on the motor shaft or installation of the motor shaft rotation speed sensor[4, 5].

To confirm the possibility of calculating the mechanical power developed by the electric motor based on expression (2) and comparing the calculation results with the power calculated according to expression (1), numerical simulation of the operation of the torque electric motor 6DBM-40 (manufactured by Mashinoapparat, Moscow) was performed [6–8].

On the basis of finite element calculations of the magnetic field of the 6DBM-40 motor, the dependences of the inductances of the motor windings (intrinsic and mutual inductances) were obtained depending on the angular coordinate of the rotor. These dependences are approximated by the Fourier series:

\[
L_{ij}(\alpha) = a_0 + a_1 \cos(\alpha \omega_1) + a_2 \sin(\alpha \omega_1) + a_3 \cos(2\alpha \omega_1) + a_4 \sin(2\alpha \omega_1),
\]

(3)

where \( \alpha \) – is the angular coordinate of the rotor, rad; \( a_0, a_1, a_2, a_3, a_4 \) – approximation weights; \( \omega_1 \) – is the angular frequency of the harmonic components of the Fourier series current.

The values of the coefficients of the formula (3) are presented in table 1; \( i, j = 1, 2, 3 \) are the numbers of the phases of the windings.

The flux linkages of the windings formed by the field of permanent magnets are approximated by the following expression:

\[
\Psi_j(\alpha) = b_0 + b_1 \cos(\alpha \omega_p) + b_2 \sin(\alpha \cdot \omega_p) + b_3 \cos(2\alpha \omega_p) + b_4 \sin(2\alpha \omega_p),
\]

(4)

where \( b_0, b_1, b_2, b_3, b_4 \) – approximation weights; \( \omega_p \) –the angular frequency of the harmonic components of the Fourier series current.
Based on calculations of the own and mutual inductances of the windings, as well as flux linkages, the electromagnetic torque developed by the motor was determined according to the expression:

\[
M = \frac{1}{2} \left( i_1 \frac{\partial L_{11}}{\partial \alpha} + \frac{\partial \psi_1}{\partial \alpha} + i_2 \frac{\partial L_{22}}{\partial \alpha} + i_1 i_3 \frac{\partial L_{13}}{\partial \alpha} + i_2 i_3 \frac{\partial L_{23}}{\partial \alpha} + i_3 i_1 \frac{\partial L_{31}}{\partial \alpha} + i_3 i_2 \frac{\partial L_{32}}{\partial \alpha} + i_1 i_2 i_3 \frac{\partial L_{12}}{\partial \alpha} \right) + \frac{1}{2} i_1 L_{11} \partial \psi_{11} + \frac{1}{2} i_2 L_{22} \partial \psi_{22} + \frac{1}{2} i_3 L_{33} \partial \psi_{33} + \frac{1}{2} L_{11} \frac{\partial \psi_{11}}{\partial \alpha} + \frac{1}{2} L_{22} \frac{\partial \psi_{22}}{\partial \alpha} + \frac{1}{2} L_{33} \frac{\partial \psi_{33}}{\partial \alpha}.
\]  

(5)

The speed of the motor rotor was calculated according to the expression

\[
\omega = \int_0^t \frac{M - M_{\text{resist}}}{J} dt,
\]

(6)

where \( M_{\text{resist}} \) – the moment of resistance to the rotation of the rotor of the engine; \( J \) – the moment of inertia of the masses driven by the engine into rotation.

The instantaneous value of the angular coordinate of the engine was calculated according to the expression:

\[
\alpha = \int_0^t \omega dt.
\]

(7)

The values of the currents consumed by the motor windings were determined according to the following expressions:

\[
\begin{align*}
    i_1 &= \int_0^t \frac{1}{L_{11}} \left( u_1 - i_1 R_1 - i_2 dL_{12} dt - i_3 dL_{13} dt - L_{11} \frac{d}{dt} L_{21} dt - L_{21} \frac{d}{dt} L_{31} dt - L_{31} \frac{d}{dt} L_{11} dt \right) dt; \\
    i_2 &= \int_0^t \frac{1}{L_{22}} \left( u_2 - i_2 R_2 - i_3 dL_{23} dt - L_{22} \frac{d}{dt} L_{32} dt - L_{32} \frac{d}{dt} L_{22} dt - L_{22} \frac{d}{dt} L_{23} dt \right) dt; \\
    i_3 &= \int_0^t \frac{1}{L_{33}} \left( u_3 - i_3 R_3 - i_1 dL_{31} dt - i_2 dL_{32} dt - L_{33} \frac{d}{dt} L_{13} dt - L_{13} \frac{d}{dt} L_{33} dt - L_{33} \frac{d}{dt} L_{23} dt \right) dt.
\end{align*}
\]

(8)

where \( u_1, u_2, u_3 \) – supply voltage, respectively, 1, 2 and 3-th motor winding phases; \( R_1, R_2, R_3 \) – active resistances of the corresponding phases of the windings; \( \frac{d\psi_{1j}}{dt}, j = 1, 2, 3 \) – back-EMF induced in the corresponding windings due to the movement next to them of permanent magnets installed on the rotor of the electric motor according to expression (4).

The numerical simulation of the given mathematical model was carried out in MATLAB Simulink [9–11].

Figure 1 shows a general block diagram of calculations, containing the following blocks: "6DBM40" – the block that provides the calculation of: currents in the motor windings (according to (8)); the angular coordinate of the rotor of the electric motor (according to expressions (3)–(7)) and the value of the mechanical power, determined by a known method based on expression (1); "\( U_{\text{sup}} \)" is an auxiliary unit that ensures the commutation of the motor windings, that is, the formation of functions of the voltages supplied to the motor windings, calculated as follows:

\[
\begin{align*}
    u_1 &= U_{\text{con}} \text{sign} (\cos (4\alpha + \alpha_0)); \\
    u_2 &= U_{\text{con}} \text{sign} (\cos (4\alpha + 120^0 + \alpha_0)); \\
    u_3 &= U_{\text{con}} \text{sign} (\cos (4\alpha - 120^0 + \alpha_0)).
\end{align*}
\]

(9)
where $U_{\text{cont}}$ – control voltage, which determines the value of the rotational speed of the output shaft of the electric motor; $\alpha_0$ – the initial shear angle between the poles of the permanent magnets mounted on the motor shaft and the poles of the stator windings; block "Pr" – determines the value of mechanical power according to the proposed algorithm based on expression (2).

Calculation results using the oscilloscope block "P, Pr" (Figure 1) were visualized in figure 2.

![Figure 1. Block diagram for calculating the value of mechanical power developed by an electric motor](image1)

![Figure 2. Results of calculations of mechanical power, developed by an electric motor](image2)

The discrepancy in the calculation results is minimal. The overshoots of the calculated function observed in the graphs (Figure 2) are explained by the passage through zero of the current value in the considered winding and have a minimal character in time.
3. Conclusion

The proposed algorithm for calculating the mechanical power makes it possible to determine the value of the mechanical power developed by each separately considered winding of the electromechanical converter.

The proposed algorithm for determining the mechanical power developed by an electromechanical converter does not require the use of mechanical torque sensors, which should reduce the cost of manufacturing monitoring systems for the load of electric drive equipment.

The proposed algorithm for determining the mechanical power makes it possible to calculate electromechanical systems with nonlinear properties, in which the intrinsic and mutual inductances of the windings can be represented, for example, in the form of Fourier series or in another convenient way.

References

[1] Kagan V G 1975 Extreme speed electric drives for motion reproduction systems (Moscow: Energia) p 240
[2] Vyrykhanov D A and Ugarov G G 2015 Analysis of the relationship of electrical circuits in a generalized electromechanical energy converter Proceedings of higher educational institutions. Electromechanics 3 p 33–37
[3] Vyrykhanov D A and Ugarov G G 2014 Algorithm for calculating the dynamic dependences of currents and spatial coordinates of the generalized electromechanical energy converter Electrotechnology Issues 1(2) pp 90–95
[4] Weinreb K and Sulowicz M 2007 Operational diagnostics of the types of internal asymmetry of windings of a synchronous machine Zeszyty Problemowe-Maszyny elektryczne 77 5964
[5] Drozdowski P, Petryna J and Weinreb K 1996 Evaluation of the efficiency of diagnostics of asynchronous electric motors based on the spectral analysis of the stator current Proc. of the SME’96. Kraków. Poland pp 31–36.
[6] Non-contact torque motors. Series 6DBM40 2014 (Moscow: OJSC Mashinoapparat). 2014.
[7] Sergienko A B 2006 Digital signal processing: Textbook for universities (St. Petersburg: Peter) p 751
[8] Elizarov I A, Martemyanov Yu F and Skhirtladze A G 2013 Modeling systems (Stary Oskol: TNT) p 136
[9] Chernykh I V 2008 Simulation of electrical devices in Matlab, Simulink (St. Petersburg: Peter), p 288
[10] German-Galkin S G 2008 Matlab & Simulink. Design of mechatronic systems on personal computers (St. Petersburg: KORONA-Vek) p 368
[11] Dyakonov V P 2008 Simulink 5/6/7. Self-study guide (Moscow: DMK Press) p 314