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Installation for experimental research of multiphase electromechanical systems

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The subject of this study is an installation for experimental research designed to study the characteristics and control algorithms of multiphase motors with the number of working phases from 3 to 8, connected by a star, a triangle, or in another way, allowing phase currents to flow, creating a rotating electromagnetic field. The installation consists of two separate independent units: a controller, or a human-machine control interface, and a power inverter module (converter). The controller is connected to the converter by a two-wire half-duplex interface (RS485) via the Modbus RTU communication protocol. The installation also includes synchronous motors with the number of phases 3, 5, 7.

Using the developed installation for experimental research, it is possible to carry out experimental studies of multiphase motors when implementing various control algorithms for a converter that implements pulse-width vector modulation. The time required to implement control algorithms is minimal. According to the results of the experiments, it is possible to carry out a comparative analysis of multiphase motors in terms of energy efficiency, in terms of vibration of electromagnetic origin, in dynamic parameters. An experimental assessment of the load of the converter keys is possible.

The created installation is an effective tool for checking the reliability of the results of theoretical studies of electromechanical systems based on multiphase motors.

Key words: installation for experimental research; multiphase motor; multiphase converter; controller touchpad

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Introduction. A significant number of publications devoted to the study of electromechanical systems based on multiphase motors emphasize their promise in traction electric drives, in particular in electric vehicles.

For example, in [1-3, 11], the theoretical principles of vector control based on direct torque control (DTC) are considered in comparison with the classical method of field-oriented control (FOC), in the implementation of which sine-pulse-width modulation (SPWM) is used. The work does not raise the question of the possibility of using vector control of multiphase electric machines. However, a direct current electric drive based on a four-phase asynchronous motor already exists and is being operated (with confidence we can assume that with vector control), which is installed on the onshore electric locomotive «Granite». The electric drive was developed by Siemens engineers. Four electric induction motors are installed on each section of the electric locomotive. The power of each motor is 1.2 MW, the number of pole pairs of the motor is $p = 4$, the converter has two frequency ranges – from 0 to 60 and from 60 to 120 Hz. A specific winding scheme is provided for each range, which is set by the automation unit depending on the frequency. Traction power ratio of one two-section locomotive is 9.6 MW.

In [4-10], studies and comparative analysis of 3-, 4-, 5-, 7-phase systems are presented. However, many theoretical results need experimental study in order to exclude their unreliability.

Many foreign theoretical works are devoted to the study of electromechanical systems based on multiphase motors [12-20]. It was found in the works that with an increase in the number of phases of the motor, the phase current decreases, the level of vibrations decreases, and the reliability of the electric drive increases. However, in these works there is no comparative analysis of the operating modes of the converter keys, i.e. the component of research results that can only be obtained through experiments is not sufficiently represented.

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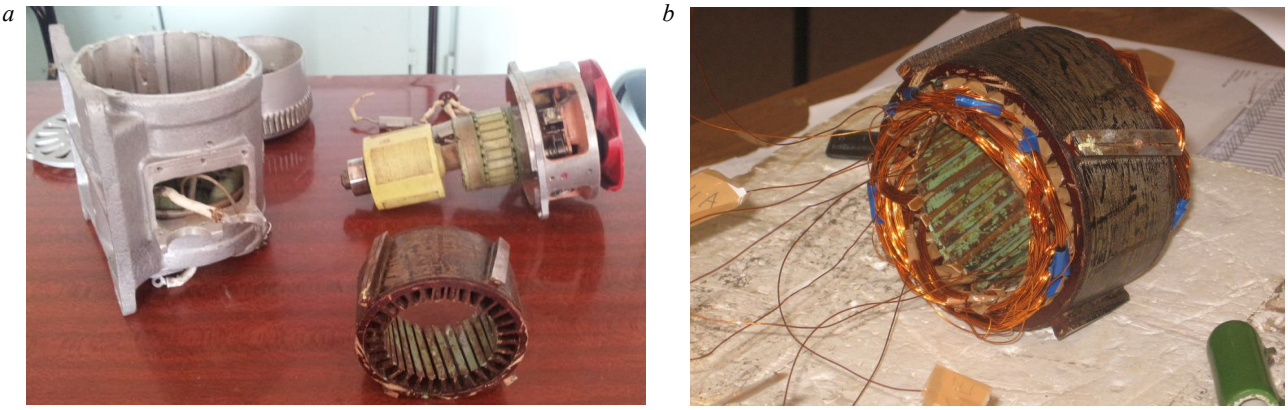


Fig.1. Electric machine (*a*) and stator (*b*) of a five-phase prototype engine

Most of the works have a theoretical orientation and do not contain the results of experimental studies. Timing diagrams obtained using engineering programs, most often MATLAB, which, in essence, are variations of theoretical studies, are given as illustrations.

This work is devoted to the description of the installation and prototype models created for experimental studies and comparative analysis of 3-, 4-, 5-, 6-, 7- and 8-phase electromechanical systems.

Formulation of the problem. To conduct experimental research and comparative analysis of multiphase electric drives, an electrical complex is required, which includes: multiphase electric machines, a converter that generates a multiphase symmetrical voltage, a programmable controller of the control system, measuring devices.

Figure 1, *a* shows an electric machine, on the basis of which 3-, 5- and 7-phase synchronous motors with excitation from permanent magnets are created, and Fig.1, *b* shows the stator of a 5-phase synchronous motor. Also, a 3-phase and 7-phase windings are stacked in a similar stator package with the number of teeth $Z = 30$. For the spatial symmetry of the 7-phase winding, $Z = 28$ is necessary, therefore, the prototype of the 7-phase motor has a spatial asymmetry of the working winding. This factor must be taken into account when analyzing the results of experimental studies.

The number of turns in the phase of the prototype samples have the following values: $W_{3ph} = 150$, $W_{5ph} = 90$, $W_{7ph} = 64$, i.e. the relation can be written as $W_{5ph} = 3/5(W_{3ph})$, $W_{7ph} = 3/7W_{3ph}$. The input voltage values of the converters must satisfy the relations: $U_{in5} = 3/5U_{in3}$, $U_{in7} = 3/7U_{in3}$, to ensure equal phase currents. With an increase in the number of phases, the machine becomes lower voltage, and the consumed input current of the converter increases in proportion to the increase in the number of phases of the motor. Copper consumption remains unchanged.

If the same stator packet is used, the number of turns in the phase will satisfy the relation $W_{3ph} = W_{5ph} = W_{7ph}$, then the phase current ratios take the form: $I_{5ph} = 3/5I_{3ph}$, $I_{7ph} = 3/7I_{3ph}$. In this case, the input voltage of the converters must have equal values.

With an increase in the number of phases of the motor with equal numbers of turns in the phase, the machine becomes more low-current, and the consumed input current of the converter remains unchanged. Copper consumption also does not change.

There is a theoretical justification for these findings, and experimental confirmation and engine prototypes are required to confirm their validity.

The most advanced for comparative analysis multiphase windings of prototype engines should have the same value q, e.g., $q_3 = q_5 = q_7 = 1$. By that, the number of stator teeth Z (of $2p = 4$) defined respectively as: $Z_3 = 12$, $Z_5 = 20$, $Z_7 = 28$. The number of stator teeth increases, and the ratios should be written as follows: $Z_5/Z_3 = 3/5$, $Z_7/Z_3 = 7/3$.

The installation allows experimental studies with engines in which the number of phases is equal to 3, 4, 5, 6, 7, 8. For a correct comparative analysis of the experimental results, it is necessary that the packages of stators of multiphase motors differ only in the number of teeth, and the

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relations will be: $Z_3 = 12$, $Z_4 = 16$, $Z_5 = 20$, $Z_6 = 24$, $Z_7 = 28$, $Z_8 = 32$. The numbers of teeth are given for windings in which $2p = 4$, $q = 1$.

The main goal of the installation is to provide the possibility of experimental studies of pulse-width modulation vector algorithms for multiphase motors and to verify the results of theoretical studies.

In [6], for example, a 4-phase winding was studied during the formation of the resulting voltage vector. However, no obvious advantages over the three-phase winding were found. Perhaps experimental studies, which will evaluate the operation of the converter keys, the energy characteristics of the complex (the input power of the converter is the mechanical power on the shaft), engine throttle response (the permissible speed of increasing the frequency of the converter), will help to identify the advantages of a 4-phase machine. For example, a prototype five-phase synchronous motor allowed a discrete increase in the frequency of the converter from 1 to 3 Hz, and when jumping from 1 to 4 Hz, the field «slipped away» and the engine fell out of synchronism. The experiment was conducted without feedback and a control system; the ten-step switching algorithm (PWM 95 %) was evaluated.

The installation will allow conducting experimental research of engines using techniques aimed at studying the features of multiphase machines.

The main need for a universal installation for experimental studies of multiphase electromechanical systems is dictated by the following circumstances.

When implementing six-step switching and vector pulse-width modulation in a three-phase system of $2^3 = 8$ vectors, 6 active-state and 2 zero-state. The use of zero vectors formed the basis for the implementation of SVPWM and DTC. Only one algorithm is possible for generating a symmetric three-phase voltage with temporary ABC phase rotation.

With the implementation of vector pulse-width modulation in a five-phase system, the formation of $2^5 = 32$ vectors, 30 active-state and 2 zero-state is possible. Zero vectors can also be used to implement SVPWM and DTC. Thirty active vectors (or 30 «chords» in 5 keys) can form three versions of a symmetrical five-phase voltage with various forms of phase voltage [5]. There are three converter control algorithms, each of which generates a symmetrical five-phase voltage. In addition, it is possible to form a time sequence of phase rotation ACEBD for a five-phase winding with spatial phase rotation ABCDE. Each of the three algorithms in combination with the ACEBD phase sequence of phase rotation generates the rotation frequency of the resulting vector, which is three times higher than the frequency of the converter. The resultant vector of the third harmonic becomes working, and the five-phase machine is a two-speed. When implementing converter control algorithms that increase the rotation frequency of the resulting voltage vector, the number of switched keys per period increases, and the switching frequency decreases. The effect was obtained theoretically, tested experimentally and needs to be investigated.

With the implementation of vector pulse-width modulation in a seven-phase system, the formation of $2^7 = 128$ vectors, 126 active-state and 2 zero-state. Zero vectors can also be used to implement SVPWM and DTC, 126 active vectors can form nine symmetrical seven-phase voltage variants with various forms of phase voltage. There are nine converter control algorithms (each algorithm implements a fourteen-step switching sequence). Each of the nine algorithms generates a symmetrical seven-phase voltage. It is possible to form time sequences of phase rotation ACEGBDF and ADGCFBE of a seven-phase winding with spatial phase rotation ABCDEFG. There is an algorithm that, in combination with the time sequence of phase rotation ACEGBDF, forms the frequency of rotation of the resulting vector, which is five times the frequency of the converter, the fifth harmonic resulting vector becomes operational. There is an algorithm that, in combination with the time sequence of phase rotation ADGCFBE, generates the rotation frequency of the resulting vector, which is three times the frequency of the converter, the resulting third harmonic vector becomes operational. Potentially, the seven-phase machine is a three-speed. When implementing converter control algorithms that increase the rotation frequency of the resulting volt-

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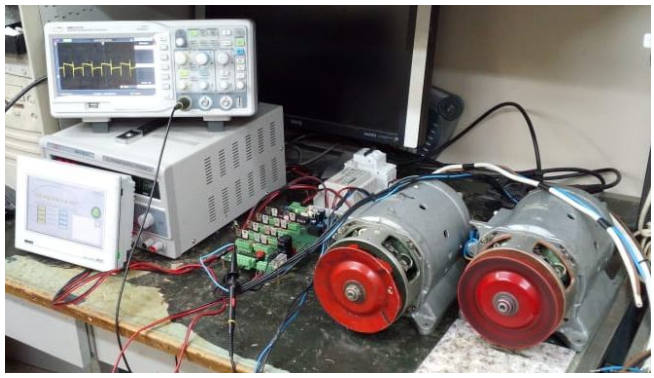
age vector, the number of switched keys per period increases, and the switching frequency decreases. This effect also requires experimental studies.

Active vectors can be formed by «chords» in six, five, four, three and two keys for a seven-phase system, as well as in four, three, two keys for a five-phase system. In this case, a symmetric seven-phase and five-phase voltage is formed. These issues were partially considered in [5, 10], but they need further experimental study.

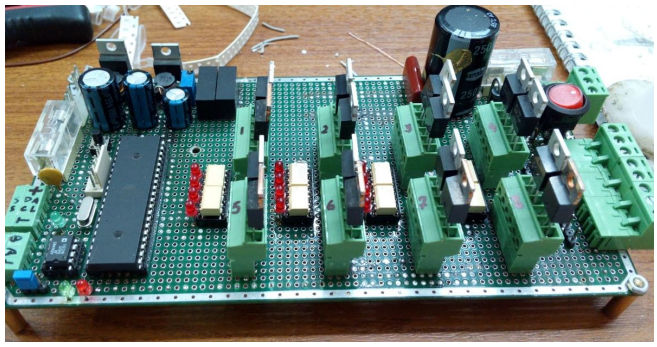
Research is needed on the ripple voltage of the common point of the multiphase winding with respect to the converter zero point. It is theoretically obvious that with an increase in the number of phases, the amplitude of the pulsations decreases, and their frequency increases. With an increase in the number of phases, the phase voltage form tends to meander, the amplitude of the voltage ripple tends to zero, and the ripple frequency tends to infinity. In practice, even with the number of phases 11, this process enters saturation.

The operability of the 11-phase system is provided by 22 keys, which form $2^{11} = 2048$ vectors, 2 of which are zero and 2046 are active. Each of 2046 active vectors is formed by a chord of 11 keys, but there are also active vectors that are formed by chords of 10, 9, 8 keys, etc. Theoretically, an 11-phase machine is potentially five-speed and at one frequency of the converter (reference frequency) has five speeds at the 1st, 3rd, 5th, 7th, 9th harmonics. All these questions are theoretically worked out and need experimental research. Installation for experimental research of multiphase electromechanical systems will help to resolve many issues when creating electric drives based on multiphase motors.

a



b



c

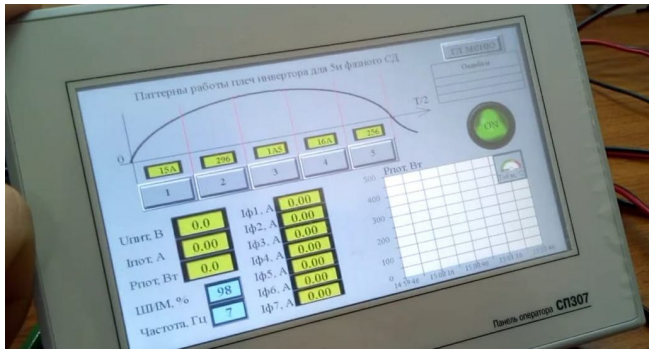


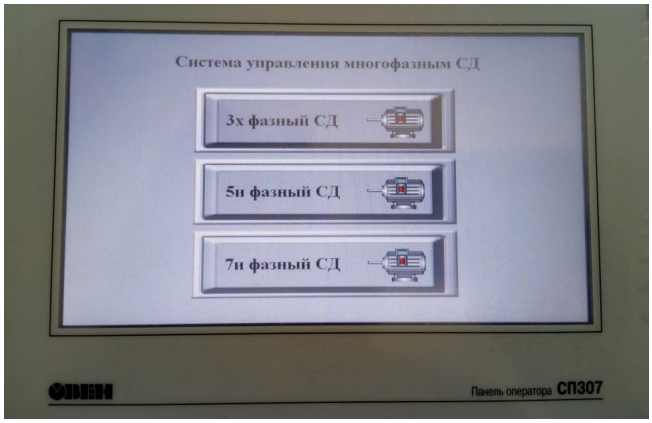
Fig.2. Installation for experimental research (*a*), debug board of the converter (*b*), controller (touch panel to control the five-phase converter modes) (*c*)

Methodology. Figure 2 shows a photo of the installation for conducting experimental studies of multiphase electromechanical systems with the 3, 4, 5, 6, 7, 8 phases. Five-phase and three-phase synchronous motors are presented that are connected to the converter.

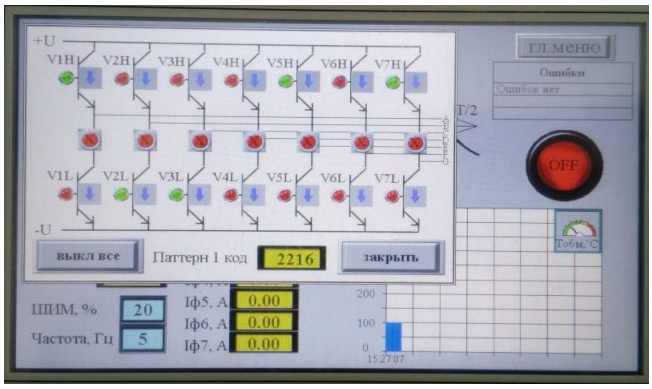
The converter is a board that is divided into a low-current control and high-current power part. The low-voltage part is made using the ATmega644 micro-controller, has its own power supply and a communication interface with the HMI (controller), as well as an I2C connector for connecting external sensors. The power unit consists of eight pairs of complementary MOSFET keys located in removable pads for quick replacement. The power part has a separate input for connecting a powerful power source up to 100 V. Both parts are completely galvanically isolated from each other. The power part is controlled by means of optocouplers and special DC / DC converters, which supply power to the key locks at the moment of their opening.

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a



b



c

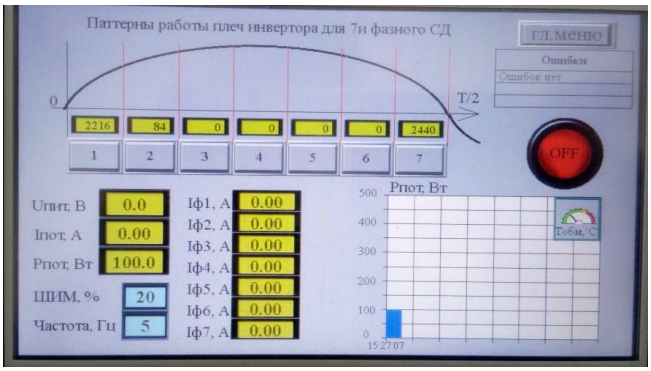


Fig.3. Touchpad of the controller: *a* – selection of a multiphase system; *b* – a seven-phase converter; *c* – control of seven-phase converter modes

The firmware implements the Modbus command exchange interface, as well as the specified key operation algorithm, start, stop, calibration and data generation from sensors and errors. The resulting algorithm is also programmatically checked for opening both keys in the shoulder to prevent through current. The power section can be emergency shut off by a switch on the board. Both parts of the converter are protected by fuses.

In this installation, the touch panel operator SP307 Aries was selected as the HMI controller. It allows using the visualization elements and modbus commands to control the converter in real time. The project, loaded into the operator panel, allows you to control 3-, 5- and 7-phase motors using the menu and the corresponding settings windows. If necessary, the project can be modified for specific engines. Added teams, sensors and graphs (trends).

To change the control algorithms, pop-up windows with a schematic representation of the inverter arms are used. The half-wave of the generated inverter voltage is divided into chords (patterns). By pressing the upper or lower shoulder key of the desired phase in the corresponding pattern, the algorithmization of work occurs. To form a «silence interval», you can turn off both keys in the shoulder (phase). To eliminate through current, accidental inclusion of both shoulder keys in the pattern is prevented. For recording and subsequent playback, each pattern has its own code.

The fields for configuring the operating mode of the converter allow you to change the duty cycle of the pulses (PWM), the limiting frequency, acceleration and resolution of the acceleration of the converter.

When starting up, the converter generates an alternating voltage with an initial frequency of 1 Hz and, with given acceleration and resolution, begins to linearly increase the frequency to a predetermined limit frequency. For a new acceleration cycle, the inverter must be stopped.

The HMI is connected to the converter with a two-wire half-duplex RS485 interface, through which the Modbus RTU communication protocol is implemented.

Fig.3 shows the touch panel of the controller, which provides the implementation of algorithms. In the variant of a multiphase system in Fig.3, *a* (for example, a seven-phase system), by touching the «7-phase SM» image, an image appears on the screen of the touch panel (Fig.3, *b*). To set the required algorithm for the converter, which will form 14 «chords» in 7 keys (or 14 vectors forming vector pulse-width modulation), just touch the image of the keys on the touch panel screen (Fig.3, *b*) in a certain sequence. For example, to implement an algorithm:

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1) 1,6,10,14,3,7,11(A+C_E_G_B+D+ F+);
2)1,6,10,14,4,7,11(A+C_E_G_B_D+ F+);
3) 1,5,10,14,4,7,11(A+C+E_G_B_D+ F+);
4) 1,5,10,14,4,8,11(A+C+E_G_B_D_F+);
5) 1,5,9,14,4,8,11(A+C+E+G_B_D_F+);
6) 1,5,9,14,4,8,12(A+C+E+G_B_D_F_);
7) 1,5,9,13,4,8,12(A+C+E+G+B_D_F_);
8) 2,5,9,13,4,8,12(A_C+E+G+B_D_F_);
9) 2,5,9,13,3,8,12(A_C+E+G+B+D_F_);
10) 2,6,9,13,3,8,12(A_C_E+G+B+D_F_);
11) 2,6,9,13,3,7,12(A_C_E+G+B+D+F_);
12) 2,6,10,13,3,7,12(A_C_E_G+B+D+F_);
13)2,6,10,13,3,7,11(A_C_E_G+B+D+F+);
14)2,6,10,14,3,7,11(A_C_E_G_B+D+F+),

you need to touch the keys in the appropriate sequence. Between the numbers given in the algorithm and the keys shown in Fig. 3, b, the relation 1-1H, 2-1L, 3-2H, 4-2L, 5-3H, 6-3L, 7-4H 8-4L, 9-5H, 10-5L, 11-6H, 12-6L, 13-7H, 14-7L. The formation of the algorithm takes no more than 1 min.

The touch panel of the controller can take the form shown in Fig. 3, c. In this mode, the touch panel allows you to configure the mode of operation of the converter, for example, you can set the mode in which the frequency of the converter will increase by 1 Hz for 1 s or another dynamic mode that needs to be investigated.

The shape of the phase voltage, which is set by the control algorithm, is fixed by a digital oscilloscope.

The development of the controller software will allow the formation of zero vectors of various durations, and on the oscilloscope screen it will be possible to observe the phase voltage shape when implementing SVPWM with a zero vector, for example, using the following control algorithms:

• SVPWM algorithm for a 5-phase system

2,4,6,8,10; 1,4,6,7,9; 1,4,6,8,9; 1,3,5,7,9; 1,4,6,8,9; 1,4,6,7,9; 2,4,6,8,10; 1,3,6,8,9; 1,4,6,8,9; 1,3,5,7,9; 1,4,6,8,9; 1,3,6,8,9; 2,4,6,8,10; 1,3,6,8,9; 1,3,6,8,10; 1,3,5,7,9; 1,3,6,8,10; 1,3,6,8,9; 2,4,6,8,10; 1,3,5,8,10; 1,3,6,8,10; 1,3,5,7,9; 1,3,6,8,10; 1,3,5,8,10; 2,4,6,8,10; 1,3,5,8,10; 2,3,5,8,10; 1,3,5,7,9; 2,3,5,8,10; 1,3,5,8,10; 2,4,6,8,10; 2,3,5,7,10; 2,3,5,8,10; 1,3,5,7,9; 2,3,5,8,10; 2,3,5,7,10; 2,4,6,8,10; 2,3,5,7,10; 2,4,5,7,10; 1,3,5,7,9; 2,4,5,7,10; 2,3,5,7,10; 2,4,6,8,10; 2,4,5,7,9; 2,4,5,7,10; 1,3,5,7,9; 2,4,5,7,10; 2,4,5,7,9; 2,4,6,8,10; 2,4,5,7,9; 2,4,6,7,9; 1,3,5,7,9; 2,4,6,7,9; 2,4,5,7,9; 2,4,6,8,10; 1,4,6,7,9; 2,4,6,7,9; 1,3,5,7,9; 2,4,6,7,9; 1,4,6,7,9; 2,4,6,8,10; 1,4,6,7,9; 1,4,6,8,9; 1,3,5,7,9; 1,4,6,8,9; 1,4,6,7,9; 2,4,6,8,10;

• SVPWM algorithm for a 3-phase system

2,4,6; 1,4,5; 1,4,6; 1,3,5; 1,4,6; 1,4,5; 2,4,6; 1,3,6; 1,4,6; 1,3,5; 1,4,6; 1,3,6; 2,4,6; 1,3,6; 2,3,6; 1,3,5; 2,3,6; 1,3,6; 2,4,6; 2,3,5; 2,3,6; 1,3,5; 2,3,6; 2,3,5; 2,4,6; 2,3,5; 2,4,5; 1,3,5; 2,4,5; 2,3,5; 2,4,6; 1,4,5; 2,4,5; 1,3,5; 2,4,5; 1,4,5; 2,4,6; 1,4,5; 1,4,6; 1,3,5; 1,4,6; 1,4,5; 2,4,6.

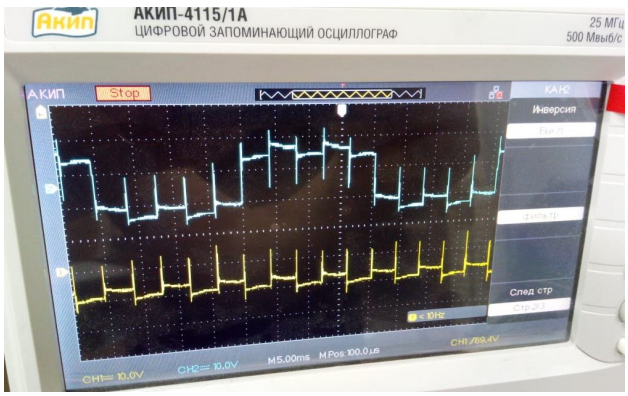
You can measure the voltage ripple between the common point of the multiphase winding and the zero of the converter and make sure that with an increase in the number of winding phases, the ripple frequency increases and the ripple amplitude decreases. For example, for a three-phase winding, the ripple frequency is the frequency of the third harmonic, for a five-phase winding it is the frequency of the fifth harmonic, and for a seven-phase winding, the ripple frequency is seven times higher than the frequency of the converter (reference frequency).

Figure 4 shows the time diagrams of the voltage ripples of the common point of the winding relative to the inverter zero for five-phase and three-phase motors.

If the winding has an even number of phases, then the ripple amplitude is zero. Perhaps this factor became the main one when choosing a 4-phase asynchronous motor for a locomotive. The ripple is zero, for example, in a five-phase winding, if a symmetrical five-phase voltage is formed by “chords” in four keys. The timing diagram of this mode is shown in Fig.5.

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a



b

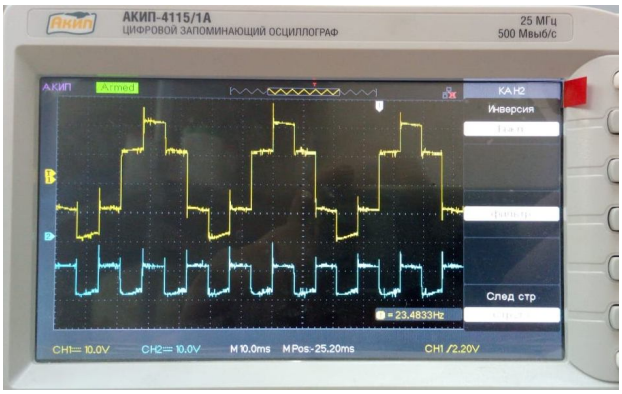


Fig.4. Ripple voltage of a common point relative to the inverter zero: *a* – five-phase motor, *b* – three-phase motor

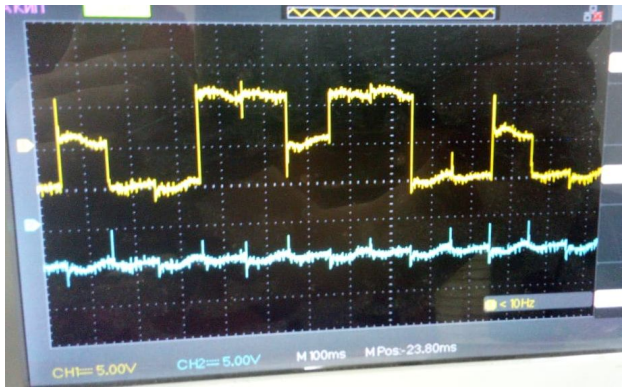


Fig.5. Four-key switching common point voltage ripple of a five-phase motor

Discussion. The experimental results obtained with the help of the created installation will allow us to conduct a comparative analysis and evaluate the expected advantages of multiphase electric drives, for example, by vibrational properties and energy characteristics, to explore new modes of operation of an electric machine that are not possible with a three-phase machine, namely, modes of changing the time sequence of phase rotation.

The study of multiphase electromechanical systems will require the study of dozens of converter operation algorithms. The created installation allows you to implement the created algorithms with minimal time on a simplified technology by touching the key images on the touch panel.

The installation can be improved in the direction of expanding functionality, as well as increasing the objectivity of the comparative analysis of multiphase systems. For this, engines with stator packages are required, which differ only in the number of teeth, as well as controller upgrades at the software level. As a result of modernization, a larger number of converter circuits will appear on the touch panel screen, and a larger number of keys forming a multiphase voltage will appear on the universal debug converter board. It will also be possible to implement algorithms using zero vectors.

Conclusion. A facility has been created for conducting experimental studies of multiphase electromechanical systems (the number of phases is 3, 5, 7). The installation allows implementing various converter control algorithms, revealing new qualities of multiphase electromechanical systems, and also checking the results of theoretical studies for reliability.

The main areas of application of the installation:

• diagnostics of vibrations of electromagnetic origin and the effect of the number of phases of the motor on its vibrational (noise) characteristics;

• a comparative analysis of the mechanical characteristics of engines with a different number of phases.

REFERENCES

1. Kozyaruk A.E. Direct torque control in an alternating current electric drive of mining machinery and mechanisms. SPGGI, St. Petersburg, 2008, p. 99.

2. Kozyaruk A.E. Modern efficient electric drives of production and transport mechanisms. *Elektrotekhnika*. 2019. N 3, p. 33-37.

3. Rudakov V.V., Kozyaruk A.E. Electric drive control systems. Direct torque control in AC drive. SPGGI, St. Petersburg, 2007, p. 75.

4. Tereshkin V.M. An analytical method for assessing vibrations of electromagnetic origin in a seven-phase AC machine. *Vestnik Ivanovskogo gosudarstvennogo energeticheskogo universiteta*. 2019. N 1, p. 61-69.

5. Tereshkin V.M., Grishin D.A. Study of the algorithms for the operation of a five-phase converter in the mode of vector pulse-width modulation. *Elektrotekhnika*. 2017. N 2, p. 46-51.

6. Tereshkin V.M. Determination of the harmonic composition of the resulting current of a 4-phase symmetrical winding of an electric machine. *Vestnik Moskovskogo aviatsionnogo instituta*. 2018. Vol. 25. N 3, p. 212-219.

7. Tereshkin V.M., Grishin D.A., Makulov I.A. Prospects for the use of multiphase AC machines, *Elektronika i elektrooborudovanie transporta*. 2017. N 1, p. 19-26.

8. Tereshkin V.M., Grishin D.A., Makulov I.A. Comparative analysis of the effectiveness of three-phase and five-phase synchronous valve machines. *Elektrotekhnika*. 2018. N 5, p. 60-67.

9. Tereshkin V.M. The theoretical justification for the possibility of reducing vibrations of electromagnetic origin in a five-phase AC machine compared to a three-phase machine. *Vestnik Moskovskogo aviatsionnogo instituta*. 2018. Vol. 25. N 4, p. 229-239.

10. Tereshkin V.M., Grishin D.A., Makulov I.A. Three-key switching mode of the five-phase converter. Generalized voltage vector of a five-phase system with three-key switching. *Elektronika i elektrooborudovanie transporta*. 2018. N 4, p. 9-16.

11. Usol'tsev A.A. Modern asynchronous electric drive of optical-mechanical complexes. St. Petersburg: SPbGU ITMO, 2011, p. 164.

12. Bermudez M., Gonzalez-Prieto I., Barrero F., Guzman H., Kestelyn X., Duran M.J. An Experimental Assessment of Open-Phase Fault-Tolerant Virtual-Vector-Based Direct Torque Control in Five-Phase Induction Motor Drives. *IEEE Transactions on Power Electronics*. 2018. Vol. 33. N 3, p. 2774-2784.

13. Guzman H., Bermúdez M., Martín C., Barrero F., Durán M. Application of DSP in Power Conversion Systems – A Practical Approach for Multiphase Drives. 2015. URL: http://cdn.intechopen.com/pdfs-wm/48835.pdf (date of access: 09.09.2018). DOI: org/10.5772/60450

14. Barrero F., Duran M.J. Recent Advances in the Design, Modeling, and Control of Multiphase Machines – Part I. *IEEE Transactions on Industrial Electronics*. 2016. Vol. 63. N 1, p. 449-455; 459-468.

15. Dwari S., Parsa L. Fault-Tolerant Control of Five-Phase Permanent–Magnet Motors With Trapezoidal Back EMF. *IEEE Transact Indust Electron*. 2011. Vol. 58. N 2, p. 476-485.

16. Levi E. Advances in Converter Control and Innovative Exploitation of Additional Degrees of Freedom for Multiphase Machines. *IEEE Transactions on Industrial Electronics*. 2016. Vol. 63. Iss. 1, p. 433-448.

17. Levi E., Bojoi R., Profumo F., Toliyat H.A., Williamson S. Multiphase Induction Motor Drives – A Technology Status Review. *IET Electric Power Applic*. 2007. Vol. 1. N 4, p. 489-516.

18. M.Bermudez, I.Gonzalez-Prieto, F.Barrero, M.J.Duran, X.Kestelyn Open-phase fault operation of 5-phase induction motor drives using DTC techniques. Proc. 41st Annual Conference IEEE Industrial Electron. Society. 2015, p. 595-600.

19. Chan C.C., Bouscayrol A., Chen K. Electric, Hybrid, Fuel-Cell Vehicles: Architectures and Modeling. *IEEE Transact Vehicular Technol*. 2010. Vol. 59. N 2, p. 589-598.

20. Williamson S., Smith S. Pulsating Torque and Losses in Multiphase Induction Machines. *IEEE Transact Indust Applic*. 2003. Vol. 39. N 4, p. 986-993.

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