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RESEARCH AND DEVELOPMENT OF AN ELECTRIC TRACTION DRIVE BASED ON A SWITCHED RELUCTANCE MOTOR

Summary. In the most developed countries, intensive studies are being carried out to utilize various types of electric machines such as synchronous motors with permanent magnets and traction motors with non-traditional magnetic systems on traction electric drives. Switched Reluctance Motors (SRM) are one of the most simple, reliable, and cost-efficient technology used in manufacture and operation. Its convenient traction performance, combined with the high overload capacity, makes its use promising for both freight and passenger rolling stock. Our research is directed to develop a control system for a four-phase SRM. The procedure of fuzzy-regulator synthesis is presented. A physical model of a switched reluctance drive is created, namely, it is a system of a wheel set and a motor. The efficiency of the control system with different types of speed regulators was checked and their main quality indicators were determined. According to the results of the analysis, it was found that the fuzzy regulator more precisely controls the regulated value.

1. INTRODUCTION

Previous studies showed that along with the improvement of the existing Control Systems (CS) through the introduction of microprocessor-based units, international companies are working on creating new system types through the usage of promising electric motors to increase the reliability and speed, and achieve a high-dynamic performance [1 - 4].

At present, synchronous (SM) and asynchronous (AM) electric motors are widely used as traction motors. The frequency converter with a scalar or vector CS is commonly used as the control element [1, 5, 6]. However, it is necessary to create complex multiloop CSs and to generate a multiphase sine wave signal to achieve high-control performance. Moreover, any ripple in the sine wave of supply voltage leads to additional losses in the motor and high - frequency noise in the power supply line. The frequency converter is a complex device consisting of several components such as rectifier, filter, inverter, sensor system, and master controller, which reduce its reliability in general [5].

In addition to the stator windings, which are common to all electric motors, SM and AM motors also have a rotor winding in the form of stacked conductors or cast “short-circuited”, respectively. These machines are much more reliable and smarter than DC machines, but are less cost-efficient than the switched reluctance motors (SRM) [2].

The SRM CS, similar to other high-precision systems, is a multiloop microprocessor-based unit, but its power unit is much simpler than that of the frequency converter. Instead of the inverter generating a sine wave of the given amplitude and frequency, the pulse-width converter is used [7, 8]. This type of converter is simpler and cheaper.

Thus, the development of a simple and effective CS for traction SRM is necessary as these machines have evident efficiency and manufacturability; however, there are no simple control methods and systems that would provide the necessary control performance. The aim of this research is to develop a laboratory model of the traction electric drive based on SRM and to perform tests with this model.

2. MATERIALS AND METHODS

To obtain the results regarding the operation of the SRM drive, the following tasks were set:

- selection of the SRM for the model;
- description of the CS structure and implementation methods;
- description of different modes and their characteristics;
- obtaining the waveforms of phase voltage and current of the motor;
- and taking the waveforms of the start-up transient of the constructed electric drive using various speed controllers.

2.1. Selection of the SRM for the model

Electromechanical power converters are an integral element in the power conversion system of the rolling stock. The type and operating conditions determine the traction electric drive structure, equipment configuration, and rolling stock composition. However, nowadays, it is difficult to conduct pilot studies on the SRM due to the lack of such machines with geometric dimensions and parameters that would correspond to the traction motors used in the existing rolling stock.

Therefore, the four-phase SRM was chosen as the control object. Its basic specifications are given in Table.1 and its configuration is shown in Fig. 1.

A general view of the model including an electric motor together with a gearbox and wheelset is presented in Fig. 2.

Table 1

Basic SRM specifications

Parameter	Value
Rated phase voltage, V	220
Maximum phase current, A	10
Rated speed, rpm	10,000
Rotor diameter, mm	57.4
Rotor active length, mm	60
Stator outer diameter, mm	106
Stator tooth width, mm	11
Rotor tooth width, mm	12.2
Number of phase winding turns	60
Rotor moment of inertia,$kg \cdot m^2$	21.6e+06
Phase DC resistance, Ohm	0.34
Rated torque, Nm	0.2
Stator core length, mm	120

The proposed functional circuit of the CS for this SRM is shown in Fig. 3. It consists of a control unit, microcontroller, high-side and low-side drivers, electronic switch, and current sensors. The dsPIC30F3011 microchip microcontroller that is specifically designed to accomplish this kind of tasks and digital signal processing was used for SRM control.

The controller core was built on the modified Harvard architecture with an expanded instruction set. The architecture is a novel development and not a modification of the conventional 8-bit cores. The dsPIC30 microcontroller supports the execution of instructions (multiply-accumulate) specific to digital signal processing algorithms and special addressing methods (modular, bit-reversed). The dsPIC30 has a vector priority interrupt system and the ability to display a part of the program memory in the RAM area, which is unrealized on the chip, and it also has the ability of symbolic computation with integers and fixed-point numbers. The instruction set of the core has two classes, namely microcontroller instructions and digital signal processing commands. Both of these classes are equally integrated into the controller architecture and are controlled by the same core. The 16-bit arithmetic logic unit allows the performance of the following operations per one instruction cycle: addition, subtraction, bit shift, and bitwise logical operations including inversion. Many elements such as analog-to-digital conversion (ADC), pulse-width modulation (PWM) control module with six outputs (pulse distributor), and quadrature encoder module (pulse counter) are already included in the microcontroller, whereby the major tasks solved with software were passed to the hardware. This development helped to reduce CPU usage and allocate the remaining time for the implementation of different control methods including the usage of complex mathematical computations.

The SRM circuit diagram has an essential advantage over the induction motor circuit diagram as it is able to prevent short-circuit currents, while opening the high-side and low-side power switches on one side. Short-circuit current may lead to the failure of the *Ud* power supply, as well as the failure of the transistors and their controllers. The electronic switch circuit diagram, showed in Fig. 4, is used to power the motor.

As the simultaneous operation of phases that are arranged relative to each other at an angle of 90 geometric degrees (phases *a, c* and *b, d*), as well as the reduction in the number of power cells in the circuit diagram, it is impossible that these phases are grouped. For the operation of a four-phase electromechanical converter with grouped phases, the circuit diagram must contain six power transistors and six free - wheeling diodes [8 –11]. The circuit diagram shown in Fig. 4 is also called as the Miller circuit. With the help of this converter, a single symmetrical phase switching with a current-limiting possibility was implemented. The electronic switch utilized the IRFPG50 field-effect transistors.

The normal operation of these transistors was ensured in the temperature range of –55 to+150°C, rated voltage of 1,000 V, and rated current of 16 A. Low stray inductance provides a high quality of transients in the transistor switching modes and has the ability to operate at high PWM frequencies.

During the phase operation when the high-side switch was closed “single” switching was performed. The current was closed through the free - wheeling Schottky diode (STTH6012). The features of such diodes are as follows: low forward drop, high speed, and virtual absence of recovered charge. Preference is given to the use of Schottky diodes in high-power converters at high switching frequencies.

The most common method to control field-effect transistors in bridge circuits is through the combined use of low-side and high-side drivers. Thus, both high - side and low-side drivers were used in this research due to the specifications of the electronic switch and switch control. When using such switching circuit, as shown in Fig. 4, two high - side and four low-side switches are necessary. Therefore, we used two high - side and two low-side drivers. The most common chips drivers in such cases are IRS21850 (high-side driver) and IR4426 (low-side driver). The microcontroller - generated PWM is transmitted to the switching circuit by the considered types of drivers (Fig. 4).

To control the rotor position, as well as speed and direction, the SRM -built-in-HEDS-4190 optical incremental encoder, which allows receiving 360 pulses per shaft revolution and coupled directly to the quadrature microcontroller encoder, was used. The encoder is a disc that is placed on the motor shaft and on a detector module that determines the disc position. The encoder has three outputs: phase A, phase B, and index output, wherein the data gathered from are decoded to obtain the information on shaft rotation. The machine rotation direction is determined by means of the encoder phases that prioritize pulsing on these outputs. The index output provides controller reset after each shaft revolution, thereby preventing error accumulation during rotation.

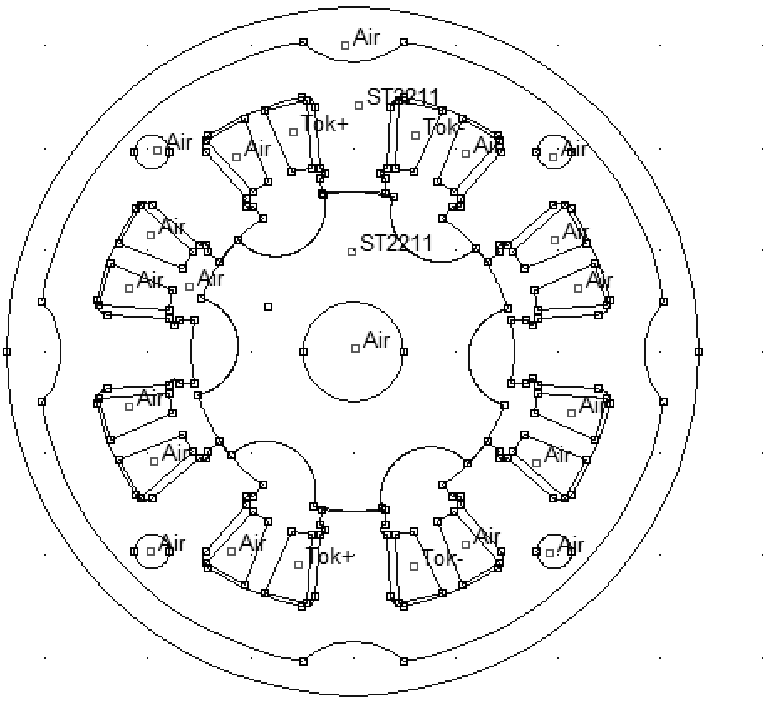

Fig. 1. Four-phase SRM configuration

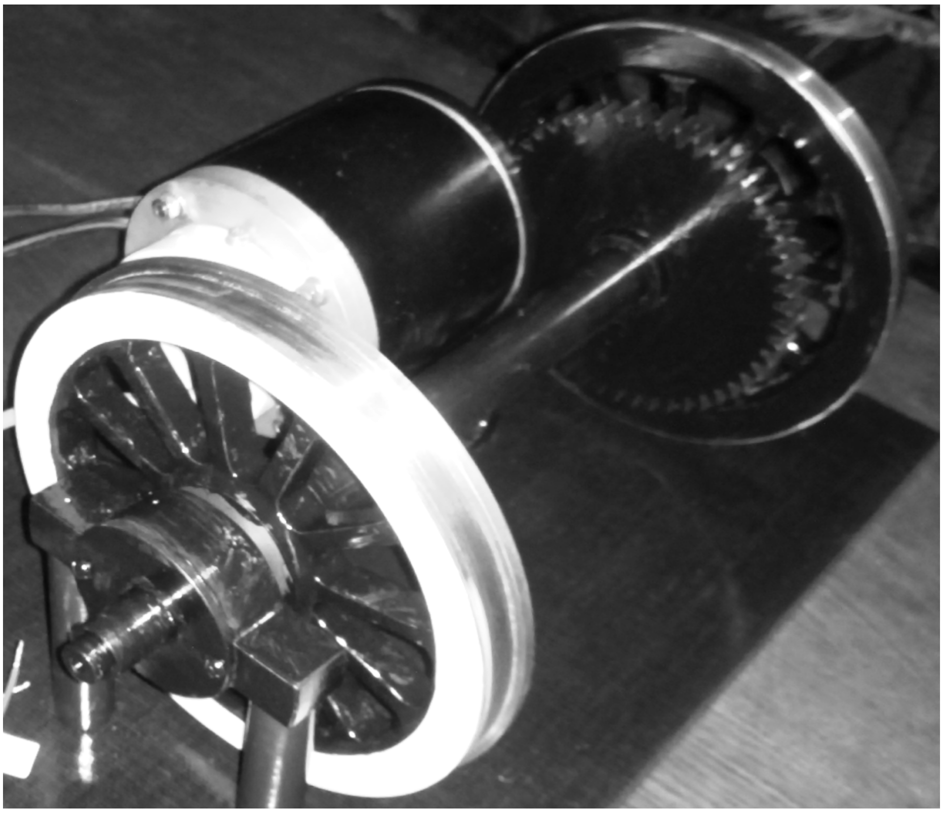

Fig. 2. Four-phase SRM traction drive model

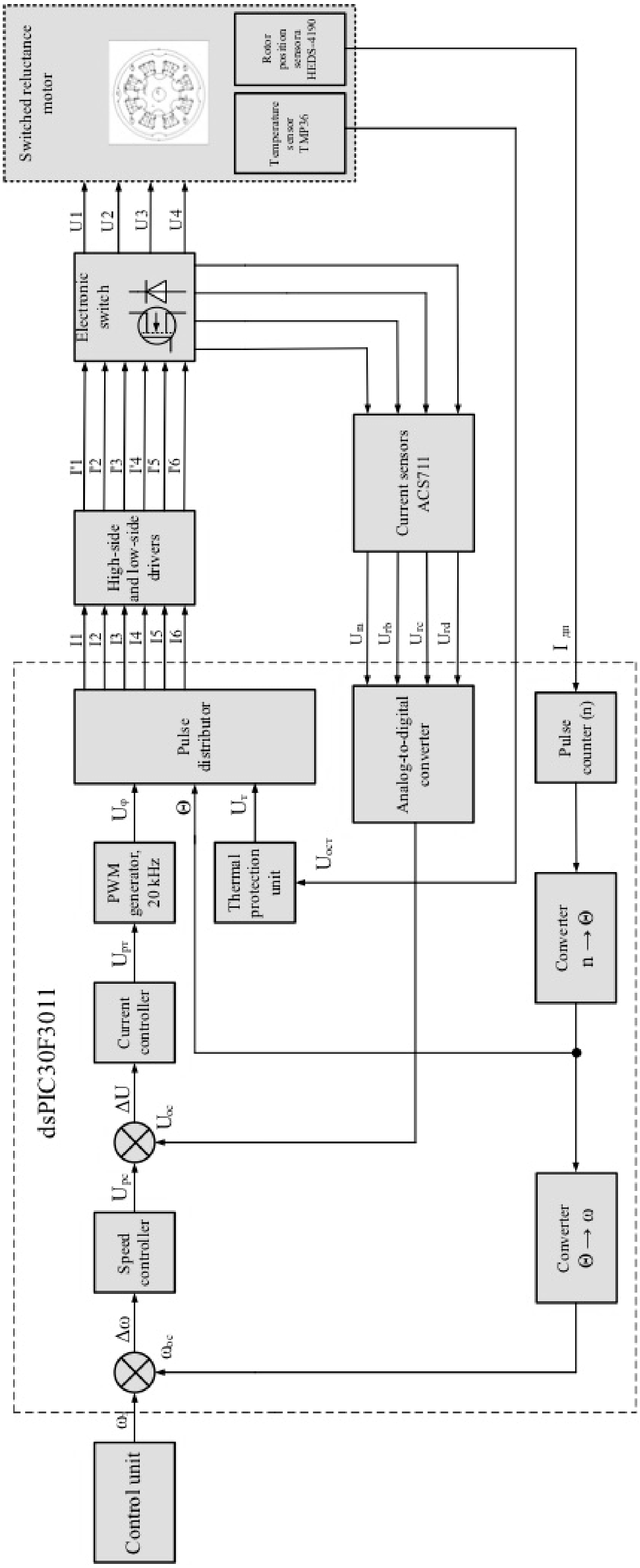

Fig. 3. SRM CS block diagram

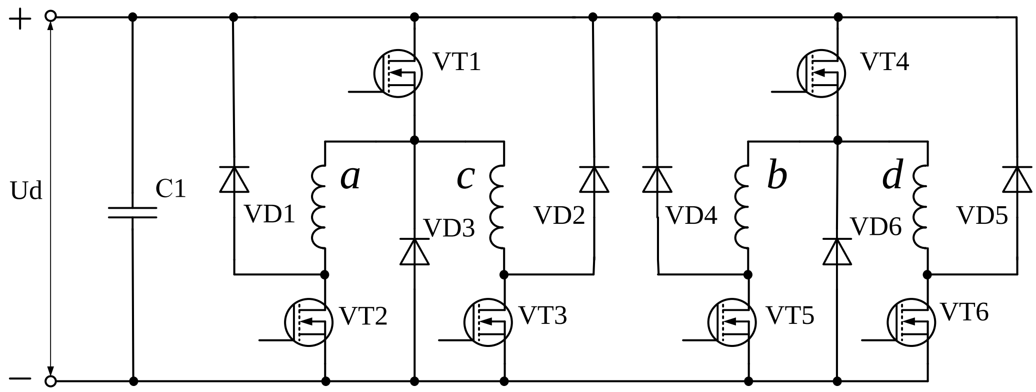

Fig. 4. Electronic switch circuit diagram

The current sensors used are ACS711 chips, which function through the Hall-effect principle; and its voltage is measured by the ADC. The advantages of these sensors include high reliability and durability, small size, and the shortcoming of constant power consumption, rather than high cost. The data on the SRM - winding temperature are taken by the TMR36 sensor.

The combined CS operation with the power unit is ensured through galvanic isolation using DC–DC P6AU converters and ADUM1201 chips with integral planar transformers. The main advantage of optoelectronic isolation over chips is its wide range of operating temperatures and other external factors. Compared to the isolation chips based on built-in high-voltage capacitors, these ADUM1201 chips allow for high differential voltage buildup rates.

Using the previously reviewed electronic components, as well as the PCAD software package for the design of printed circuit boards, the electric circuit for the SRM CS was created.

The model of the switched reluctance electric drive is shown in Fig. 5. In this case, the wheelset is mounted on the racks to the stand by the two support bearings. The gear is mounted on the motor shaft and the cogwheels with 16 and 51 teeth, respectively, are mounted on the wheelset. The gear ratio is equal to 3.2. The engine is rigidly fixed on the stand. The power cables and control wires are separated and shielded to protect against interference and noise. The mechanical brake lever was used as a load. The supply voltage *Ud =100 V* in the tests was maintained constant with a 20 kHz PWM frequency and 3 A current limit. The LCD connection, with the display of different information, was provided for convenience, which is especially important at the debugging stage.

2.2. Results

Electric drive tests were carried out using the previously discussed CS. The experiments aimed to analyze the drive at various machine speeds and speed stabilization to ensure smooth motor and wheelset acceleration, and to take the waveforms of the main transient co-ordinates. The computer produced a full-drive control by selecting the speed controller, range, smoothness and direction of control, and the smooth start-up algorithm, and by ensuring the required starting force. The controller firmware was written in C++ using the MPLAB studio.

The setting command includes the user's ability to get the required drive operation: selection of intensities of start, stop, rotation speed, starting current, and type of speed regulator. After selecting the drive operation settings and enabling the "START" command, the controller determines the rotor position, calculates the current speed, and transfers it to the required duration value of PWM (depending on the type of the speed regulator), switches off the PWM. Then the controller uses current sensors to measure the phase current and limit it. The algorithm of the selected type of speed regulator is performed by the block "duration calculation PWM ". After the end of one cycle of this algorithm, the controller interrogates the STOP command, and after its confirmation, the controller returns to the standby mode of the drive operation setting command and then the START command.

The phase current and voltage charts using the previously discussed converter were taken on the RIGOL DS5022M digital oscilloscope. Figure 6 shows the phase voltage and current waveforms for different machine speeds (n=1,000 rpm; n=1,500 rpm, n=2,000 rpm). The operating phase cycle was 22.5º, with the possibility of advance, lag, and no-phase shift switching. In this case, the advance phase switching was performed at an angle of 7º [12].

The natural mechanical characteristic of SRM, as shown in Fig. 7, was determined using the model sample. The SRM test results for several load torque values are given in Table. 2.

Table 2

Model sample test results

M, *Nm*	0.05	0.1	0.2	0.25	0.3	0.4	0.5
n, *rpm*	13,790	10,885	9,160	8,465	7,880	7,110	6,060
I, *A*	1.69	2.22	2.38	2.61	3.21	3.58	3.89

Using the known fuzzy controller principle, the coefficients of proportional, integral, and differential units were synthesized, and their distribution is shown in Fig. 8 [13, 14].

To research and select the controller that delivers the most high - quality speed transient, three types of operations, namely Proportional-Integral (PI), Proportional-Integral-Derivative (PID), and fuzzy PID (FPID) [14] controllers, were implemented. The current speed, as determined through calculation, was transmitted by the universal asynchronous receiver/transmitter to the additional 8-bit PIC18F14K50 microcontroller. Such controller has a built-in module for data transfer via USB serial bus through which it was connected to the computer.

Figure. 9 shows the speed transient characteristics with different types of controllers. After reaching the engine speed of 2,000 rpm at the time point of 13 seconds, the additional load, which corresponds to the speed drawdown, was applied stepwise. On the basis of the waveforms, the most high-quality transient was observed when using the FPID controller. With the PI controller, there was a static error and the overshoot was 10%. The speed transient with the PID controller also had a significant overshoot of 7%, which was almost negligible (1–1.5%) when a fuzzy logic controller was used instead.

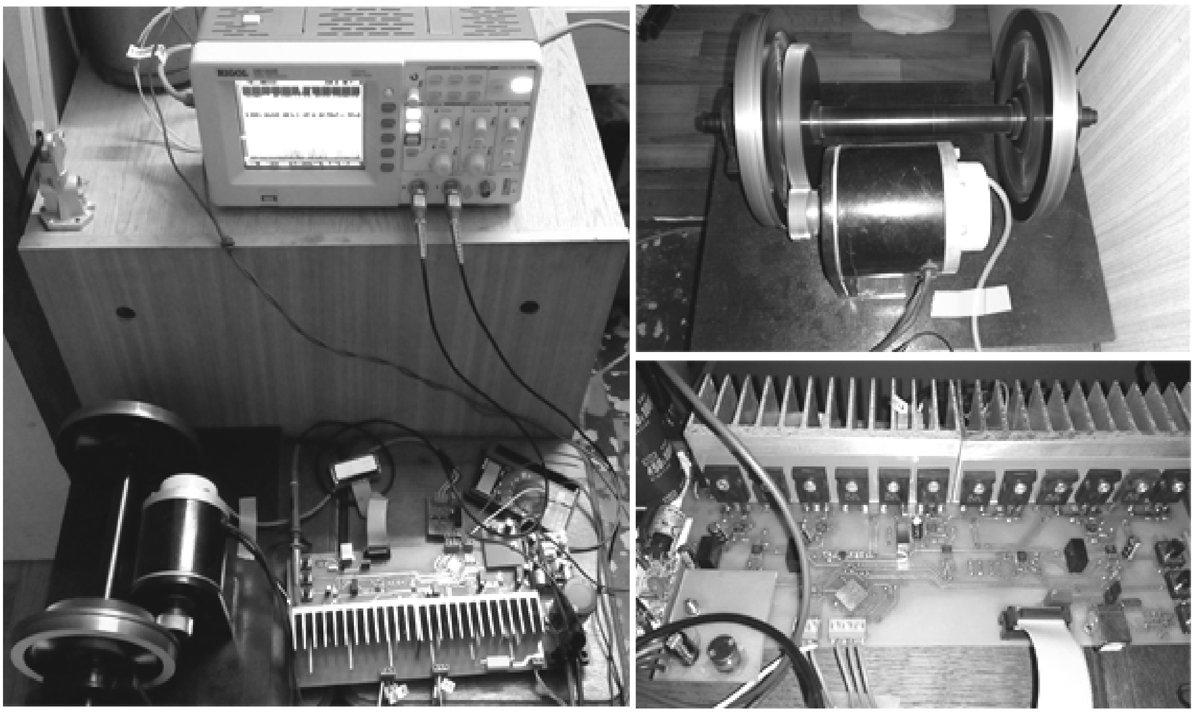

Fig. 5. Switched reluctance electric drive model sample

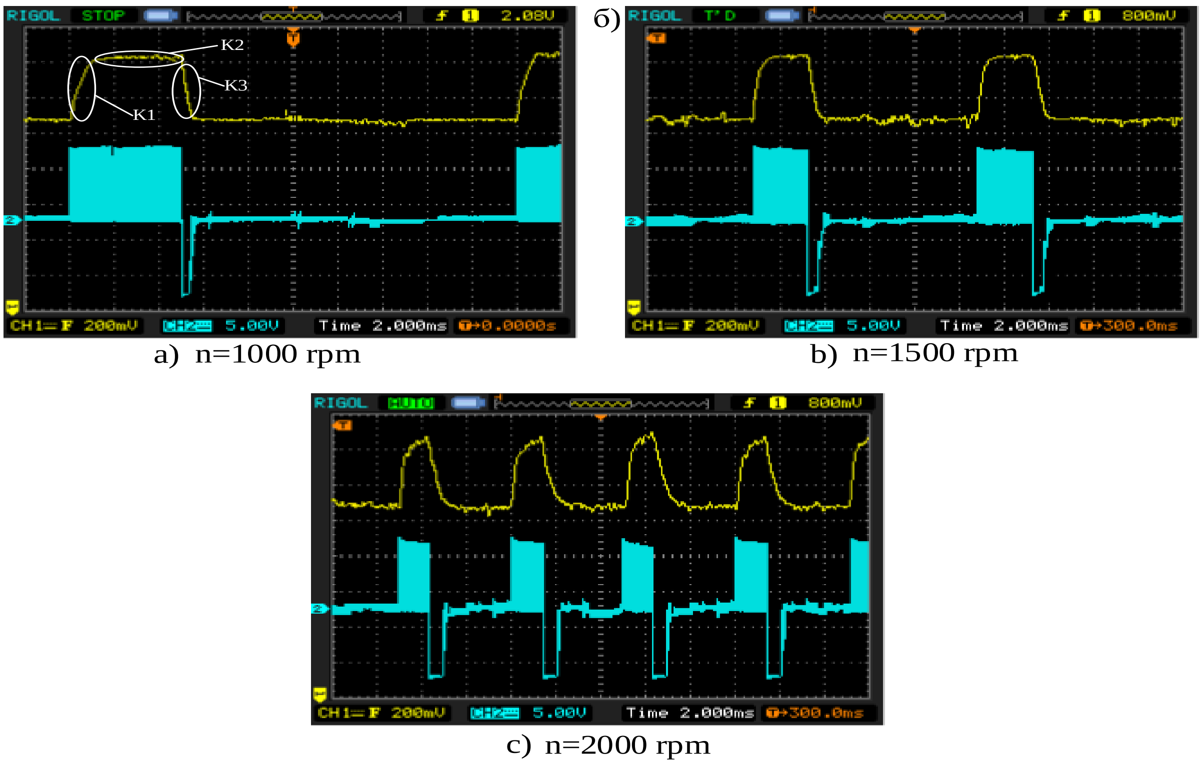

Fig. 6. Experimental waveforms of SRM phase current and voltage for different speeds and torques. The single cell scale: current – 2 A; voltage – 50 V

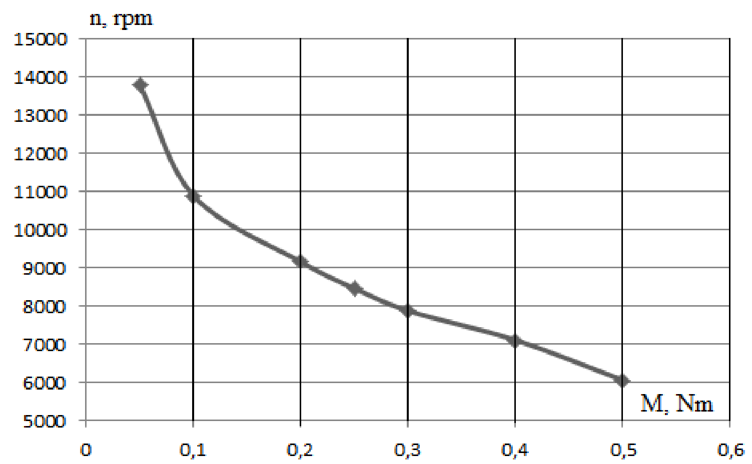

Fig. 7. SRM speed-torque characteristic

It should also be noted that the motor emergency mode was examined during the drive operation using the fuzzy logic, and the opening of one of the phases was artificially set in the converter. At the same time, the smooth operation of the model was continued, which was confirmed by the waveforms shown in Fig. 10.

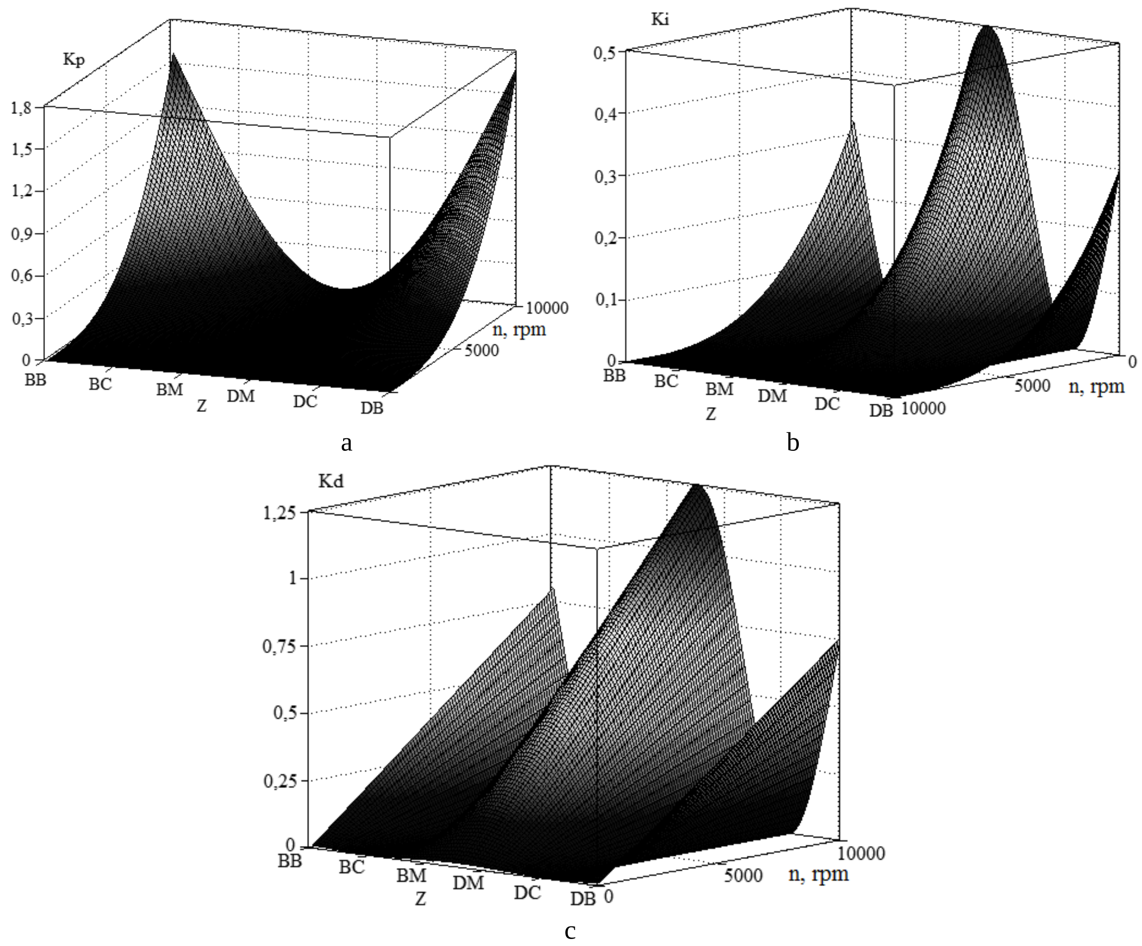

Fig. 8. Distribution of FPID controller coefficients

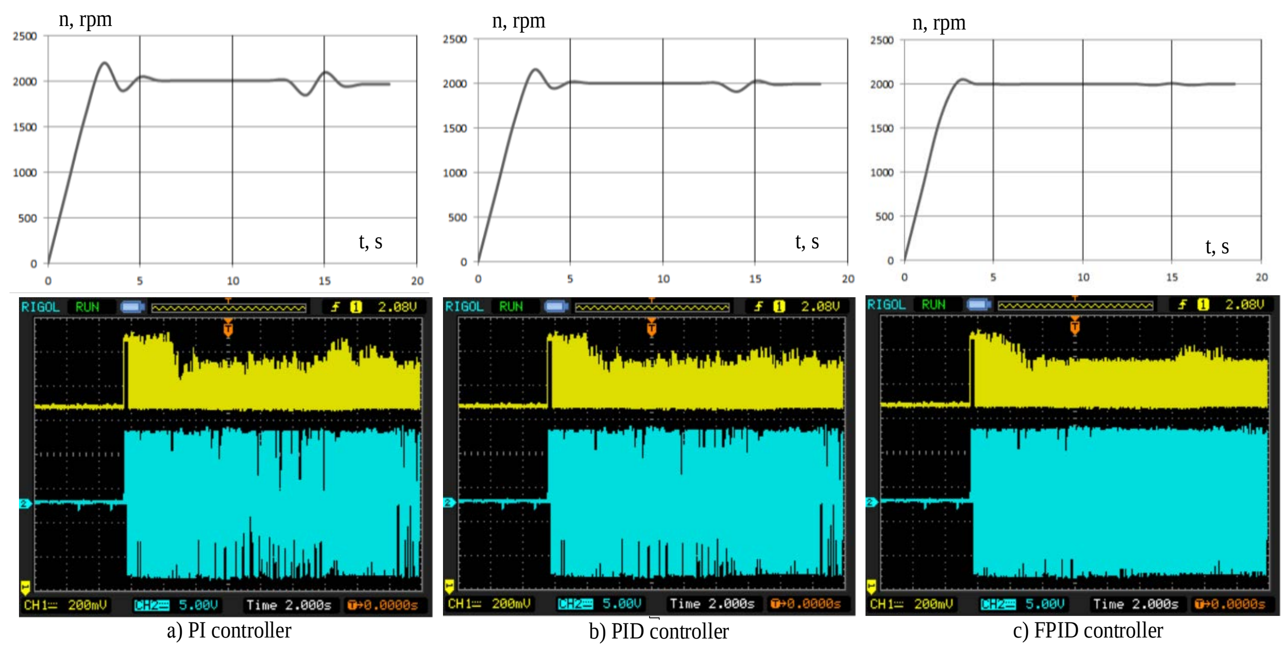

Fig. 9. Waveforms of SRM with different types of controllers

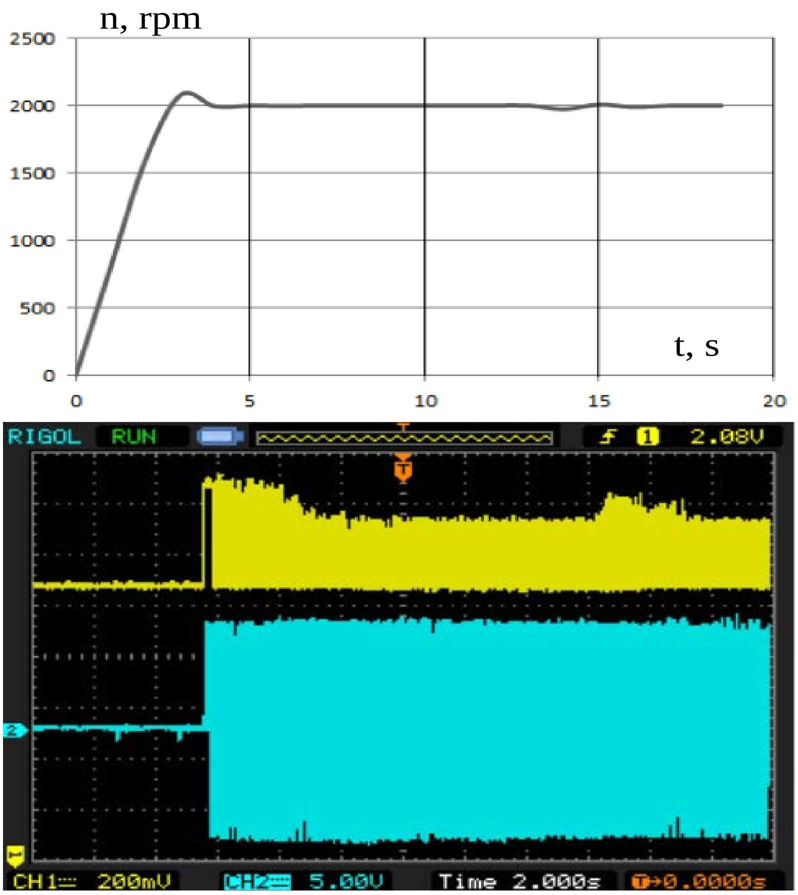

Fig. 10. Waveforms of SRM with artificially opened phase

The research we conducted implies, in future, studying the operation of control systems not only under traction regime, but also under regenerative mode.

3. CONCLUSIONS

1. The efficiency of the proposed control system was confirmed.
2. The usage of a microprocessor CS, which extends the drive functionality, allows the use of new-generation proximity sensors, and protects the engines from overload during operation.
3. Various types of speed regulators were synthesized.
4. The most qualitative transient process of speed is observed by using of the FPID regulator (the excessive correction is 1–1,5% and the control time is 3.8 s.). For the control system with using the PI regulator, the excessive correction is 10% and the control time is 5.75 s, and with using the PID regulator, the excessive correction is 7% and the control time is 4.9 s, respectively.
5. Converter usage allowed the motion process control by adjusting the motor speed, which significantly improved the dynamic performance of the drive. Moreover, usage of the FPID controller in the CS allowed for better speed adjustment.
6. The research results have shown that the construction of drives based on VIE makes it possible to improve the quality indicators of the control system. This would ensure the process of control over train motion along a section of the track with the assigned profile and motion schedule.

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