The use of energy routers to improve reliability of power supply to non-traction consumers

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Abstract. The purpose of the studies presented in the article was to determine the effectiveness of the use of energy routers (ER) in railway power supply systems to increase the uninterrupted power supply to non-traction consumers, reduce unbalance and nonsinusoidality, and reduce voltage dips in emergency modes. The research was carried out by means of computer modeling using the Matlab software system based on the developed models of power supply systems (PSS) equipped with ER with energy storage devices. The results obtained show that in standard circuits of PSS for linear consumers with short circuits in the supply network, voltage dips occur, the depth of which reaches 100%. The use of an ER and an energy storage device connected to DC buses allows maintaining voltage at consumer clamps near the nominal value in case of short circuits in the 10 kV feed line and 25 kV overhead contact system. The ER significantly limits the recharge of the short circuit location from the power storage. In addition, on the basis of the ER it is possible to provide the normative quality of electricity considering voltage deviations, asymmetry and harmonic distortions on the 0.4 kV buses of the substation that feeds non-traction consumers.

1. Introduction

In modern conditions, increased requirements for efficiency, quality of electric power and reliability of energy supply to consumers are imposed on power supply systems (PSS). It is possible to meet these requirements by upgrading PSS using smart grid (intellectual electric power supply network) technologies [1-5]. Smart grid networks allow one to implement a new generation of PSS, different from the existing ones by the following features:

- Uninterrupted and guaranteed supply of consumers with high quality electric power (EP);
- Flexible interaction of PSS segments through the use of active devices and smart controls;
- The availability of interfaces that connect EP storage devices and distributed generation (DG) plants that use, among other things, renewable sources.

A promising direction allowing the implementation of the listed properties consists in the use of energy routers (ER) [6-23], the central part of which are solid-state transformers (SST) [7, 8]. The ER can be classified as a cyber-physical system that provides management of energy flows, information exchange between active devices and electrical receivers, and integration of energy storage devices (ESD) and DG plants into PSS. The most significant effect of the introduction of ER equipped with ESD is a significant increase in the reliability of electric power supply in emergency and post-emergency PSS modes. In addition, it is necessary to note the possibilities of ER to improve the electric power quality, which is especially important for the power supply system of rail transport.

On the railway tracks there are transport facilities, which in terms of the degree of uninterrupted electricity supply belong to a special group and impose increased requirements for the continuity of electricity supply and the quality of the electric power supplied [24]. These consumers include telecommunications facilities, as well as signaling and interlocking arrangements (SIA). The safety of these trains depends on the reliable operation of such facilities.
Below are the results of a simulation of power supply system modes designed to supply power to these facilities and the energy supply organization (ESO) connected to the network through an ER.

2. Energy router structure
The central link of the ER, which connects to medium voltage networks of 6-10 kV and can be used in PSS of telecommunication facilities or signaling and interlocking arrangements, is a solid-state transformer (Figure 1). This device is usually made in a single-unit design and includes the following segments: high-frequency power transformer; two active bridges made on the elements of power electronics.

The following positive results are achieved by having DC buses and high-frequency voltage conversions:
- the size and weight of the power transformer is significantly reduced;
- it is possible to connect DC- and AC-powered electric receivers, as well as storage devices in the form of accumulator batteries;
- an interface is formed to connect DG plants implemented on the bases of synchronous and asynchronous machines, DC generators, photovoltaic panels, and fuel cells.

3. Simulation results
To assess the effectiveness of the use of energy routers to organize highly reliable power supply for linear consumers of a special group, which include telecommunications facilities, as well as signalling and interlocking arrangements, modeling of normal and emergency modes was performed. The electricity system under study (Figure 2) included a traction substation, fragments of the overhead contact system, a 10 kV power transmission line mounted on separate supports, to which a linear consumer was connected through a 10/0.4 kV transformer to a specific group of the first category. The simulation was done with the Simulink and SimPowerSystems packages of the MATLAB system. The diagram of the developed computer model of energy router is shown in Figure 3.

When simulating the ER, a high-frequency 10/0.4 kV transformer with a capacity of 3000 kVA was used. The consumers' load on 0.4 kV buses was 1 + j0.5 MVA. The simulation compared the quality of electricity in the PSS using an ER and a standard power transformer of the same power.

Figure 1. Energy router: (a) – power supply scheme with an energy router; (b) – a diagram of a router built on the basis of a solid-state transformer (SST).

Figure 2. Power supply diagram of a linear consumer through an ER.
As a result of the simulation, it was found that when the ER is switched on without a high harmonics filter, there are significant harmonic distortions in the 10 kV network on the high voltage side compared to the situation in which the standard transformer was considered: voltage harmonics ratios increase by about 3...4 times. This is due to the fact that a power router equipped with sophisticated power electronics generates additional odd harmonics into the network. The use of a passive filter on the 10 kV side allows one not to pass through these harmonics into the network. The results of the measurement of electric power quality indicators (EPQIs) on 10 kV TP buses, the receiving end of the 10 kV line and on 0.4 kV buses are presented in the table 1, and the corresponding time dependences of voltages – in Figures 4 and 5.

| A method of connecting consumers of signaling and interlocking arrangement | Electric power quality indicators measuring place | Voltage harmonic coefficients, % | Voltage unbalance ratio in reverse sequence, % |
|-----------------------------|-----------------------------------------------|----------------------------------|-----------------------------------------------|
| Through a standard power transformer | 10 kV TP buses | $k_{u1}$ | $k_{u2}$ | $k_{u3}$ | $k_{2U}$ |
| 25 km of 10 kV after power transmission line | 5.9 | 6.1 | 4.3 | 5.2 |
| On 0.4 kV buses | 5.4 | 5.5 | 4.01 | 5.2 |
| Through ER with harmonic filter | 10 kV TP buses | 6.6 | 6.6 | 4.5 | 5.3 |
| 25 km of 10 kV after power transmission line | 3.3 | 6.8 | 5.4 | 5.5 |
| On 0.4 kV buses | 0.2 | 0.2 | 0.2 | 0.03 |

Figure 3. Schematic diagram of an ER model equipped with an energy storage.

Figure 4. Time dependences of voltages on 10 kV TP buses.
The results of computer modeling led to the following conclusions:

- to eliminate a decrease in the electric power quality in the supply network according to the criterion of sinusoidal voltage and current curves when using an ER, it is necessary to use harmonic filters;
- The use of an ER allows one to solve the problem of low quality of electric power in the network of 0.4 kV consumers, completely eliminating voltage unbalance and harmonic distortion.

With the help of an ER, one can connect power storage devices to the DC network without the use of additional equipment. In the experiments, we used a model of the ESD, operating on the basis of lithium-ion batteries, with a control system that monitors the consumers' voltage in order to connect the ESD when the power drops and turn it off if the set value is exceeded.

Below are the results of simulations of emergency modes caused by three-phase short circuits (SC) on 10 kV TP buses, the receiving end of the 10 kV line and the SC of the contact wire on the rail in the 25 kV network. Voltage dips with 0.4 kV consumers were investigated for the following situations: 1) a standard PSS without an ESD; 2) a standard PSS with an ESD; 3) a standard PSS with an ER without an ESD; 4) a standard PSS with an ER and with an ESD.

For situation 2, the ESD was connected through an inverter on 0.4 kV buses. The simulation results are shown in Figures 6-8 in the form of time dependences of voltages on 0.4 kV buses of a non-traction consumer (telecommunications facility or signaling and interlocking arrangement).

The simulation results of emergency modes made it possible to formulate the following conclusions:

- In a standard PSS designed to in-feed telecommunications facilities or signaling and interlocking arrangements, in the considered emergency modes significant voltage dips are observed (Figures 6-8), the depth of which reaches 100% of the nominal;
- The use of ESD in such circuits, connected through an inverter on the 0.4 kV side of the standard power energy storage, makes it possible to reduce the voltage dip by an average of 60% (Figures 6-8). However, in this case, there is a large recharge of the damage area with current from the ESD. The corresponding time dependences of the currents flowing on the 10 kV side of the feeder transformer are shown in Figure 9, a.
- The ER allows reducing the voltage dip up to 20% of the nominal value due to the presence of rectifiers, inverters and LC filters. The use of a ER and a controlled ESD connected to the DC buses allows maintaining the voltage close to the nominal value of the consumers in all the considered emergency modes; in this case, the feeding of the damage area by the current from the ESD is significantly limited. The corresponding time dependences of the currents flowing on the 10 kV side of the ER are shown in Figure 9, b.
Figure 6. Time dependences of the RMS voltage values on the 0.4 kV buses: (a) – at a three-phase SC at the receiving end of a 10 kV line 25 km long; (b) – with three-phase SC on 10 kV TP buses; (c) – in case of a SC in a 25 kV contact network; 1 – a standard transformer without an ESD; 2 – a standard transformer with an ESD; 3 – an ER without an ESD; 4 – an ER with an ESD.

Figure 7. Currents flowing on the 10 kV side of the transformer with a SC at the receiving end of the 10 kV line: (a) – a standard 10/0.4 kV transformer was used; (b) – an ER was used.

4. Conclusion
An energy router built on the basis of an SST with a double active bridge can be used to form reliable power supply systems for critical non-traction consumers, which include telecommunication facilities and signaling and interlocking arrangements. This approach allows one to get high electric power quality indicators on the buses of the consumer's 0.4 kV substation by voltage deviations, unbalance \( k_u = 0.03\% \) and harmonic distortions \( k_h = 0.2 \% \). In emergency modes caused by short circuits on the power transmission line or in the overhead contact system, the power supply system, equipped with an energy router with an energy storage, makes it possible to eliminate voltage dips on 0.4 kV buses.

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