ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2014, № 2 (50)

# АВТОМАТИЗОВАНІ СИСТЕМИ УПРАВЛІННЯ НА ТРАНСПОРТІ

**UDC [656.257:625.151.3]:519.87**

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## MATHEMATICAL MODELING OF AC ELECTRIC POINT MOTOR

**Purpose.** In order to ensure reliability, security, and the most important the continuity of the transportation process, it is necessary to develop, implement, and then improve the automated methods of diagnostic mechanisms, devices and rail transport systems. Only systems that operate in real time mode and transmit data on the instantaneous state of the control objects can timely detect any faults and thus provide additional time for their correction by railway employees. Turnouts are one of the most important and responsible components, and therefore require the development and implementation of such diagnostics system. **Methodology.** Achieving the goal of monitoring and control of railway automation objects in real time is possible only with the use of an automated process of the objects state diagnosing. For this we need to know the diagnostic features of a control object, which determine its state at any given time. The most rational way of remote diagnostics is the shape and current spectrum analysis that flows in the power circuits of railway automatics. Turnouts include electric motors, which are powered by electric circuits, and the shape of the current curve depends on both the condition of the electric motor, and the conditions of the turnout maintenance. **Findings.** For the research and analysis of AC electric point motor it was developed its mathematical model. The calculation of parameters and interdependencies between the main factors affecting the operation of the asynchronous machine was conducted. The results of the model operation in the form of time dependences of the waveform curves of current on the load on engine shaft were obtained. **Originality.** During simulation the model of AC electric point motor, which satisfies the conditions of adequacy was built. **Practical value.** On the basis of the constructed model we can study the AC motor in various mode of operation, record and analyze current curve, as a response to various changes of the load on engine shaft.

*Keywords:* mathematical modeling; electric motors; turnout; electric drive; railway automation; automated diagnostics

### Introduction

Railway transport is the safest existing transport mode today. Everyday tens of thousands of employees operate technological process for maintenance and repair of the railway equipment. But, unfortunately, there are unforeseen situations that could lead to serious consequences. Incidents are not uncommon; sometimes accidents and catastrophes take place. It is impossible to analyze all the cases of violations, because in the majority of cases the workers, if it is possible, try to keep such cases in the dark. They wish to avoid any punitive measures for negligent performance of their duties. In addition, at the moment many railroad sections operate obsolete equipment, moreover, now are commonly found the devices, the use period of which several times exceed the rated service life guaranteed by manufacturer. In a large number of violations and failures in train schedule this is also one of the key factors.

In this situation, it takes more than one decade for general replacement of equipment, which is itself expensive. In the case of transition to new technological solutions with possible application of the new bases of fulfillment, it is required a perfect study of traffic safety aspects, as the traffic safety

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is the main task in railway transport operation. There is high risk in application of time untested prototypes.

Recently, at a quick rate the high-speed train movement is implemented. It became possible owing to purchase of foreign manufactured trains and production of domestic rolling stock of the new model. In addition, the practice of movement of heavy trains with large number of coupled cars has been used successfully. Large number of cars causes the long length of the train. Therefore such a long train can not be accepted by the side receiving and departure track of the majority of stations. The stations that can accept it are the top class stations or junctions, which are the destination stations. Therefore, these trains require either non-stop handling in the intermediate stations, or train splitting within the station performing maneuvers for relocating on the side tracks in order to clear the main way for passenger train handling. The above mentioned changes in the order of train movement are caused by the need and desire to increase the capacity of railway in terms of freight traffic, and make the railway transport more competitive as compared to the road transport for passenger transportations.

Under conditions of high competition in the transport service market such measures should have high-efficient implementation in order to make the rail transportations as much as possible advantageous as compared to any other transport modes.

High usage rate of railway transport technical means necessitates the introduction of achievements of scientific and technological progress in the field of technology and advanced methods of work organization. Solution of these problems is to a large extent provided by introduction of modern means for automation and control of technical condition of railway automation devices.

## Purpose

In the light of foregoing it is apparent that in order to provide the high speed of passenger and goods transportations, it is necessary to increase the train motion speed and the capacity of mainline track sections in general. In addition to speed of passengers and goods transportations there is one more important factor. It is the traffic safety of the trains, as well as the cargo safety. Only the proper use of funds, facilities and equipment for the organization and provision of transportation work can provide these factors. Indeed, without preliminary preparation of the technical base for implementation of the new equipment and without provision of possible causes of faults in its hardware one can find oneself in the situation, when the money spent on the purchase of expensive transport units will not be justified. This is caused by impossibility of using in full volume the properties, which possess the given vehicles as compared to their earlier models. Thus, to apply newer technologies in operation, it is necessary to incorporate and develop the innovative principles of technical maintenance and monitoring of their condition.

Since in the vast majority of instructions on the railway device servicing is used the principle of planned preventative maintenance, in connection with this there is a high failure probability of any element in the inter-repair period of time. This to a lesser extent may lead to failure in the train schedule and stoppage of goods in transit, and to a greater extent may cause a decrease of railway transportation safety and increase the risk of dangerous failure [8, 9].

So, the important task in terms of services ensuring the train movement in the conditions of strict requirements to the issue of railway device maintenance is to control the state of objects, providing the train movement in real time mode, which could give an evaluated value of the object state at the current time. Implementation of systems of this type will solve a number of problems occurring during maintenance of railway devices. First of all it concerns the equipment workers should come to. It is located in the area of train movement. Constant remote monitoring of floor equipment can not only reduce the inspection schedule, which includes access to the area of train movement, but also predict the failure occurrence and thus to prevent their occurrence.

The second important advantage of the use of remote control systems in real time mode is the accuracy and consistency of measurements. But at the present time, most technical processes depend on the skills of railway workers. Therefore the conditions of reliable operation largely depend on their experience, ability of instant perception and the ability to make decisions that are influenced by the physical and psycho-emotional state, weather conditions, etc.

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Thus, the purpose of creating the control systems of railway object condition in real time mode is to automate the process of diagnosing. Let us consider the implementation of such system with automated approach to the process of diagnosing the state of object in real time mode using the example of the switch electric engine of AC.

## Methodology

First, let us consider the switch AC electric engine as an object of diagnosing.

Any object in terms of diagnosing can be considered as a black box. That is the object, parameters of which are unknown. One can set the signals that are known by the shape and size on its input or inputs and study its condition and properties depending on the signals at the output or outputs, if there are several ones.

Another method of studying the object is its mathematical model, taking into account external parameters, the so-called input variables and parameters describing the internal condition of the studied object.

The second method is more effective in the cases when the internal parameters of the research object are known. In addition it is also more informative, as it allows correcting the state of object in two ways. So let us study operation modes and the reaction of the switch electric engine of AC on the external factors using its mathematical model describing its parameters and characteristics.

Selecting the type of switch electric engine to produce a mathematical model and diagnose its work on the basis of the constructed model is based on the fact that the introduction of railway turnouts of heavy types required the development and use of asynchronous motor, which would be able to develop high starting torques. It is the asynchronous engine that was required, as in comparison with DC electric engines (which are also used in turnouts) it has many advantages. First of all they include the absence of commutator and power supply to the electric motor windings by the industrial-frequency current. So it does not require additional conversion to another kind of current, as it is necessary when using DC electric engines [14, 17]. To represent the switch electric engine as the object of modeling it is necessary to determine how one can describe its internal state and external influence on it.

To describe the internal state of the electromechanical object, which is electric drive, one can use the formulas and thus to present it in an analytical form. Another mathematical way of object internal state assignment is its state space representation. The first way is the most suitable in the preparation of graphical mathematical model, when all the elements of object structure are presented as the separate boxes with properties that exactly reflect the properties of modeling object. In this method, dependencies of the output values on the input ones are represented by the formulas, which are used for both the description of internal state of the modeling object, and the description of its response on the input signal. Whereas, in the second method the object state and reaction in the form of formulas is a mathematical model of the object. Such method has the most suitable form for the solution in analytical form, when the formulas already contain its parameters and input values, and the solution is output reaction. Using these formulas the object was described.

Mathematical modeling of the electric switch mechanism with AC engine will be carried out in the software environment Simulink of the mathematical package MATLAB. Thus, we will use the first method of mathematical modeling of the two ones listed above.

For this purpose we consider the main parameters and characteristics of the switch electric engine of AC.

As the switch electric engine of AC current the electric engine of MCT series were applied. They are AC asynchronous engines, which have a fixed part – a stator and a rotating part, which is called rotor.

In the three-phase engine three windings are placed on the stator. They create three separate flows shifted relative to each other by 120°. The rotor winding of the "squirrel cage" type is made of copper bars, short-closed on the ends with two welded rings. The bars are laid in the rotor core slots, without any isolation. The stator and rotor are interconnected through a magnetic flow generated by the stator and penetrating the rotor. Therefore the air gap between the stator and rotor should be as small as possible to increase the electromagnetic coupling between them.

All switch electric engines of MST series have the same working principle and differ only in some design features. Let us consider the design features

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of electric engine of the type MCT-0,3 and construct its mathematical model [11, 18].

Winding sections of stator of the switch electric engine have the following parameters:

– number of windings – 29;
– mark of the wire – PEV-2;
– wire diameter – 0.69 mm;
– resistance at 20 °C – 0.5 Ohm;
– mass – 0.036 kg.

The scheme of electrical connections of stator winding is performed with the following indices:

– number of poles – 2*p* = 6;
– number of slots – z = 36;
– number of phases – m = 3;
– number of slots for pole and phase q = 2;
– number of parallel paths – 1;
– number of reel to reel groups – 18;
– slot pitch – y = 1 ÷ 6:
– resistance of each phase winding – 6 Ohm.

The rotor of electric engine of MST-0.3 has 26 half-closed slots. In comparison with the closed form it slightly increases the starting torque and overload capacity of engine. The rotor winding consists of 26 pear-shaped bars and two short-closing rings with sections 36 mm$^2$.

Starting characteristics of engine differ by low multiplicity of starting current $I_п/I_н$ = 2.3 and the satisfactory one of starting torque $M_п/M_н$ = 2.5. The satisfactory starting torque is achieved by the slip increase using the ratio increase of active resistance of rotor cage to the induction one of the engine.

To increase the starting torque it was increased the slip, which at the rated load reaches 18%.

Nominal parameters of the switch electric engine MST-0.3 (Y/delta):

– power supply voltage – 190/110 V;
– current consumption – no more than 2.1/3.6 A;
– power – 300 W;
– deflecting torque – 3.43 N/m;
– rotation frequency – 850 ± 5% r/min;
– efficiency coefficient – no less than 66%;
– power coefficient – cos φ = 0.72;
– frequency – 50 Hz.

By heat engines are designed to operate in intermittent mode with 15% duty cycle. Assigned operation time 500.000 switch operations while meeting the requirements of operation.

Operating characteristics of the engine during Y-connection are shown in Figure 1. Speed characteristic n = f($P_2$) is a rigid one and represents a curve slightly inclined to the horizontal axis. Moment characteristics $M$ = f($P_2$) represents a curve whose curvature is determined by the speed characteristic. Power factor cos φ = f($P_2$) increases rapidly with load increase and at values $P_2$, which are a little larger than the nominal power, reaches the maximum level. Since the induction motor consumes considerable magnetizing current, its cos φ is always less than unity. The efficiency curve η = f($P_2$) has usual character. It increases rapidly with the load increase near to half of the nominal one and decreases with further load increase.

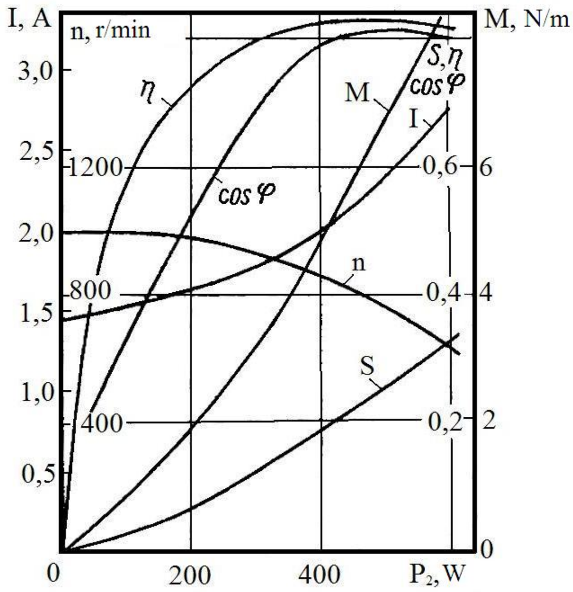


Fig. 1. Operating performance of electric motor, type MST-0.3

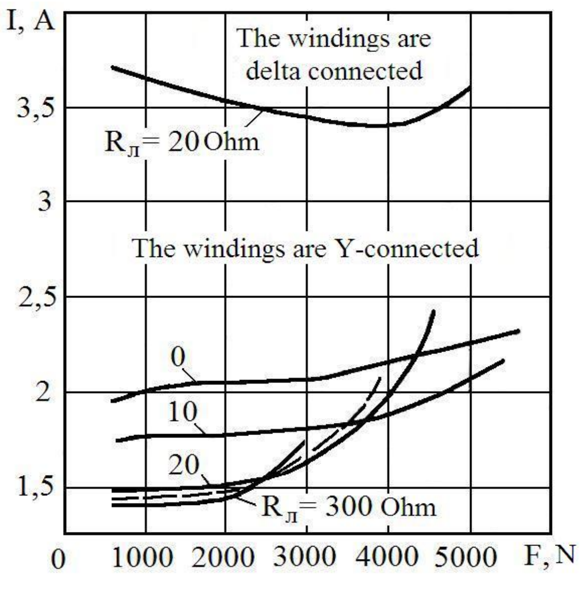


Fig. 2. Load curves of the electric operation, type PM-6

Figure 2 shows the dependence diagram of the electric current consumed by electric drive type PM-6 with electric engine type MST-0.3 at different loads on the valve leaf and contact line resistance of cable connection. The diagram shows that the electric engine type MST-03 ensures reliable operation of electric drive under load up to 4 500 N without core duplicating at a distance up to 850 m.

The engines were tested on mechanical stand with the Y- and delta connection of the stator windings. Cable line resistance was simulated by wire resistors. Voltage at the motor terminal $U_л$, current consumption $I_л$, active power $P_1$ and rotation frequency $n_1$ were measured respectively by voltmeter, ampere meter, electric power meter and tachometer.

Rotational moment $M$ was calculated according by the formula:

$$M = \frac{F\ r_2}{\xi\ \eta}, \qquad (1)$$

where $F$ – is traction effort of electric drive, N; $\eta$ – is reduction gear efficiency; $r_2$ – is traction effort arm.

In turn, the gear reduction ratio $\xi$ is defined by the formula:

$$\xi = \frac{\omega_1}{\omega_2}, \qquad (2)$$

where $\omega_1$ – is angular speed of rotation of drive shaft (of electric engine); $\omega_2$ – is angular speed of rotation of driven shaft (main drive shaft).

Net power $P_2$ was determined by the formula:

$$P_2 = \frac{F\ l}{t}, \qquad (3)$$

where $F$ – is valve leaf load, N; $l$ – is valve leaf path length (0.154 m); $t$ – is operation time, sec.

Electric drive efficiency was determined by the formula:

$$\eta = \frac{P_2}{P_1}, \qquad (4)$$

where $P_1$ and $P_2$ – are the power consumed by electric drive (active) and net power.

The power consumed by electric drive can be determined by the formula:

$$P_1 = U\ I, \qquad (5)$$

where $U$ – is a voltage on electric engine terminals, V; $I$ – is a circuital current of electric engine, A.

Slipping $S$, which is characteristic of the rotor retardation is determined by the ratio

$$S = [(n_1 - n)/n_1]\,100\%, \qquad (6)$$

where $n_1$ – is the speed of stator rotating field; $n$ – is the speed of rotor rotating field.

Whereas, the resultant magnetic field generated by three-phase stator is the rotating one. Revolutions per minute are determined by the formula:

$$n_1 = \frac{60\ f}{p}, \qquad (7)$$

where $f$ – is the current frequency of stator; $p$ – number of stator terminal pairs.

Power coefficient can be obtained from the formula:

$$\cos\varphi = \frac{P_1}{\sqrt{3}\ U\ I}, \qquad (8)$$

where $P_1$, $U$ and $I$ – are the power consumed by electric drive (W), the voltage at the terminals of electric engines (V) and the circuital current of electric engine (A).

Now that we know the basic laws, dependencies, parameters and features let us start the construction of a mathematical model of the switch AC electric engine MST-0.3.

Let us construct a mathematical model of the switch electric engine using the software environment Simulink of the MATLAB package [2].

Asynchronous machine model includes the model of electrics presented by the state space model of the fourth order, and the model of mechanical part in the form of second-order system.

To build the model (Fig. 3), we use a generalized model of virtual installation for the study of an induction machine, which contains [3, 12]:

– three-phase alternating voltage source *Three-Phase Programmable Voltage Source* from the Library of Power System Block-set/Extras/Electrical Sources;

– measurer of three-phase voltage and current *Three-Phase V-I Measurement* (Library Power System Blockset/Extras/Measurement);

– three-phase induction machine under study *Asynhronous Machine* (Library Power System Blockset/Extras/Machines);

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– for measuring the active and reactive power in the system a standard block *Active & Reactive Power*, which is included in the section SimPowerSystems/ ExtraLibrary/ Measurements is used;

– *Display* block for quantification the measured powers P1 Q1;

– *Scope* block for monitoring the rotor and stator currents, as well as the speed and torque of asynchronous machine (main library Simulink/ Sinks);

– *Moment* block to set the mechanical torque on the machine shaft (main library of Simulink/ Source);

– Block *Machines Measurement Demux*, which is designed to extract the state variables from the vector measured by variables of electric machine;

– Block *Current Measurement* from the library SimPowerSystems/ Measurements measures the instantaneous current flowing through the connecting line (wire);

– *RMS* block from the library SimPowerSystems/ Extra Library/ Measurements calculates the true value of harmonic component or DC;

– block *Display1* for quantification of machine speed, electromagnetic torque and stator current (main library Simulink/ Sinks);

– Block *Mux*, combining three signals into one vector signal (from main library Simulink/Sygnal&System);

– *Powergui* block, located in the library SimPowerSystems, is a tool for a graphical user interface. It allows one to perform various tasks.

Block *Asynhronous Machine* simulates asynchronous machine in the motor or generator modes. Mode of operation is determined by the sign of the electromagnetic torque of machine.

Ports of the model A, B and C are the terminals of machine stator winding, and the ports a, b and c are the windings of machine rotor. Tm port is designed to feed the resistance moment to the motion, which is carried out by means of the block *Moment.* At the out port m the vector signal is formed. It consists of 21 elements: currents, flows, rotor and stator voltages in the fixed and rotating coordinate system, electromagnetic torque, angular speed of shaft rotation, as well as its angular position. The given vector signal is decomposed into separate components using the block *Machines Measurement Demux*. Then it is fed to the Scope for monitoring the temporal variations in the rotor and stator currents, and the speed and torque of asynchronous machine [13, 15, 16].

Parameters of asynchronous machine are partially taken from the passport data of switch AC electric engine MST-0.3, and partially are calculated on the basis of passport data.

The accurate parameter calculation of asynchronous machine equivalent circuit based on its passport data is a very difficult task, since its torque is connected with parameters by non-linear dependence. Besides, the electric machine is essentially a system with variable parameters.

Now that the model has been built, one should input the parameter values in the fields of block settings. To do this one should calculate these parameters, using the basic laws and rules of electric machines calculation.

Having considered the setting fields in block properties of the model shown in Fig. 3 we come to a conclusion that the parameters of switch electric engine that were given before are not enough to fill all of them. That is why one needs to perform additional parameter calculation of the mathematical model of the switch AC electric engine MST-0.3.

Let us define the equivalent circuit parameters of asynchronous machine in its passport data. Since the operation of any asynchronous motor depends on the connecting circuit of its windings, let us initially determine that the stator windings of switch electric engine type MST-0.3 are Y-connected and all the relevant passport data will be taken with respect to this method of windings connection.

Let us present the formulas and carry out the calculations of parameter values of the mathematical model. After that one should input the obtained values in the setting fields of the respective model blocks [4, 5].

The rated slip is determined using the formula:

$$s_H = \frac{n_s - n_H}{n_s}, \qquad (9)$$

where $n_s$ – is synchronous speed (the rotation speed of the magnetic field), r/min; $n_H$ – is the nominal speed of engine rotation, r/min.

Switch electric engines of MST series are made with greater slip, reaching at the rated load 18%.

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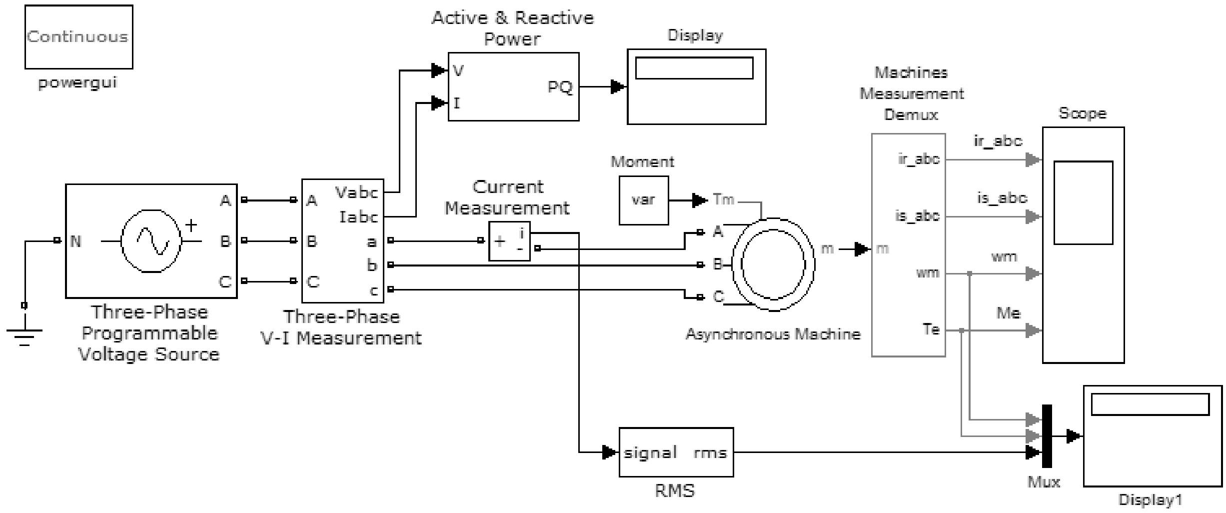


Fig. 3. Virtual setup model for the asynchronous machine research

The critical slip can be found using the formula:

$$s_k = (m_k + \sqrt{m_k^2 - 1})\ s_H\ , \qquad (10)$$

where $m_k$ – is the ratio of short circuit (starting) torque to the nominal torque; $s_H$ – is the nominal sleep.

In turn, the coefficient $m_k$ is determined using the ratio:

$$m_k = \frac{M_K}{M_H}\ , \qquad (11)$$

where $M_K$ and $M_H$ – are the short circuit torque (when starting) and the nominal torque accordingly.

The ratio of the starting and nominal torques represents the starting performance and for the engine type MST-0.3 it is equaled 2.5.

With known components of the formula (10) now let us calculate the critical slip value:

$$s_k = (2{,}5 + \sqrt{2{,}5 - 1})\ 0{,}18 = 0{,}67$$

The structural factor can be determined using the following formula:

$$c_1 = 1 + \frac{L_{ls}}{L_m}\ , \qquad (12)$$

where $L_{ls}$ – is the leakage inductance of the stator and rotor, H; $L_m$ – is the mutual induction between the stator and rotor, H.

Originally the constructive factor is set in the range from 1.02 to 1.05 for the preliminary calculation of equivalent circuit parameters. Smaller values are accepted for machines of larger capacity. After calculating the inductance in the equation (12), it is necessary to compare the obtained value with the originally selected one and specify the calculation. Usually during two or three iterations the agreement of the received and the calculated structural factor can be achieved.

As in this case we observe the low-power asynchronous machine we take the initially greater value of constructive factor and assume that $c_1 = 1.05$.

The formula for determining the viscous friction coefficient has the following form:

$$B_m = \frac{\Delta P_m}{(2\ \pi\ n_H / 60)^2}\ , \qquad (13)$$

where $\Delta P_m$ – are the mechanical losses, W; $\pi$ – is a mathematical constant; $n_H$ – is the nominal speed of engine rotation.

In equation (13) the mechanical losses $\Delta P_m$, representing bearing friction and losses for machine ventilation are determined using the equation:

$$\Delta P_m = \sqrt{3}\ I_H\ U_H\ \cos\varphi\ \eta - P_H\ , \qquad (14)$$

where $I_H$ – is the current in the circuit of asynchronous engine in the operation mode for nominal load, A; $U_H$ – is voltage at the terminals of asynchronous motor in the operation mode for rated load, V; cos $\varphi$ – is the power coefficient of asynchronous motor; $\eta$ – is the efficiency coefficient of asynchronous motor; $P_H$ – is the power that is necessary to be developed by asynchronous motor to overcome the resisting force of the rated load, W.

Let us perform the calculation of mechanical losses $\Delta P_m$ according to formula (14), substituting the variables and coefficients by their corresponding known values: $\pi = 3.14$, $I_H = 2.1$ A, $U_H = 190$ V, $\cos\varphi = 0.72$, $\eta = 0.66$, $P_H = 300$ W. The formula (14) will take the following form:

$$\Delta P_m = \sqrt{3}\cdot 2{,}1\cdot 190\cdot 0{,}72\cdot 0{,}66 - 300 = 28{,}41 \text{ W}.$$

According to design requirements for the rated operating conditions of the machine the mechanical losses should be 0.1 ÷ 0.5% of output power. Let us define a relative measurer of mechanical losses in our case. To do this we find out the mechanical losses ratio to the useful power, i.e. power that is required to perform the work for overcoming the resistance to the motor shaft movement:

$$\frac{\Delta P_m}{P_H} = \frac{28{,}41}{300} = 0{,}095,$$

The percentage is 9.5%. Thus, for the engine type MST-0.3, the mechanical losses value is almost 20 times exceed the upper limit of electric machine losses, which is an acceptable indicator for low power machines.

Therefore, returning to the calculations, we substitute the value found for the mechanical losses and the known value of the rated motor speed $n_H = 850 \pm 5\%$ r/min in the formula for determining the coefficient of viscous friction (13) and define its numerical value:

$$B_m = \frac{28{,}41}{(2\cdot 3{,}14\cdot 850/60)^2} = 0{,}0036 \text{ N/m/s}$$

The stator resistance can be determined using the formula:

$$R_s = \frac{3}{2}\,\frac{(U_H/\sqrt{3})^2\,(1-s_H)}{c_1(1+c_1/s_k)\,M_k\,(P_H+\Delta P_m)}, \quad (15)$$

where $U_H$ – is the voltage at the terminals of asynchronous motor in the mode of operation at the rated load, V; $s_H$ – is the nominal slip; $c_1$ – is the structural factor; $s_k$ – is the critical slip; $M_k$ – is the short circuit torque (during the starting); $P_H$ – is the power that is necessary to be developed by asynchronous motor to overcome the resisting force of rated load, W; $\Delta P_m$ – are the mechanical losses, W.

In the formula (15) only the short-circuit torque $M_k$, which can be found using the formula (11) value is still remains unknown.

Let us rewrite the formula (11) with respect to short-circuit torque $M_K$ taking into account the fact that the coefficient value $m_k = 2.5$ and the torque at the motor shaft in the nominal load $M_H = 3.43$ N/m are known and determine its value:

$$M_k = 3{,}43\cdot 2{,}5 = 8{,}575 \text{ N/m}$$

Now that we know the values of all variables and coefficients, which are the part of formula let us perform a calculation of the stator resistance value $R_s$ according to the expression (15), substituting the variables and coefficients by the corresponding known and previously found values: $U_H = 190$ V, $s_H = 0.18$, $c_1 = 1.05$, $s_k = 0.67$, $M_K = 8.575$ N/m, $P_H = 300$ W, $\Delta P_m = 28.41$ W. In this case the formula will take the following form:

$$R_s = \frac{3}{2}\,\frac{(190/\sqrt{3})^2}{1{,}05\,(1+1{,}05/0{,}67)}\times$$

$$\times\frac{(1-0{,}18)}{8{,}575\,(300+28{,}41)} = 1{,}95 \text{ Ohm}$$

The rotor resistance can be determined using the formula:

$$R_r = \frac{1}{3}\,\frac{(P_H+\Delta P_m)}{(1-s_H)\,i_k^2\,I_H^2}, \quad (16)$$

where $P_H$ – is the power that should be developed by asynchronous motor to overcome the resisting force of rated load, W; $\Delta P_m$ – are the mechanical losses, W; $s_H$ – is the nominal slip; $i_k$ – is the ratio of short circuit current to the nominal current; $I_H$ – is the current in the asynchronous motor circuit in the mode of motion for nominal load, A.

Coefficient $i_k$ is in turn determined using the ratio:

$$i_k = \frac{I_K}{I_H}, \quad (17)$$

where $I_K$ – is the short circuit current (staring), A; $I_H$ – is the nominal current (current in the asynchronous motor circuit in the operation mode for nominal load), A.

The ratio of starting current value to the value of nominal one represents a starting performance and is equal to 2.3 for engine type MST-0.3.

Perform the calculation of the rotor resistance $R_r$ according to expression (16), substituting the variables with their corresponding known and previously found values: $P_H = 300$ W, $\Delta P_m = 28.41$ W, $s_H = 0.18$, $i_k = 2.3$, $I_H = 2.1$ A.

In this case the formula (16) will take the following form:

$$R_r = \frac{1}{3} \cdot \frac{(300 + 28,41)}{(1 - 0,18) \cdot 2,3^2 \cdot 2,1^2} = 5,72 \text{ Ohm}$$

Inductance of stator and rotor is determined using the following formula:

$$L_s \cong L_r = \frac{1}{2\,\pi\, f_H} \times$$

$$\times \frac{U_H / \sqrt{3}}{I_H\, [\sqrt{1 - (\cos\varphi)^2} - \cos\varphi\; s_H / s_k]}, \qquad (18)$$

where $\pi = 3.14$ – is a mathematical constant; $f_H$ – is the current frequency in the circuit of asynchronous motor with nominal load at the shaft; $U_H$ – is the voltage at the terminals of asynchronous motor in the mode of operation for nominal load, W; $I_H$ – is the current in the circuit of asynchronous motor in the mode of operation for nominal load, A; $\cos\varphi$ – is the power coefficient of asynchronous motor; $s_H$ – is the nominal slip; $s_k$ – is the critical slip.

Let us perform the calculation of stator inductance $L_s$ and rotor inductance $L_r$ according to the formula (18), substituting the variables and coefficients with their corresponding known and previously found values: $\pi = 3.14$, $f_H = 50$ Hz, $U_H = 190$ V, $I_H = 2.1$ A, $\cos\varphi = 0.72$, $s_H = 0.18$, $s_k = 0.67$. The formula (18) in this case will take the following form:

$$L_s \cong L_r = \frac{1}{2 \cdot 3,14 \cdot 50} \times$$

$$\times \frac{190 / \sqrt{3}}{2,1 \cdot [\sqrt{1 - 0,72^2} - 0,72 \cdot 0.18 / 0,67]} = 0,3324 \text{ Henry}$$

The leakage inductance of stator and rotor can be determined using the formula:

$$L_{ls} \cong L_{lr} = \frac{1}{4\,\pi\, f_H} \times$$

$$\times \sqrt{\left(\frac{U_H / \sqrt{3}}{i_k\; I_H}\right)^2 - (R_s + R_r)^2}, \qquad (19)$$

where $\pi$ – is a mathematical constant; $f_H$ – current frequency in the circuit of asynchronous motor with nominal load at the shaft, Hz; $U_H$ – is the voltage at the terminals of asynchronous motor in the mode of operation for nominal load, W; $i_k$ – is the ratio of short circuit to the nominal current; $I_H$ – is the current in the circuit of asynchronous motor in the mode of operation for nominal load, A; $R_s$ – is the resistance of stator winding, Ohm; $R_r$ – is the resistance of rotor winding, Ohm.

Let us perform the calculation of leakage inductance of the stator $L_{ls}$ and rotor $L_{lr}$ according to the formula (19); substituting the variables and coefficients their corresponding known and previously found values: $\pi = 3.14$, $f_H = 50$ Hz, $U_H = 190$ V, $I_H = 2.1$ A, $i_k = 2.3$, $R_s = 1.95$ Ohm, $R_r = 5.72$ Ohm. In this case the formula (19) will take the following form:

$$L_{ls} \cong L_{lr} = \frac{1}{4 \cdot 3,14 \cdot 50} \times$$

$$\times \sqrt{\left(\frac{190 / \sqrt{3}}{2,3 \cdot 2,1}\right)^2 - (1,95 + 5,72)^2} = 0,034 \text{ Henry}$$

Mutual inductance between stator and rotor windings can be found using the formula:

$$L_m = L_s - L_{ls}, \qquad (20)$$

where $L_s$ – is the stator inductance, Henry; $L_{ls}$ – is the leakage inductance of stator, Henry.

Let us perform the calculation of mutual induction between the stator and rotor windings according to the formula (20), substituting the known values of stator inductance and stator leakage inductance: $L_s = 0.3324$ Henry, $L_{ls} = 0.034$ Henry. In this case the formula (20) will be rewritten in the following form:

$$L_m = 0,3324 - 0,034 = 0,2984 \text{ Henry}$$

Let us come back to the calculation of the structural factor $c_1$ using the formula (12). Now we substitute the stator leakage inductance $L_{ls}$ and mutual inductance $L_m$ with their values found using the formulas (19) and (20) and carry out corresponding calculations:

$$c_1 = 1 + \frac{0,034}{0,3324} = 1,1023.$$

In order to verify the found constructive factor value one should recalculate the value of the stator leakage inductance $L_{ls}$, the calculation of which includes the resistance of stator winding $R_s$ taking into account the constructive factor. In addition, one needs to redefine the mutual inductance value of stator and rotor $L_m$, the formula of which includes the stator leakage inductance $L_{ls}$. After performing these calculations, it is necessary to calculate the value of constructive factor using the formula (12) once again. Let us perform the listed calculations.

To variables differed from the above, we introduce the notation in their bar. In order to make the variables different from the presented above let us put a stroke in their symbols. First of all let us define the value of the stator winding resistance $R_s$ using the formula (15):

$$R_s^{'} = \frac{3}{2} \cdot \frac{(190/\sqrt{3})^2}{1,1 \cdot (1 + 1,1/0,67)} \times$$

$$\times \frac{(1 - 0,18)}{8,575 \cdot (300 + 28,41)} = 1,81 \text{ Ohm}$$

Now, substituting in the formula (19) the new value of stator winding resistance $R_s^{'}$ we find the value of stator leakage inductance $L_{ls}$:

$$L_{ls}^{'} \cong L_{lr}^{'} = \frac{1}{4 \cdot 3,14 \cdot 50} \times$$

$$\times \sqrt{\left(\frac{190/\sqrt{3}}{2,3 \cdot 2,1}\right)^2 - (1,81 + 5,72)^2} = 0,0341 \text{ Henry}$$

Let us define the new value of mutual inductance between stator and rotor $L_m$ using the formula (20):

$$L_m^{'} = 0,3324 - 0,0341 = 0,2983 \text{ Henry}$$

Therefore, according to the formula (12) the structural factor $c_1$ will take the following value:

$$c_1^{'} = 1 + \frac{0,0341}{0,3324} = 1,1026 .$$

Since the discrepancy between the values of structural factor is only 0.0003 or:

$$\frac{c_1^{'} - c}{c_1^{'}} 100\% = \frac{1,1026 - 1.1023}{1,1023} 100\% = 0,027\% ,$$

so let us round off the value of structural factor and accept $c_1 = 1.1$.

The power consumed by motor from the network in the mode of nominal load can be determined using the formula:

$$P = m\, U_H\, I_H \cos\varphi , \qquad (21)$$

where $m$ – is the number of engine phases; $U_H$ – is the voltage at the terminals of asynchronous engine in the operation mode for the rated load, V; $I_H$ – is the current in the circuit of asynchronous engine in the operation mode for the rated load, A; cos φ – the displacement angle between voltage and current in the circuit of electric engine.

Let us perform the calculation of power consumed by the motor from the network in the mode of rated load according to the formula (21) bearing in mind that the power is supplied from a three-phase network and $m$ = 3, and substituting the known values of supply voltage, current in the circuit and the displacement angle between them: UH = 190, IH = 2.1 A, cos φ = 0.72. In this the formula will be rewritten in the following form:

$$P = 3 \cdot 190 \cdot 2,1 \cdot 0,72 = 861,84 \text{ W}$$

Inertia moment of the motor shaft with load is determined according to the equation of dynamics of the electromechanical system from the formula:

$$J \frac{dw}{dt} = M - M_H \qquad (22)$$

Using the existing methods of presented inertia moment definition of the electric drive [1, 6, 7] the value of inertia moment for the motor shaft with the load, which is 0.025 kg/m$^2$ was calculated.

## Findings

Operating characteristics taken during the model operation are presented in the Figure 4. Mechanical shaft torque Tm is set 3.43 N/m, equating it to the rated torque of the motor shaft and substituting the variable var in the block *Moment*.

Operating characteristics show that the currents of stator and rotor windings (Fig. 4, *a), b)*) do not exceed 2.5 A, and the actual current in phase A in this case is 2.1 A. The angular velocity of the motor shaft rotation (Fig. 4, *c)*) reaches about 88 radians per second, which is 841 r/min. The electromagnetic rotation torque developed by the model of asynchronous machine at shaft tends to 3.5 N/m. The obtained results almost do not differ from the passport data of the switch AC electric engine of MST-0.3 type.

Thus, the constructed mathematical model of the switch AC electric engine of MST-0.3 type meets the requirements of the model adequacy. It uses the parameters obtained by calculation based on the passport data of the machine and the operating characteristics of the model do not differ from the main indices of operating characteristics for this type of electric engine.

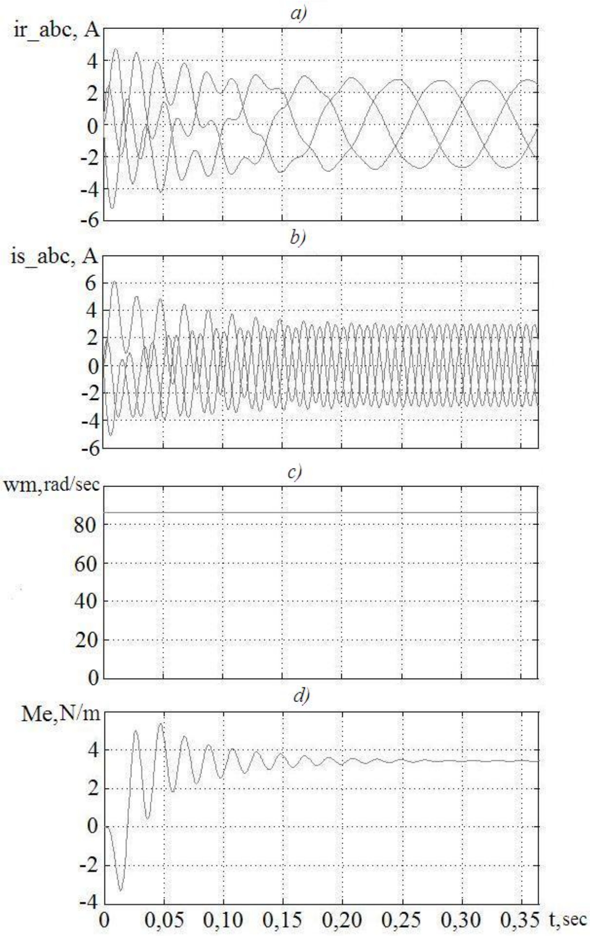


Fig. 4. Operating characteristics of the model:
*a* – rotor winding currents; *b* – stator currents; *c* – angular frequency of the rotor rotation; *d* – electromagnetic torque.

In addition, the presented method for calculation of asynchronous machine parameters can be used not only in such tasks of modeling of switch AC electric engines, but also in dealing with other of tasks that are not related to modeling because they are the universal ones.

## Originality and practical value

Originality lies in the first developed and constructed mathematical model of the switch AC electric engine based on the calculation of asynchronous machine in its passport data. The obtained results of modeling of asynchronous machine operation confirm the model adequacy, since the parameters of its operating characteristics at the proper level coincide with those of the real analog.

From the viewpoint of practical value a new approach in the process of creating the database of failures for asynchronous motors, which are used in switch electric drives is proposed. Due to the developed model, there is an opportunity to conduct the preliminary tests of different modes of operation to determine the engine response for both the changes that you can easily reproduce in real conditions, and that you can not easily reproduce in the real world or it is impossible to reproduce them without damaging the object [10].

## Conclusions

Diverging from the principle of planned preventative maintenance with the constant need of railway workers to come to the area of rolling stock movement it is required in the created automated remote control systems to lay the greatest possible number of different situations and states of diagnosing objects with feeding them into memory. This allows except the ability to determine the parameter change to give a prediction of further state, as well as to give the recommendations to eliminate the damages.

Since the simulation results properly coincide with the real operating characteristics of the switch electric engine, so it is possible to set different loads and study the model response suggesting in advance that this response is the same as the response of the object under study.

This gives us the opportunity to predict the behavior and character of current change in the electric engine circuit, both in the standard mode, and with the deviations from the norm of the operation of electric engine itself or the turnout in general.

This mathematical model meets all the requirements for modeling of the objects created with the purpose of virtual testing to create a database of diagnostic features.

LIST OF REFERENCE LINKS

1. Амелин, С. В. Путь и путевое хозяйство / С. В. Амелин, Л. М. Дановский. – 3-е изд., перераб. и доп. – М. : Транспорт, 1972. – 216 с.
2. Буряк, С. Ю. Математичне моделювання стрілочного електроприводу / С. Ю. Буряк // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Д., 2010. – Вип. 34. – С. 172−175.

3. Герман-Галкин, С. Г. Компьютерное моделирование полупроводниковых систем в MATLAB 6 : учеб. пособие / С. Г. Герман-Галкин. – СПб. : КОРОНА принт, 2001. – 320 с.
4. Герман-Галкин, С. Г. Электрические машины : лаборатор. работы на ПК / С. Г. Герман-Галкин. – СПб. : КОРОНА принт, 2003. – 256 с.
5. Герман-Галкин, С. Г. Matlab & Simulink. Проектирование мехатронных систем на ПК / С. Г. Герман-Галкин. – СПб. : КОРОНА-Век, 2008. – 368 с.
6. Дайнеко, В. А. Электрооборудование сельскохозяйственных предприятий : учеб. пособие / В. А. Дайнеко, А. И. Ковалинский. – Минск : Новое знание, 2008. – 320 с.
7. Иванов, Г. Я. Электропривод и электрооборудование : учеб. пособие / Г. Я. Иванов, А. Ю. Кузнецов, В. В. Дмитриев. – Новосибирск : Новосиб. гос. аграр. ун-т. Инженер. ин-т, 2011. – 54 с.
8. Маловічко, В. В. Автоматизовані системи управління на транспорті / В. В. Маловічко, В. І. Гаврилюк, В. Я. Кізяков // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Д., 2007. – Вип. 16. – С. 5−8.
9. Маловічко, В. В. Використання системи контролю стану стрілочних двигунів по кривій споживання струму в ремонтно-технічних дільницях / В. В. Маловічко, В. І. Гаврилюк, М. І. Решетняк // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Д., 2007. – Вип. 18. – С. 11−15.
10. Парфенов, В. И. Анализ дефектов и возможности диагностики стрелочных переводов / В. И. Парфенов, А. П. Разгонов, М. А. Ковригин // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Д., 2007. – Вип. 15. – С. 16−18.
11. Резников, Ю. М. Электроприводы железнодорожной автоматики и телемеханики / Ю. М. Резников. – М. : Транспорт, 1985. – 288 с.
12. Черных, И. В. Моделирование электротехнических устройств в MATLAB SimPowerSystems и Simulink / И. В. Черных. – М. : ДМК Пресс, 2008. – 288 с.
13. Beucher, O. Introduction to MATLAB & Simulink : a project approach / O. Beucher, M. Weeks. – 3-rd ed. – Hingham, Massachusetts New Delhi : Infinity Science Press LLC, 2008. – 390 p.
14. Ong, Chee-Mun. Dynamic simulation of electric machinery using MATLAB and Simulink / Chee-Mun Ong – Upper Saddle River, New Jersey : Prentice Hall PTR, 1998. – 627 p.
15. Chaturvedi, Devenndra K. Modeling and simulation of systems using MATLAB and Simulink / Devenndra K. Chaturvedi – New York : CRC Press Taylor & Francis Group, 2010. – 711 p.
16. Giurgiutiu, V. Micromechatronics modeling, analysis, and design with MATLAB / Victor Giurgiutiu, Sergey Edward Lyshevski. – 2-nd ed. – New York : CRC Press Taylor & Francis Group, 2009. – 920 p.
17. Karris, Steven T. Introduction to Simulink with engineering applications / Steven T. Karris. – 2-nd ed. – Orchard Publications, 2008. – 716 p.
18. Theeg, G. Railway Signaling and Interlocking. International Compendium / G. Theeg, S. Vlasenko. – Hamburg : Eurailpress, 2009. – 448 p.

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# МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ СТРЕЛОЧНОГО ЭЛЕКТРОДВИГАТЕЛЯ ПЕРЕМЕННОГО ТОКА

**Цель.** Для обеспечения надежности, безопасности, а самое главное – непрерывности перевозочного процесса, необходимо разрабатывать, внедрять, а затем и усовершенствовать автоматизированные методы диагностики аппаратов, устройств и систем железнодорожного транспорта. Только лишь системы, которые работают в режиме реального времени и передают данные о мгновенном состоянии объектов контроля, могут своевременно обнаружить какие-либо неисправности и таким образом обеспечить дополнительное время на их устранение работниками железнодорожного транспорта. Стрелочные переводы являются одним из важнейших и ответственных узлов, а поэтому требуют разработки и внедрения подобной системы диагностики. **Методика.** Достижение цели наблюдения и контроля за объектами железнодорожной автоматики в режиме реального времени возможно только с применением автоматизированного процесса диагностирования состояния объектов. Для этого необходимо знать диагностические признаки объекта контроля, по которым определять его состояние в каждый момент времени. Наиболее рациональным способом дистанционной диагностики является анализ формы и спектра тока, протекающего в силовых цепях объектов железнодорожной автоматики. Стрелочные переводы содержат электродвигатели, которые получают питание по электрическим цепям, а форма токовой кривой зависит как от состояния самого электродвигателя, так и от условий технического содержания стрелки. **Результаты.** Для исследования и анализа работы стрелочного электродвигателя переменного тока была разработана его математическая модель. Проведен расчет параметров и взаимозависимостей между основными показателями, влияющими на работу асинхронной машины. Получены результаты работы модели в виде временных зависимостей формы сигналов токовых кривых от нагрузки на валу двигателя. **Научная новизна.** В процессе моделирования была построена модель стрелочного электродвигателя переменного тока, которая удовлетворяет условиям адекватности. **Практическая значимость.** На основании построенной модели можно изучать работу электродвигателя в различных режимах работы, записывать и анализировать кривую тока, как реакцию на различные изменения нагрузки на валу двигателя.

*Ключевые слова:* математическое моделирование; электродвигатели; стрелочный перевод; электропривод; железнодорожная автоматика; автоматизированная диагностика

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# МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ СТРІЛОЧНОГО ЕЛЕКТРОДВИГУНА ЗМІННОГО СТРУМУ

**Мета.** Для забезпечення надійності, безпеки, а найголовніше – безперервності перевізного процесу, необхідно розробляти, впроваджувати, а потім і вдосконалювати автоматизовані методи діагностики апаратів, пристроїв і систем залізничного транспорту. Тільки лише системи, які працюють в режимі реального часу і передають дані про миттєвий стан об'єктів контролю, можуть своєчасно виявити будь-які пошкодження і таким чином забезпечити додатковий час на їх усунення працівниками залізничного транспорту. Стрілочні переводи є одним з найважливіших і відповідальних вузлів, а тому вимагають розробки та впровадження подібної системи діагностики. **Методика.** Досягнення мети спостереження і контролю за об'єктами залізничної автоматики в режимі реального часу можливо тільки із застосуванням автоматизованого процесу діагностування стану об'єктів. Для цього необхідно знати діагностичні ознаки об'єкта контролю, за якими визначати його стан у кожний момент часу. Найбільш раціональним способом дистанційної діагностики є аналіз форми і спектра струму, що протікає в силових ланцюгах об'єктів залізничної автоматики. Стрілочні переводи містять електродвигуни, які отримують живлення по електричних колах, а форма струмової кривої залежить як від стану самого електродвигуна, так і від умов технічного утримання стрілки. **Результати.** Для дослідження та аналізу роботи стрілочного електродвигуна змінного струму була розроблена його математична модель. Проведено розрахунок параметрів і взаємозалежностей між основними показниками, що впливають на роботу асинхронної машини. Отримано результати роботи моделі у вигляді часових залежностей форми сигналів струмових кривих від навантаження на валу двигуна. **Наукова новизна.** У процесі моделювання була побудована модель стрілочного електродвигуна змінного струму, яка задовольняє умовам адекватності. **Практична значимість.** На підставі побудованої моделі можна вивчати роботу електродвигуна в різних режимах роботи, записувати й аналізувати криву струму, як реакцію на різні зміни навантаження на валу двигуна.

*Ключові слова:* математичне моделювання; електродвигуни; стрілочний перевід; електропривод; залізнична автоматика; автоматизоване діагностування

## REFERENCES

1. Amelin S.V., Danovskiy L.M. *Put i putevoye khozyaystvo* [Track and track facilities]. Moscow, Transport Publ., 1972. 216 p.
2. Buryak S.Yu. Matematychne modeliuvannia strilochnoho elektropryvodu [Mathematical modeling of electric drive turnouts]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan], 2010, issue 34, pp. 172-175.

3. German-Galkin S.G. *Kompyuternoye modelirovaniye poluprovodnikovykh sistem v MATLAB 6.0* [Computer simulation of semiconductor systems in MATLAB 6.0]. Saint Petersburg, KORONA print Publ., 2001. 320 p.
4. German-Galkin S.G. *Elektricheskiye mashiny: laboratornyye raboty na PK* [Electrical machines: laboratory works on PC]. Saint Petersburg, KORONA print Publ., 2003. 256 p.
5. German-Galkin S.G. *MATLAB & Simulink. Proyektirovaniye mekhatronnykh sistem na PK* [MATLAB & Simulink. Mechatronic systems design on PC]. Saint Petersburg, KORONA-Vek Publ., 2008. 368 p.
6. Dayneko V.A., Kovalinskiy A.I. *Elektrooborudovaniye selskokhoziaystvennykh predpriyatiy* [Electrical equipment of agricultural enterprises]. Minsk, Novoye znaniye Publ., 2008. 320 p.
7. Ivanov G.Ya., Kuznetsov A.Yu., Dmitriyev V.V. *Elektroprivod i elektrooborudovaniye* [Electric drive and electrical equipment]. Novosibirsk, 2011. 54 p.
8. Malovichko V.V., Havryliuk V.I., Kiziakov V.Ya. Avtomatyzovani systemy upravlinnia na transporti [Automatic control system on transport]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan], 2007, issue 16, pp. 5-8.
9. Malovichko V.V., Havryliuk V.I., Reshetniak M.I. Vykorystannia systemy kontroliu stanu strilochnykh dvyhuniv po kryvii spozhyvannia strumu v remontno-tekhnichnykh dilnytsiakh [Using the system condition monitoring of turnouts engines on curve in power consumption at repair and technical stations]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan], 2007, issue 18, pp. 11-15.
10. Parfenov V.I., Razgonov A.P., Kovrigin M.A. Analiz defektov i vozmozhnosti diagnostiki strelochnykh perevodov [Defect analysis and diagnostic capabilities of turnouts]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan], 2007, issue 15, pp. 16-18.
11. Reznikov Yu.M. *Elektroprivody zheleznodorozhnoy avtomatiki i telemekhaniki* [Electric drives of railway automatics and remote control]. Moscow, Transport Publ., 1985. 288 p.
12. Chernykh I.V. *Modelirovaniye elektrotekhnicheskikh ustroystv v MATLAB SimPowerSystems i Simulink* [Modeling of electrotechnical devices in MATLAB SimPowerSystems and Simulink]. Moscow, DMK Press Publ., 2008. 288 p.
13. Beucher O., Weeks M. Introduction to MATLAB & Simulink: a project approach. Hingham, Massachusetts New Delhi, Infinity Science Press LLC Publ., 2008. 390 p.
14. Ong Chee-Mun. Dynamic simulation of electric machinery using MATLAB/Simulink. Upper Saddle River, New Jersey, Prentice Hall PTR Publ., 1998. 627 p.
15. Chaturvedi Devenndra K. Modeling and simulation of systems using MATLAB and Simulink. New York, CRC Press Taylor & Francis Group Publ., 2010. 711 p.
16. Giurgiutiu V., Sergey Edward Lyshevski. Micromechatronics modeling, analysis, and design with MATLAB. New York, CRC Press Taylor & Francis Group Publ., 2009. 920 p.
17. Karris Steven T. Introduction to Simulink with engineering applications. Orchard Publications, 2008. 716 p.
18. Theeg G., Vlasenko S. Railway Signaling and Interlocking. International Compendium. Hamburg, Eurail-press Publ., 2009. 448 p.

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Received: Feb. 05, 2014
Accepted: March 14, 2014