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MODELING OF ELECTROMECHANICAL SYSTEMS

Introduction

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.

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.

Goal

Purpose of creating the control systems of railway object condition in real time mode is to au-tomate the process of diagnosing. Let us consider the implementation of such system with auto-mated approach to the process of diagnosing the state of object in real time mode using the ex-ample of the switch electric engine of AC.

Let us study operation modes and the reaction of the switch electric engine of AC on the ex-ternal factors using its mathematical model describing its parameters and characteristics.

Mathematical modeling of the electric switch mechanism with AC engine will be carried out in the software environment Simulink of the mathematical package MATLAB.

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 MST (turnout three-phase machine) series were applied.

Methods

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 of electric engine of the type MST-0,3 and construct its mathematical model [6, 9].

The scheme of electrical connections of stator winding is performed with the following indices: number of poles – $2p = 6$; 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 – $y = 1 \div 6$; resistance of each phase winding – 6 Ohm.

The rotor winding consists of 26 pear-shaped bars and two short-closing rings with sections 36 mm^2. The air gap between the stator and the rotor should be between 0.25 and 0.39 mm.

Starting characteristics of engine differ by low multiplicity of starting current $I_п/I_н = 2{,}3$ and the satisfactory one of starting torque $M_п/M_н = 2{,}5$.

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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.

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

$$M=\frac{F\cdot r_2}{\xi\cdot\eta}, \tag{1}$$

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

In turn, the gear reduction ratio ξ is defined by the formula:

$$\xi=\frac{\omega_1}{\omega_2}, \tag{2}$$

where ω_1 – is angular speed of rotation of drive shaft (of electric engine); ω_2 – is angular speed of rotation of driven shaft (main drive shaft).

Net power P_2 was determined by the formula:

$$P_2=\frac{F\cdot l}{t}, \tag{3}$$

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:

$$\eta=\frac{P_2}{P_1}, \tag{4}$$

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:

$$P_1=U\cdot I, \tag{5}$$

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:

$$S=\frac{n_1-n}{n_1}\cdot 100\%, \tag{6}$$

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:

$$n_1=\frac{60\cdot f}{p}, \tag{7}$$

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

Power coefficient can be obtained from the formula:

$$\cos\varphi=\frac{R}{\sqrt{3}\cdot U\cdot I}, \tag{8}$$

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).

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

To build the model (Fig. 1), we use a generalized model of virtual installation for the study of an induction machine, which contains [3, 7]: three-phase alternating voltage source *Three-Phase Programmable Voltage Source* from the Library of Power System Blockset/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); 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.

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 [8].

Let us define the equivalent circuit parameters of asynchronous machine in its passport data. The stator windings of switch electric engine type MST-0.3 are Y-connected.

The rated slip is determined using the formula:

$$s_H = \frac{n_S - n_H}{n_S}, \quad (9)$$

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.

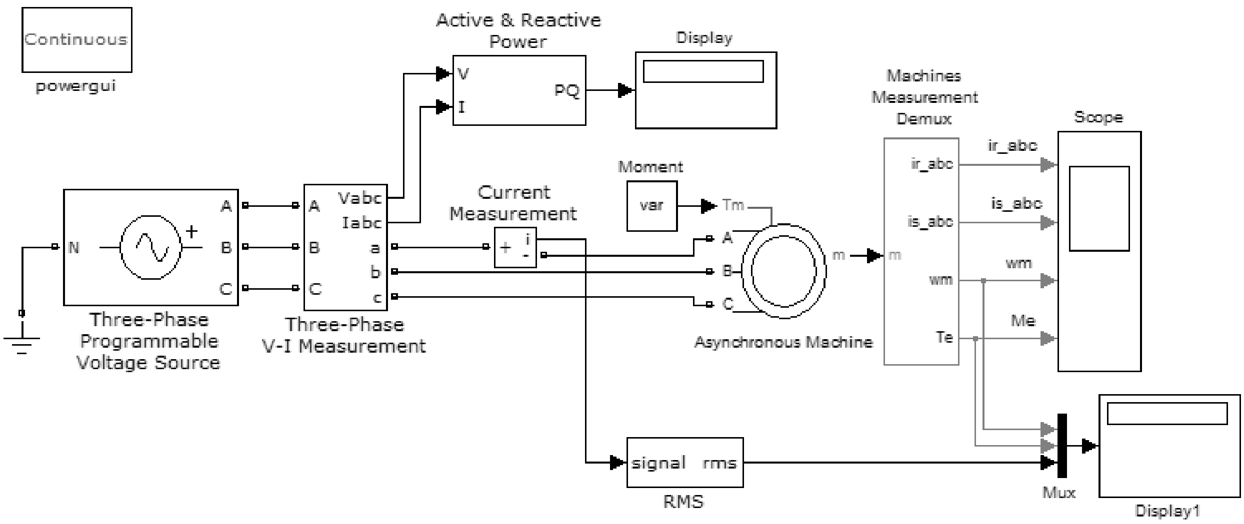

Fig. 1. Virtual model systems for research of asynchronous machine

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

The critical slip can be found using the formula:

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

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:

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

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.

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:

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

where ΔP_m – are the mechanical losses, W; π – is a mathematical constant; n_H – is the nominal speed of engine rotation.

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

$$\Delta P_m = \sqrt{3} \cdot I_n \cdot U_n \cdot \cos\varphi \cdot \eta - P_H, \qquad (14)$$

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 φ – is the power coefficient of asynchronous motor; η – 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 ΔP_m according to formula (14), substituting the variables and coefficients by their corresponding known values: π = 3.14, I_H = 2.1 A, U_H =190 V, $\cos\varphi$ = 0.72, η = 0.66, P_H = 300 W. The formula (14) will take the following form:

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

Let us define a relative measurer of mechanical losses in our case:

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

Therefore, returning to the calculations, define numerical value of the coefficient of viscous friction from the formula (13):

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

The stator winding resistance can be determined using the formula:

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

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. ΔP_m – are the mechanical losses, W.

Let us rewrite the formula (11) with respect to short-circuit torque M_K:

$$M_k = 3{,}43 \cdot 2{,}25 = 8{,}575\ N \cdot m.$$

In this case the formula (15) will take the following form:

$$R_s = \frac{3}{2} \cdot \frac{\left(190/\sqrt{3}\right)^2 \cdot (1-0{,}18)}{1{,}05 \cdot \left(1+\dfrac{1{,}05}{0{,}67}\right) \cdot 8{,}575 \cdot (300+28{,}41)} = $$
$$= 1{,}95\, Ohm$$

The rotor winding resistance can be determined using the formula:

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

where P_H – is the power that should be developed by asynchronous motor to overcome the resisting force of rated load, W; ΔP_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:

$$i_k = \frac{I_k}{I_H}, \qquad (17)$$

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

The ratio is equal to 2.3 for engine type MST-0.3.

Formula (16) will take the following form:

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

Inductance of stator and rotor:

$$L_s \cong L_s = \frac{1}{2 \cdot \pi \cdot f_H} \cdot$$
$$\cdot \frac{U_H/\sqrt{3}}{I_H \cdot \left(\sqrt{1-(\cos\varphi)^2} - \cos\varphi \cdot s_H / s_k\right)}, \qquad (18)$$

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 φ* – is the power coefficient of asynchronous motor; s_H – is the nominal slip; s_k – is the critical slip.

The formula (18) will take the following form:

$$L_s \cong L_r = \frac{1}{2 \cdot 3{,}14 \cdot 50} \cdot$$
$$\cdot \frac{190/\sqrt{3}}{2{,}1 \cdot \left(\sqrt{1-0{,}72^2} - 0{,}72 \cdot 0{,}18 / 0{,}67\right)} = 0{,}3324.$$

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

$$L_{ls} \cong L_{lr} = \frac{1}{4 \cdot \pi \cdot f_H} \cdot$$
$$\cdot \sqrt{\left(\frac{U_H/\sqrt{3}}{i_k \cdot I_H)}\right)^2 - (R_s + R_r)^2}, \qquad (19)$$

where π – 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.

The formula (19) will take the following form:

$$L_{ls} \cong L_{lr} = \frac{1}{4 \cdot 3,14 \cdot 50} \cdot \sqrt{\left(\frac{190/\sqrt{3}}{2,3 \cdot 2,1)}\right)^2 - (1,95 + 5,72)^2} = 0,034\,H.$$

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

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

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

The formula (20) will be rewritten in the following form:

$$L_m = 0,3324 - 0,034 = 0,2984\,H.$$

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:

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

Let us to verify the found constructive factor value First of all let us define the value of the stator winding resistance R_s using the formula (15):

$$R_s' = \frac{3}{2} \cdot \frac{(190/\sqrt{3})^2 \cdot (1 - 0,18)}{1,1 \cdot (1 + 1,1/0,67) \cdot 8,575 \cdot (300 + 28,41)} = 1,81\,Ohm.$$

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}:

$$L_{ls}' \cong L_{lr}' = \frac{1}{4 \cdot 3,14 \cdot 50} \cdot \sqrt{\left(\frac{190/\sqrt{3}}{2,3 \cdot 2,1}\right)^2 - (1,81 + 5,72)^2} = 0,0341\,H.$$

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

$$L_m = 0,3324 - 0,0341 = 0,2983\,H.$$

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:

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

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:

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

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.

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, the formula will be rewritten in the following form:

$$P = 3 \cdot 190 \cdot 2,1 \cdot 0,72 = 861,84\,W.$$

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

$$J \cdot \frac{d\omega}{dt} = M - M_H. \quad (22)$$

Using the existing methods of presented inertia moment definition of the electric drive [1, 4, 5] the value of inertia moment for the motor shaft with the load, which is 0.025 kg/m^2 was calculated.

Results

Operating characteristics taken during the model operation are presented in the Figure 2. 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. 2, 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. 2, 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.

Scientific novelty and practical value

The constructed model of a turnout AC motor based on the calculation of an asynchronous machine based on its passport data allows to obtain a new approach in the method of creating a base of failures for asynchronous motors that are used in electric drives. Thanks to the developed model, it became possible to carry out preliminary tests of various operating modes in order to determine the response of the engine, both to such changes that can be easily reproduced in real conditions and to those that in real conditions are either difficult to reproduce or impossible without damaging the motor itself , or drive components.

Conclusions

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.

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.

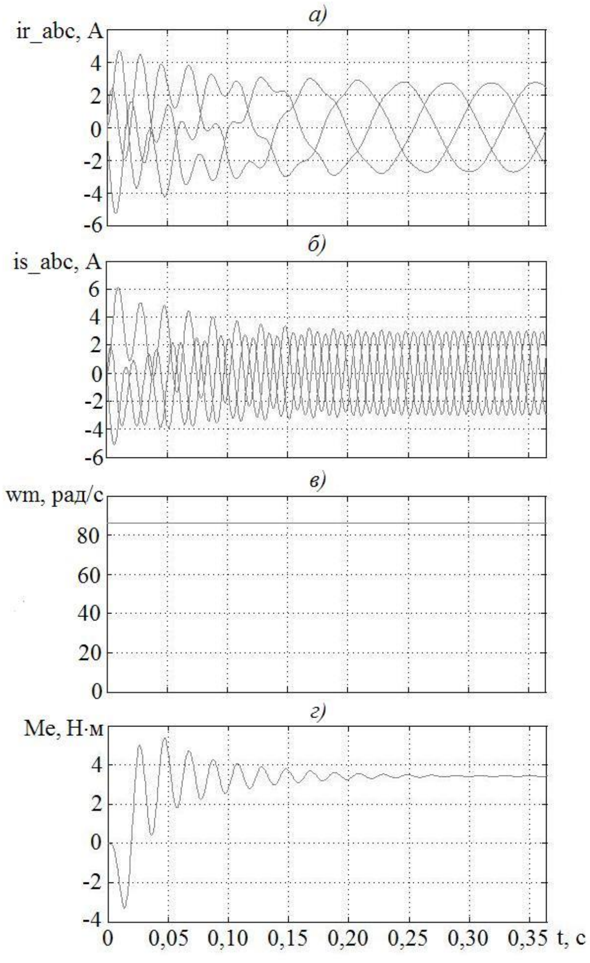

Fig. 2. Operating characteristics of the model:
a) rotor winding currents; b) stator currents;
c) angular frequency of the rotor rotation;
d) electromagnetic torque

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Ключові слова: моделювання, розрахунки параметрів, структурна схема, машина змінного струму, осцилограми роботи моделі.

Ключевые слова: моделирование, расчеты параметров, структурная схема, машина переменного тока, осциллограммы работы модели.

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