

## DEVELOPMENT OF DIGITAL MODELS FOR DETERMINING THE MODES OF THE DC TRACTION POWER SUPPLY SYSTEM

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### ABSTRACT

The article proposes a universal methodology for modeling DC traction power supply systems. The modeling method is based on dividing the system into AC and DC segments. The modeling results obtained using Fazonord AC-DC software confirm the advantages of using a twelve-pulse converter. Key findings show a 14% reduction in the maximum imbalance factor  $k_{2U}$  and a 25% reduction in the total harmonic distortion (THD) factor. In addition, the minimum voltage at the locomotive current collector increased by 4%. This method is universal and can be used to determine the modes and quality indicators of electrical energy for various railway power supply systems and traction network configurations.

*Keywords:* Traction power systems, the DC railway power supply system, six-pulse converters, the rectifier-inverter block, the total harmonic distortion.

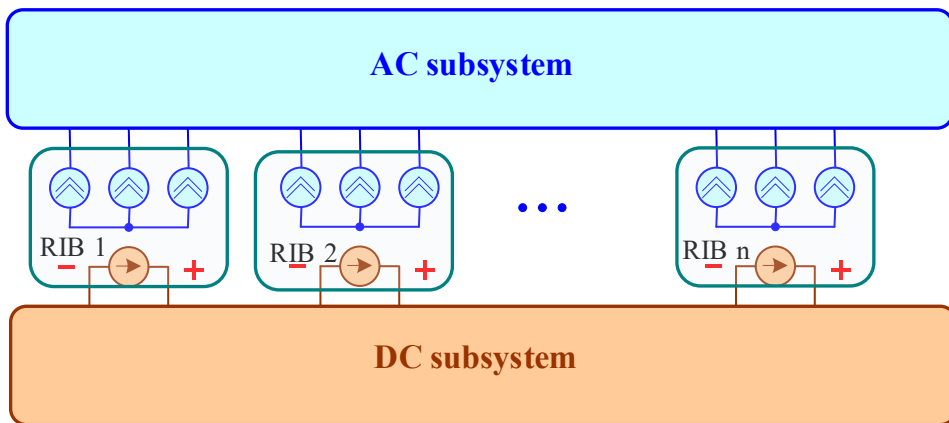
### 1. INTRODUCTION

The digitization of the transport power industry significantly increases the relevance of developing computer modeling tools for power systems with AC and DC networks. Approaches to solving these problems have been considered in a number of works. For example, an analysis of the influence of traction loads on DC traction power supply systems is presented in [1]. The effect of voltage and power regulation of a bidirectional inverter on peak power, as well as on rail and traction network voltages, is studied in [2]. In [3], a DC railway power supply system is modeled to simulate current in various scenarios using reversible substations. Article [4] proposes a simulation model for calculating short-circuit current (SC) in DC railway power supply systems with energy storage equipment. Research on SC processes and train starting currents in metro traction power supply systems is conducted in [5]. Article [6] proposes a dynamic model for determining rail voltage in the DC power supply system of an urban railway network. [7] presents a model that allows one to construct a picture of the distribution of stray currents at a DC substation. [8] describes algorithms for simulating the impact of electric rolling stock on power grids. [9] presents a method for determining the location of rail insulation damage in a DC network based on their dynamic potential. Article [10] proposes a methodology for calculating a DC power supply system that takes into account voltage regulation devices. In [11], the problem of modeling the electromagnetic effects of a DC contact network on telecommunication

channels is solved. In [12], the effects of voltage harmonics caused by the power supply system connecting the Cat Linh-Ha Dong urban railway line to the 22 kV power grid are considered.

An analysis of the presented works and many other publications related to the calculation of DC traction network operating modes shows that a comprehensive method for simultaneous modeling of DC and AC traction systems to optimize power quality, taking into account converters and dynamic loads in them, has not been proposed. To solve this problem, the algorithms and software described in [13] can be used. The method of modeling DC power supply systems in the Fazonord AC-DC environment consists in the ability to model asymmetric, non-sinusoidal, and emergency operating modes using phase coordinates. In addition, this approach makes it possible to simulate thermal processes and calculate electromagnetic field intensities in DC networks. It is also possible to flexibly integrate active elements of a smart grid, such as distributed generation and FACTS devices, which improves power quality in the presence of varying traction loads. In particular, the use of AC and DC segment connection algorithms based on the “fixed EMF” method has made it possible to completely solve the convergence problem for large-scale systems and implement a highly reliable tool that accurately takes into account the actual operation of modern DC traction systems. The proposed methodology demonstrates a significant advantage over traditional modeling approaches by ensuring superior numerical convergence and enabling the integrated, simultaneous calculation of both AC and DC segments. While conventional techniques often rely on decoupled analysis or simplified single-line diagrams—which may fail to capture complex electromagnetic interactions in multi-wire systems—this study leverages a unified framework. By implementing the 'fixed EMF' algorithm within a phase-coordinate system, the model provides a robust solution for determining the operational modes of large-scale traction networks, maintaining high computational stability even under conditions of significant harmonic distortion.

## 2. METHODOLOGY



*Fig. 1. Block diagram of the network model with AC and DC segments*

Modeling of the operating modes of the DC traction power supply system is carried out by decomposing it into two parts: alternating current and direct current (Fig. 1).

The Fazonord AC-DC software package uses Newton-Raphson and Gauss-Seidel algorithms to solve nonlinear systems of equations of high dimension in phase coordinates. The diacopics method was used to account for the interaction between the AC network and the DC load through the rectifier-inverter block (RIB). The calculation algorithm includes the following steps:

1. By solving the steady-state equations written in phase coordinates, the AC segment is calculated in the absence of DC loads:

$$F^{(AC)}(X^{(AC)}) = 0 \quad (1)$$

where  $F^{(AC)}$  is a nonlinear vector function corresponding to the steady-state AC segment;  $X^{(AC)}$  are the operating parameters of the AC segment, including modules and phases ( $\dot{U}_k = U_k e^{j\varphi_k}$ ) or real ( $U'_k = U_k \cos \varphi_k$ ) and imaginary ( $U''_k = U_k \sin \varphi_k$ ) components of the nodal voltages.

2. Based on the voltages at the inputs of the rectifier-inverter converter, which are part of the vector  $X^{(AC)}$ , the electromotive force of the sources on the DC side is calculated:

$$E^{(DC)} = \mathfrak{F}(X^{(AC)}) \quad (2)$$

and their equivalent resistances are calculated  $R^{(DC)}$  is determined through the parameters of the step-down and converter transformers.

3. The determination of the DC segment is carried out by solving the corresponding steady-state segment:

$$F^{(DC)}(X^{(DC)}) = 0 \quad (3)$$

where  $F^{(DC)}$  is a nonlinear vector function corresponding to the steady-state DC segment;  $X^{(DC)}$  are the operating parameters of the DC segment, including the voltages of the DC subsystem nodes.

After calculating the DC segment, the absence of consumption by the rectifiers and the power output by the inverters is monitored from the side DC. If the result is negative, the corresponding rectifier-inverter converters are disconnected. The calculations are repeated in an iterative cycle until the control results require further switching.

4. The vector of rectified currents is calculated  $I_d$ , which is used to determine the input currents of the converters.  $\dot{I}^{(AC)}$  and a refined calculation of the AC segment mode is carried out by solving system (1).

AC and DC subsystems are performed after determining the fundamental frequency segment. To do this, the following systems of equations are solved:

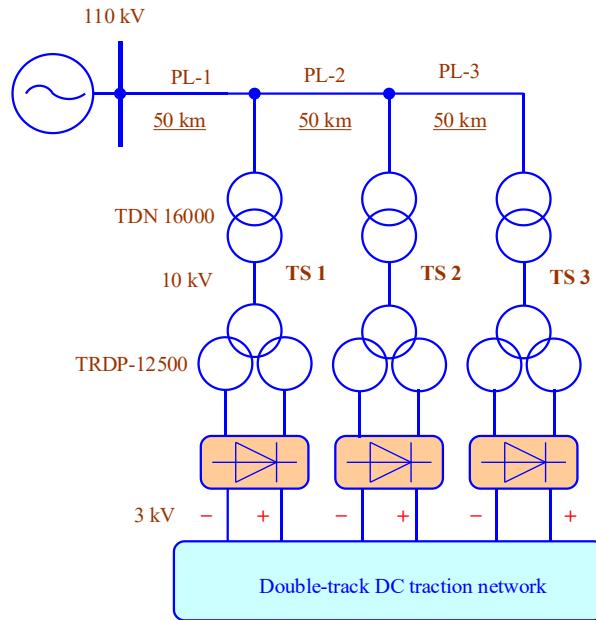
$$\begin{aligned} F[X(f_1)] &= 0; \\ \underline{Y}(f_2)\dot{U}(f_2) &= \dot{I}(f_2); \\ \dots \underline{Y}(f_{40})\dot{U}(f_{40}) &= \dot{I}(f_{40}), \end{aligned}$$

where  $f_i$  – harmonic frequencies,  $f_i = if$ ;  $f = 50$  Hz;  $\underline{Y}(f_i)$  – calculated matrix for  $f_i$ , the conductivity matrix of the computational model of electric power systems;  $\dot{U}(f_i)$  the voltages in the network nodes that are obtained as a result of determining the mode at the frequency  $f_i$ ;  $\dot{U}(f_i)$  – the voltages at the network nodes, which are obtained as a result of determining the mode at the frequency  $f_i$ ;  $\dot{I}(f_i)$  the vector formed by the currents of the harmonic components sources.

At the current frequency  $f_i = 50i$  for the DC segment, the parameters of the current sources associated with the converter models are calculated. Equivalent circuits for the AC and DC components at the frequency  $f_i$  with the corresponding element reactances are then generated, and their operating modes are determined.

### 3. SIMULATION RESULTS

The operating modes of the traction power supply system (TPS) were determined using the Fazonord AC-DC industrial software package. The TPS simulation results for the DC railway section, the schematic of which is shown in Fig. 2, are presented below.



*Fig. 2.* Now describes the simulated network a DC railway section comprising three substations and two inter-substation zones, each 50 km in length

The simulated system included three substations and two inter-substation zones, each 50 km long. Schematic fragments corresponding to the converter models of traction substation 1 are shown in Fig. 3. The simulation was conducted for two variants with different converter unit designs. The first variant utilized six-pulse converters, while the second utilized twelve-pulse converters.

The simulated traction power supply system included:

- Three models of AC-400 (PL) power lines;
- Three TDN-16000 -115/11 kV step-down transformers with a short-circuit voltage of 10.5%;
- Three TRDP-12500-10 converter transformers;
- Three pairs of six-pulse rectifiers combined into twelve-pulse circuits. The parameters of these rectifiers are determined by the parameters of the step-down and converter transformers;
- Two models of double-track sections of the traction network, each section is 20 km long.

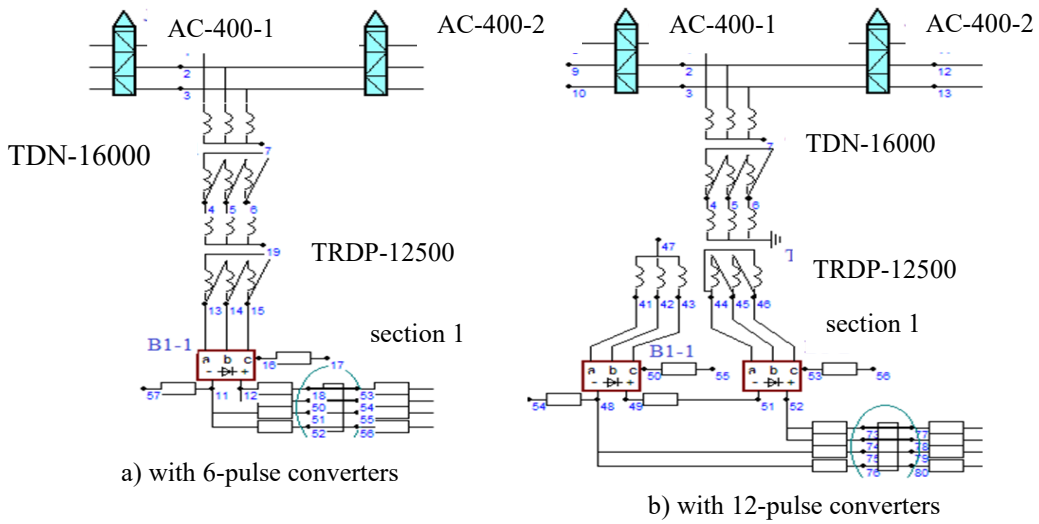


Fig. 3. Part of the calculation scheme with a DC traction network

Simulation of traction power supply system (TPSS) modes was performed in the Fazonord AC-DC software package according to the train schedule shown in Fig. 4 a. The current profiles of the locomotives are shown in Fig. 4 b, c.

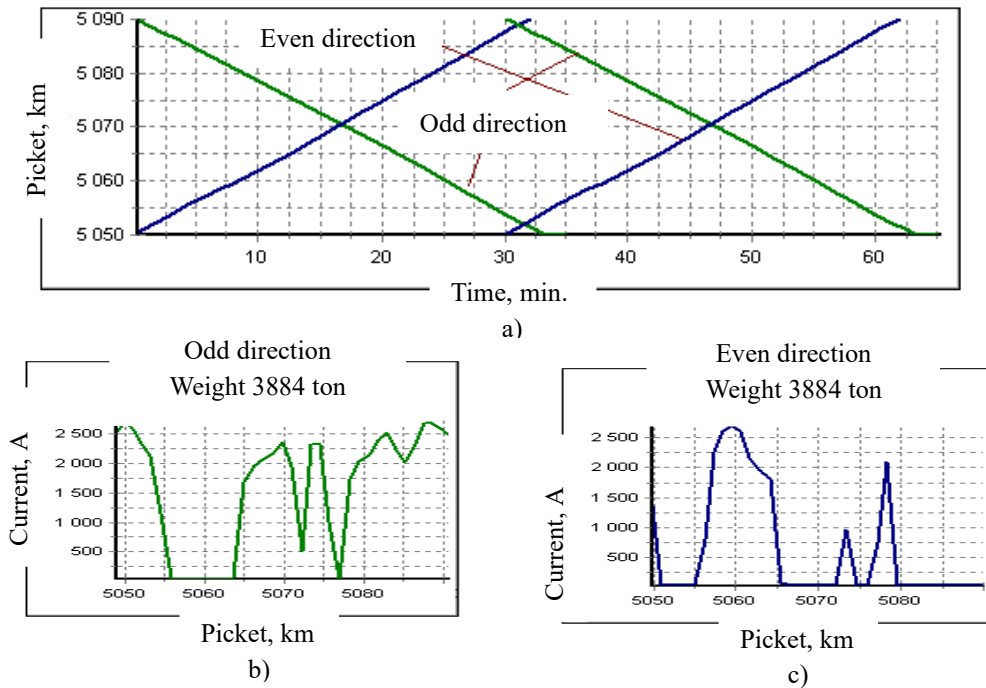
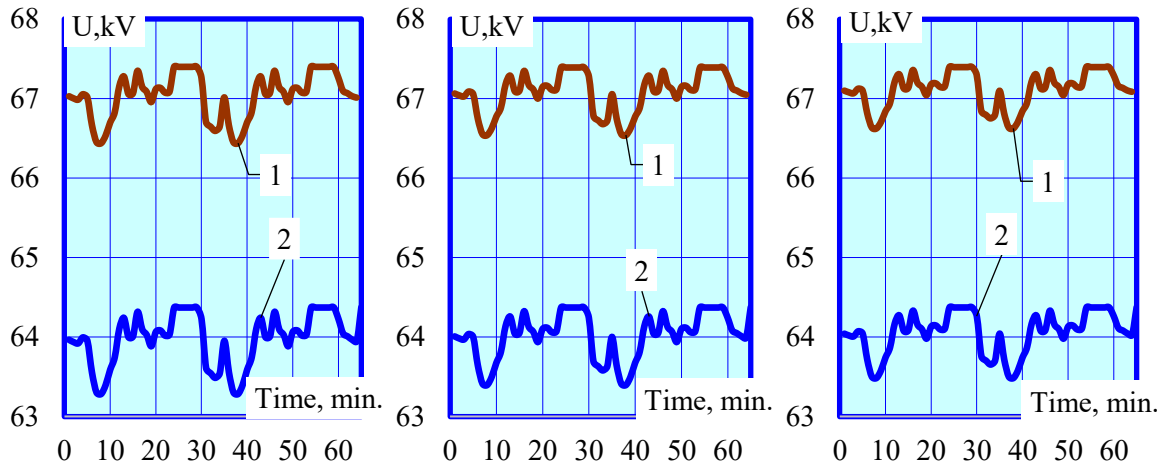
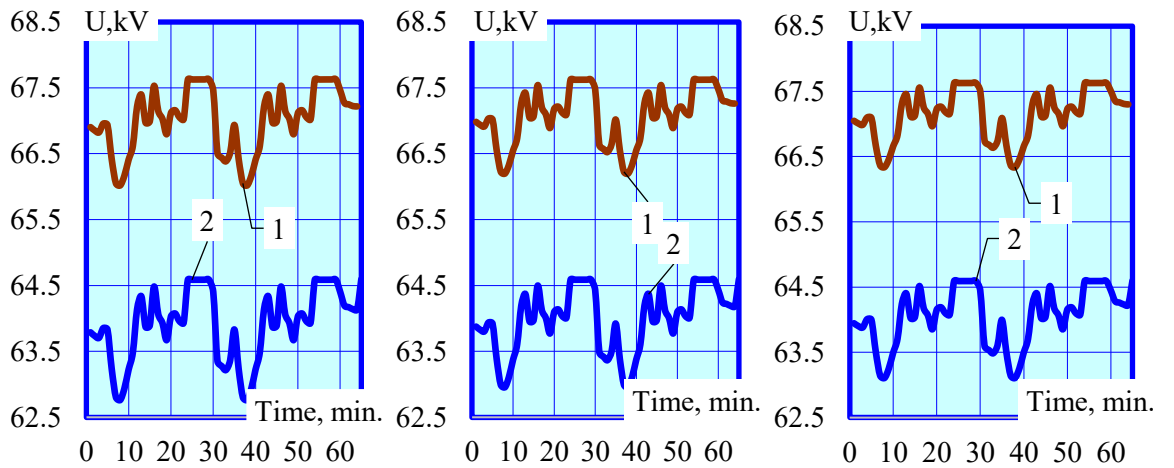


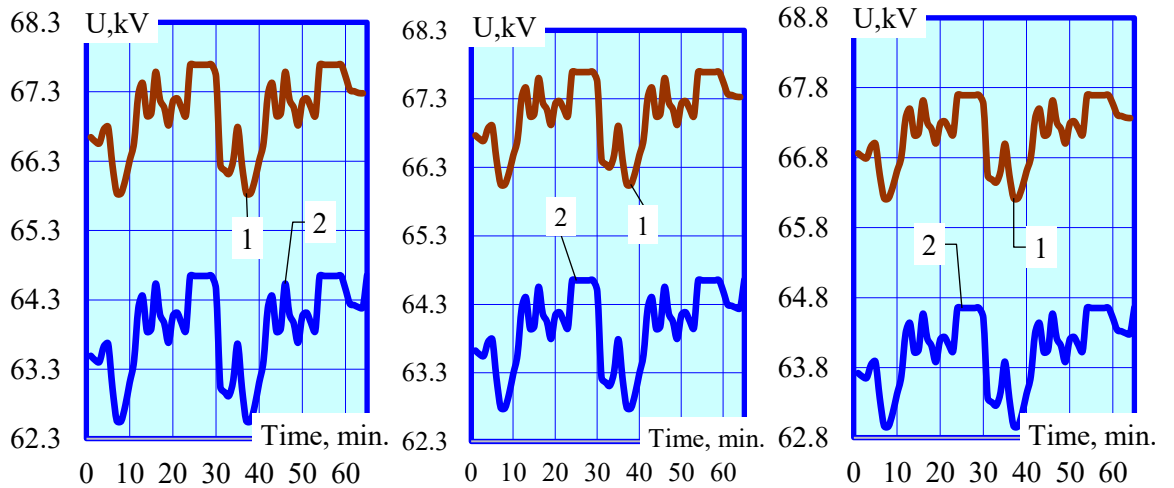
Fig. 4. Train schedule for the simulated section (a); Current profiles of odd (b) and even (c) trains



a) voltage at the inputs of TS-1



b) voltage at the inputs of TS-2



c) voltage at the inputs of TS-3

Fig. 5. Voltage at the traction substation (TS) inputs: 1 – six-pulse converter; 2 – twelve-pulse converter.

The simulation results are shown in Fig. 5–11. Fig. 5 shows the voltages at the inputs of the 110 kV traction substations (TS). Fig. 6 presents the nature of the voltage variations at the locomotive pantograph. Fig. 7 displays the curves corresponding to the dependencies, which characterize the  $k_{2U} = k_{2U}(t)$  asymmetry levels at the connection points where the traction substations link to the 110 kV networks. It should be noted that the values of the asymmetry coefficients do not exceed the permissible limits according to GOST 32144-2013, as well as IEEE 519:2014 and IEC 61000-3-2. Fig. 8 shows the graphs of the dependencies  $k_{2U} = k_{2U}(L)$ . The graphs presented in Fig. 9-11 are constructed based on the determination of non-sinusoidal modes. Table 1 presents the simulation results of the 6-pulse converter versus the 12-pulse converter. Their analysis shows that the maximum permissible non-sinusoidal levels are violated, which requires the implementation of measures to reduce harmonic distortion.

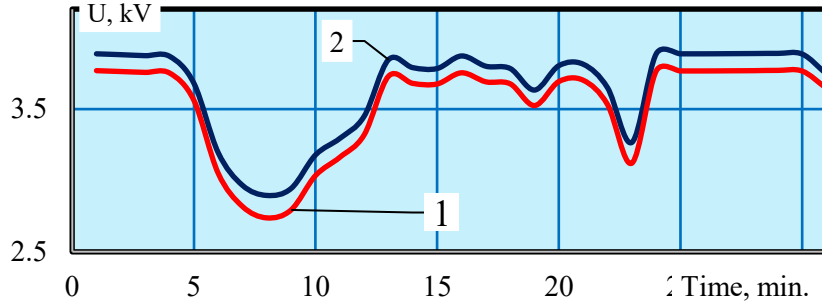


Fig. 6. Voltage at the locomotive pantograph: 1 – six-pulse converter; 2 – twelve-pulse converter

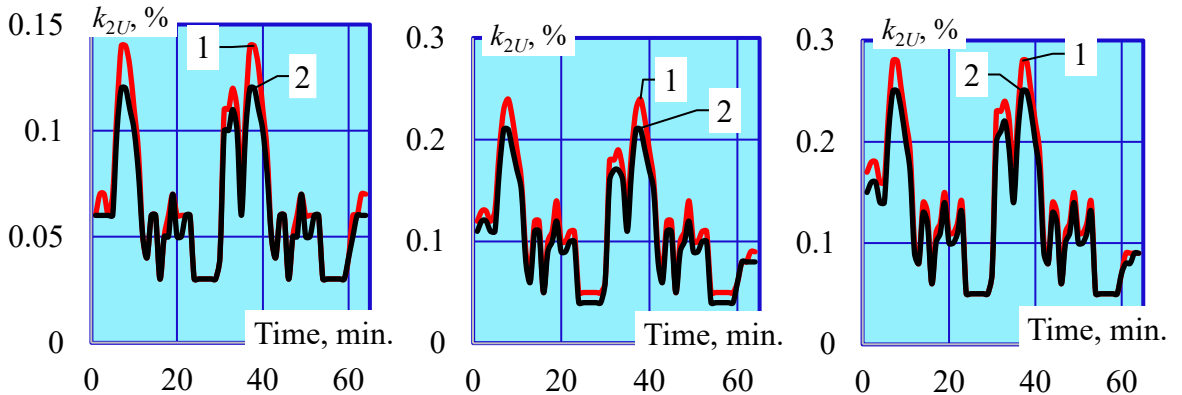


Fig. 7. Asymmetry coefficients at the 110 kV transformer substation inputs: 1 – six-pulse converter; 2 – twelve-pulse converter.

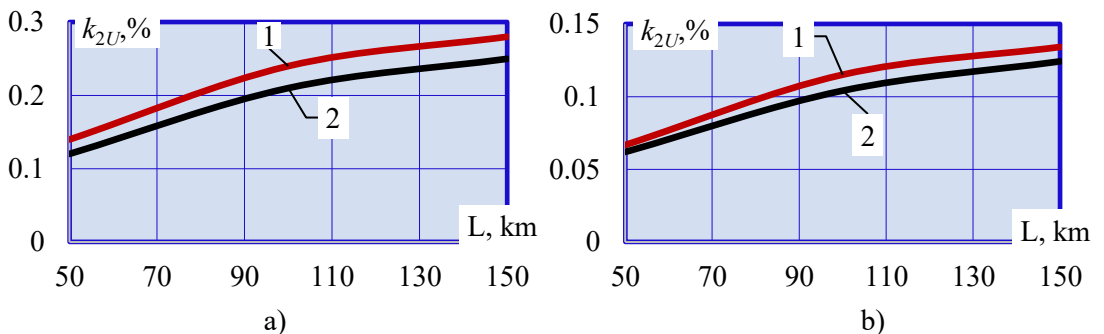


Fig. 8. Maximum and average values of asymmetry coefficients at the 110 kV TS inputs: a – average values; b – maximums: 1 – six-pulse converter; 2 – twelve-pulse converter.

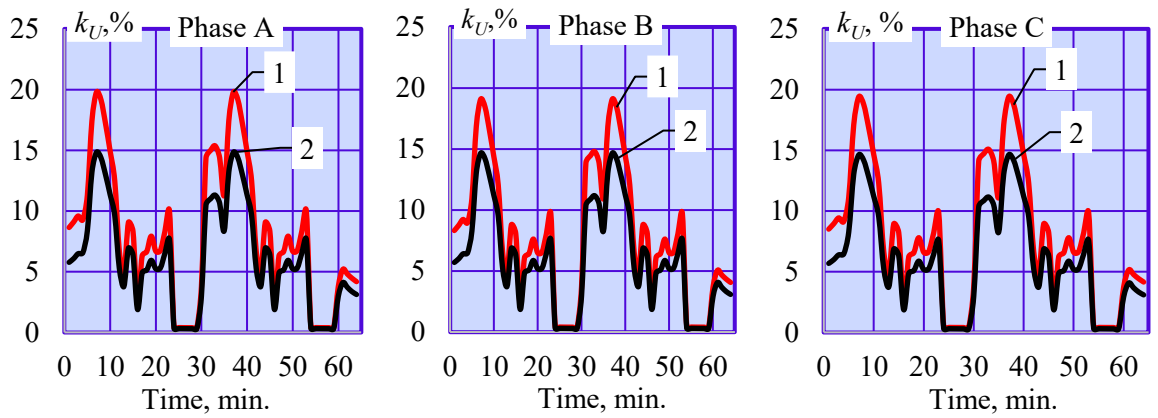


Fig. 9. Total harmonic distortion (THD) coefficients at the input of 110 kV TS 3:  
1 – six-pulse converter; 2 – twelve-pulse converter.

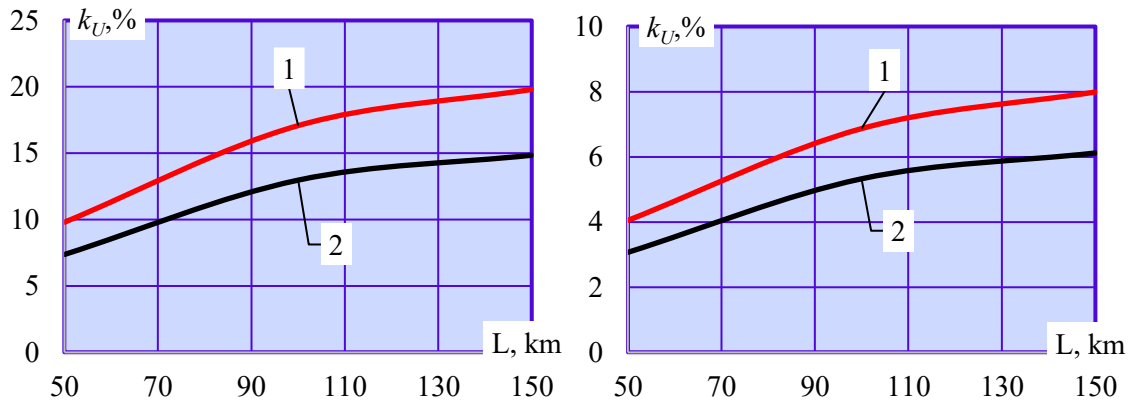


Fig. 10. Maximum and average values of the harmonic distortion coefficient for the 110 kV input voltage corresponding to phase A: 1 – six-pulse converter; 2 – twelve-pulse converter.

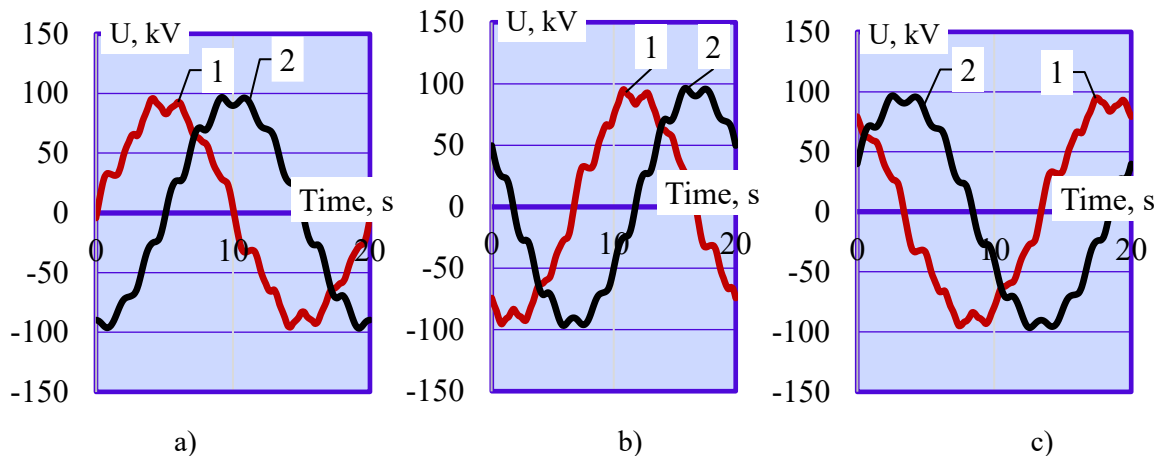


Fig. 11. Voltage waveforms at the 110 kV inputs of TSS 3: a – phase A; b – phase B; c – phase C.

Table 1. Compare simulation results: 6-pulse vs. 12-pulse converter

Performance Indicator	Unit	6-pulse Converter	12-pulse Converter	Improvement (%)
Minimum Pantograph Voltage ( $U_{\min}$ )	kV	2.785	2.896	+4.0%
Maximum Voltage Unbalance Factor ( $k_{2U \max}$ )	%	2.14	1.84	-14.0%
Average Voltage Unbalance Factor ( $k_{2U \text{ avg}}$ )	%	1.55	1.33	-14.2%
Maximum Total Harmonic Distortion (THD max)	%	19.73	14.80	-25.0%
Average Total Harmonic Distortion (THD avg)	%	15.20	11.40	-25.0%

Based on the results presented in Fig. 5–11 and table 1, the following conclusions can be drawn:

1. By using a 12-pulse RIC, the minimum three-minute voltage on the pantographs of freight electric locomotives can be increased by 4%, which is important when there are long grades on the track profile.

2. Using this type of converter improves the power quality indicators of traction substation buses in terms of asymmetry and harmonic distortion. The maximum  $k_{2U}$  value is reduced by 14%, and the total harmonic distortion indicator by 25%. However, the maximum total harmonic distortion value reaches 14.8%, which exceeds the permissible value according to GOST 32144-2013, as well as IEEE 519:2014 and IEC 61000-3-2.

3. From the simulation results analysis, we see that the 12-pulse converter significantly reduces harmonics, but it is not an absolute standalone solution for heavy load conditions. Therefore, active harmonic filters or FACTS (Flexible AC Transmission Systems) can be used to improve power quality.

#### 4. CONCLUSION

A methodology and digital models for determining the operating modes of a DC traction power supply system are proposed. Phase coordinates were used to create the models in the Fazonord AC-DC software package. These models can be used to solve a number of problems related to improving energy efficiency and power quality in DC traction power supply systems. In addition to determining DC traction power supply system operating modes, these models also enable the solution of a number of additional problems, such as: calculating ice melting modes in DC traction networks; calculating the strengths of electromagnetic fields generated by traction networks; determining conductor heating; calculating short-circuit faults, etc.

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