Study of the operation of high-frequency electrical plants of railway consumers

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Abstract. The article discusses the issues of improving the quality of electricity in the networks of non-traction railway consumers through the use of energy routers. Model studies of the electricity supply system of railways with high-frequency routers were carried out. Results have been obtained that allow using energy routers to supply electricity to plants of railway consumers with increased requirements for electric power quality. The article presents the results of the calculation of the high-frequency transformer and its experimental characteristics obtained in the study of high-frequency electrical plants of consumers.

1. Introduction
The railway system is the basis of the transport communication of the country and the continent. This is a well-developed infrastructure, including travel facilities, overhead systems, electric power supply, loco depots, repair companies, etc. Like any other complex structure, all elements of which are interconnected in a single technologically process, the system strives to reduce consumption at each production stage, make extensive use of existing internal capabilities and advantages, and improve control over the resources used. In this regard, the power supply of consumers' installations operating in the railway system also has its own specifics, due to the unified power system of railway transport, designed to provide electricity to both traction and other consumers. This feature results in a significant deterioration in the quality of electricity supplied to electrical plants of non-traction consumers.

This is a known issue, and there are a number of technical measures aimed at reducing the impact of traction load on the operation of electrical plants of other consumers, united by a single electric power supply system. However, there is no general solution to the problem. The proposed measures mainly reduce the amount of distortion – they reduce the asymmetry and non-sinusoidal voltage coefficients to the values acceptable by the quality standard (GOST 32144-2013). This does not ensure the complete elimination of distortions in the form of the supply voltage, which, in some cases, is not enough for the normal supply of electrical plants to responsible consumers with increased requirements for electric power quality. Currently, this problem is partially solved by the use of stand-alone generating units, or uninterrupted power sources. These technical solutions cannot be called successful, because, by their nature, they are closer to meeting the requirements for electric power supply of a special group of consumers, and are not designed for long-term use. To solve the problem completely, it is required to develop power plants that allow the consumer to provide high-quality electricity during long-term operation.
Currently, Smart Grid technologies are widely introduced in electric power supply systems. They are based on intelligent generation and consumption of electricity, using distributed generation plants and semiconductor converter devices designed to improve the quality and reliability of generation, power supply and consumer facilities [1–3]. This integrated approach determines the close relationship between all the elements involved in the electric power process. The electric power systems of railway transport are also actively introducing elements of intelligent systems to solve problems related to improving the characteristics of their own electric power supply networks.

One of the ways of introducing intelligent elements into the electric power supply network is to organize a special type of transformer substations, including special transformers and controlled conversion devices, so-called energy routers (ER) [4–6]. These devices are designed to organize controlled energy consumption, connect distributed generation plants, and provide two-way energy flows.

2. Energy Routers
To solve the problem of energy quality in the traction electric power supply networks, when connecting consumer plants with increased requirements to electric power parameters, it is proposed to organize special ERs, which provide almost sinusoidal voltage of stable frequency in combination with the ability to maintain a constant amplitude. Modern elemental base of power electronics allows one to create converter devices that operate reliably in high-voltage networks, capable of switching high currents, and perform high-frequency switching. The power of ER should be comparable with the energy characteristics of power transformers used in electric power supply networks of 10 / 0.4 kV (no more than 2.5–3.2 MVA).

Fig. 1 shows the flow chart of the ER, arranged by the principle of high-frequency transformation [7], with a capacity of 3 MVA.

![Figure 1. The flow chart of the energy router](image)

The proposed ER scheme consists of an input rectifier (high-voltage, industrial frequency), inverter 1 (it generates 5–15 kHz high-frequency pulses of a rectangular shape), a high-frequency transformer (its magnetic core is made of 0.1 mm electrical steel sheet when used at high frequencies), the output controlled rectifier (low-voltage, high-frequency), inverter 2 (it generates an almost sinusoidal output voltage of the mains frequency, for example, a resonant inverter [8–10]).

In the circuits of small and medium power routers, field Mosfet transistors are used in a high-frequency inverter, which have good dynamic characteristics allowing them to be used in systems with a frequency up to 100 kHz. The operating frequency of such ER is approximately 20 kHz. However, these semiconductor elements have limitations on the magnitude of the transmitted current up to 100 A.

A bipolar IGBT transistor, capable of switching currents above 1 kA, is used in the high-frequency inverter of the proposed ER. The effective use of this transistor is limited by the switching frequency at which the losses are within acceptable limits, ensuring a sufficiently high conversion efficiency (above 90 %). This frequency is approximately equal to the clock frequency of the frequency converter – up to 5 kHz.

2.1 ER model studies
On the basis of the proposed flow chart, an ER model was compiled in the Matlab-Simulink environment, shown in Fig. 2. In accordance with the flow chart, the model has two uncontrolled rectifiers to rectify voltages in the high-voltage and low-voltage parts of the circuit, and two inverters,
respectively, to receive pulses of 5 kHz frequency (Invertor_5000Hz) and output 50 Hz voltage (Invertor_50Hz). The ER is designed as a Ehnergorouter subroutine, which can be integrated into any model of the energy system. In this case, the system of traction electric power supply is being investigated (Fig. 3), where the ER is used to supply high-quality electric power to the plants of non-traction consumers.

Figure 2. The Energy Router Model

Figure 3. The traction electric power supply system with ER

In the studied model of the traction power supply system, there is a three-winding transformer, the secondary windings of which serve to supply energy to the electric stock and to the plants of non-traction consumers. The load power for the ER is 2.24 MVA, with power factor \( \cos \phi = 0.89 \). Model studies were conducted with the ER turned on and off.

Fig. 4a shows the simulation results with the ER turned off. Obviously, there is a significant amount of asymmetry (Nesimmetria, 5.265, maximum allowable – 4) and unsinusoidality (Nesinusoidalnost, max. 6.598, maximum allowable – 5) (Fig. 4b) in the form of voltage supplied to the consumer from the traction transformer.

The ER operation is characterized by indicators of digital frequency measurement units (Fig. 3) and voltages on the windings of a high-voltage transformer (Fig. 5a, b).

Fig. 6 presents a diagram of voltage (a) and indicators of quality of electricity (b) supplied to electrical plants of a consumer through the ER.

The type of output characteristics of the ER shows that the voltage supplied to the consumer is almost sinusoidal with a frequency of 50 Hz, there are virtually no deviations in magnitude (0.0565) and in form (max. 0.434).
Figure 4. Voltage (a) and electric power quality parameters (b) of a non-traction consumer without an ER

Figure 5. Voltages at the high-frequency transformer, from the side of 10 kV (a), from the side of 0.4 kV (b)

Figure 6. Voltage (a) and power quality parameters (b) when the consumer is powered through the ER

3. Experimental studies of the operation of high-frequency electric plant

The concept of ER and the possibility of technical implementation were experimentally tested on a high-frequency power supply unit of a technological plant developed at Trans-Atom LLC, Russia, by order of the Cuban Railway (Ferrocarriles de Cuba), The Republic of Cuba.

The principle of operation of the converter is based on double conversion of electrical energy. First, the three-phase mains voltage is supplied to the bridge unregulated diode rectifier. Then the rectified voltage, using a bridge single-phase Mosfet transistor inverter, is converted into a rectangular AC voltage with a frequency of up to 15 kHz. The calculated values of the currents in the primary winding are less than 100 A, so the use of these high-frequency transistors is justified and expedient. The voltage is further applied to the primary winding of the power transformer. A load is connected to the secondary winding, the permissible value of which depends on the frequency of the voltage pulses.

Regulation of the RMS voltage value at the load is made by changing the interpulse period at the output of the power inverter and, therefore, at the windings of the transformer. The converter operation and protection management is controlled from the control board, which is located in the converter. Fig. 7a shows the arrangement of the high-frequency power supply unit of the process plant.

3.1 Calculation of high-frequency transformer

The resistance of the windings and, as a consequence, their heating is determined by the current density in the wire, which was set when calculating. Based on practical experience, it is recommended to use the value of current density in a copper wire not exceeding 3.2 A/mm$^2$. The transformer is calculated
from the operating conditions of the magnetic system on the linear portion of the magnetization characteristic, since according to technological conditions, the frequency of operation is variable (10–15 kHz), and in order to perform high-precision control, it is better to control the process of tuning the frequency with linear characteristics dependencies. In this case, the determining factor is the choice of the magnitude of the magnetic induction.

When the basic design conditions are fulfilled, the efficiency of a high-frequency transformer will be at least 95%. Based on this, an efficiency value of 0.95 pu is used in the calculations.

The determining value for the calculation of the transformer makes it possible to place the windings in the aperture of the core of the magnetic circuit. The recommended value of the fill capacity factor of the core aperture with copper ($K_m$) for frame shell-type or core-type magnetic circuits is 0.45. With wide frames and a large winding length of one layer, the value of $K_m$ can be as high as 0.5…0.55, as, for example, in magnetic circuits of type B69 and B35. With frameless industrial winding $K_m$ can have values up to 0.6 … 0.65. In general, the theoretical limit of the value of $K_m$ for layered arrangement of a round wire without insulation in a square aperture is 0.87.

The given practical values of $K_m$ are achievable only if the wire is laid strictly turn to the turn, with thin interlayer and interwinding insulation, and the leads are sealed outside the core aperture (on the lateral winding overhangs). In the manufacture of frame windings in laboratory or pilot production, the value of $K_m$ should not be more than 0.3 … 0.4.

The power-to-size ratio of the transformer, in watts, is determined by the following expression:

$$P = \frac{4.44 \eta \cdot S_c \cdot S_0 \cdot f \cdot B \cdot j \cdot K_m \cdot K_c}{(1 + \eta) \cdot 100},$$

where $\eta$ is the transformer efficiency, pu;
$S_c$ and $S_0$ are the cross-sectional areas of the core and the aperture, respectively [square cm];
$f$ is the lower operating frequency of the transformer, Hz;
$B$ is magnetic induction, T;
$j$ is the current density in the wire windings, A / mm$^2$;
$K_m$ is the fill capacity factor of the core aperture with copper;
$K_c$ is the fill capacity factor of the core section with steel.

With the known voltage in the windings, the number of turns can be calculated by the formula:
\[ n_1 = \frac{U_1 \times 10^4}{4.44 \times f \times B \times S_c \times K_c}, \]

where \( U, U, \ldots \) are the winding voltages in volts, and \( n, n, n, \ldots \) are the number of turns of the windings.

Table 1 shows the main parameters of the high-frequency transformer designed for installation.

| Parameter          | Value          |
|--------------------|----------------|
| \( S_c \)          | The cross-sectional area of the core, \( \text{cm}^2 \) | 13.65 |
| \( S_o \)          | Aperture area, \( \text{cm}^2 \)   | 33.5  |
| \( \eta \)         | Efficiency     | 0.95  |
| \( V \)            | Magnetic induction, \( \text{T} \) | 0.35  |
| \( j \)            | Current density in the wire windings, \( \text{A/mm}^2 \) | 3.2   |
| \( K_m \)          | The fill capacity factor of the core aperture with copper; | 0.3   |
| \( K_c \)          | The fill capacity factor of the core section with steel. | 0.93  |
| \( f \)            | Frequency (kHz) | 10, 12, 15 |
| \( P \)            | Calculated power-to-size ratio, \( \text{kW} \) | 31, 37, 46 |
| \( U_1 \)          | Primary Voltage, \( \text{V} \) | 535   |
| \( U_2 \)          | Secondary Voltage, \( \text{V} \) | 100   |
| \( I_1 \)          | Primary winding current, \( \text{A} \) | 54    |
| \( I_2 \)          | Secondary winding current, \( \text{A} \) | 290   |
| \( n_1 \)          | The number of turns in the primary winding | 27, 23, 18 |
| \( n_2 \)          | The number of turns in the secondary winding | 5, 4, 3 |
| \( W \)            | Weight, \( \text{kg} \) | 6     |
| Dimensions, \( \text{mm} \) (LxWxH) | 196x84x150 |

According to the calculated data, a high-frequency transformer was made, which is one of the main components of the power supply unit. The use of this transformer has reduced the weight and dimensions of the plant. For example, consider the main indicators of industrial frequency dry power transformers (Table 2).

Table 2. Comparative characteristics of industrial frequency dry transformers

| №   | Type         | Dimensions, \( \text{mm} \) | Weight, \( \text{kg} \) |
|-----|--------------|-----------------------------|-------------------------|
| 1   | TS-25/10     | 880x520x925                 | 340                     |
| 2   | TS-40/10     | 940x520x985                 | 420                     |
| 3   | OSU-20 / 0.5 | 540x420x555                 | 136                     |
| 4   | OSU-40/0.5   | 740x575x765                 | 283                     |

It is obvious that all the transformers presented in Table 2 are significantly inferior to the developed high-frequency transformer according to the given characteristics (Table 1). Depending on the design, the transformer weights differ by more than 70 (three-phase) and 48 (single-phase) times. In terms of dimensions, the differences range from 3 to 6 times.

3.2 Experimental studies of high-frequency transformer

The high-frequency power supply unit was studied by the oscillography of signals of currents and voltages characterizing the qualitative and quantitative conversion parameters. Fig. 7b shows a general view of the experimental plant, which includes the object of research and the measuring instrument - a Tektronix TPS 2024B oscilloscope. This device makes it possible to obtain accurate frequency values, which is an important indicator in the regulation and fixation of the RMS voltage. To obtain results compatible with computer processing, the Hantek DSO-2090 digital oscilloscope was also used in the studies.
Fig. 8a shows one of the results of experimental studies to determine the characteristics of the high-frequency transformer of the plant — transformation ratio, pulse distortion, phase shift of input and output characteristics, conversion frequency.

![Image](image.jpg)

**Figure 8.** The results of experimental studies: a – characteristics of the high-frequency transformer, b – currents and voltages in the primary winding

The measurements showed that the high-frequency transformer fully complies with the calculated data (table 1): the transformation ratio was 5.4, the voltage pulses have a clearly defined rectangular nature, the signal is transmitted through the magnetic circuit without distortion in shape and angle of phase shift, the frequency was 12.07 kHz.

Fig. 8b shows the combined waveforms of currents and voltages at the high-voltage side of the transformer. The amplitude of the voltage pulses was 550 V at a frequency of 12.1 kHz. The current oscillogram corresponds in time to the voltage pulses, the amplitude value is 100 A. The currents and voltages are practically coincide in phase, that is, after automatic frequency control, reactive power compensation occurs, and the transformer is switched on to a purely active load. Obtaining this operation mode is justified by minimizing the load to obtain more rigid output characteristics of the transformer.

4. Conclusion

It was determined that the inclusion of intelligent elements in the power supply network allows one to solve a number of tasks to improve the quality and reliability of energy supply of railway transport facilities. The use of energy routers as sources of power supply to responsible consumers makes it possible to completely solve the problems of power quality in the networks of non-traction consumers. The results of model studies of the ER with a high-frequency transformer showed that its use completely eliminates the drawbacks of the quality of electricity in traction power supply networks. The developed high-power ER model can be used to analyze the operation of the electric power system, including digital objects. The capabilities of the ER model allow it to be used as an integrating and controlling element in the implementation of intelligent power supply systems.

A design and technical implementation of a high-frequency transformer for a process plant was carried out. The results of experimental studies of the work of high-frequency transformer confirmed its correspondence to the calculated parameters. The effect of the application of these transformers in the power supply units of the electrical devices of consumers very considerably decreases the mass-dimensional indices of power transformer, which substantially increases the consumer properties of these power supply systems.

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