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Reactive Power Compensation for Non-Traction Railway Consumers

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Summary

This paper deals with the problems of power supply efficiency for non-traction railway customers. Unlike public distribution networks, the non-traction power supply network is within the zone of influence of electromagnetic fields and the conductive influence of the distorted traction current. As a result, poor power quality and additional losses are typical for non-traction railway networks. Subsequently, conflicts due to the low quality of electricity may arise between the railway and its customers powered by the distribution networks of the railway. The influence of a reactive power compensation device on the voltage drop in a non-traction power line is investigated in the article. The implementation of reactive power compensation allows voltage losses during its transmission to the final consumer to be reduced by almost 5% and electricity losses by 3%.

Keywords: non-traction consumer, power factor corrector, reactive power compensator, graph of electric network, nodal analysis

1. Introduction

Improving the energy efficiency of the railway technological processes is an urgent problem for many countries, especially in states with a deficit of their own energy resources. A known way to solve this problem is to integrate power factor correction devices into the power supply networks of non-traction consumers. The issue of reactive power compensation is given considerable attention in the modern power industry. In particular, this is typical for the power supply system in countries which have fast-growing economies, such as China, India and Southeast Asia. The modernization of electrical networks is stimulated by the development of industry in such countries. A popular area of modernization is the introduction of reactive power compensation.

Recently, more scientific studies have been published by scientists from these countries, which are devoted to issues of increasing the power factor or tasks related to reactive power. For example, in [1], the author describes various aspects of increasing the power factor in industrial enterprises in India. It is proposed to use batteries of static capacitors connected as fixed shunt capacitor banks to a line voltage of 34.5 kV and a reactive power equal 3600 kvar. The author described the general method of determining the required power of the compensating device and studied the effect of the installed compensating device on the energy losses in the enterprise power grid.

Technical solutions for reactive power compensation at a substation in Myanmar are described in [13]. The algorithm of step regulation of reactive power that was developed based on the schedule of electric loading of the substation was presented in the publication. A 230 kV busbar was selected to connect the compensating device; with total power of the compensating device being 60 Mvar.

The issues of reactive power compensation in low-voltage networks are considered in [11]. Power factor dynamic correction was proposed, which was based on monitoring the reactive power flow in the grid and the corresponding adjustment of compensating devices to increase the power factor of individual consumers. The issue of ensuring electromagnetic compatibility when using technologies of dynamic or active adjustment of the power factor is covered in another publication [9]. A more comprehensive overview of reactive power correction methods in low-voltage sources is presented in [10], with the characteristics

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of methods being considered and basic recommendations for specific conditions provided.

At the same time, the problem of reactive power compensation in the electrical networks of the most economically developed countries in Europe and North America is also relevant. Reactive power compensation devices with automatic regulation are an integral part of smart grid systems and are produced by leading electrical concerns [4].

Photo-voltaic (PV) systems are mentioned in scientific publications as sources of power for non-traction loads [5, 12]. Solar panels installed on the roofs of train stations and depots are a way to reduce dependence on external networks. In addition, there have been several proposals [2, 14], where it was proposed to use inverters of the photo-voltaic system to compensate for reactive power in distribution systems in recent years.

Note that most scientific publications do not take into account the specifics of the structure and features of the loads of non-traction railway networks. Accordingly, the obtained scientific results may be used to determine rational ways of integrating compensating devices to non-traction power grids of railways, but not in all cases.

2. Problem formulation

In Ukraine, traction substations of railway transport are designed to supply power to non-traction consumers that are non-railway consumers. This situation is typical of electrified railways in post-soviet states. About only half of the input electricity turns into traction, and the rest is used by non-traction consumers on Ukraine railways [17]. At the same time, the issue of implementing compensating devices is actually at the initial stage of implementation. In the vast majority of areas of electrical networks, compensating devices are completely absent. As a comparison, during 2015 and 2016 the Polish railway company PKP Polskie Linie Kolejowe S.A. installed 164 and 70 reactive power compensation devices, respectively [6, 7], with a total length of non-traction power supply lines of 751 km [8].

In our opinion, the lag of Ukrainian railways in this matter can be overcome only by the gradual integration of power factor correction devices to non-traction power grids. At the same time, there is the problem of rational connection places of these means and economically expedient volumes of reactive power compensation. We propose to solve this problem in two stages. First, the main electrical indicators of operation should be determined for different variants of the location of the compensating device or devices by mathematical modeling. Then, based on the method of expert assessments, a decision about the most rational configuration of the location of compensating devices in the network can be made. Options are compared according to the following requirements:

1. Changing the supply voltage in accordance with [18];
2. Providing the necessary electrical power in case of a need to connect new consumers by unloading network equipment from reactive power flows;
3. Achieving the maximum integrated economic effect during the first 8 years of operation of the compensating device [19].

3. The structure of the electrical network

The scheme is typical for the areas of power supply of non-traction consumers of the railways in Ukraine with a voltage of 10 kV, as shown in Figures 1 and 2. In the article, the calculation results are given for the case of using a static compensator, but part of these results can be used as a basis for calculating the power of the inverter. The substation (TS-1) with a static compensator or with an invert (alternative) is shown in Fig. 1 too. It is advisable to use the node-voltage analysis of electrical circuits to create a model of extensive structure networks [12]. Thus, the overall network model is as follows:

$$\left[\underline{Y}\right]\left[\underline{U}_{\Delta}\right]=\left[\underline{J}\right] \quad (1)$$

where:
$\left[\underline{Y}\right]$ – the matrix of admittance,
$\left[\underline{U}_{\Delta}\right]$ – the voltage drop vector from each independent node to the base node,
$\left[\underline{J}\right]$ – the current node vector.

Then the voltage drops and currents in the lines can be derived from the following equations:

$$\left[\underline{U}_{B}\right]=\left[M\right]_{\mathrm{T}}\left[\underline{U}_{\Delta}\right] \quad (2)$$

$$\left[\underline{I}\right]=\left[\underline{Y}_{B}\right]\left[M\right]_{\mathrm{T}}\left[\underline{U}_{\Delta}\right] \quad (3)$$

where $[M]_{\mathrm{T}}$ – is the transposed incident matrix for nodes.

Power losses were determined in each line and network with expressions (4) and (5):

$$\Delta P_i = R_i \cdot I_i^2 \quad (4)$$

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \quad (5)$$

where:
R_i – the active resistance of the i-th line,
n – the number of power lines.

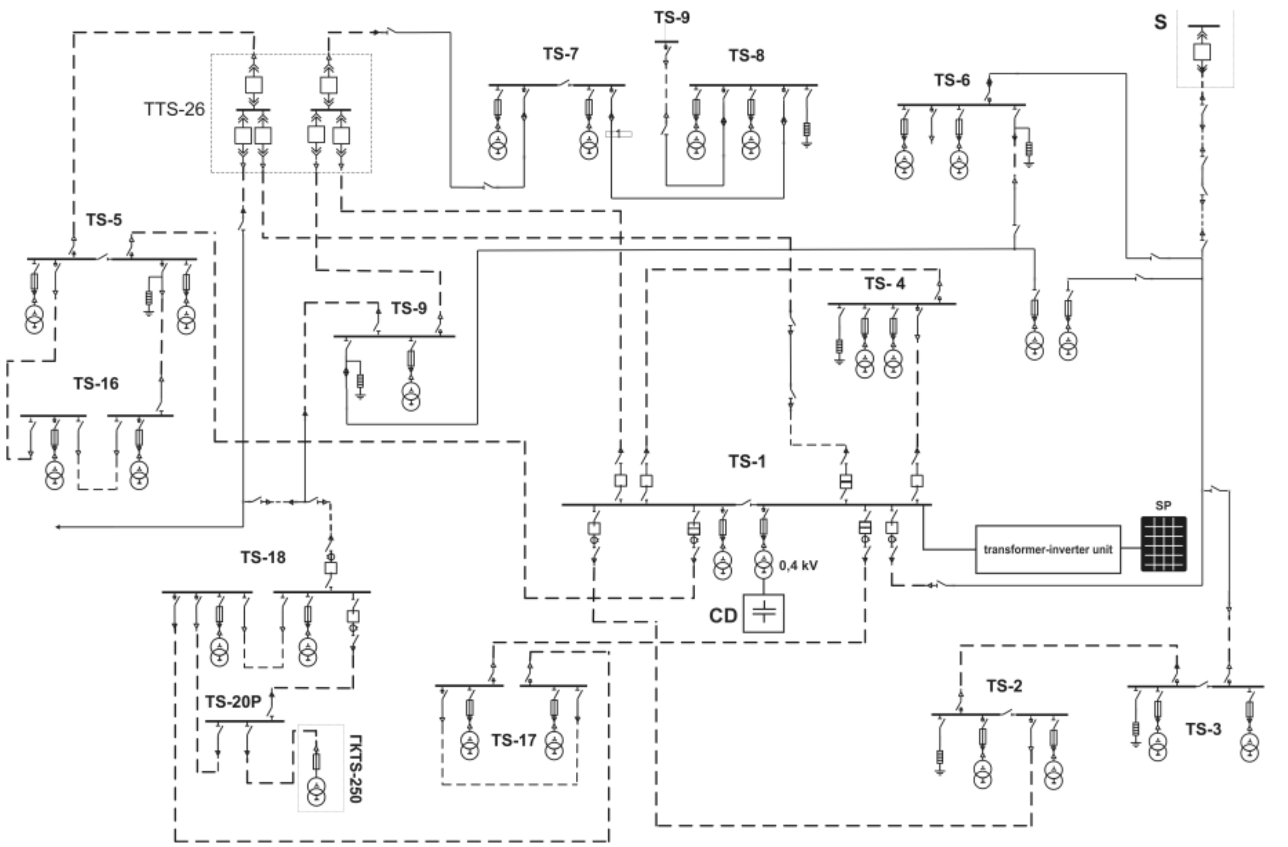

Fig. 1. Scheme of electric power supply network of non-traction consumers 10 kV: TTS – transformer traction subsection, TS – transformer subsection, S – power system, CD – compensating device, SP – solar panels [the author's own elaboration]

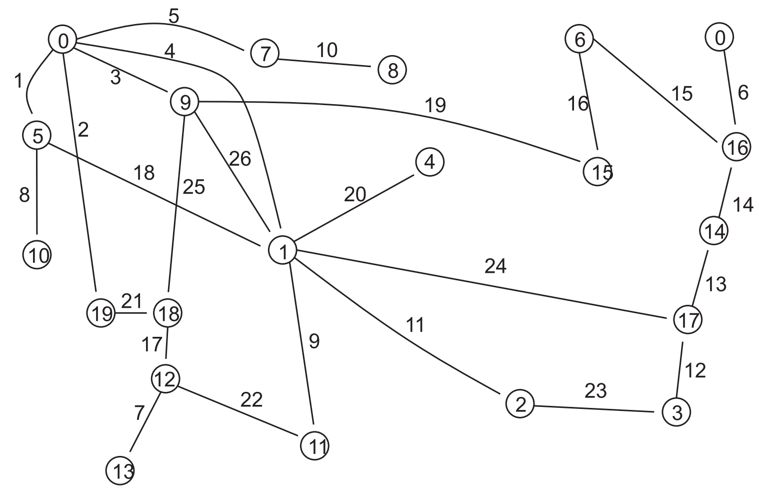

Fig. 2. Graph of the scheme of the electrical network in Fig. 1 [the author's own elaboration]

The theory of calculation is described in detail in [12]. Note that the installation of a compensating device is proposed in the 0.4 kV network because it reduces investment.

4. Determination of the optimal amount of reactive power compensation

The power of the compensating device is determined by the method in [19], where the power selection criterion is the maximum integrated effect after 8 years of operation of the compensating device. The criterion is determined by the formula:

$$IE_i = \sum_{i=1}^{8} \frac{(F_1 - F_2) + W_t \cdot c - W_{cd} \cdot c - B}{(1+E)^{\text{з}}} - In \qquad (6)$$

where:

i – the year of the cash flow,

F_1 – the annual fee for the flow of reactive power without compensation, USD,

F_2 – the annual fee for the flow of reactive power with compensation, USD,
W_t – the change of active power losses in the transformer with compensation, kWh,
c – the electricity tariff, USD/kWh,
W_{cd} – the annual loss of electric energy in the compensating device, USD,
B – the annual maintenance and repair cost of the compensating device, USD,
E – the discount rate of the National Bank of Ukraine, which is equal to 0.17,
In – is the cost of installing compensation, USD.

Annual and daily scheduled electrical loads (Fig. 3–6) of the substation were used for calculations.

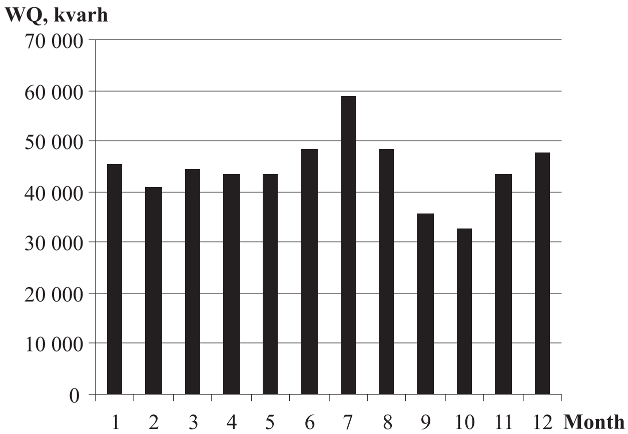

Fig. 4. Annual schedule of reactive electricity consumption by non-traction loads of the transformer substation [the author's own elaboration]

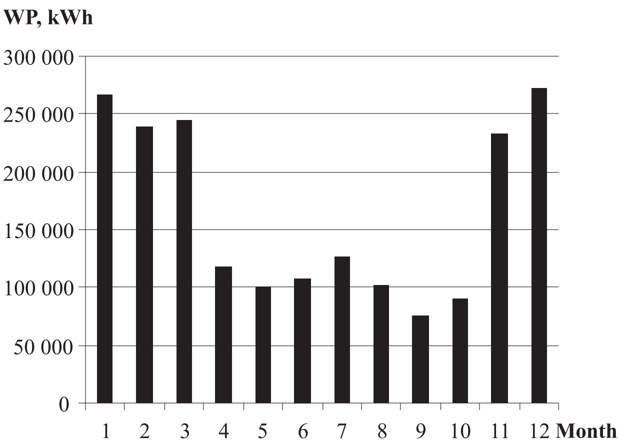

Fig. 3. Annual schedule of active electricity consumption by non-traction loads of the transformer substation [the author's own elaboration]

The following calculations were performed. The annual reactive power flow from the source to load is determined by the expression:

$$\Delta WQ_1 = WQ + \frac{i_\mu}{100} \cdot S_{pr} \cdot T_p + \left(\frac{WP}{T_p \cdot \cos(arctg(\varphi_1)) \cdot S_{pr}} \right)^2 \cdot \frac{U_k \cdot S_{pr} \cdot T_p}{100}, \quad (7)$$

where:
WQ – the consumption of reactive electricity per year, 533 Mvarh,
i_μ – the idling current, 2.3%,
U_k – the short-circuit voltage, 4.5%,
S_{pr} – the power rating, 250 kW,

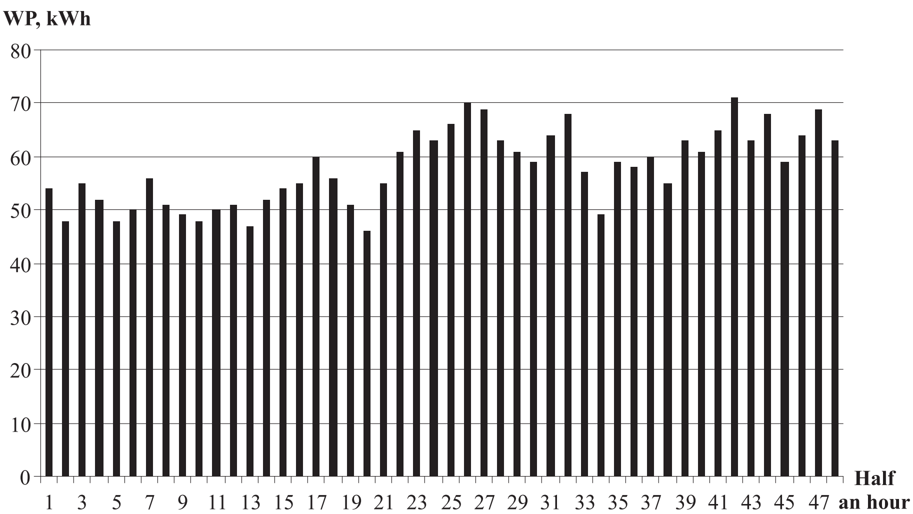

Fig. 5. Half-hour schedule of active electricity consumption by non-traction loads of the transformer substation daily [the author's own elaboration]

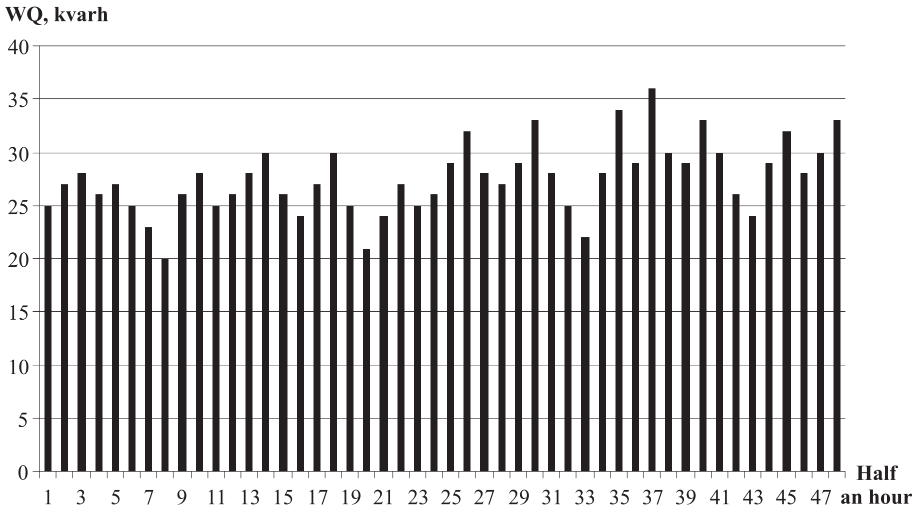

Fig. 6. Half-hour schedule of reactive electricity consumption by non-traction loads of the transformer substation daily [the author's own elaboration]

$cos(arctg(\varphi_1))$ – the power factor which is determined by the relationship WQ and WP,
T_p – length of the year in hours, 8760 hours.

After calculations, ΔWQ_1 is 619 124 kvarh.

Payment for the flow of reactive power without a compensator is determined by the expression:

$$F_1 = \Delta WQ_1 \cdot c \cdot k_{ep} \cdot (1 + 1{,}3 \cdot (k_\varphi - 1)), \quad (8)$$

where:
k_{ep} – a coefficient that depends on the power factor, 1.0004,
k_φ – the economic equivalent of $tg\varphi$, 0.05,
F_1 – value is 2638 USD at 0.085 USD/kWh.

The load on the transformer is:

$$S_1 = \sqrt{\left(\frac{WP}{T_p}\right)^2 + \left(\frac{WQ}{T_p}\right)^2} = 233 \quad \text{kVA}.$$

Annual losses of active electricity in the substation transformers in the absence of a compensating device:

$$\Delta W_{t1} = \Delta P_k \cdot \left(\frac{S_1}{S_{pr}}\right)^2 \cdot T_p + \Delta P_{ind} \cdot T_p, \quad (9)$$

where:
ΔP_k – the short circuit loss of the transformer, 3.7 kW,
ΔP_{ind} – the no-load loss of the transformer, 1.05 kW,

The calculation result is 37 429 kW.

Calculation for compensation devices with different power was performed. Calculation for the device with 50 kvar is shown as an example. The flow of reactive energy in the new conditions is calculated by the next formula:

$$\Delta WQ_2 = \left(WQ - Q_{cd} \cdot T_p\right) + \frac{i_\mu}{100} \cdot S_{pr} \cdot T_p + \\ + \left(\frac{WP}{T_p \cdot \cos(arctg(\varphi_2)) \cdot S_{pr}}\right)^2 \cdot \frac{U_k \cdot S_{pr} \cdot T_p}{100}. \quad (10)$$

The power factor is determined by the ratio $WQ–Q_{cd}T_p$ and WP. The calculated value of the power flow is 175 433 kvarh. The following calculation with $k_\varphi = 1$ gives the values:

$$F_2 = 747 \text{ USD},$$

$$\Delta W_{t1} = 35572 \text{ kW}.$$

Reduction of active power loss in the transformer:

$$\Delta W_t = \Delta W_{t1} - \Delta W_{t2} = 1857 \text{ kW}.$$

Annual loss of active electricity in the compensating device:

$$\Delta W_{cd} = (1 + 0{,}2) \cdot Q_{cd} \cdot 10^{-3} \cdot T_p = 525 \quad \text{kWh}. \quad (11)$$

The cost of the compensation device, the development of design documentation and installation of the device is 1 950 USD [20]. Two percent of this amount is the cost of operating the compensating device. The resulting values are used in (6) to calculate the integrated effect.

Based on the calculation, it has been established that it is advisable to install a compensating device with power equal to 50 kvar. The growth of the integrated effect through the introduction of compensating devices of different power is shown in Fig. 7. The payback period of the device with 50 kvar is less than a year, and the integrated effect after 8 years of operation is 6300 USD (Fig. 8).

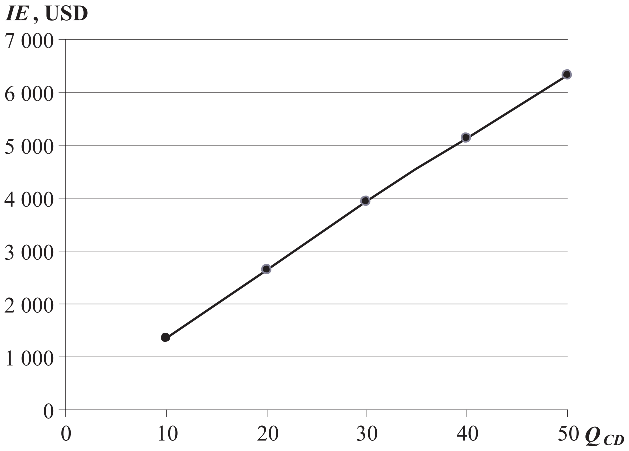

Fig. 7. The value of the predicted integrated effect depending on the power of the compensating device [the author's own elaboration]

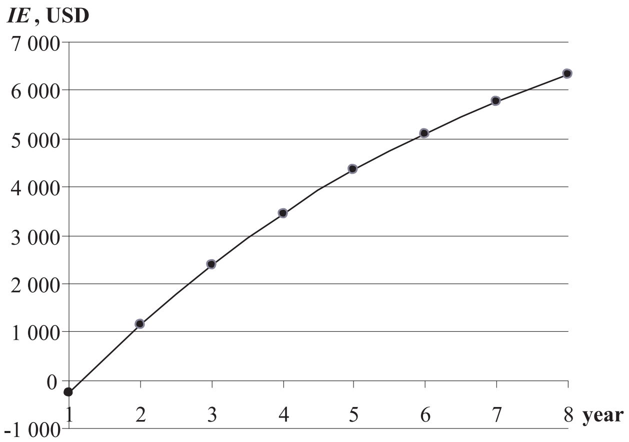

Fig. 8. The growth of the integrated effect over the years of operation of the compensating device capacity of 50 kvar [the author's own elaboration]

5. Influence of the compensating device on the voltage mode of consumers

Voltage loss in the supply line without a compensating device can be determined by a ratio [18]. The annual flow of reactive electricity from the power supply to load where U is rated mains voltage: R, X are active and reactive resistance of the supply line.

The average annual value of active power consumption:

$$P = \frac{WP}{T_p}. \quad (12)$$

The average annual value of reactive power flow:

$$Q = \frac{WQ}{T_p}. \quad (13)$$

Voltage loss in the supply line with a compensating device can be determined by the ratio:

$$\Delta U_2 = \frac{P \cdot R + (Q - Q_{cd}) \cdot X}{U} \quad (14)$$

where:
U_i – rated mains voltage,
R – active resistance,
X – reactive resistance,
Q_{cd} – rated power of the reactive power compensation device.

Reduction of voltage loss in the power line of the substation when using a compensating device:

$$\delta = \frac{\left|\Delta U_1 - \Delta U_2\right|}{\Delta U_1} \cdot 100\ \%. \quad (15)$$

The introduction of reactive power compensation allows voltage losses during its transmission to the final consumer to be reduced by almost 5%.

6. Conclusions

1. The introduction of a reactive power compensation device is a modern global trend that is inherent in the energy systems of both developed and developing countries. However, the problem of reactive power compensation for non-traction loads of railways has been insufficiently studied in Ukraine. A distributed reactive power compensation strategy is most appropriate in this situation because investment in compensating installations is quite significant. Therefore, a distributed reactive power compensation strategy is most appropriate in this situation because the investment in compensating installations is quite significant.
2. The required amount of reactive power and the power of the compensating device were determined

by the maximum integrated effect criterion. The introduction of reactive power compensation has reduced the voltage change by 5%, and reduced losses in the transformer by 1857 kWh during the year.

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