Utilizing digital twin technology for electric locomotive performance and fault analysis

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Abstract. Increase of traction and energy efficiency and reliability of electric locomotive operation can be ensured, including through the use of digital technologies. The purpose of this research is modeling of electric locomotive parameters and possible malfunctions on the way based on the "Digital Twin" technology. The paper presents the developed computer model of the electric locomotive electrical part, describes the approaches used for modeling of faults and prevention of emergency situations in transit, and also presents the results of the study.

1 Introduction

The digital transformation of railway enterprises is based on the principles of Industry 4.0. The interconnection of such technologies as: digital twin, machine learning, big data, internet of things, augmented reality, etc. allow solving a number of problems related to design optimization, fault prediction and decision aid. A digital twin is a multi-scale and probabilistic computer model of a real object, process or system that can be used for simulation, analysis, optimization and prediction of possible faults [1-3]. With the help of various sensors, monitoring and control systems, the interaction between the physical object and the virtual twin can be realized in real time. The use of this technology will optimize operating costs, increase the number of tests and experiments, it will be possible to predict malfunctions and monitor the technical condition of the object in real-time mode.

The issues of using the "Digital Twin" technology at railroad enterprises are the subject of research by many authors.

The basis of the digital twin is a computer model of a physical object or system, the advantages of this technology are to increase the efficiency of electric rolling stock, due to predictive detection of malfunctions or failures, predictable behavior of the object in the future, conducting experiments on the object in a virtual environment and reducing costs, which in turn will allow to switch to maintenance and repair on the actual state. Implementation of the "Digital Twin" technology is an urgent topic and requires further research development.

Having analyzed the existing works [4-8], we can conclude that the authors are interested in the use of the "Digital Twin" technology; sources [9-11] consider the creation of digital twins for predicting faults in the train braking system. In addition, some authors are interested in the development and application of digital twins for traction motors [12-15].

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In these works, the authors consider different approaches to the application of “Digital Twin” technology, but the developed digital twins of electric locomotives in this context and the ways of their application are not presented in the publications.

The purpose of this work is to use the developed computer model of the electric locomotive electrical part to simulate the parameters and possible faults in transit.

2 Materials and methods

The methods of electric traction theory, automatic control theory and the basics of mathematical modeling were used in the work. The computer model of the electric part of the locomotive was made using the *Simulink* graphical environment based on *Matlab* software. Model development was performed using built-in elements and created subsystems, in which apparatuses and control system were realized. For modeling of possible faults, the model provides the corresponding blocks and elements (Table 1). The computer model of the electric locomotive electrical part is shown in Fig. 1.

Table 1. Elements and blocks used to build a simulation model

Name of the block/element in the model	Block/element name in Matlab environment	Function of the used block/element
QF1/KA1	Subsystem	Fast-acting switch VAB-55 and differential relay RDZ-068 ET are intended for protection of electric locomotive equipment against short-circuit currents and overloads
Fault simulator		Circuit short circuit simulator
Management system		Control system for signaling
KM1/4	Ideal Switch	Contactors for switching from independent excitation to series excitation
KPV1/4		
K27/30, K33-34, K37/40		Contactors for disconnecting faulty traction motors or electric truck sections from the circuit
KF1/2		Contactors for disconnecting power supply to excitation windings of traction motors

The object of modeling is the electrical part of electric locomotive 2ES6, where traction DC motors EDP810 are used. Technical characteristics of the selected motors are used as input data for the “DC Machine” block.

Operation of the computer model is carried out as follows: at the set time from the voltage source “XA1” through the noise-suppressing choke “L1” the power is supplied to the quick-release switch “QF1” and differential relay “KA1”, then the current starts to flow through the starting rheostat “R3-R4”, where the current surges during the circuit starting are limited, after that the voltage is supplied to the windings of the traction motors “M1/4” in series connected in the head section and “M_1/4” in the trailer section. Power supply of excitation windings is realized by means of subsystem “EI 1/4”, which consists of block “Matlab Function”, where the law for regulation of voltage of excitation windings is written. The load torque is calculated and supplied to the motors from the “Moment_G/P” subsystems.

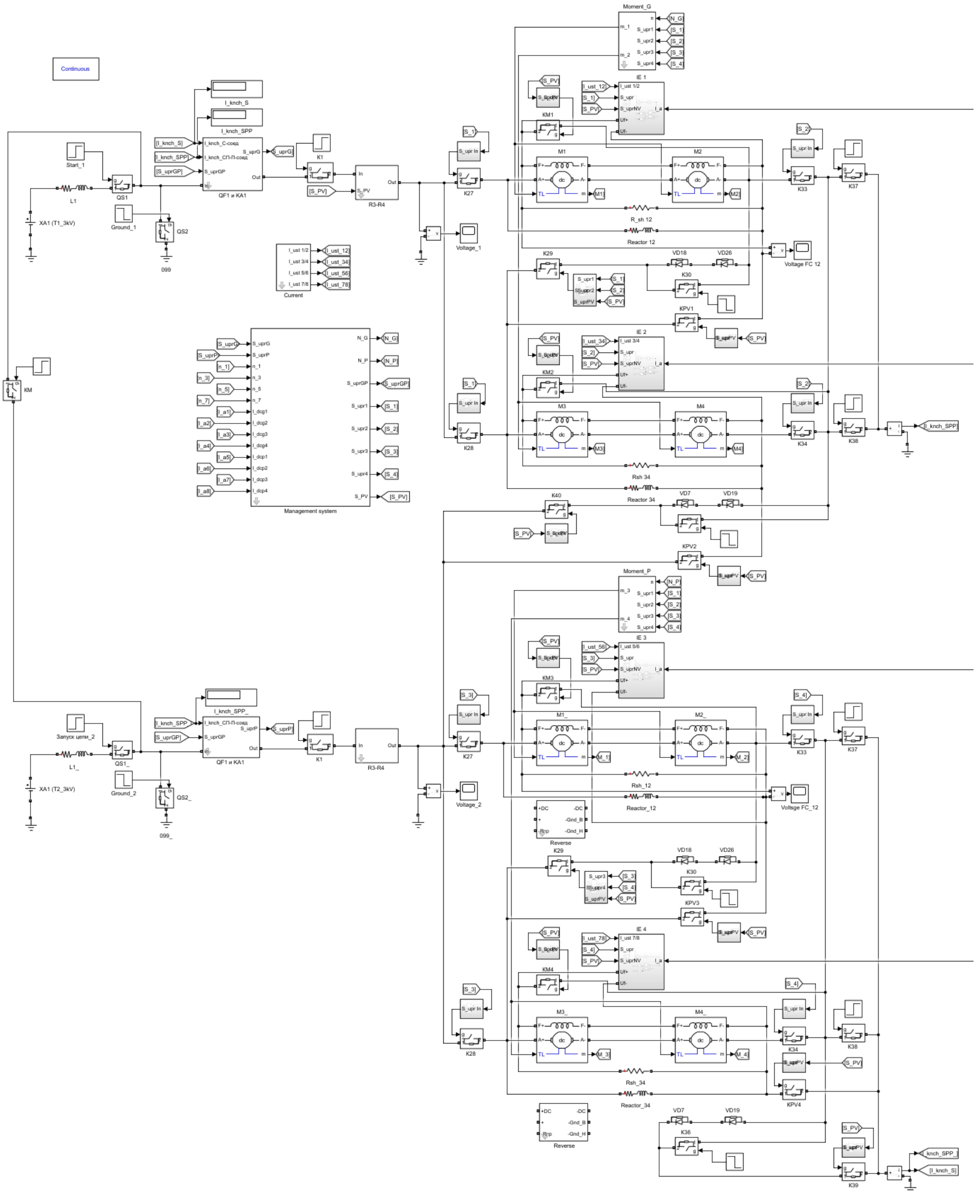

Fig. 1. Computer model of electric part of electric locomotive 2ES6

Protection devices “QF1/KA1” are realized by means of subsystems and are shown in Fig. 2. The principle of operation of the differential relay “KA1” is to compare the difference between the currents at the beginning and end of the circuit with the current set point of the relay RDZ-068 ET. In case of detection of deviations, the control signal is received from the unit to disconnect the quick-acting switch “QF1”, moreover, in case of current surges in the circuit, exceeding the values of the setpoint current, the unit switches to the open state, providing protection of the high-voltage equipment of the locomotive.

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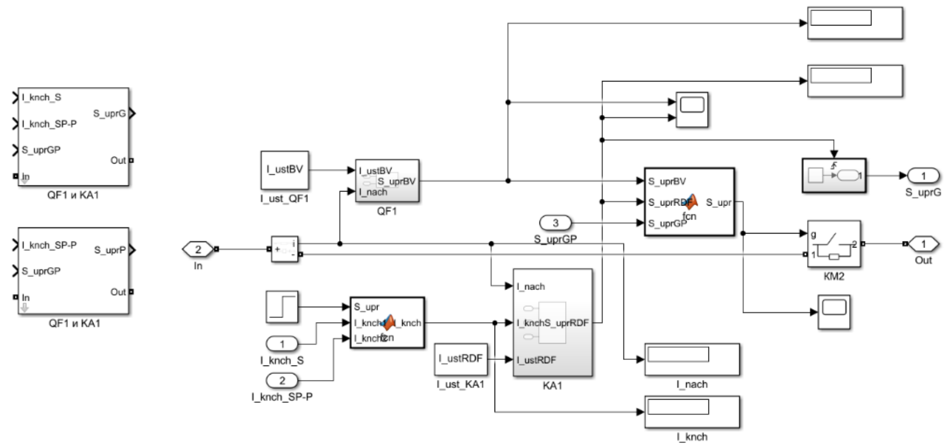

Fig. 2. Protection devices "QF1/KA1"

To simulate some faults in the electric circuit of the electric locomotive, a block for short-circuit simulation "Fault simulator" was developed (Fig. 3). The block is designed as a subsystem, where there is an output for connection to any point of the developed model of the electric locomotive electrical part.

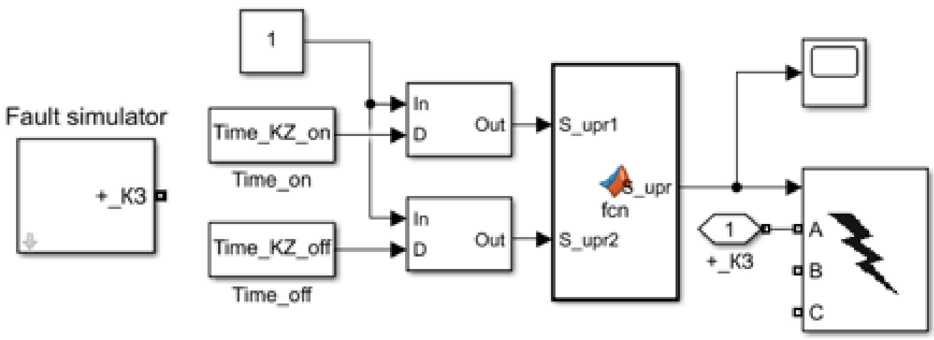

Fig. 3. Short circuit simulator "Fault simulator"

Block "Management system" is made with the help of subsystem and has a lot of input and output signals (Fig. 4). When a fault occurs, signals are received from the protection apparatuses, the whole circuit is checked and then control signals are transmitted to the contactors, to perform certain algorithms.

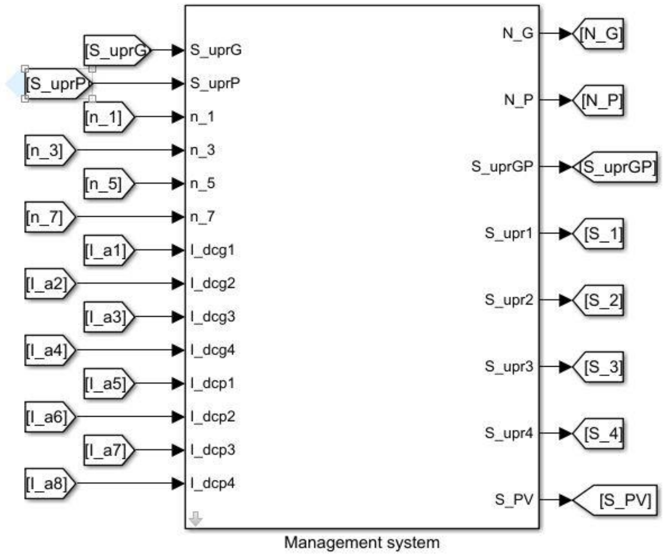

Fig. 4. Management system" subsystem

Before starting the modeling of possible malfunctions in the electrical part of the electric locomotive 2ES6, the model was run and the graphs of parameter dependencies were obtained when the circuit is in good condition. The simulation time was 65 seconds, during this time 23 positions of serial connection of traction motors of the electric locomotive are realized. The calculated parameters are fixed with the help of measuring blocks, which are presented in Fig. 5. The plots of dependencies of the second motor of the head section are presented in Figs. 6, 7 and 8.

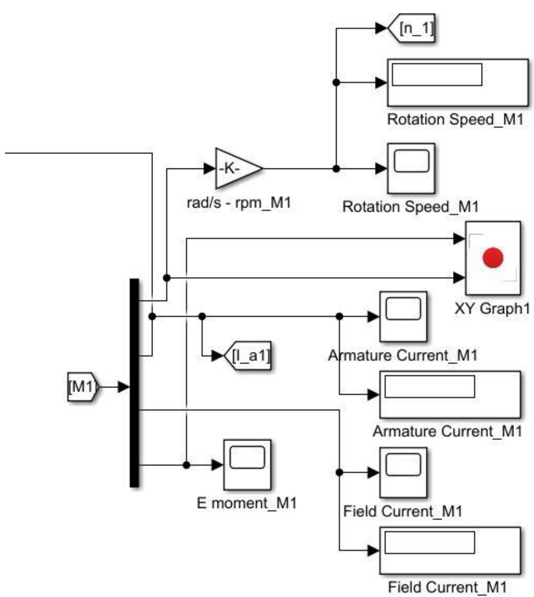

Fig. 5. Measuring units

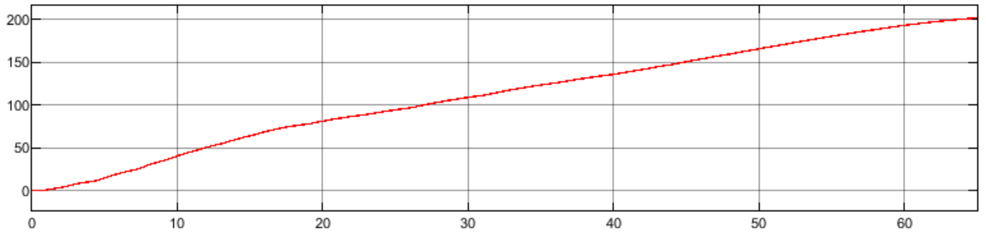

Fig. 6. Traction motor rotation speed "M2"

At the end of the simulation the speed of the second traction motor was 206 rpm.

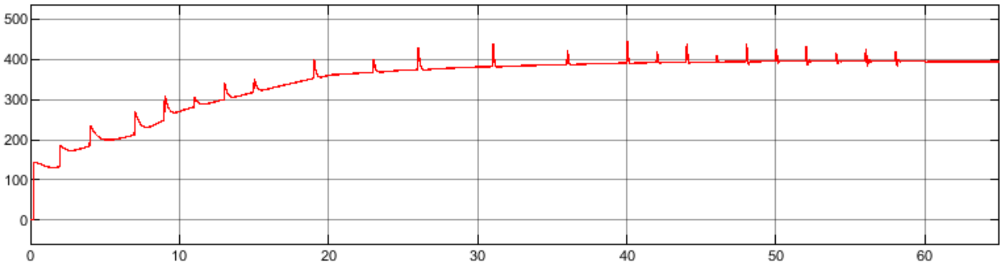

Fig. 7. Armature current of traction motor "M2"

On the graph of the traction motors armature current change there are throws caused by the withdrawal of the starting rheostat from the resistance circuit. The current at the end of modeling was 394.1 A.

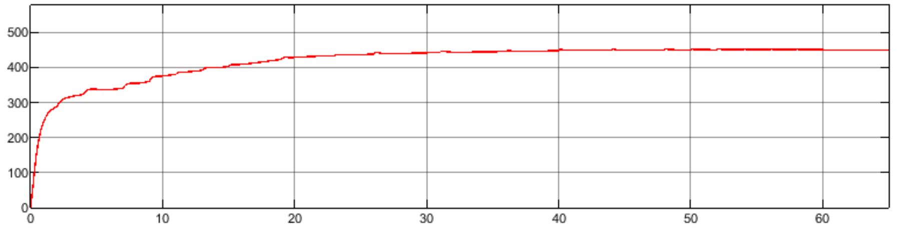

Fig. 8. Excitation current of traction motor "M2"

Power supply of excitation windings of traction motors is realized depending on the setpoint current and armature current, the final value was 449.8 A.

The following situation was selected as a fault: when traveling in the traction or braking mode, there is a tripping of the quick-release switch with tripping of the differential relay on one of the sections, due to a short circuit in the circuits of traction motors.

Modeling of electric locomotive parameters in the event of a fault on the track is performed using the previously presented block "Fault simulator", this subsystem is connected to the circuit of traction motors of the second pair of the head section (M3 and M4). After connection at the moment of simulation at the 25th second, a short circuit of two points of the electric circuit with different potential values is formed in the circuit. From the protection devices signals are transmitted to the "Management system" unit, where the circuit of traction motors of all sections is checked, having identified the faulty pair of motors, the subsystem generates control signals, which are transmitted to the corresponding contactors for the output of the faulty motors.

Graphs of change of parameters of serviceable engine “M2” of the head section are presented in Fig. 9, 10 and 11.

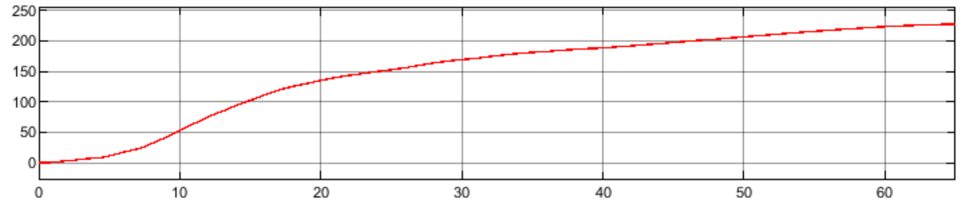

Fig. 9. Rotational speed of traction motor “M2”

The speed varied smoothly and at the end of the simulation was 222.4 rpm. A slight increase in speed is due to the removal of a faulty pair of motors from the circuit and distribution of the load on the serviceable motors.

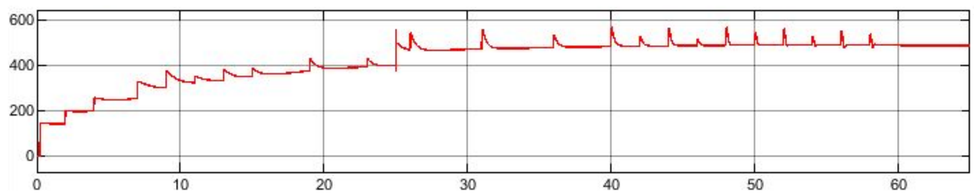

Fig. 10: Armature current of traction motor “M2”

The armature current of the electric motor varied stepwise, at the 25th second after the occurrence of a short circuit in the circuit of the head section, a current rush and an increase in this parameter is noticeable. At the end of the simulation, the armature current was 486.1 A.

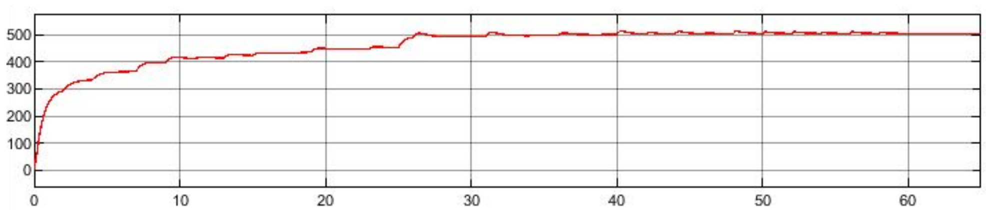

Fig. 11: Excitation current of traction motor “M2”

Since the supply of the field windings depends on the armature current feedback, at the moment of short circuit there was also a slight increase in this parameter, at the end of the simulation process the current value was 503.6A.

For comparison, the graphs of change of parameters of the faulty motor “M4” of the head section are presented (Fig. 12, 13 and 14).

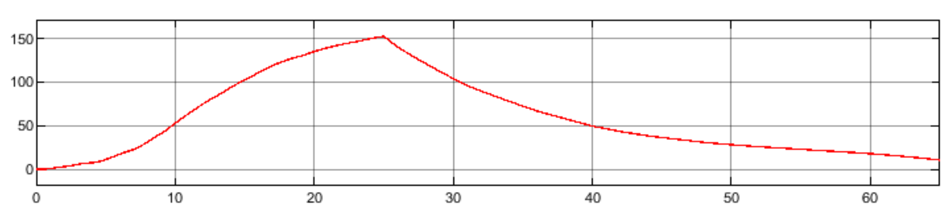

Fig. 12: Rotational speed of traction motor “M4”

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The maximum speed was recorded at the 25th second of the simulation and amounted to 150 rpm. After removing the faulty pair of motors from the circuit, the speed began to decrease.

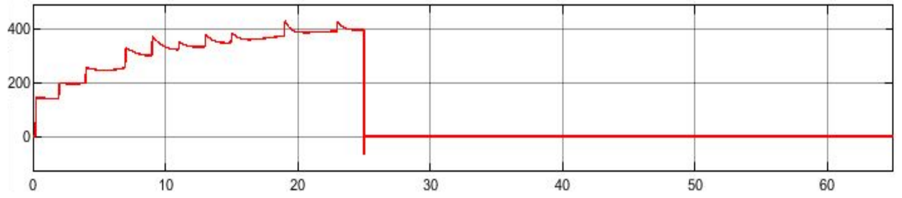

Fig. 13: Armature current of traction motor "M4"

The armature current of the traction motor varied stepwise up to the 25th second, after the short circuit occurred, the armature current decreased to a negative value.

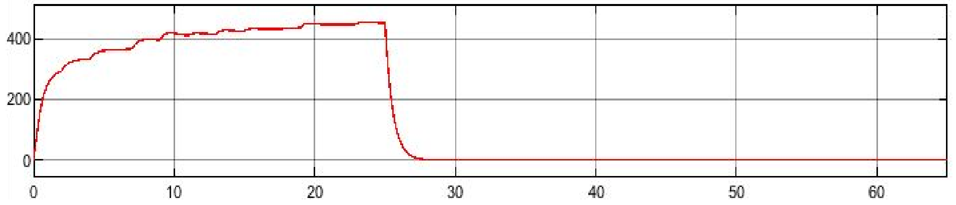

Fig. 14: Excitation current of traction motor "M4"

Up to the 25th second, the field current of the motors varied according to the setpoint current and armature current feedback. After the short-circuit occurred and the armature current decreased, this parameter also decreased to zero.

Let's consider the following fault: when switching on the quick-acting switch, it is switched off in one of the sections, with tripping of the differential relay, due to the occurrence of insulation breakdown of wire 006 from the block "QF1/KA1" to the contactor "K1".

To simulate the insulation breakdown of wire 006, the subsystem "Fault simulator" is connected between block "QF1/KA1" and contactor "K1". After starting the simulation on the 15th second there is a short circuit on the wire 006, there is a tripping of the quick-acting switch, the control signal goes to the subsystem "Man-agement system", having determined the faulty section signals from the block are transmitted to the necessary contactors for the output of traction motors, the power supply of the serviceable section is carried out through the second power source "XA1". The graphs of dependencies obtained after modeling are shown in Fig. 15, 16 and 17.

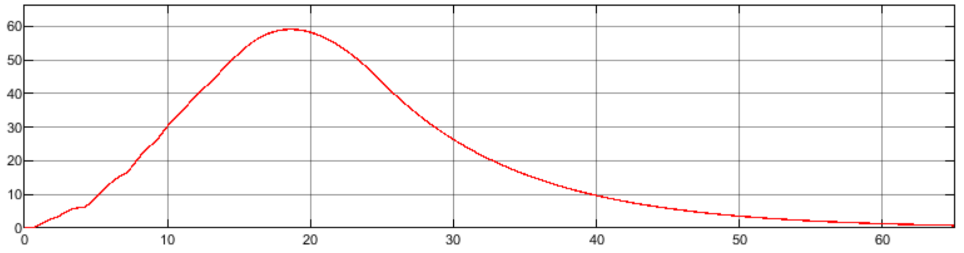

Fig. 15. Speed of traction motor "M2" of the head section

At the end of the simulation, the traction motor speed decreased to zero, with a maximum value of 59.5 rpm.

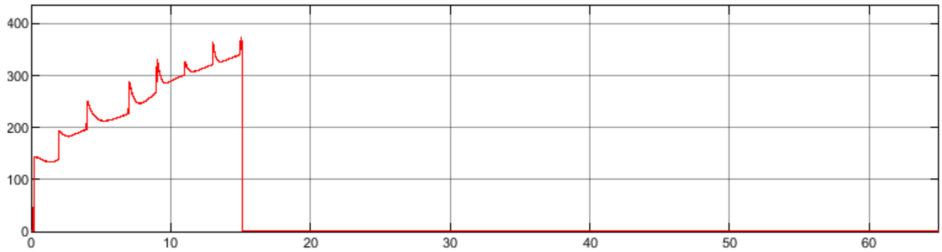

Fig. 16: Armature current of traction motor "M2" of head section

Up to the 15th second, the armature current of the traction motor varied in the same range as in the general circuit modeling, when the short-circuit mode occurred, the current in the motor decreased to zero, which indicates that all pairs of motors of the faulty section are completely removed from the circuit.

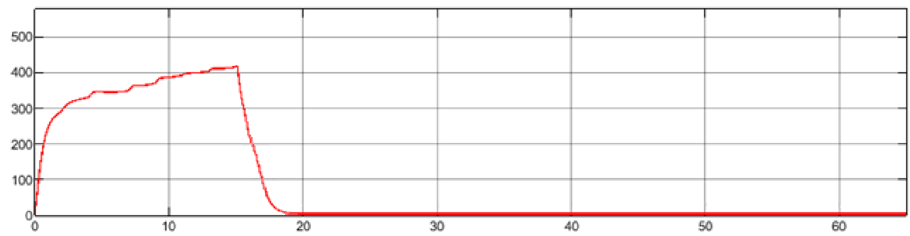

Fig. 17: Excitation current of traction motor "M2" of head section

When the 15th second was reached, the value of the field current decreased to zero because the subsystem "EI 2", which provided power to the field windings, was taken out along with the faulty pair of traction motors.

Dependences of the parameters of the serviceable section are presented in Fig. 18, 19 and 20.

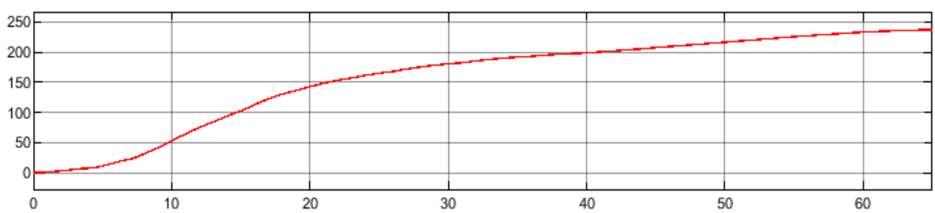

Fig. 18: Speed of traction motor "M2" of the trailed section

The operation of traction motor "M2" was carried out without emergency mode. The rotational speed at the end of the simulation was 235.8 rpm.

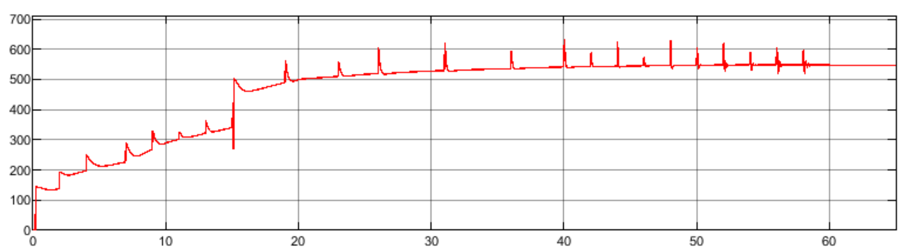

Fig. 19: Armature current of traction motor "M2" of the trailed section

When the short circuit occurred, a current surge occurred at the 15th second, at the end of the simulation the armature current was 551.4 A.

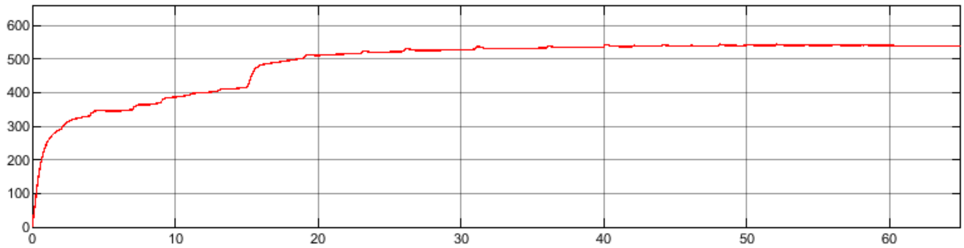

Fig. 20: Excitation current of traction motor “M2” of the trailed section

The excitation current varied in the same range of parameters, except that a current jump is observed, which occurred during the withdrawal of the faulty section from the circuit. The current value at the end of the simulation was 536.4 A.

3 Results

Having analyzed the received graphs of dependences at modeling of the first fault the following conclusions are made: the difference between the received values of armature current makes 92 A or 23,3%, between excitation currents 53,8 A or 11,9%, and the difference between rotation frequency made 16,4 rpm or 7,9%. The increase in all parameters is due to the distribution of the load on the remaining motors, after removing the faulty pair of traction motors from the circuit.

The analysis of the data in the second fault modeling showed the following difference of the obtained parameters: rotational speed 29.8 rpm or 14.4%, armature current 157.3 A or 39.9%, excitation current 86.6 A or 19.2%. In view of the load distribution on the traction motors of the electric locomotive working section, the growth of all measured parameters is observed, which indicates the correct operation of the algorithms prescribed in the developed blocks.

4 Conclusion

The computer model of the electric part of the 2ES6 locomotive allows to simulate the parameters of the electric locomotive and possible malfunctions or emergency situations on the way.

The results of modeling of two faults are presented in the form of graphs of parameter dependencies on the total simulation time. Analyzing the parameters and graphs it is possible to speak about operability of the developed control and protection apparatuses of the electric circuit of electric locomotives.

The potential of digital twins is not limited to simple modeling of malfunctions in electric circuits of electric locomotives, in the future it is planned to develop methods and techniques for prediction of malfunctions on the way, thus predicting further actions to prevent emergency modes of operation of the electric part of electric locomotives.

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