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MODELING ISSUES OF LOW-SPEED ELEVATOR MOTOR OF BIINDUCTOR TYPE

А. Бойко, В. Іванов, І. Климчук, Д. Ігнатенко. **Питання моделювання тихохідного ліфтового електродвигуна біiндукторного типу**. Більшість усієї електроенергії, яка використовується при експлуатації ліфтів, споживає ліфтовий електропривод, тому основна увага при проектуванні сучасних конструкцій ліфтів приділяється покращенню енергетичних характеристик саме лебідок та їх систем керування. Електроприводи пасажирських ліфтів, які експлуатуються, мають в своєму складі одно- або двошвидкісні асинхронні електродвигуни і черв'ячні редуктори. В сучасному ліфтобудуванні, є дві тенденції удосконалення електроприводів приводів машин, а саме забезпечення плавного розгону і гальмування робочого органу; перехід від електропривода, у якому застосовується механічний редуктор, до безредукторного приводу. Вказане дозволяє збільшити коефіцієнт корисної дії, за рахунок відмови від елемента з низьким коефіцієнтом корисної дії. Одним із шляхів вирішення проблеми синтезу сучасного безредукторного елеваторного електроприводу є можливість використання низькообертового електродвигуна біiндукторного типу (біiндукторного електродвигуна) з безобмотковим циліндричним ротором. В роботі проведено технічний аналіз вимог, які пред'являються до електроприводів пасажирських ліфтів. Зазначено переваги безредукторних ліфтових електроприводів та актуальні потреби в тихохідних приводних двигунах. Розглянуто можливість, у цій якості, застосування електричного двигуна біiндукторного типу з безобмотковим циліндричним ротором. Зазначено, що конструктивна схема біiндукторного двигуна забезпечує підвищення питомих значень потужності та моменту, це особливо важливо за знижених номінальних частот обертання безредукторних ліфтових лебідок. Розглянуто основні конструктивні параметри двигуна біiндукторного типу та запропоновано його еквівалентну структурну схему. Виконано математичний опис запропонованого електродвигуна, як складної електромеханічної системи з багатовимірними нелінійними об'єктами. Показано можливість переходу до спрощеної структурної схеми двигуна, яка, за низки припущень, дає змогу форматувати будь-яку передавальну функцію, як для керівного, так і для збурювального впливу.
Ключові слова: ліфт, тихохідний двигун, біiндукторний двигун, ліфтовий електропривод, безредукторний електропривод, математичний опис

A. Boiko, V. Ivanov, I. Klimchuk, D. Ignatenko. **Modeling issues of low-speed elevator motor of biinductor type.** Most of the electricity used in the operation of elevators consumes elevator electric drive, so the main focus in the design of modern elevator designs is to improve the energy characteristics of winches and their control systems. Electric drives of passenger elevators, which are operated, include single or two-speed asynchronous electric motors and worm gearboxes. In modern elevator construction, there are two trends in improving the electric drives of machine drives, namely, ensuring smooth acceleration and braking of the working body; transition from an electric drive, in which a mechanical gearbox is used, to a gearless drive. This allows you to increase the efficiency by eliminating the element with a low efficiency. One of the ways to solve the problem of synthesis of a modern gearless elevator electric drive is the possibility of using a low-speed biinductor-type electric motor (biinductor electric motor) with a non-winding cylindrical rotor. The work conducted a technical analysis of the requirements for electric passenger elevators. The advantages of gearless elevator electric drives and the actual needs for low-speed drive engines are indicated. The possibility, in this capacity, of using an electric motor of biinductor type with a non-winding cylindrical rotor is considered. It is noted that the design scheme of the biinductor motor provides an increase in the specific values of power and torque, this is especially important with reduced rated speeds of gearless elevator winches. The basic structural parameters of the engine of biinductor type are considered and its equivalent structural scheme is proposed. The possibility of moving to a simplified structural scheme of the engine is shown, which, according to a number of assumptions, makes it possible to format any transfer function, both for the control and for the disturbing effect. Mathematical description of proposed electric motor is made as complex electromechanical system with multidimensional nonlinear objects.
Keywords: elevator, low-speed motor, biinductor motor, elevator electric drive, gearless electric drive, mathematical description

Introduction

In Ukraine, more than 100 thousand passenger elevators are in operation, of which no less 60% have developed a normative service life of 25 years and are subject to replacement or modernization. To replace them, elevators are needed that correspond to the modern level of development of science and technology. More than 50% of all electricity used in the operation of elevators consumes elevator electric drive, so the main attention in the design of modern elevator designs is paid to improving the energy characteristics of winches and their control systems [1]. Electric drives of passenger elevators, which have been operated in Ukraine since the 70s of the last age, have in their composition one or two-speed asynchronous electric motors and worm gearboxes. The efficiency of such electric drives is small, it is about 60% with steady motion and does not exceed 12…15% during acceleration. In mod-

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ern mechanical engineering, and in particular in elevator construction, there are two trends in improving the electric drives of machine drives [2]:

– providing smooth acceleration and braking of the working element (cabin), which allows to improve dynamic characteristics and significantly reduce the dynamic load during acceleration and braking, and thus increase the equivalent efficiency;

– transition from an electric drive, in which a mechanical gearbox is used, to a gearless drive, which allows increasing the efficiency, due to the rejection of an element with a low efficiency.

Analysis of literary data and problem statement

In gearless elevator winches, the cable pulley is attached directly to the shaft of the drive motor, which makes the structure more compact and facilitates its placement in the elevator shaft. The absence of a gearbox significantly increases the efficiency of the electric drive, and also improves the distribution of weight in favor of the load and allows you to effectively recover energy to the network [3]. The problem remains the presence of low-speed (50...150 rpm) elevator motors with the necessary parameters and acceptable weight and dimensions. The developers offer technical solutions aimed at reducing the requirements for the minimum speed of the cable pulley and the engine to 300...500 rpm, but most of them are unsatisfactory [4]. It is known that the dimensions of an electric machine (EM), its mass and the moment of inertia of the rotor at the same power are significantly dependent on its nominal rotation frequency [1]. Elimination of gearbox with gear ratio ip, from the electric drive requires, by the same amount, a decrease in engine speed and an increase in torque [5]. For this, for example, AC machines of traditional design must have a winding with an increased number of poles, which theoretically can reach 100...150. In such cases, in order to obtain the required torque, it is necessary to increase the cross-section of the magnetic core, which leads to a significant increase in the size and weight of the slow-moving engine [6]. This is due to the limited use of seamless winches with low-speed asynchronous or collector machines [1, 7]. For mass-purpose elevators, with relatively low speeds of cars (up to 1...1.6 m/s), the problem of synthesizing new types of gearless electric drives can be solved by using new types of low-speed engines with the necessary properties and parameters.

The purpose of this work is a mathematical representation of a low-speed electric motor of a biinductor type with a non-winding rotor, taking into account its design features; generation of universal transfer function EMBT.

To achieve this goal, you need to solve the problem:

– analyze existing elevator electric drives;

– to develop a mathematical model of a low-speed electric motor of biinductor type and an equivalent structural diagram of the motor is proposed.

Materials and methods of research

One of the ways to solve the problem of synthesis of modern gearless elevator electric drive is the possibility of using a low-speed electric motor of two-inductor type (biinductor electric motor) with a non-winding cylindrical rotor (EMBT), which is used at the Odessa Polytechnic National University [8, 9]. In the low-turn version, the proposed electric machine manages to provide high energy and dynamic indicators due to the innovative design of its magnetic system.

Design features of EMBT. Electric motor consists of fixed part *1* and rotating rotor *2* (Fig. 1). The fixed part *1* includes an annular structure *3* on the inner surface of which there are three stators *4*, *5*, *6*. In slots of stators *4*, *5*, *6* there are sections of armature winding *7*, and in gaps between stators *4*, *5* and *5*, *6* – excitation windings *8*, *9* [8]. End shields of rotor *15*, *16*, *17*, *18* are rigidly connected to shaft *14*, providing fastening of ferromagnetic poles *19*, *20*, *21* of cylindrical rotor *2*, which are separated from stators *4*, *5*, *6* by working air gap of δ. Unlike the classical design of a DC machine, in the proposed EMBT, regardless of the number of pole divisions, there are only two excitation windings *8*, *9* and there are no windings of additional

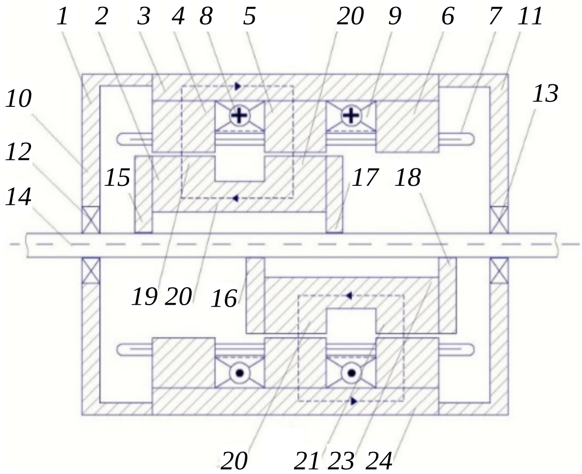

Fig. 1. EMBT structural diagram

poles, since the limitation of the armature reaction is provided by constructive methods. Ring structure *3* of fixed part 1 consists of a number of separate magnetically unrelated ferromagnetic rods – H-shaped teeth, each of which contains three teeth belonging to stators *4*, *5*, *6*, united by a longitudinal rod – base *24*. End parts of longitudinal rods *24* are fixed on nonmagnetic end panels *10*, *11* forming rigid structure of fixed part 1 of electric machine. In spaces – slots between rods-teeth of Ш-shape, sections of armature winding *7* [6] are laid.

The presence of a stator with magnetically unbound ferromagnetic gear elements makes it possible to place two excitation windings, each of which creates its own magnetic flux. These magnetic fluxes having oppositely parallel directions ensure full use of the active surface of the central stator EMBT and half use of the active surface of the extreme stators during energy conversion. This increases the specific values of the electromagnetic torque of the machine. The absence of a massive ferromagnetic rotor core reduces the mass of the rotating part of the engine, and, accordingly, significantly reduces its inertia and increases the speed of operation in transient modes [9]. The EMBT design scheme provides for an increase in the specific values of power and torque, which is especially important at reduced rated speeds of rotation of gearless elevator winches. The EMBT design provides a modular principle of its manufacture for different capacities by sequentially alternating the disk rotor and the anchor module. The use of combined excitation makes it possible to increase the power of the machine by another 2 times with unchanged weight and size indicators [6]. The speed of rotation and reversing of the motor is controlled by the method of regulating the supplied voltage, which is known for classic DC machines. An electric switch [8] is used to power and control the EMBT.

Features of the mathematical description of EMBT

A biinductor motor with a cylindrical rotor winding is a complex system with multidimensional nonlinear objects in projection on the axis d, q. This implies a transition to a simplified transfer function under a number of conditions and assumptions: linearization of Park-Gorev differential equations [3]; continuous approximation of the current relay; Consideration of transients in the area of small deviations from the established working point; constancy of the obtained magnetic flux in the machine gap; neglect of higher current harmonics; neglecting the distortions introduced by the valves of the distribution board, as well as the switching time of the valves. Based on the studies conducted in the works [6, 9, 10, 11, 12], an equivalent structural diagram of the biinductor engine is proposed, which is shown in Fig. 2.

The independent control parameter of the electric machine, in this case, is the angle of ψ, by means of which the projections of the amplitudes of the fundamental harmonic of the currents of the stator Imi on the coordinate axis d, q are forcibly set.

Constant coefficients of the block diagram (Fig. 2) can be found:

$$\left.\begin{aligned}
&K_1=\frac{k_{cx}}{\sqrt{2}}pL_{ed};\ K_2=\frac{k_{cx}}{\sqrt{2}}p(L_d-L_q);\ K_3=K_1;\ K_4=\frac{k_{cx}}{\sqrt{2}}pL_{eq};\\
&K_5=\frac{k_{cx}}{\sqrt{2}}L_{ed};\ K_6=\frac{k_{cx}}{\sqrt{2}}\left(2(L_d-L_q)+L_{ed}\left[\frac{K_f(1-K_{kd})+K_{kd}(1-K_f)}{1-K_fK_{kd}}\right]\right);\\
&K_7=K_5;\ K_8=\frac{k_{cx}}{\sqrt{2}}L_{eq};\ K_9=\frac{k_{cx}K_f(1-K_{kd})}{\sqrt{2}(1-K_fK_{kd})};\ K_{10}=\frac{k_{cx}K_{kd}r_{kd}(1-K_f)}{\sqrt{2}(1-K_fK_{kd})};\\
&K_{11}=\frac{k_{cx}K_{kq}}{\sqrt{2}}-r_{kq};\ K_{12}=\frac{L_{kd}}{L_fL_{kd}-L_{ed}^2};\ K_{13}=\frac{2L_{ed}(L_{kd}-L_{ed})}{\sqrt{3}(L_fL_{kd}-L_{ed}^2)};\ K_{14}=K_{13};\\
&K_{15}=\frac{L_{ed}r_{kd}}{(L_fL_{kd}-L_{ed}^2)};\ K_{16}=\frac{2L_{ed}}{\sqrt{3}L_{kd}};\ K_{17}=K_{16};\ K_{18}=\frac{L_{ed}}{L_{kd}};\ K_{19}=\frac{r_{kd}}{L_{ed}};\\
&K_{20}=\frac{2L_{eq}}{\sqrt{3}L_{kq}};\ K_{21}=K_{20};\ K_{22}=\frac{r_{kq}}{L_{kq}};\ K_f=\frac{L_{ed}}{L_f};\ K_{kd}=\frac{L_{ed}}{L_{kd}};\ K_{kq}=\frac{L_{eq}}{L_{kq}}.
\end{aligned}\right\},\qquad (1)$$

where L_{eq}, L_{kq} – projections of inductances of the windings of the electric machine on the axis q;

L_{ed}, L_{kd} – projections of inductances of the windings of the electric machine on the axis d;

r_f, r_{kd}, r_{kq} – active resistance, respectively, of excitation windings and EM rotor along axes d, q;

K_f , K_{kd}, K_{kq} – coupling coefficients, respectively, of excitation windings and damping circuits of EM rotor along axes d, q;

k_{cx} — schematic current switch factor;

p – number of EM pole pairs.

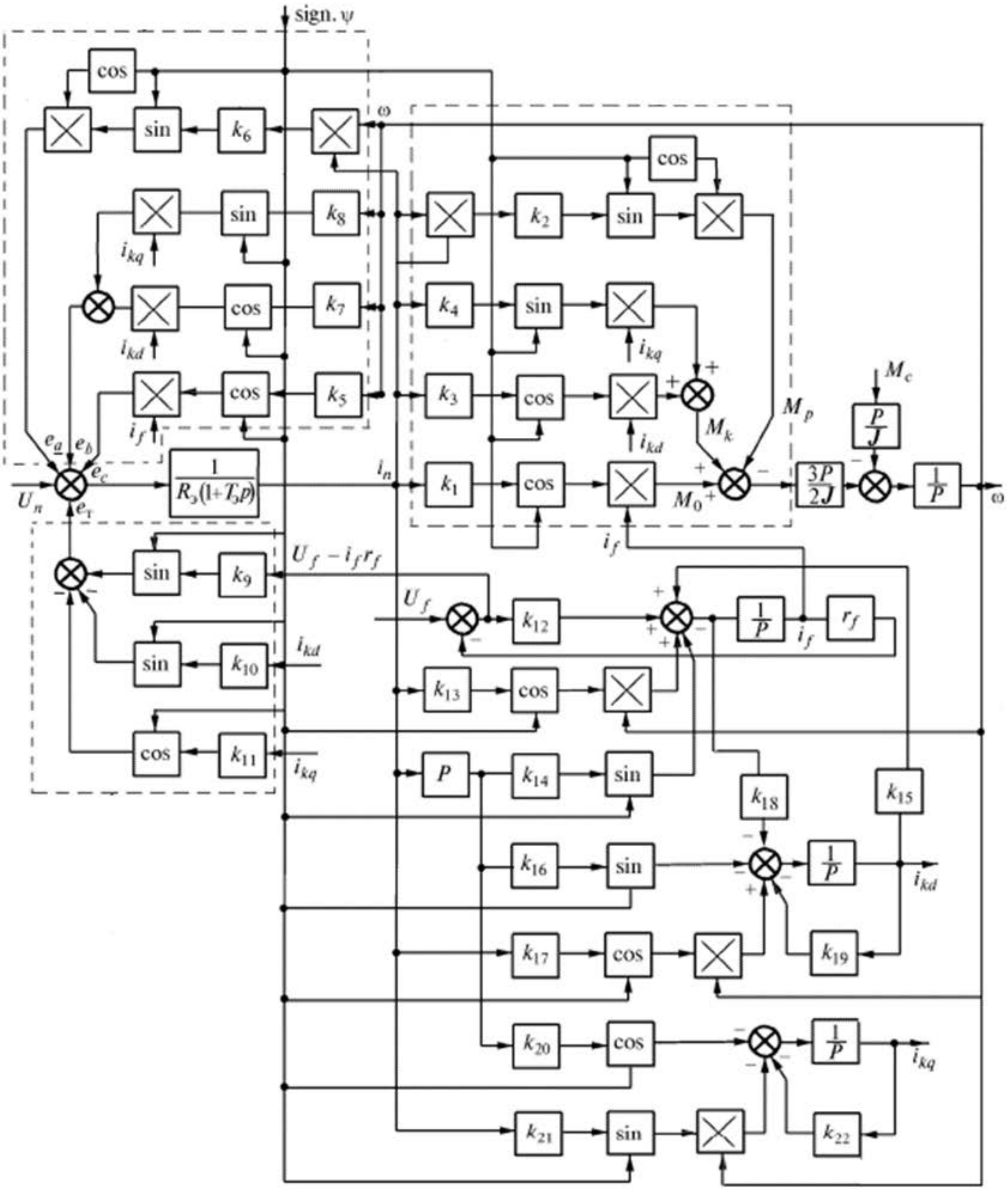

Fig. 2. Equivalent block diagram of EMBT

Voltage equilibrium for EMBT input circuit in their growth is recorded as:

$$dU_n = \kappa_{cx} dU_{ml} \cos\varphi_1 + \frac{R}{C_i(0)} dI_{ml} + \frac{L}{C_i(0)} \frac{dI_{ml}}{dt} + \Delta U_b, \tag{2}$$

where R, L – resistance and inductance of DC circuit of electric motor respectively;

φ_1 – phase angle between the first harmonics of voltage and current;

$C_i(0) = \frac{I_{ml}}{I_{n_0}} = \frac{2\sqrt{3}}{\pi}$ – the coupling coefficient between the input current of the switch and the current amplitude at the switching angle $\gamma = 0$, ΔU_b – voltage drop across the switch valves.

The connection between the input values of the electric motor is established using linearized equations of the synchronous motor in the form of Park-Gorev, recorded along the axes d and q. Assuming $\sin\Delta\theta = \Delta\theta$ and $\cos\Delta\theta = 1$ can be written:

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$$\left.\begin{aligned}
&U_{\mathrm{ml}_0}\cos\theta_0\Delta\theta+\Delta U_{\mathrm{ml}}\sin\theta_0=r\begin{bmatrix}I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)\Delta\theta+\Delta I_{\mathrm{ml}}\sin(\varphi_1+\theta_0)\Delta\theta+\\+I_{\mathrm{ml}}\sin(\varphi_1+\theta_0)\end{bmatrix}+\frac{d\Delta\psi_{\mathrm{d}}}{dt}-\psi_{\mathrm{q}_0}\Delta\omega-\Delta\psi_{\mathrm{q}}\Delta\omega;\\
&U_{\mathrm{ml}_0}\sin\theta_0\Delta\theta+\Delta U_{\mathrm{ml}}\cos\theta_0=r\begin{bmatrix}-I_{\mathrm{ml}_0}\sin(\varphi_1+\theta_0)\Delta\theta+\Delta I_{\mathrm{ml}}\sin(\varphi_1+\theta_0)\Delta\theta+\\+I_{\mathrm{ml}}\sin\left(\varphi_1+\theta_0\right)\end{bmatrix}-\frac{d\Delta\psi_{\mathrm{q}}}{dt}-\psi_{\mathrm{d}_0}\Delta\omega-\Delta\psi_{\mathrm{d}}\Delta\omega;\\
&\Delta U_{\mathrm{f}}=r_{\mathrm{f}}\Delta i_{\mathrm{f}}+\frac{d\Delta\psi_{\mathrm{f}}}{dt};\\
&0=r_{\mathrm{kd}}\Delta i_{\mathrm{kd}}+\frac{d\Delta\psi_{\mathrm{kd}}}{dt};\\
&0=r_{\mathrm{kq}}\Delta i_{\mathrm{kd}}+\frac{d\Delta\psi_{\mathrm{kq}}}{dt}.
\end{aligned}\right\}\quad(3)$$

$$\begin{aligned}
&\Delta\psi_{\mathrm{d}}=L_{\mathrm{d}}[I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)\Delta\theta-\Delta I_{\mathrm{m}_1}\sin(\varphi_1+\theta_0)]-L_{\mathrm{ed}}(\Delta i_{\mathrm{f}}-\Delta i_{\mathrm{kd}});\\
&\Delta\psi_{\mathrm{q}}=L_{\mathrm{q}}[I_{\mathrm{ml}_{10}}\sin(\varphi_1+\theta_0)\Delta\theta-\Delta I_{\mathrm{m}_1}\cos(\varphi_1+\theta_0)]+L_{\mathrm{eq}}\Delta i_{\mathrm{kd}};\\
&\Delta\psi_{\mathrm{f}}=L_{\mathrm{ed}}[-I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)\Delta\theta-\Delta I_{\mathrm{m}_1}\sin(\varphi_1+\theta_0)-\Delta i_{\mathrm{kd}}]+L_{\mathrm{d}}\Delta i_{\mathrm{f}};
\end{aligned}\quad(4)$$

$$-\frac{p}{J}\Delta M_l.$$

$$\begin{aligned}
&\Delta\psi_{\mathrm{kd}}=L_{\mathrm{ed}}[I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)\Delta\theta+\Delta I_{\mathrm{ml}_0}\sin(\varphi_1+\theta_0)-\Delta i_{\mathrm{f}}]+L_{\mathrm{kd}}\Delta i_{\mathrm{kd}};\\
&\Delta\psi_{\mathrm{kq}}=L_{\mathrm{eq}}[I_{\mathrm{ml}_0}\sin(\varphi_1+\theta_0)\Delta\theta+\Delta I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)]+L_{\mathrm{kd}}\Delta i_{\mathrm{kd}};\\
&\frac{d\Delta\omega}{dt}=\frac{3p^2}{2J}\begin{pmatrix}M_l+[\psi_{\mathrm{d}_0}\Delta I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)-\psi_{\mathrm{q}_0}\Delta I_{\mathrm{ml}_0}\sin(\varphi_1+\theta_0)]+\\ [\Delta\psi_{\mathrm{d}}I_{\mathrm{ml}_0}\cos(\varphi_1+\theta_0)-\Delta\psi_{\mathrm{q}}I_{\mathrm{ml}_0}\sin(\varphi_1+\theta_0)].\end{pmatrix}
\end{aligned}\quad(5)$$

where U_{ml_0}, I_{ml_0} – replaceable electric motors in the established mode at zero initial conditions;

L_{d}, L_{q} – projections of the resulting inductances of the electrical machine on the axis d, q;
θ_0 – initial value of load angle,
J – total moment of inertia of the elevator electric drive;
ΔM_l – load moment increase.

Analytical solution of the obtained system of equations with respect to speed increments, stator current and rotor circumferential currents, after elimination of intermediate variables, is recorded in the form of Cauchy:

$$\left.\begin{aligned}
&a_{11}p^2\Delta\omega+a_{12}p\Delta\omega+a_{13}p\Delta\theta+a_{14}p\Delta i_{\mathrm{f}}+a_{15}p\Delta i_{\mathrm{kd}}+a_{16}p\Delta i_{\mathrm{kq}}=\\
&=\Delta U_n+\Delta M_l+2\Delta U_{\mathrm{b}}+b_{11}\Delta\omega+b_{12}\Delta\theta+b_{13}\Delta i_{\mathrm{f}}+b_{14}\Delta i_{\mathrm{kd}}+b_{15}\Delta i_{\mathrm{kq}}+b_{16};\\
&a_{21}p^2\Delta\omega+a_{22}p\Delta\omega+a_{23}p\Delta\theta+a_{24}p\Delta i_{\mathrm{f}}+a_{25}p\Delta i_{\mathrm{kd}}+a_{26}p\Delta i_{\mathrm{kq}}=\\
&=\Delta U_n+\Delta M_l+2\Delta U_{\mathrm{b}}+b_{21}\Delta\omega+b_{22}\Delta\theta+b_{23}\Delta i_{\mathrm{f}}+b_{24}\Delta i_{\mathrm{kd}}+b_{25}\Delta i_{\mathrm{kq}}+b_{26};\\
&a_{31}p^2\Delta\omega+a_{33}p\Delta\theta+a_{34}p\Delta i_{\mathrm{f}}+a_{35}p\Delta i_{\mathrm{kd}}+a_{36}p\Delta i_{\mathrm{kq}}=b_{33}\Delta i_{\mathrm{f}}+\Delta U_{\mathrm{f}};\\
&a_{41}p^2\Delta\omega+a_{43}p\Delta\theta+a_{44}p\Delta i_{\mathrm{f}}+a_{45}p\Delta i_{\mathrm{kd}}+a_{46}p\Delta i_{\mathrm{kq}}=b_{44}\Delta i_{\mathrm{kd}};\\
&a_{51}p^2\Delta\omega+a_{53}p\Delta\theta+a_{54}p\Delta i_{\mathrm{f}}+a_{55}p\Delta i_{\mathrm{kd}}+a_{56}p\Delta i_{\mathrm{kq}}=b_{55}\Delta i_{\mathrm{kq}},
\end{aligned}\right\}\quad(6)$$

where a_{ij}, b_{ij} – constant coefficients, i = 1, 2, 3…, j = 1, 2, 3…

$$a_{11}=\frac{4JI_{\mathrm{m1}_0}}{3p^2[2M_{\mathrm{e}}+(L_{\mathrm{d}}-L_{\mathrm{q}})I^2_{\mathrm{m1}_0}\sin2(\varphi_1+\theta)]}\left[\frac{3\sqrt{3}}{\pi}L_{\mathrm{q}}\cos^2\varphi_1\right]-$$
$$-\frac{1}{2}L_{\mathrm{d}}\sin2\varphi_1\mathrm{tg}\theta_0+\frac{L}{C_i(0)};$$

$$a_{12}=\frac{4JI_{m10}}{3p^2[2M_{\mathrm{e}}+(L_{\mathrm{d}}-L_{\mathrm{q}})I^2_{\mathrm{m1_0}}\sin 2(\varphi_1+\theta)]}\times$$

$$\times\left\{\frac{3\sqrt{3\cos\varphi_1}}{\pi\cos\theta_0}\left[r\cos(\varphi_1+\theta)-L_{\mathrm{d}}\omega_0\sin(\varphi_1+\theta)\right]+\frac{r}{C_i(0)}\right\}.$$

...

at

$$b_{11}=\frac{3\sqrt{3}}{\pi}\frac{\Psi_{\mathrm{d_0}}}{\cos\theta_0}\cos\varphi_1;$$

...

$$b_{16}=b_{26}=0 \text{ при } M_{\mathrm{e_0}}=M_{l_0},$$

where J – total moment of inertia of the elevator electric drive;

M_{e}, M_l – engine moments and loads respectively.

Presented equation (6) in Laplace operator form for increments of output values in functions of input quantities, taking into account the external disturbing action:

$$\begin{bmatrix}\Delta\omega(p)\\ \Delta\theta(p)\\ \Delta i_{\mathrm{f}}(p)\\ \Delta i_{\mathrm{kd}}(p)\\ \Delta i_{\mathrm{kq}}(p)\end{bmatrix}=[W^0_{ij}(p)]_{m\times n}\begin{bmatrix}\Delta U_n(p)\\ \Delta U_n(p)\\ \Delta U_{\mathrm{f}}(p)\\ 0\\ 0\end{bmatrix}+[W^{\mathrm{f}}_{ij}(p)]_{m\times 1}\begin{bmatrix}\Delta M_l(p)\\ \Delta M_l(p)\\ 0\\ 0\\ 0\end{bmatrix}, \quad (7)$$

where $[W^0_{ij}(p)]=\dfrac{[Q_{ij}(p)]_{m\times n}}{|Q(p)|}$ matrix of the transfer function of the electric motor for input (control) actions; $|Q(p)|$ – determinant of the system (7):

$$|Q(p)|=\begin{vmatrix}A_{11} & A_{12} & A_{13} & A_{14} & A_{15}\\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25}\\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35}\\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45}\\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55}\end{vmatrix}\neq 0, \quad (8)$$

where $[Q(p)]$ – transposed matrix;

$Q_{ij}(p)$ – algebraic complement of determinant $|Q(p)|$;

A_{ij} – operator coefficients:

$$A_{11}=a_{11}p^2+a_{12}p-b_{11};$$

...

$$A_{55}=a_{56}p-b_{55};$$

$$i,\ j=1,\dots 5;\ m=5;\ n=2;\ l=1.$$

Solving (7) taking into account (8), a system of equations is determined:

$$\left.\begin{aligned}\Delta\omega(p)&=W^0_{11}(p)\Delta U_n(p)+W^0_{12}(p)\Delta U_{\mathrm{f}}(p)+W^f_{13}(p)\Delta M_l(p);\\ \Delta\theta(p)&=W^0_{21}(p)\Delta U_n(p)+W^0_{22}(p)\Delta U_{\mathrm{f}}(p)+W^f_{23}(p)\Delta M_l(p);\\ \Delta i_{\mathrm{f}}(p)&=W^0_{31}(p)\Delta U_n(p)+W^0_{32}(p)\Delta U_{\mathrm{f}}(p)+W^f_{33}(p)\Delta M_l(p);\\ \Delta i_{\mathrm{kd}}(p)&=W^0_{41}(p)\Delta U_n(p)+W^0_{42}(p)\Delta U_{\mathrm{f}}(p)+W^f_{43}(p)\Delta M_l(p);\\ \Delta i_{\mathrm{kq}}(p)&=W^0_{51}(p)\Delta U_n(p)+W^0_{52}(p)\Delta U_{\mathrm{f}}(p)+W^f_{53}(p)\Delta M_l(p),\end{aligned}\right\} \quad (9)$$

where – transfer functions, respectively, of control and disturbance effects, i = 1, ... 5; j = 1, … 3.

Research results

The resulting expressions allow us to determine the transfer functions and calculate the necessary frequency characteristics of EMBT under any type of influence, but the practical use of these equations is associated with rather cumbersome computational operations.

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A significant improvement in the EMBT structure can be obtained by clock synchronization of the switch by the position of the motor rotor (ψ_1 = const) or by synchronization by the voltage of the armature winding (φ_1=const) and the use of artificial switching means that minimize the spatial angle between the reaction vector and the transverse axis of the rotor [9]. So, for example, with the appropriate setting of the rotor position ($\psi_1 \approx 0$), which ensures engine idling at almost $\theta_0 = I_d = 0$, all dynamic EMBT processes are associated with the transverse axis of the magnetic system of the machine. It can be assumed that:

$$\begin{aligned} \Delta\psi_d &\cong \Delta\psi_f \cong -L_{ed}\Delta I_f; \\ \Delta\psi_q &\cong L_q I_q \neq 0; \\ \Delta\psi_{kd} &\cong 0. \end{aligned} \tag{10}$$

The results of the analysis under this assumption may be acceptable for the case of a loaded engine, structurally represented in Fig. 3, с φ_1 = const 1:

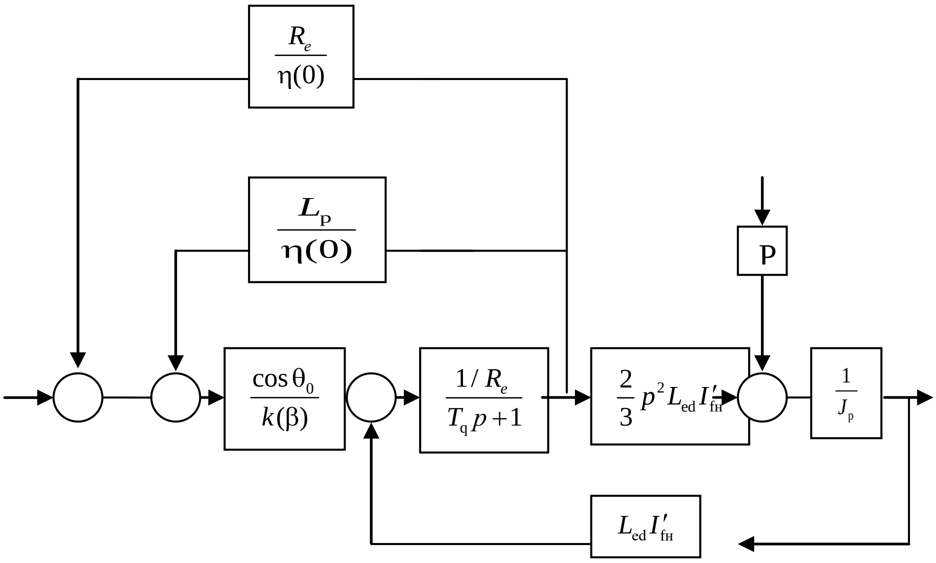

Fig. 3. Simplified block diagram of EMBT

The diagram shows: R_e is the equivalent resistance of the armature, taking into account the resistance of the smoothing throttle and the switching phenomenon of the switch, I^{fn} is the rated excitation current of the motor reduced to the stator winding.

Based on the simplified block diagram above, any transfer function EMBT can be determined. For example, by the control effect of $\Delta U_n(P) \neq 0$ to increment the speed, the transfer function will be:

$$\frac{\Delta\omega(p)}{\Delta U_n(P)} = W_{11}^0(p), \tag{13}$$

where $W_{11}^0(p) = \dfrac{b_1 p + b_2}{a_1 p^3 + a_2 p^2 + a_3 p + a_4}$;

$a_1 = 2J_r T_q [T_q KrC_i(0) - L\cos\theta_0]$;

$a_2 = 2J_r [2K_r C_i(0) T_q + T_q (R_e + r)\cos\theta_0 - L\cos\theta_0]$;

$a_3 = r[2J_r KC_i(0) + 2J(R_e + r)\cos\theta_0 + 3KC_i(0) p^2 L_{ed}^2 I_f^2 T_q]$;

$a_4 = 3L_{ed}^2 I_f^2 [K_r C_i(0) + (R_e + r)\cos\theta_0]$;

$b_1 = 3r^2 L_{ed}^2 I_f^2 rC_i(0) T_q \cos\theta_0$;

$b_2 = 3r^2 L_{ed}^2 I_f^2 rC_i(0) \cos\theta_0$.

A further direction of scientific research is the development of methods for mathematical modeling of EMBT, the synthesis of multi-circuit closed control systems for biinductor engines, as well as the adjustment of automatic control unit. Taking into account the characteristic of EMBT as a multi-dimensional nonlinear object, describing it as a control object requires solving an atypical problem.

Conclusions

In the synthesis of innovative gearless elevator electric drives, the need for low-speed drive engines with speeds of 50...150 rpm is urgent. To produce such engines with traditional design approaches, and with acceptable weight and dimensions, today, it is difficult.

As a drive motor of a gearless winch, it is proposed to use an innovative low-speed biinductor engine with a non-winding cylindrical rotor.

The equivalent block diagram of a biinductor engine with a non-winding cylindrical rotor is a complex electromechanical system with multidimensional non-linear objects. The transition to a simplified block diagram of the electric motor, with a number of assumptions, allows you to format any transfer function, both for control and for perturbation.

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