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AC/DC Converter for DC Traction Power Supply System with High-Speed Train Operation

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Abstract **– Purpose of the work is improved approaches to ensure the required quality parameters of voltage in the traction network based on modern technologies and equipment. The pulsating mode of the power consumption in the railroad power supply network is the cause of the occurrence of voltage pulsations in the contact network. The use of active rectifiers in the electric power supply system of the railroad is proposed. The control system is developed by the converter, which allows to stabilize the output voltage in the DC link and also provides the unit power factor consumed by the converter and the THD consumption current at the level of 8%. A mathematical model of the converter was developed and a study of its main modes of operation was performed.**

Keywords – AC/DC converter, power quality, traction power supply system, voltage quality, traction network force, operation modes, power fluctuation, THD

I. Introduction

The introduction of high-speed train operation with the use of a direct current power supply system causes a significant increase in the load on the external power supply system, an increasing in the consumption of reactive power and higher harmonic levels. Another negative factor in the increase in traction load is a significant reduction in the voltage of the current collectors of electric locomotives in the traction network and the deterioration of the energy characteristics of consumption, such as power loss and power factor.

Connecting to the power supply of various semiconductor energy converters and non-linear loads leads to a decrease in power factor. The distortion of the current consumed by such devices negatively affects other electrical equipment, which causes problems of their electromagnetic compatibility (EMC).

In order to prevent such negative impacts on the supply networks, since the 1980s, special standards and norms have been introduced in many countries, which are being consistently tightened. All manufacturers of electronic devices entering the international market should maintain these standards. This led to the need for special measures and prompted equipment designers to develop various options for schemes that ensure increasing in the power factor and reducing the distortion of the input current. International EMC standards are represented by IEEE 519 [1], IEC61000 [2], etc. They, as a rule, determine the harmonic content of the current consumed up to the 50th harmonic.

The modern element base using the principles of pulse modulation allows to provide a power factor ratio close to one per unit of power converters. In most practical cases, the value of the power factor is 0.99 and is sufficient to assume that the consumer's influence on the supply network is insignificant.

Power factor correction in all industrialized countries represents one of the most important directions in the development of energy-saving power electronics technologies.

There widely used 6-pulse and multipulse uncontrolled and controlled rectifiers, three-phase active rectifiers, various VIENNA rectifiers, etc. The main disadvantage of classical uncontrolled rectifiers is the significant coefficient of harmonic distortion consumed from the current network. In the case of a controlled rectifier, a non-unit power factor is added to this. Multipulse rectifiers ($p > 6$) reduce the input current THD, but require the use of phase shifter transformers with a nominal installed power of at least load power, which significantly impairs the bulk converter values. The converter mass reduction can be achieved using the autotransformer phase shifter devices [3]. There are known solutions of transformer phase-shifting devices, having a smaller mass compared with the above [4]. In all of the above cases, the mass of transformer equipment is significant. The dynamic loss of switching is negligible.

The radical reduction in the mass of the magnetic elements of the converter is achieved in semiconductor power factor correctors. For all power factor correctors using the PWM boost technology, the unit power factor and low harmonic current consumption in the low-frequency region

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(up to the 50th harmonic of the mains frequency) due to the shift of the generated current harmonics to the high-frequency region. Modern power semiconductors allow you to increase the switching frequency above the 50th harmonic – the frequency of the supply network up to several tens of kilohertz (depending on the power and voltage). These converters have an increased power loss due to switching losses in power switches. In connection with the increased switching frequency, it becomes important to ensure the electromagnetic compatibility of electronic devices.

Direct normalization of the current harmonics generated in the supply network is carried out in the frequency range 100 – 2500 Hz (at 50 Hz network) [1, 5, 6, 7]. On the other hand, it is necessary to provide EMC, for which modern standards require the control of interference in the frequency range 9-150 kHz, 150 kHz-30 MHz [8, 9]. Meeting the EMC requirements imply indirect rationing of the current harmonics generated in the supply network.

The need to provide EMC leads to the use of input filters for AC/DC converters designed to operate at a frequency of one hundred kilohertz, applying meaningful measures that reduce the level of symmetric interference in the power supply. Such measures make the technical and economic indicators of high-frequency power factor correctors worse. One of the ways to improve EMC can be providing special switching modes of power switches.

The purpose of this work is to develop and study the operating modes of the active rectifier for DC power supply systems of railway transport.

II. STRUCTURE AND OPERATION PRINCIPLE OF THREE-PHASE ACTIVE RECTIFIER

Three-phase active rectifier (TAR) is shown in Fig. 1. This converter operates in a three-phase pulse-width converter (power factor corrector) [10].

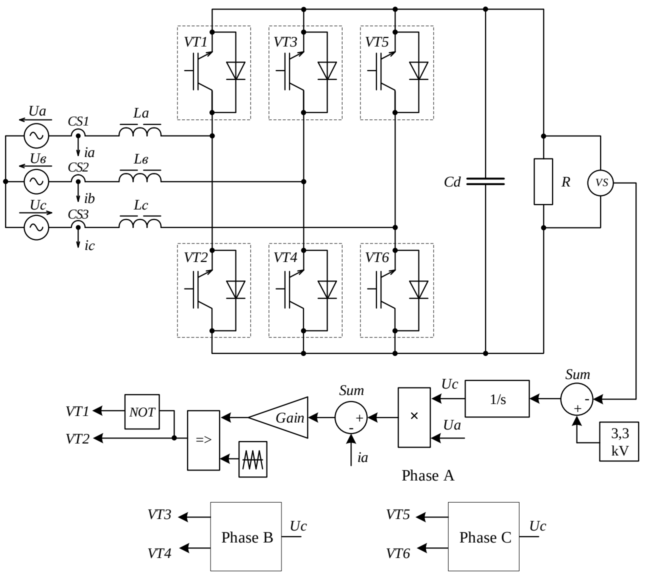

Fig. 1. Full-bridge three-phase active rectifier scheme

The power part of the converter (Fig. 1) consists of an input filter (*La-Lв-Lc*), a power switch with switched alternating current switches *VT1-VT6*, and an output *Cd* filter.

The operation of the circuit principle is based on dosing energy selection from the supply network and subsequent transfer of this "portion" of energy to the load. In this case, the current consumed from the network has the form of a sinewave with a high-frequency component superimposed on it, and this sinewave does not have a phase shift relative to the supply voltage.

This control system has a two-circuit control system. The integral regulator of the primary loop provides the stabilization of the output voltage. The time constant of the regulator is chosen in such a way as to exclude the influence of high-frequency voltage ripples on the load, introduced by a pulse-width modulator.

The second loop is based on the proportional controller and forms a sine-wave input signal that coincides in phase with the input voltage. To ensure the stability of the automatic control system, it is necessary to ensure the relationship between the derivative signal of the assignment and the sawtooth signal of the modulator 1:2, as shown in Fig. 2.

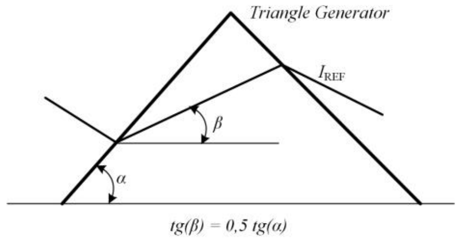

Fig. 2. The principle of the reference-input signal formation to ensure the stability of the system

Since, in its topology, the converter is boosting, the ratio $U_{in} < U_{out}$ should be followed.

Following the above principles of building SAR allows to achieve a power factor close to unity and to ensure the consumption of a simple harmonic current from the network.

The inductance of the input filter chokes depends on the modulation frequency, as well as the parameters of the input and output values.

The ability of the active rectifier to operate in the inverter mode allows the use of a DC link (at the connection point of the *Cd* filter capacitor), energy-intensive electrical energy storage devices connected via an additional DC/DC matching converter [11]. This solution allows to improve the energy characteristics of the system, to increase its stability under conditions of non-stationary load, as well as to perform a temporary utilization of the energy of recovery and its subsequent return.

The main advantages of using an active rectifier as part of the power supply system of railway transport:

- the possibility of bidirectional energy flow;

- ensuring the phase currents of the network, close in shape to sine-wave;

- maintaining a high power factor;

- stabilization of the output voltage level.

It should be noted that the minimum level of the rectified voltage in this circuit is

$$U_d = 1.45 \cdot U_m \quad (1)$$

where U_d is the average value of the rectified voltage;

U_m – amplitude value of voltage.

Since the active rectifier in its structure is a step-up converter, the voltage at its output U_d cannot be less than the amplitude of the linear input voltage of the supply network, and taking into account the possible variation of the supply voltage within ± 10% is given by the value of the voltage *Ud* with some reserve (30-35 %).

III. THE CONTROL SYSTEM OF ACTIVE RECTIFIER USING PWM

The generalized structure of the active rectifier control system is presented in Fig. 3

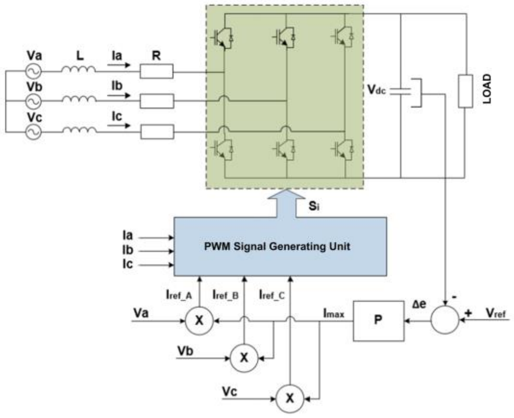

Fig. 3. Active Rectifier Control System

The goal of the control system is to minimize the difference in the form of current consumed from the network from sine-wave and also to stabilize the output voltage. In this case, the amplitude of the current reference curve I_{max} is determined from the expression:

$$I_{max} = P \cdot \left(U_{ref} \cdot U_{dc}\right) \quad (2)$$

where *P* is the transfer function of the controller.

Providing a sinusoidal form of currents consumed from the network is provided by the signal *Iref*, which is calculated by mathematical multiplication of the output value of the regulator *Imax* by the value of a single sinusoidal signal coinciding in phase with the frequency of the supply voltage in each of the phases. In order to eliminate the phase shift between the consumed currents and voltages in each of the phases, the reference single sinusoidal signal is synchronized with the moment the voltage curve passes through zero. At the same time, for the operation of the digital control system, synchronization with only one phase is sufficient; the remaining two reference signals can be obtained by shifting 120 and 240 degrees, respectively.

When a voltage regulator *P* is introduced into the system with voltage feedback (assuming small increments of the variables used), the control system of the active rectifier can be represented as a diagram shown in Fig.4.

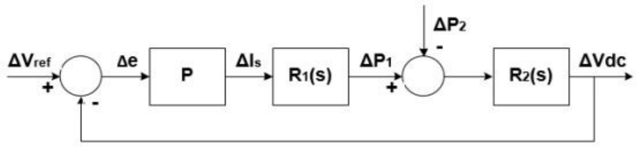

Fig. 4. Control System of Active Voltage Rectifier

The blocks $R_1(s)$ and $R_2(s)$ are the transfer function of the active rectifier in the vicinity of the operating point and the transfer function of the DC link, respectively. Thus, this scheme allows to linearize the control system of the active rectifier in the vicinity of the operating point.

$$R_1(s) = \frac{\Delta P_1(s)}{\Delta I_s(s)} = 3 \cdot \left(U \cdot \cos(\varphi) - 2 \cdot R \cdot I_s - L \cdot I_s \cdot s\right) \quad (3)$$

$$R_2(s) = \frac{\Delta U_{ds}(s)}{\Delta P_1(s) - \Delta P_2(s)} = \frac{1}{U_{ds} \cdot C_{dc} \cdot s} \quad (4)$$

where $\Delta P_1(s)$ и $\Delta P_2(s)$ are Laplace images of the input and output powers of the rectifier;

U is the effective value of the phase voltage;

Is is the effective value of the current consumed from the mains, the shape of which is given by the reference curve of the current *Iref*;

R and *L* are resistance and inductance of input chokes;

cos(φ) is the input power factor of the rectifier;

Udc is the output voltage of the DC link;

Cdc is output capacitor capacity;

s is complex variable

For the stability of a system with a proportional-integral (PI) regulator, shown in Fig. 3, the following estimated inequalities are proposed for the effective value of the current consumed from the network:

$$I_s \le \frac{C_{dc} \cdot U_{dc}}{3 \cdot K_p \cdot L} \quad (5)$$

$$I_s \le \frac{K_p \cdot U \cdot \cos(\varphi)}{2 \cdot R \cdot K_p + L \cdot K_i} \quad (6)$$

where *Kp* and *Ki* are the proportional and integral coefficients of the PI controller.

The work of the active rectifier, provided that the above inequalities are met, will stabilize *Vref* voltage level for any type of load.

The pulse-width modulation provides the switching algorithm of the power switches of the active rectifier in order to form a sinusoidal curve of the current consumed from the network. Three methods of forming PWM are most widely used: periodic, hysteresis, and triangular.

1) Periodic PWM method: in it transistors are switched along the clock edge with a fixed frequency. For each phase, the comparator unit compares the measured current value

with the task signal of the current consumption form. With the help of a synchronous D-flip-flop, the output value of the comparator is memorized and a control information signal is generated for a pair of power switches. Thus, the minimum switching time of transistors is limited by the clock period. But at the same time, the average switching frequency of the power switches is not clearly defined.

2) Hysteresis PWM method: the switching of transistors occurs at the moment when the error between setting the current consumption and the measured current value reaches a certain value (hysteresis limit). The switching frequency of the power switches is also not defined, but its maximum value can be estimated by the formula:

$$f_{k(\max)} \leq \frac{U_{dc}}{4 \cdot h \cdot L} \quad (7)$$

where h is the width of the hysteresis loop.

3) PWM triangular method: in this method, the difference between the current-input signal and the measured value of the current consumed passes through the PI controller, and then compared with the reference triangular signal. The expression below allows to estimate the error (distortion) of the consumed current form.

$$D(\%) = \frac{100}{I_{RMS}} \cdot \sqrt{\frac{1}{T} \cdot (I_i - I_{ref})^2 dt} \quad (8)$$

where I_{RMS} is the current value of the consumed current.

This formula takes into account the ripple, amplitude, and phase shift of the measured current, as opposed to the harmonic distortion factor (THD), which does not take into account offsets, the effect of scaling, and phase shift.

To control the proposed converter was considered a variant of the triangular pulse-width control. The advantage of this method is the ease of implementation, the constant frequency of pulse-width modulation, which in turn facilitates the operation of power filters.

IV. MODELING OF OPERATING ACTIVE RECTIFIER MODES

For constructing the Matlab model and calculation of the main energy characteristics of the active rectifier are indicated in Tab. 1.

IGBT modules of CM900HB-90H Mitsubishi Electric Corporation [12] can be used as power key. This module has a permissible collector-emitter voltage of 4500 V, a collector current of 900 A. Thus, the IGBT module has a 1.5-fold voltage margin, but does not meet the current requirements. To meet current requirements, use parallel connection of modules. For 1.5 times the current margin, it is necessary to connect three modules in parallel. Thus, the total number of switches used is 18.

The estimate of static and dynamic losses in the power switches of the converter at a PWM frequency of 1000 Hz is about 0.98%, as determined by the method [13]. To meet the requirements for THD at a given PWM frequency, the inductances of the input chokes were determined by known methods: $La = Lb = Lc = 0.15$ mH.

Simulation Matlab-model of active three-phase rectifier is shown in Fig. 5.

TABLE I. THE MAIN ENERGY CHARACTERISTICS OF ACTIVE RECTIFIER

Parameter of model	Value
Nominal output power, kW	5200
Rated output current, A	1600
Output rectifier voltage, V	0 ÷ 3300
Inductive traction network, mH/km	0,8 – 0,85
Capacity of the traction network, μF/km	0,014
Pulsation coefficient of voltage, %	20
THD current consumption, %	8
PWM frequency, Hz	1000

The model of the converter control system is based on the principle described above and is shown in Fig. 6. Due to the fact that the load for the developed active rectifier circuit is rolling stock, it is advisable to carry out a study of the converter operation under conditions typical for this type of load.

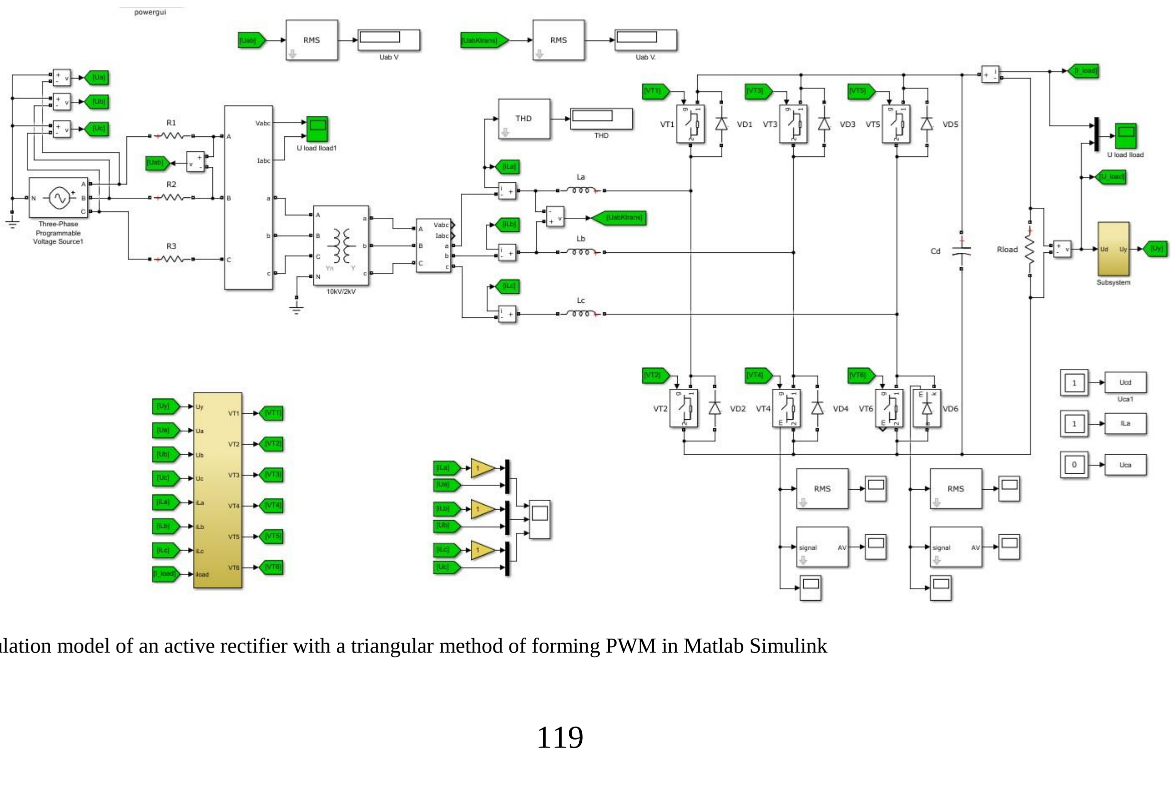

Fig. 5. Simulation model of an active rectifier with a triangular method of forming PWM in Matlab Simulink

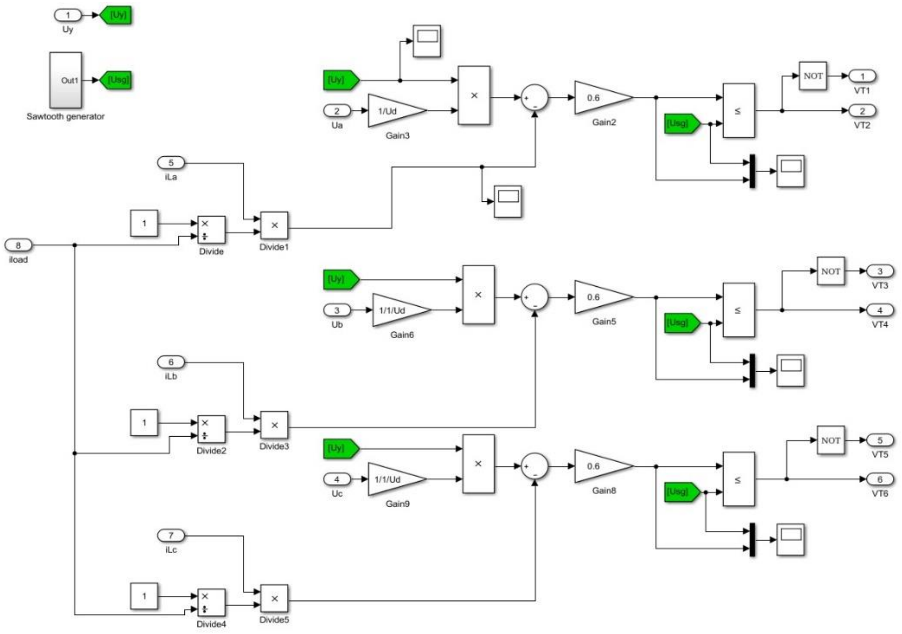

Fig. 6. Control system of the converter in the Matlab Simulink environment

Fig. 7 shows oscillograms of phase currents and voltages in the steady state mode of the converter operation.

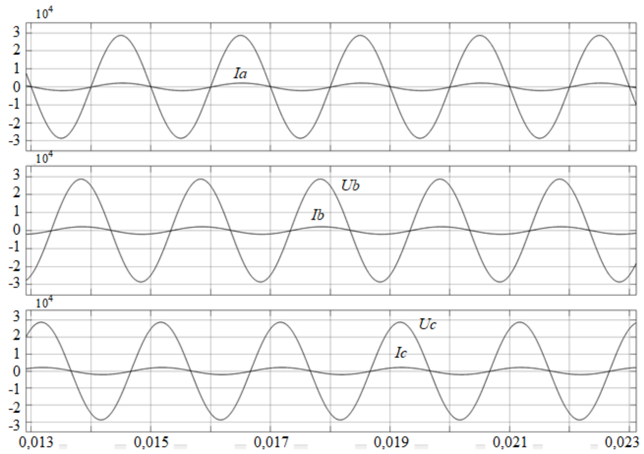

Fig. 7. Oscillograms of phase currents and voltages in the steady state mode of the converter operation

As can be seen, the control system provides a zero phase shift between the current and voltage curves in each of the phases. Form of input current shown in Fig. 8.

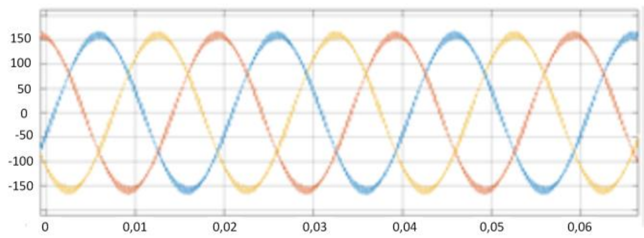

Fig. 8. Oscillograms of input current

Under conditions of stationary load and changes in the level of the supply voltage in the range of ± 20%, the converter control system ensures the stabilization of the output voltage of the contact network (Fig. 9).

At the same time, with a decrease in the level of the input voltage, an increase in the THD is observed due to the increase of the consumed current. Thus, the calculation of the input chokes parameters should be carried out for the worst mode of operation - an increased input voltage.

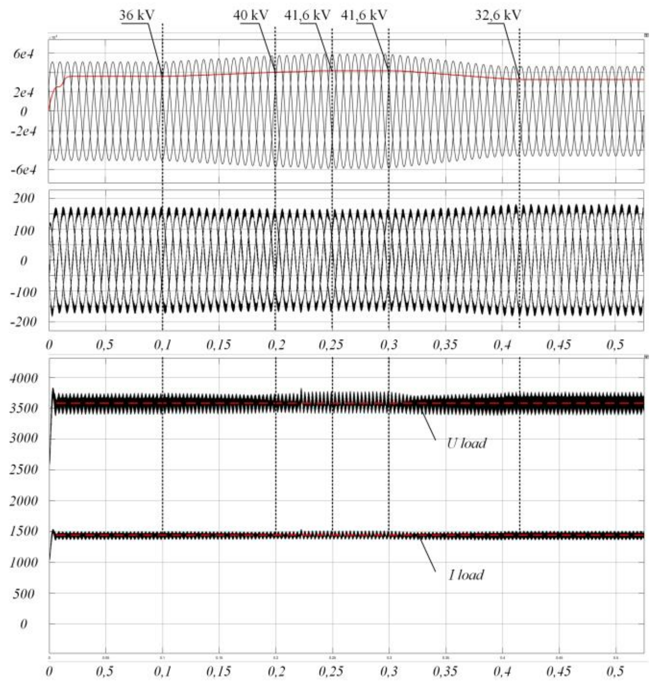

Fig. 9. Oscillograms of the output current and voltage of the contact network with a change in the input voltage level of the supply network.

The model also studied the short-term mode (with a duration of less than one network period) pantograph separation. The duration of the transition process to the steady state in this case takes about 0.5 period of the network (Fig. 10).

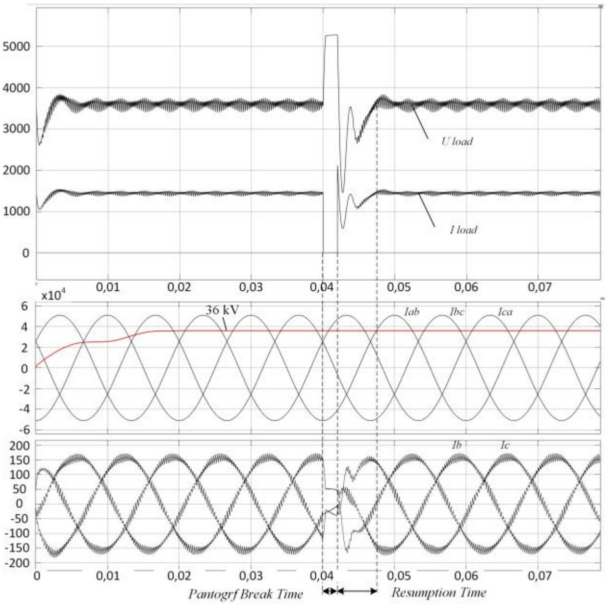

Fig. 10. The result of the experiment mode of the pantograph bouncing

In Fig. 11 shows the response of the system to an abrupt load change from *Pn* to *2Rn* (the entrance of the second rolling stock to the section of the traction network, from which the main rolling stock was powered).

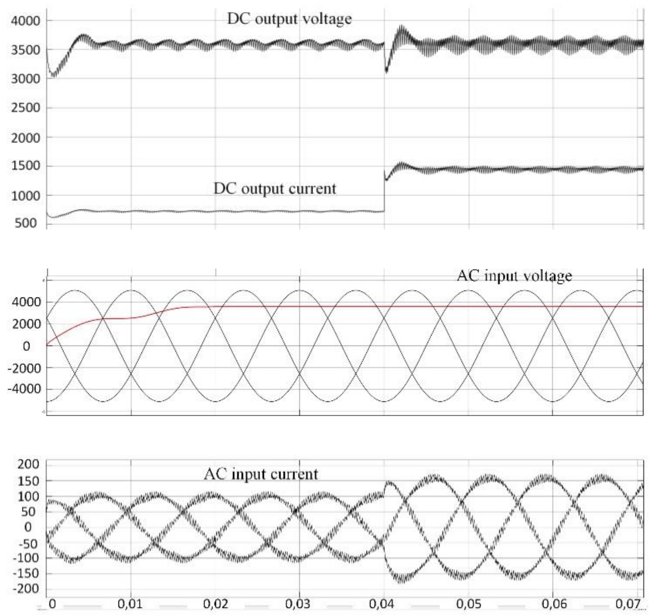

Fig. 11. Oscillograms of input and output current and voltage with an abrupt load change

An important feature of the developed system is its possibility of two-way energy exchange. This allows using it not only consumption mode, but also in the recuperation mode.

The operation of the converter in the mode of energy transfer in the reverse direction also provides high power factor parameters. A detailed description of the operation of the converter in the recuperation mode will be considered in the next materials of the authors.

CONCLUSION

The use of active rectifiers in the power supply systems of the railway transport allows to stabilize the output rectifier voltage at the required level and the proximity of the transmitter power factor to one. In this case, currents close in form to sinusoidal are consumed from the network. An important advantage of this converter is the two-way transmission of electricity, which allows you to recover electricity at the time of the rolling stock deceleration.

The introduction of the main control loop for the current consumed from the network and the use of well-studied PWM methods for generating control pulses to control power IGBT transistors greatly simplifies the task of building a control system.

In Matlab Simulink, using the Power Electronics package, a mathematical model of an active rectifier supplying rolling stock with a capacity of 5 MW was developed, with a supply voltage of 3.3 kV. By means of the created mathematical model, the main operating modes of the converter were studied. The harmonic content of the current consumed in the steady state nominal mode complies with current standards.

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