

Article

Modeling of Traction Power Supply Systems Equipped with Renewable Energy Sources

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Abstract

The study presents the results of research aimed at developing digital models for determining the operating parameters of railway power supply systems equipped with distributed generation plants based on renewable energy sources (RESs). RESs can be used in railway transport to increase the reliability of power supply to facilities located in areas with insufficiently developed power grids. This primarily applies to consumers, for whom a power failure can lead to significant damage, accidents, and a threat to human life. RES can serve as independent power sources for special-group consumers and can increase energy conversion efficiency. Furthermore, large-scale implementation of renewable energy sources can significantly reduce energy supply costs and improve power quality. The study employs phase-coordinate modeling, which is characterized by the following features: a systems approach, which implies determining operating conditions while considering the properties and characteristics of complex traction and supply networks; versatility, which enables modeling of power supply systems of various structures and designs; and comprehensiveness, which involves calculating normal, emergency, and special operating parameters—crucial for scenarios such as ice melting on catenary wires. The modeling results obtained using the Fazonord AC-DC software (ver. 5.3.5.2) show that RES-based distributed generation plants provide a variety of beneficial effects: reduction in electricity consumption from power system networks; decrease in voltage unbalance and harmonic distortion on the busbars of regional windings of traction substations; and stabilization of voltage levels on current collectors of electric locomotives.

Keywords: railway power supply systems; digital models of operating conditions; distributed generation plants; renewable energy sources



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1. Introduction

Railway transport is beginning to actively utilize distributed generation (DG) plants based on various energy sources, including renewable ones—for example, micro hydro-electric power plants, wind turbines [1,2], geothermal power plants, and photovoltaic systems [3,4]. The integration of such DG units into traction power supply systems is driven by the need to enhance energy efficiency, reduce carbon footprint, and ensure uninterrupted operation under variable grid conditions.

The DG plants can be employed in the following key areas:

- Providing electricity to facilities located in regions with unstable or insufficient power supply—In remote or mountainous areas where the main power grid is either absent or prone to frequent outages, DG units based on local renewable resources can serve as primary or backup sources. This is particularly relevant for signaling systems, communication devices, and maintenance infrastructure.
- Boosting the reliability of power supply to essential consumers, whose shutdown during system accidents can lead to serious consequences—First-category consumers (e.g., traffic control systems, emergency lighting, and critical switching equipment) require near-zero downtime. DG plants can provide uninterruptible power through islanded operation or seamless transition during grid faults, thereby reducing the risk of cascading failures and ensuring passenger safety.
- Creating transport and energy corridors that integrate railway routes, high-voltage power lines, and communication lines—Such corridors represent a novel infrastructure concept where railway rights-of-way host not only catenary and signaling systems but also renewable DG installations (e.g., wind turbines along embankments or solar panels on noise barriers). This synergy reduces land use conflicts, allows shared maintenance access, and enables direct supply of green energy to traction substations, thus lowering transmission losses and dependency on external grids.
- Powering individual transport facilities [5–7]—Stand-alone railway objects, such as remote crossing points, block posts, track circuit huts, and station buildings, can be supplied by small-scale DG plants sized to match local loads. This eliminates the need for long low-voltage feeder lines, which are costly and prone to faults, while also enabling autonomous operation and real-time load management through smart control systems.

Furthermore, recent studies indicate that the coordinated operation of multiple DG plants within a railway power supply system can contribute to voltage regulation, reactive power support, and reduction in harmonic distortion at the point of common coupling. When combined with energy storage systems (e.g., batteries or supercapacitors), RES-based DG units can also smooth power fluctuations caused by passing trains and rapidly changing renewable generation, thereby improving overall system stability and power quality.

2. Literature Review

The importance of using renewable energy sources to power transport is confirmed by numerous publications devoted to this topic.

According to [6], the growing daily demand for urban travel and the expansion of city lands are increasing the relevance of building urban rail transit systems. This situation implies a rise in power consumption required to maintain operational stability. Therefore, the authors propose implementing a traction power supply system (TPSS) with a coordinated control strategy based on the load schedule at an existing traction substation. The substation voltage is used as a control signal, optimized via a performance index. Simulation results demonstrate that the developed TPSS reduces substation peak power

and voltage fluctuations, which is confirmed by both short-term and long-term simulations. Moreover, this approach enhances substation capacity to meet growing demand.

A detailed overview of current traction power supply systems is provided in [8]. Based on this overview, the authors propose new TPSS architectures that integrate renewable energy into AC and DC railways. These architectures ensure stable power supply during grid disruptions and failures, such as those caused by natural disasters or extreme weather. This facilitates the development of next-generation TPSS with increased flexibility. A comparative analysis yields a brief overview of future trends, concluding that resilient TPSS enable renewable energy sources (RES) integration and protection against grid failures.

Reference [9] shows that TPSS consume significant amounts of electricity. The constantly increasing demand is the main driver for developing combined TPSS. Insufficient availability of traditional energy sources and environmental pollution necessitate the use of RES, with wind turbines being a viable option for TPSS.

As analyzed in [10], the integration of RES introduces changes to short-circuit currents in TPSS. The literature analysis indicates a continuing trend of increasing the RES share in the overall energy balance and a rise in electricity consumption for train traction. The developed method relies on equivalent circuits, where the “solar panel—inverter” pair is represented as an EMF with equivalent resistance, significantly simplifying subsequent calculations. The results show that RES integration does not lead to a substantial increase in short-circuit currents in the traction network, even when photovoltaic panel power is comparable to that of existing converter units at traction substations. This is due to the physical nature of photovoltaic panels and their power supply mode. Hence, RES integration does not cause an unacceptable rise in short-circuit currents.

Performance analysis of a hybrid TPSS using renewable energy sources is performed in [11]. Given the limited availability of traditional sources and pollution from fossil fuel combustion, renewable energy sources are presented as an alternative. A new control strategy is introduced, coupling RESs with TPSSs. The behavior of the system was analyzed through simulation and experimental measurements on a hybrid TPSS, and both advantages and limitations of the proposed approach are discussed.

Addressing the problem of integrating energy storage and RESs into AC TPSSs to reduce carbon emissions and energy costs, ref. [12] solves it by noting that high-speed trains consume vast amounts of energy. Most power plants supplying the grid are fossil fuel-fired, leaving a large carbon footprint. Consequently, railway operators face significant electricity bills and carbon taxes. Integrating RESs and energy storage systems into TPSSs can mitigate these issues. Calculation results show considerable cost savings due to reduced grid electricity demand and lower carbon tax liabilities.

Safety aspects are considered in [13], where signaling and automatic block devices must operate continuously at nominal parameters. To reduce energy consumption, an alternative power supply solution is proposed: electricity from a photovoltaic system installed near the equipment rack. This PV system, together with the existing power supply, provides reliable backup.

A neural-network-based algorithm for selecting RES to supply auxiliary power in TPSS is proposed in [14]. It focuses on powering auxiliary loads of the metro using wind–solar RESs, with the selection performed by a neural network.

Comparative analysis of topologies for integrating photovoltaic sources into AC railway TPSSs is carried out in [15]. It shows that the growing application of RES in power systems will soon extend to railway power supply. The paper compares technical and economic advantages of several configurations with power electronics converters for PV integration. For each configuration, a design methodology for component selection is proposed, with unbalance requirements on the feeding transmission line conforming

to current standards. The methodology applies to high-speed railway power supply. The studied configurations are numerically compared based on technical feasibility and cost, with RES generating capacity as an independent variable. The analysis reveals that with gradual RES integration into TPSSs, configurations using power converters feeding overhead lines may become more advantageous.

The integration of a photovoltaic power plant into TPSSs is discussed in [16], noting that supercapacitors are suitable for traction applications but limited by energy density. Using supercapacitors and battery systems allows peak power reduction and utilization of recuperation energy. An optimal design is proposed to reduce the cost of batteries integrated with photovoltaic plants.

To reduce carbon emissions in train scheduling with wind turbines, ref. [17] proposes a linear programming model. Currently, carbon emission reduction is a priority worldwide, while transportation and energy sectors still have high emissions. With intelligent transportation systems and RES integration, further reductions may be possible. The model coordinates TPSSs and the power grid with wind generation to minimize carbon emissions. Train timing for each inter-station section can be adjusted, and optimal wind turbine power is obtained after optimization. Results show that by coordinating TPSSs and the power grid, energy consumption and carbon emissions from train operations can be reduced by 12% and 13%, respectively, compared to the original solution.

Power quality improvements are described in [18], where a traction power supply system integrating photovoltaic panels is presented. The authors solved the problem of enhancing TPSS power quality through RESs and distributed generation integration. They considered the design and control of a solar photovoltaic installation with two single-phase five-level inverters connected to a LeBlanc transformer to supply two single-phase loads and generate power. The proposed configuration fully compensates asymmetric loads, reactive power, and current harmonics in a three-phase network. Both inverters are controlled using sliding mode, regulating DC bus voltage, compensating reactive power and current harmonics, and reducing asymmetry.

A hybrid DC TPSS with hydrogen production is presented in [19]. The combined use of electric and hydrogen trains is becoming an important trend for future metros. A new hybrid DC TPSS is introduced for integrating RESs and a hydrogen subsystem. A router based on a triple active bridge converter is developed for efficient subsystem integration. A power management and control strategy is proposed to enable smooth transitions between different modes. Simulation results verify the approach and control structure, showing that the proposed TPSS can effectively utilize RESs and regenerative braking energy to achieve energy savings.

The photovoltaic power generation system for an electrified railway and its control strategy are detailed in [20]. Integrating PV panels into the traction power supply system facilitates placing RESs near consumers, as well as energy conservation and carbon emission reduction. In the proposed system, photovoltaic energy is output on the DC side of the converter. Converter optimal power is dynamically calculated according to operating conditions, with independent converter control. Excess power compensates for the reactive power and negative-sequence current of the TPSS. A simulation model built in Simulink confirmed the effectiveness of the proposed system and control strategy.

An innovative concept integrating TPSSs with EV charging stations, regenerative energy, storage, and PV panels is proposed in [21]. Significant progress in transport electrification has occurred recently due to technological developments, and environmental and geopolitical issues in the energy sector worldwide. The authors developed a framework integrating rail transport systems with EV charging stations and renewable energy production. Charging power demand is met by various charging strategies that account

for unused capacity of the energy infrastructure and TPSS regenerative energy. A canopy project for renewable energy production using PV panels in an existing parking lot is also implemented. An optimal energy management system is developed, considering uncertainties associated with EV charging demand.

Permafrost stabilization using solar panels on railways is addressed in [22]. To prevent permafrost embankment melting caused by global warming, a solar heat pump system is considered. This approach combines passive protection from solar radiation and precipitation with active cooling in summer and is compared to currently used methods of maintaining frozen ground. Key advantages include positive feedback of power output with solar radiation, no need for fuel supplies, and compatibility with existing thermosyphons. The feasibility of preventing melting is demonstrated, and procedures for selecting suitable site configurations are discussed.

Locomotive-roof PV systems are studied in [23] for a South African railway. The operational route is selected based on geographical mapping of high temperatures in the country. The planned PV systems are designed to withstand environmental conditions and operational requirements of South African railways. The motivation is the annual increase in freight demand, which leads to high costs for upgrading traction substations. High freight demand results in significant train congestion and substation overloading. A study assessed the applicability of PV systems to power AC and DC electric locomotives and ancillary components (fans, lighting, control circuits). The main objective is to integrate PV panels as an alternative energy source to reduce traction substation congestion, thereby lowering energy consumption and enabling more freight to be carried to meet demand.

In the current context, the problems of integrating renewable energy sources must be solved using digital models that take into account the specific operating conditions of TPSSs, which are as follows:

- Traction loads significantly deteriorate power quality and negatively affect the operation of electrical networks serving non-traction consumers that intend to use RES-based DG plants.
- The non-stationary nature of traction loads causes considerable voltage deviations on the 6–10 kV busbars to which RESs are connected.
- The single-phase traction load introduces substantial voltage unbalance, which in some cases significantly exceeds standard limits.
- Rectifier–inverter converters of electric locomotives inject harmonics into the network, increasing the levels of non-sinusoidal distortion.

The analysis of the presented publications shows that the issues of modeling the operating conditions of TPSSs equipped with renewable energy sources have not been fully resolved. To address them, the modeling methods presented in [24–28] can be used. The approach proposed in those publications implements a modeling technique distinguished by the following features:

- Systems approach—determining operating conditions by analyzing the properties and characteristics of complex TPSS and the overall power supply system.
- Versatility—enabling modeling of power supply systems of various structures and designs.
- Comprehensiveness—calculating normal, emergency, and special operating parameters, which is crucial for scenarios such as ice melting on catenary wires.

The novelty of the proposed approach is defined by the following contributions:

1. General methodological principles have been established for modeling static multi-wire systems, enabling the correct accounting of mutual inductive and capacitive couplings.

2. Methods have been developed for modeling multi-wire overhead and cable lines of various designs, including traction networks of electrified railways, new types of power transmission lines, three-phase cable lines, and single-phase cable systems. A methodology and algorithm have been prepared for obtaining model parameters based on reference data and the geometric coordinates of the conductor system.
3. Methods have been proposed for modeling single-core single-phase, three-core, and five-core three-phase transformers with arbitrary winding connections and taking into account the configuration of the magnetic system. A methodology and algorithm have been developed for deriving transformer model parameters from reference information.
4. A procedure has been created for integrating individual network element models into a unified computational scheme, and the main principles for its visualization have been proposed.
5. New methods have been proposed for the analysis of electromagnetic compatibility and electromagnetic safety.
6. Methods have been developed for calculating non-sinusoidal operating conditions generated by moving traction loads.

Below are the results of the research aimed at developing methods for modeling the operating conditions of railway power supply systems equipped with renewable energy sources.

3. Methodology

For installations with RES, you can use the mathematical models presented below. The following system of nonlinear equations corresponds to a renewable energy installation with a generator not equipped with automatic voltage regulation:

$$\left. \begin{aligned} P_{Gj}^{(A)} - P_{Lj}^{(A)} - P_{Cj}^{(A)}(\mathbf{X}) &= 0; \\ P_{Gj}^{(B)} - P_{Lj}^{(B)} - P_{Cj}^{(B)}(\mathbf{X}) &= 0; \\ P_{Gj}^{(C)} - P_{Lj}^{(C)} - P_{Cj}^{(C)}(\mathbf{X}) &= 0; \\ Q_{Gj}^{(A)} - Q_{Lj}^{(A)} - Q_{Cj}^{(A)}(\mathbf{X}) &= 0; \\ Q_{Gj}^{(B)} - Q_{Lj}^{(B)} - Q_{Cj}^{(B)}(\mathbf{X}) &= 0; \\ Q_{Gj}^{(C)} - Q_{Lj}^{(C)} - Q_{Cj}^{(C)}(\mathbf{X}) &= 0, \end{aligned} \right\} \quad (1)$$

where $P_{Gj}^{(k)}, Q_{Lj}^{(k)}$ —active and reactive power of the renewable energy installation for phase k ($k = A, B, C$) of j network node; $P_{Lj}^{(k)}, Q_{Lj}^{(k)}$ —active and reactive power of the load connected to phase k of the j network node; $P_{Lj}^{(k)}, Q_{Lj}^{(k)}$ —network power of phase k of the j network node; $\mathbf{X}$ —vector of nodal stresses represented in Cartesian or polar coordinates.

The RES installation with a generator with automatic voltage regulation corresponds to the following system of nonlinear equations:

$$\left. \begin{aligned} P_{Gj}^{(A)} - P_{Lj}^{(A)} - P_{Cj}^{(A)}(\mathbf{X}) &= 0; \\ P_{Gj}^{(B)} - P_{Lj}^{(B)} - P_{Cj}^{(B)}(\mathbf{X}) &= 0; \\ P_{Gj}^{(C)} - P_{Lj}^{(C)} - P_{Cj}^{(C)}(\mathbf{X}) &= 0; \\ (U'_{jA})^2 + (U''_{jA})^2 - U_{jAZ}^2 &= 0; \\ (U'_{jB})^2 + (U''_{jB})^2 - U_{jBZ}^2 &= 0; \\ (U'_{jC})^2 + (U''_{jC})^2 - U_{jCZ}^2 &= 0; \\ Q_{Gj\min}^{(A)} \leq Q_{Gj}^{(A)} \leq Q_{Gj\max}^{(A)} & \\ Q_{Gj\min}^{(B)} \leq Q_{Gj}^{(B)} \leq Q_{Gj\max}^{(B)} & \\ Q_{Gj\min}^{(C)} \leq Q_{Gj}^{(C)} \leq Q_{Gj\max}^{(C)} & \end{aligned} \right\} \quad (2)$$

where U'_{jk}, U''_{jk} —real and imaginary phase voltage components k ($k = A, B, C$) for j -th network node; $Q_{Gj\min}^{(k)}, Q_{Gj\max}^{(k)}$ —reactive power restrictions; U_{jkZ} —given phase of modulus k .

The models were implemented in the Fazonord AC-DC [23,25]. With its help it is possible to solve the following tasks:

- Assessment of the impact of renewable energy sources on the quality of electricity;
- Determination of areas of their application in the power supply system;
- Identifying the best locations for renewable energy sources in networks.

Calculations were carried out for the power supply system (Figure 1) of a section of the main railway. The considered cantilever power supply of traction substations (TSs) occurs in forced operating conditions and is permitted for permanent use in some categories of railways. The modeled network included the following components: 220 kV overhead line made with AC-300 wires; traction transformers 40,000/220; overhead catenaries MF-100 + PBSM-95, and rails R 50. Parameters of local loads are indicated in Table 1.

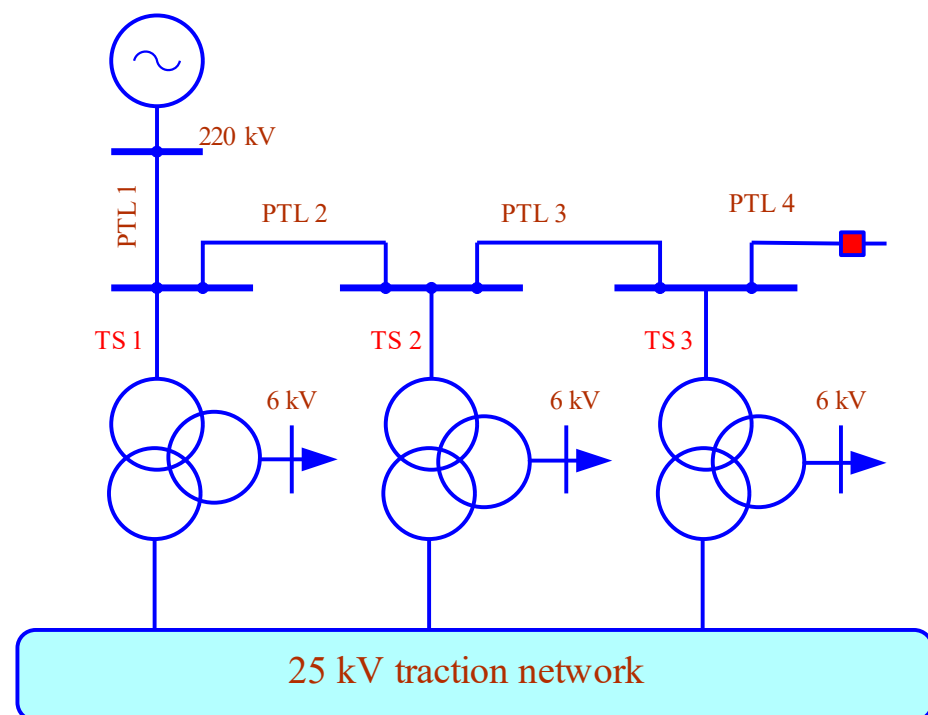


Figure 1. TPSS diagram.

Table 1. Local load parameters.

TS 1		TS 2		TS 3	
P, MW	Q, MVar	P, MW	Q, MVar	P, MW	Q, MVar
6	3	4	2	3	1

Note: the indicated loads are applied to each phase.

The movement of freight trains is modeled according to the timetable shown in Figure 2. Up trains weigh 6000 tons (Figure 3b) and down trains weigh 3200 tons (Figure 3a). Consideration is given to two operating scenarios described in Table 2 and illustrated in Figure 4.

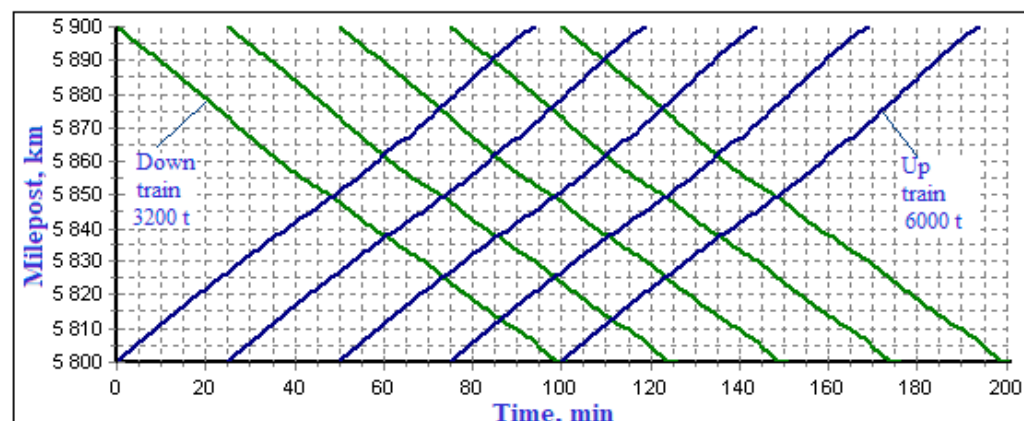


Figure 2. Timetable.

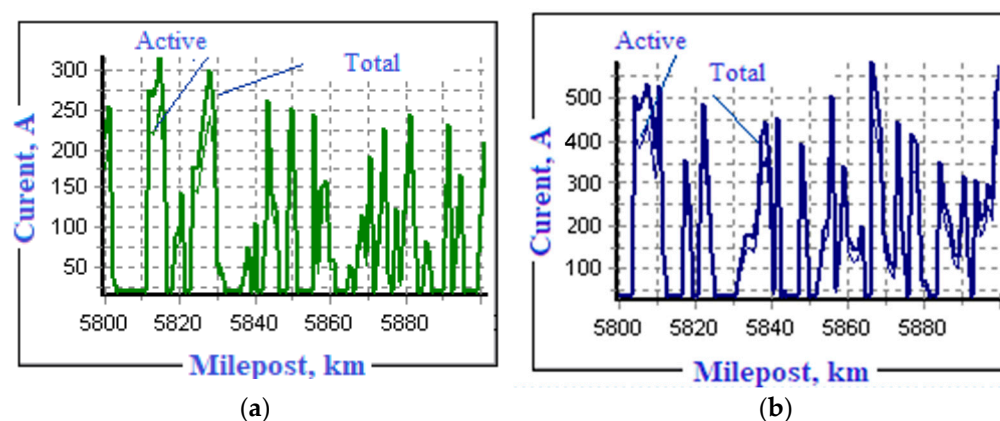


Figure 3. Current profiles: (a) down-train direction; (b) up-train direction.

Table 2. Characteristics of the considered operating scenarios.

No	Description of the Operating Scenario
1	The loads are supplied to the 6 kV TS busbars according to Table 1.
2	The loads are supplied to the 6 kV TS busbars according to Table 1, RES and RPS are connected. The reactive power generation limits for each phase are $-6...+10$ MVar.

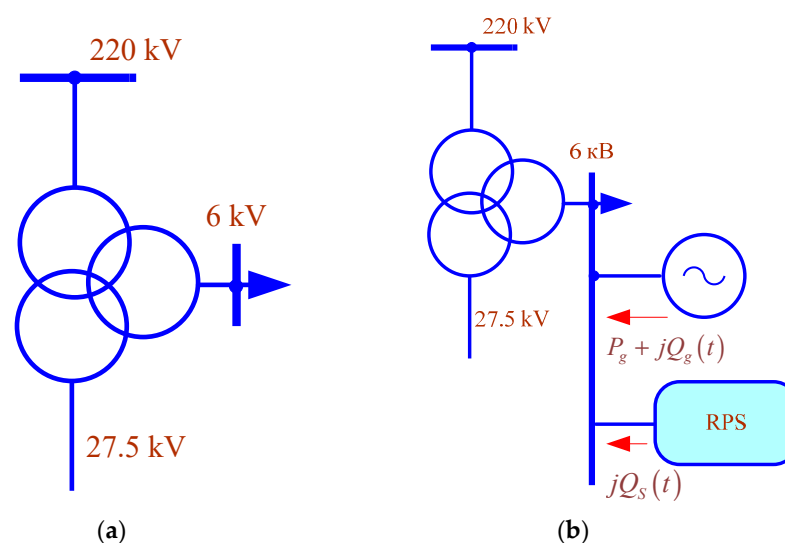


Figure 4. Diagrams of operating scenarios: (a) scenario 1; (b) scenario 2.

To stabilize voltage levels at RES connection points in scenario 2, phase-controlled reactive power sources (RPSs) are employed. The RPSs manufactured using FACTS technologies allow gaining of the following benefits:

- Improving the quality of electricity in the traction network and the external network;
- Boosting energy efficiency by reducing power and energy losses.

4. Modeling Results

Figure 5, for example, illustrates graphs of reactive power generation from a source installed at TS 3. Figure 6 shows the time dependences for voltage and current of electric locomotives. The minimum voltage levels averaged over three minutes are presented in Table 3. The presented results show that in the absence of renewable energy sources, the minimum three-minute voltage at pantographs does not meet standard requirements of $U_{\min} \geq 21$ kV. The largest decrease is observed for heavier up trains. Single-phase loads created by electric locomotives result in unbalance in the networks adjacent to the traction substation, in particular on the windings of 6 kV traction transformers (Table 4, Figure 7).

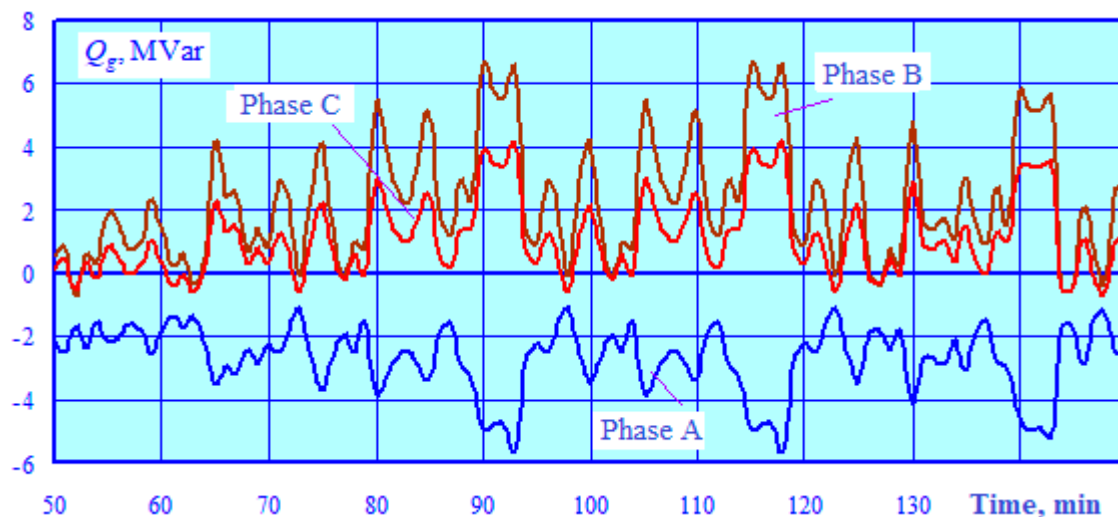


Figure 5. Reactive power generation from RPS at TS 3 for operating scenario 2.

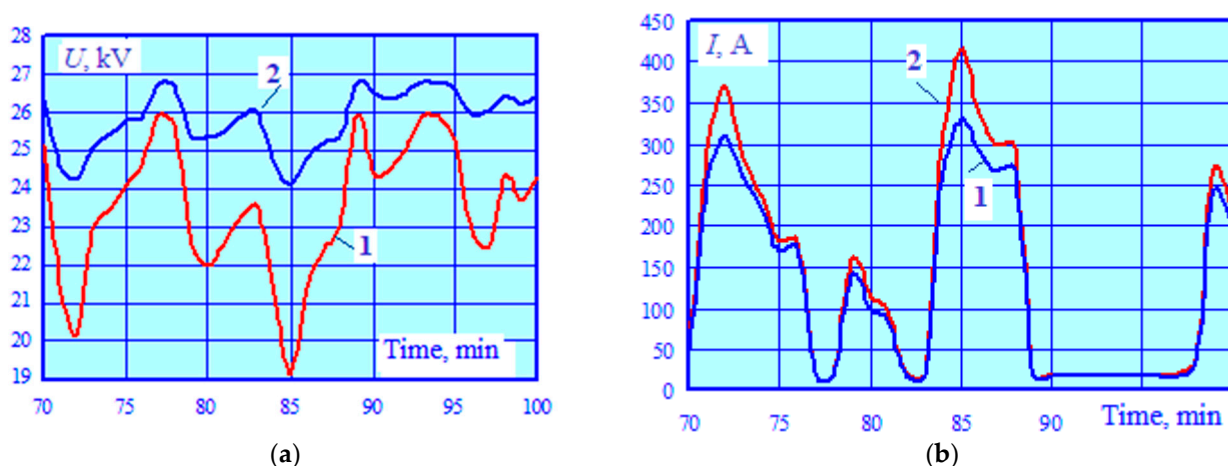


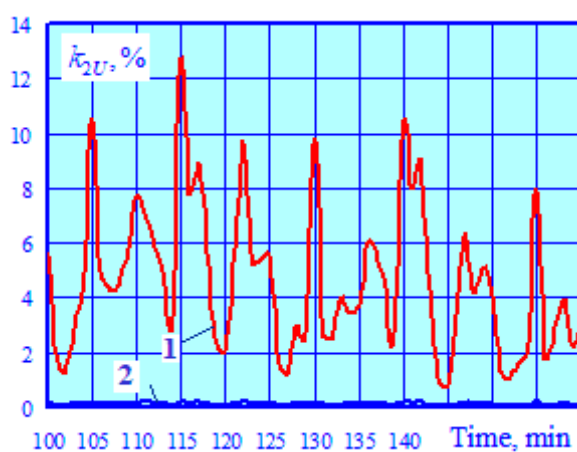
Figure 6. Voltage (a) and current (b) for the electric locomotive of the first train: blue and red graphs indicate the operating scenarios 1 and 2, respectively.

Table 3. Minimum three-minute voltage at pantographs.

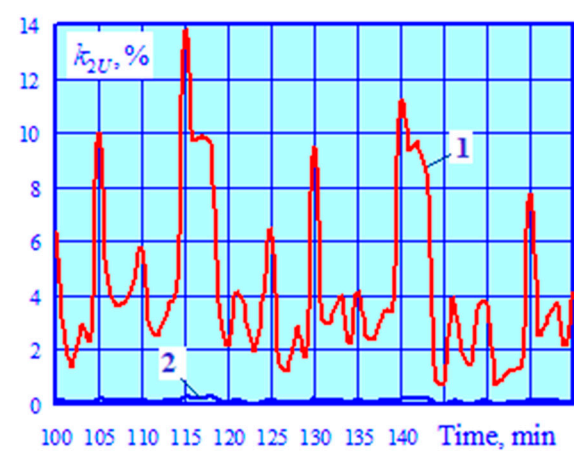
Direction	Train Number	Operating Scenario	
		1	2
Down train	1	20.6	24.5
	2	20.6	24.5
	3	20.2	24.6
	4	20.2	25.2
	5	20.4	25.4
Up train	6	19.6	23.6
	7	17.4	23.2
	8	17.4	23.3
	9	18.6	23.4
	10	20.3	23.8

Table 4. Average and maximum values of negative-sequence unbalance factor k_{2U} at 6 kV TS busbars, %.

Parameter	TS	Operating Scenario			
		1	2	3	4
Average value	TS 1	3.07	2.43	0.09	0.4
	TS 2	3.56	3.01	0.11	0.44
	TS 3	3.06	2.61	0.09	0.19
Maximum value	TS 1	11.7	8.77	0.34	3.57
	TS 2	12.67	8.25	0.31	4.77
	TS 3	13.67	9.33	0.3	2.64



(a)



(b)

Figure 7. Dynamics of changes in unbalance factors. (a) TS 2; (b) TS 3; red and blue graphs indicate operating scenarios 1 and 2, respectively.

Based on the modeling results, we can draw the following conclusions:

- In the absence of RES, the maximum factors k_{2U} are more than three times higher than the maximum permissible value of 4% (Table 4, Figure 7);
- With RES connected, the unbalance decreases by 25–34%, but it still remains outside the standard range;

- Compliance with state-standard (GOST) requirements can only be achieved in operating scenario 2 when turning on the RPS with control limits of $-6/+10$ MVar (Figure 7).

Figure 8 shows the time dependence of the voltage at the 6 kV TS windings for operating scenario 1 in the absence of RESs and RPSs.

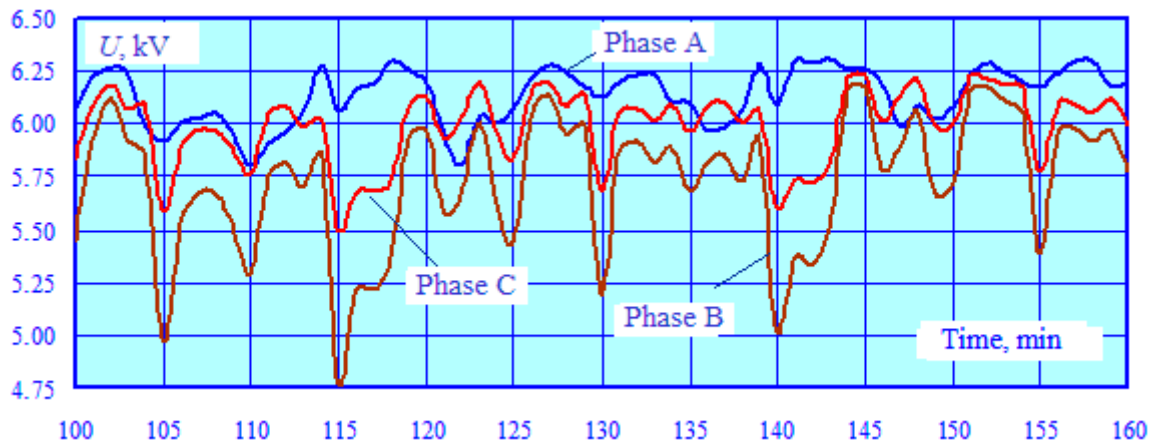


Figure 8. Voltage on the TS3 transformer windings for operating scenario 1.

The presented graphs of $U = U(t)$ demonstrate significant changes in the voltage within the range of 4.75 to 6.3 kV. In operating scenario 2, full voltage stabilization is achieved at a level of 6.3 kV.

Figures 9 and 10 illustrate the total power losses determined for traction transformers.

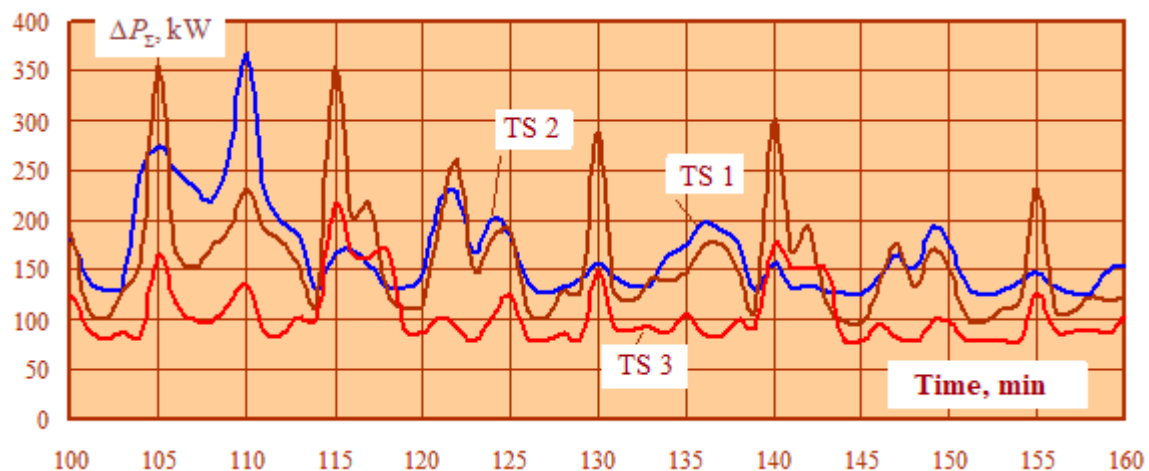


Figure 9. Losses in transformers for operating scenario 1.

As seen in Figures 10 and 11, the total losses exceed the standard level of 286 kW in operating scenario 1. In operating scenario 2, there is a noticeable decrease in the losses; the maximum value of ΔP_{Σ} does not reach 160 kW.

Figures 12 and 13 present the phase currents determined on the 220 kV side of TS 3.

As seen in Figure 12, there is an overload of traction transformers in the absence of RESs and RPSs. The current of phase C considerably exceeds the nominal value of 105 A.

In operating scenario 2, overload of the traction transformers does not occur; the currents of the phase windings do not exceed the nominal values of 105 A (Figure 13, Table 5).

Modeling in the Fazonord AC-DC software allows calculating of the currents of individual coils of traction transformers (TT), which enables simultaneous assessment

of winding insulation heating and aging. Due to rapid variations in traction load, the duration of which is comparable to the heating time constant, thermal inertia is taken into account in the calculations. In a two-winding traction transformer, the windings heat up approximately equally. In a three-winding traction transformer, the primary winding is the most loaded, and its currents are monitored when determining temperatures and insulation wear. The calculated hot-spot temperatures (HSTs) are shown in Figure 14. Figure 15 presents graphs corresponding to the maximum HST values. The highest values $\max(\Theta_{\text{HPT}})$ are observed in operating scenario 1.

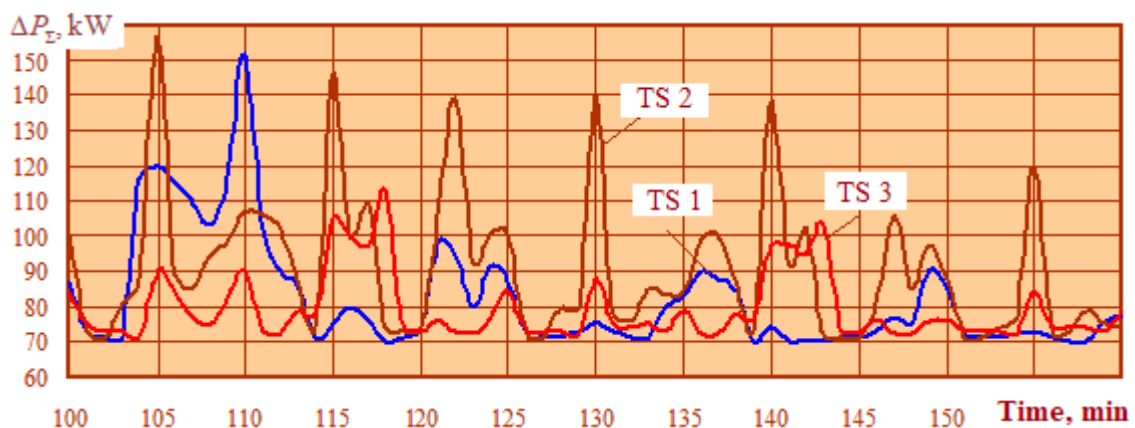


Figure 10. Losses in transformers for operating scenario 2.

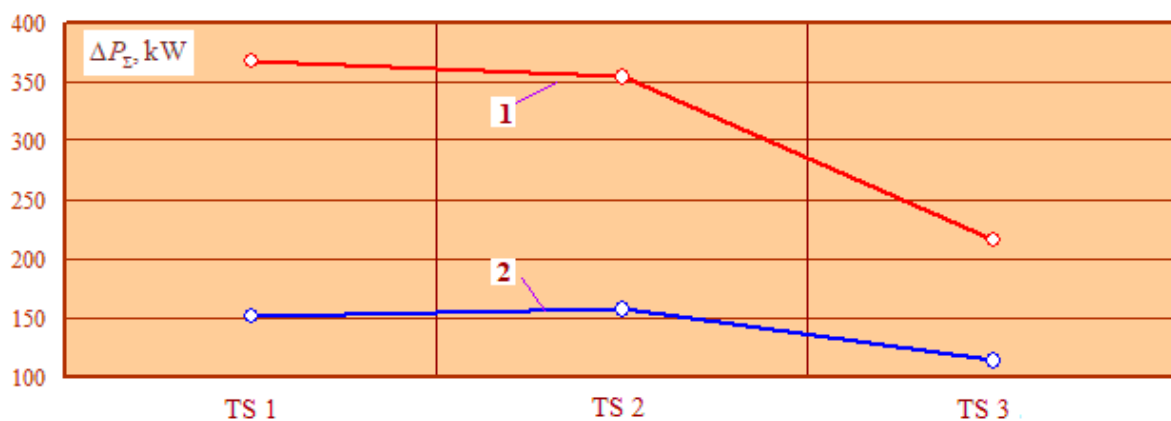


Figure 11. Maximum total losses: red and blue graphs indicate operating scenarios 1 and 2, respectively.

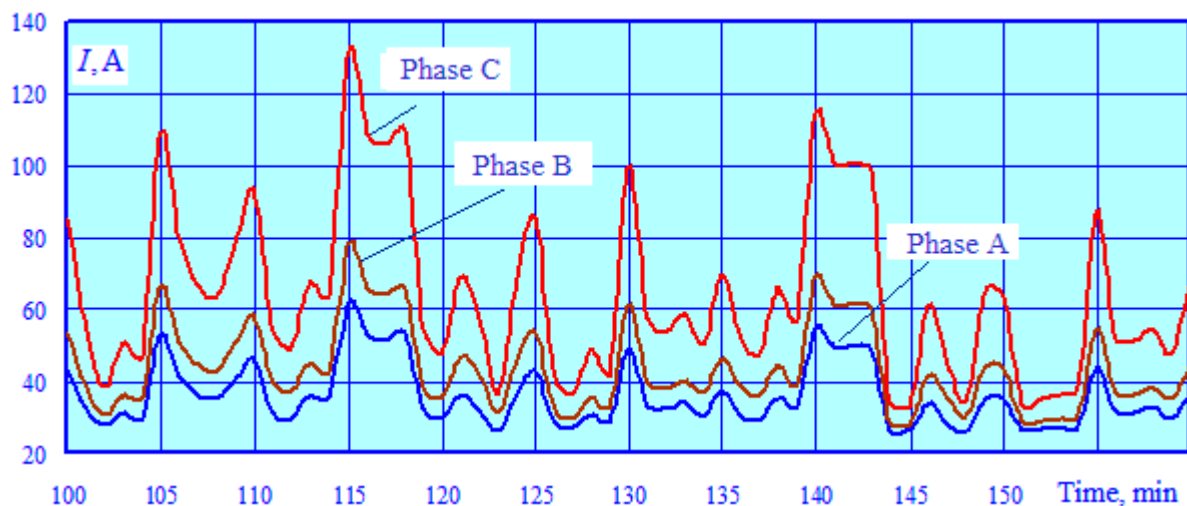


Figure 12. TS3 transformer currents on the high-voltage side for operating scenario 1.

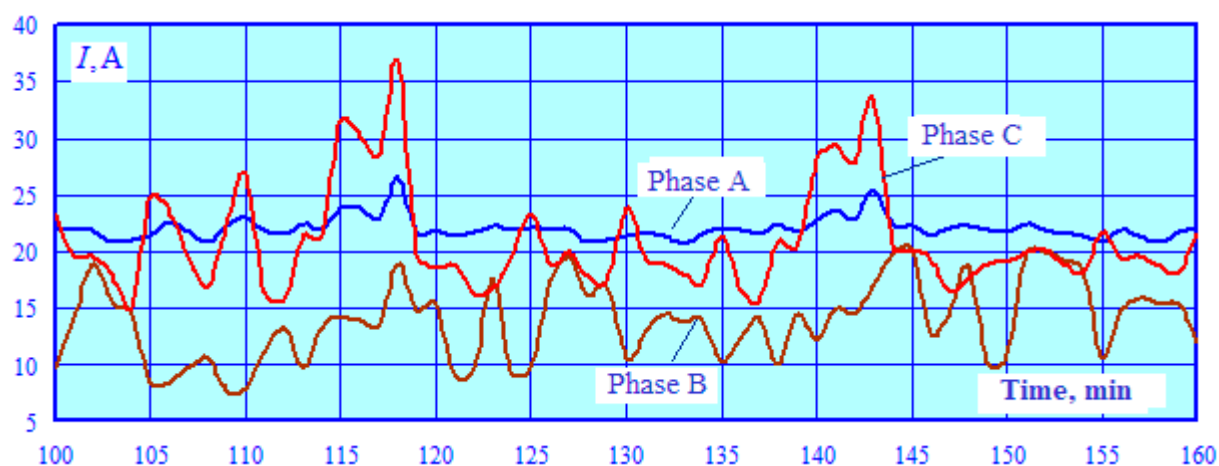


Figure 13. TS3 transformer currents on the high-voltage side for operating scenario 2.

Table 5. Maximum currents on the high-voltage side of traction substation, A.

Operating Scenario	TS 1			TS 2			TS 3		
	A	B	C	A	B	C	A	B	C
1	178.8	94.6	112.4	143.2	165	92.6	61.9	78.4	131.5
2	64.6	39.1	48.8	53.4	55.8	39.7	26.5	22.7	36.9

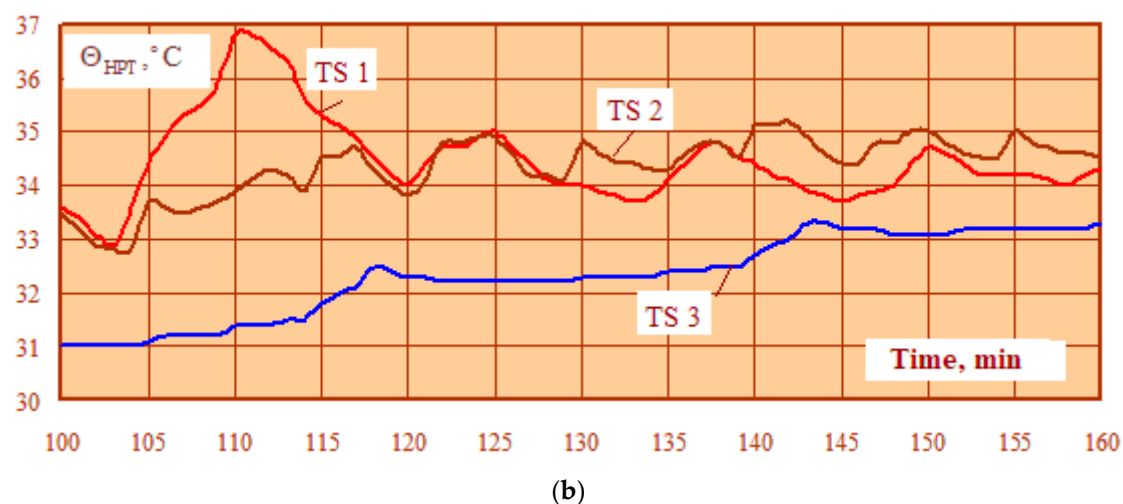
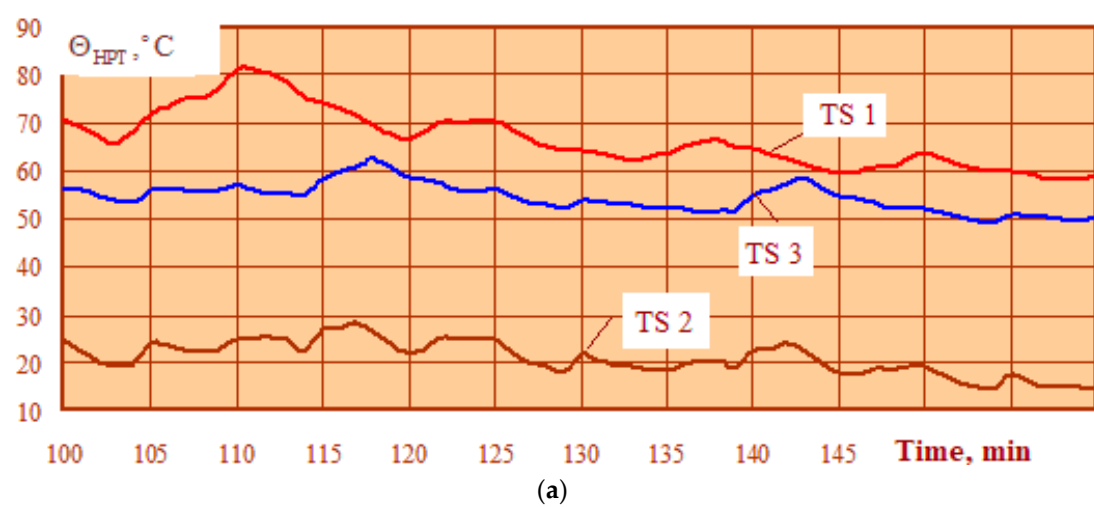


Figure 14. Hottest point temperatures for transformers: (a) scenario 1; (b) scenario 2.

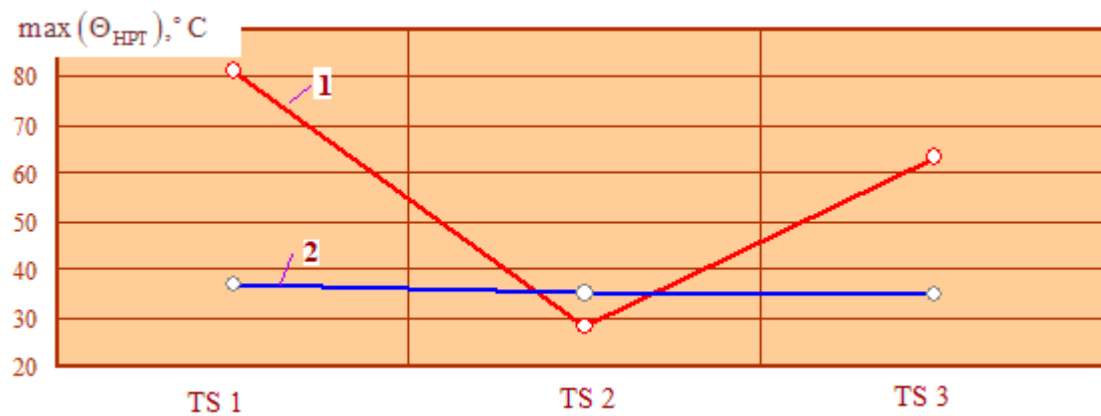


Figure 15. Hottest point temperatures: red and blue graphs indicate operating scenarios 1 and 2, respectively.

The findings shown in Figure 16 demonstrate the energy efficiency achieved through the use of RESs. As seen in the figure, with the renewable energy sources employed, the maximum power losses in the head power transmission line 1 are reduced by approximately six times. The same parameter for EPS is reduced from 85 to 35 MW.

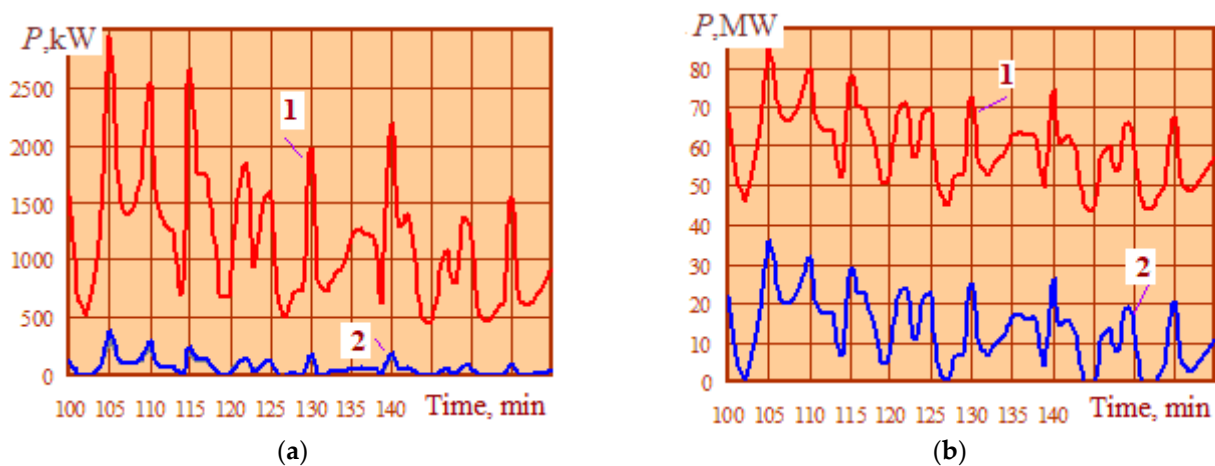


Figure 16. Losses (a) and flows (b) in power line 1: red and blue graphs indicate operating scenarios 1 and 2, respectively.

Figures 17–20 present the results of calculating non-sinusoidal conditions for operating scenarios 1 and 2.

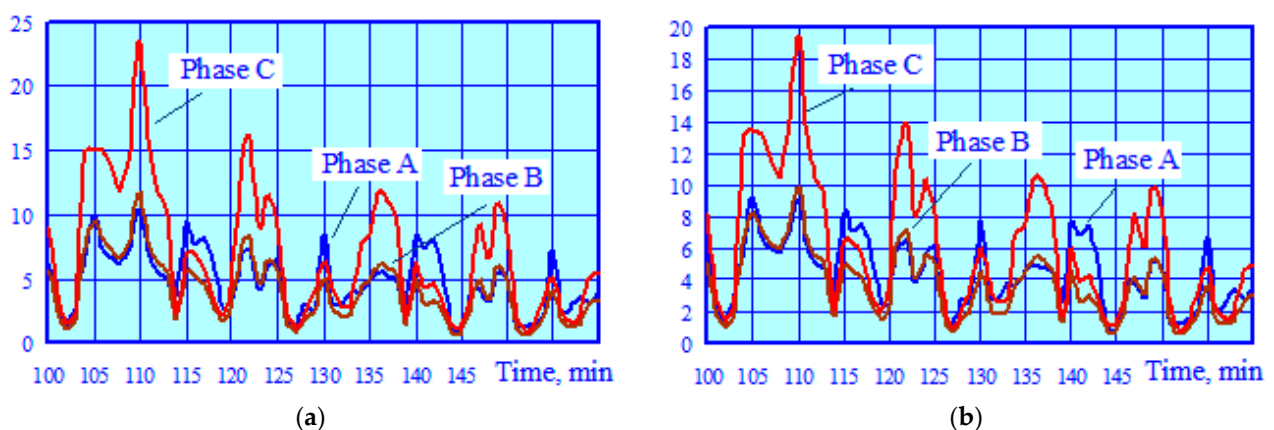


Figure 17. Total harmonic factors on 6 kV TS1 busbars: (a) operating scenario 1; (b) operating scenario 2.

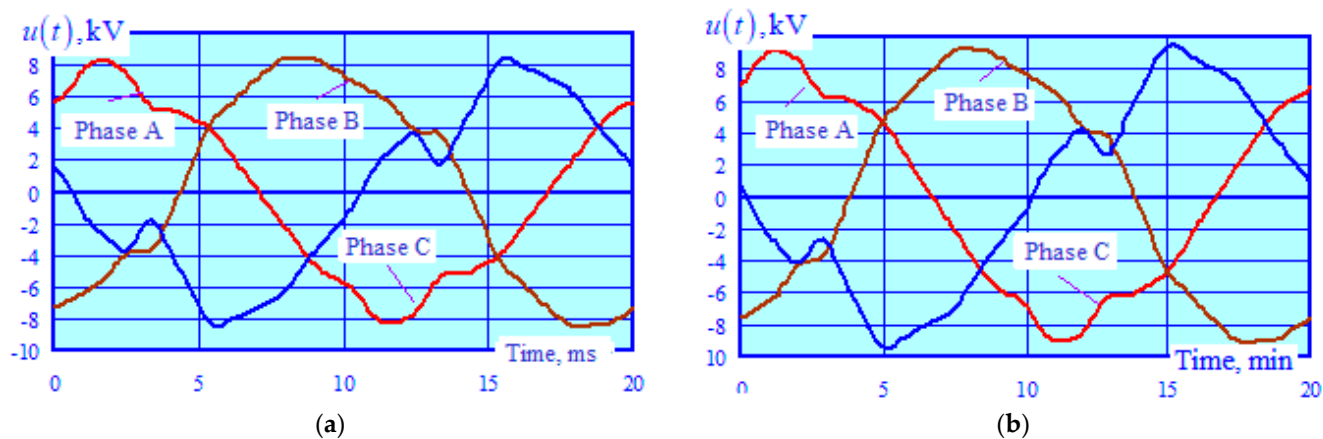


Figure 18. Voltage waveforms on 6 kV TS 1 busbars: (a) operating scenario 1; (b) operating scenario 2.

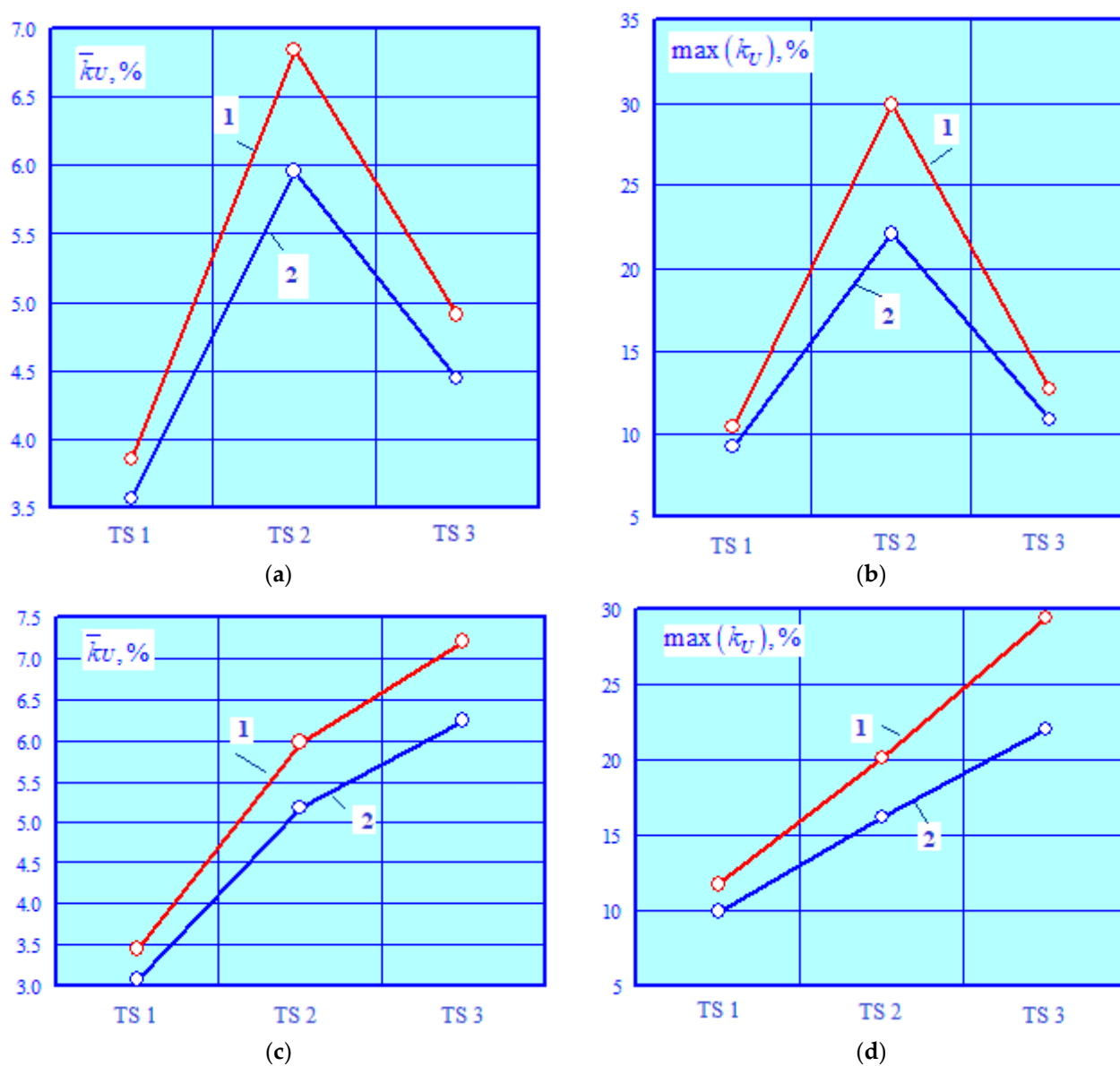


Figure 19. Cont.

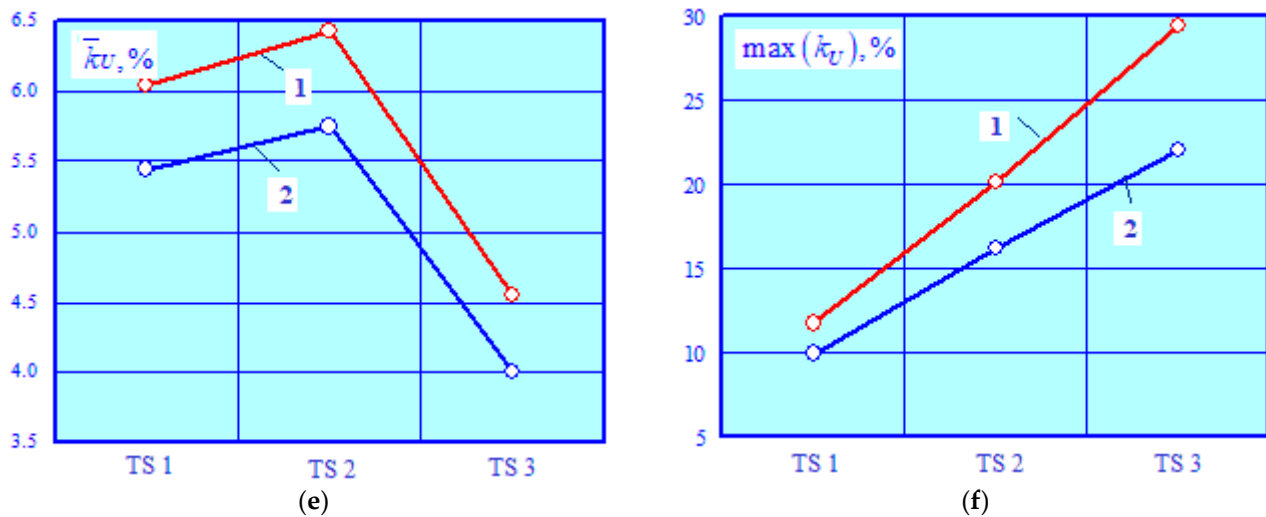


Figure 19. Average (a,c,e) and maximum (b,d,f) values of k_U : (a,b) phase A; (c,d) phase B; (e,f) phase C; red and blue graphs indicate operating scenarios 1 and 2, respectively.

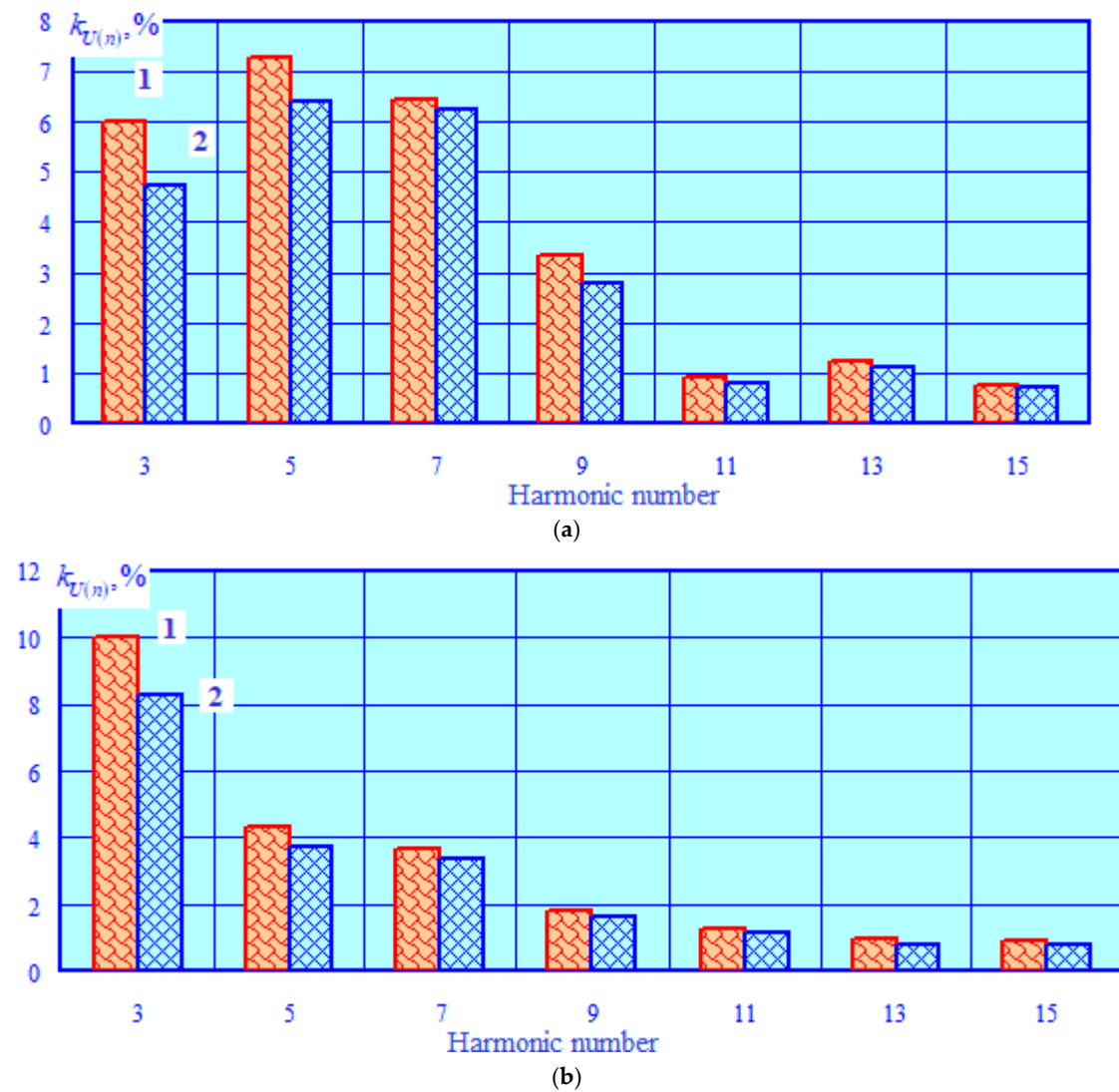


Figure 20. Cont.

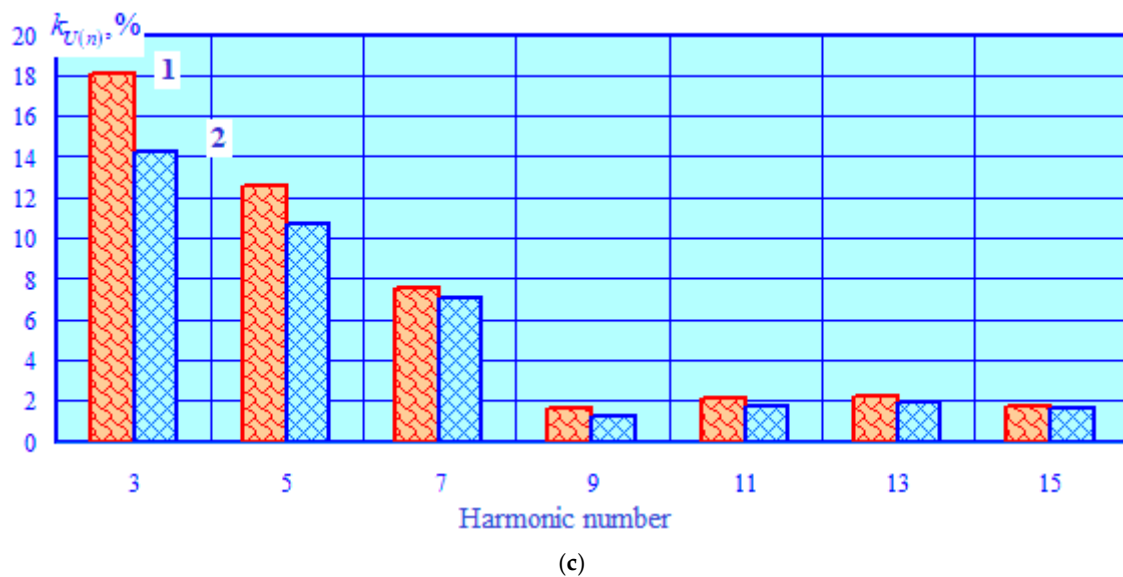


Figure 20. Harmonic content of voltage on 6 kV TS1 busbars: (a) phase A; (b) phase B; (c) Phase C; red and blue columns indicate operating scenarios 1 and 2, respectively.

As seen in Figures 17–20, the use of RES improves the quality of electricity according to the criterion of harmonic distortion. The average values of the total harmonic factors decrease by 7–14%, and the maximum values by 11–26%. The harmonic content of voltage on 6 kV TS busbars is also improved.

5. Conclusions

- These renewable energy source technologies can be employed in railway transport to address the following issues:
 - Increasing the reliability of power supply to facilities located in regions with an insufficiently developed power grid. This primarily concerns first-category consumers, for whom a power failure can lead to significant damage, accidents, and a threat to human life.
 - Providing a third independent source for electric loads of a special group that does not allow interruptions in power supply.
 - Creating transport and energy corridors by integrating railway routes and high-voltage power lines.
 - Enhancing the efficiency of energy conversion.
 - Reducing energy supply costs and radically improving power quality.
- RES models have been developed and implemented in the Fazonord AC-DC software. They provide practical solutions to the following problems:
 - Assessing the impact of renewable energy sources on power quality.
 - Determining application areas within transport facilities.
 - The developed models are also useful for solving complex optimization problems related to selecting rational locations for renewable energy sources.
- Based on the results of digital modeling of the power supply system for a main railway section, the following conclusions can be drawn:
 - The use of renewable energy sources makes it possible to stabilize voltage on the current collectors of electric locomotives and reduce the levels of unbalance and non-sinusoidal distortion on the 6 kV traction substation busbars. In the absence of renewable energy sources, the maximum values of the k_{2U} coefficients exceed

the maximum permissible value of 4% by more than three times. When renewable energy sources are switched on, the asymmetry decreases by 25–34%, but remains outside the regulatory range. Compliance with standard requirements can only be achieved when reactive power sources with control limits of -6 to $+10$ MVar are switched on. In the presence of renewable energy sources, the average values of the total harmonic distortion coefficients decrease by 7–14%, and the maximum values decrease by 11–26%. Full compliance with the standard for harmonic distortion is possible only when active harmonic filters are used.

- The presence of renewable energy sources leads to a decrease in power consumption from power system networks, a reduction in power losses in transmission lines and traction transformers, and a significant decrease in heating of traction transformers.
4. The active use of RES in traction power supply systems (TPSSs) can reduce carbon emissions into the environment, thereby contributing to the implementation of the sustainable development goals formulated by the United Nations.

The results presented in the article were obtained using methods and algorithms for modeling the operating conditions of electric power systems in phase coordinates, implemented in the Fazonord AC software package. The adequacy of this approach has been repeatedly verified by comparing simulation results with measurements taken at real facilities. For example, for one of the main alternating current railways, the difference between calculated and measured values of the voltage unbalance coefficients does not exceed 0.6%, while the differences in phase voltage magnitudes are less than 2.3%.

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