Analysis of energy conversion in the instantaneous power transfer process in the electromechanical system with variable inductance

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Abstract. The paper presents the analysis of energy conversion processes in the dc electromechanical devices with variable inductances. With respect to the instantaneous power balance in the electromechanical system, the mechanical power transfer is considered for the operating cycle. The generalized structural model of the electromechanical converter with variable inductance is proposed. The model consists of three subsystems which are cascaded by instantaneous power transfer channels. The model is distinguished by the internal magnetic energy source in the magnetic subsystem with additional channels for magnetic power transfer. Energy conversion conditions influence the instantaneous power transfer channel operation. The magnetic energy restoring factor and its sign are the criterions of the energy conversion processes difference. The instantaneous power flux circulation accompanied by complicated electromagnetic energy conversion processes in dynamic modes is established by experiments.

1. Introduction

Electromagnetic motors (EMM) are widely used in industry for providing various technological processes and production [1–7]. The EMM are widely used in switching devices and traction electric drives [8–17]. One of the perspective areas of electromagnetic motors application is drives of impact mechanisms and machines [18–27].

The impact mechanisms application in drives of impact machines greatly simplifies the kinematic scheme of the machines and in certain cases allows increasing their energy indicators [28–32].

According to the classification of electromechanical devices, the EMMs are considered to be linear electromechanical energy converters with variable inductance. In recent decades, a number of papers have been published, analyzing the processes of energy conversion in the EMM [33–36]. Currently much attention is paid to the optimization of EMMs modes of operation based on the analysis of energy conversion processes [37, 38]. However, the absence of a sufficiently substantiated universal model for energy processes research complicates the solution of many problems, including optimization and control in dynamic modes of device operation.

The proposed generalized model of EMM in the form of a structural model makes it possible to understand the physics of the energy conversion processes. The generalized model is based on the fact that any electromagnetic device with variable inductance, in particular the EMM, is represented as separate subsystems (electrical, magnetic, and mechanical) cascaded with each other by energy transfer.
channels of mechanical power. One of the features of the model is the introduction of the additional source of magnetic energy.

Figure 1 shows variants of single-coil EMMs for electric drives used in switching equipment, vibrators, impact devices, etc.

![Figure 1. Single-coil EMM construction variants](image)

It is assumed that the magnetic core in a single-coil EMM is not saturated and there are no eddy currents and hysteresis loss. Friction loss in the mechanical system is neglected.

2. Theory

The processes occurring in the EMM if the dc voltage is applied are described by the electrical balance equation:

\[ U = ir + \frac{d\psi}{dt}, \]

where \( U \) is the voltage applied to the coil, \( i \) is the coil current, \( r \) is the coil active resistance, \( \psi \) is the flux linkage.

The second component of the equation (1) right side determines the instantaneous value of the electromotive force:

\[ \frac{d\psi}{dt} = e = \frac{\partial \psi}{\partial i} \frac{di}{dt} + \frac{\partial \psi}{\partial x} V, \]

where \( V = \frac{dx}{dt} \) is the speed of the EMM armature mechanical movement.

Multiplying the left and right sides of the equation (1) by the current \( i \) gives:

\[ Ui = i^2 r + i \frac{d\psi}{dt} = i^2 r + \frac{dW_{em}}{dt}, \]

where \( \frac{dW_{em}}{dt} = \frac{\partial \psi}{\partial i} \frac{di}{dt} + \frac{\partial \psi}{\partial x} V = p_{em} \) is the instantaneous electromagnetic power, \( i^2 r = p_q \) is the instantaneous power of heat loss, \( ui = p_e \) is the instantaneous electrical power.

The ratio between the instantaneous values of the electromagnetic and magnetic power:

\[ \frac{dW_{em}}{dt} = \frac{dW_m}{dt} + dA_{mec} = \]

\[ = \frac{1}{2} \left( i \frac{\partial \psi}{\partial i} \frac{di}{dt} + \psi \frac{di}{dt} + i \frac{\partial \psi}{\partial x} V \right) + \frac{1}{2} \left( i \frac{\partial \psi}{\partial i} \frac{di}{dt} - \psi \frac{di}{dt} + i \frac{\partial \psi}{\partial x} V \right), \]

(3)
where \( \frac{dW_m}{dt} = p_m = \frac{1}{2} \left( \frac{\partial \psi}{\partial i} \frac{di}{dt} + \psi \frac{di}{dt} + i \frac{\partial \psi}{\partial x} V \right) \) – the instantaneous power of the magnetic field,

\( \frac{dA_{mech}}{dt} = p_{mech} = \frac{1}{2} \left( i \frac{\partial \psi}{\partial i} \frac{di}{dt} - \psi \frac{di}{dt} + i \frac{\partial \psi}{\partial x} V \right) \) – the instantaneous mechanical power used for the armature movement.

With respect to (2) and (3) and total differential, the power balance takes the form:

\[ U_i = i^2 r + \frac{1}{2} \left( \frac{d\psi}{dt} + \psi \frac{di}{dt} \right) + \frac{1}{2} \left( i \frac{d\psi}{dt} - \psi \frac{di}{dt} \right) = p_Q + p_m + p_{mech}, \tag{4} \]

where

\[ p_m = \frac{1}{2} \left( \frac{d\psi}{dt} + \psi \frac{di}{dt} \right), \quad p_{mech} = \frac{1}{2} \left( i \frac{d\psi}{dt} - \psi \frac{di}{dt} \right). \]

The instantaneous power transmission process in the EMM has been analyzed during the total cycle of the armature movement. The dependence of the instantaneous powers \( p_e, p_{em}, p_m, p_Q, p_{mech} \) on time has been obtained from (3) and (4).

3. Analysis of theoretical results by simulation

With respect to the electric balance equation, the derivative of the flux linkage is:

\[ \frac{d\psi}{dt} = U - ir. \]

Graphic integration of \( \frac{d\psi}{dt} \) gives the flux linkage:

\[ \psi(t) = \int_0^t \frac{d\psi}{dt} dt = \int_0^t (U - ir) dt. \]

Current derivative \( \frac{di}{dt} \) is found by graphical differentiation of the dependence \( i(t) \) (Figure 3). For example, the process of applying the dc voltage \( U = 98 \) V to the EMM with the active coil resistance \( r = 29.8 \) Ohm is shown in the tabular form in Figure 2. The first column reflects the time in seconds and the second one is the current in amperes.

All necessary calculations were performed in Mathcad to improve the accuracy of calculation and to reduce the probability of graphical integration and differentiation errors.

Special attention was paid to the question of error-free differentiation and integration. For example, the linear interpolation error is too high. The best results were achieved by replacing the initial function of the current by segments of cubic polynomials using spline approximation. In this case, the coefficients of polynomials obtained as a result of calculations ensure the continuity of its first and second derivatives. For the implementation of the spline approximation the MathCAD function spline (X, Y) was used to calculate the values of currents at given points. The example of data entry and the description of a function for performing spline interpolation is stated in Figure 2.

The result of the spline interpolation of the current using 12 nodal points is shown in Figure 3. As it is shown in Figure 3, the interpolation function curve fits well with the nodal points.
As an example of using the spline interpolation, the graphs of the current derivative \( \frac{di}{dt} \), flux linkage derivative \( \frac{d\psi}{dt} \) and flux linkage \( \psi \) are stated in Figure 4.

The graphs for the instantaneous values \( p_r, p_Q, p_m, p_{mech} \) in the time interval of the movement of the EMD armature are shown in Figure 5. Taking into account the characteristic features of the circulation of power when mechanical work is performed, the whole process of energy conversion (Figure 5) should be divided into two regions, the boundary of which is the condition when \( p_m = 0 \).

The first region (Figure 5) is characterized by the positive sign of the magnetic energy differential (\( dW_m > 0 \)) and the power of the magnetic field (\( p_m > 0 \)). At the same time, the work moving the armature is done only at the expense of the source energy, and a part of the source energy is spent on increasing the energy of the magnetic field which is stored by the system.
The second region (Figure 5) is characterized by the negative sign of the magnetic energy differential \(dW_m < 0\) and the magnetic field power \(p_m < 0\). At the same time, the work moving the armature is performed both by the energy received from the source and by the energy of the magnetic field.

The important condition for the implementation of the balance of instantaneous power is the equality of the left and right parts of (4) over the entire interval of the operation of the EMD, i.e.:

\[
\Delta p(t) = p_e(t) - \left[p_Q(t) + p_m(t) + p_{mech}(t)\right] \approx 0.
\] (5)

The \(\Delta p(t)\) is reflected in the graph in Figure 5 as a straight line of the zero level.

The process of EMD functioning is accompanied by quite complex phenomena of electromechanical transformation of energy during the time of movement of the armature. Such phenomena is associated primarily with the processes of circulating power flows in dynamic modes that effect on the dynamic characteristic of magnetization \(\psi = f(i)\).

To analyze the processes of circulation of power flows at the level of the structural scheme, the EMD model with an additional instantaneous power transmission channel associated with the internal source of magnetic energy is considered.

The structural model of an electromechanical converter based on the EMM is shown in Figure 6. The model is represented by three subsystems, cascade-related energy channels for power transmission.

A feature of the model (Figure 6) is the presence in the magnetic subsystem of the internal source of magnetic energy responsible for the circulation of magnetic power \(p_m\).
Opening and locking the power transmission channels in a certain way depends on the conditions of energy conversion processes. The boundary between these processes is described by the magnitude and sign of the recovery coefficient of magnetic energy \( k_{\text{rec}} \).

When \( dW_{\text{m}} > 0 \), a part of power from the external power source is used to charge the internal source and to increase the magnetic field energy stored in the system. Energy conversion process with respect to \( dW_{\text{m}} < 0 \) is accompanied by intensive discharge of the internal source and the transmission of magnetic power through the channel formed in the mechanical subsystem. If \( k_{\text{rec}} < -1 \), parallel channel is opened and the magnetic power is transferred to the electrical subsystem, causing the “generator effect”. The energy conversion mode is caused by the combination of the motor and generator modes and the transmission of electrical power to the mentioned above source.

The additional channel of transmission of the power of the internal source to the mechanical subsystem is accompanied by an additional effect, causing an excess of the instantaneous mechanical power \( P_{\text{mech}} \) over the instantaneous power consumption \( p_e \) from an external source.

The EMD control by moving the armature in case \( dW_{\text{m}} < 0 \) may be lost. On the other hand, the application of energy conversion mode at \( dW_{\text{m}} < 0 \) allows increasing the final speed of the armature together with the impact energy when the instantaneous power received from the source is constant or even reduced.

4. Conclusion
The universal generalized structural model of the electromagnetic converter with variable inductance has been developed on the basis of the features of energy conversion in the EMM.

The research results obtained by the theoretical analysis have been approved by the simulation in MathCAD.

The generalized model exactly describes the physical processes of producing the useful mechanical work. This model can be applied in the EMM design and in the study of the instantaneous mechanical power transmission.

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