Improving the efficiency of the railway electric power system

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Abstract. The railway productivity can be increased by increasing the efficiency of the electric power system, the main elements of which are traction substations, overhead contact systems and electric locomotives. The paper analyzes the technical infrastructure of the electric power system of the railway and evaluates the energy efficiency of the equipment. To assess the energy efficiency of the system elements, the revised law of conservation of energy in the electromagnetic field, spectral analysis of electrical quantities and mathematical computer modeling of electromagnetic processes in the system are used. The proposed energy characteristics of the elements of the electric power system made it possible to determine the reasons that hinder the further development of the throughput and carrying capacity of the railway. In order to eliminate the negative impact of inductive resistance of the system elements on the energy indicators of the traction supply and the AC electric rolling stock, the feasibility of the use of high voltage DC electric traction has been proved. Through the complete and continuous use of the voltage of the electricity system for electric traction, it is possible to ensure movement in the intersubstation zone of three linked multiple trains instead of one and increase the speed of trains by 20%. Using high-voltage direct current, the efficiency of electric traction of trains can be increased by 7% compared to electric traction of trains using alternating current by reducing the current by 40% in the overhead contact system.

1. Introduction

The throughput and carrying capacity of the railway largely depends on the energy supply system for train movement and electric traction rolling stock. From the analysis of the directions of research [1, 2], design and engineering work [3 – 5] and the production of equipment for electric traction of trains [6, 7], it follows that the problem of increasing the productivity of transport operations is urgent.

The tasks of energy-saving use of electric energy in the technological process of transport works and reducing the negative technogenic impact on the environment remain unresolved [8, 9]. On Russian railways, 3.3 kV DC voltage and 27.5 kV AC voltage with a frequency of 50 Hz are used for electric traction of trains. Three-phase transformers, twelve-, twenty-four pulse three-phase rectifier-inverter converters with supply and amplifying wires in the overhead contact system are used at DC traction substations. Electric rolling stock with collector traction electric motors and contactor power control are mainly used in a DC system. Three-phase transformers with voltage distribution over the feeder zones of the overhead contact system are mostly used at AC traction substations; to enhance the traction power supply, a 2 × 25 kV system with autotransformer points on the line is being introduced.
Electric locomotives with collector traction electric motors and pulse-phase power control of a single-phase reversible converter are mainly used in the AC system. Two-system electric locomotives with three-phase asynchronous traction electric motors have been developed and tested, the power of which is regulated by a four-quadrant 4-qS input converter and three-phase autonomous inverters (AIV) with pulse-width modulation (PWM) of a frequency-controlled three-phase voltage on the stator windings of the traction electric motors. To increase the traction power of locomotives, the plants manufacture them in a three-section, four-section design and technology of driving linked multiple trains is introduced. The experience of operating three-sectional electric locomotives on separate railway sections is accompanied by the maximum permissible voltage deviations, slack of the contact wire and the decrease in the speed of trains. Our research [10] is confirmed by the results of the experimental driving of linked multiple trains, the results of acceptance tests of new traction rolling stock. Equipment for cleaning and monitoring systems, electric rolling stock with collector and three-phase asynchronous traction motors are used in the system of direct and alternating current of the national railways, and enterprises of the machine-building industry in Russia continue to manufacture them.

The theory of energy processes, which is used in educational institutions in Russia and abroad, has methodological contradictions with the theory of fundamental electrical engineering, power supply, electrical machines and electric drives. Future specialists are focused on improving the features that allow one to evaluate energy processes in the use of electrical energy, and thus develop, exploit and eliminate the consequences of unsatisfactory equipment operation [11].

2. Materials and methods
Insulating materials with increased dielectric and mechanical strength, made on the basis of modern nanotechnology, allow using high voltage in power equipment of the energy supply system for train movement and electric rolling stock. In power transformers, reactors, electrical machines and other electromagnetic devices with the use of hard magnetic, ferrite and other core materials instead of electrical steel, the efficiency of galvanic isolation and energy transfer increases, the ability to match the voltage of high voltage electrical circuits with the voltage of the traction networks of the energy supply system for train movement, with the voltage of the windings of the traction electric motor of the electric rolling stock. The use of modern electric energy storage devices gives new properties to semiconductor power regulators. Modern advances in digital electronics can be used to control power semiconductor devices and implement control algorithms. The above-mentioned equipment allows one to implement modern scientific developments to improve the efficiency of the railway electricity system.

Based on the specified law of conservation of energy in the electromagnetic field [12], this study uses new energy characteristics of elements of the electric power system [13], spectral FFT analysis of non-sinusoidal voltage and current to evaluate the efficiency of the electric power system. Calculations were performed using the MATLAB computer program in the Simulink environment. The error of the results of the study is assessed on the basis of the proposed power balance.

3. The study of electric power efficient use in transport
The power balance at the inlet of electrical plants with semiconductor converters [13] is obtained with the application of the second law of Kirchhoff and spectral analysis of voltage and current:

$$\sqrt{S^2 - \Delta S^2} = \sqrt{P^2 + Q^2},$$

where $S$ is the full power at the inlet of the electrical plant with semiconductor converters;

$\Delta S$ is the part of the full power at the inlet of the electrical plant during the non-conductive state of the converter power semiconductor devices;

$P$ is the active power at the inlet of the electrical plant;

$Q$ is the reactive power at the inlet of the electrical plant.
The balance of power constituents (1) is calculated using spectral voltage and current analysis at the inlet of the electrical plant.

Full power at the inlet of the electrical plant:

\[ S = \sqrt{\sum_{k=0}^{n} U_k^2} \cdot \sqrt{\sum_{k=0}^{n} I_k^2} = U \cdot I, \]  

(2)

where \( U_k \) is the RMS voltage of the \( k \)-th component of the Fourier series at the inlet of the electrical plant;
\( I_k \) is the RMS current of the \( k \)-th component of the Fourier series at the inlet of the electrical plant;
\( U \) is the RMS voltage at the inlet of the electrical plant;
\( I \) is the RMS current at the inlet of the electrical plant;
\( k \) is the number of the Fourier series component;
\( n \) is the number of the last harmonics to be considered.

The power at the inlet of the electrical plant during the non-conductive state of the converter power semiconductor devices:

\[ \Delta S = \sqrt{\sum_{k=0}^{n} U_{pk}^2} \cdot \sqrt{\sum_{k=0}^{n} I_k^2} = U_p \cdot I, \]  

(3)

where \( U_{pk} \) is the RMS voltage of the \( k \)-th component of the Fourier series at the inlet of the electrical plant during the non-conductive state of the converter power semiconductor devices;
\( U_p \) is the RMS voltage at the inlet of the electrical plant during the non-conductive state of the converter power semiconductor devices.

Active power at the inlet of the electrical plant:

\[ P = U_{c0} \cdot I_{c0} + \sum_{k=1}^{n} U_{ck} \cdot I_k \cdot \cos \phi_k, \]  

(4)

where \( U_{c0}, I_{c0} \) are the constant components of the Fourier series, respectively, voltage, current during the conducting state of the converter power semiconductor devices;
\( U_{ck}, I_k \) are the RMS voltage, current of the \( k \)-th harmonics of the Fourier series at the inlet of the electric plant during the conducting state of the converter power semiconductor devices;
\( \phi_k \) is the phase displacement angle of the \( k \)-th harmonic relative to the similarly named \( k \)-th voltage harmonic.

Reactive power at the inlet of the electrical plant:

\[ Q = \sum_{k=1}^{n} U_{ck} \cdot I_k \cdot \sin \phi_k. \]  

(5)

The argument \( \phi_S \) of the total inlet power and the inlet electrical resistance of the electrical plant can be calculated using the formula:

\[ \phi_S = \arccos \frac{P}{S} = \arccos \left[ \frac{U_{c0} I_0 + \sum_{k=1}^{n} U_{ck} I_k \cos \phi_k}{U I} \right]. \]  

(6)

Using the proposed energy characteristics, the studies of the energy efficiency of a 12 kV DC traction power supply system and a three-section electric freight locomotive with a traction electric motor (figure 1) are carried out in work [14].
In contrast to the AC electric power supply system, the inductivity of the substation’s traction transformers, the overhead contact system and the inductivity of the traction transformers of electric rolling stock are eliminated, and the negative impact of inductive resistance on the efficiency of the railway electricity system is suppressed. The design of the traction electric motor of the electric rolling stock, thanks to the use of the High Voltage Electric Semiconductor Variator (ESV) input converter, allows one to change the way the three-section traction electric motor is linked in time and thus eliminate the grouping of the traction electric motor. Intermediate electrical energy storage devices C, IGBT transistor modules and reverse diodes provide practically constant current in the traction electric motor windings (current pulsation rate is no more than 2%) without the use of smoothing reactors. The energy of the electric field of C storage devices, the magnetic field of traction electric motor windings is used for the traction of the train and to compensate for the loss of active power with full and continuous use of voltage on the current collector.

If the loss of active power in the electrical circuits of the traction electric motor of the electric rolling stock is neglected, how many times the voltage of the Ud across the windings of the traction electric motor is less than the voltage across the current collector Utp. The current consumed by the electric rolling stock from the overhead contact system reduces by the same amount. Calculations performed with computer simulation and expressions (1–6) allow one to take into account the loss of effective power in the electrical traction system. Voltage across the current collector is Utp = 9221V. The current in the electric rolling stock current with the operation of 12 traction electric motors with a nominal load amounted to I = 1111 A, i.e. it exceeds the nominal current of one traction electric motor by 11%. The total current of 12 traction electric motors is 9723 A, which indicates that the power regulator has the property of an electric variator. The results of this study confirm the possibility of increasing the efficiency of the power regulator and traction electric motor of the electric rolling stock to 94.3%. The voltage on the current collector provides a nominal speed of the train movement. However, the efficiency of the DC overhead contact system with a voltage of 12 kV is 75.8%. In this regard, the total loss of active power in the AC electric traction system with a voltage of 27.5 kV and in the electrical traction system at a constant current of 12 kV is almost identical.
Three-phase six-pulse rectifiers assembled on diodes can be installed at the traction substations, which are equipped with traction three-phase transformers with a linear voltage of secondary windings of 27.5 kV. Voltage stabilization can be provided by regulators similar to ESV designs. The rectified voltage on the substation's DC buses is 37.1 kV. The power equipment of the traction transformer substation, the contact suspension and the equipment of the high-voltage electric rolling stock input converter must be manufactured with high dielectric, mechanical strength and through the use of modern technologies for the manufacture of materials for power equipment of the energy supply system for train movement and electric rolling stock. The mathematical model of the 37.1 kV DC traction power supply system consists of an overhead contact system, which is applied at a variable voltage of 27.5 kV, and a three-section electric rolling stock with a high voltage input converter, ESV, and collector's traction electric motors. The results of the simulation were performed for the study of the start and acceleration to the 5 km/h steady-state speed of the train with a nominal moment of resistance on the shaft of the traction electric drive 7772 N·m in the middle of the intersubstation zone and are presented in Figures 2, 3. In the steady-state mode of electric traction of the train, electric rolling stock consumes the current $I_{tg} = 75.51$ A from the contact network. The voltage on the electric rolling stock collector is 36910 V. The voltage on the windings of the traction electric motor is $U_d = 135.4$ V, current $I_d = 806.2$ A flows along the windings of each traction electric motor, and the total current of 12 traction electric motor is equal to $I_d = 9733$ A (Figure 2). Active power at the inlet of the traction electric motor is 2787 kW. The efficiency of the traction electric motor is 69.8%, the ESV efficiency is 47.2% due to the low voltage mode on the traction electric motor windings. After 0.2 seconds from the beginning of oscillographing, the voltage of 37.1 kV is applied and the current $I_{tg} = 1656$ A flows along the electric rolling stock current collector to charge the intermediate electric energy storage device. At a moment of time of 0.25, the control pulses are coming in on the ESV IGBT transistors, so the current $I_{dv}$ begins to flow in the winding of each traction electric motor. With the increase in the current of the traction electric motor to $I_{dv} = 1000$ A, the shaft of the electric motor begins to rotate, and the current on the electric rolling stock collector is reduced exponentially to $I_{tg} = 600$ A (Figure 3).

![Mathematical model of the DC power supply system](image)

**Figure 2.** The mathematical model of the DC power supply system with a voltage of 37.1 kV and a traction electric motor of a three-section freight locomotive at a train speed of 5 km/h.
Figure 3. The current oscillograms across the current collector $I_{tp}$, current in the windings of the traction electric motor $I_{dv}$, and the rotation speed of the shaft $n$ in the traction electric motor of the electric rolling stock.

The maximum starting current in the windings of a single traction electric motor is $I_{dv} = 1150$ A, and the overhead contact system is loaded with a current of $I_{tp} = 400$ A (Figure 3). In the steady-state mode, currents are equal to: $I_{dv} = 806$ A, $I_{tp} = 75$ A, the rotation speed of the traction electric motor shaft $n = 94$ rpm.

The results of the calculation of the DC current traction power supply system with a voltage of 37.1 kV and a three-section electric rolling stock in the nominal mode of operation were obtained using a mathematical model presented in Figure 4.

Figure 4. The mathematical model of the DC traction power supply system with a voltage of 37.1 kV and a traction electric motor of a three-sectional freight locomotive at a train speed of 54 km/h.
The results of the study of start and acceleration modes of electric rolling stock show a significant decrease in the current in the overhead contact system compared to the current in the windings of the traction electric motor, which is necessary for the traction and acceleration of the train. This result is achieved by the preliminary charge of the intermediate electric energy storage device and the properties of the electric variator.

The study found that with the transition to the DC energy supply system for train movement, together with increased voltage, eliminates inductive resistance of the overhead contact system and traction transformer of the electric rolling stock, and the speed and mass of trains can be increased. In a 27.5 kV overhead contact system, the RMS current is 1.4 times higher than the current in the same overhead contact system at a constant current of 37.1 kV. The 43 km/h speed of the train was obtained due to the voltage limit on the electric rolling stock current collector with reversible converter in the AC energy supply system for train movement due to the voltage drop on active and inductive resistances in the energy supply system for train movement. The voltage level across the ESV DC electric rolling stock allows one to drive three high-speed linked multiple trains when using the DC energy supply system for train movement.

Active power in the DC energy supply system for train movement and EPS with 11820 kW ESV is spent on train traction and the loss of active power in the power electrical circuit of the electric rolling stock. And the AC energy supply system for train movement and the electric rolling stock with reversible converter as part of the full-capacity $S_G = 11480$ kVA contains the active capacities of the harmonic components $P_1 = 9773.1$ kW, $P_3 = 98.4$ kW, $P_5 = 44.4$ kW, $P_7 = 2.9$ kW, $P_15 = 1.14$ kW, $P_9 = 1.16$ kW. Reactive magnetization powers of harmonic components of the electric rolling stock traction transformer are $Q_1 = 4745.6$ kVAr, $Q_3 = 350.6$ kVAr, $Q_5 = -86.7$ kVAr, $Q_7 = 15.7$ kVAr, $Q_9 = -6.7$ kVAr, $Q_{11} = 5.2$ kVAr, $Q_{13} = -3.3$ kVAr, $Q_{15} = 1.2$ kVAr, $Q_{17} = -0.24$ kVAr, $Q_{19} = 0.022$kVAr. Due to the operation of the traction transformer of the electric rolling stock with reversible converter in a short-circuit mode during the switching of current in the reversible converter tiristors, as part of the full-capacity $S_G$, the power is formed by the power $\Delta S = 3202$. And the voltage across the AC electric rolling stock current collector and the train speed are reduced. The efficiency of AC energy supply system for train movement is 94.6% and the electric rolling stock efficiency with reversible converter is 79.3% due to significant losses of active power in power electrical circuits of the electric rolling stock.

The efficiency of DC energy supply system for train movement is 97.8% efficiency and the efficiency of the electric rolling stock traction electric motor with ESV is 83.7%, so the efficiency of DC electric traction of trains increases by 7% compared to the AC electric traction of trains.

In well-known scientific works, in addition to energy efficiency, other advantages and disadvantages of AC and DC electric traction are considered in sufficient detail. Once again, this study proves the feasibility of increasing voltage with an increase in the amount of work performed with electric energy.

4. Conclusion
Technical solutions have been developed on the basis of the refined law of energy conservation in the electromagnetic field. The energy characteristics of the elements of the railway's electricity system have been proposed. The application of the new power regulator ensures the full and continuous use of the voltage of the electric power supply system to perform transport work. In the high-voltage DC electric traction system, it is possible to ensure the movement of three linked multiple trains in the intersubstation zone of the railway with a modern contact suspension and increase the train speed by 20%. The RMS current in the overhead contact system is reduced by 40% due to the efficient use of voltage. The efficiency of high-voltage DC electric traction trains is 7% higher than the efficiency of AC electric traction trains.

Significant amounts of scientific and technical work are needed to implement electric traction at a constant high voltage current. In the development of design documentation, it is important to use mod-
ern insulation materials with high dielectric and mechanical strength. It is advisable to develop and manufacture electromagnetic machines, electric machines for electric traction by applying magnetic conductors with high magnetic permeability. Using the latest advances in power and information electronics, electric energy storage devices allow one to implement promising directions for further development of electric traction trains.

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