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DEVELOPMENT OF THE GEARLESS ELECTRIC DRIVE FOR THE ELEVATOR LIFTING MECHANISM

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Розглянуто можливість застосування, вдосконаленого тихохідного електричного двигуна бііндукторного типу з безобмотковим ротором. Подібний двигун виконується з ротором торцевого типу і статором, що не мають загального ярма. Ротор являє собою кілька феромагнітних полюсів, закріплених на немагнітному диску. Сформовано основні проектні дані бііндукторних двигунів для ряду швидкостей руху ліфтової кабіни. Надані рекомендації щодо вибору відповідності швидкостей ліфтових лебідок і діаметрів канатоведучих шківів. Проведено синтез системи управління ліфтового електроприводу.

Пропонується використання мікропроцесорної системи підлеглого управління з використання релейного регулятора струму, ПІ-регулятора швидкості та П-регулятора положення. За результатами дослідження показано, що надається можливість точного відтворення заданої траєкторії руху кабіни і точної зупинки, яка виконується на певному поверсі без додаткових операцій підходу до заданої точки. Рух виконується згідно з розрахованою траєкторією з обмеженням заданої швидкості на рівні номінальної, прискорення – до 1 м/с^2 та ривка – до 3 м/с^3. Ці параметри повністю відповідають умовам комфортного переміщення пасажирів. Різниця між експериментальними даними та результатами моделювання не перевищують 7 % в статичних і 15 % – в динамічних режимах. Зазначені основні переваги запропонованого безредукторного ліфтового електроприводу. Зокрема, визначено, що запропонований електропривод, за рахунок конструктивних особливостей тихохідного двигуна, має масу, габарити і інерційність, значно менші, ніж у традиційного у базовому варіанті, при подібних інших параметрах

Ключові слова: ліфтова лебідка, безредукторний електропривод, бііндукторний двигун, безколекторний двигун, механізм підйому

1. Introduction

The elevator industry is a powerful component of the global technology and economy, which by its significance reflects one of the most important features of modern civilization. The main task of all passenger elevators is providing transportation in the vertical plane in the buildings and structures for different purposes. Elevators not only facilitate everyday physical movement of people, but quite often are the only means of such movement. In large cities, the total daily volume of transportations in passenger elevators exceeds the volume that is carried out by all kinds of public transport [1]. At the turn of the last two centuries, the elevator building, like virtually all areas of technology, saw a quality jump, thanks to the achievements of mechanics, electromechanics, power- and microelectronics, and mecha-

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tronics. However, when it comes to the elevators installed in the houses of the 1970s up to the early 1990s, the years of mass housing construction, they are characterized by moral and physical deterioration and are physically heavily worn-out. Given that the estimated service life of an elevator is not more than 25 years, among more than 70 thousand passenger elevators in Ukraine, not less than 50–60 % have serviced this term [2]. By this feature, it is possible to expect the mass stop of lifts in the middle of the current decade. While the annual production of elevators in Ukraine is unlikely to exceed 1,000 items, from 4,000 to 5,000 elevators are required only for the planned replacement of the elevators that finished their service life. Taking into consideration the necessity of mass replacement of elevators in the current decade and the possible export, the annual output of elevators should be much larger. As a forced measure, it has been practiced lately to prolong artificially the service life and replace separate equipment elements, which only perpetuates the technical backwardness of elevator economy and does not contribute to an increase in the quality and reliability of elevators operation. By its significance, the problem of passenger elevators in Ukraine long ago grew out of the technical-economical problem into the social one [1]. It should be emphasized that the problem of replacement of the obsolete fleet with the new electric drives (ED) exists not only in Ukraine. Thus, there is also a significant number of such elevators in the countries of the former USSR. Most of them take a segment similar to mass passenger elevators of Ukraine that are installed in high-rise buildings, have a load capacity of up to 1,000 kg and a speed of up to 1.6 m/s [2]. For example, there is a similar problem in Russia, where about 500 thousand elevators are in operation [3]. No less than half of the existing elevator systems need replacing or upgrading [4].

Thus, the development and production of new energy-efficient passenger elevators with improved energy and dynamic indicators is an economic, social and technical problem of the state level, and the work that focuses on solving this problem is relevant, has scientific interest and is of practical importance for the economy.

2. Literature review and problem statement

A modern direction in the development of elevator drives is the transition from gear structures to gearless ones and application of the regulated control systems. The vast majority of researchers are currently working in this direction. An example of this can be found in papers [5, 6]. But, at the same time, the problems that are not always given publicity by designers and manufacturers are known to arise during the synthesis and application of new types of gearless winches. One of the main and fundamental challenges is the need to have the driving motors of winches that meet the requirements [6]. Scientific analysis of a number of modern developments showed that it is a fact that many electric elevator drives of new types with satisfactory dynamic, weight and dimensional parameters have an increased power consumption, which was shown in papers [1, 7]. Article [8] illustrated that a wide variation of reduced rates of drive electric motors leads to a significant deterioration in energy efficiency of ED, especially in the range of the elevator car motion speed of 1–1.6 m/s. The use of high-rate serial motors in the lower rate range leads to a significant increase in energy indicators, which essentially discredits the idea of using gearless lift winches [2]. The other way, which is described in [9], is the application of slow-moving drive motors, however there are no serial slow-moving elevator motors, which would fully meet the requirements, and the problem of development and implementation of motors is relevant nowadays.

At the same time, the developers widely use the technical solutions, which are positioned as innovative and greatly facilitate the requirements to the minimum motor rate, but most of them can be considered unsatisfactory due to:

– an increase in multiplicity of the tackle block leads to an increase in the number of shifting units. This decreases reliability and makes installation of a lift difficult, increases the wear of ropes, and reduces coefficient of efficiency of the rope gear. In paper [10], it is emphasized that the car lifting height is limited, the load on the guides increases, causing wear of guides and an increase in mechanical losses;

– refusal of the balances leads to a significant increase of the established power of the winch motor, even in comparison with the power of the traditional double-rate asynchronous motor for the same conditions and modes of operation [5];

– an increase in the length of the rope transmission at constant cross section leads to great demonstration of the ropes flexibility, which manifests itself in increased spring vibrations of a lifting mechanism and a decrease in the accuracy of car positioning. The authors of paper [8] also argue about it.

Thus, it is a relevant task to develop the modern gearless elevator slow-moving electrical drive with the restricted use of technical solutions that facilitate the requirements to the rated motor rates. An electric drive should provide conditions for comfortable carrying passengers and be characterized by excellent dynamic and energy qualities.

3. The aim and objectives of the study

The aim of this research is the synthesis and analysis of contemporary gearless elevator electric drive with the brushless bi-induction DC motor with the unwound rotor (BBDCM). This will provide the opportunity, under the assigned comfortable conditions, to carry passengers, demonstrate energy efficiency, to have an affordable cost of an elevator, and be competitive in comparison with known international samples.

To accomplish the aim, the following tasks have been set:

– to improve the structure of the slow-moving brushless bi-induction DC motor with the unwound rotor;

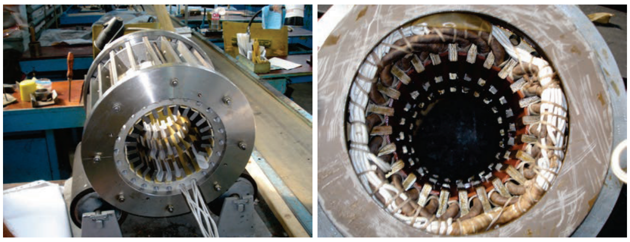
– to determine the requirements and criteria of application of BBDCM;

– to perform synthesis of parameters of the gearless elevator electric drive with BBDCM and analysis of its operation.

4. Materials and methods of research

4. 1. Experimental basis of research

During the experimental study, a physical model of the electric drive of the passenger lift was used. The model was constructed with the use of the research sample of the bi-induction DC motor with a power switch and a control system. The motor was developed at the Institute of Electromechanics and Energy Management of Odessa National Polytechnic University, Ukraine (Fig. 1, 2) [11].



a *b*

Fig. 1. Experimental sample of BBDCM:
a — general outlay, *b* — general outlay of the stator structure

Fig. 2. General outlay of the examined sample of the elevator electric drive

During the experiment, we used the following control and measuring devices: REFCO Halt-08, Fluke-16, National Instruments NI6009, NI9201-USB9162 from Odessa National Polytechnic University, Ukraine.

4. 2. Features of mathematical modeling of the elevator electric drive

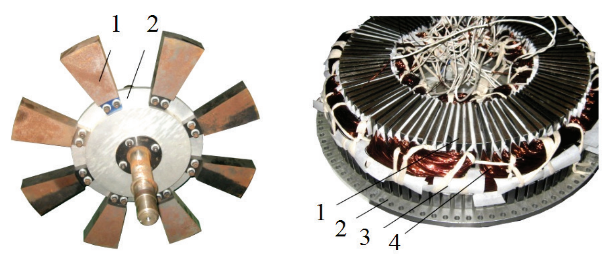
An elevator is a complex multi-weight dynamic system, which is under the influence of a periodic exciting force. Within this study, a comprehensive modeling of the electromechanical systems (EMS) was performed. The EMS includes: a winch and moving mechanical parts, a drive slow-moving brushless DC electric motor with the power electronic switch; the control system. The mathematical models of devices are a system of interrelated differential, algebraic and logical equations that reflect the conditions of the mechanical and electrical balance. In the synthesis of the mathematical model of the elevator lifting mechanism, the number of variables that influence the vibratory process of the system elements was previously determined. When constructing the model, we took into account the factors that affect a change in the weights of the elements of a structure, depending on the position of the car by the height. When calculating the presented weight of the car, the influence of the attached weight of the suspension rope and of the attached weight of the balancing chains was taken into account [12].

In the mathematical modeling of the lifting mechanism, a number of important assumptions were made: a multi-rope suspension was considered as one rope, assuming that separate parts of the rope are similarly loaded. The ropes do not slide in relation of the RDP rim. The winch was considered as a concentrated weight, mounted on the spring base of shock absorbers of constant rigidity. The source of the disturbing force has a harmonious character. Compliance of the connecting clutch with the brake pulley is by two orders of magnitude lower that the compliance of ropes, so it is not taken into consideration in calculation. The dynamic model was considered with reduction of the inertial masses and rigidities to the RDP shaft. Angular vibrations of the winch on the shock absorbers in relation of the main longitudinal and transverse axes of inertia were not taken into account. Only vertical vibrations of the concentrated weight of the dynamic elevator system were considered. It was taken into account that the presented values of the masses and rigidities of the dynamic system depend on the height of the position of the car and counterweights in the elevator shaft. Coefficients of damping the vibrations of the ropes and shock absorbers were determined experimentally. Coefficient of damping of the driver was determined by the parameters of the linear section of mechanical characteristic of the motor. Mutual influence of vibrations of the car ropes and of the counterweight was taken into account by the magnitude of the angular vibrations of the RDP. The point of the suspension of car ropes and of the counterbalances are at a constant distance by height.

4. 3. Determining the structures of the slow-moving brushless DC motor with the unwound rotor

The problem of synthesis of new types of gearless elevator drives can be possibly solved through the application of the brushless bi-induction DC motor with the unwound rotor (Fig. 1) [11].

Such motor is made with the rotor of the face or cylindrical type and the stator, which do not have a common yoke. The rotor of the face BBDCM (Fig. 3) comprises a few ferromagnetic poles 1, fixed on non-magnetic disc 2. The stator (Fig. 3, *b*) consists of a series of separate ferromagnetic elements (teeth) that are not linked magnetically 3, fixed on non-magnetic panel 4. At the internal surface of the stator, there is a toroidal coil of excitation winding 5. Teeth 3 form the teeth zone, in the intervals (slots) of which there are conductors of anchor winding 6.



a *b*

Fig. 3. Outlay of the components of BBDCM:
a — rotor and *b* — stator

In a minimum configuration (Fig. 4), BBDCM consists of two fixed stators connected by transverse ferromagnetic rods 7, between which the rotor, separated from the stator by the working air gap δ, rotates. The closed magnetic circle of the motor together form teeth 3, transverse rods 7 and poles 1, separated from the teeth by the working air gap δ. Such a structural solution makes it possible: to dampen significantly the anchor reaction and to bring the handling ability for current $K_i=I_{Perm}/I_n$ to 5–7, as the teeth do not have total yoke and are not connected magnetically; to reduce (up to 30 %) the costs of winding copper due to the absence of additional poles and compensatory winding; to improve significantly the conditions of heat removal through the structural gaps between the rods of the stator; improve energy indicators of the motor [8].

Fig. 4. Physical appearance of BBDCM

The weight of the similar rotor is 3–5 times smaller than that of the classic motor, the moment of inertia decreases proportionally. In this case, the motor rate increases by 5–7 times, and therefore, of the electric drive in general. At such a decrease in moment of inertia of the rotor, energy losses in transient modes in BBDCM are by the order of magnitude lower than in the classic DC motor. Such design ensures a modular principle of manufacturing for different power by sequential alternation of the disk rotor and the anchor module. Improvement of the motor by mounting permanent magnets on the rotor (that is, the use of combined excitation), made it possible to increase the power by 1.6 times at constant weight and dimensional indicators [11].

4. 4. Determining the requirements and features of application of the brushless DC motor

Calculation data, obtained during the synthesis of parameters of the gearless winches, determined the design data of the drive bi-induction DC motors with the unwound rotor of the face type with excitation from permanent magnets. They are given in Table 1. The calculated moment is equivalent for heating for a long-time operating mode S1. For all speeds of the car, during plotting the optimal diagram, the winch motor should develop virtually the same moments both under heating condition, and under overload condition. In the ideal case, while maintaining optimum loads of the active part of the motor, its weight and dimensions will depend only on the assigned moment and will not depend on the assigned rate. In reality, at a significant decrease in the assigned speed, the motor weight and dimensions increase considerably. The acceptability criteria of the possible use of the slow-moving motors of the winches are determined: weight, equal to or less than the weight of the basic double-rate asynchronous motors; efficiency that is higher than the equivalent efficiency of the double-rate motor and the worm gear. Similarly, in further research during designing and selecting the winch motors, it is a promising possibility to consider a compromise solution – to regard not power, but moment that will make it possible to use a higher-rate motor as the main parameter.

With this approach, it is necessary to pay attention to the required speed control range, operation safety of the passenger elevator and power parameters of the elevator lifting mechanism. In addition, during transition to gearless winches, one of the problems is alignment of the motor rate and the diameter of the rope drive pulley (RDP). Based on the requirements for the motor configuration, it is desirable to have the highest speed possible, but in this case, the higher the motor rate, the smaller pulley diameter is required. The pulley diameter, in turn, can not be less than a certain critical magnitude, associated with requirements for wear of ropes and slippage elimination [12]. For example, Table 2, based on the normalized series of synchronous speeds of electrical machines, shows respectively the required number of poles of the motor and the diameters of the rope drive pulley for the tackle block suspension of the elevator car at the speed of the car motion of 1.6 m/s.

Table 1

Design data of the elevator bi-induction DC motors with the unwound rotor

Indicator	Unit of measuring	Speed of elevator car motion					
		1.0 m/s		1.6 m/s		2.0 m/s	
		Without pulleys	With pull.	Without pulleys	With pull.	Without pulleys	With pull.
Rated speed	1/s	4.2	8.5	6.8	13.5	8.4	16.8
Rated moment	N·m	835	425	911	460	1,032	532
Rated power	W	3,507	3,613	6,195	6,210	8,669	8,938
Rated efficiency	%	79	83	81	85	86	88
Moment of rotor inertia	kg·m^2	0.270	0.104	0.320	0.120	0.350	0.143
Dimensions (length × diameter)	m/m	0.3/0.46	0.35/0.38	0.38/0.46	0.38/0.38	0.38/0.49	0.41/0.39
Weight	kg	246	194	297	223	362	281

Table 2

Series of winch motor rates and rope drive pulley diameters

Recommended series of rates	1/min	100	125	150	160	187	250	300	375	500	600
	1/s	10.5	13.1	15.7	16.9	19.7	26.2	31.5	39.4	52.5	63
Number of poles	rel./un.	60	48	40	36	32	24	20	16	12	10
Diameter of pulley	m	0.61	0.49	0.41	0.38	0.33	0.24	0.20	0.16	0.12	0.10

From the shown series of parameters of the gearless winches, as an option, it is possible to recommend the compromise variant of the motor with 40 poles and the pulley of the diameter of 0.41 m.

5. Synthesis of control system for the gearless elevator winch

Electric drive of the gearless elevator lifting mechanism consists of a winch, a power electrical part and a control system. Its functional diagram is shown in Fig. 5. The power electrical parts include: a three-phase rectifier (Rectifier – R); Electric filter with a controlled discharge switch (Electric filter – F). Unit of power switches (Load-bearing module – LBM), which is assembled by the 12-phase bridge IGBT transistor circuit. This circuit makes it possible to switch the motor windings and to control it by the bipolar pulse-width modulation [13]. The current filter, not shown in the diagram, is mounted at the output of the unit of power switches. A filter is required to improve the current form and a substantial reduction of its pulsations. The winch includes its mechanical structural component, the main elements of which are the rope drive pulley (RDP) and the slow-moving brushless bi-induction DC motor with the unwound rotor (BBDCM).

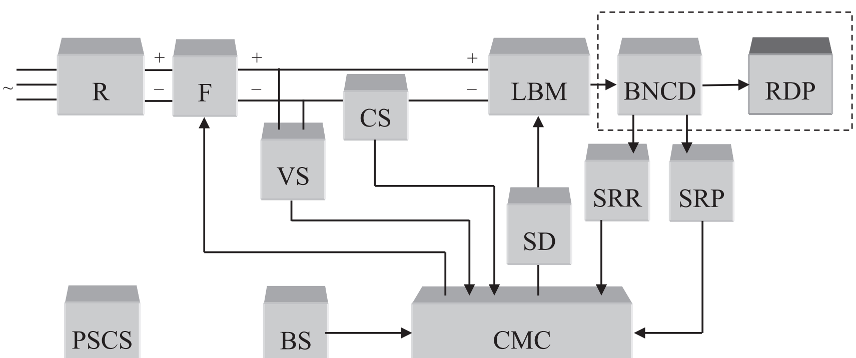


Fig. 5. Functional diagram of the gearless elevator electric drive

The control system consists of a number of devices. Current sensor (CS) and Voltage sensor (VS) are the integral sensors of parameters that operate based on the Hall effect. Sensor Rotor Rate (SRR) is the encoder that converts the angle of the EM shaft rotation into electric signals and generates the sequential pulse digital code, which contains the information on current angle of rotor turn. Sensor Rotor Position (SRP) is the optical sensor, intended to obtain information about the state of the rotor of the BBDCM at every moment. Block of stimulus (BS) is necessary to form controlling signals that determine conditions and operation mode of the winch. Signals decoder (SD) is produced based on the programmed logical integral scheme, which performs the functions of decoding signals that arrive from the optical Sensor of Rotor Position (SRP) and the Sensor of Rotor Rotation (SRR). Controlling microcontroller (CMC), at the correspondent discrete and analogue inputs of which the signals from feedback sensors arrive. Controller of the ATmega32 type of ATMEL company, on which the WPM was assembled and the three-circuit subordinate control system, as well as the module of calculation of the digital encoder rate are used as the controlling microcontroller. The output WPM signal is sent through the signals decoder (SD) to the controlling inputs of the intellectual Load bearing module (LBM). Power supply unit of the control system (PSCS). To simplify an analysis, the elements of protection, signalization and other auxiliary devices are not shown in the structure of the system [14].

Regulators of the subordinate control system are the following: current regulator is relay, the speed regulator is proportional-integral (PI), position regulator is proportional (P) [15]. The corresponding transmission functions of the regulators are shown below.

Current regulator:

$$H_{CR}(p)=\frac{1}{K_{CS}}, \qquad (1)$$

where K_{CS} is the coefficient of current regulator.

Rate regulator:

$$H_{RR}(p)=\frac{K_{CS}\cdot J_{\Sigma}}{4\cdot T_{\mu}p\cdot C\cdot K_{SRR}}\cdot\frac{(8\cdot T_{\mu}p+1)}{8\cdot T_{\mu}}, \qquad (2)$$

where K_{SRR} is the coefficient of rate regulator; C is the coefficient of Electromotive force; J_{Σ} is the total moment of inertia; T_{μ} is the non-compensated time constant.

Position regulator:

$$H_{PR}(p)=\frac{K_{SRR}}{16\cdot T_{\mu}\cdot K_{SRP}}, \qquad (3)$$

where K_{SRP} is the coefficient of the sensor of rotor position.

To compensate for the unwanted effects of time constant, the filter with transmission function is used at the input of the rate regulator.

$$H_{F}(p)=\frac{1}{8\cdot T_{\mu}+1}. \qquad (4)$$

The position contour is set to the modular optimum.

With regard to setting the contour of rate to the symmetric optimum, the application of the proportional position regulator provides the control system with the astatism of the first order, both by the controlling and by the excitation influence. This is a necessary and a sufficient property of the elevator winch control system, which operates in the positioning mode [16, 17].

6. Discussion of results of operation of the elevator electric drive

When analyzing the operation modes, motions of the elevator car up and down are considered. The upward motion of the elevator car is considered as an example (Fig. 6). During a stop on a floor, the car is held in a stationary position due to the disk brakes (t=0). During the stop on a floor, passengers get in or out. Before the movement of the elevator car starts, the process of the brake removal occurs with the simultaneous activation of the electric drive, due to which there occurs the process of electrical holding of a car due to moment of the motor ($0<t<0.5$ s). After complete removal of the brake, the motor stays in the short circuit mode waiting for the start command. The current sign is negative, the work is the 2nd quadrant. After getting the start command, the elevator car starts motion by the assigned trajectory with the assigned restriction of jerk and acceleration with a maximum permissible constant of motion speed (trapezoidal) diagram ($0.5<t<1.8$ s). Current changes its sign, the working point of the ED moves to 1st quadrant within time interval ($0.7<t<1.7$ s). In the interval ($1.8<t<3.8$ s), the winch moves at constant rate $\omega=4.12$ 1/s, which corresponds to the rated speed of the car $h=1$ m/s. The motor current in this mode has a negative sign, which is caused by existence of a counterweight in the system and current load of a car. The electric drive operates in the 2nd generator mode. When arriving at the required floor, there occurs the process of braking by the assigned trajectory with the restriction of dynamic parameters of the elevator car motion ($3.8<t<5.0$ s). After the stop, the ED operates in the mode of electrical holding the car. There is no self-braking property in a gearless winch, in contrast, for example, to the traditional one with the worm gear. The active nature of forces of the weight of the load, the car and the counterweight are determined completely. If this factor is not taken into consideration, there can be characteristic «subsidence» of the car with the load (counterweight) at the beginning and at end of the motion when removing (overlying) the electromagnetic brake. This problem is solved by means of a control system by introducing the so-called «car holding mode» into the cycle of motion sector. At the beginning of the motion, a zero task both on speed and position is stated simultaneously with giving the command to remove brakes, or 0.5–1 s earlier. The winch holds the car at the floor level by creating a moment that counteracts the sum of active forces of the elements of the lifting mechanism. After complete removal of the brake, the command to start the car motion is given and the winch is run by the optimal diagram of the assigned form. The start process begins under nonzero initial conditions for current, which is determined by moment of static load, which positively affects the quality of the dynamic process [8]. Similarly, at a stop on a floor, when speed and movement errors reach zero, the power supply of BBDCM is off not at once, and with a specified time lag, keeping the car in the «zero» position before the brakes are overlaid. The introduction of the car holding mode by the winch with the control system not only provides comfort of car motion when starting and stopping, but positively changes the nature of the operation of mechanical brakes [18]. Thus, the slippage in the shoe brakes is not observed, which greatly increases their durability.

In the case of using the controlled ED in the precise stop mode, there is no need to apply a sensor of precise stop, since the system is closed and passes the assigned trajectory with high accuracy. In Fig. 6 shows that the use of the synthesized control system provides an opportunity for the winch to reproduce accurately the assigned trajectory of the elevator car motion and of the precise stop, which is performed on a certain floor without additional operations of approaching the assigned point. The motion is performed with the restriction of the assigned speed at the level of rated acceleration of up to 1 m/s^2 and of the jerk – up to 3 m/s^3, which in this case corresponds to angular magnitudes $\xi=4.17$ 1/s^2 and $\rho=12.5$ 1/s^3. These parameters meet the conditions of comfortable passengers carrying. The calculated shape of the speed diagram is trapezoidal with the applied jerk constraints.

Experimental characteristics of motion and rate of the ED with the BBDCM, which were obtained using a physical model, are shown in Fig. 7, 8.

The difference between the experimental data and the results of modeling do not exceed 7 % in static and 15 % in dynamic modes.

Experimental characteristics of the winch motion and rate, obtained during the experiment, are shown in Fig. 7, 8, respectively.

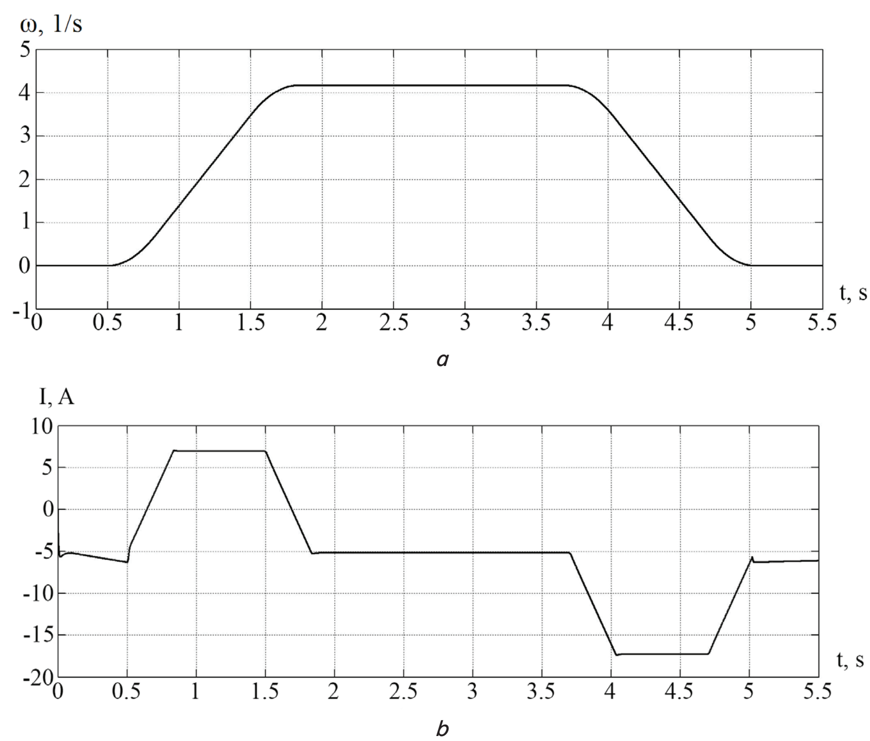


Fig. 6. Diagrams of the elevator car motion with a current load of 80 kg: *a* — speed, *b* — current

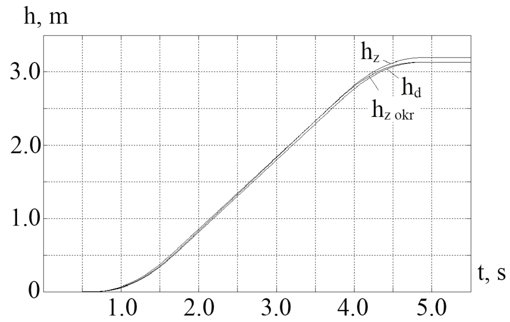


Fig. 7. Diagrams of elevator car motion at the assigned control system

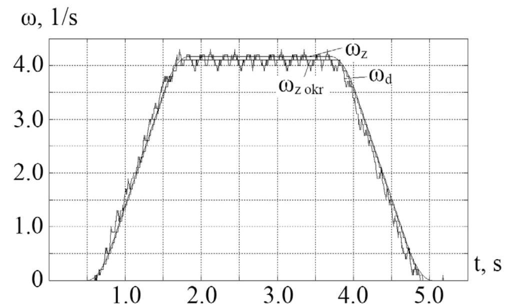


Fig. 8. Diagram of a change in angular velocity of the winch during motion of the elevator car with the load of 80 kg at the assigned control system

Designations in Fig. 7, 8: ω_z, h_z are the angular velocities of the winch and the path it passes, assigned with the fraction path; $\omega_{z\,okr}$, $h_{z\,okr}$ are the angular velocity of the winch and the passed distance, assigned with integer; ω_d, h_d are the angular velocity of the winch and the passed distance at integer number task. To form the width-pulse modulations (WPM), the 8-bit WPM was used, that is why the task of off-duty ratio composes of integers from 0 to 255 [13]. In the obtained calculation values, the task of off-duty ratio was used taking into account the fraction part and with rounding to integer values. The diagram of speed corresponds to the task with the fraction part during traveling to one floor (3.2 m). The passed distance in this case amounts to 3.1395 m, which is by 6 cm less than the needed one. The result of this is the task was sent to the input of the speed regulator in the form of 4.1 1/s·10=41 discrete, instead of 4.16 1/s 4.16 (max task on the S-characteristic). When using the value of the task with the integer, the error of passed distance is 0.12 mm, the corresponding diagram of speed. Angular velocity and the passed distance at the output of the motor at the integer task are designated in Fig. To compensate for the difference between the task with the fraction part and the integer part, it is necessary to introduce the correction factor or to increase the PWM bit range up to 10 bits.

Requirements for the elevator mechanism and its drive in the current work are based on their analysis as a whole electromechanical system. The decision about the overall design and parameters of the system are accepted if they all meet the requirements for the highest energy efficiency at minimum dimensions and weight. This is especially true of the motor and the mechanical gear. If we take an existing elevator with the speed of 1 m/s and the asynchronous double-rate electric motor as a basis, we first set the task to obtain the gearless winch with the best energy performance and the weight not exceeding the weight of the existing winch (the motor weighs 400 kg and the worm gear is of the same weight). Energy efficiency was calculated for two typical modes: the static mode of lifting the rated load and the start upwards mode with a fully loaded car as well. In the static mode, the overall efficiency of the system increased (from 61.3 % to 85.7 %, and in the start mode from 15.8 % to 51.9 %). It should be noted that the actual weight of the gearless winch turns out to be significantly lower than that of the existing one, and energy efficiency is potentially too much better due to the possibilities of energy recuperation in dynamic modes.

It is possible to track two characteristic directions in development of foreign manufacturers KONE (EcoDisc, PowerDisc), OTIS (ReGen), ThyssenKrupp (Evolution classic), ZIEHL – ABEGG (ZETASYN). The first is that the synchronous motor with the excitation system on permanent magnet is most often used as a part of the electric drive. This makes it possible to reduce the weight and dimensions of the machine and increase its efficiency. Secondly, they are not too much focused on creating quietly moving motors and prefer compromise solutions, that is, an increase of the rated speed of an elevator and the motor, and very often not completely use a motor rate range. A typical example is the gearless winches with synchronous motors and frequency control New BOMCO2 of Chinese production. The elevator speed scale is extended from 1 m/s up to 2.5 m/s, but at the same loading capacity, all of these speeds are achieved at the expense of frequency control of one motor that has the rated rate of 300 rpm. Thus, for elevators with the speed of 1 m/s, the rated frequency of 11 Hz is used, which is by 4.5 times less than the rated frequency of the motor. This technical solution leads to a significant decrease in efficiency of the winch. Given the fact that in Ukraine the most common are the elevators with a speed of 1 m/s, this technical solution cannot be accepted.

The practical value of the outcomes of this research lies in the significant decrease in consumption of electric energy through the use of the proposed electric drive, in enhancing performance and comfort of passengers carrying. Another positive aspect of the implementation of gearless winches is a decrease in the environmental load. This is due to refusal to do large amounts of metal work and to use in operation a large number of environmentally hazardous oils that are characteristic for winches with worm gears.

The research results described in this paper will be useful in development of the plans for modernization of the elevator economy of the state, as well as for enterprises that produce lifting equipment. Thus, the basic Ukrainian company «Karat Liftokomplekt» (Vyshhorod, Ukraine) produces all the elevator elements except for winches with the worm gear, which they receive from the elevator building factory (Mogilev, Belarus). The transition to gearless winches promises to reduce dependence on foreign supplies, which coincides with modern tendencies to reduce import dependence of the Ukrainian economy.

The proposed elevator electric drive does not have any special restrictions in use and further operation. But the conducted studies revealed that it is characterized by the highest efficiency in the tackle block variant of performing the suspension of the lifting mechanism in the range of car motion speeds of $2 \leq v \leq 4$ m/s. The effectiveness of the new ED is caused, first of all, by high efficiency of the lower power consumption in comparison with other variants of the elevator ED.

The prospects and directions for further research should be aimed at increasing energy efficiency of the elevator electromechanical system as a unified whole. For the static mode, it is an increase in energy efficiency, two degrees of energy conversion: of the rope transmission of the elevating mechanism and the drive motor. An efficiency increase is theoretically possible but is associated with a decrease in electrical and electromagnetic loads, thus increasing the weight of the active materials and their costs. This causes a detailed technical and economical substantiation. Taking into consideration the attained efficiency of 81.2 %, this figure is close to saturation. However, a further increase in efficiency is possible due to the elements of mechanism of lifting the rope driving pulley, auxiliary units, ropes, guides etc.

With regard to the start mode, we should pay attention to the fact that, for example, the proposed motor compared to the baseline two-rate AD, accumulates at start the kinetic energy that is by 1,400 times less. In the winch, in the absence of the gearbox, a part of the motor rotor energy, accumulated at the start in relation to the load energy load, decreases from 3.7 to 0.002. But as the analysis revealed, a similar revolutionary decrease in winch inertia does not lead to an equally radical improvement of the equivalent energy indicators. This is due to significant inertias of the rope driving pulley of the winch and of the lifting mechanism (car, counterweight, auxiliary units, etc.), which consume a significant portion of energy. The energy saving reserve is in a decrease in the weight of all the moving elements, but not at the expense of reliability and durability. The first step in this direction should be to reduce the weight of the car through the use of lighter materials and more efficient structural profiles. With a decrease in the weight of the car, the required weight of the counterweight decreases. One should pay attention to a decrease in inertia of the pulleys and units, because in this structure they are characterized by the total kinetic energy, which is by 1.6 times higher than the kinetic energy of carrying a car with a load. In the synthesis of the elevator drives, the problem of the minimum diameter of the rope driving pulley requires a separate study and substantiation, because technical requirements, proposed for the motor rate, and, consequently, its weight and dimensions depend on it. In order to reduce the diameter of the RDP, it is advisable to consider the options with an increased number of ropes streaks and their decreased diameter. Characteristically, a decrease in the diameter of the RDP causes a decrease in its weight and inertia, simultaneously with a decrease in the weight and inertia of the winch motor. It is possible to change the diameter of other pulleys and units of the elevator lifting mechanism with a change in the RDP weight.

7. Conclusions

1. The problem of synthesis of new types of gearless elevator drives makes it possible to solve the problem of application of the brushless bi-induction DC motor with the unwound rotor. The weight of the rotor of a similar motor is by 3–5 times lower than in the classic motor, and moment of inertia proportionally decreases. In this case, the motor rate increases by 5–7 times, therefore, so does the rate of the electric drive in general. At such a decrease in the moment of the rotor inertia, energy losses in transient modes of the BBDCM are by an order of magnitude lower than of the classic DC motor. Application of combined excitation makes it possible to increase the power of the improved BBDCM by two times at the unchanging weight and dimensions indicators.

2. The determined criteria of acceptability of the possible to use slow-moving motors of the elevator winches were determined: the weight that is equal or less than the weight of the basic double-rate asynchronous motors; coefficient of efficiency that is higher than the equivalent efficiency of the double-rate motor and the worm gear. During selecting and designing the motors of winches, it seems possible to consider a compromise solution – to regard not power, but moment as the main parameter, which will allow using a higher-speed motor.

3. The possibility of the synthesis and application of the gearless elevator electric drive with the innovative brushless bi-induction electric DC motor with the unwound rotor was proved. The gearless drive consists of the winch, the power electrical part and the control system. It is proposed to use the microprocessor system of subordinate control with the use of the relay current regulator, PI-controller of rate and P-controller of position. It was noted that the proposed electric drive, due to the design features of the slow-moving motor, has the considerably lower weight, dimensions than the traditional basic option at another similar parameter. The elevator electric drive ensures accurate reproduction by the elevator car of the assigned optimal diagram and the stop that is made on the desired floor without additional operations when approaching the assigned point. The motion is implemented according to the calculated trajectory with the necessary restrictions of the assigned speed at level of the rated one, the acceleration is up to 1 м/s^2 and the jerk is up to 3 m/s^2, which meets the condition of comfortable passenger transportation. The maximum error on the car motion regarding the task does not exceed 2.52 mm. Energy efficiency was calculated for two typical modes: the static mode of rated load lifting and the start upwards mode at a fully loaded car as well. In the static mode, the overall efficiency of the system increased from 61.3 % to 85.7 %, and in the start mode from 15.8 % to 51.9 %.

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