Improving the electric power quality in the networks adjacent to the railroad traction substations

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Abstract. A significant deterioration in the electric power quality indicators (EPQI) is observed in the 110-220 kV electrical networks, which are directly adjacent to the traction substations of the Trans-Siberian Railway. Such situations are typical of many regions of Siberia and the Far East. The article presents the results of research aimed at improving the electric power quality in the networks adjacent to the traction substations. The simulation algorithms used were based on application of phase coordinates and lattice equivalent circuits. Software tools Matlab and AnyLogic were used to model transition processes and evaluate the effectiveness of the concept of an intelligent electricity quality controlling system. On the basis of the results, technical solutions have been proposed to bring the electric power quality indicators to standard values. It is shown that a comprehensive approach, including the following segments, is needed to address the problem of reduced electric power quality: the use of technology to improve electric power quality indicators; reinforcing 110-220 kV networks that feed traction substations; technologies of smart customization and control of technical means.

1. Introduction.
In the electrical networks that feed traction substations (TS) of the main AC railway lines, the problem of reduced quality of electric power (EP) has become particularly critical. There is a significant deterioration in electric power quality in Siberia and the Far East, because in some regions of these areas the main networks 110-220 kV are directly adjacent to the substations of the Trans-Siberian Railway [1–3]. Abruptly variable, non-linear and single-phase traction loads, as well as reduced short-circuit (SC) capacity levels at the points of connection of individual traction substations, cause the electric power quality indicators in these networks to go far beyond acceptable limits.

The results of the instrumental measurements of the electric power quality indicators show that there are significant violations of voltage symmetry and sinusoidality on high voltage buses of Transsib traction substations [2, 3]. The average per day of the voltage unbalance ratios in reverse sequence $k_{U2}$ regularly reach 3... 4%, and the maximum reach 6... 7%; similar data on the total ratios of harmonic constituents $k_{U}$ are appropriately equal to: 5... 6 and 8... 10%.

Electric power quality indicators that go beyond regulatory limits can lead to the following negative consequences: disruption of technological processes; reducing product quality; reducing the performance of machines and mechanisms; increasing electric power losses; reducing the credibility of
electric power accounting; reduced electric power reliability due to accelerated aging of insulation and malfunctioning of relay protection and automation devices [4, 5].

In recent years, the Irkutsk State Transport University has conducted comprehensive research aimed at developing multifunctional modelling methods for electric power systems (EPS) and railway electric power supply systems (REPSS) [6]. A unified methodological approach to the construction of models of elements of EPS and REPSS, implemented by lattice equivalent circuits, has been proposed. On the basis of this approach, methods and computer technologies have been implemented, the distinctive features of which are [6]:

- multiphasal nature, providing simulations of single-phase, three-phase, four-phase, six-phase systems, etc.;
- multi-mode nature, which is to be able to determine a wide range of electric power system and railway electric power supply system modes: normal, emergency, asymmetrical and non-sinusoidal, as well as limiting modes on static aperiotic resistance;
- multitasking, consisting of a number of additional tasks, such as the definition of induced voltages on adjacent electric power transmission lines (EPTL) and communication lines; calculating the strengths of the electromagnetic field created by electric power transmission lines and traction networks; parametric identification of electric power transmission lines and transformers based on measurements from PMU WAMS devices; taking into account the active elements of the smart grid when modeling electric power systems and railway electric power supply systems; correct accounting of the surface effect, as well as the proximity effect when modeling current wires with solid buses.

The article presents the results of research aimed at solving problems of improving the electric power quality in the networks adjacent to the traction substations. To improve electric power quality indicators, one can use intelligent electrical network technologies [7–11] and multi-agent control systems [12, 13]. On the basis of the results, technical solutions have been proposed to bring the electric power quality indicators to standard values.

2. The simulation technique.
Railway electric power supply systems are a combination of complex subsystems: the part of the electric power systems adjacent to traction substations; traction power supply system (TPSS); electric power supply regions (EPSR) of non-traction and non-transport consumers. Simulation methods are used to model railway electric power supply system modes; in this case, the study time interval is broken down into small intervals, within which the parameters of the railway electric power supply systems are considered unchanged. A comparison of measurements on real-world objects and computer simulation results [6] shows that the accepted assumption does not make a noticeable error in the results of the calculations.

The algorithm of simulation of the railway electric power supply system is based on the application of phase coordinates and lattice equivalent circuits with fully meshed topology. Details of the simulation of electricity sources, electrical loads, and elements used to regulate the modes of the electric power systems are discussed in work [6]. To model transient processes and form the concept of an intelligent electric power quality controlling system, extra software tools were used, such as Matlab and AnyLogic.

3. Methods for improving electric power quality.
The problem of improving the quality of electric power in the networks adjacent to the traction substations can be solved by building a control system for the railway electric power supply system modes. The global goal of such controlling is uninterrupted energy-efficient and high-quality supply of electric power to electric rolling stock (ERS) and non-traction consumers. To implement it, one needs to solve the following problems:

- ensuring voltage levels at electric rolling stock current collectors required by regulations;
- reducing equalizing currents and losses of electricity in traction networks and EPSR to optimal values;
- compliance of electric power quality indicators at the railway electric power supply systems
and the supply electric power system with regulatory requirements.

To solve the problem of the reduced electric power quality, one can use technical means presented in table 1. It is necessary to note the versatility of the presented technical devices.

**Table 1** The main and additional functions of technical means to improve the electric power quality

| Technical equipment group | Tasks solved | Additional technical equipment |
|---------------------------|--------------|--------------------------------|
| Stabilization of voltage levels in the traction network | Reducing voltage deviations on buses 6 (10, 35) – 110–220 kV traction network | Distributed generation plants, DC inserts, energy routers [15] |
| Reducing voltage asymmetry on buses 6 (10, 35) –110–220 kV traction network | | |
| Reducing harmonic distortions on buses 6 (10, 35) –110–220 kV traction network | | Distributed generation plants, unbalance-to-balance transformer, balancing devices based on the Steinmetz scheme [16] |
| Flicker in 0.4 kV EPSR networks in the presence of distributed generation plants | | DC inserts, energy routers |

Voltage fluctuations can be significantly reduced by the use of regulated reactive power sources (RPS). Reducing voltage deviations and fluctuations can be obtained with energy storage that allow improving the non-stationary performance of the traction power supply system mode.

The use of phase-controlled reactive power source makes it possible to lower the voltage asymmetry ratios $k_{2U}/U$ on the buses of the power voltage of traction substations. The degree of lowering depends on the volume of the train traffic, the short circuit capacity and the condition of the track profile.

One of the most effective means of reducing harmonic distortions are active harmonic conditioners (AHC). The results of simulation of real electricity systems of the main railway lines showed that on the basis of the AHC, installed on the power supply arms of the traction network, levels of non-sinusoidality on the buses of 110-220 kV traction substations can be reduced to standard limits.

Modelling of the prospective modes of the electric power supply system (EPSS) of one of the main railway lines of Eastern Siberia has shown that without the use of means of improving the electric power quality, the maximum values of harmonic components ratios $k_U$ are up to 23%. When placing
blocks of single-phase active harmonic conditioners on the inputs of 27.5 kV traction substations, the maximum of $k_U$ on 220 kV buses did not exceed 2%.

To improve the quality of electric power and to develop the concept of intelligent electrical networks, it is necessary to apply energy routers (ER) in EPSS. These energy routers should be constructed with the use of high-frequency solid-state transformers (Figure 1), which are single-phase high-frequency power transformers in mono-block design, equipped with two active semiconductor bridges.

![Diagram of energy router](image1.png)

**Figure 1.** The electric power supply scheme with an energy router (a) and the router scheme built on the basis of a high-frequency transformer (b)

In order to be able to regulate voltage, the inverter, working on the 0.4 kV network, should be provided with an automatic control system. The consumer electric power quality depends on its correct operation. Taking into account the requirements described in the MATLAB system, Simulink and SimPowerSystems developed an energy router model with a voltage regulator. The results of the studies carried out on the railway electric power supply model with distributed generation plants connected through the energy router to the electric power supply region of non-traction consumers showed that when using the energy router, consumers received a quality electric power (Figure 2 b). It lacked the negative characteristics inherent in the networks of railway non-traction consumers. For the example considered on the 10 kV buses of the energy router, the maximum values of ratios $k_U$, $k_{2U}$ reached 10.7 and 4.2% respectively. On 0.4 kV buses, these values were 0.1 and 0.05 percent (table 2).
Figure 2. 10 kV bus (a) and non-traction consumer 0.4 kV bus voltage oscillograms in the presence of an energy router (b)

Table 2 Voltage harmonics ratios and asymmetry ratios according to the reverse sequence, %

| Place of measurement | $k_{Uab}$ | $k_{Ubc}$ | $k_{Uca}$ | $k_{2U}$ |
|----------------------|-----------|-----------|-----------|-----------|
| 1 On 10 kV buses     | 10.66     | 9.11      | 8.74      | 4.24      |
| 2 On 0.4 kV buses    | 0.09      | 0.09      | 0.09      | 0.05      |

The simulation results also showed that the ER makes it possible to effectively integrate distributed generation plants into EPSS, including those based on renewable energy sources.

The use of distributed generation plants allows one to unload networks, which helps to reduce electric power losses, improve the reliability of electric power supply to consumers and electric power quality. However, low-power generators can cause voltage fluctuations that lead to a flicker [19–21]. This effect usually manifests itself with a sharp decrease in voltage in the connection node of the distributed generation plant generator [22] and is associated with the interaction of equipment and the dynamic behavior of machines. Studies carried out in the MATLAB system on the electric power supply system model with distributed generation plants have shown that when turbine generators with mismatched excitation and frequency controllers operate, oscillations may occur, leading to flicker in the connection node of the distributed generation plant. The corresponding oscillograms of frequency and voltage, as well as flickermeter readings, are presented in figures 3 and 4.
Figure 3. Fluctuations in the rotation rate of the generator rotor (a) and the voltage in the distributed generation plant (b) connecting node when a powerful load is turned on and off.

Figure 4. Flickermeter reading.

Studies have also shown that the use of predictive control algorithms in harmonized regulators of distributed generation excitation and frequency allows one to eliminate flicker. The corresponding flickermeter readings are presented in Figure 5.
The problem of reduced electric power quality in the railway electric power quality systems can also be effectively solved by applying the concept of intelligent electrical networks (smart grid) and multi-agent technologies [23, 24]. The structural diagram of the multi-agent control system (MACS) by the railway electric power supply system modes is presented in Figure 6.

The autonomous MACS agents interacting with each other are partially independent and have
limited representation, as each agent does not have complete information about the object of controlling and external environment. The concept of decentralization is also being used; there are no agents who fully control the entire object.

Work [24] provide the results of a simulation of a multi-agent system for controlling distributed generation plants based on synchronous generators, in which agents had the following basic set of properties:

- activity – the ability to organize and implement impacts on the controlled object, as well as on other agents;
- reactivity – perception of an object's condition through sensors and messages from other agents;
- autonomy – relative independence from the environment, as well as the presence of "freedom of will" in some agents, conditioning their own behavior;
- the sociability provided by advanced communication protocols that enables an individual agent to solve its problems together with others;
- purposefulness, which implies the presence of one's own sources of motivation.

The results of MACS simulations of distributed generation plants in electric power supply region, obtained in the AnyLogic environment, showed a 91% reduction in voltage and frequency regulation time and a 10% overregulation, as well as an improvement in electric power quality indicators and transient process quality [24].

4. Conclusion

The problem of reduced quality of electric power in the railway electric power supply systems can be effectively solved on the basis of a comprehensive approach, which includes the following segments:

- the use of technical equipment to improve electric power quality indicators;
- reinforcing of 110-220 kV networks that feed traction substations connected to nodes with reduced capacity of short circuit;
- applying intellectual technologies of customization and control of technical means.

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