У тягових електроприводах електрорухомого складу змінного струму використовуються діодні та тиристорні випрямлячі, які зумовлюють ряд недоліків. До таких недоліків відносяться значна емісія реактивної потужності та вищих гармонік струмів до контактної мережі, а також відсутність можливості реалізації рекуперації електроенергії до контактної мережі. В зв'язку з цим перспективним є застосування однофазних чотириквадрантних активних випрямлячів з корекцією коефіцієнта потужності. Перевагою цих перетворювачів є забезпечення коефіцієнта потужності близького до одиниці, реалізація синусоїдального вхідного струму, а також можливість реалізації рекуперації електроенергії до мережі живлення.

У системах керування активними випрямлячами досить поширеними є системи керування з гістерезисною модуляцією. Проте гістерезисна модуляція зумовлює необхідність реалізації високої та змінної частоти комутації силових ключів, що негативно впливає на втрати потужності в перетворювачі. Тому запропоновано систему керування з покращеною гістерезисною модуляцією. За рахунок удосконаленого алгоритму комутації силових ключів запропонована покращена гістерезисна система керування дозволяє знизити число перемикань силових ключів. Це дозволяє знизити динамічні втрати потужності в активному випрямлячі, що дає змогу збільшити ККД електрорухомого складу в цілому.

У програмі Matlab 2017b проведено імітаційне моделювання, що підтверджує ефективність запропонованого алгоритму модуляції. Крім того, під час реалізації запропонованого алгоритму комутації спостерігається покращення гармонічного складу вхідного струму. Підтверджено зниження амплітуд вищих гармонік вхідного струму та покращення результуючого коефіцієнта гармонічних спотворень

Ключові слова: активний чотириквадрантний випрямляч, гістерезисна модуляція, динамічні втрати, енергоефективність, коефіцієнт потужності

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RESEARCH INTO ENERGY CHARACTERISTICS OF SINGLE-PHASE ACTIVE FOUR-QUADRANT RECTIFIERS WITH THE IMPROVED HYSTERESIS MODULATION

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1. Introduction

Diode and thyristor four-zone rectifiers that are used by electric rolling stock (ERS) of alternating current have a series of shortcomings. They predetermine a significant emission of the current higher harmonics and produce a rather low power coefficient (0.65÷0.85), which significantly reduces energy efficiency of both ERS itself and the entire system of traction electricity supply [1, 2]. In turn, the presence in a traction electrical network of a significant reactive component of power leads to the need to use quite expensive reactive power compensators [3, 4].

It is promising to use active four-quadrant rectifiers with a power coefficient correction, known as 4QS converters, in ERS [5, 6]. In contrast to conventional thyristor rectifiers, 4QS-converters have a series of significant advantages [7, 8]:

– they provide the shape of current used close to the sinusoid;

– they produce a power coefficient close to unity;

– they ensure low level of high-harmonic current emission to the power supply network (the coefficient of harmonic distortions below 5 % can be ensured);

– they implement the bilateral transmission of electric energy;

– they ensure regulation and stabilization of voltage in a DC circuit.

The power scheme of the traction electric drive of electric rolling stock of alternating current with a 4QS-converter, which powers an autonomous voltage inverter (AVI) and a traction induction motor (IM), is shown in Fig. 1.

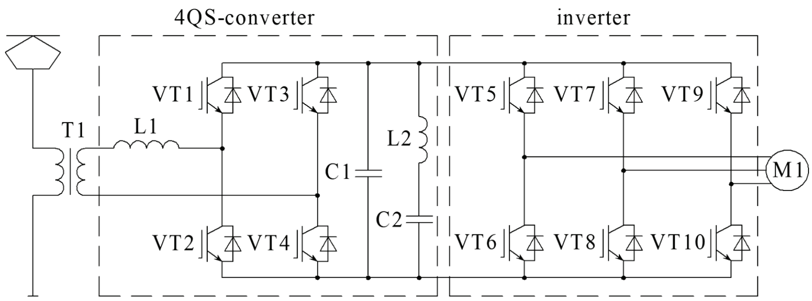

Fig. 1. Power scheme of a traction electric drive of electric rolling stock of alternating current with a 4QS-converter

In Fig. 1, an active four-quadrant rectifier consists of throttle L1, IGBT-transistors VT1÷VT4, capacitive filter C1, and rejector filter C2-L2. The capacitive filter C1 is used to reduce the pulse amplitude of output voltage, and the rejector link C2-L2 is intended to suppress the 100 Hz harmonic in output voltage.

2. Literature review and problem statement

The systems that control active four-quadrant rectifiers are a very important component as the indicators of electricity quality and power loss depend on them. Existing control systems based on width-pulse and hysteresis modulation in single-phase active four-quadrant rectifiers have a series of shortcomings [10–13]. In particular, the hysteresis modulation algorithms in active rectifiers predetermine high indicators of electricity quality but have significant losses of power. At the same time, control algorithms with a width-pulse modulation predetermine the worsened quality indicators of electrical energy and the need to use the higher frequency of power key switching.

Studies [14–17] show that the disadvantage of existing hysteresis CS (control system) is the presence of a sufficiently high and variable frequency of switching power keys, which leads to high losses of power. Papers [18, 19] report research into a single-phase active four-quadrant rectifier as part of the asynchronous electric drive. The disadvantage is that these papers contain almost no description of the control system, and the implemented shape of the input current of the active rectifier has a significant content of higher harmonics. The coefficient of higher harmonics in [19] is 8.1 %, and in [18] it is 21 %, which in both cases is a rather low indicator. In addition, according to [18], efficiency of the designed converter is 87 %, which is also quite low.

Paper [20] reports a research into power losses in an active rectifier with PWM; it is reported that efficiency of an active rectifier can reach 76 %, which is a quite low indicator.

3. The aim and objectives of the study

The aim of this study is to substantiate the use of a new algorithm of control over power keys in a single-phase active rectifier and to investigate energy indicators during its implementation, namely the formation of an input current close to the sinusoid, with a reduced number of switching power keys and, consequently, with the reduced dynamic losses and improved efficiency of the transducer.

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

– to analyze and identify shortcomings in the existing hysteresis control system of an active rectifier;

– to investigate a possibility of reducing the number of switching of power keys and improving the sinusoidal character of input current in an active rectifier when using the proposed algorithm of control over power keys for an active four-quadrant converter;

– to perform the approximation of energy characteristics of power IGBT for the calculation of static and dynamic losses of power in an active rectifier with the basic and improved control system;

– to confirm reliability of reducing the dynamic losses in an active rectifier when implementing the proposed algorithm by simulation modeling employing the MATLAB 2017b software.

4. Basic hysteresis control system

The principle of forming a sinusoidal input current by a 4QS-converter with the basic (known) hysteresis CS is shown in Fig. 2.

The principle implies comparing the signal for setting input current i_{in}^{*} with an actual instantaneous value of the input current i_{in} and receiving an error signal Δi [21].

Next, the unit of hysteresis modulator caries out a comparison between the error signal Δi and the preset hysteresis setpoint h.

Under condition $\Delta i > h$ when the instantaneous current value exceeds its setting signal by the magnitude h, the control system sends a disable signal to the pair of power transistors VT1 and VT4. This causes the switching of the input current with a decrease (reduction) in its instantaneous value.

Similarly, under condition $\Delta i < -h$ when the value for an instantaneous input current relative to its setting signal is less by the magnitude h, the control system sends an enable signal to the pair of power transistors VT2 and VT3.

At the same time, there is an increase in the instantaneous value i_{in}. The iterative implementation of this algorithm provides for the creation of a sinusoidal current corridor [22, 23].

When activating the transistors VT1 and VT4, the input throttle is fed, from the active converter, a voltage of DC circuit $+U_{out}$, which is higher than the amplitude value of the input voltage. This causes a drop in the instantaneous value of input current. Conversely, enabling the pair of transistors VT2 and VT3 causes an increase in the instantaneous value of the input current.

Thus, each switching of input current switches all four power keys, which, under condition of a sufficiently high frequency of switching, predetermines rather high dynamic losses in the converter.

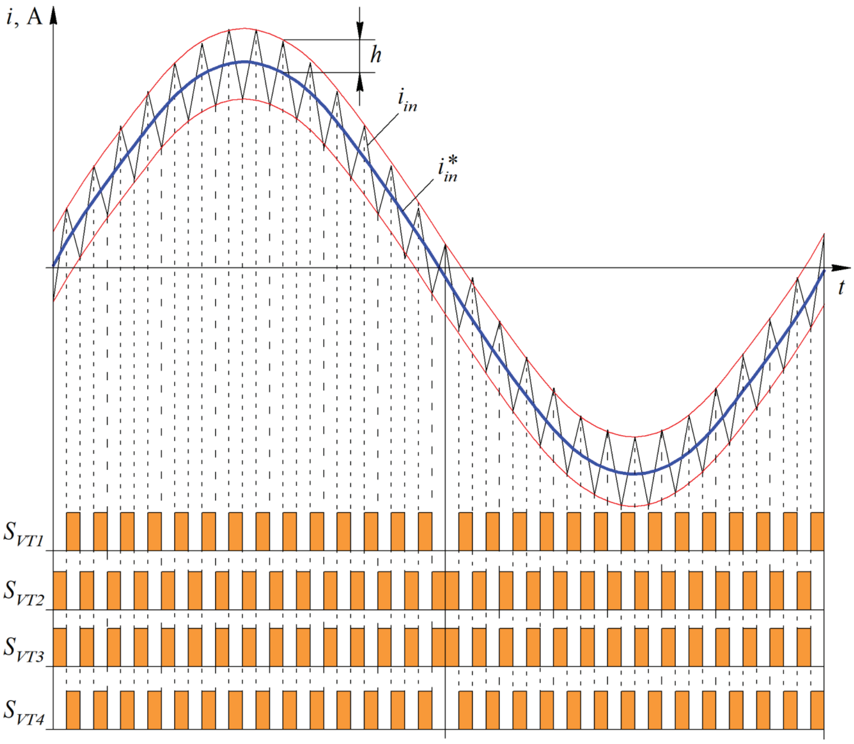

Fig. 2. The principle of forming a sinusoidal input current by a 4QS-converter with the basic hysteresis control system

the stages of input current switching, at which the switching of respective power keys does not occur.

Table 1

Power key switching sequence at the improved hysteresis modulation

Power key	Switching positions of power keys at the positive polarity of input voltage			
VT1	0	1	1	1
VT2	1	0	0	0
VT3	0	0	1	0
VT4	1	1	0	1
$I_{in}(t)$	ascends	decends	ascends	decends
Step	Step 1	Step 2	Step 3	Step 4
Power key	Switching positions of power keys at the negative polarity of input voltage			
VT1	0	1	0	0
VT2	1	0	1	1
VT3	1	1	1	0
VT4	0	0	0	1
$I_{in}(t)$	decends	ascends	decends	ascends
Step	Step 1	Step 2	Step 3	Step 4

5. Improved hysteresis control system

We have synthesized the improved algorithm of hysteresis modulation in an active four-quadrant converter, which makes it possible to decreasing the number of switching of power keys and thereby reduce dynamic losses in the converter. It is proposed that the sequence of switching of power keys should be supplemented with switching states for simultaneously enabling the pair of transistors VT1 and VT3 and the pair of VT2 and VT4. These switching states, at the positive polarity of the input voltage, predetermine an increase in the instantaneous value of input current, and at the negative polarity of input voltage, they contribute to a decrease in the input current. That makes it possible, during a positive semi-wave of input voltage, to switch from the VT1–VT4 switching position to the VT1–VT3. In this case, the instantaneous value of input current changes from a descending state to the ascending, but, unlike the basic switching algorithm, only two power keys are switched in this case. At the negative polarity U_{in}, one can also use short-circuited positions: switching from the VT2–VT3 switching position to VT1–VT3.

The proposed improved algorithm for the switching of power keys consists of six switching positions, given in Table 1, in which gray color shows

The principle of forming a sinusoidal input current by a 4QS-converter with the proposed hysteresis CS is shown in Fig. 3. It should be noted that the advantage of the proposed algorithm is that all four keys of the modulation algorithm have the same dynamic losses.

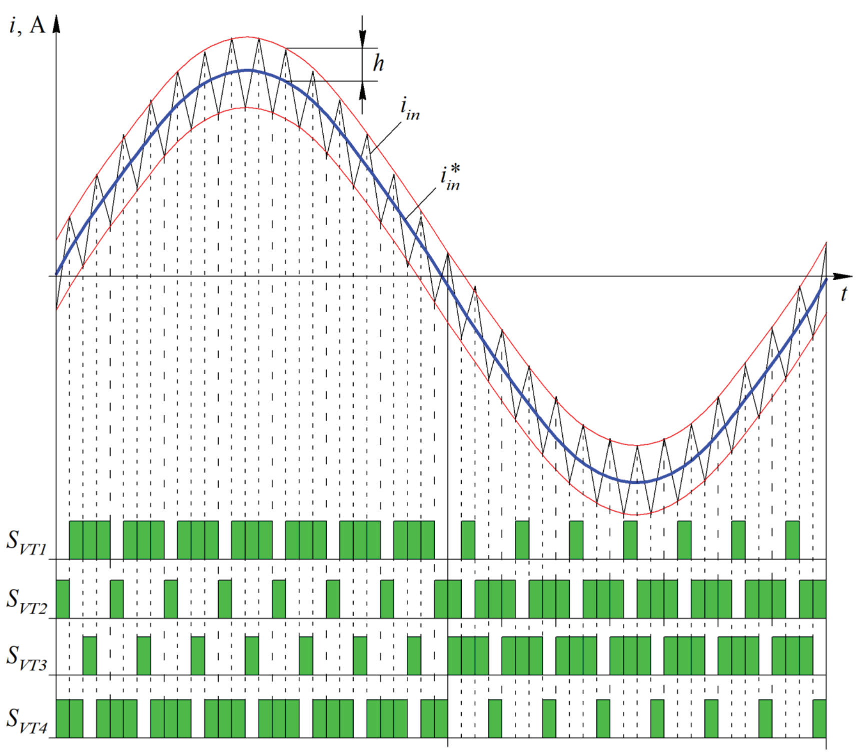

Fig. 3. The principle of forming a sinusoidal input current by a 4QS-converter with the proposed hysteresis control system

Fig. 3 and Table 1 demonstrate that the proposed switching algorithm makes it possible to reduce the number of keys switches. This decreases the overall dynamic loss in the keys of the 4QS-converter with the hysteresis control system by up to 50 %, thereby improving its efficiency.

6. Determining power losses in power keys

To determine the energy-saving effect from implementing the improved hysteresis algorithm of hysteresis modulation, we calculated power losses in the active four-quadrant converter at its output voltage of 3,000 V [24].

The calculation was performed using the power IGBT-keys with a rated voltage of 4,500 V, the type of CM1200HG-90R [25].

Basic parameters for the transistor CM1200HG-90R are given in Table 2.

Table 2

Boundary parameters for transistor CM1200HG-90R

Parameter	Value
Voltage between the collector and emitter, V	4,500
Voltage gate-emitter, V	±20
Permissible loading direct current, A	1,200
Permissible pulse current, A	2,400
Insulation voltage, V	10,200
Permissible temperature of transistor, °C	–50÷150

The actual oscillographs of the process of current and voltage switching for the power IGBT-key CM1200HG-90R are shown in Fig. 4.

In calculations, the total power losses in power transistors are divided into two components: static and dynamic losses [26].

The power losses in IGBT-transistors can be determined by calculating the static P_{DC} and the dynamic P_{SW} losses in the IGBT-transistors and parallel diodes [27, 28].

$$P = P_{DC} + P_{SW}, \tag{1}$$

where P_{DC} are the static losses in the IGBT-transistors; P_{SW} are the dynamic losses in the IGBT-transistors.

The static power losses P_{DC} in the power IGBT-transistors are determined from expression:

$$P_{DC} = \int_{t_2}^{t_3} U_{ce} \cdot I_c \cdot \mathrm{d}t, \tag{2}$$

where U_{ce} is the voltage drop between the collector and emitter of the transistor; I_c is the current of the transistor's collector; α is the fill coefficient at modulation.

The dynamic power losses P_{SW} in the power IGBT-transistors are determined from expression:

$$P_{SW} = \left(E_{on} + E_{off}\right) \cdot f, \tag{3}$$

where E_{on} is the energy that dissipates in the transistor when activated; E_{off} is the energy that dissipates in the transistor when deactivated; f is the switching frequency of power keys.

$$E_{on} = \int_{t1}^{t_2} U_{ce} \cdot I_c \cdot \mathrm{d}t, \tag{4}$$

$$E_{off} = \int_{t3}^{t_4} U_{ce} \cdot I_c \cdot \mathrm{d}t. \tag{5}$$

Energy characteristics of the power transistor CM-1200HG-90R are shown in Fig. 5. Fig. 5, *a* shows a voltage dependence between the collector and emitter on a load current. Fig. 5, *b* shows the dependence of transistor switching energy on a load current.

In practice, power losses are determined according to specifications for each specific power IGBT-transistor.

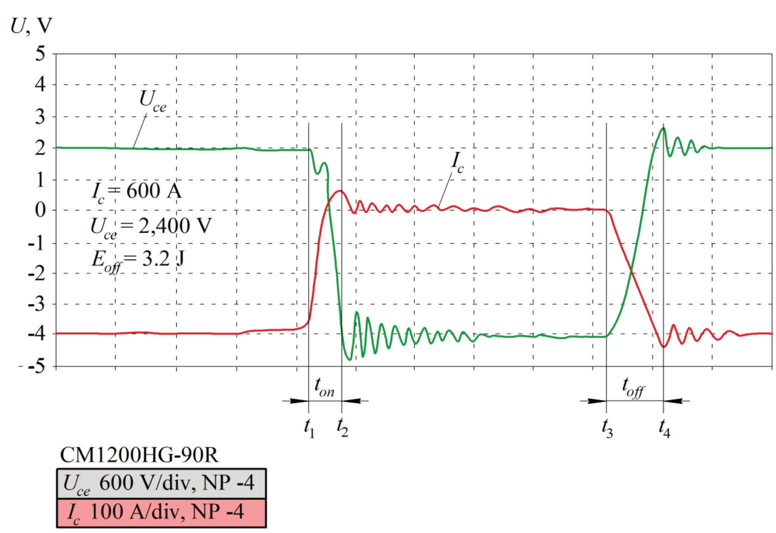

Fig. 4. The process of current and voltage switching for the power IGBT-key CM1200HG-90R

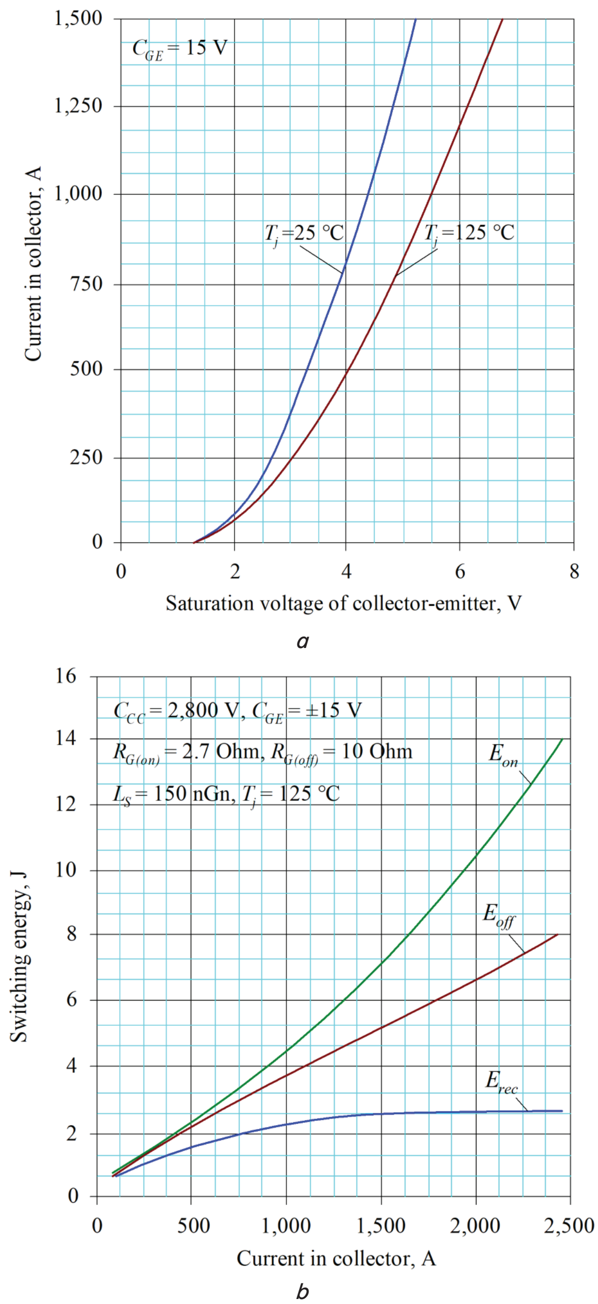

Fig. 5. Energy characteristics of power transistor CM1200HG-90R: *a* – dependence of voltage between the collector and emitter on a load current; *b* – dependence of transistor switching energy on a load current

7. Calculating power losses in the IGBT-transistors by approximating their energy dependences

To perform automated calculation of power losses in the power IGBT-keys, the volt-amper characteristics of the transistor and the dependences of activation energy and deactivation energy on a load current were approximated by the least square method [29]. The least square method is based on the principle of minimizing the sum of squares of the deviations of some functions from the desired variables [30]. Approximation can be performed using different-order polynomials. The greater the power of the polynomial that describes the order of the equation, the higher the accuracy. At the same time, increasing the power of a polynomial complicates calculation and prolongs simulation time.

The result of the approximation of the volt-ampere $U_{ce}(I)$ characteristic of the power IGBT-transistor CM1200HG-90R by polynomial functions of the fifth, fourth and third order is recorded in the following expressions:

$$U_{ce5}(I)=0.7622\cdot I^5-4.4108\cdot I^4+$$
$$+9.6859\cdot I^3-10.245\cdot I^2+7.1998\cdot I+1.0169, \quad (6)$$

$$U_{ce4}(I)=-0.5901\cdot I^4+2.9832\cdot I^3-$$
$$-5.311\cdot I^2+5.8917\cdot I+1.0803, \quad (7)$$

$$U_{ce3}(I)=0.5776\cdot I^3-2.3224\cdot I^2+4.6356\cdot I+1.1783. \quad (8)$$

In expressions (6) to (8), current is given in kA.

The dependence of reliability of the approximation (R^2) of the relative calculation error $U_{ce}(I)$ on the order of the equation is given in Table 3.

Table 3

Approximation reliability parameters

Degree of polynomial approximation $U_{ce}(I)$	Approximation reliability (R^2)
$U_{ce3}(I)$	99.72
$U_{ce4}(I)$	99.89
$U_{ce5}(I)$	99.96

Dependence of the relative calculation error $U_{ce}(I)$ on the order of the equation is given in Table 4.

The results from approximating the volt-ampere characteristic by the fifth-order polynomial showed that the relative reduced error does not exceed 1 %, which ensured sufficient accuracy of calculation. Therefore, the polynomial function of the fifth degree has been chosen for the approximation.

The dependences of power-on energy $E_{on}(I)$, power-off energy $E_{off}(I)$, and recuperation energy $E_{rec}(I)$, on a load current are approximated by using expressions:

$$E_{on}(I)=-0.1543\cdot I^5+0.8469\cdot I^4-$$
$$-1.2428\cdot I^3+1.0141\cdot I^2+3.6928\cdot I+0.3506, \quad (10)$$

$$E_{off}(I)=0.2133\cdot x^5-1.2646\cdot x^4+$$
$$+2.9355\cdot x^3-3.3899\cdot x^2+4.875\cdot x+0.3208, \quad (11)$$

$$E_{rec}(I)=-0.1871\cdot I^5+1.1556\cdot I^4-$$
$$-2.5588\cdot I^3+1.7071\cdot I^2+1.6364\cdot I+0.5092. \quad (12)$$

In expressions (10) to (12), current is given in kA.

The results from approximating energy characteristics of the power transistor C1200HG-90R are shown in Fig. 6.

The results of calculating power losses for the classical hysteresis modulation and the improved hysteresis modulation are given in Table 4. The calculations conducted show that using the proposed algorithm for switching power keys makes it possible to reduce power losses in power keys.

Table 4

Dependence of the relative calculation error on the order of the equation

Collector current, I, A	U_{ce} according to specifications for transistor, V	U_{ce5}, V	Relative reduced error for calculating by the fifth-order polynomial, %	U_{ce4}, V	Relative reduced error for calculating by the fourth-order polynomial, %	U_{ce3}, V	Relative reduced error for calculating by the third-order polynomial, %
0.00	1.01	1.02	–0.68	1.08	–6.96	1.18	–16.66
0.10	1.65	1.64	0.38	1.62	1.86	1.62	1.87
0.20	2.15	2.12	1.50	2.07	3.76	2.02	6.18
0.30	2.50	2.48	0.70	2.45	2.18	2.38	4.98
0.40	2.75	2.77	–0.81	2.76	–0.47	2.70	1.89
0.50	3.00	3.01	–0.48	3.03	–1.15	2.99	0.41
0.60	3.20	3.23	–0.89	3.27	–2.23	3.25	–1.51
0.70	3.40	3.43	–0.82	3.48	–2.46	3.48	–2.45
0.80	3.65	3.62	0.76	3.68	–0.83	3.70	–1.27
0.90	3.83	3.82	0.25	3.87	–1.14	3.89	–1.71
1.00	4.05	4.02	0.77	4.05	–0.10	4.07	–0.47
1.10	4.20	4.20	–0.04	4.24	–0.99	4.24	–0.86
1.20	4.40	4.39	0.19	4.43	–0.77	4.39	0.12
1.30	4.55	4.57	–0.55	4.63	–1.82	4.55	0.03
1.40	4.75	4.75	0.01	4.84	–1.85	4.70	1.03
1.50	4.90	4.91	–0.28	5.05	–3.04	4.86	0.90
1.60	5.05	5.07	–0.37	5.26	–4.21	5.02	0.68
1.70	5.20	5.22	–0.35	5.48	–5.29	5.18	0.29
1.80	5.38	5.37	0.09	5.68	–5.70	5.37	0.16
1.90	5.60	5.54	1.10	5.87	–4.88	5.56	0.65
2.00	5.70	5.74	–0.72	6.04	–6.03	5.78	–1.42

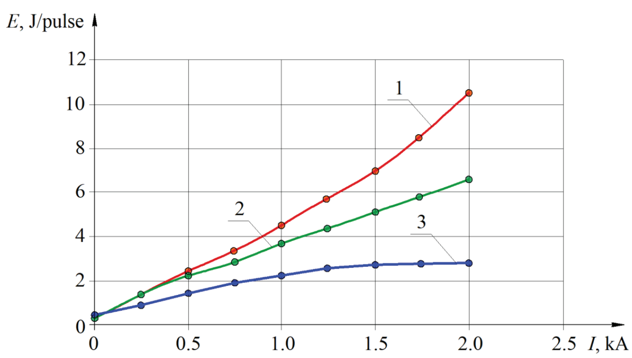

Fig. 6. Results from approximating the dependence of power-on energy (1), power-off energy (2), and recuperation energy (3), on a load current

8. Simulation modeling of an active four-quadrant rectifier as part of the traction asynchronous electric drive

To confirm the reduction of dynamic losses of power and the improvement in the quality of input current of the active rectifier, we employed the MATLAB 2017b programming environment to construct a simulation model. The devised simulation model describes the electromechanical system of the main electric locomotive of alternating current DS-3, namely the 4QS–AVI–IM system. Parameters for the electric locomotive DS-3 are given in Table 5.

The simulation model implements the basic and improved hysteresis control system for an active four-quadrant converter. The basic parameters for the simulation model are given in Table 6. The model describes the electromagnetic processes in an active four-quadrant converter with the basic and improved hysteresis modulation of the electromechanical system (Fig. 7).

Table 5

Parameters of the electric locomotive DS-3

Parameter	Value
Voltage in contact network, kV	25
Output voltage of traction transducer, V	800
Output voltage of 4QS-converter (voltage in a direct current circuit), V	1,400
Input inductance of 4QS-converter, mH	0.5
Capacitance of output condenser, mF	24
Load current, A	200÷1,200

Table 6

Basic simulation model parameters

Parameter	Value
Sampling time of simulation model calculation, μs	1
Permissible simulation error, %	0.1
Amplitude value for the input voltage of an active four-quadrant converter, V	600
Value for regulation coefficient ξ	1÷2.5
Input inductance, mH	0.4÷0.8
Active impedance of input inductance, mOhm	15
Filter capacitance in a direct current circuit, mF	3
Rated voltage in a direct current circuit, V	600÷1,500
The rms value of the load current of an active converter, A	590
Parameters for a traction engine based on type	CTA1200

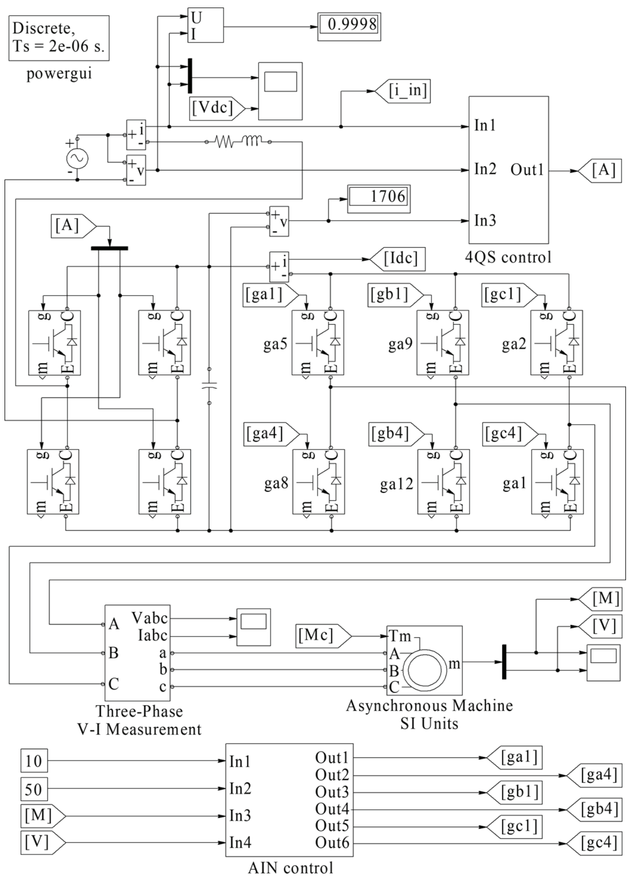

Fig. 7. Simulation model of the electromechanical system 4QS–AVI–IM

Simulation was carried out when solving differential equations describing the models, using the ode23tb operator that employs using an implicit Runge-Kutta method at the beginning of solving, and a method that uses the inverse differential formulae of the second order afterwards. Permissible relative calculation error is 0.01 %.

To assess the dynamic losses in the power transistors of an active four-quadrant converter, the model employed a counter of power-on/off signals for power keys.

It is worth noting that using the proposed algorithm for switching power keys in order to implement a hysteresis modulation leads to a reduction in the amplitudes of input current higher harmonics and a simultaneous expansion of its spectrum. Results from simulating the system of a traction electric drive at the value of input inductance 0.4 mH and the hysteresis setpoint of 20 A are shown in Fig. 8.

The results obtained from simulation modeling confirm a decrease in the number of switches of power keys and, accordingly, the reduction in dynamic losses. Given that the frequency of power keys switching is variable, its assessment was performed based on the averaged values for a power voltage period.

Table 7 shows the energy characteristics of 4QS-rectifier when implementing different magnitudes of input inductance and different magnitudes of the hysteresis setpoint (voltage in the dc circuit is 1 kV, a load current is 200 A).

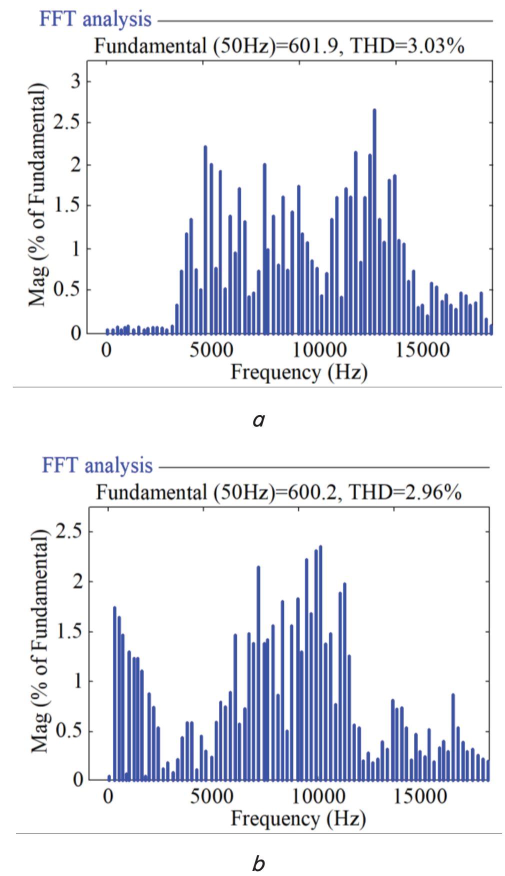

Fig. 8. A Fourier analysis of the input current of an active rectifier: *a* – with the basic hysteresis control system; *b* – with the improved hysteresis control system

Table 7 demonstrates that the losses of power and the value of a harmonic distortion coefficient for the improved hysteresis control system are considerably lower than those for the classical one, thereby confirming the expediency of its use.

Table 7

Energy characteristics of 4QS-converter

Input inductance, mH	Hysteresis setpoint, A	Classical hysteresis control system			Improved hysteresis control system		
		Switching frequency averaged over a period, Hz	THD, %	Power losses, kW	Switching frequency averaged over a period, Hz	THD, %	Power losses, kW
0.4	20	13,340	3.26	49.44	7,230	2.96	27.76
	30	9,400	4.60	35.44	4,810	4.36	19.2
	40	7,250	5.96	27.84	3,740	5.79	15.4
0.6	20	9,300	3.07	35.12	5,430	2.83	21.4
	30	6,440	4.43	24.8	3,690	4.20	15.2
	40	4,930	5.78	19.6	2,790	5.58	12.02
0.8	20	7,070	2.99	27.2	4,020	2.79	16.38
	30	4,850	4.34	19.32	2,720	4.28	11.76
	40	3,700	5.70	15.28	2,060	5.66	9.4

The simulation model that we constructed makes it possible to investigate the rectification and recuperation modes in traction converters. A rectification regime will be implemented when the value of adjustment coefficient ξ is in a positive range of values. In this case, energy from a contact network will be transferred from the power supply network through an input 4QS-converter, through the DC link and an autonomous voltage inverter to the induction traction motor. Under recuperation mode, the induction traction motor enters a generator mode while the input 4QS-converter should work in the negative range of adjustment coefficient ξ.

9. Discussing the results of studying the proposed control system

This paper has described and substantiated using the proposed control system for power keys of a single-phase active four-quadrant rectifier, which makes it possible to reduce dynamic power losses, enhance efficiency of the transducer and improve the sinusoidal character of input current.

The results obtained, namely the reduction in the dynamic losses of an active rectifier are explained by that the proposed modulation algorithm, shown in Fig. 3 and in Table 1, employs in the specified sequence the new switching combinations of enabling the pair of power keys VT1 and VT3 and the pair of VT2 and VT4. When switching from basic switching positions VT1 and VT4 or VT2 and VT3 to the proposed switching position, two of the four transistors are not switched, which, relative to the basic switching algorithm, reduces the total number of switches by two times.

The results from our simulation of a single-phase active rectifier have confirmed the reduction of dynamic losses in power transistors when using the proposed algorithm.

Special feature of the current research is the fact that in order to confirm the energy-saving effect from the proposed control algorithm we have calculated the static and dynamic losses in power keys by the polynomial approximation of IGBT energy characteristics. This calculation showed, in particular, that the use of the proposed algorithm for switching power keys at the value of the hysteresis setpoint for an input current of 20 A and the magnitude of input inductance of 0.4 mH makes it possible to reduce the power losses in the active rectifies owing to the proposed control system, from 49.44 kW to 27.76 kW. That does confirm that the proposed control system reduces dynamic losses in a single-phase active rectifier.

A certain limitation of the current study is due to that the constructed simulation model works adequately only under the rated modes; the model would inadequately represent emergency regimes at which the current and voltage values exceed the rated values. Such a limitation should be taken into consideration in practical application when studying starting and emergency modes. The disadvantage of the current study is the absence of descriptions for an automated regulation system over an active rectifier and transient processes when the load current is changed. In addition, another drawback is the lack of an experimental sample and physical experiments involving a single-phase active rectifier with the proposed control system. The further research necessitates conducting experimental studies; to this end, the development of prototype samples with microprocessor control systems is planned, as well as the design of an automated regulation system.

10. Conclusions

1. Our analysis has identified the shortcomings in the existing hysteresis control system of an active rectifier, namely large dynamic power losses in power transistors due to the high frequency of switching.

2. The study that we conducted has demonstrated that the proposed algorithm for controlling power keys of an active four-quadrant transducer enables a reduction in the number of switches of power keys, as well as the improvement of the sinusoidal character of input current.

3. The method of least squares has been applied for the approximation of energy characteristics of power IGBT CM1200HG-90R with polynomial functions of the fourth degree. The approximation performed has made it possible to calculate the static and dynamic power losses in an active rectifier with the basic and improved control system. For example, at a value of the hysteresis setpoint for input current of 20 A and a magnitude of input inductance of 0.4 mH the power losses in the active rectifier, due to the proposed control system, reduced from 49.44 kW to 27.76 kW (by 43.8 %).

4. The MATLAB 2017b software was employed to construct a simulation model of the active rectifier, which confirmed the improvement of the sinusoidal character of input current. At a value of the hysteresis setpoint for input current of 20 A and the input inductance of 0.4 mH a coefficient of harmonic distortion of the input current in the active rectifier decreases, due to the proposed control system, from 3.26 % to 2.96 %.

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