The Electrical Schematic Diagram of Power Part and the Methods of Forming the Inverter Output Voltage

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Abstract. Author using computer simulation methods investigates characteristics of the device supply auxiliary circuits of dc electric locomotive in static mode. The electrical schematic diagram of power part of this device comprises a capacitive dc voltage divider, autonomous voltage source inverter, three-phase transformer with a particular connection scheme IIIy. Due to the use of construction of three-phase transformer with a single magnetic core must take into account the presence of strong electromagnetic coupling between the phases. To do this, used a mathematical model of three-phase transformer, allowing to get arbitrary schemes of winding connection, including all 12 standard phase displacement groups in a clockwise notation. The study presents results of a comparative review of the energy characteristics of the device at three methods to generate a regulated voltage at the output of the inverter. For example take into account the use of catenary voltage, efficiency, harmonic structure, the power factor. In the benefits of this study recommended control mode for transistors of the inverter.

Keywords: autonomous voltage source inverter; 3-phase transformer; mathematical model; phase displacement group; pulse-width modulation; efficiency

INTRODUCTION

Currently on a board of DC main electric locomotives are quite common electrical consumers feeding by three-phase and single-phase AC voltage. One of the problems to be solved in the development of devices for the needs of auxiliary circuits supply is to choose a method of catenary DC high voltage conversion in the low three-phase AC voltage. Some schematics for DC electric locomotives which based on two-level and three-level bridge-type circuits of autonomous voltage source inverter (VSI), including devices with a three-phase transformer, were published by experts from Europe and Japan [1, 2]. They have some of disadvantages. Usage the bridge-type two-level VSI with a minimum number of semiconductor switches (6 pieces) and the highest reliability is most common, but requires at a voltage of 3 kV catenary to use transistors with an operating voltage of 6.5 kV, which are expensive. Usage of three-level bridge VSI allows us to take advantage of more cheap power transistors with the value of the operating voltage of 3.3 kV, but at the cost of doubling their number and at more complicated control algorithms for VSI. The aim of this paper is to offer the device for feeding an auxiliary consumers onboard of DC electric locomotive which is based on three-phase transformer and autonomous VSI, enabling use of a minimum number of relatively low-voltage power transistors with a simple wiring diagram.

THE ELECTRICAL SCHEMATIC DIAGRAM OF POWER PART OF DEVICE

Due to the best weight and size, it is advisable to use not three-phase group of single-phase transformers, but three-phase transformer with a single magnetic core, for example three-limb core. Offered scheme of the device involves independent (without electrical connection with each other, an open circuit) connection of phases of the primary winding of transformer to output terminals of inverter (see Fig. 1).

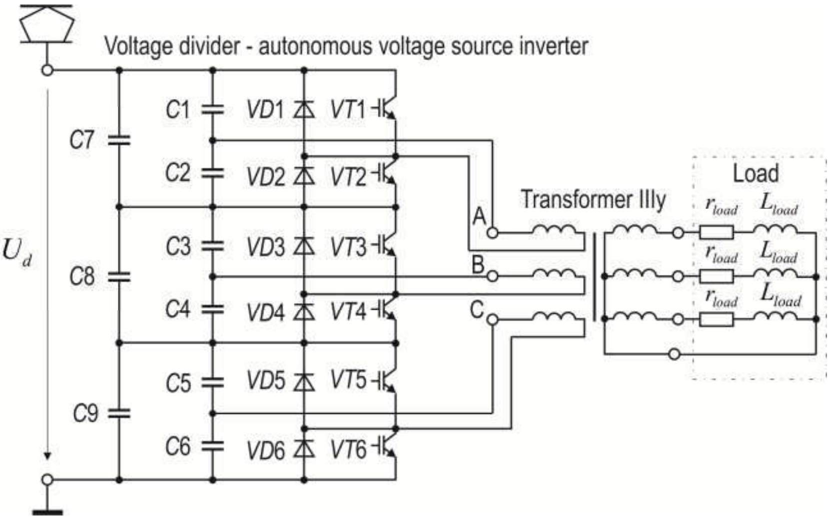

Figure 1. The electrical schematic diagram of power part of the device supply auxiliary circuits of dc electric locomotive

The device in Fig. 1 converts DC voltage into three-phase alternating voltage, the frequency and magnitude of which can be adjusted. Each phase of the primary winding three-phase transformer is connected to the cell of converter. Each the cell is a single-phase half-bridge autonomous VSI. For example, phase A is connected to the cell that includes the transistor switches VT1 and VT2, diodes VD1 and VD2 and capacitors C1 and C2. Transistors VT1 and VT2 are opens alternately at equal time intervals, forming the alternating voltage on the phase A of primary winding of the transformer. Series-connected capacitors C7, C8 and C9 represent a capacitive divider that divides the input DC voltage of catenary in three equal parts (three is the number of phases of the transformer and number of cells of the converter). A pair of transistors in the other two phases work the same as in phase A, but shifted in time by 120° and 240°, forming on the windings of the transformer the three-phase symmetric system of supply voltages.

In accordance with [4] common connections for 3-phase transformers are recommended with vector groups 0, 1, 5, 6, 11 and additional connections with vector groups 2, 4, 7, 8, 10 (meaning the combination of the connection circuits of a D, Y, Z). Known three-phase transformer T-164 (Fig. 2) with the scheme and winding connection group Dyn7, wich designed for galvanic isolation and conversion of the channel of auxiliary circuit power supply unit voltage to voltage for auxiliary power consumers onboard of electric locomotive.

For the analysis of operation modes of the proposed device, it is expedient to use computer simulation tools. The simulator of a three phase transformer must be able to receive a standard group connection of windings in a clockwise notation [3], and use independent connection of the windings to the voltage source and to take into account the strong magnetic connection between the phases of the transformer, assembled on a single magnetic core. The required properties of a simulator based on the equations given in [4]. These equations provide the ability to configure the model of transformer for any of 12 standard windings connection groups.

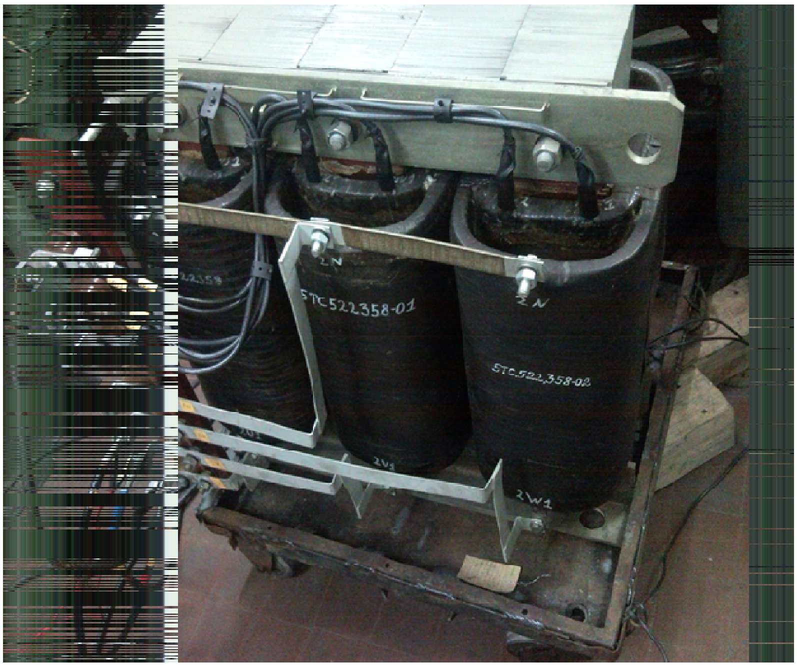

Figure 2. Three-phase transformer T-164 with the scheme and winding connection group Dyn7 for usage onboard of electric locomotive

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THE MATHEMATICAL MODEL OF THREE-PHASE TRANSFORMER WITH SINGLE MAGNETIC CORE

In compact form we can write the equations of the mathematical model of three-phase transformer as:

$$\begin{cases} v_{j1} - r_{j1} i_{j1} - L_{\sigma j1} \dfrac{di_{j1}}{dt} = v_{j01} \\ e_{j2} - r_{j2} i_{j2} = v_{j2}. \end{cases} \quad (1)$$

The system (1) is written for each phase of transformer. We denote the belonging to a certain phase as follows: $j = a, b, c.$ Additionally, we introduce the notation for the possible permutations of the phase indexes: $j-1 = c, a, b;$ $j+1 = b, c, a.$

Let us describe the components of equations (1). EMF of primary winding and secondary windings of transformer, respectively.

$$e_{j1} = -\left(v_{j01} + L_{\sigma j1} \frac{di_{j1}}{dt} \right), \tag{2}$$

$$e_{j2} = \mp \left(\frac{w_2}{w_1} v_{j01} + L_{\sigma j2} \frac{di_{j2}}{dt} \right). \tag{3}$$

Here: v – phase voltage, V; i – phase current, A; L_σ – inductance of phase winding, H; r – active resistance of the phase winding, Ohm; w – number of turns in the phase winding. The index 1 indicates belonging to a primary winding of transformer, and index 2 – to the secondary.

For each phase, the voltage drop in the branches of the magnetization of the primary winding in a series connection in the branch of the main inductance L_m and resistance r_m, on which stand the iron losses is described by the expression:

$$v_{j01} = L_m(i_{\mu j}) \frac{2}{3} \left[\left(\frac{di_{j1}}{dt} + \frac{w_2}{w_1} \frac{di_{j2}}{dt} \right) - \frac{1}{2} \left(\left(\frac{di_{(j+1)1}}{dt} + \frac{w_2}{w_1} \frac{di_{(j+1)2}}{dt} \right) + \left(\frac{di_{(j-1)1}}{dt} + \frac{w_2}{w_1} \frac{di_{(j-1)2}}{dt} \right) \right) \right] +$$
$$+ r_m \frac{2}{3} \left[\left(i_{j1} + \frac{w_2}{w_1} i_{j2} \right) - \frac{1}{2} \left(\left(i_{(j+1)1} + \frac{w_2}{w_1} i_{(j+1)2} \right) + \left(i_{(j-1)1} + \frac{w_2}{w_1} i_{(j-1)2} \right) \right) \right] =$$
$$= L_m(i_{\mu j}) \frac{di_{\mu j}}{dt} + r_m i_{\mu j}, \tag{4}$$

where i_μ is the current in the branches of the magnetization phase of the transformer.

The “+” sign in the expression (3) corresponds to the case when the primary and the secondary coils which are located on the same one limb have the same direction of winding and similar location of the beginnings and the ends – inductors coupled positively. The sign “–” is used for the case of opposite direction of winding of the coils or change the beginning and end of one winding relative to another – inductors coupled negatively.

Using permutations of the phase indexes, we can write (4) as (5), and (3) as (6):

$$v_{j01} = L_m(i_{\mu j}) \frac{2}{3} \left[\left(\frac{di_{j1}}{dt} + \frac{w_2}{w_1} \frac{di_{(j+1)2}}{dt} \right) - \frac{1}{2} \left(\left(\frac{di_{(j+1)1}}{dt} + \frac{w_2}{w_1} \frac{di_{(j-1)2}}{dt} \right) + \left(\frac{di_{(j-1)1}}{dt} + \frac{w_2}{w_1} \frac{di_{j2}}{dt} \right) \right) \right] +$$
$$+ r_m \frac{2}{3} \left[\left(i_{j1} + \frac{w_2}{w_1} i_{(j+1)2} \right) - \frac{1}{2} \left(\left(i_{(j+1)1} + \frac{w_2}{w_1} i_{(j-1)2} \right) + \left(i_{(j-1)1} + \frac{w_2}{w_1} i_{j2} \right) \right) \right]; \tag{5}$$

$$e_{j2} = \mp \left(\frac{w_2}{w_1} v_{(j-1)01} + L_{\sigma j2} \frac{di_{j2}}{dt} \right). \tag{6}$$

Through the use of other permutations of the indices of the phases can also be written (4) to (7), and (3) to (8):

$$v_{j01} = L_m(i_{\mu j})\frac{2}{3}\left[\left(\frac{di_{j1}}{dt}+\frac{w_2}{w_1}\frac{di_{(j-1)2}}{dt}\right)-\frac{1}{2}\left(\left(\frac{di_{(j+1)1}}{dt}+\frac{w_2}{w_1}\frac{di_{j2}}{dt}\right)+\left(\frac{di_{(j-1)1}}{dt}+\frac{w_2}{w_1}\frac{di_{(j+1)2}}{dt}\right)\right)\right]+$$

$$+ r_m\frac{2}{3}\left[\left(i_{j1}+\frac{w_2}{w_1}i_{(j-1)2}\right)-\frac{1}{2}\left(\left(i_{(j+1)1}+\frac{w_2}{w_1}i_{j2}\right)+\left(i_{(j-1)1}+\frac{w_2}{w_1}i_{(j+1)2}\right)\right)\right]; \qquad (7)$$

$$e_{j2} = \mp\left(\frac{w_2}{w_1}v_{(j+1)01}+L_{\sigma j2}\frac{di_{j2}}{dt}\right). \qquad (8)$$

Matching equations, wiring diagrams, signs in front of the right part of the expression for the EMF of the secondary winding and vector group in the mathematical model of three-phase transformer summarized in table 1. Computer implementation the above-described mathematical model of three-phase transformer by means of PSpice [6] provides twelve terminals of the windings, thus achieving the possibility of its use in any connection diagram.

Table 1. Compliance in the mathematical model of three-phase transformer for various vector groups

Connection scheme of windings	**Yd, Dy**		**Yy, Dd**		**Yd, Dy**		**Yy, Dd**		**Yd, Dy**		**Yy, Dd**	
Rooms of expressions, describe the mathematical model	– (4)				(1), (2), (5), (6)				(1), (2), (7), (8)			
The sign in front of the right part of the expression for the EMF of the secondary winding	+	–	+	–	+	–	+	–	+	–	+	–
Winding vector group clockwise notation	11	5	0	6	7	1	8	2	3	9	4	10

Methods of Forming Output Voltage of the Inverter

With the aim of making better use of the input DC voltage should be used the angle of conduction of the transistors $\Theta = 180°$ for the formation of the largest voltage across the primary winding of transformer. Thus, obtain the output voltage curve in the form of a meander. For regulation of the magnitude of alternating voltage is possible in this case to use the rectangular-triangular pulse width modulation (PWM): triangular bipolar carrier frequency voltage and the modulation voltage in the form of a meander (we shall call this "Method 1", see Fig. 3).

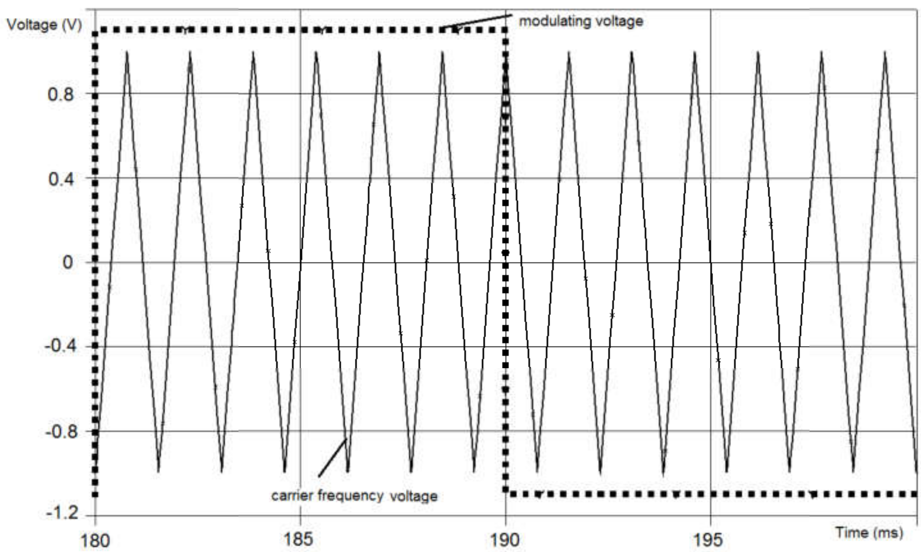

Figure 3. PWM in accordance with Method 1

The main disadvantage of the above mentioned method of forming the voltages (control method of the converter) follows from the harmonic composition of the signal shape of a meander: contains all the odd-order harmonic components, the relative amplitude of harmonics decrease inversely proportional to its number (relative amplitude of the 1st harmonic equals 1, the 3rd harmonic is 1/3, 5-th – 1/5). Third harmonic voltage is very high, which determines the magnitude of the third harmonic current of the primary winding of transformer (2.13 times higher than the 1st harmonic) and the significance of additional losses from its occurrence.

To overcome this drawback is proposed as a modulating voltage to use the signal form "meander with a pause" when the pulse width 120° (we shall call this "Method 2", see Fig. 4).

For comparison as the "Method 3" we'll use an algorithm of sine-triangle PWM with third harmonic having 0.167 relative magnitude from the first harmonic injection and the first harmonic overmodulation (see Fig. 5). The injected third harmonic is in-phase with the first.

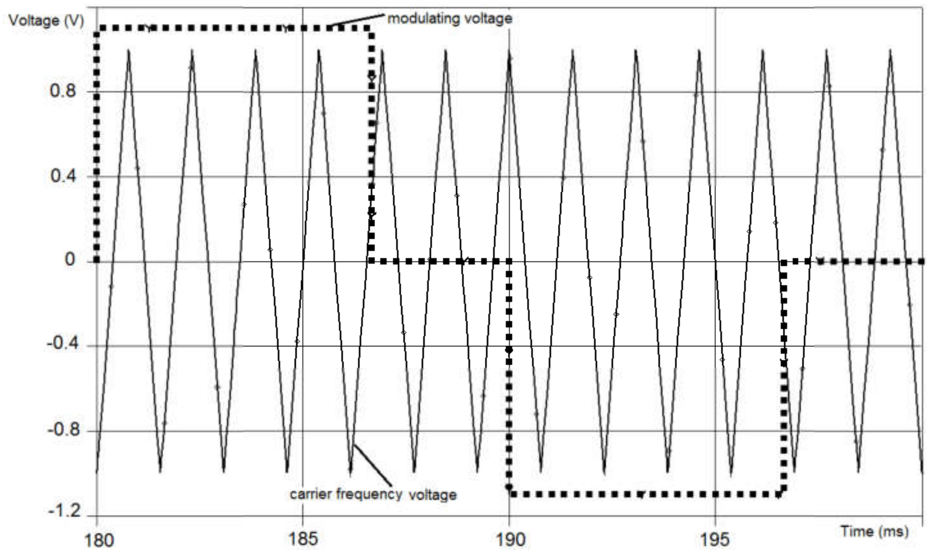

Figure 4. PWM in accordance with Method 2

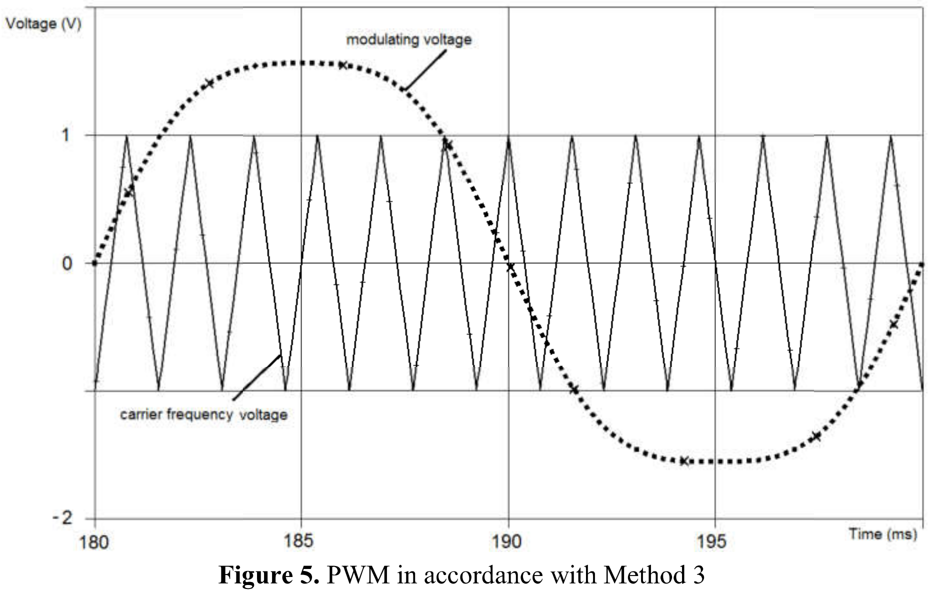

Figure 5. PWM in accordance with Method 3

The results of simulations for comparison of three methods of forming output voltage of the VSI are summarized in table 2. In all cases, the parameters of transformer and load are the same. The load is symmetrical. The frequency of the modulating voltage of 50 Hz, the carrier frequency of 650 Hz. All values in table 2 are presented in relative units.

If any of the considered methods do not exist or quite small the harmonics with order multiple of three in phase and phase-to-phase voltages of the secondary winding of transformer. This has a positive effect on the harmonic composition of the current in the secondary winding. The potential of the neutral point of the load (Fig. 1) is close to zero.

From the point of view the harmonic composition of currents and voltages generated by the converter, preferably, when the period of the modulating voltage is placed an odd number of periods of the voltage of the carrier frequency. Otherwise the currents and voltages will contain even harmonics (according to table 2 it has little effect on the energy characteristics of the electrical system).

Method 2 allows to drastically reduce the amount of current of the 3rd harmonic in the primary winding T (to 11.09 % from 1st harmonic).

In Method 3, the 3rd harmonic current in the primary winding of transformer is 150.62 % from 1st harmonic, which is lower than with Method 1, where 212.76 %.

The simulated curves of voltages and currents of the transformer are shown for Method 1 in Fig. 5, for Method 2 in Fig. 6 and for Method 3. – in Fig. 7, where the curves: 1 – phase voltage of the primary winding, 2 – phase current of the primary winding, 3 – phase current of the secondary winding, 4 – phase voltage of the secondary winding, 5 – inverted in sign phase-to-phase voltage of the secondary winding.

From table 2 it is seen that the highest value of the $\eta_T \cdot \cos\varphi_1$ demonstrates the Method 2. However, it is noticeably inferior to the other two methods by using the input voltage and, as a consequence, the active power at the load. Out on the set of power characteristics, that is, the value of the product $\eta_T \cdot \cos\varphi_1 \cdot \overset{*}{V}_{1phase}$ is preferable to Method 3.

Table 2. Comparative results of calculation of characteristics of the device for supply of three-phase and single-phase auxiliary circuits of DC electric locomotive with different methods of forming output voltage of the VSI

Name of characteristics	**1st harmonic of the phase voltage of primary winding of the transformer**	**Active power at output of the transformer**	**Power factor at input of the transformer**	**Efficiency of the transformer**	$\eta_T \cdot \cos\varphi_1$	**–**
The symbol	$\overset{*}{V}_{1phase}$	$\overset{*}{P}_2$	$\cos\varphi_1$	η_T	K_E	$K_E \cdot \overset{*}{V}_{1phase}$
When the carrier frequency is 650 Hz (voltage PWM based on 13 periods of carrier frequency for one period of the modulating)						
Method 1	1.000 (520.9 V)	1.000 (73.2 kW)	0.845	0.917	0.775	0.775
Method 2	0.859	0.759	0.829	0.970	0.804	0.691
Method 3	0.969	0.925	0.833	0.939	0.782	0.758
When the carrier frequency is 600 Hz (voltage PWM based on 12 periods of carrier frequency for one period of the modulating)						
Method 1	1.000 (518.7 V)	1.000 (73.0 kW)	0.847	0.910	0.771	0.771
Method 2	0.873	0.761	0.834	0.966	0.806	0.704
Method 3	0.966	0.925	0.825	0.961	0.793	0.766

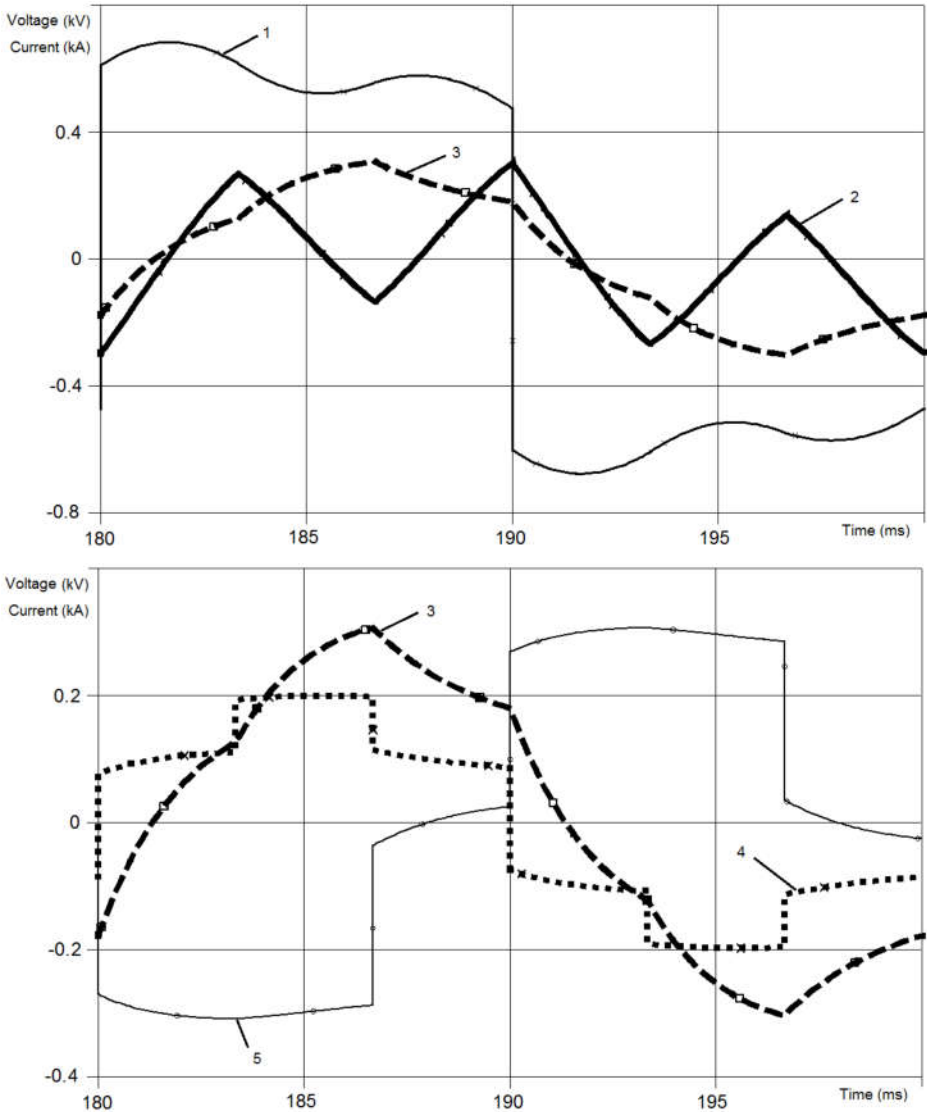

Figure 6. Voltages and currents of the transformer in case of control of the VSI according to the Method 1

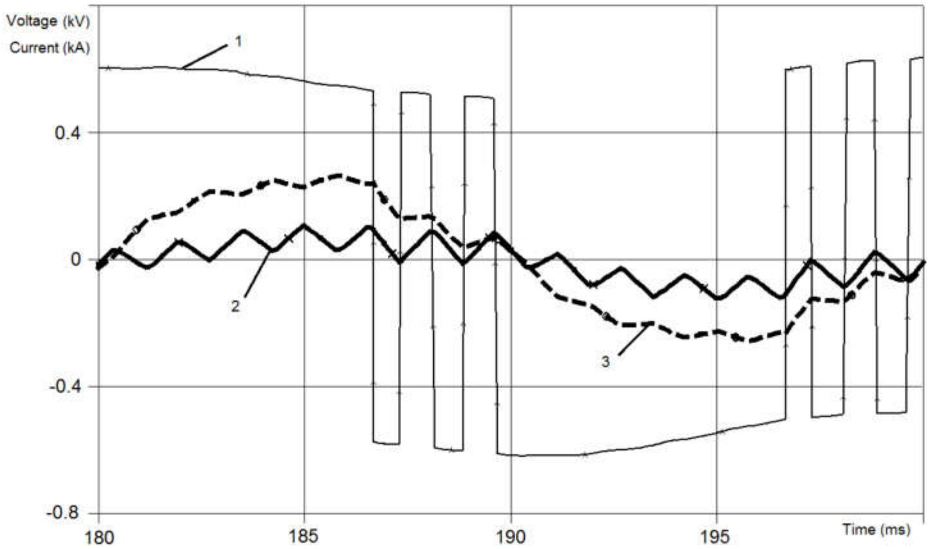

Figure 7. Voltages and currents of the transformer in case of control of the VSI according to the Method 2

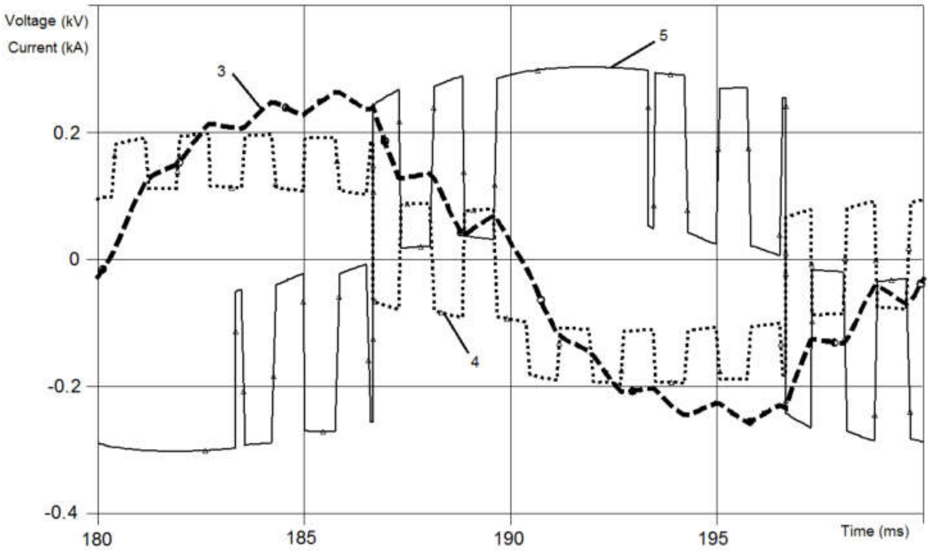

Figure 7 (continued)**.** Voltages and currents of the transformer in case of control of the VSI according to the Method 2

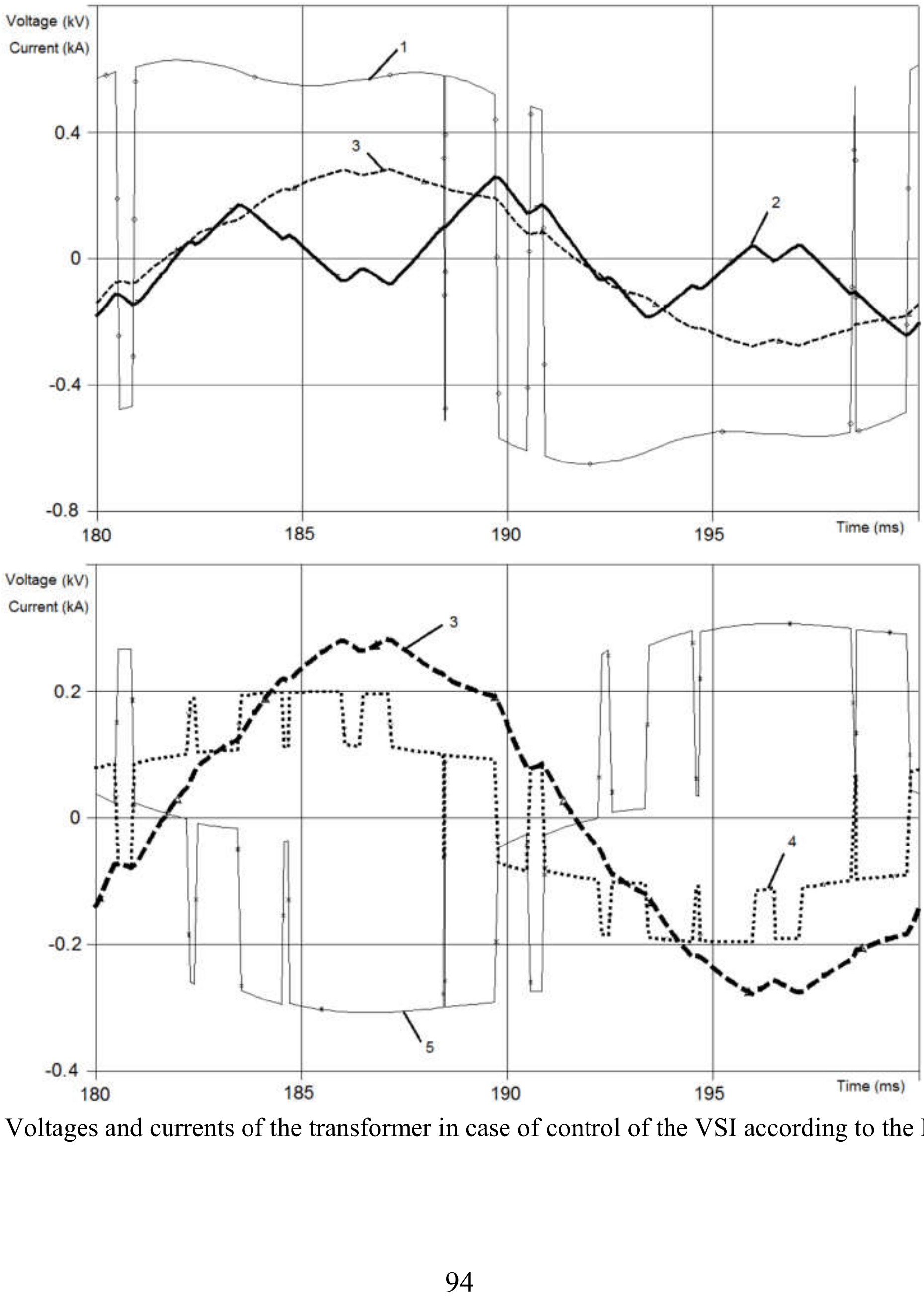

Figure 8. Voltages and currents of the transformer in case of control of the VSI according to the Method 3

CONCLUSION

The suggested scheme of power supply of auxiliary circuits of DC electric locomotive on the basis of the three-phase half-bridge autonomous VSI and three-phase transformer with winding connection scheme IIIy, with the following advantages: the number of power transistors is minimal, transistors with relatively low operating voltage, which reduces the device cost. The cost of the set of semiconductor switches can be reduced to 1.5–2.0 times in comparison with the known technical solutions.

Through a simulation using the original mathematical model of three-phase transformer is analyzed the methods of control of power switches. The best method for the totality of the energy characteristics and aspects of electromagnetic compatibility of suggested device recommended. Methods of forming output voltage of the proposed inverter does not differ from that used in known circuits. This allows to use technology of digital space vector PWM to control this VSI.

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