Modeling the Operation of Traction Power Systems Incorporating Wind Turbines

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Abstract: The paper presents the outcomes of the research aimed at developing digital models for calculating the operating conditions of railway power supply systems (RPSS) incorporating wind turbines. The implementation of the models relies on the methods of phase coordinates, which enable a systems, universal, and comprehensive approach. The systems dimension is achieved by considering all the significant properties of a complex RPSS and a supply network. The versatility is ensured by modeling traction networks, power lines, and transformers of various designs. The comprehensiveness lies in the possibility of calculating the normal, emergency, and special operating conditions in the RPSS. The study highlights a variety of applications of the wind turbines: to power the facilities located in regions with unstable energy supply; to enhance the reliability of power supply to the consumer whose disconnection could lead to serious consequences; to supply energy to relatively low-power facilities. The creation of the calculation model for the RPSS requires the implementation of an algorithm for the interaction of models of individual components and includes the following stages: modeling the rolling stock traffic schedule; developing instantaneous diagrams corresponding to specific time instants and calculating their operating parameters; determining integrated modeling indices. The results obtained using the Fazonord software indicate that the use of wind turbines can bring about the following benefits: cutting down energy supply costs; reducing unbalance on the busbars of traction substations, stabilizing voltage levels on the current collectors of electric locomotives.

1 INTRODUCTION

In order to enhance the reliability of power supply, improve the quality of electricity, and reduce the cost of energy supply in railway transport, an emerging solution is the adoption of self-generation (SG) plants utilizing renewable energy sources (RES), for example, micro hydroelectric power stations (Bulatov, 2022), wind turbines (Shevlyugin, 2008; Petrushin, 2021), geothermal and solar power plants (Samarov, 2017).

The self-generation plants can be used to:

- power the facilities located in regions with unstable energy supply;
- boost the reliability of power supply to the consumer whose disconnection could lead to serious consequences;
- supply energy to individual facilities of relatively low power (Rylov, 2021).

The significance of using renewable energy sources (RES) in transport is demonstrated by a wealth of publications suggesting various approaches to address this issue. For example, (Cheng, 2021) provides an overview of fault-tolerant traction power supply systems (TPSS) and concludes that the integration of RES ensures a reduction in damage from disruptions and failures in the network. The use of renewable energy sources to improve the efficiency

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of solar power plants in India is discussed in (Bade, 2018). The findings of the study into short circuit processes in power plants with renewable energy sources are presented in (Kuznetsov, 2022). The efficiency of a traction network incorporating renewable energy sources is assessed in (Singh, 2016). Methods for solving the problem of integrating renewable energy sources into traction power system to reduce carbon emissions and energy costs are discussed in (Tian, 2020). An overview of the traction power systems equipped with RES is given in (Bade, 2018). Important aspects related to the use of renewable energy sources to ensure train safety are considered in (Spunei, 2019). The problem of forming wind-solar traction power systems is solved in (Bakre, 2020). A comparative analysis of options for integrating photovoltaic sources into traction networks is carried out in (D' Arco, 2018). The tasks of using solar power plants in transport energy systems are described in (Di Noia, 2019). A method for generating a traffic schedule, considering a wind farm, is described in (Wu, 2022). A traction power supply system with photovoltaic modules is presented in (Rageh, 2018). Hybrid DC traction power system with renewable energy sources is described in (Yu 2021). The photovoltaic system for traction power system and a strategy for its control are presented in (Mingliang, 2017). The issues of integrating rail-based public transportation system and using regenerative energy are considered in (Çiçek, 2022). The issue of identifying optimal sites for installing solar-powered permafrost stabilization systems on railways is resolved in (Loktionov, 2019). The efficiency of photovoltaic panels placed on locomotive roofs is the focus of (Lencwe, 2016).

In modern context, the integration of renewable energy sources must be addressed on the basis of digital models that take into account the specifics of RPSS, which are as follows:

- Traction loads greatly worsen the quality of electricity in electrical networks of non-traction consumers, where it is planned to use RES-based SG plants;
- The non-stationary nature of single-phase traction loads leads to significant voltage deviations on the busbars of substations to which SG plants are connected;
- Single-phase traction load causes a marked unbalance on these busbars, which, sometimes, considerably exceeds permissible limits;
- Electric locomotive converters generate harmonics into the network.

An analysis of the presented publications shows that modeling the RPSS with SG plants based on RES has not been fully examined (Monakov, 2023, Shushpanov, 2021). To study this issue comprehensively, one can use the methods presented in (Zakaryukin, 2005, 2023, Bulatov, 2020). Based on the approaches proposed in these articles, it is possible to implement the modeling methodology that has the following distinctive features:

- The ability to model operating conditions considering the properties and characteristics of a complex traction power system and electric power supply system (EPS);
- The versatility, providing modeling of traction networks (TN), power lines, and transformers of various designs;
- The comprehensiveness, which implies the possibility of determining normal, emergency, and special conditions in RPSS, for example, those arising when ice melts on the traction networks.

Below are the results of the research aimed at developing methods for modeling RPSS incorporating wind turbines.

2 METHODOLOGY

A formalized description of the RPSS can be provided by the following model:

$$\frac{d\mathbf{X}}{dt} = \mathbf{\Phi}(\mathbf{X}, \mathbf{V}, \mathbf{S}, \mathbf{C}, t), \tag{1}$$

where $\mathbf{X}$ is *an n-* dimensional vector of parameters characterizing the operating condition, for which Cartesian or polar coordinates of nodal voltages are used; $\mathbf{\Phi}$ is an *n*-dimensional nonlinear vector function; $\mathbf{V}$ is an *m*-dimensional vector of disturbances, the components of which are active and reactive loads and generations; $\mathbf{C}$ is an ℓ -dimensional vector of control actions, generated based on the train schedule, and instructions coming from the control center; $\mathbf{S}$ is a q -dimensional vector, including elements of the conductance matrix corresponding to the RPSS electrical network.

Due to insufficient information available, the practical use of model (1) is only possible in the future. Therefore, it is reduced to a set of static (instantaneous) diagrams. In doing so, the interval under study T_M is divided into small intervals Δt, within which the above parameters are considered to be constant. At each interval Δt, the following nonlinear system of equations describing the steady state of the corresponding instantaneous diagram is solved:

$$\mathbf{F}[\mathbf{X}_k, \mathbf{S}_k, \mathbf{C}_k, \mathbf{V}_k] = \mathbf{0}, \tag{2}$$

where $\mathbf{X}_k, \mathbf{S}_k, \mathbf{C}_k, \mathbf{V}_k$ are the vector values of $\mathbf{X}, \mathbf{S}, \mathbf{C}, \mathbf{V}$ for the *k-th* instantaneous diagram.

The simulation modeling methodology proposed in (Zakaryukin, 2005) and implemented in the Fazonord software enables calculations of operating parameters for the RPSS, including the supply network of EPS, the traction power system, and areas of power supply to non-traction consumers.

3 RESULTS OF MODELING

Model in the form of system (2) is used for modeling the operating conditions of the RPSS with SG plants based on wind turbines. The mathematical model, which can be used for wind turbines, is as follows:

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

where $P_{Gj}^{(k)}, Q_{Gj}^{(k)}$ are active and reactive power of the wind turbine generator connected to phase k (k=A, B , C) of the j-th network node; $P_{Hj}^{(k)}, Q_{Hj}^{(k)}$ are active and reactive power of the load connected to phase k of the j-th network node; $P_{Cj}^{(k)}, Q_{Cj}^{(k)}$ are network active and reactive power of phase k of the j-th network node.

The effects of using wind turbines are quantified by modeling the traction power system, including three traction substations (TSs). The modeling is carried out using the Fazonord software version 5.3.4.1-2024 (Zakaryukin, 2023). A fragment of the original RPSS diagram is shown in Figure 1. Consideration is given to the movement of trains weighing 3200 tons in a down direction and 6000 tons in an up direction, with an interval of 30 minutes (Fig. 2). The modeling results are presented in Figures 3 – 6.

Modeling was performed for two options:

1. There are no wind turbines in the RPSS.
2. Wind farms (WFs) with the total capacity of wind turbines shown in Figure 1 are connected to 6 kV busbars of traction substations.

Graphs of changes in WF power are shown in Figure 4.

Single-phase traction loads create significant unbalance on the busbars of 6 kV traction substations (TSs), which can have a negative impact on wind turbine equipment. This problem can be addressed by using phase-controlled sources of reactive power (SRP), (Fig.5), which can reduce the unbalance to acceptable limits. The power equipment of SRP represents reactors and static capacitor banks, which can be connected in a “star” (Fig. 6) or “delta” (Fig. 7) configuration.

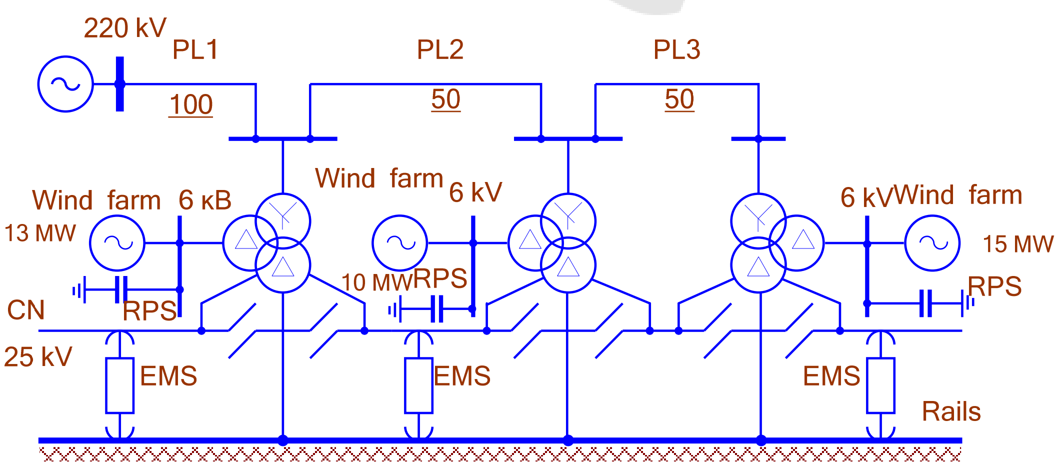


Figure 1: RPSS diagram: CN – contact network; EMS – electromotive stock.

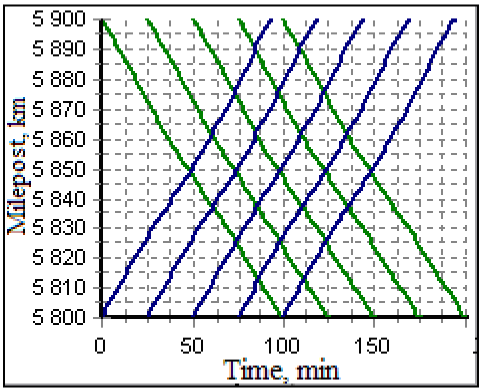
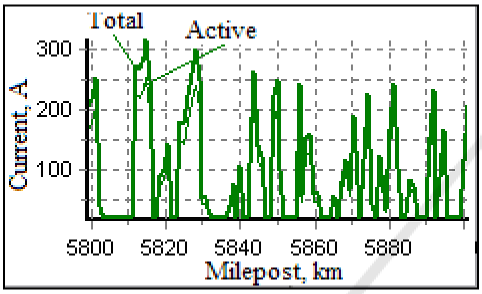
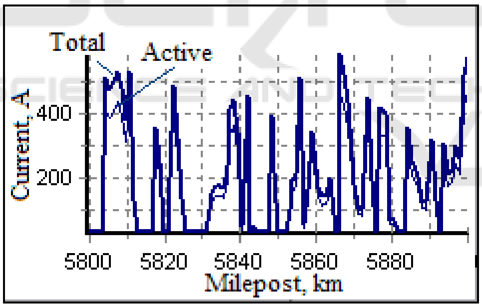


Figure 2: Train schedule.



a)



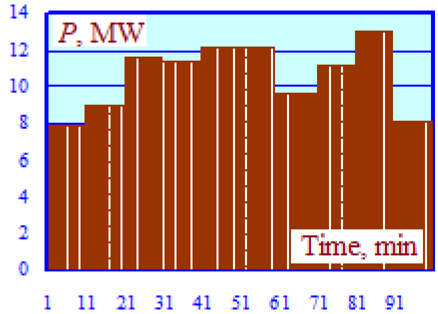
b)

Figure 3: Current profiles of electric locomotives; a – down direction; b – up direction.

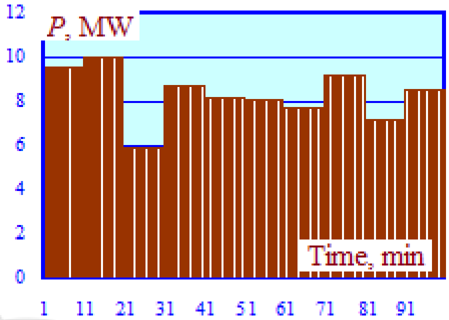
The SRP models are built by fixing the required levels of linear or phase voltages with the possible setting of constraints on generated reactive power:

$$Q_{j\min}^{(A)} \le Q_j^{(A)} \le Q_{j\max}^{(A)};$$
$$Q_{j\min}^{(B)} \le Q_j^{(B)} \le Q_{j\max}^{(B)};$$
$$Q_{j\min}^{(C)} \le Q_j^{(C)} \le Q_{j\max}^{(C)},$$

where $Q_{j\min}^{(k)}, Q_{j\max}^{(k)}$ are reactive power constraints.



a)



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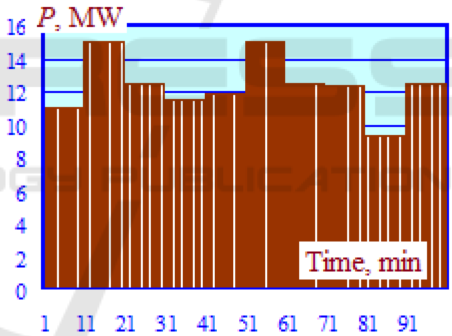


c)

Figure 4: Dynamics of changes in the total power of wind farms: a – WF connected to TS1; b – WF connected to TS 2; c – WF connected to TS 3.

The studies performed for a real-world railway power supply system show that the use of SRP with delta-connected power equipment provides better balancing. A “star” connection of the SRP phases with a grounded neutral causes a zero-sequence voltage. The SRP whose equipment is delta-connected do not have this downside. Therefore, the models used below rely on the SRP diagrams with delta-connected power equipment.

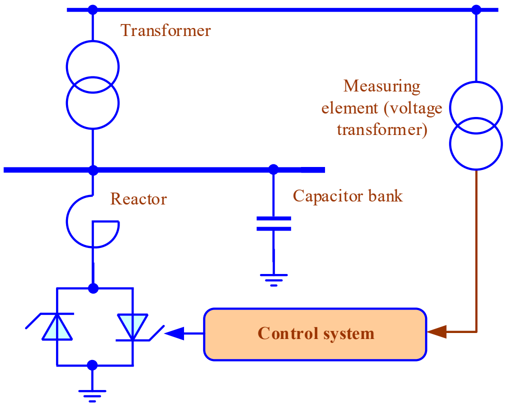


Figure 5: SRP diagram.

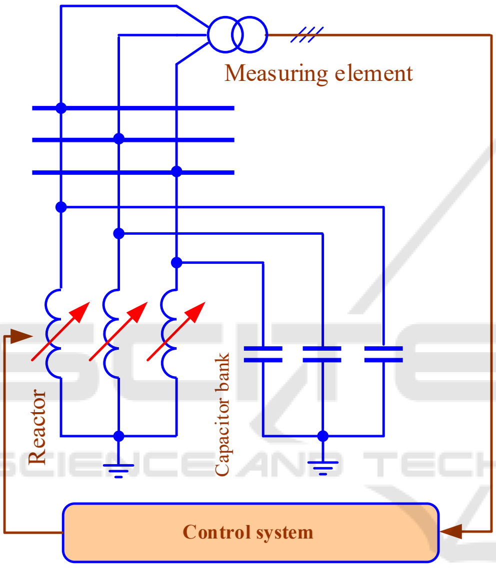


Figure 6: SRP in the case of star connection.

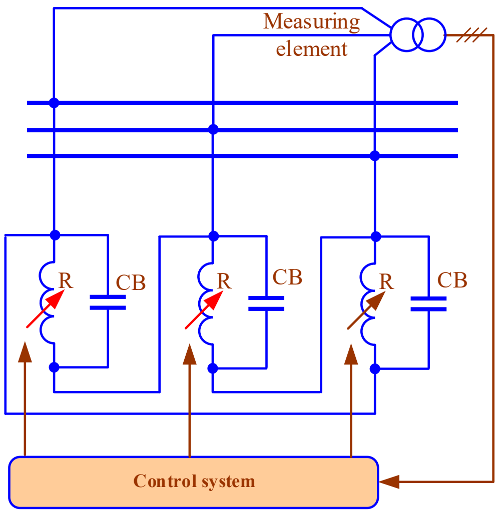


Figure 7: SRP in the case of delta connection.

The modeling results are presented in Figures 8 – 17. Figures 8-10 show the graphs characterizing voltage changes on the current collectors of electric locomotives. As seen in the Figures, when the wind farm is connected, the minimum levels of these voltages increase by 3.2% for a down train and by 5.3% for an up train.

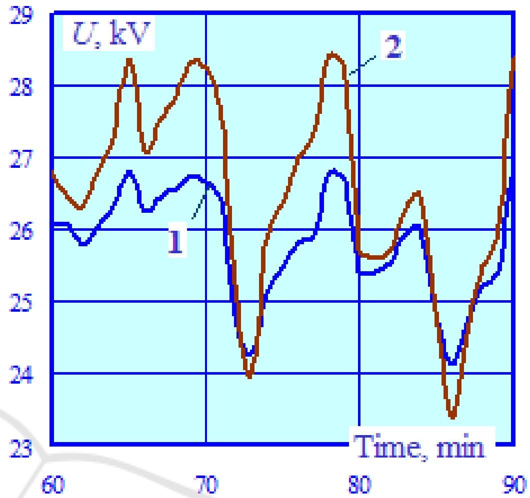


Figure 8: Dynamics of voltage changes on the current collector of the first down train: 1 – WFs are on; 2 – WFs are turned off.

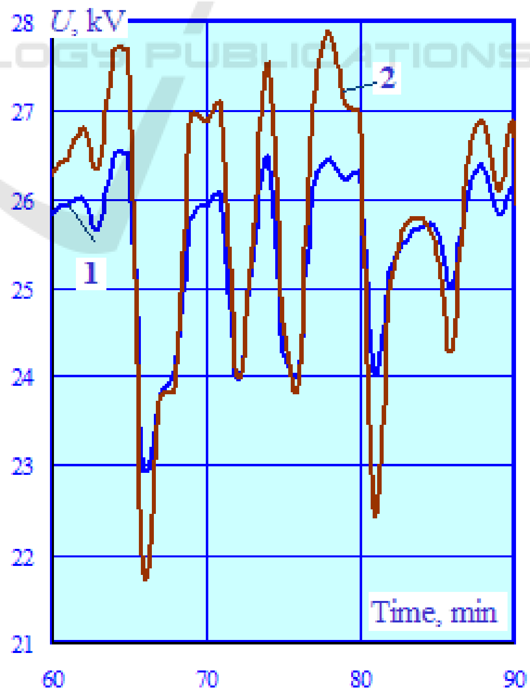


Figure 9: Dynamics of voltage changes on the current collector of the first up train: 1 – WFs are on; 2 – WFs are turned off.

Figure 11 shows the time dependences of the power generated by reactive power sources. Their use provides a reduction in the voltage unbalance on the buses of 6 kV traction substation to acceptable limits (Figures 12, 13). Additional reactive power flows do not cause overload of traction transformers, as evidenced by the dependences of losses shown in Figures 14, 15.

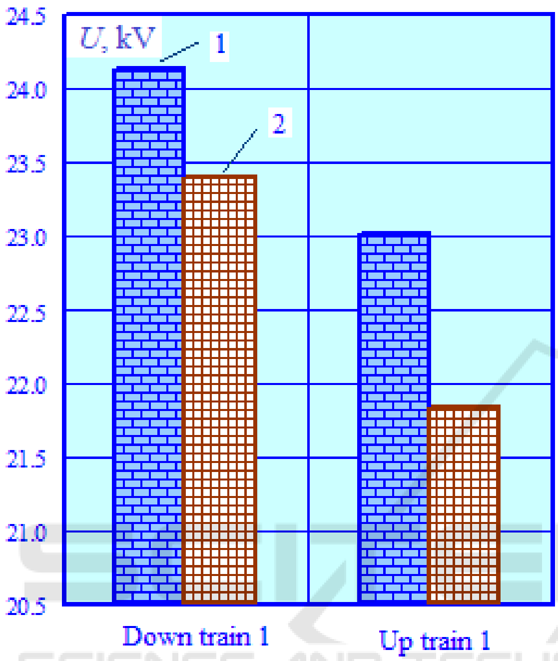


Figure 10: Minimum voltage levels on current collectors of electric locomotives: 1 – WFs are on; 2 – WFs are turned off.

When the wind farms are turned on, the power consumption from the EPS goes down, as evidenced by the graphs of changes in active power flows along power line 1 (Fig. 16); At the same time, at some points in time, the energy of the wind farm is transferred to the EPS. The maximum power losses in power line 1, when the wind farm is turned on, are reduced by a factor of 2.5 (Fig. 17).

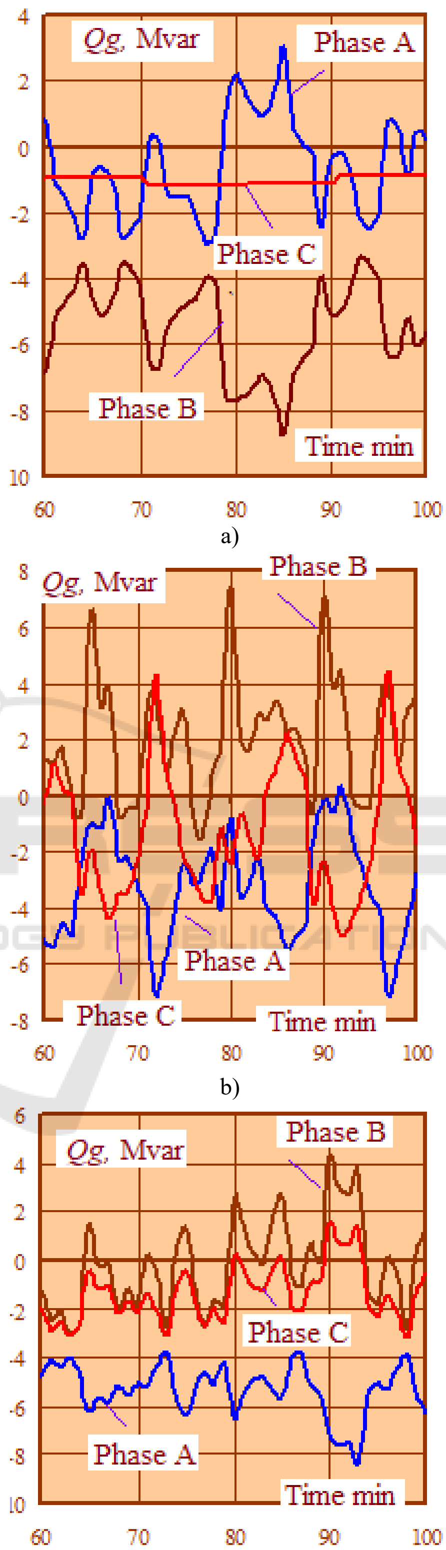


Figure 11: Generation of reactive power by SRP: a – SRP installed at TS 1; b – SRP installed at TS 2; c – SRP installed at TS 3.

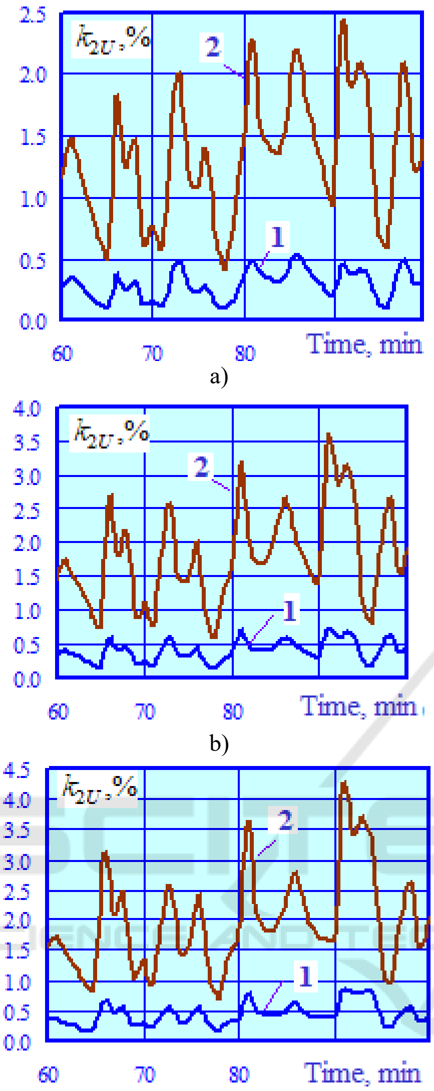


Figure 12: Dynamics of changes in factors of negative-sequence unbalance on busbars of 220 kV traction substations: a –TS1; b –TS2; c –TS3; 1–WFs are on; 2–WFs are turned off.

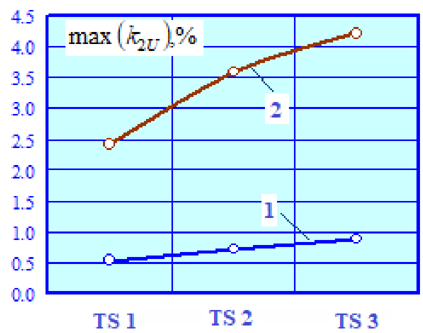
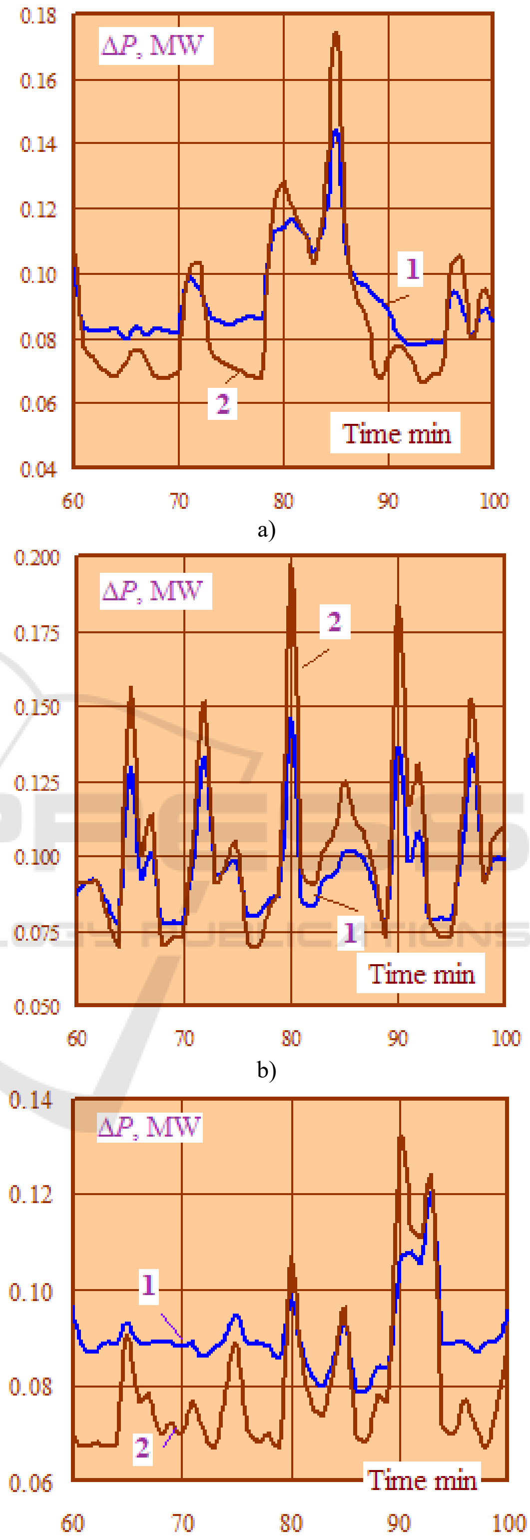


Figure 13: Maximum values of unbalance factors: 1 – WFs are on; 2 – WFs are turned off.



c)

Figure 14: Dynamics of changes in losses in traction transformers: a – TS 1; b – TS 2; c – TS 3; 1 – WFs are on; 2 – WFs are turned off.

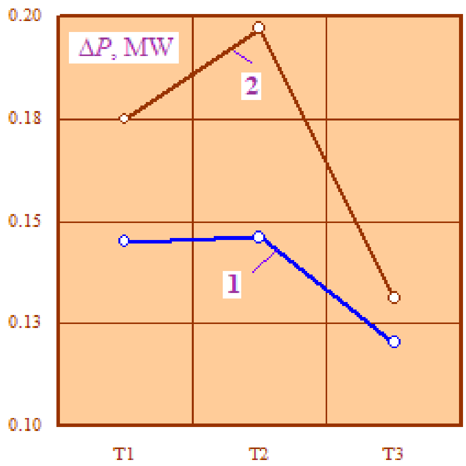


Figure 15: Maximum loss levels in traction transformers:1 – WFs are on; 2 – WFs are turned off.

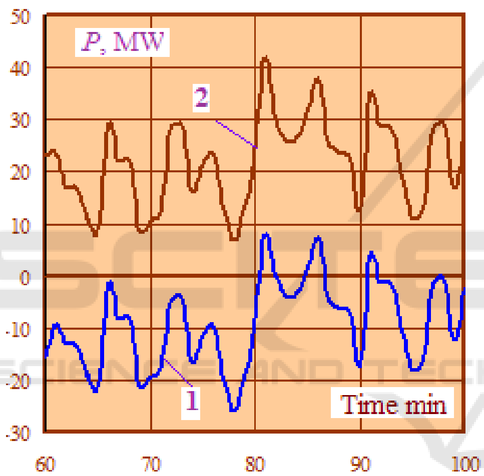


Figure 16: Dynamics of changes in flows along power line 1:1 – WFs are on; 2 – WFs are turned off.

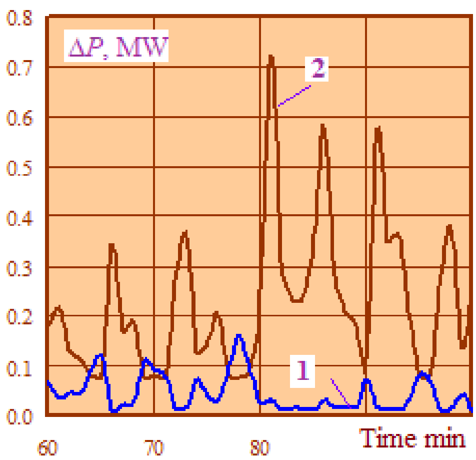


Figure 17: Dynamics of changes in losses in power line 1: 1 – WFs are on; 2 – WFs are turned off.

4 CONCLUSIONS

1. The paper presents the findings of the research aimed at developing digital models to calculate the operating parameters of railway power supply systems incorporating wind farms. The implementation of these models involved a methodology for modeling the operating parameters in phase coordinates. This methodology is distinguished by the following features: systems dimension, consisting in the ability to factor in all the important characteristics of traction and external power supply systems; versatility, providing modeling of traction networks and power lines of various designs; comprehensiveness, which implies the possibility of calculating normal, emergency, and special operating parameters.

2. Modeling of the operating conditions was carried out for two options. The first focused on a typical RPSS without self-generation plants. The second involved modeling the RPSS with wind generators connected to the 6 kV busbars of traction substations.

3. The modeling results have demonstrated that with the wind farms operating in the RPSS, it is possible to cut down electricity consumption from EPS networks; increase the reliability of power supply to the essential consumers by using wind turbines for backup; and improve the quality of electricity in traction networks and 6-10 kV networks, which power stationary railway transport facilities.

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