Development of a Control Algorithm for Three-Phase Inverter in Two-Phase Electric Drives Reducing the Number of Commutations

Aleksey Sergeevich Belousov
Lipetsk State Technical University
Lipetsk, Russia
011bas962@gmail.com

Viktor Nikolayevich Meshcheryakov
Lipetsk State Technical University
Lipetsk, Russia
mesherek@stu.lipetsk.ru

Stanimir Valtchev
University NOVA of Lisbon
CTS/FCT, Portugal
ssv@fct.unl.pt

Oleg Viktorovich Kryukov
Gazprom VNIIGAZ
Moscow, Russia

***Abstract*—Important requirements for the modern electric drives are the high overload capacity and a wide range of speed control. A two-phase adjustable low-power drive has these properties, but its implementation in small-scale mechanics is hindered by the need a frequency converter that provides a three-phase power grid into a two-phase network, which is important when the power of the mechanisms increases. Previous studies have already shown the possibility of using a typical frequency converter based on a three-phase full-bridge voltage inverter applying space-vector PWM method. The switching frequency of the inverter remains, unfortunately, relatively high. It is not possible to reduce this frequency without degrading the harmonic composition. The goal of this work is to develop an algorithm for controlling the two-phase electric drive system, while reducing the numberof commutations of the switching devices of the three-phase inverter, and at the same time keeping the deviations of the instantaneous values of the phase currents close enough to the reference.**

***Keywords*—two-phase motor, three-phase bridge inverter, switching devices, control system, relay current regulator**

I. INTRODUCTION

Over the past ten years, a number of papers have been published about the problems of controlling a two-phase motor. Historically, a two-phase induction motor (IM) was invented a year earlier than the three-phase one. However, there were significant design flaws (concentrated windings, four supply wires, etc) that were eliminated in the three-phase version, so the two-phase electric drive was not widely adopted. The low-power capacitor motors were exclusively used in many household appliances, and the two-phase hollow-rotor micromotors were used in small fans. On the contrary, two-phase machines of medium and high power were practically not manufactured [1]. It should be noted that at approximately equal mass-dimensional parameters, two-phase IMs can have a larger number of pole pairs, thus a higher maximum torgue can be achieved [1].

One of the main disadvantages of the two-phase electric drives is the difficulty to generate the required voltages at the required 90° phase difference between them. Each motor winding can be powered from its own single-phase source, for example, when connecting them to a common three-phase system through a transformer, according to the Scott scheme. However, this greatly complicates the circuit and increases the cost of the drive. In the capacitive two-phase IMs, the role of the phase-shifting element is played by the capacitor itself, but this option is suitable only for household drives powered from one phase of the power grid. To connect a two-phase IM to a three-phase source, a frequency converter is required that combines the functions of regulation and the functions of changing the number of phases. There are several options for this converter, the simplest one for implementation is a converter with a DC link, designed for a three-phase drive, with a modified strategy of commutations of the switches. An important task in the development of the control system is the creation of a new algorithm for the operation of the inverter switching devices using the relay principle of phase current regulation. In this case the number of switching and the risk of overheating of the power devices are reduced.

II. DESCRIPTION OF THE CONTROL ALGORITHM

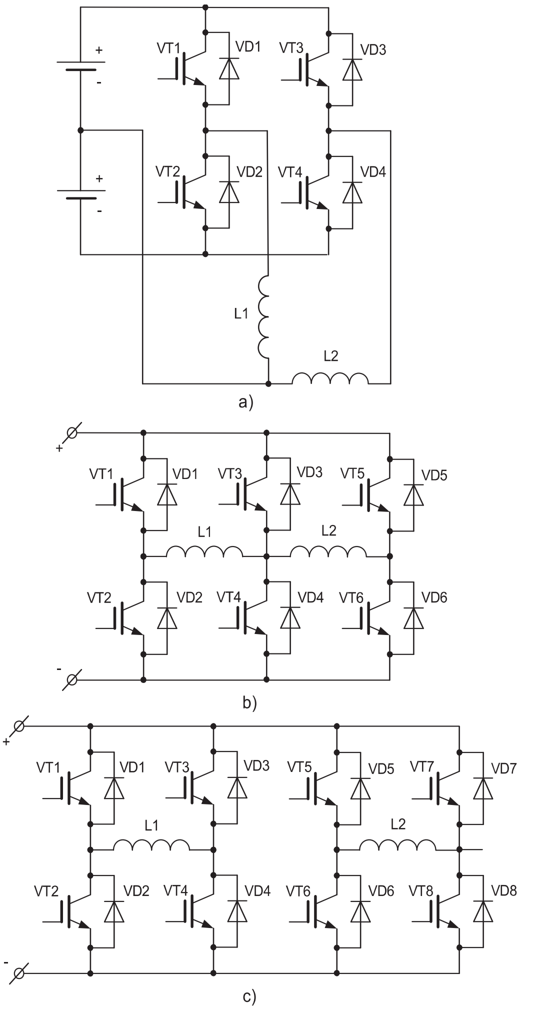
The three-phase IMs, as well as the two-phase IMs, can be connected to the grid supply through direct frequency converters (DFC) and frequency converters with a DC link. The research of the two-phase IM with the thyristor DFC in [1] showed that the total number of thyristors in a two-phase drive circuit is less than in a three-phase one. However, the such scheme provides a connection to the two-phase grid instead three-phase grid. The additional structural elements are needed for changing the number of phases, and it is impossible to speak unequivocally about the cheapness of the design. The required two-stage converter system was developed at the University of Zilina in Slovakia [2, 3]. The two-stage system consists of the direct current source, the single-phase inverter, the high-frequency transformer with two secondary windings, and the two single-phase half-bridge matrix DFCs. In this system, the number of power devices is quite less, each phase is controlled separately, while input and output are galvanically separated. However, in this scheme, the transformer is needed to branches of the central points of the secondary windings. It reduces its reliability and increases the cost. In another version, the two-stage two-phase system is made with the branches from central points of the IM windings. It complicates the design of the motor.

The converters with a DC link and a voltage source inverters don't have these problems. The three inverter designs are possible for the two-phase IMs: two-leg, three-leg (they are used in three-phase inverters) and four-leg (Fig. 2).

The inverter commutation is carried out according to the pulse-width modulation (PWM) principles, which can be

---

The paper was powered by research grant RFBR 19-48-480001 "Development, investigation and optimization of energy-saving electrical and electrically driven automated".



a)

b)

c)

Fig. 1. The inverter designs: a — two-leg; b — three-leg; c — four-leg

sinusoidal (SPWM) and space-vector (SVPWM). In systems with SPWM it is possible to control the voltage amplitude of one winding to regulate the voltages with the constant angle between them or regulate the angle of the phase shift between the voltages with a constant amplitude [4]. The most popular control method is the space-vector pulse-width modulation, which is based on changing the moment when the switches are turned on or off. This change depends on which sector of the circular field the voltage vector is located at the moment.

For the various inverter designs, the vector voltage diagrams are different [5]. For the two-phase IM with the three-phase inverter, the vector voltage area looks like a non-equilateral hexagon divided into six sectors of an equal area [6]. This means that while the voltage vector is in the first quadrant, the full voltage from the DC link is applied to the windings, and in the second it decreases to 70.7% of the full.

The most optimal configuration of the inverter is a typical three-phase, because such inverter does not require an additional leg with capacitors or transistors. Fighting the shortcomings associated with the asymmetric operation of the inverter allows breaking the entire period of the voltage sine wave into two parts, in each of which its own SVPWM algorithms are implemented. The patents [8, 9] are also aimed at optimizing the switching algorithm, in which it is proposed to keep the first switch of one leg permanently closed and the second are opened while the voltage vector is in a certain subsector, thereby controlling two other pairs.

The problem of optimizing the switching frequency in all systems with PWM is in the fact that with these conditions the switching frequency of the inverter reaches the frequency of the PWM itself. The switching frequency exceeded 6 kHz in [6]. However, if there are no switches when the deviations of the stator currents are found within certain minimum limits, then the switching frequency will decrease significantly. This control system is called the system with relay current regulators (RCR). For the two-phase inverter, such system was considered in [10]. The target amplitudes and frequency of phase currents are formed in the external speed loop. The target currents are compared with the feedback signals, and the deviations are fed to the hysteresis blocks, that serve as relay regulators. The outputs of these blocks serve as control signals of the upper group of switches, and their inverse signals are used for the lower group. For the electric drive with the three-phase inverter this principle is not applicable, since it is necessary to generate control signals for leg switches, the middle point of which is common to the two windings. The control algorithm in this case is proposed in the patent [11], the results of its research are given in [12].

The considered two-phase IM control system based on the voltage source inverter with the RCR (Fig. 2). The device contains the two-phase IM 1, the unregulated diode rectifier 2, the DC link with the capacitive filter 3 and the three-leg voltage source inverter 4, made of IGBT transistors with reverse diodes. The current sensors 5 are installed in the outputs of the motor windings. The control system 6 contains a block of RCR 7, at the input of which the comparison unit 8 is installed to which target current and feedback current signals are supplied. The block signals generated by RCR and their reverse signals as well as logical "0" and "1" from the block 10 are sent to the inverter driver 9, which generates combinations of the inverter switches states based on the set logical signals. The winding beginnings are marked with asterisks "*".

The principle of the switching algorithm is clarified by using the current waveforms for one period (Fig. 3). The current waveforms must have a 90° phase shift, while the entire period is divided into 4 sections, depending on the values of each current. So, in the first section, the winding current Ia is positive, and the windings Ib are negative. Fig. 3 shows the directions of current flow in each section. The switching algorithm should provide appropriate current loops depending on the current time. In this case, in accordance with

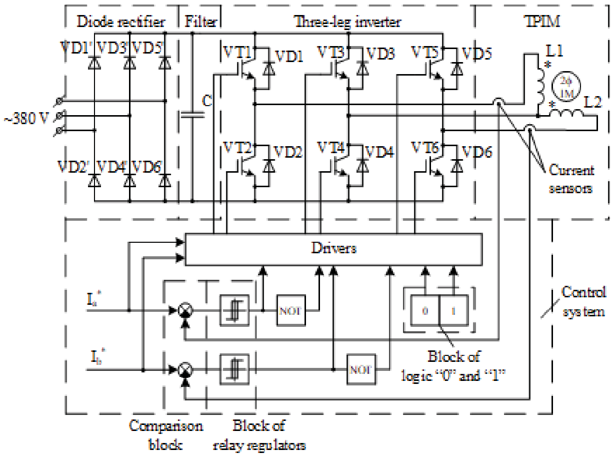


Fig. 2. The block diagram of the two-phase control system with the relay current regulator and the three-leg inverter

the principles of the relay control, when one of the currents reaches the boundary of the hysteresis zone, the switches of the inverter leg responsible for the current circuit should be switched. There are 4 possible combinations of switches in one time section and 16 combinations of switches in total. The contours of the flow of currents for various combinations in the first two sections are shown in Fig. 4. Similarly, the current flow contours of the other two sections are determined.

The fundamental difference from the commutation strategy developed for the three-phase electric drive [13] is as follows. When the hysteresis zone is reached, the only one switch belonging to the upper group is switched. The switch located on the same leg as the first switch remains in the same state. In the three-phase drives, this principle allows to apply the reverse voltage to the windings, reduce the current values (according to the commutation principle, the current on the inductance coil cannot change abruptly) and "hold" them for longer in the given zone. However, in two-phase systems it is not possible. For example, if the switch VT2 is opened when the switch VT1 is closed, then the current from the winding L2 will not flow through the winding L1, but will flow through the opened switch VT4, which has a zero resistance. The residual energy L1 induces the same small current loop L1-VT4-VD2 (Fig. 4, b), as with the closed switch VT2.

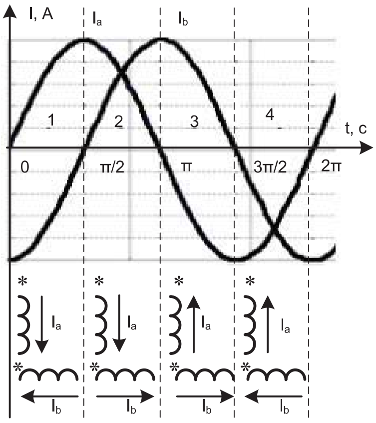


Fig. 3. The two-phase currents of the motor for one period

Thus, the simultaneous commutation of two transistors in one leg only leads to an increase in the number of commutations, which is a negative phenomenon. All possible combinations of the states of the inverter switches that provide the required current flow circuits are presented in the table. The model of a two-phase control system with RCR was developed in the Matlab Simulink (Fig. 5) to implement a commutation algorithm that provides commutation of these combinations.

TABLE I. THE STATE OF THE INVERTER SWITCHES, DEPENDING ON THE LOCATION OF THE CURRENT VALUES IN THE HYSTERESIS ZONE

Section	**$I_1 \in h(I_1^*)$, $I_2 \in h(I_2^*)$**			**$I_1 \notin h(I_1^*)$, $I_2 \in h(I_2^*)$**			**$I_1 \notin h(I_1^*)$, $I_2 \notin h(I_2^*)$**			**$I_1 \in h(I_1^*)$, $I_2 \notin h(I_2^*)$**		
$I_1 \geq 0$, $I_2 \leq 0$	1	0	1	0	0	1	0	0	0	1	0	0
	0	1	0	0	1	0	0	1	0	0	1	0
$I_1 \geq 0$, $I_2 \geq 0$	1	1	0	0	1	0	0	0	0	1	0	0
	0	0	1	0	0	1	0	0	0	0	1	0
$I_1 < 0$, $I_2 \geq 0$	0	1	0	0	1	0	0	1	0	0	1	0
	1	0	1	0	0	1	0	0	0	1	0	0
$I_1 < 0$, $I_2 < 0$	0	1	1	0	0	1	0	0	0	0	1	0
	1	0	0	0	1	0	0	0	0	1	0	0

This model works as follows. Two comparators compare the reference signals to a zero. The logical elements AND and NOT based on this comparison determine the current section of the sinusoidal currents. For each section, its own combination of inverter control pulses is formed as the signals from the outputs of RCR (hysteresis blocks) and their inverse signals. If the section does not provide for changes in the state of the switches of the common leg, the logical "0" or "1" are applied to them. Since situations are possible when the both switches of the common leg have the same state (Fig. 4, h), a blocking from their simultaneous inclusion is necessary, which is implemented by the AND block.

Thus, the developed algorithm for the operation of the relay controller performs the following operations:

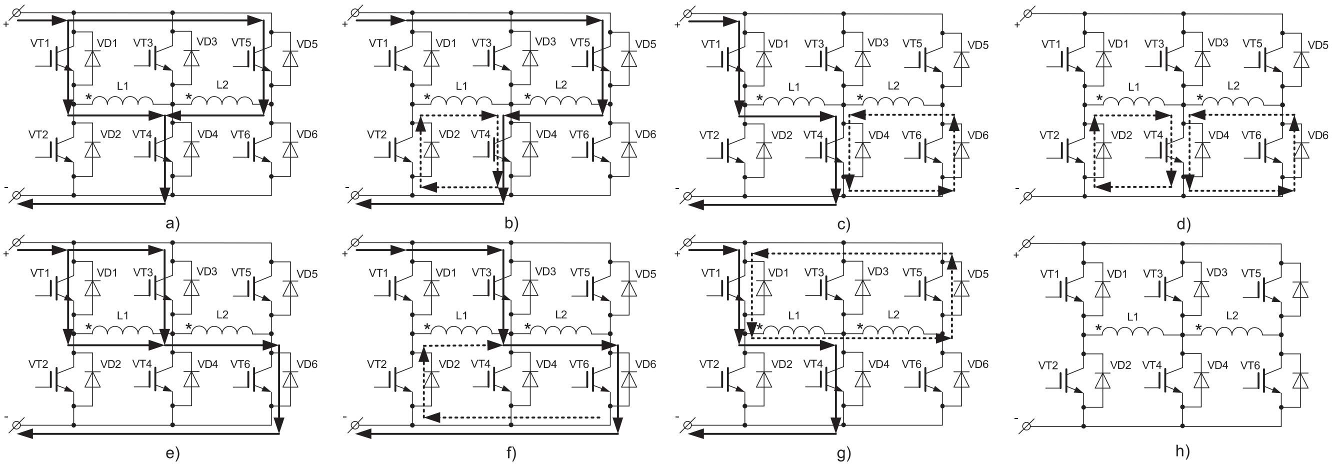


Fig. 4. The current flow contours of the motor windings and the inverter in the first two sections of the one period: a — currents within the band zone; b — the current of the first winding has left the zone; c — the current of the second winding has left the zone; d — both currents left the zone in the first section of the period of the sinusoid; e — currents within the band zone; f — the current of the first winding out of the zone; g — current of the second winding out of the zone; h — both currents left the zone in the second section of the period of the sinusoid

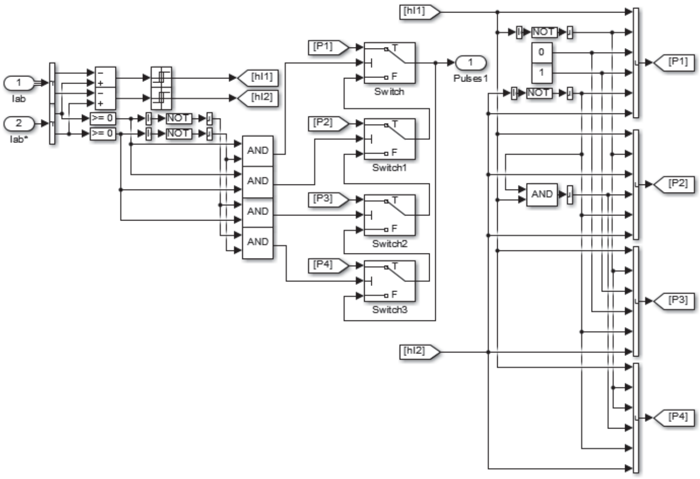


Fig. 5. The model of a current regulator of a two-phase electric drive

- the current signals section of currents is determined by the reference signals;
- in the first section, when the difference between the set and the measured values of the phase current reaches the lower boundary of the threshold level, the switches of the upper group of the corresponding phase is turned off (Fig. 4, b, c). When the difference between the set and the measured values of the current reaches the upper boundary of the threshold level, the upper group of the corresponding phase is turned on (Fig. 4, a);
- in the second section, when the difference between the set and the measured values of the phase current reaches the lower boundary of the threshold level, the switch of the upper group of the phase *a* (Fig. 4, f) is turned off. In the similar case for the phase *b*, the upper switch of the common leg is turned off and the lower switch of the common leg (Fig. 4, g) is turn on. When the difference between the set and the measured values of the current reaches the upper boundary, the reverse commutation occurs (Fig. 4, e);
- in the third and the fourth sections the commutation algorithm is similar to the first and the second sections, while the phase currents within the boundaries of the threshold level satisfy the graphs in Fig. 3.

In the framework of this research, the model of the two-circuit control system for the two-phase IM with the external speed loop and a slip compensation (Fig. 5) based on the functional vector control circuit (Fig. 7) was developed.

This functional circuit (Fig. 7) was compiled on the basis of the indirect vector control system for two-phase IM, described in [14] for the two-phase electric drive with a two-leg inverter controlled by SVPWM. The difference lies in the fact that instead of using PI current controllers in a fixed DQ coordinate system, RCRs are installed inside the general current circuit, already recalculated in the phase coordinate system AB. This allows to get rid of the additional coordinate conversion units characteristic for the vector control systems, since in the two-phase motors the windings of phases *a* and *b* already have a 90° shear angle.

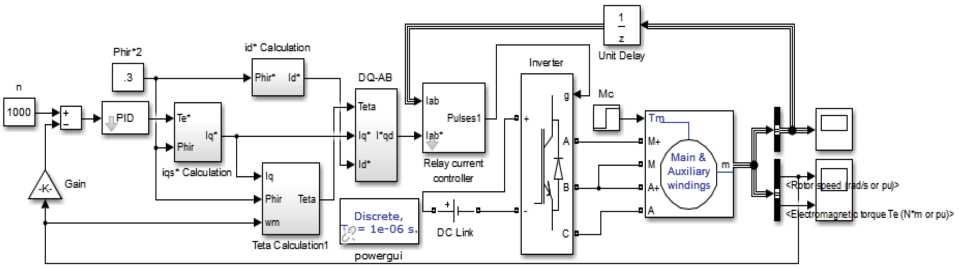


Fig. 6. The model of the two-circuit control system for the two-phase IM with relay current regulator

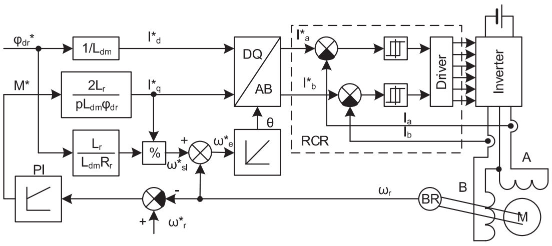


Fig. 7. The functional diagram of the two-circuit control system for the two-phase IM with relay current regulator

The system operates as follows. The torque of a motor is

$$M = \frac{2}{p} \cdot \frac{L_{dr}}{L_r}(i_{qs}\varphi_{dr} - i_{ds}\varphi_{qr}) \tag{1}$$

where M — torque; p — poles number; L_{dr} — d-component of rotor induction; L_r — rotor induction; i_{qs} — q-component of stator current; i_{ds} — d-component of stator current; φ_{dr} — d-component of rotor flux; φ_{qr} — q-component of rotor flux.

Moreover, we can assume that $\varphi_{qr} = 0$, $\varphi_{dr} = const$. Therefore, the torque is

$$M = \frac{2}{p} \cdot \frac{L_m}{L_r} i_{qs}\varphi_{dr} \tag{2}$$

where L_m — mutual inductance.

We can calculate q- and d-components of stator currents:

$$i_{qs} = \frac{2L_r M}{pL_m\varphi_{dr}} \tag{3}$$

$$i_{ds} = \frac{\varphi_{dr}}{L_{dm}} \tag{4}$$

where L_{dm} — d-component of mutual inductance.

To convert the components of the stator currents from the dq system to the phase coordinate system AB, the angle of field rotation θ is necessary. It can be obtained as an integral of the angular velocity of rotation of the engine field ω_e. In this case, the field rotation speed itself is equal to the sum of the rotor rotation speed and the slip velocity ω_{sl}:

$$\omega_e = \omega_r + \omega\mathrm{sl} = \omega_r + L_m i_{qs}/\tau_r\varphi_{dr} \tag{5}$$

Consider the operation of the control system (Fig. 7). The difference between the speed reference signal and its feedback goes to the PI speed controller, the output of which serves as the torque reference. By (3), the current in the projection onto the q axis is determined, and by (4) the current in the projection onto the d axis is determined. Knowing the values of the speed and flow of the rotor, the angle of rotation of the field (5) is determined, then the currents of phases a and b is calculated:

$$\begin{Bmatrix} I_a = I_d\cos\theta - I_q\sin\theta \\ I_b = I_d\sin\theta + I_q\cos\theta \end{Bmatrix} \tag{6}$$

If the motor is asymmetric (the parameters of the phase windings are somewhat different), then the task of one of the currents is multiplied by the correction factor a. The current setting is supplied to the input of the RCR block (Fig. 5). The developed system of implicit vector control of the two-phase IM with the RCR will allow precise control of the motor speed with a relatively low number of commutations of the inverter.

III. THE RESULTS OF THE RESEARCH

The Matlab standard model "Single Phase Asynchronous Machine" with main and auxiliary windings and with standard parameters was taken for modelling. Power is 0,25 hp, voltage is 110 V, frequency is 50 Hz, resistance and induction of the first stator winding are 2,02 Om, 7,4 mH, resistance and induction of the second stator winding are 7,14 Om, 8,5 mH, resistance and induction of the rotor are 4,12 Om, 5,6 mH, mutual inductance is 177,2 mH; the inertia moment is 0,0146 kgm^2, 2 poles, the winding factor is 1,18. The simulation was carried out with a constant sampling step of 1 μs. In the engine model, eddy currents, saturation of the magnetic circuit, and heat loss were not taken into account.

The current graph obtained in the system with a two-phase RL load simulating stator windings, the reference current of 50 A amplitude and a 1 A hysteresis zone is shown in Fig. 8. This graph indicates the achievement of the goal — obtaining a two-phase current at the inverter output, controlled by the developed algorithm with RCR.

The simulation results of the two-circuit electric drive control system are shown in Fig. 9. They depict stator currents (Fig. 9, a), angular velocity (Fig. 9, b), and torque (Fig. 9, c).

The current graphs are close to sinusoidal. When approaching the value of phase b current to 0, the switching of the switches is clearly visible when the boundary of the specified zone is reached, which is typical for systems with a relay controller. It is worth noting that in the second and fourth sections of the Sinusoid, the switching frequency and the range of a given zone increase.

This is due to the fact that when currents are found in a given zone, one of the windings is not supplied with full voltage (Fig. 4, e). At this moment, the current sharply decreases and goes beyond the zone, after which the switching of the switches and its return follows. When the upper limit is reached, the current decreases again and the process is repeated until the end of the section limits. The effect on the shape of the graph is negligible.

The speed increases smoothly and keeps at a predetermined level, without decrements under the action of the load, which indicates the development of slip compensation (5). The load itself was chosen 2 times larger than the nominal load (2 Nm) and applied at the time of starting the engine in order to verify the main advantages of a two-phase motor. Thus, it was found that a two-phase motor is able to start with a stable value of the starting torque when the load is increased from zero speed. The moment fluctuates around a given value, the oscillation zone, which is 20% of the task. For comparison, the zone of moment fluctuations in the modified direct torque control system of a two-phase electric drive with a three-leg inverter [15] was 40%.

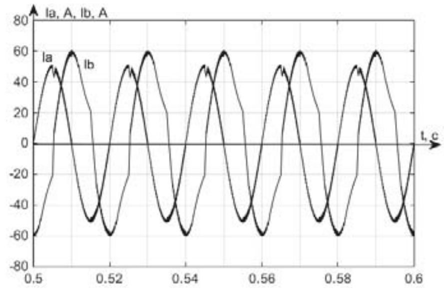


Fig. 8. The currents of two-phase RL-load

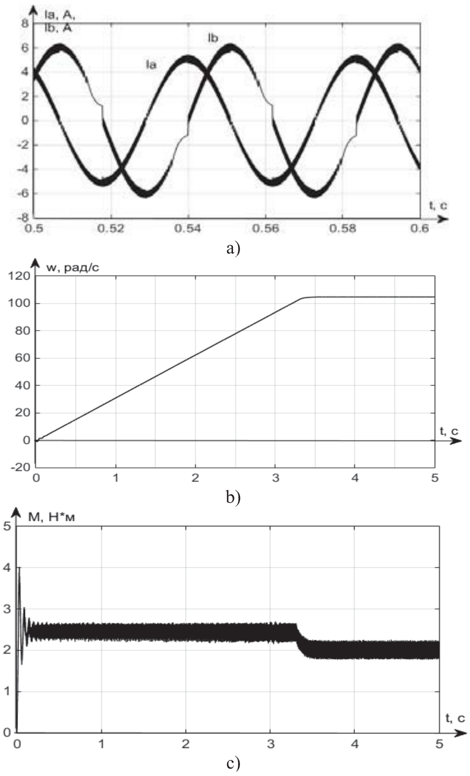


Fig. 9. The results of modeling a two-circuit control system: a — currents of two phases; b — angular velocity; c — motor torque

The switching frequency and the harmonic composition of the phase currents were compared in the developed model with RCR and the SVPWM control system [6]. The switching frequency was determined using the counter of control pulses. In the model of a system with a RCR with a hysteresis zone of 1 A, the switching frequencies of each switch were: 5320 Hz for VT1, VT2; 5000 Hz for VT3; 5830 Hz for VT4; 4650 Hz for VT5, VT6. In the model of a SVPWM system with a control frequency of 6 kHz, the switching frequencies were 5700 Hz for the switches of the first and second legs and 6000 Hz for the switches of the third leg.

The results of harmonic analysis (Powergui block) are given on Fig. 10. The abscissa axis shows the number of harmonics, and the ordinate axis shows the harmonics as a percentage of the fundamental sinusoid with a frequency of 50 Hz. Harmonic analysis showed that the shape of the currents of the system with SVPWM is better, since the third harmonic is the most significant parasitic.

IV. CONCLUSION

The developed model of the suggested control system with a relay current regulator of a two-phase electric drive allows an indirect vector control. The principle of operation of the new control system is to combine the operation of the external speed loop with a vector control and the internal current loop with relay current controllers that specify the control signals to the switching devices of the three-phase bridge inverter. The verification of the operability of each circuit and the entire system is made by a computer simulation. It testifies that the sinusoidality of the voltages and the high quality of the phase currents together with the possibility of starting from zero speed at high load, are optimized.

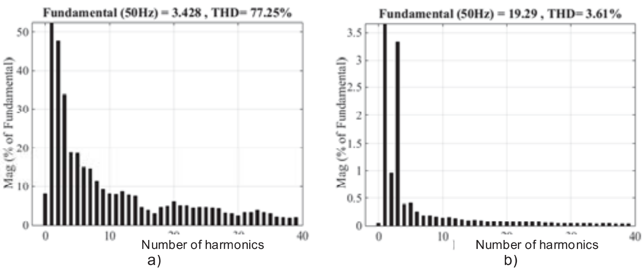


Fig. 10. The harmonic composition of the motor currents in the system with the relay regulator (a), in the system with the SVPWM (b)

A comparative analysis of the graphics in Fig. 10 showes that the harmonic composition is better in a system with SVPWM (b), but the switching frequency in systems with RCR (a), is lower. The considered frequency control system with RCR can be used for two-phase electric drives of small-scale mechanization, e.g. household appliances and is promising as a replacement for the less economical single-phase motors.

REFERENCES

[1] Ya. Bespalov, E. V. Kachalina, “Comparative characteristics of induction motors with three-phase and two-phase windings for frequency-controlled electric drive (Сравнительные характеристики асинхронных двигателей с трехфазными и двухфазными обмотками для частотно-регулируемого электропривода),” Elektrichestvo, no. 7, 2010, pp. 45–48.

[2] B. Dobrucky, et al. “Two-phase power electronic drive with split-single-phase induction motor,” IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society, IEEE, 2010, pp. 1683–1688.

[3] M. Prazenica, “Design, modelling and simulation of two-phase two-stage electronic system with orthogonal output for supplying of two-phase ASM,” AEEE, vol. 9, no. 1, 2011, pp. 56–64.

[4] D.-H. Jang, “Voltage, frequency, and phase-difference angle control of PWM inverters-fed two-phase induction motors,” IEEE Trans. Power Electron., vol. 9, no. 4, 1994, pp. 377–383.

[5] D.-H. Jang, D.-Y. Yoon, “Space-vector PWM technique for two-phase inverter-fed two-phase induction motors,” IEEE Trans. Ind. Appl., vol. 39, no. 2, 2003, pp. 542–549.

[6] D.-H. Jang, “PWM methods for two-phase inverters,” IEEE Ind. Appl. Mag., vol. 13, no. 2, 2007, pp. 50–61.

[7] D. C. Martins, L. C. Tomaselli, T. B. Lazzarin, I. Barbi, “Drive for a symmetrical two-phase induction machine using vector modulation,” IEEJ Trans. Ind. Appl., vol. 126, no. 7, 2006 pp. 835–840.

[8] “Converter for rotational speed variable operation of a capacitor motor and method for controlling a capacitor motor,” patent WO 2004008623 A1, H02P 1/44, 25/04. DANFOSS DRIVES A/S, 22.01.2004, 41 p.

[9] H. Kragh, B. Henriksen, “Two-phase permanent magnet motor,” patent US 2008143284 A1, H02P 6/08, 1/42, 19.06.2008, 19 p.

[10] Abdel-Rahim, M. B. Naser, A. Shaltout, “An unsymmetrical two-phase induction motor drive with slip-frequency control,” IEEE Transactions on energy conversion, vol. 24, no. 3, 2009, pp. 608–616.

[11] V. N. Meshcheryakov, A. S. Belousov, “The method of controlling two-phase AC motor using a three-phase bridge inverter,” patent №2682242 RF; 18.03.2019, 13 p.

[12] A. S. Belousov, A. V. Kokorev, A. A Muravyev, “Algorithm for controlling a two-phase inverter (Алгоритм управления инвертором двухфазного тока),” HTCS, 2017, pp. 91–96.

[13] V. N. Meshcheryakov, “Analysis of current and voltage inverters with relay control systems (Анализ инверторов тока и напряжения с системами релейного управления),” Vesti vysshih uchebnyh zavedenij Chernozemya, no. 2, 2016, pp. 13–18.

[14] D.-H. Jang, “Problems incurred in a vector-controlled single-phase induction motor, and a proposal for a vector-controlled two-phase induction motor as a replacement,” IEEE Trans. Power Electron., vol. 28, no. 1, 2013, pp. 526–536.

[15] S. Ziaeinejad, Y. Sangsefidi, H. P. Nabi, A. Shoulaie, “Direct torque control of two-phase induction and synchronous motors,” IEEE Trans. Power Electron., vol. 28, no. 8, 2013, pp. 4041–4050.