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Improving the Energy Efficiency of Traction Power Supply Systems by Means the Implementation of Alternative Power Sources

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Abstract

The materials of the article present the structure of the railway power supply system with the implementation of solar and wind power plants, as well as powerful lithium-ion storage devices. It is established that the proposed structure of the power supply system allows it to significantly improve energy efficiency, reduces electricity costs, as well as provides the necessary indicators of electricity quality. An important element of such systems is semiconductor power converters, which provide modes of selection of maximum power of solar panels, modes of efficient charging / discharging of lithium-ion batteries, as well as electromagnetic compatibility of electric rolling stock of railways and power supply systems. The presented computer simulation model of the traction power supply system with alternative power sources was developed in the Matlab / Simulink software environment. The results of computer simulations made it possible to determine the main energy indicators of the system and indicators of electricity quality.
KEY WORDS: *traction power supply system, alternative power sources, solar panels, energy efficiency, electromagnetic compatibility*

1. Introduction

Most technological processes in industry are associated with the production, transmission, distribution and use of electricity, as it is most convenient for the conversion into other types of energy [1, 2].

The main component of the costs of rail transport and subways are the cost of electricity. Given the constant increase in the cost of fuel and electricity, reducing electricity costs is an urgent task [3, 4]. Reducing electricity costs is possible in several ways:

– application of more energy efficient traction electric drives, such as asynchronous electric drive and electric drive with valve motors with permanent magnets;

– optimization of modes and schedule of electric trains according to the criterion of minimizing electricity costs;

– reduction of electricity losses in the ohmic resistance of the contact wire in the railway power supply system by increasing the voltage level in the catenary, reducing the current and, accordingly, reducing power losses in the ohmic resistance;

– reduction of additional losses in the ohmic resistance of the electrical network from voltage dips and higher harmonics.

The use of alternative sources of electricity in the structure of railway power supply is an urgent scientific and technical task [5]. Thus for realization of implementation of alternative sources of the electric power to systems of railway power supply it is necessary to solve a number of scientific and technical problems:

– instability of electricity generation from alternative sources;

– ensuring the quality of electricity from alternative sources to the railway traction network;

– implementation of the selection of maximum power from solar panels by entering the point of maximum power.

2. Analysis of Recent Research and Publications

Studies of ways to improve energy efficiency and electromagnetic compatibility of railway power supply systems have been considered in numerous scientific papers.

In [6] the time characteristics of voltage ripple in the catenary are presented and a mathematical model is given, which allows to assess the quality of power consumption processes and the area of stability of the traction power supply system. However, the paper does not provide ways to improve the quality of electricity.

In [7] a study of the operation of traction substations with the addition of solar panels Jinko Solar JKM305M60 Eagle is presented. The disadvantage of this work is the lack of research on the impact of solar panels on electricity quality indicators. In addition, it is not clear from the work whether the operation of solar panels at the point of maximum power has been optimized.

In [8], in order to minimize reactive power and higher harmonics of currents, as well as to improve the electromagnetic compatibility of traction power supply networks and railway automation systems, a study was conducted on the use of active four-quadrant rectifiers on modern electric rolling stock. On the basis of the carried out researches the technical and economic expediency of use of the scheme of the three-level active rectifier with control system on the basis of two-channel equal-shifted sinusoidal width-pulse modulation (PWM) is proved. The limitations of this study are that the proposed control system can operate with a modulation factor in the range from 0 to 1 and cannot operate in remodulation mode. In addition, the disadvantages of this study include the lack of consideration during the simulation of the impact of the pulse nature of the load of a three-level active rectifier.

In [9] the results of the research of the railway power supply system are presented, in which the voltage stabilization in the catenary by proposing the insertion of solar panels in the interstation intervals is proposed. A significant disadvantage of this work is the description of the structure and modes of operation of the conversion units between the solar panels and the catenary. In addition, the paper does not take into account the peculiarities of the instability of the level of generated voltage of solar panels depending on the level of solar radiation and ambient temperature. Also, the work does not take into account where the electricity generated by solar panels will go, when the electric rolling stock does not consume electricity.

In [10, 11] the research of increase of stability of work of the railway traction substation by implementation of capacitive accumulators of the electric power is resulted. Due to the accumulated electricity in the supercapacitors, voltage stabilization in the catenary is achieved. The disadvantage is the lack of research on the modes of charge / discharge of capacitive drives, the lack of research on the modes of operation of semiconductor converters and quality indicators of electricity generated from the drive to the catenary.

The conducted literature review allows us to conclude that the use of alternative sources of electricity in the structure of railway electricity supply is relevant and needs to be considered.

3. Purpose and Main Objectives of the Article

The purpose of the study is to create a structure of railway electricity supply with the implementation of alternative sources of electricity, which will increase energy efficiency and ensure high quality of electricity. To achieve this purpose, the following tasks are set:

– synthesis of the power part and control system of semiconductor converters, which will provide the mode at the point of generation of maximum power of solar panels;

– to explore the effect of current pulsation.

4. The Main Material of the Article

Consider the characteristics of a single-crystal solar panel STKM-60-270. The main technical characteristics of the solar panel are given in Table.

Table

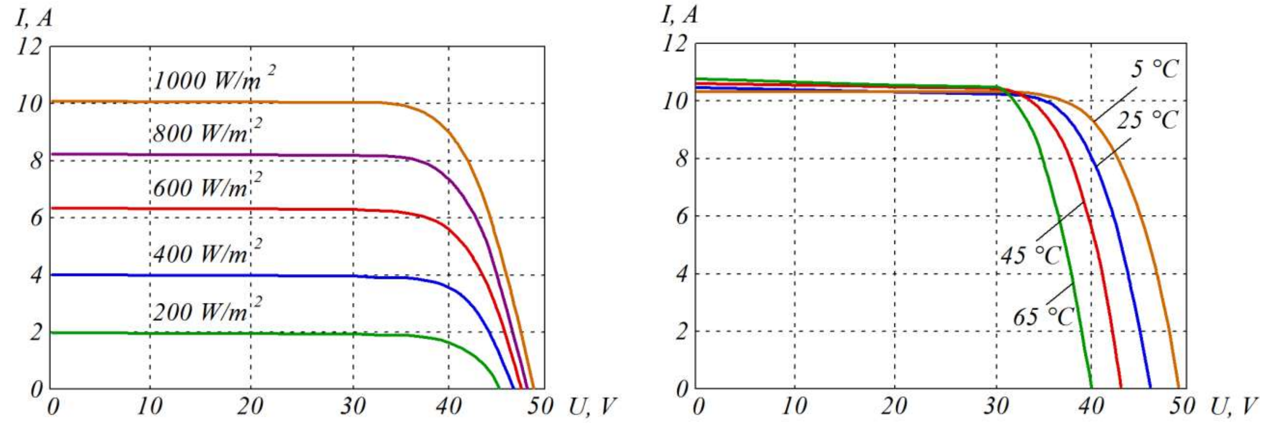
Technical parameters of the solar panel STKM-60-270

Parameter	Value
The maximum power of the solar panel at illumination is 1000 W/m^2, W	270
Idle voltage of the solar panel, V	38.4
Current at maximum power, A	8.51
Voltage at maximum power, V	31.15
Current in short circuit mode, A	8.97
Efficiency of the solar panel, %	18.20
Operating temperature range, ºC	from – 40 to + 85
Temperature current factor, %/ºC	± 0.05
Temperature coefficient of voltage of the solar panel, %/ºC	– 0.34
Temperature coefficient of maximum power, %/ºC	– 0.42
Solar panel area, m^2	1.66

The peculiarity of the solar panel is its low voltage, so to achieve the required voltage level in the catenary requires a series connection of a certain number of solar panels.

The technical parameter that determines the energy dependences of single-crystal solar panels of the STKM-60-270 type is its nonlinear volt-ampere characteristic, which significantly depends on the level of solar radiation and temperature (Fig. 1).

A feature of electricity generation from a solar panel is the dependence of the power generated by the solar panel not only on the amount of solar radiation, but also on the amount of current consumed by the solar panel. The dependence of the generated power of the solar panel in the function is given in Fig. 2.



a b

Fig. 1 Volt-ampere characteristics of the solar panel STKM-60-270: a – at levels of solar radiation of 200 W/m^2, 400 W/m^2, 600 W/m^2, 800 W/m^2, 1000 W/m^2; b – at environment temperature 5ºC, 25ºC, 45ºC, 65ºC

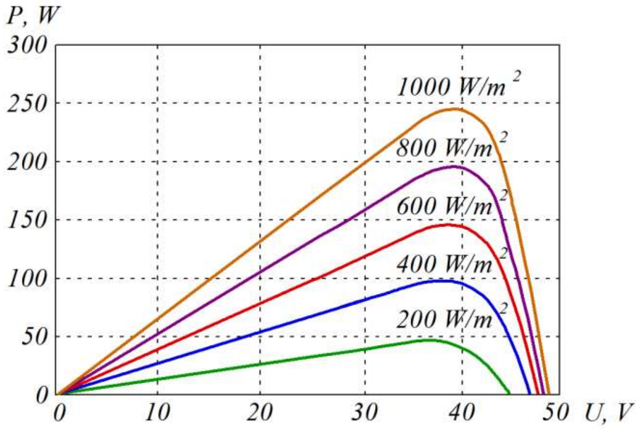


Fig. 2 Power dependences on the voltage of the solar panel and the corresponding points of maximum power at different levels of solar radiation

Thus, a feature of the volt-ampere characteristic of the solar panel is the presence of a generation point of maximum power. Ensuring the operation of the solar panel at the point of maximum power generation is achieved by adjusting the current of the solar panel by a semiconductor converter connected to the solar panel.

To analytically determine the point of maximum power, a polynomial approximation of the volt-ampere characteristic of the solar panel was performed:

– at levels of solar radiation of 1000 W/m^2:

$$U = -44500 \cdot I^5 + 31375 \cdot I^4 - 7716 \cdot I^3 + 764.46 \cdot I^2 - 24.859 \cdot I + 18.22; \tag{1}$$

– at levels of solar radiation of 800 W/m^2:

$$U = -46402 \cdot I^5 + 33583 \cdot I^4 - 8493.8 \cdot I^3 + 866.81 \cdot I^2 - 29.099 \cdot I + 14.728; \tag{2}$$

– at levels of solar radiation of 600 W/m^2:

$$U = -198088 \cdot I^6 + 176912 \cdot I^5 - 60166 \cdot I^4 + 9587 \cdot I^3 - 698.89 \cdot I^2 + 17.999 \cdot I + 10.996; \tag{3}$$

– at levels of solar radiation of 400 W/m^2:

$$U = -209032 \cdot I^6 + 189327 \cdot I^5 - 64729 \cdot I^4 + 10272 \cdot I^3 - 739.43 \cdot I^2 + 18.681 \cdot I + 7.0972; \tag{4}$$

– at levels of solar radiation of 200 W/m^2:

$$U = -101643 \cdot I^6 + 88034 \cdot I^5 - 28944 \cdot I^4 + 4443.5 \cdot I^3 - 311.29 \cdot I^2 + 7.6989 \cdot I + 3.499. \tag{5}$$

The power generated by solar panels depends to a large extent on many factors, namely the amount of solar radiation, ambient temperature, the angle of the solar panel, the number of years of operation of the solar panel, and so on.

5. Computer Model of Traction Power Supply System

The DC power supply of the hybrid inverter is a series of solar panels or a battery pack. The magnitude of the voltage generated by solar panels is variable and varies depending on the light, temperature and number of years of operation of solar panels.

Thus, given the variable value of the input voltage, the problem of stabilizing the output voltage of the hybrid inverter can be solved by using automatic control systems in the control system of the hybrid inverter by changing the modulation factor in sinusoidal pulse-width modulation [12].

The model of a hybrid inverter with an output LC-filter, powered by a battery pack, was developed in the Matlab / Simulink software environment and is given in Fig. 3.

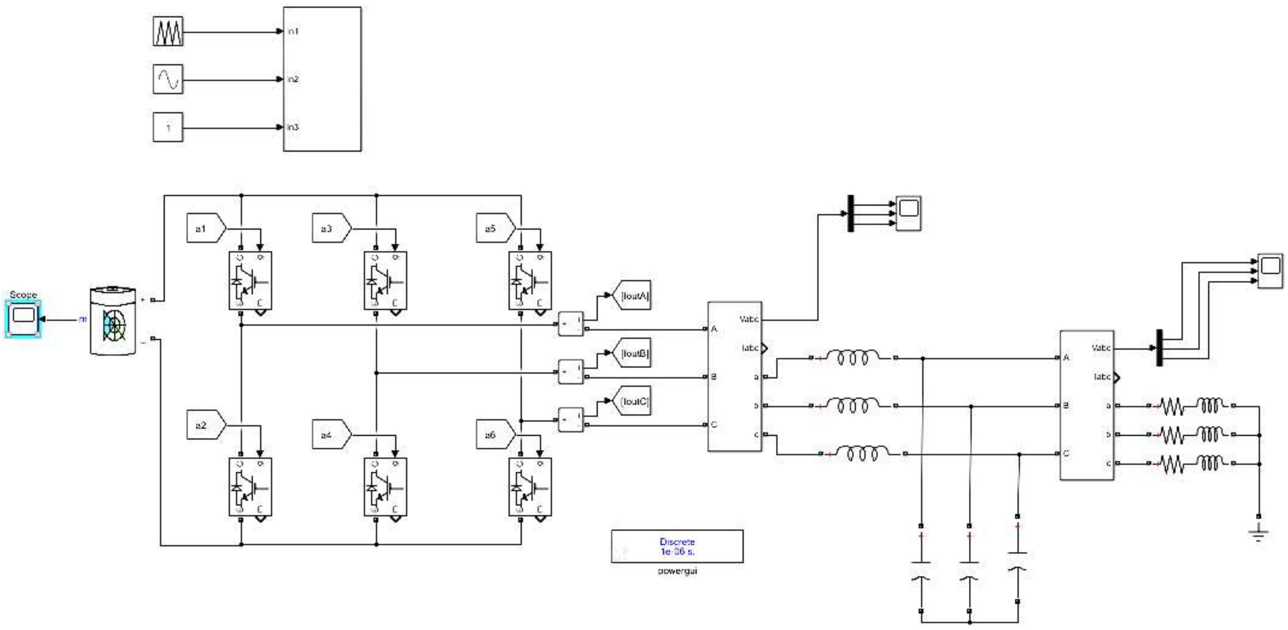


Fig. 3 Model of a hybrid inverter with an output LC-filter

Another feature of the hybrid inverter is the need to form a pure sinusoidal shape of the output voltage. In this case, the classical autonomous voltage inverter has the form of an output voltage, which is obtained by sinusoidal pulse-width modulation, which is given in Fig. 4.

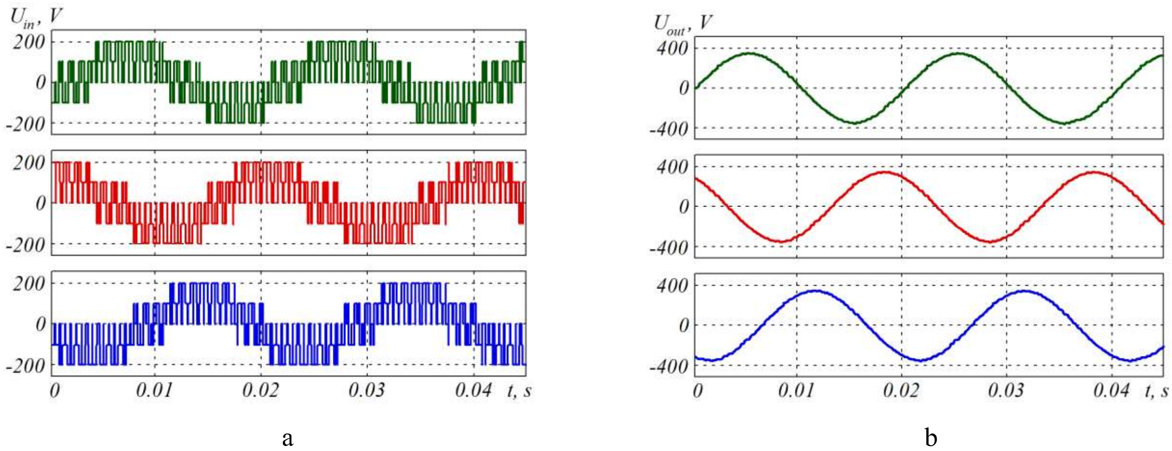
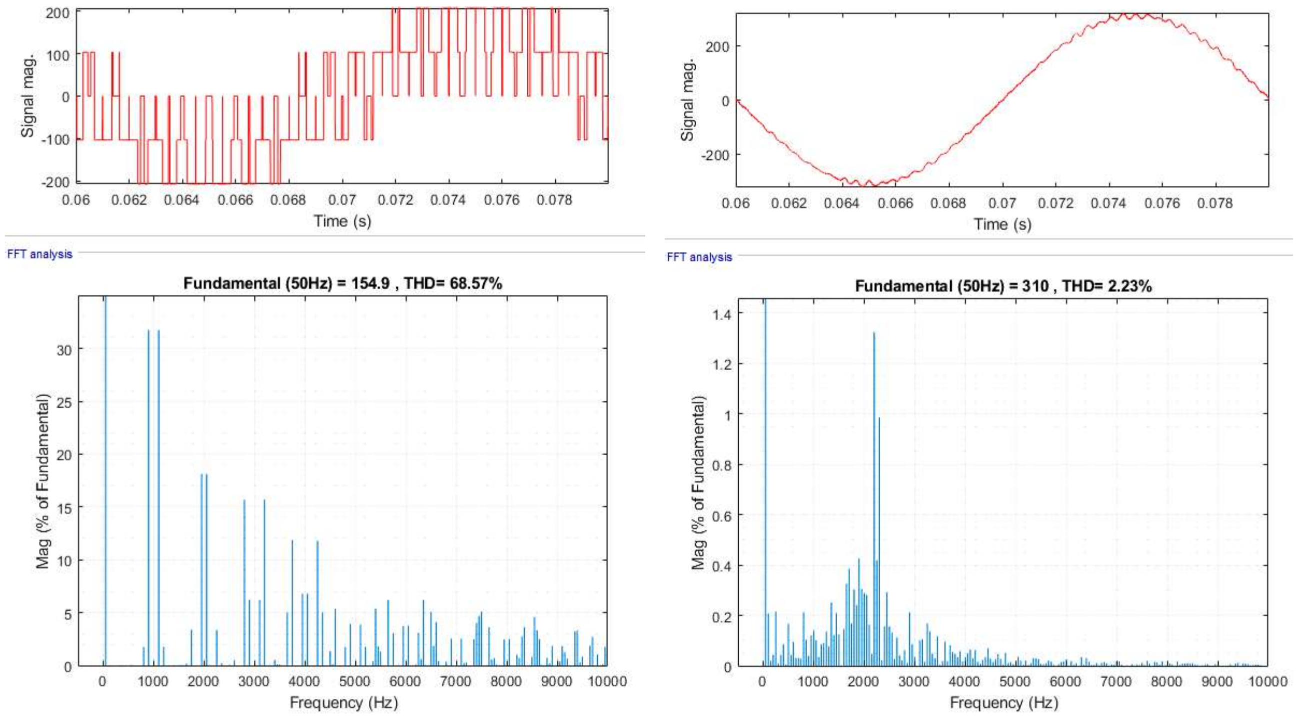


Fig. 4 Form of three-phase output voltage of autonomous voltage inverter with sinusoidal pulse-width modulation: a – before filtration; b – after filtration

The solution of the problem of forming a pure sinusoidal voltage is possible by electrical filtration. To do this, determine the harmonic composition of the output voltage. The result of the harmonic analysis by fast Fourier transform is given in Fig. 5.



a b

Fig. 5 Harmonic composition of the output voltage form of the voltage inverter: a – before filtration; b – after filtration

The total coefficient of harmonic distortion of the analyzed form is equal to 68.57%, despite the fact that international standards regulate the value of not more than 12%. In addition, it is determined that the highest content has a higher harmonic with the frequency of pulse-width modulation, and its content is 34% of the value of the first harmonic.

Improving the sinusoidality of the output voltage is possible by electrical filtration, for example by using an LC-filter.

The amplitude-frequency characteristic of the LC-filter is given in Fig. 6.

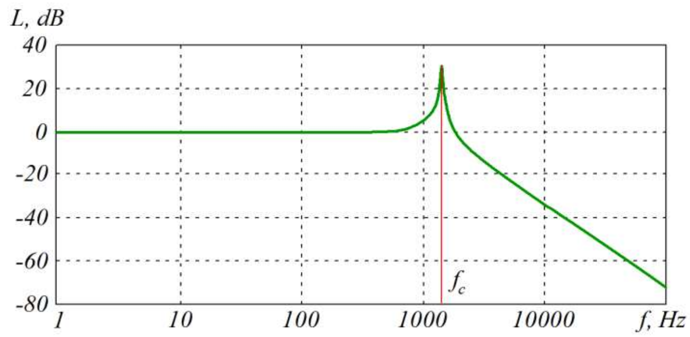


Fig. 6 Amplitude-frequency characteristic of the LC-filter

As can be seen from Fig. 6, the amplitude-frequency characteristic has a resonant frequency at which the amplitude of the output signal is significantly increased, and part of the signal with a frequency above this frequency in the form of the output signal is suppressed.

The resonant frequency, also known as the cut-off frequency of the LC-filter, is determined by the expression [13]:

$$f_c = \frac{1}{\pi \cdot \sqrt{L \cdot C}}. \tag{6}$$

The resonance frequency cannot be set to the frequency of the first harmonic of 50 Hz.

A simulation computer model consisting of a battery subunit, a three-phase voltage inverter, an autonomous voltage inverter control unit, an LC-filter, and an RL-load was used to confirm the implementation of the sinusoidal shape of the output voltage. For the reduced form of the output voltage of the hybrid inverter after filtration by LC-filter performed a fast Fourier transform, which shows that passive filtering can significantly reduce the harmonic composition of the output voltage and provide a value of harmonic distortion of 2.23%, which corresponds to all requirements for electricity quality indicators. The amplitude of the first harmonic of the output voltage is 310 V, which meets the requirements for the critical parameters of the voltage deviation.

6. Conclusions

The structure of the traction power supply system with the implementation of the solar panel unit is proposed. The generation of solar panels to the traction power supply system is implemented through a hybrid inverter. The automatic control system of the hybrid inverter provides electricity generation from solar panels to the electrical network, compensation of higher harmonics of the traction substation, as well as the ability to work at the point of maximum power generation from solar panels by adjusting the current.

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