Computer Simulation of Auxiliary Converter of Electric Locomotive: Solving Direct and Inverse Problem

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Abstract: - This article discusses the sort of auxiliary converter - secondary power source (SPS) of mainline DC electric locomotive in the focus of the problem of providing a soft switching. A conclusion is made about the insufficiency of passive means (selection of parameters of the output filter of the rectifier of the auxiliary converter) to ensure soft switching in case of variability of the input voltage and the need to stabilize the voltage on the load.

Key-Words: - Computer simulation, secondary power source, auxiliary converter of electric locomotive, soft switching, waveform, filter parameters.

Received: May 18, 2024. Revised: January 24, 2025. Accepted: March 28, 2025. Published: June 2, 2025.

1 Introduction

An SPS is a device used to convert electrical energy from the primary power supply into electrical energy with the required characteristics and parameters to feed electrical loads. In addition to fulfilling the functional purpose, it is advisable for the SPS to be an energy-efficient device. This is important, since SPS often perform multiple conversions of electrical energy, and it is especially important if the SPS has a relatively high power, as in the case of a converter for the auxiliary needs of a mainline electric locomotive.

The DC voltage of the catenary supplying the electric locomotive can vary within 2–4 kV [1]. This voltage is divided in half by a capacitive divider. An SPS cell is connected to each half, the electrical circuit diagram of the power section of which is shown in Fig. 1, where a high DC voltage of V_d = 1–2 kV is fed to the input of the capacitive divider C1 and C2, which forms a bridge with a vertical pair of IGBT named VT1 and VT2, into the diagonal of which the primary winding of the isolating single-phase transformer is included. Each transistor is shunted by an antiparallel diode (VD1 and VD2). Thus, the transistors, diodes and capacitors together form a single-phase autonomous voltage source inverter assembled according to a half-bridge circuit. The secondary winding of the transformer T1 is loaded onto a diode rectifier assembled according to a single-phase bridge circuit (diodes VD3 – VD6), which, in turn, is loaded onto an output L-shaped LC filter formed by L_f and $C_{f\Gamma}$, stabilizing the constant voltage on the load V_{load} = 660 V. The role of the load in Fig. 1 is played by a resistor r_{load}, the rated load power is 100 kW. On an electric locomotive, three-phase autonomous voltage source inverters are used as a load, supplying induction motors of motor-fans and motor-compressors [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. Semiconductor devices of the inverter and rectifier are protected from switching overvoltages by RC snubbers. The terminals of the secondary windings of single-phase transformers of SPS cells can be connected in series or in parallel when loaded by single rectifier. Or each SPS cell can supply a separate rectifier. Due to the design features of the SPS circuit, the primary winding of the isolating transformer is fed with voltage in the form of a meander or a meander with a platform (depending on the duty cycle of the voltage pulse γ): at a given voltage frequency (900 Hz), the duration of the rectangular monopulse on the half-period is regulated, which is a stabilization tool for V_{load}.

Examples of experimental voltage v_1 and current i_1 curves at a frequency of 400 Hz on the primary winding of transformer T1, obtained at $V_d = 1.1$ kV and $V_d = 1.8$ kV, respectively, are shown in Fig. 2 and Fig. 3 for the case of the absence of C_f in the circuit in Fig. 1.

2 Problem Formulation

It turned out that the value of the output filter choke inductance L_f significantly affects the shape of currents and voltages in the transformer windings, distorting the shape of the voltage meanders on the transformer windings with oscillatory processes. When L_f removed from the circuit, the voltage distortions disappeared, and the current through the transistor acquired a classic triangular shape, which was confirmed by both computer simulating and physical tests on the bench. But removing L_f from the filter is impractical. In addition, an idea arose to use the resonant properties of the output filter by introducing a capacitor C_f into its composition (see Fig. 1) to deform the shape of the current through the inverter transistors in such a way as to perform their soft switching [13], [14], [15], namely switching at current values close to zero (that is, using only passive means for soft switching). At the same time, the current in the transformer windings becomes almost sinusoidal.

The consequence of this would be a reduction in dynamic losses in the inverter (switching losses in semiconductor valves) and losses from higher harmonics in the transformer.

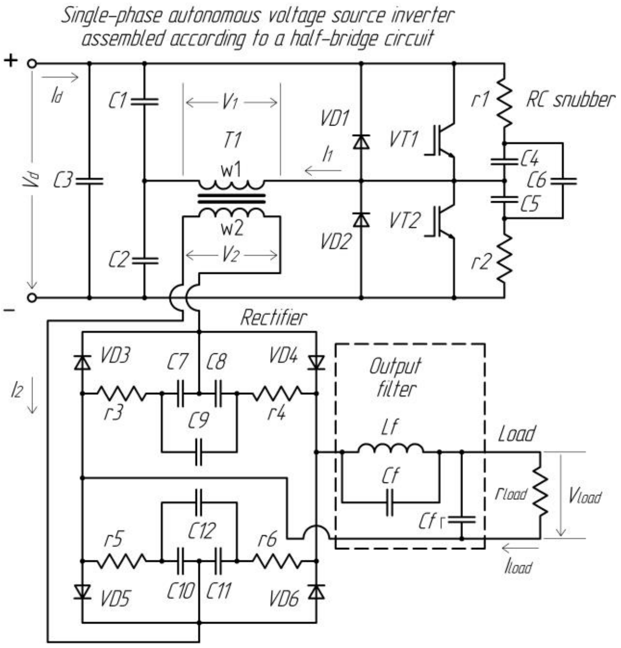

Fig. 1. Electrical schematic diagram of the power section of SPS cell

3 Problem Solution

3.1 Solution of the direct problem

The task was set to calculate the parameters of the output filter, allowing to implement soft switching - this is a direct simulating task. The computer model was built in the OrCAD [16], [17], [18], the mathematical model of a single-phase transformer taking into account the iron losses and the nonlinearity of the magnetization curve corresponds to that described in [19], [20]. Fig. 4 shows the dependence of the combinations of parameters of the resonant circuit L_f, C_f the output filter (including the resonant frequency f_{res}), allowing to achieve a current in the primary winding of the transformer, close to sinusoidal (see Fig. 5), obtained as a simulation result (it was assumed $C_{f\Gamma} = 643$ μF). Fig. 5 shows the simulation results for currents and voltages at $L_f = 0.1$ mH, $C_f = 100$ μF, $C_{f\Gamma} = 643$ μF, $V_d = 1.1$ kV and $\gamma = 0.8$. Fig. 6 shows the same, but at $V_d = 2$ kV and $\gamma = 0.5$. Curves in Fig. 5 and Fig. 6: 1 – i_1; 2 – v_1; 3 – v_d; 4 – i_d; 5 – control voltage of transistor VT2 in the computer model (amplitude increased).

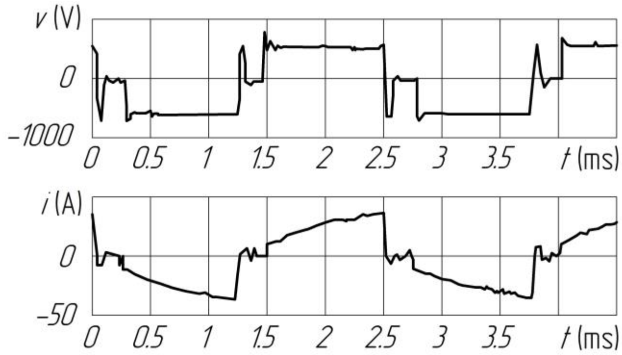

Fig. 2. Experimental voltage v_1 and current i_1 curves at a frequency of 400 Hz on the primary winding of T1, obtained at $V_d = 1.1$ kV

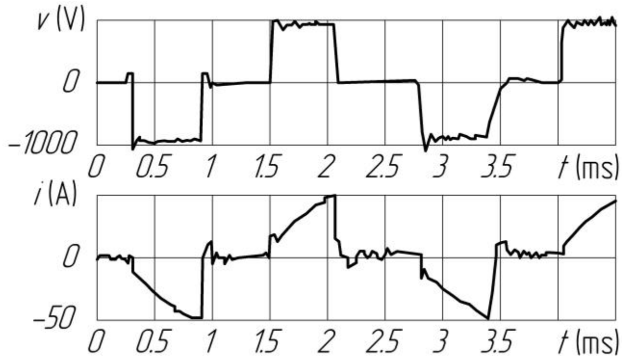

Fig. 3. Experimental voltage v_1 and current i_1 curves at a frequency of 400 Hz on the primary winding of T1, obtained at $V_d = 1.8$ kV

Unfortunately, we have to state the fact that it is not possible to achieve a completely sinusoidal current in the transformer windings and a zero current value through the transistor at the moment of its switching by varying the parameters of the output filter. It also turned out that when changing γ and fixed filter parameters, it is not possible to maintain the effect of the sinusoidal current through the primary winding of the transformer - gradually, with a decrease in γ, it approaches a triangular shape (see Fig. 6).

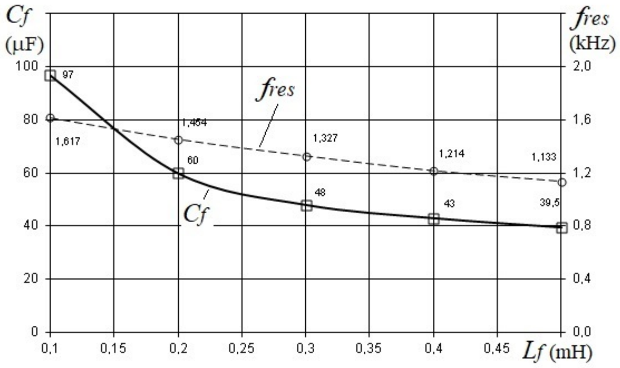

Fig. 4. Relationships for L_f and C_f the output filter obtained as a computer simulation result (parameters of the resonant output filter, when configured to switch the current through the transistor at a minimum value)

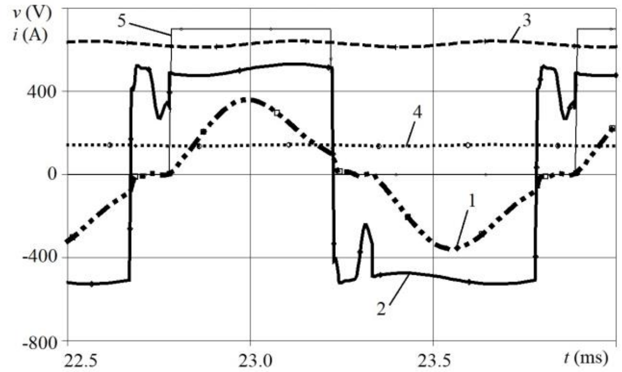

Fig. 5. simulation results for currents and voltages at $L_f = 0.1$ mH, $C_f = 100$ μF, $C_{f\Gamma} = 643$ μF, $V_d = 1.1$ kV and $\gamma = 0.8$

To determine the influence of the resonant circuit in the output filter at different duty cycles of the output voltage pulse on the currents and voltages in the primary winding of the isolating transformer (I_1, V_1), in the secondary winding (I_2, V_2) and the load (I_{load}, V_{load}), computer simulations were also carried out at a fixed value of voltage at the input of the circuit. The results are shown in Fig. 7.

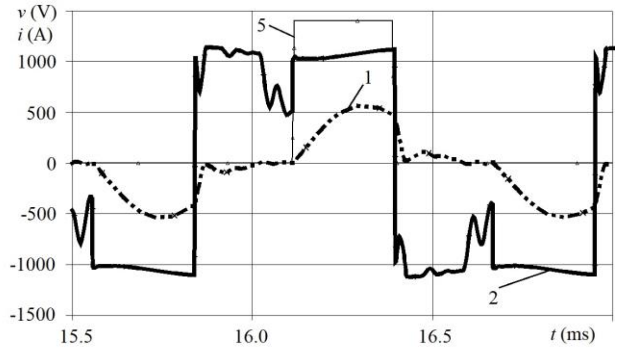

Fig. 6. simulation results for currents and voltages at $L_f = 0.1$ mH, $C_f = 100$ μF, $C_{f\Gamma} = 643$ μF, $V_d = 2$ kV and $\gamma = 0.5$

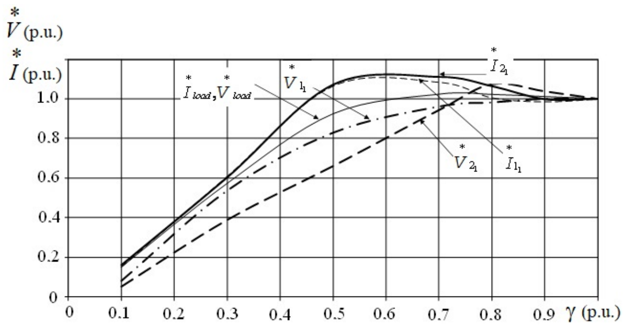

Fig. 7. Control characteristics of the SPS cell at $L_f =$ 0.1 mH, $C_{f\Gamma} = 643$ μF, C_f in accordance with Fig. 4 and constant V_d voltage (dependences of relative voltages and currents of the SPS cell on γ (for rectified signals - the constant component, for AC signals - the first harmonic))

They indicate a significant nonlinearity of the control characteristics of the SPS cell, which is most clearly manifested precisely in the zone of the most frequently used values of $\gamma = 0.5 - 1.0$. Moreover, the highest values of currents and voltages are achieved not at $\gamma = 1$.

3.2 Solution of the inverse problem

After obtaining the results given above, an inverse problem of computer simulation was set: for the given parameters of the output filter, determine what the voltage shape on the primary winding of the transformer should be in order to provide a sinusoidal current in the primary winding of the transformer and a zero value of the current through the transistor at the moment of its switching. To solve this problem, a sinusoidal current source was introduced into the transformer T1 primary winding circuit in the computer model. The simulation result obtained at $L_f = 0.5$ mH, $C_f = 39.5$ μF, $C_{f\Gamma} = 643$ μF is shown in Fig. 8.

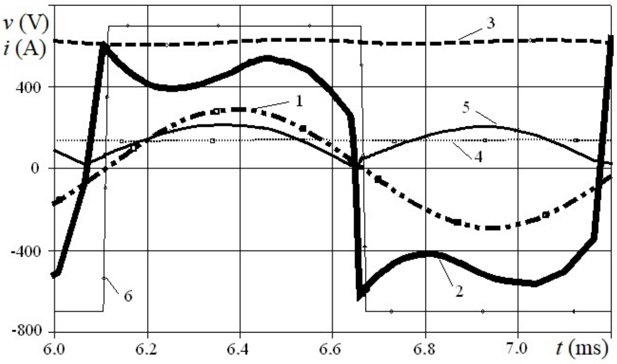

Fig. 8. Computer simulation results of the primary winding voltage of the transformer with an imposed sinusoidal current in it: 1 - imposed sinusoidal current i_1; 2 – voltage v_1; 3 – voltage v_d; 4 – current i_d; 5 - current at the rectifier output (at the filter input); 6 - control voltage of transistor VT2 in the computer model (amplitude increased)

When a sinusoidal current flows through the primary winding of the transformer and the current through each transistor of the half-bridge inverter is a half-period of the current in the primary winding, the voltage waveform obtained on the primary winding of the transformer resembles a meander modulated in amplitude by a sinusoid with a frequency higher than the fundamental one. In other words, the simulation result indicates that the voltage waveform on the primary winding in the form of a meander or a meander with a pause is not capable of ensuring the flow of sinusoidal current in the primary winding of the transformer in the RES circuit under study. Analysis of the waveform of the voltage curve of the primary winding of the transformer in Fig. 6 suggests the need for pulse-width regulation of the voltage of the primary winding of the transformer using current feedback in it.

4 Conclusion

Thus, the solution by means of computer simulation of direct and inverse problems showed that it is not possible to achieve the effect of soft switching (and therefore high energy efficiency of SPS) under conditions of V_d variability and the need for V_{load} stabilization by using only passive means.

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