FORMATION OF FUNCTIONAL DEPENDENCES FOR CONTROLLING THE RETURN-ROTARY MOTION OF BRUSHLESS MAGNETOELECTRIC MOTORS

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The article investigates an approach to the control of the return-rotary motion of the actuator based on a special brushless slotless magnetoelectric motor, using which the direct control of the amplitude and frequency of mechanical shaft oscillations is possible. It is proposed a method for the formation of functional frequency dependences of stator voltage parameters for controlling the return-rotary motion in an open-loop control system, considering the adopted performance indexes. Examples of functional frequency dependences of the stator voltage amplitude and the angular length of the zero shelf for rectangular alternating voltage are presented.

Keywords: brushless magnetoelectric motor, return-rotary motion, functional dependence

1. Introduction

One of the tasks arising in the development of various electromechanical devices is the control of the return-rotary motion of the actuating element of mechanisms, for example, in construction equipment, in hand-held power tools and medical devices. At the same time, the regulation ranges of the amplitude and frequency of mechanical oscillations of the actuating element are important factors in choosing the rational structure of the return-rotary motion system. If it is necessary to regulate the frequency of oscillations with a constant amplitude, it is possible to implement a relatively simple electromechanical system based on a standard actuating electric drive and a mechanical converter of rotary motion into oscillatory motion [1, 2].

There are also devices in which the implementation of the return-rotary motion is based on the resonance effect of mechanical oscillations. In such

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devices, in combination with a special control system, standard electric motors are used, for example, an asynchronous [3] or a double-fed motor [4], however, in this case, the effective operation of the mechanism is possible only at one resonant frequency.

This article examines an approach to the implementation of a return-rotary motion system based on a special brushless magnetoelectric motor (BMM) [5], while the actuating element of the device is installed directly on the motor shaft. In this case, it is possible to directly control the frequency and amplitude of mechanical oscillations by controlling the alternating voltage of the stator.

The purpose of the article is to develop an approach to the formation of functional frequency dependences based on the electromechanical characteristics of a BMM for controlling the return-rotary motion in an open-loop control system.

2. The structure and mathematical model of BMM of return-rotary motion

A scheme of a specialized BMM [5] for controlling the return-rotary motion is shown in fig. 1. Here, in the body 1 there are a cylindrical slotless magnetic circuit 2, as well as two bearings 3, in which the rotor shaft 4 with a bipolar permanent magnet 5 and a actuating element 6 is installed. On the inner surface of the magnetic circuit 2 there are two coils 7 and 8 of the stator winding, and an additional permanent magnet 9 is installed in the space between the coils to realize the effect of a magnetic spring.

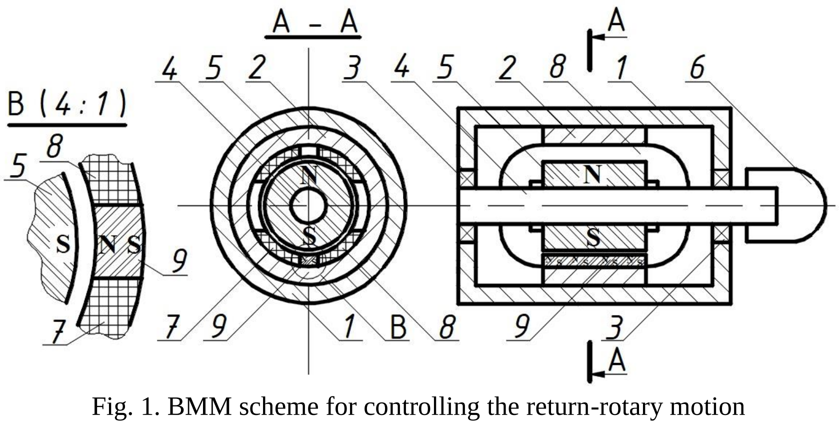

Fig. 1. BMM scheme for controlling the return-rotary motion

When de-energized stator winding, the magnet 9, interacting with the field of the rotor magnet 4, forcibly orientates the rotor so that its poles are located against the active parts of the winding and at the same time provide an elastic connection between the rotor and the stator when the rotor deflects. When the winding is connected to a power source, an electro-magnetic moment arises, which brings the rotor out of a stable equilibrium position and deflects it by a certain angle, at which the electromagnetic moment of the winding balances the moment of interaction of the rotor magnet 4 with the stator magnet 8. Thus, by changing the amplitude and frequency of the alternating current in the winding, direct control of the amplitude and frequency of mechanical oscillations of the actuating element 9 is achieved.

The mathematical model of BMM for controlling the return-rotary motion is described by the equations [6]:

$$L\frac{di}{dt} = -Ri - k_m \omega \cos\alpha + u; \tag{1}$$

$$M = k_m i \cos\alpha; \tag{2}$$

$$M_\omega = k_\omega \omega; \tag{3}$$

$$M_\alpha = k_\alpha \sin\alpha; \tag{4}$$

$$J\frac{d\omega}{dt} = M - M_\omega - M_\alpha - M_R - M_L; \tag{5}$$

$$\frac{d\alpha}{dt} = \omega, \tag{6}$$

where ω, α are angular speed and angle of the rotor shaft oscillations; L, R are inductance and active resistance of the stator winding; i, u are current and control alternating voltage of the stator; k_m is motor torque coefficient; J is rotor moment of inertia; M_ω, M_α, M_R, M_L are torques of viscous friction and elasticity, reactive torque of bearings and torque of loading, respectively; k_ω, k_α are viscosity and elasticity coefficients.

The reactive torque of bearings is determined according to the equation

$$M_R = M_B\, sign(\omega), \tag{7}$$

where M_B is bearing friction torque.

Also, we assume the following dependence for setting the load mechanical torque

$$M_L = k_L \omega, \tag{8}$$

where k_L is viscosity coefficient of the motor load.

3. Methods of controlling the BMM of the return-rotary motion

Previous studies have shown the possibility of controlling the BMM in two ways:

- in a closed-loop system of the control of the rotor oscillations angle amplitude and limiting the stator current effective value [7], while it is necessary to form the corresponding feedback signals, which significantly complicates the hardware part of the system;

- in an open-loop system by forming functional frequency dependences of the value of the amplitude and the shape parameter of the control alternating voltage of the stator, which can be formed based on the electromechanical characteristics of the BMM with given performance indexes of its operating mode [6].

The control action can be sinusoidal or rectangular shape with a zero shelf. Then the stator voltage is described by two variants of the formulae

$$u = U_A \sin 2\pi f_O t ; \quad (9)$$

$$u = 0{,}5U_A \left(sign\left(\sin 2\pi f_O t - 0{,}5\varphi_1\right) + sign\left(\sin\left(2\pi f_O t + 0{,}5\varphi_1\right)\right)\right); \quad (10)$$

where U_A is the amplitude of the stator control voltage; f_O is the frequency of rotor shaft oscillations; φ_1 is the angular length of the zero shelf of the rectangular form voltage; t is the time.

The main output parameters of the BMM operating mode are:

f_O – carrier frequency of rotor mechanical oscillations in the operating range of 1-100 Hz;

α_A – the amplitude of the rotor oscillations angle in the range of 20 degrees;

I – the effective value of the stator current.

BMM is an object with nonlinear dependencies of input and output parameters. In this case, the BMM of the return-rotary motion can operate in one of two modes:

- in the mode of limiting the amplitude of the rotor oscillations angle at a given level in the low-frequency range of operation (up to 20-30 Hz);

- in the mode of limiting the effective value of the stator current at values of the oscillation frequency more than 20-30 Hz, while the effective value of the current is limited by the conditions of motor cooling.

In other words, one of two conditions must be met:

$$\alpha_A = \alpha_3 \text{ at } f_O < f_P \text{ or } I = I_3 \text{ at } f_O > f_P , \qquad (11, 12)$$

where α_3, I_3 are the reference values of the amplitude of the angle of rotor oscillations and the stator current effective value; f_P is the value of the oscillations frequency at which the transition from one mode of operation of the BMM to an-other occurs.

In [6] it is shown that the effective work of the BMM is obtained while ensuring the maximum of one of two parameters, where:

$k_1 = \dfrac{\alpha_A}{I^2}$ is an index of the efficiency of the BMM operating mode at a given frequency and amplitude, as well as at a minimum value of losses in the stator winding;

ω_A is the amplitude of the angular speed of the rotor oscillations.

Fig. 2 shows the dependences of the main parameters of the operating mode α_A, I, ω_A, k_1 and U_A on the frequency f_O in the range up to 100 Hz, subject to the limitations of the amplitude of the oscillation angle and the stator current effective value $\alpha_3 = \pi/9$ $rad.$ and $I_3 = 0{,}14$ A. Here, number 1 denotes a variant of generating a sinusoidal stator voltage (9). Numbers 2, 3 and 4 designate variants for rectangular alternating voltage (10) with three parameter values φ_1 – 0, 80 and 160 electrical degree. The calculations were performed for equations system (1–8) with the following parameter values: $R = 40\,Ohm$, $L = 0{,}012\,Hn$, $k_m = 0{,}125\ N\,m/A$, $k_\omega = 6{,}5 \cdot 10^{-5}\ N\,m\,s/rad.$, $k_\alpha = 0{,}0448\,N\,m/rad.$, $J = 2{,}4 \cdot 10^{-6}\ kg\ m^2$, $k_L = 1{,}7 \cdot 10^{-4}\ N\,m\,s/rad.$, $M_B = 2 \cdot 10^{-4}\ N\,m$.

The analysis of the given electromechanical characteristics shows that none of the variants of the formation of the alternating stator voltage with fixed parameters can provide a maximum of one of the performance indexes of the BMM operation mode in the entire frequency range. In this case, it can be concluded that it is possible to select the optimal parameters of the alternating stator voltage at each value of the carrier frequency to generate frequency dependences for motor control. It is also obvious that the values of the cut-off frequency f_P of the transition from the oscillation angle amplitude stabilization mode to the current limiting mode are different when different variants of the stator alternating voltage are formed.

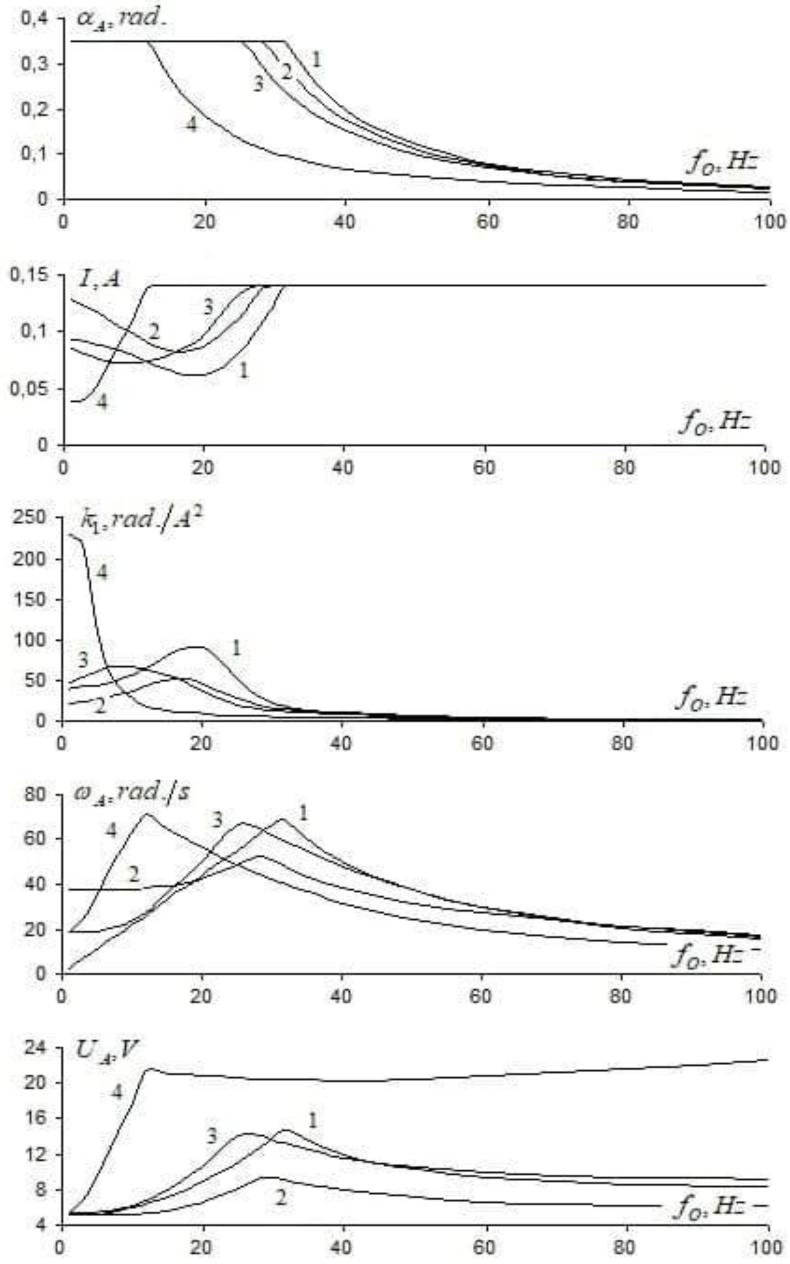

Fig. 2. Dependences of parameters α_A, I, ω_A, k_1 and U_A on frequency f_O

4. Formation of functional frequency dependences

Let us note the features of the studied approach to the formation of functional frequency dependences:

- the control of the return-rotary motion is carried out subject to the provision of a maximum value of one of the performance indexes of the BMM operation mode;
- the formation of functional dependencies implies the composition of the dependences of the amplitude U_A and the parameter φ_1 of the stator voltage form on the rotor oscillations frequency f_O, taking into account the accepted performance indexes k_1 or ω_A of the operating mode in the entire frequency range with the given values of the oscillations amplitude α_3 and the current effective value I_3;
- the compilation of such dependencies is carried out on the basis of the electromechanical characteristics of the BMM.

Finally, we define the sequence of formation of functional frequency dependences in the form $U_A(f_O)$ and $\varphi_1(f_O)$:

1. For a number of frequency values at given values of the oscillations angle amplitude α_3 and the stator current effective value I_3 on the basis of the mathematical model (1–8), the calculation of performance indexes k_1, ω_A and the amplitude U_A for sinusoidal and rectangular stator voltages depending on the parameter φ_1 was performed.

Fig. 3 shows examples of graphs of such dependences $k_1(\varphi_1)$, $\omega_A(\varphi_1)$ and $U_A(\varphi_1)$ for four values of the oscillations currier frequency – 5, 10, 20 and 40 Hz. The straight line indicates the values of the performance indexes at sinusoidal voltage.

2. Further, for each performance indexes k_1 and ω_A, their maximum values are determined and the value of the voltage amplitude U_A of the form that turns out to be the best under one of the indexes is fixed; in the case of choosing a rectangular voltage, the corresponding value of angular length φ_1 of the zero shelf is fixed;

3. For performance indexes k_1 and ω_A, dependences $U_A(f_O)$ and $\varphi_1(f_O)$ (for non-sinusoidal voltage) are formed, and in the entire operating frequency f_O range there may be several sub-ranges of using different forms of the alternating voltage.

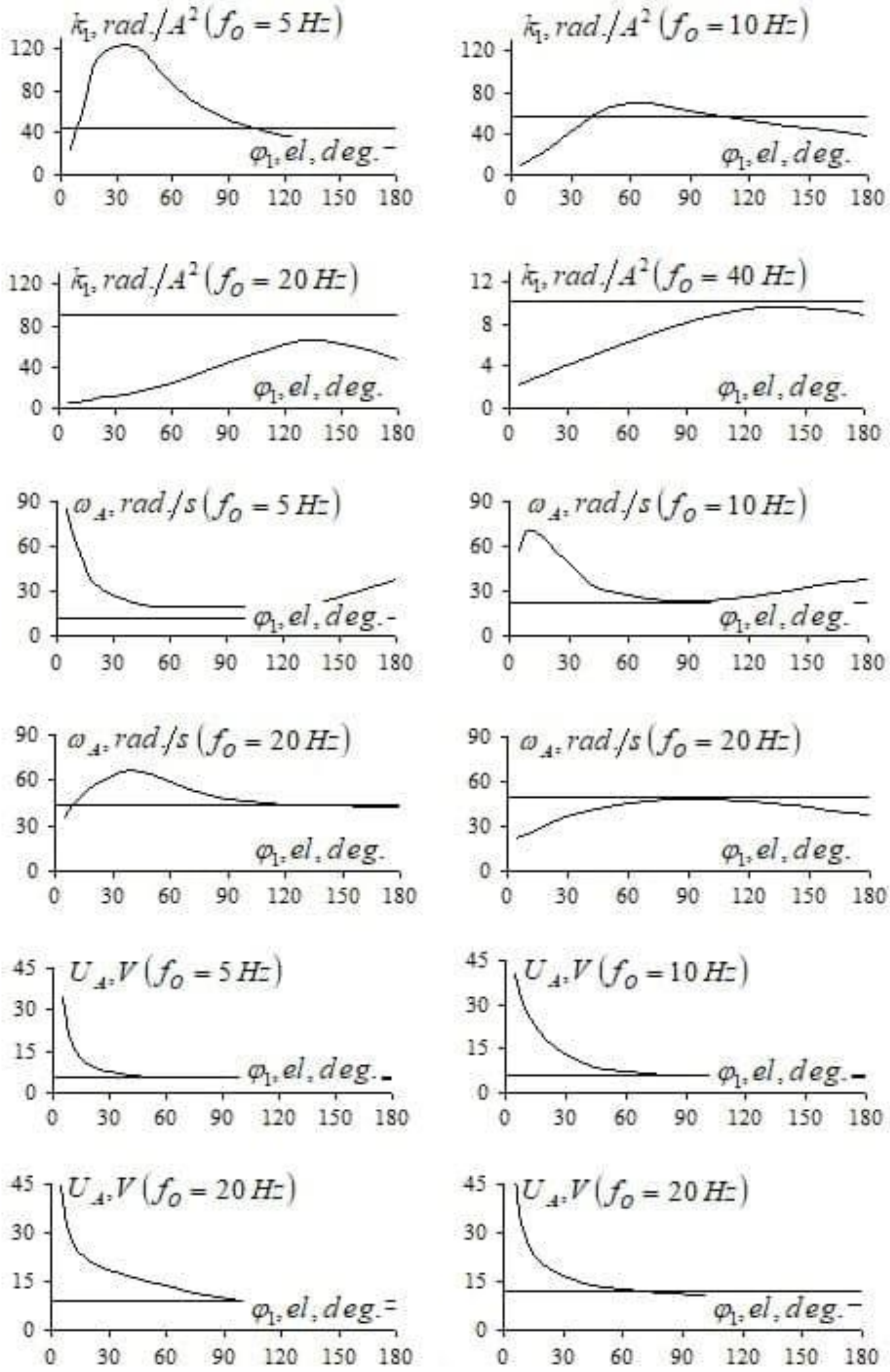

Fig. 3. Dependences of parameters k_1, ω_A, and U_A on parameter φ_1

Fig. 4 shows the formed functional dependences $U_A(f_O)$ and $\varphi_1(f_O)$, as well as the corresponding dependences of indexes $k_1(f_O)$ and $\omega_A(f_O)$. The letters A and B designed the variants of the formation of sinusoidal and rectangular voltages respectively.

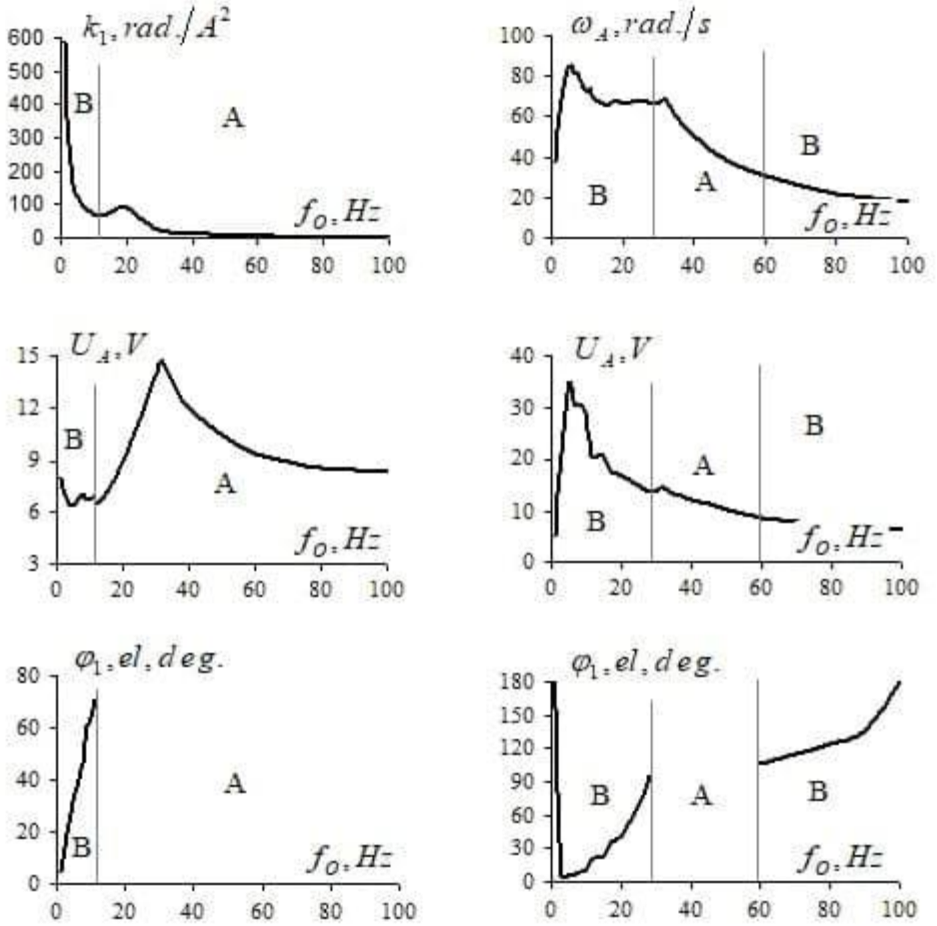

Fig. 4. Functional dependences $U_A(f_O)$ and $\varphi_1(f_O)$ as well as the corresponding dependences of indexes $k_1(f_O)$ and $\omega_A(f_O)$

5. Conclusions

The use of functional frequency dependences makes it possible to control the BMM of the return-rotary motion using an open-loop control system without using feedbacks, which minimizes its hardware.

The formation of the stator voltage with different parameters allows to provide the operation modes of the BMM of the return-rotary motion either by minimizing losses in the stator winding, or by ensuring the maximum amplitude of the angular speed of the rotor shaft oscillations.

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