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IMPROVING THE ENERGY CHARACTERISTICS OF A FOUR-QUADRANT CONVERTER WITH PULSE-WIDTH MODULATION

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The characteristics of the input energy converter of an electric locomotive with an induction traction electric drive were studied. The efficiency of the 4QS converter has been increased and the level of current harmonic distortions in the power supply system has been reduced. The research resulted in proposals for improving the control algorithm of the input energy converter to improve the traction-energy indicators of the electric drive and reduce the emission of high-frequency harmonics into the contact network. The results were obtained on the basis of simulation modeling of the "traction transformer – 4QS-converter" system on the example of the alternating current electric locomotive DS3 (Dnipro-Simens-3).

Modeling of the operation of the 4QS-converter of the electric locomotive was performed for the case of the maximum load of the drive under a traction mode. Two versions of the input converter control algorithm were studied and compared: the basic version of the DS3 electric locomotive and the modified version proposed by us. It was found that in the case of the basic variant of the converter control algorithm, conditions are created at certain time intervals when the capacitor of the constant voltage link on the secondary winding of the traction transformer is discharged under a traction mode. The consequence of this is a decrease in the efficiency factor of the converter and a deterioration of the harmonic distortion factor of the rectified voltage. In the modified algorithm, the discharge time of the capacitor of the constant voltage link on the secondary winding of the traction transformer is significantly reduced and the efficiency of the 4QS converter is increased

Keywords: 4QS converter, converter control algorithm, pulse width modulation, simulation model, energy characteristics, higher current harmonics

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1. Introduction

The induction traction electric drive is widely used in electric rolling stock all over the world, due to its high energy and technical and economic indicators. This type of electric drive is used by most modern passenger and freight electric locomotives, high-speed and super-speed electric trains. The use of 4QS converters on AC rolling stock is due to a number of functional capabilities necessary to improve the technical and economic indicators of electric rolling stock. 4QS-converters under a traction mode provide rectification, increase of the rectified voltage, and its stabilization in the constant voltage circuit (CVC).

Under the mode of regenerative braking, the converter works as a network-driven voltage inverter. A significant advantage of 4QS converters is the possibility of bidirectional transmission of electricity between the external power supply system and electric locomotives with a power factor close to unity, a reduction in the level of high-frequency harmonics and the approximation of the input current of the traction transformer (TT) to a sinusoid; significant increase in energy efficiency of AC electric drives. The significant advantages of 4QS converters make them an indispensable part of a modern electric drive. Leading European manufacturers of electric locomotives continue their work in the direction of improvement and creation of single and multi-system rolling stock using 4QS converters. In the future, their number and functional purpose will expand. The main energy performance of electric locomotives and its impact on the power supply system largely depend on the characteristics of 4QS converters. Therefore, studies of processes related to the operation of 4QS converters are currently important and necessary for improving their characteristics. Issues of improving the technical and economic characteristics of 4QS converters are considered in many works [1–16]. Technical solutions known today, which ensure the improvement of the energy characteristics of 4QS converters, can be conditionally combined into three main groups:

1) improvement of converter circuitry;
2) improvement of systems and their management algorithms;
3) increasing the switching frequency of power switches.

The power and efficiency coefficients, as well as the level of emission of high-frequency harmonics into the contact network, largely depend on the control system.

Improving the control algorithm of 4QS converters makes it possible to increase the efficiency and power of the converter, reduce the harmonic distortion of the current and voltage of the contact network, and reduce the level of voltage ripple in CVC.

Therefore, the research of transient switching processes of transistor IGBT modules of 4QS converters, energy parameters and harmonic voltage distortions of 4QS converters are relevant.

2. Literature review and problem statement

The issue of using 4QS converters on modern electric rolling stock and their further improvement are considered in many scientific works [1–16]. One of the main tasks set in these studies were attempts to solve the problem of compensation of higher harmonics and reduction of the level of harmonic current distortions in the power supply system of the electric locomotive based on the improvement of converter control methods and algorithms.

The task of improving the energy parameters of 4QS converters when implementing control systems with different types of modulation was set in articles [1, 2]. In particular, the structure of a converter with an active four-quadrant rectifier under the power factor correction mode is proposed in [1] using the example of a charging station for electric vehicles. The represented MATLAB model of the charging station takes into account the parameters of the power grid, the parameters of the switches of the active rectifier and its automatic control system, and the equivalent model of the battery compartment. In the work, the qualitative characteristics of the power supply, in particular, the harmonic distortion of the voltage of the 4QS converter, remained outside the scope of the analysis.

In [2], it is shown that the indicators of the quality of electric power and the power loss of an electric locomotive are significantly dependent on the control systems of 4QS converters. At the same time, the work does not formulate proposals for improving the quality indicators of electric power of the contact network.

According to the authors of work [3], improvement of the characteristics of the 4QS converter can be achieved using the proposed method of current control without transient processes. When setting up the control signal model of the constant voltage link, the concept of average power control was used. The work does not analyze ways of reducing the emission of high-frequency harmonics into the contact network.

Paper [4] discusses the use of soft switching methods in the branches of the 4QS converter. The effect that soft switching can have on the quality characteristics of multiport converters is shown. The paper does not analyze the influence of soft switching in the branches of the 4QS converter on the level of high-frequency harmonic voltage distortions in the contact network.

Classical and industrial four-quadrant DC/DC converters are compared in work [5]. The peculiarities of the operation of the converters under the reverse and regenerative braking modes are analyzed. The experimental characteristics of the new four-quadrant DC/DC converter of the second generation are presented. However, the quality characteristics of the power supply, namely the power factor and the harmonic distortion factor, are not analyzed in the work.

Works [6, 7] consider active rectifiers in the power conversion system of electric locomotives. In particular, work [6] provides an overview and schemes of an active rectifier, which, according to the authors, will make it possible to correct the power factor and eliminate higher harmonics of the input current. A number of requirements are given, on the basis of which the optimal rectifier scheme of the traction substation was chosen. However, the work does not contain ways of implementing the considered schemes. In article [7], a new bidirectional AC-DC multilevel converter based on four-quadrant switches is proposed. Despite the fact that the proposed converter works as an active rectifier, and as a grid inverter, and as a voltage inverter, its circuit is too complex for effective voltage control.

New or updated strategies for vector control of the rectifier, in contrast to the traditional ones, are considered in works [8, 9]. Solving the problem of voltage instability in the power supply network of the electric drive is based on the use of a spatial complex vector in a two-phase stationary coordinate system and a direct power control scheme based on an adaptive sliding mode observer. Both strategies are aimed at suppressing fluctuations in the dynamic characteristic of the voltage in the DC circuit,

In works [10, 11], the sources of distortions of electric locomotive power supply characteristics are analyzed due to the reverse influence of electric locomotives on the contact network, in particular, due to pantograph switching and the passage of contact inserts by the electric locomotive at the border of the contact network sections. The given analysis is very important for the development of algorithms for the compensation of higher current harmonics in the power supply system of electric rolling stock, however, the authors do not provide in their works a comparative quantitative analysis of the influence of these sources on the contact network of electric locomotives.

In [12], models of scalar and vector control of the output converter are proposed, taking into account asymmetric modes of operation of the electric drive. The starting characteristics of the traction drive for different control methods are obtained on the model. The analysis of the study results requires further research into algorithms for efficient control of converters due to the lack of quantitative assessment of the impact of various control methods on the qualitative characteristics of the voltage in the contact network of electric locomotives.

In [13], a study of power losses in an active rectifier with PWM is reported; it is indicated that the efficiency of the active rectifier does not exceed 76 %, which is a rather low indicator.

In [14], the algorithm for controlling the 4QS converter of an electric locomotive is considered, which allows improving the dynamic performance of the converter while minimizing harmonics in the network. However, the authors have not fully investigated the mutual influence of the power factor and the factor of higher harmonics of the power system.

Work [15] presents the developed methodology for determining the optimal parameters of pulse width modulation of a single-phase 4qs converter to minimize the reactive power of the converter. The features of the proposed method are the separation of the PWM parameter determination process into 2 stages. At the first stage, a pair of PWM parameter values are determined, at which the highest power factor of the electric locomotive drive is realized. At the second stage, the dependences of the efficiency and the coefficient of nonlinear distortion of the mains current on the clock frequency of the converters are determined. The rational value of the clock frequency (900...2000 Hz) was detere mined, at which the efficiency of the converter reaches the maximum value (98...95 %), and the coefficient of nonlinear distortions will be minimal (5...12 %). It was determined that the exclusion of the snubber link from the power circuit can significantly reduce the total electrical losses. It was established that the losses on the parasitic resistances of the filters are insignificant, so they can be disregarded in the overall balance of losses.

In [16], the algorithm for controlling the 4QS converter of an electric locomotive is considered, which allows improving the dynamic performance of the converter while minimizing harmonics in the network.

Article [17] gives a simulation mathematical model of the 4QS converter, which makes it possible to study the influence of control parameters on the qualitative and quantitative characteristics of the converter. The presented model needs clarification regarding the control laws (algorithms) of the converter switching keys.

The above review of information sources on this topic allows us to state that the possibility of improving the energy characteristics of 4QS-converters of electric locomotives due to the improvement of the control algorithms of pulse width modulation parameters has not been fully used. Therefore, there is reason to believe that there is a reserve for improving the energy characteristics of the four-quadrant converter with pulse-width modulation based on the modification of the control laws (algorithms) of the converter switching keys.

3. The aim and objectives of the study

The purpose of this work is to modify the switching key control algorithms of 4QS converters to improve their energy characteristics.

To achieve the goal, the following tasks were set:

– to propose an improved control algorithm for the 4QS converter;

– to determine the influence of the parameters of the control algorithm on the quality indicators of the 4QS converter.

4. The study materials and methods

The object of our research is electromagnetic processes in the 4QS converter of an electric locomotive. As a hypothesis of the research, the assumption about the possibility of improving the energy characteristics of the four-quadrant 4QS-converter due to the rational control of the current flow in the constant voltage circuit is accepted.

The study was performed on the basis of simulation modeling of the "traction transformer – 4QS-converter" system of the DS3 alternating current electric locomotive.

The simulation model was made on the basis of the Simulink MATLAB software package. The model is a subsystem of the general control system, which includes the PWM Generator (2-Level) unit, which forms pulses of pulse width modulation to control the 4QS converter.

The simulation of the operation of the 4QS-converter of the electric locomotive is carried out for the case of the maximum load of the drive – when the electric locomotive starts moving. Two versions of the input converter control algorithm were studied and compared: the standard version of the DS3 electric locomotive and the modified version that we proposed.

With the standard version of the control algorithm, when the polarity of the secondary winding of the traction transformer is changed, conditions are created for the flow of rectified current through the closed modules of the opposite arms of the converter from the constant voltage link to the circuit of the secondary winding of the traction transformer. With a modified version of the algorithm, a ban on such overflow is created programmatically.

Classical theory of electric circuits and methods of simulation modeling of converters were used. The calculation and study of the parameters of the electromagnetic processes of the 4QS-converter were performed on the basis of the calculation scheme of the replacement of the 4QS-converter. At the same time, the following simplifications and assumptions were adopted:

– transistor modules are considered as ideal key elements, which in the open state short-circuit sections of electric circuits, and in the closed state break them;

– the absence of pauses between signals for turning off and turning on transistors of one phase, to consider the change of state of transistors VT1 and VT2 or VT3 and VT4 as simultaneous.

The Simulink visual programming software, which is an application of the MATLAB package, was used for simulation modeling of electromagnetic processes of 4QS converters and determination of their energy indicators.

The study of the parameters of the electromagnetic processes of the 4QS converter was performed on the basis of the calculation scheme of the replacement of the 4QS converter shown in Fig. 1.

The control system of the 4QS converter using the sinusoidal pulse width modulation algorithm was investigated. A sinusoidal modeling voltage $U_M(t)=\sin(\omega t+\psi)$ with a frequency of $\omega=2\pi f$ is compared with a triangular clock voltage $U_T(t)=2/\pi\cdot\arcsin\left[\sin(\omega t+\pi/2)\right]$.

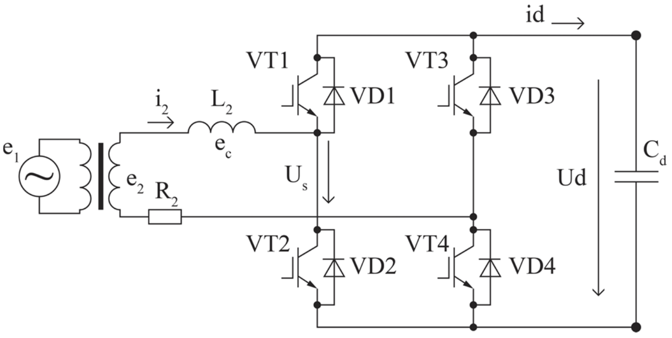

Fig. 1. Calculation scheme for replacing the 4QS converter: VT1–VT4 – IGBT modules; VD1–VD4 – reverse diodes of the modules; e_1, e_2 – electromotive forces of the windings of the traction transformer (TT); R_2, L_2 – respectively, the active resistance and dissipation inductance in the circuit of the secondary winding of TT

In the process of modeling, the multiplicity coefficient was used:

$$\varepsilon = f_T / f_M = 9, \tag{1}$$

where f_T, f_M are the frequencies of the clock and modeling signals, respectively.

The modulation depth $\mu=U_M/U_T$ was set to 0.8.

The state of the transistor modules VT1–VT4 is determined by the corresponding logical variables $S1$, $S2$. When the VT1 module is turned on, $S1=1$, when the VT1 module is turned off, $S1=0$.

The state of the single-phase module VT2, opposite to the state of VT1, is defined as the inversion of the logic variable $\overline{S1}$. Similarly, the state of the VT3 module corresponds to the logic variable $S2$, and that of the VT4 module – $\overline{S2}$. Taking into account the accepted notations, the switching function of the modules will take the form:

$$K(t)=\begin{cases}1\_\text{at}\_S1=1\_\_\text{i}\_\overline{S2}=1,\\ -1\_\text{at}\_e_2\le 0;\overline{S1}=1\_\text{i}\_S2=1,\\ 0\_\text{at}\_S1=1\_\text{i}\_S2=1,\\ 0\_\text{at}\_\overline{S1}=1\_\text{i}\_\overline{S2}=1.\end{cases}\tag{2}$$

In this case, the instantaneous value of the voltage at the input of the 4QS converter can be determined from the following expression:

$$U_S=K(t)\cdot U_d.\tag{3}$$

The effective value of the electromotive force of the secondary winding of the transformer in all variants of the study was taken to be equal to e_2=1300 V.

In the process of switching the modules, in accordance with the control algorithm, the secondary winding of TT is short-term closed and opened. In the time intervals in which the commutation function $K(t)=0$, the secondary winding of the transformer is closed by one of the transistor modules. The current i_2 in the circuit of the secondary winding of TT increases according to a linear law, electromagnetic energy is accumulated in the inductance L.

The equation for the circuit created after switching:

$$\overline{U_R}+\overline{U_L}=\overline{e_2},\tag{4}$$

where $U_L=L\cdot di_2/dt$ – voltage drop across the inductance L.

Upon subsequent opening of the transistor module, the electromotive force of self-induction $e_L=-L\cdot di_2/dt$ changes its sign due to the decrease in current i_2.

The voltage at the input of the 4QS converter, which opens the corresponding diodes VT1–VT4:

$$\overline{U_S}=\overline{e_2}+\overline{e_L}-\overline{i_2}\cdot R_2.\tag{5}$$

The accumulated electromagnetic energy enters CVC with the storage capacitor C_d (Fig. 2, *a*). The shift angle ψ is regulated by the phase shift of the modeling and clock signals in the PWM system and ensures the absence of a shift between the fundamental harmonics of TT voltage and current.

As a result of changes in the control algorithm, there is a lag of the first harmonic of the current relative to the emf of the secondary winding of TT and a decrease in the power factor. The power factor level close to unity is provided by the decrease in the phase shift angle ψ. The specific value of the phase shift angle is selected for each model in the range from $-\pi/3.4$ to $+\pi/3.6$ by trial and error from the maximum power factor condition.

During the U_S pulse, TT current i_2 decreases in absolute value. If we do not take into account the voltage drop on the diodes of the modules, the instantaneous values of the pulses U$_S$ are equal to the CVC voltage, i.e., $U_S=U_d$. Taking into account the last expression, the magnitude of the current in the circuit according to (5):

$$i_2=\frac{e_2+e_L-U_d}{R}.\tag{6}$$

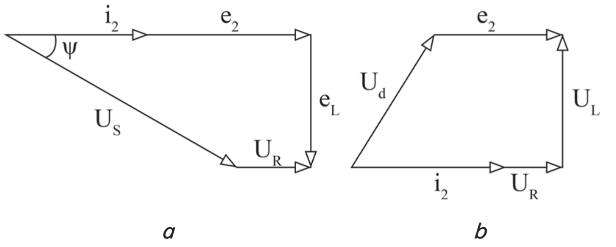

Fig. 2. Vector diagrams of the 4QS converter for the traction mode: *a* — when the energy is stored in the constant voltage circuit; *b* — when discharging the capacitor C_d

It can be seen from expression (6) that the current at the output of the 4QS converter $i_d\ge 0$ when the transistor modules of the opposite arms VT1, VT4, or VT2, VT3 are simultaneously open occurs only when the following condition is met:

$$e_2+e_L\ge U_d.\tag{7}$$

In the intervals of time when the specified inequality is not fulfilled, the current under a traction mode flows in the reverse direction from CVC to the TT winding, i. e., $i_d\le 0$.

This mode corresponds to the vector diagram (Fig. 2, *b*) and the voltage balance equation:

$$e_2+U_d=U_L+U_R.\tag{8}$$

Based on (8), the circuit voltage equilibrium equation, in which $i_d\le 0$, can be formulated by the following expression:

$$IF\left(OR\left(\begin{aligned}&AND\left(e_2\le 0;\ S1=1;\ \overline{S2}=1\right);\\ &AND\left(e_2\ge 0;\ S2=1;\ \overline{S1}=1\right)\end{aligned}\right);\ i_d\le 0\right).\tag{9}$$

When condition (9) is fulfilled, current i_d flows in the reverse direction under the action of voltage U_d through open modules VT1, VT4 at $e_2\le 0$ (Fig. 3), or through open modules VT2, VT3 at $e_2\ge 0$.

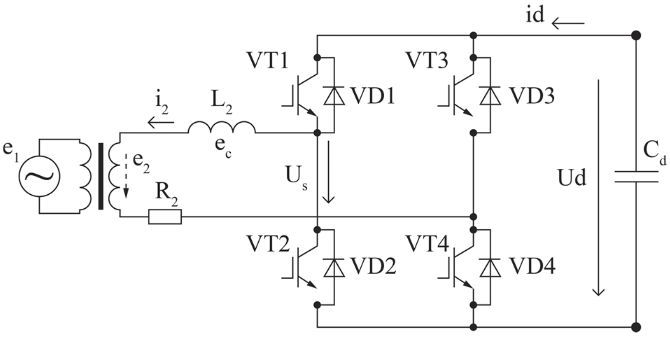

Fig. 3. Electric circuit of current i_d when condition (2) is fulfilled

At the same time, the direction of the current coincides with the direction of the emf e_2. The capacitor C_d is discharged to the secondary winding of TT.

In order to limit the duration of the i_d current flow in the reverse direction, the module control algorithm was changed to the standard algorithm (modified algorithm) in the form of a software ban on turning on the VT2 or VT4 modules depending on the polarity of the electromotive force e_2. At the same time, the possibility of simultaneous closing of the modules of the opposite arms after changing the polarity of the electromotive force e_2 is excluded. The modified algorithm in the VT2 and VT4 module control algorithm can be written in the form of a logical function:

$$IF\left(OR\left(\begin{matrix} AND\left(e_2 \le 0;\ S1=1\right); \\ AND\left(e_2 \ge 0;\ S2=1\right) \end{matrix} \right);\ i_d \ge 0 \right). \qquad (10)$$

In accordance with expression (10), we implemented in Simulink package a virtual model of VT2 and VT4 modules control system (Fig. 4).

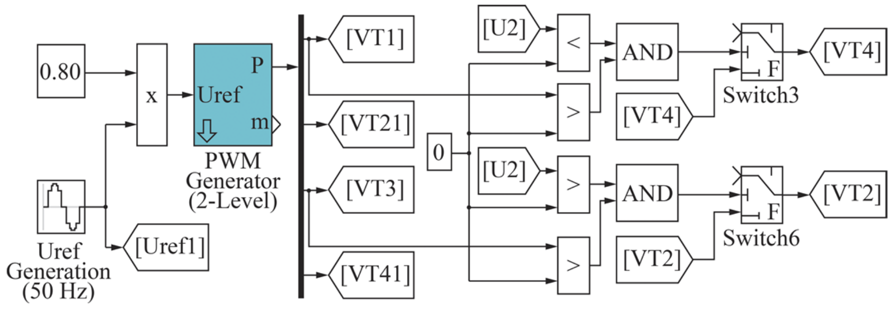

Fig. 4. Model of the control subsystem of IGBT-modules of the bridge VT1-VT4 with amendments, according to condition (10)

The given model is a subsystem of the general control system, which includes the PWM Generator (2-Level) block, which forms pulses of pulse-width modulation for controlling the VT1–VT4 modules according to the standard control algorithm.

5. Results of studying the energy characteristics of the four-quadrant 4QS converter

5. 1. Results of using the 4QS converter control algorithm

The results of simulation of transient processes are represented in the form of oscillograms in Fig. 5, 6. In Fig. 5, the current i_d in the circuit of the direct current link after changing the direction e_2 changes its sign (negative pulses i_d) and closes through the TT winding, i.e., $i_2=i_d$.

In the considered intervals, when the impulses i_d are negative, the directions of the current i_2 and the electromotive force e_2 in the TT winding coincide, that is, the secondary winding of TT does not transmit energy to the power system, therefore, the capacitor C_d discharges.

A similar situation occurs in the second half-cycle under the condition $e_2 \ge 0$, when modules VT2, VT3 are open at the same time.

In order to check the effectiveness of using the proposed control algorithm, a study of the models of two similar induction electric drives was carried out.

The first model is for controlling one converter with pulse-width modulation according to a standard algorithm.

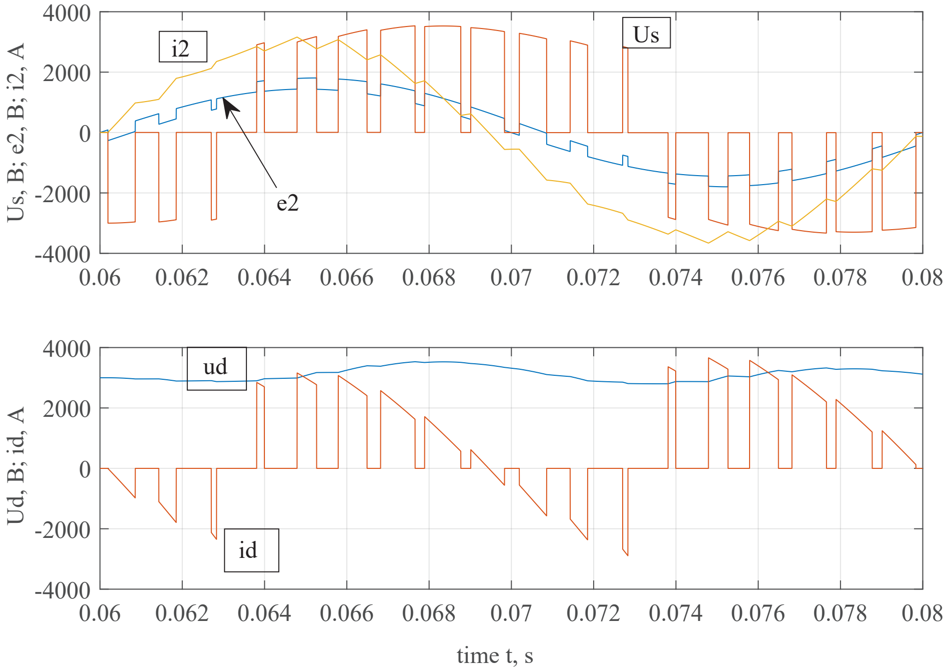

Fig. 5. Voltage and current oscillogram of the model when using the standard control algorithm of the 4QS converter

The second model is for controlling one converter with pulse-width modulation according to the modified algorithm.

5. 2. Analysis of the influence of control algorithm parameters on the quality indicators of the 4QS converter

The oscillograms in Fig. 6 of the voltage and current for the modified algorithm of controlling the IGBT modules of the bridge VT1–VT4 show that the duration of the negative pulses of the i_2 current and the duration of the discharge of the capacitor of the constant voltage link are significantly reduced.

Also, the discharge time of the capacitor C_d on the secondary winding of the traction transformer was significantly reduced. The discharge of the capacitor C_d is limited and takes place only at $e_2 \geq 0$ through open modules VT1, VT4, and at $e_2 \leq 0$, respectively, through – VT2, VT3.

At the same time, the magnitude of the voltage of the electromotive force e_2 of the secondary winding and the electromotive force of self-induction is not enough to open the valves VD1, VD4, or VD2, VD3.

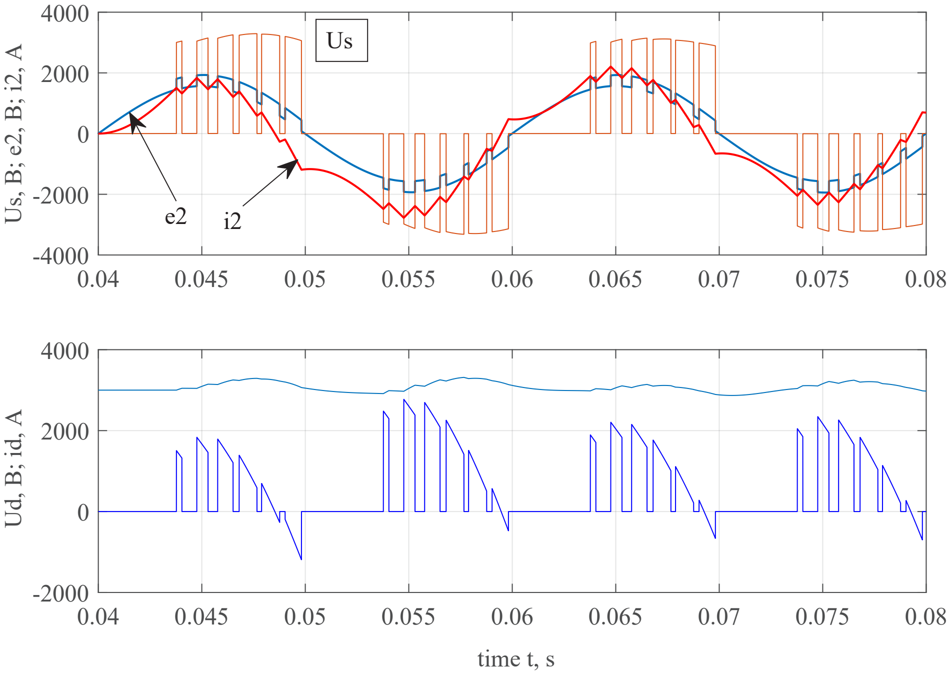

Fig. 6. Oscillograms of voltage and current for the modified algorithm of controlling the IGBT modules of the bridge VT1–VT4

To determine the efficiency, a section of the functional circuit of the converter was selected: the primary winding of TT, the 4QS-converter, the output circuit of CVC.

The efficiency is determined by the formula:

$$\eta = P_2 / P_1, \tag{11}$$

where P_1 and P_2 are, respectively, the value of the active power consumed by the primary winding of TT and the power transmitted from the constant voltage link to the autonomous voltage inverter. The value of the active power P is obtained by calculating the arithmetic mean value of the instantaneous value of the full power using the Mean block:

$$P = T^{-1} \int_0^T u(t) \cdot i(t) \mathrm{d}t. \tag{12}$$

The research was carried out by the method of mathematical modeling using the MATLAB software. A method that takes into account all parameters of both input and output currents and voltages was used to calculate the energy indicators of the link. At the same time, the active power at the input of TT and at the output of CVC was simultaneously calculated. At the same time, one of the Matrix Multiply blocks calculated the product of instantaneous values at the TT input $P_1 = u_1 \cdot i_1$, and the second – the product of instantaneous pulsations at the CVC output $P_2 = u_d \cdot i_d$.

The non-sinusoidal nature of the voltage and current and the phase shift and current distortion were taken into account in the calculations.

The simulation results are given in Table 1.

In Table 1, the data in the EXP1 column refer to the converter model with the standard control algorithm; EXP2 – to the converter model with a modified algorithm.

The degree of difference of the signal shape from the sinusoidal one was estimated by the coefficient of nonlinear distortions – THD (Total Harmonic Distortions). THD was calculated as the ratio of the sum of the powers of the higher harmonics to the power signal of its first harmonic.

Our results show that under a traction mode, as a result of changes in the control algorithm, the efficiency and the efficiency factor of the converter circuit increase. At the same time, the coefficient of harmonic distortion of the current of the primary winding of the traction transformer increases due to the action of harmonics $h3$, $h5$, $h7$, $h9$, $h13$ and $h17$, which are multiples of the main harmonic of 50 Hz. The simulation results that are given in Table 1 characterize the operation of a separate 4QS converter. Four 4QS converters are used in the traction electric drive of the electric locomotive, which are connected in parallel, and their control systems are synchronized. In the presence of several converters, the compensation of higher harmonics can be ensured by the mutual shift of the pulse-width modulation clock signals by an angle equal to $\phi = 2/360m$, where m is the number of converters connected in parallel to the secondary winding of the traction transformer.

At the same time, the phase shift of the clock signals in the scheme with four input converters had the following values: 0°, –90°, –45°, 45°. At the same time, different frequency multipliers were used in the implementation of the modified control algorithm of 4QS converters. Thus, pulse-width modulation of the first and third 4QS converters is carried out with a multiplicity of $\varepsilon = 9$, and of the second and fourth – with a multiplicity of $\varepsilon = 8$. Thanks to this, there is an additional decrease in the coefficient of harmonic distortion of the current to the level of THD=2.51 %. The modeling signals for the first and second converters are shifted by angles of 0° and –45°, respectively, and the modeling signals of the third and fourth converters are shifted by 45° and 90°, respectively. At the same time, the initial phase shift between the clock and modeling signals remains unchanged. As a result of phase shifts, some harmonics in the current of the primary winding of TT will be completely absent, others will be weakened.

Table 1

Energy parameters of the 4QS-converter with the control system according to the standard algorithm of sinusoidal pulse width modulation and according to the modernized algorithm

Model parameters	EXP1	EXP2
Efficiency of TT–CVC winding section	0.75	0.88
Power factor	0.99	0.998
Efficiency factor	0.74	0.878
Clock frequency, Hz	450	450
Harmonic current distortion coefficient THD i_1, %	4.6	14.6
Harmonic voltage distortion coefficient THD u_d, %	14.3	11.1

Fourier analysis of the input current of the primary winding of TT is shown in Fig. 7.

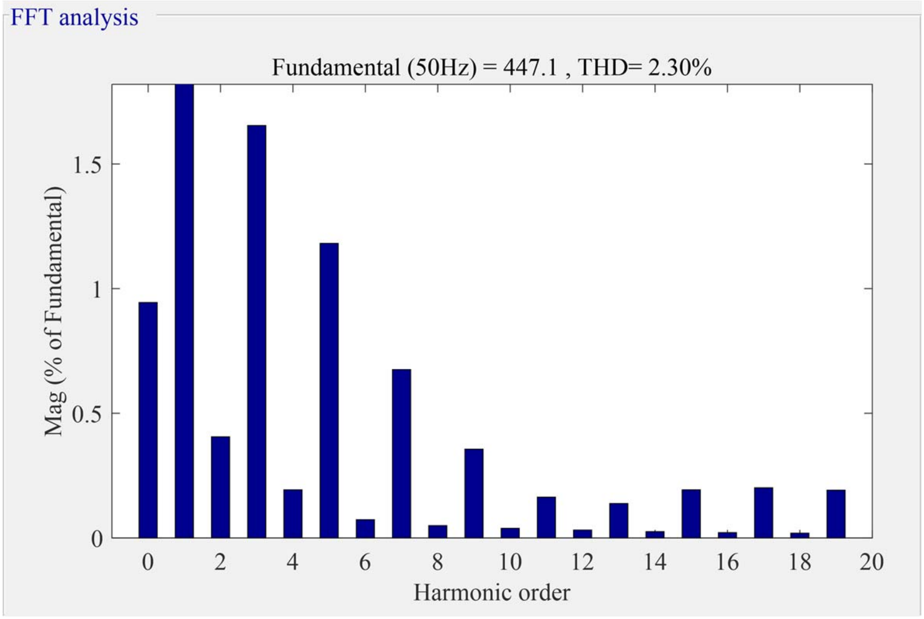

Fig. 7. Fourier analysis of the input current of the primary winding of a traction transformer during operation of four 4QS-converters

Our simulation results of the 4QS converter show that the main energy indicators are improved thanks to the use of the modified control algorithm: efficiency, efficiency ratio.

Reducing the level of harmonic current distortions can be implemented in the traction electric drive of an electric locomotive using four 4QS converters, which are connected in parallel.

Fourier analysis of the input current of the primary winding of the traction transformer during the operation of four 4QS converters shows that only harmonics No. 1, 3, 5, 7 have the largest amplitude. The remaining harmonics have an amplitude that does not exceed the level of 0.5 % of the amplitude basic harmonics.

6. Discussion of results of studying the energy characteristics of a four-quadrant 4QS converter

Based on the results of the study, changes were made to the control algorithm of power modules VT2 and VT4. The changes relate to the condition of reverse current flow in the secondary winding of the traction transformer – in accordance with (9).

With the standard control algorithm, when the polarity of the secondary winding of the traction transformer changes, conditions are created according to algorithm (9), in which conditions are created for the flow of rectified current through the closed modules of the opposite arms in the reverse direction, from the link of constant voltage to the circuit of the secondary winding of the traction transformer. At the same time, the share of active power transmitted to CVC is returned to the circuit of the secondary winding of TT.

The modified control algorithm provides for a ban on turning on the VT2 and VT4 modules after the EMF polarity of TT secondary winding changes in accordance with the logical expression (10). Thanks to the changes made, the duration of negative current pulses and the duration of discharge of the CVC capacitor are significantly reduced. This excludes the possibility of power flow from the CVC, which contributes to increased efficiency and the efficiency factor of the converter circuit.

The high level of power factor is obtained due to two factors:

– reducing the lag angle between the modeling voltage and the voltage of the secondary winding of the traction transformer;

– attenuation and compensation of harmonic distortions of the current by using the shift in the phase of clock frequencies, using different values of coefficients of multiplicity of clock frequencies relative to modeling ones. With the parallel operation of four synchronized 4QS converters working with a phase shift of the modulation clock signals, there is complete compensation or weakening of the level of high-frequency harmonics (Fig. 7).

The reduction of the harmonic distortion coefficient of the rectified voltage is obtained due to the reduction of the share of negative pulses in the rectified current. On the oscillogram in Fig. 6, the values of $i_2<0$ occur only in the transition zone of the voltage of the secondary winding of the transformer due to the zero value.

Thanks to this, an increase in efficiency and a smaller pulsation of the rectified voltage were also obtained.

Two-channel 4QS converter control system based on bilateral PWM is the most promising. However, its relative disadvantage is that under the traction mode, during the transfer of energy from the traction transformer to the DC link, part of the energy returns and is consumed in the secondary winding of the transformer.

With the help of a modified control algorithm, the opening of the modules of the opposite arms is prohibited according to the expression of the logical function (10), and the discharge intervals of the filter capacitor and energy loss in the constant voltage circuit are minimized. Thanks to this, the efficiency of the section of the TT-4QS-CVC converter increases. The advantage of this solution is also the relatively low switching frequency of the power switches (450 Hz).

Thanks to the use of a modified control algorithm, the efficiency of the TT-4QS-CVC section of the converter increases by 17 %. The algorithm with a reduced number of switching of power switches (450 Hz) additionally reduces dynamic losses in the switches and improves the efficiency of the converter as a whole.

The high level of the power factor (0.998), the reduction of the level of harmonic distortions of the current to 2.51 % and the voltage to 11.1 % indicate that the modified algorithm makes it possible to obtain higher energy characteristics in the traction electric drive of the electric locomotive using four 4QS converters, included in parallel.

Fourier analysis (Fig. 7) reveals that the range of high-frequency harmonics is significantly reduced due to their compensation or attenuation.

The limitations of the research are that the results obtained in the study process depend on a number of external factors and parameters of the converter. In order to obtain positive results in each specific case, there must be an adaptation to the specified factors, which in practical application is carried out by an automatic converter control system.

The shortcomings of the study include the fact that it does not take into account possible changes in the inductance of the primary winding of the traction transformer when the distance between the locomotive and the traction substation changes.

The development of this direction of research is the use of virtual models of an autonomous voltage inverter and an induction motor when the load changes. In the future, with the help of the developed virtual model, it is possible to study transient processes during the operation of the electric drive under traction and regenerative braking mode.

7. Conclusions

1. The proposed improvement of the power module control algorithm is based on a change in the reverse current flow condition in the secondary winding of the traction transformer, namely, a ban on turning on the power modules when the polarity of the electromotive force of the secondary winding of the traction transformer is changed. The difference between the improved algorithm and the existing ones is the use of different frequency multipliers: for the first and third 4QS-converters – with a multiplier of $\varepsilon=9$, and for the second and fourth – with a multiplier of $\varepsilon=8$. At the same time, the modeling signals for the first and second converters are shifted by angles from 0° to $-45°$, and the modeling signals of the third and fourth converters are shifted from 45° to 90°, respectively, while maintaining the initial phase shift between the clock and modeling signals.

2. As a result of the analysis of the influence of the control algorithm on the quality indicators of the 4QS converter, it was found that the quality indicators of the 4QS converter can be significantly improved by choosing a rational control algorithm. In particular, this allows improving the energy performance of 4QS converters of electric locomotives: the efficiency increases by 17 %, the current harmonic distortion coefficient decreases to 2.51 %. During the parallel operation of four synchronized 4QS converters operating with a phase shift of the modulation clock signals and different values of the multiplicity coefficients, the level of high-frequency harmonics is compensated.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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