Запропоновано структуру перетворювача, що перебудовується, електричного приводу електротехнічного комплексу рудникового електровозу від джерел живлення з різними рівнями напруги – від контактної мережі та батареї тягових акумуляторів. Характерна особливість перетворювача полягає в наявності інверторних блоків, які можуть бути підключені або послідовно, або паралельно. При живленні від джерела низької напруги інверторні блоки включені паралельно у всьому діапазоні зміни вихідної напруги. У разі живлення від джерела високої напруги інверторні блоки з'єднуються послідовно в діапазоні низьких вихідних напруг і паралельно в діапазоні високих вихідних напруг. Такий відхід дозволяє вирівнювати рівні напруги живлення тягових асинхронних двигунів рудникових електровозів на більш низькому рівні. Очікуване вирівнювання рівнів напруги здійснюється на більш низькому рівні порівняно зі стандартною схемою трифазного мостового автономного інвертора і досягається управлінням спареними мостами контуру живлення тягових асинхронних двигунів. Завдяки цьому частота напруги широтно-імпульсної модуляції не змінюється, що важливо для процесу зниження динамічних втрат енергії в елементах приводу.

Підтверджено, що зниження коефіцієнта спотворення вихідної напруги в IGB-транзисторах інвертора з мінімальним рівнем втрат енергії в елементах електроприводу досягається шляхом модуляції напруги при постійній частоті комутації на різних рівнях напруги. Доведено факт, що найкращі показники коефіцієнта гармонік отримані на частотах близько 30 Гц, які є робочими, тому режим роботи перетворювача на цих частотах найбільш ефективний. В результаті аналізу класичної схеми інвертора встановлено, що при збільшенні частоти широтно-імпульсної модуляції в три рази значно збільшуються електричні втрати в обмотках тягового електричного двигуна. У запропонованій схемі перетворювача напруги живлення двигуна при вирівнюванні напруги на низькому рівні немає необхідності підвищувати частоту широтно-імпульсної модуляції, що не викликає зростання електричних втрат в тяговому двигуні

Ключові слова: асинхронний двигун, автономний інвертор напруги, широтно-імпульсна модуляція, електричні втрати, коефіцієнт гармонік, рудниковий електровоз

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DEVELOPMENT OF THE CONVERTER STRUCTURE THAT ENABLES POWER SUPPLY TO TRACTION INDUCTION MOTORS OF MINE ELECTRIC LOCOMOTIVES FROM DIFFERENT LEVELS OF VOLTAGE

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1. Introduction

Electrical equipment, including components of traction electric drives for mine electric locomotives, as well as the electric locomotives themselves, are produced in more than 15 countries by 30 firms that are leaders in this industry [1]. However, it should be noted that only a small part (about 10 %) of contact and accumulator-based mine electric locomotives is equipped with induction traction electric drives.

Other types of electric rolling stock are equipped with ineffective traction electrotechnical complexes (TETC) with contact-resistor control systems and series-wound

DC motors. In addition to low energy efficiency, they have a significant drawback associated with safety for miners. Touching a contact wire by workers is especially dangerous at sites where minerals are loaded and unloaded, where an open contact network can cause accidents related to electric shock. It is possible to achieve a sufficient level of efficiency of the rolling stock and electrical safety in iron ore mines through the construction of a modern traction electric drive and the elimination of a contact wire at sites of loading and unloading of minerals.

In recent years, the world practice of mechanical engineering has seen new models of energy-efficient traction electric drives with IGBT-converters of power voltage for induction motors (IM). Efforts by scientists and machine-builders of Ukraine produced a new type of the traction electric drive – a contact-accumulator one [2], powered both by contact network (CN) and the traction accumulator battery (TAB), which makes it possible to greatly expand the scope of its application.

The result of analysis of electromagnetic processes in the traction induction electrical drive (TID) of the classic structure of a mine traction electrotechnical complex has revealed that when powered by different levels of voltage sources the actual values for energy losses are substantial [3]. In this case, the coefficients that describe the non-sinusoidal curve of induction motor voltage have rather high values that do not agree with acting GOST [4]. Thus, there is a need to improve quality indicators for the shape of a voltage curve to the rated values, which can be achieved through the selection of a rational structure for the drive system and a technique to control different levels of power voltage in the traction induction motors (TIM) of mine electric locomotives.

That necessitates, based on analysis of known structures [5], the substantiation and development of recommendations for applying the law of control over power voltage of TIM – traction systems of electric drives.

2. Literature review and problem statement

Paper [6] proposed a two-level structure of the TID for accumulator drives. The purpose of designing such a structure was to primarily decrease the losses of electrical energy in power transistors of the voltage source and to reduce specific start-up loads on TAB. The proposed structure has an inflated number of transistor-thyristor elements and a rather complicated control algorithm.

Study [7] considered basic approaches to determining losses in the traction induction motor when powered by a semiconductor converter under the modes of a one-time and a spatial-vector pulse-width modulation (PWM) that make it possible to optimize operation modes of the traction induction motor for the criterion of minimum losses, taking into consideration the thermal state of the motor. The work fails to consider losses in TID at different levels of power voltage, which would minimize losses in TAD.

Paper [8] examined a classic structure of TID and proposed a traditional vector control with a PWM of power voltage in traction induction motors. The application of such a scheme, relative to the structure of the drive with a two-level power, leads to misalignment in terms of choosing a vector control as a control system.

Work [9] suggested a new structure of the energy converter based on a three-phase inverter to power a six-phase IM. The result of applying such a solution is that the total capacity of the entire AC drive is distributed equally among the four isolated DC sources. Such a structure of the converter makes it possible to supply power from sources at different levels, but it requires the application of a specially-executed engine (six-phase).

Paper [10] developed a multi-level inverter and described an algorithm of vector control over power of the six-phase motor for conditions of power from different voltage levels. A drive circuit consists of four two-level three-phase voltage converters. Such a structure of the inverter operates with sources of different voltage levels, however, as is the case in [9], it requires a specialized engine.

Work [11] proposed a variant for the hybridization of the electric locomotive VV460000 by installing a traction induction electric drive. This makes it possible to significantly decrease the rated power of the diesel generator. Another proposal is the option to apply Ni-Cd batteries as an autonomous source of electric energy and power for TID. The work suggested a scheme for modernization of main electric locomotives. The classic scheme of the inverter is employed as a converter, which must change the frequency of PWM when switching to power from the source of another level. However, this leads to a decrease in dynamic losses in elements of the converter.

Paper [12] examined the feasibility of using AC drive in relation to a traction electric drive. The authors studied and proposed a new method of vector control, which is focused on the development of a system to control the structure inverter-TIM. The paper aimed to analyze a method of vector control over TIM of the classic structure of converter. This, in turn, leads to difficulties in building a control system powered by different voltage levels.

Thus, an analysis of the scientific literature revealed that all current studies related to the development of TID are built based on the classic schemes of inverters applying a vector control system. Even though these systems have the required level of simplicity and reliability, their practical implementation under conditions of a two-level power supply is not feasible, due to the complexity of constructing a control system. This relates to the fact that when switching to power from a source of the higher level, it is required to increase PWM frequency, and this leads to an increase in the losses of dynamic power in IGB-transistors and to an increase in the electricity losses in the engine. These issues have remained insufficiently examined up to now and thus require a more detailed study. There is therefore a need to design a new structure for the converter of the structure inverter-TIM for conditions of power supply from sources of different levels.

3. The aim and objectives of the study

The aim of this study is to design a new structure of the converter that could power TID of mine electric locomotives from different voltage levels: CN and TAB.

To accomplish the aim, the following tasks have been set:

– to develop a structure of the power voltage inverter that could power TID from different voltage levels;

– to explore and analyze the harmonic composition of TIM power voltage;

– to analyze quality of the converted energy and to estimate energy losses in the TID elements by studying PWM of power voltage.

4. Analysis and development of a power converter structure to power TIM by different voltage levels

Implementation of frequency characteristic when the inverter is powered by voltage sources of different levels leads to problems in the realization of voltage PWM, which necessitates the research into this problem [13].

Part of the problems associated with the application of the vector sinusoidal voltage PWM is solved by employing a circuit of the traction electric drive, shown in the simplified form in Fig. 1 [14, 15].

According to this circuit, a three-phase converter consists of three single-phase inverter bridges UIA, UIB, UIC, each supplying power to its individual winding at engine M, respectively A, B, C. The phase windings A, B, C are not in contact electrically with each other and form an "open triangle".

In the alternative circuit, current loads on IGB-transistors in each shoulder of single-phase bridges are twice less than those in a standard circuit. Seemingly, this should lead to lower static power losses in IGB-transistors; this, however, does not happen because the current contour employs twice the number of IGB transistors than that in a standard circuit. In the case when ΔU voltage drops are equal:

– in a standard circuit $\Delta P=3UI$;

– in the alternative circuit $\Delta P=6UI/2$, that is, we obtain almost equal static power losses in IGB-transistors.

Energy is saved by reducing the dynamic power losses in IGB-transistors within the alternative circuit through a method of direct PWM voltage formation in line with the assigned law. Indeed, forming a positive half-wave of the output voltage involves the transistor modules DP and MP. In this case, the module MP is enabled constantly during a half-wave while DP modulates.

As a result, the bridge has two states:

– DP and MP are enabled; current flows along the circuit D(+)–DP–0–MP–M(–), voltage U_d is applied to winding;

– DP is disabled, MP is enabled; current flows along the circuit: A–MP–MN–A, A winding voltage is zero.

A dual-mode-powered TETC implements the following operation regimes in terms of a frequency characteristic [13, 16]:

– when loading or unloading, electric transport vehicles moves at minimum speed. The electric drive can be powered both by a traction accumulator battery (TAB) at voltage U_B and by CN at voltage U_n. In line with control law U_s/f_s= =const, a TETC accelerates to a speed proportional to frequency f_{SB};

– at higher speeds (frequencies f_s) along the road track, a higher voltage is required for the motor, which is provided by CN.

Control over the magnitude of voltage U_s of the motor is executed via PWM. At the end of the acceleration to frequency f_{Sn}, the motor is reset for a field weakening mode: U_{sn}=const, f_s=var up to the maximum frequency.

When powered by a contact network at frequencies $f_s \leq f_{SB}$, the frequency of modulation f_M of the converter output voltage should be roughly three times higher than that when powered by a low-level voltage source. This is necessary to ensure the pulsation of current in the motor within the permissible range. Accordingly, dynamic power losses in IGB-transistors, when compared to battery-powered at the same speed, increase. Fig. 2 shows diagrams of voltages and currents at modulation at the voltage level U_B.

Fig. 2 exhibits a fragment of voltage PWM for the case when modulation at voltage less than U_B is performed at the same frequency f_{MB}, powered both by the accumulator battery and by a contact network. It follows from the equality of pulse areas S_n=S_B:

$$U_n\tau_n = U_B\tau_B, \quad \tau_n = \frac{U_B}{U_n}\tau_B = \frac{80}{250}\tau_B \approx \frac{1}{3}\tau_B.$$

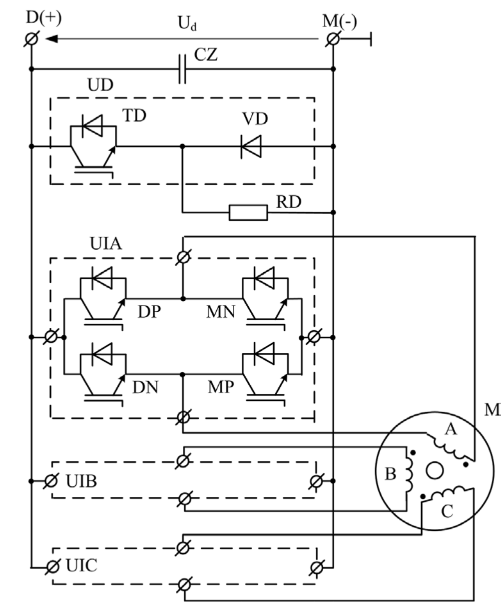

Fig. 1. Simplified circuit of alternative TID

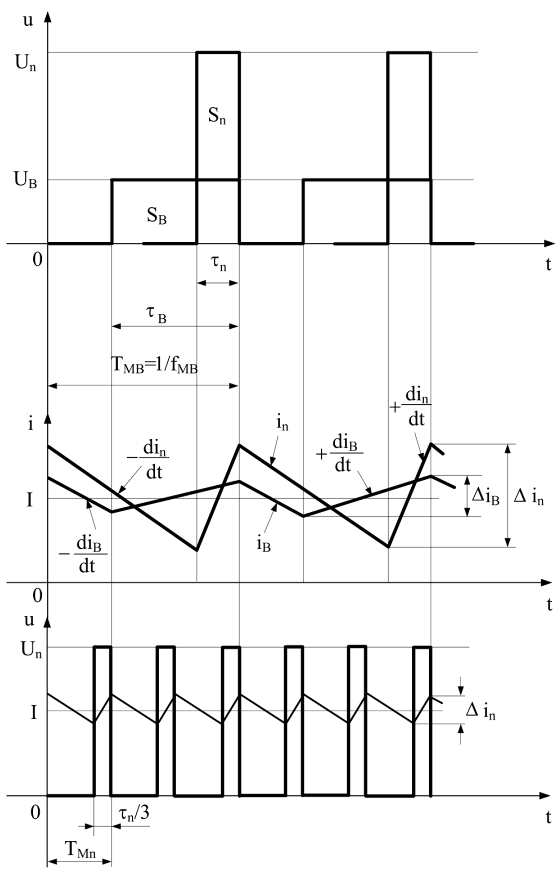

Fig. 2. Voltage and current diagrams at modulation at the voltage level U_B

In this case, currents of the motor will change in a manner shown in Fig. 2, where the descent fronts of currents i_n and i_B are, respectively, powered by a contact network and by the accumulator battery:

$$-\frac{di_n}{dt} = -\frac{di_B}{dt}.$$

Current ascent fronts:

$$\frac{di_n}{dt} \approx 3\frac{di_B}{dt},$$

with respect to:

$$\frac{di_n}{dt} = \frac{U}{L}.$$

As a result, the spread of the motor's current fluctuations when powered by a contact network will be unacceptably high. Hence the need to increase the modulation frequency $f_{Mn}=1/T_{Mn}$, at least by three times, as shown in Fig. 2; as noted above, that leads to an increase in dynamic power losses in IGB-transistors.

It is possible to avoid increasing the frequency of TID power voltage by aligning the levels of the converted voltages. This is achieved by constructing an algorithm to control the paired bridges of TIM power circuit. When powered by TAB and CN with a high level of output voltage, the parallel and synchronous activities are involved. When powered by a contact network with a low level of output voltage, the bridges disable adjacent IGB-transistors, while the extreme ones modulate.

The result is a single bridge, which powers the same sequentially connected motor's windings; each is given half of the converted voltage, comparable in magnitude with the voltage converted when powered by the accumulator battery. Thus, there occurs the levelling of voltages at a low level of output voltage; the result is that it is not required to increase the frequency of PWM. In addition, when connecting the windings sequentially in a single paired bridge, static power losses in IGB-transistors are twice, while the dynamic losses are four times, less than those in a standard inverter [15].

One of the means to align the voltage is to apply converters with a reconfigurable structure. Such converters include inverter units that can be connected in parallel or sequentially. When powered by a low-voltage source, inverter blocks are connected in parallel over the entire range of change in the output voltage. When powered by a high voltage source, inverter units are connected serially in the range of low output voltages and in parallel in the range of high output voltages.

A variant of the circuit for converter with a reconfigurable structure is shown in Fig. 3; the circuit is adapted to the alternative system of electric drive [14]. Instead of a vector PWM, we adopted a direct PWM of voltage. Control diagrams and fragments of curves for the converter output voltage are shown in Fig. 4, 5 for the case of simultaneous synchronous formation of a positive half-wave at the inverter 1UI and a negative half-wave in the inverter 2UI.

The interval τ_{0S} includes the enabled IGB-transistors 1D1, 2M1, and the thyristor 1S2 (Fig. 3). Thus, there forms a serial connection of windings of the motors 1MA and 2MA, and, consequently, the current flows along the circuit D(+)–1D1–1MA–1S2–2MA–2M1–M(–). In this case, voltage at each winding of the motor corresponds to the magnitude $U_d/2$.

The interval τ_0 includes the enabled IGB-transistors 2M1 and the thyristor 1S2, the IGB-transistor 1D1 is disabled, the current flows along the circuit 1MA–1S2–2MA–2M1–1M1–1MA, voltage at the windings is zero.

A change in the ratio of duration of intervals τ_0 and τ_{0S} in the modulation period T_M (a PWM process) adjusts the magnitude of voltage at each winding of the motor in the range from 0 to $U_d/2$ (Fig. 4).

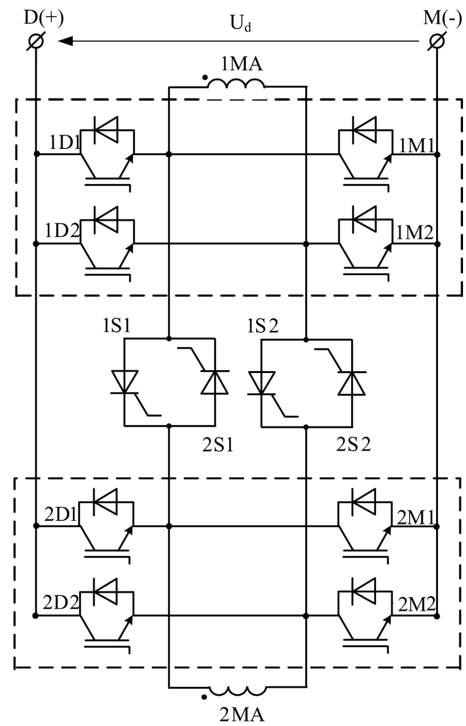

Fig. 3. Main diagram of reconfigurable inverter with intermediate thyristors

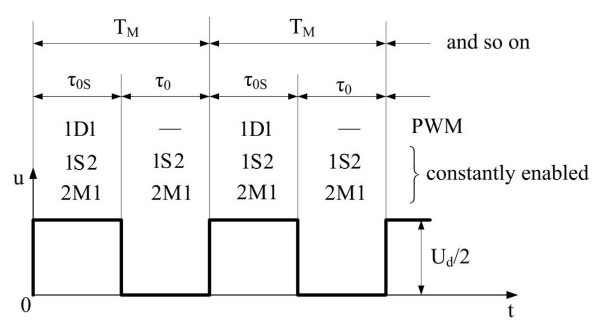

Fig. 4. Diagrams of converter output voltage in the range from 0 to $U_d/2$

Next, in order to increase the converted voltage above $U_d/2$, the circuit employs a control algorithm as shown in Fig. 5. The interval τ_1 includes the enabled IGB-transistors 1D1, 1M2, 2D2, 2M1; the currents flow along the parallel circuits D(+)–1D1–1MA–1M2–M(–) and D(+)–2D2–2MA–2M1–M(–); voltage U_d is applied to each winding of the motor.

The interval τ_{0S} includes the enabled IGB-transistors 1D1, 2M1, and the thyristor 1S2; the IGB transistors 1M1, 2D2 are disabled; $U_d/2$ at windings. The ratio τ_1 to τ_{0S} defines a range of the voltage change at windings $\left[\frac{U_d}{2}...U_d\right]$.

The integral sinusoid of output voltage $U_{m1}\sin\omega_s t$ at $U_{m1} > \frac{U_d}{2}$ is built based on the combination of algorithms as shown in Fig. 4, 5, specifically: from zero to $U_d/2$ – in line with algorithm $\tau_0 + \tau_{0s}$; from $U_d/2$ and above – in line with algorithm $\tau_{0s} + \tau_1$.

The advantage of the presented reconfigurable circuit of the inverter and a technique to control is a reduction in the number of switching semiconductor devices. Disabling the thyristors, for example, 1S2, does not require any specialized devices for a forced commutation. The thyristor 1S2 is disabled at a moment when the IGB-transistors 2D2–1M2 (τ_1 start) are enabled under the action of voltage from source U_d, applied to it in the opposite direction.

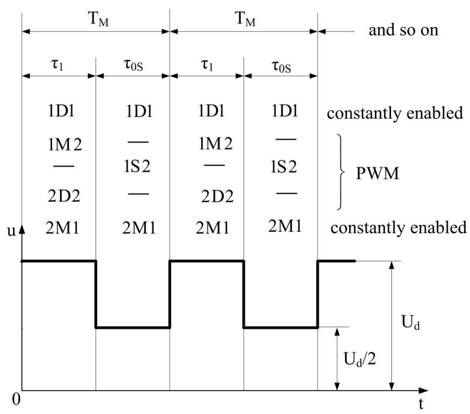

Fig. 5. Diagrams of converter output voltage in the range $\left[\frac{U_d}{2}...U_d\right]$

The circuit is adapted to the alternative system of electric drive as shown in Fig. 1 [14]. Instead of a vector PWM, we adopted a direct voltage PWM.

In contrast to the previous circuit, a transition from one algorithm to another takes place not in a smooth fashion, but rather through the state of zero current. Since the transition process lasts for milliseconds, it has no effect on the motion of TETC. A drawback of the circuit is a double current load on the IGB-transistors D1, D2, M1, M2.

5. Mathematical modeling of the voltage inverter in a traction electric motor

In order to examine and analyze the quality of energy conversion and to estimate losses in TID elements by investigating a power voltage PWM, we have developed a model of the structure of a reconfigurable inverter with intermediate thyristors. A model of the system is shown in Fig. 6; it includes the following units:

Unit 1 – Power supply system. A given unit simulates the operation mode of the inverter powered by the accumulator battery and a contact network.

Unit 2 – IGB-transistor converter consisting of two single-phase inverter bridges with intermediate thyristors [14, 15].

Units 3 and 4 – Open windings 1MA and 2 MA, respectively.

Unit 5 – IGB-transistor converter control system.

Unit 6 – Thyristor control system.

Unit 7 – Unit for switching the modes contact network–accumulator battery.

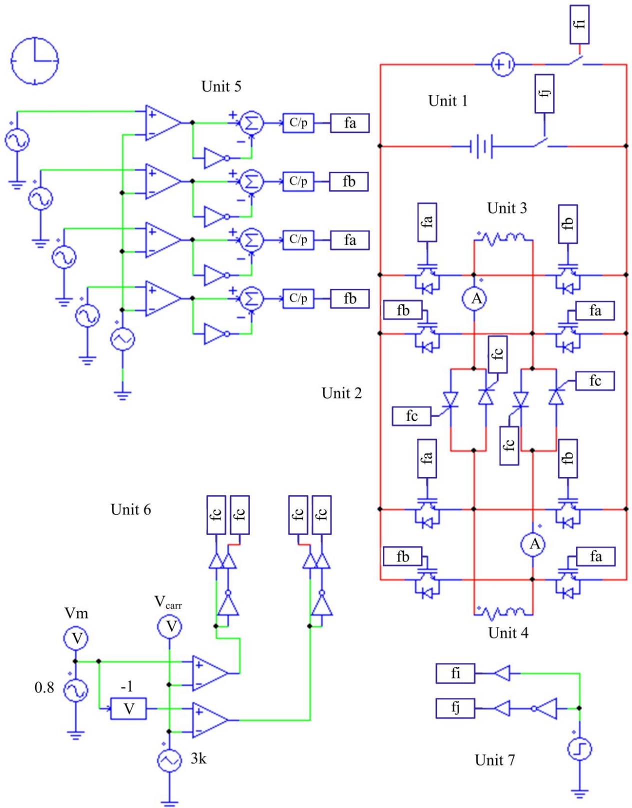

Fig. 6. Model of a power voltage inverter in the traction electric motor

The model implies a dual-mode power supply to the inverter: powered both by CN (275 V) and TAB (80 V). The two operating modes of the system were considered as a control regime:

– a system to form the power voltage for windings when they are connected in parallel (powered by TAB);

– a system to form the power voltage for windings when they are connected sequentially (powered by CN).

An analysis of harmonic composition of the output voltage and current in an autonomous voltage inverter, resulting from PWM, was performed at switching frequencies of transistor keys in the range from 2 to 6 kHz.

The results of modeling (Fig. 7) show that for PWM in line with a sinusoidal law the low-frequency voltage range includes only the main harmonic of frequency f_{out} (k=1). In the high frequency domain, the groups of composed harmonics are located near the frequencies that are multiple to the switching frequency f_n. The main harmonic amplitude at a bipolar PWM equals $UK_m/2$, where U is the voltage of a power source. The frequency of the n-th harmonic is calculated from:

$$f_k = af_n \pm bf_1, \quad (1)$$

where f_1 is the main frequency of the 1-st harmonic; f_n is the switching frequency of the inverter transistors; a is the multiplicity of group of high-frequency harmonics; b is the multiplicity of the main frequency in the group of the main harmonic.

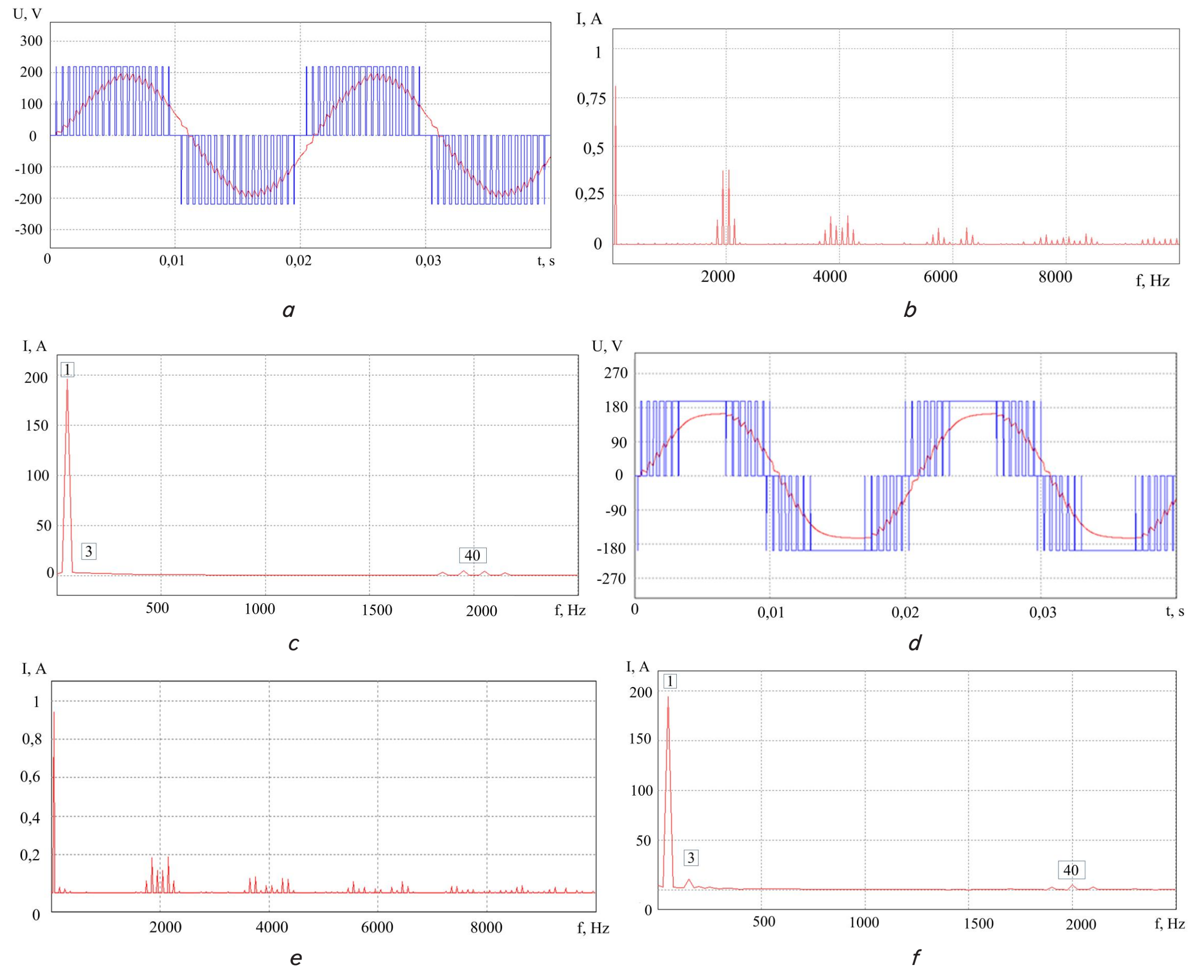

Fig. 7. Oscillograms of phase voltages and currents on the windings 1MA and their harmonic composition: *a* – voltage at sequential connection; *b* – current at sequential connection; *c* – harmonic current composition when connected in parallel; *d* – voltage when connected in parallel; *e* – current composition when connected in parallel; *f* – current composition when connected in parallel

An analysis has revealed that an increase in the frequency of a carrier signal leads not to the exclusion of a series of harmonic components from the spectrum of the output voltage of the converter, but rather to their shift towards the region of higher frequencies. This, in turn, could lead to an increase in the losses in TIM. Therefore, it is an important issue to select the optimal PWM frequency in order to minimize energy losses in TIM.

6. Discussion of results of modeling the power voltage inverter in a traction electric motor

As is known from [4, 7, 17], the intensity of higher harmonic components in the spectrum of a PWM-sequence characterizes a harmonics coefficient:

$$k_{\text{g.k.}} = \frac{C_e}{C_1} = \frac{\sqrt{\sum_{k=2}^{N} C_k^2}}{C_1}, \qquad (2)$$

where C_1 is the amplitude of the main harmonic in output voltage; k is the number of a harmonic; N is the quantity of harmonics.

At known parameters of load, coefficient $k_{g.k}$ makes it possible to determine the harmonics coefficient for the output current of the inverter:

$$k_{\text{g.i}} = k_{\text{g.k}} \frac{Z(f_{out})}{Z(f_k)}, \qquad (3)$$

where $Z(f_{\text{out}})$ and $Z(f_k)$ are the module of load resistance at the output frequency and at the frequency of switching. The accuracy of calculation based on expression (3) increases with an increase in the frequency of switching.

A double-sided modulation of fronts in the spectrum of a three-phase PWM reduces harmonic components near the switching frequency, while significantly increasing the components in the domain of the second harmonic in the frequency of switching [7].

These harmonics, despite their twice-as-large frequency, can significantly affect the load current, which has an inductive reaction for higher harmonics.

In the course of a study based on the model, we derived a dependence of harmonic coefficient K_g on frequency f of the output voltage, shown in Fig. 8.

As is known, the losses in the windings and steel of IM depend on the frequencies and amplitudes of harmonics of current and voltage, while an increase in the frequency of a carrier signal leads to an increase in the electrical losses in IM [18]. Electrical losses in the windings of IM due to the higher harmonic current are equal to:

$$\Delta P_{el.\nu}=\frac{K_n^2\Delta P_{el.nom}}{\nu}\left(\frac{U_\nu}{U_1}\right)^2, \quad (4)$$

where $\Delta P_{\text{el.nom}}$ are the electrical losses in windings under the rated mode for the first harmonic; K_{st} is the multiplicity of starting current (for the frequency-controlled TIM – 45 kW, accepted equal to K_{st}=4.2); U_v is the amplitude of voltage of a v – harmonic; U_1 is the voltage amplitude of the first harmonic.

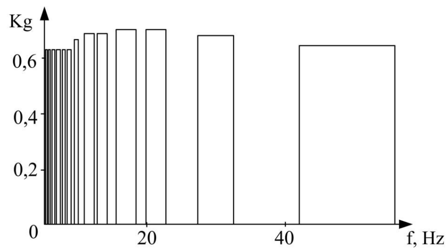

Fig. 8. Dependence of harmonic coefficient K_g on frequency f of the output voltage

A gain coefficient of electrical losses in the windings of IM due to the higher harmonic currents is determined from expression:

$$K_{el}=\frac{\Delta P_{el.nom}+\sum_{\nu=5}^{N}\Delta P_{el.\nu}}{\Delta P_{el.nom}}=1+K_n^2\sum_{\nu=5}^{N}\left[\frac{1}{\nu}\left(\frac{U_\nu}{U_1}\right)^2\right], \quad (5)$$

where $\Delta P_{\text{el.v}}$ are the electrical losses in the windings of IM for the v-th harmonic. A gain coefficient of electrical losses in IM steel magnetic circuit due to the action of higher voltage harmonics is:

$$K_{st}=\frac{\Delta P_{st.1}+\sum_{\nu=5}^{N}\Delta P_{st.\nu}}{\Delta P_{st.1}}=1+K_{h.h.st}\sum_{\nu=5}^{N}\left[\frac{1}{\nu^{0,7}}\left(\frac{U_\nu}{U_1}\right)^2\right], \quad (6)$$

where $\Delta P_{\text{st.1}}$ are the power losses in IM steel magnetic circuit under the rated mode for the first harmonic; $\Delta P_{\text{st.v}}$ are the power losses in IM steel magnetic circuit for the v-th harmonic; $K_{\text{h.h.st}}$ is the higher harmonics coefficient.

Results of determining the gain coefficients of electrical losses in the windings and steel of IM are shown in Fig. 9.

Electrical losses in the windings of IM are about 60 %, while losses in the steel magnetic circuit of an induction motor are 25 % of total losses [18]. Therefore, determining a gain coefficient for increasing losses in IM due to the effect of higher harmonics of voltage and current, at an increase in PWM frequency, is important when choosing the switching frequency of power keys in the converter and filter-compensating devices.

We have proposed the new structure of the converter, as well as a technique to control the inverter bridges in a TIM power supply unit. Control is executed via a direct PWM, which makes it possible to reduce the number of switches by power transistors in contrast to the systems of vector control.

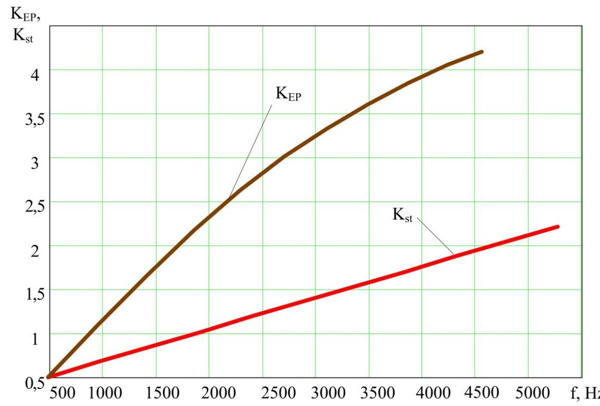

Fig. 9. Dependence of a gain coefficient of electrical losses in the windings of IM and a gain coefficient of losses in the steel magnetic circuit of IM on frequency f of the output voltage of voltage inverter

The reconfigurable structure of the converter makes it possible to power TIM by sources of voltage with different levels without changing the frequency of PWM, which was impossible to implement within the classic structure of the converter. This will reduce the level of electrical energy losses in the conversion circuit of TIM power voltage.

The disadvantages include the need to enable-disable a thyristor in the process of PWM, which, however, reduces the frequency capacity of PWM as the time to enable/disable a thyristor is an order of magnitude longer than that for an IGB-transistor. In addition, the presence of intermediate thyristors makes the device heavier. Therefore, in the future it is well worth considering the options for a reconfigurable circuit of the converter with intermediate IGB-transistors.

A theoretical study into the structure of mine contact-accumulator electric locomotives with a two-level TIM power supply is insufficient for a complete analysis of TETC operational modes in general. Therefore, the further advancement of our work is the development and investigation of an experimental sample of the inverter with a two-level TIM power supply.

The above capabilities of the proposed TID circuit make it a versatile one, capable to operate effectively both when powered by the accumulator battery and when powered by a contact network. The developed new structure of the contact- accumulator TETC paves the way for constructing new, energy-efficient and electricity-safe, samples of mine electric locomotives.

Results of this research are recommended for the further implementation at mine and industrial electric locomotives of appropriate types.

7. Conclusions

1. We have proposed a circuit of the inverter to power TID at mine electric locomotives by various sources (a contact network, a battery of traction accumulators) that can align the levels of TIM power voltage at a lower level. This is achieved by the appropriate algorithm to control the inverter bridges in the circuit of power supply. Owing to the levelling of voltage, a PWM frequency does not change, which in turn leads to a reduction of dynamic losses in

transistors, at least by 3 times, compared to a standard circuit of the inverter.

2. The research has found that the best indicators for a harmonics coefficient were obtained at frequencies from 10 to 30 Hz, which are the most common for the motion of an electric locomotive under the speed mode of 4–5 km/h (frequency 10 Hz) and at a haulage speed of 12 km/h (frequency 30 Hz), that is the operation mode of the converter is the most efficient at these frequencies.

3. The classic circuit of the inverter implies that in a transfer to a higher voltage level, as mentioned above, it is necessary to increase the frequency of PWM by 3 times. That will increase the coefficient of electrical losses in the windings of IM by 3.42 times, and the coefficient of losses in the steel magnetic circuit by 2.02 times. In the case of application of the proposed circuit for the inverter, voltage alignment at a low level does not require any increase in the frequency of PWM, which would not increase electric losses in IM.

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