Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Economics, Management and Humanities

EXAMINATION OF ELECTRICAL ENERGY QUALITY OF GAS CONDENSATE FIELD

MASTER THESIS

Study Program: Electrical Engineering, Power Engineering and Management
Branch of study: Management of Power Engineering and Electrotechnics
Scientific Supervisor: Ing. Bc. Blanka Kučerková

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MASTER‘S THESIS ASSIGNMENT

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Examination of electrical energy quality of gas condensate field

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Examination of electrical energy quality of gas condensate field

Guidelines:

1. Describe electrical energy quality problem at gas condensate field and methods to improve it.
2. Analyze electrical energy quality parameters.
3. Propose measures to improve electrical energy quality for the analyzed network.
4. Evaluate economic efficiency of proposed improvements
5. Perform sensitivity analysis

Bibliography / sources:

1. GOST 32144-2013 Elektricheskaya energiya. Sovmestimost tekhnicheskikh sredstv elektromagnitnaya. Normy kachestva elektricheskoy energii v sistemakh elektrosnabzheniya obshchego naznacheniya, 2013.
2. BREALEY, R., MYERS, S., ALLEN, F. Principles of Corporate Finance, 12th ed. McGraw-Hill, 2016. ISBN:9781259253331

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I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

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Abstract

The purpose of this work is to assess the quality of electric energy (EE) of the gas condensate field and propose measures to improve it. The quality of EE is a set of its certain characteristics, at which the power receiver performs the required functions. The low quality of EE leads to a deterioration in the operating conditions of electrical equipment, significant losses in industry, technological and electromagnetic damage.

The object of study of this work is the quality of electrical energy of a drilling rig located at the Kazanskoye gas condensate field. The drilling rig is characterized by a sharply variable load schedule and a non-linear load, the main part of which is electric motors. To assess the quality of electrical energy, measurements were made of voltages, currents, active and reactive powers of the overhead line at the input to the drilling rig. The following parameters of EE quality were evaluated: steady-state voltage deviation, negative sequence voltage unbalance factor, zero sequence voltage unbalance factor. The analysis of losses of power and electric energy was carried out.

After evaluating the above parameters, the following problems were identified: a high negative sequence unbalance factor and the necessity for reactive power compensation. The high unbalance factor was due to a sharp drop in voltage on account of the operation of the overcurrent protection by reason of the connection of a new load. The solution was applied to recalculate short-circuit currents, select new high-voltage circuit breakers and recalculate relay protection settings. To compensate the reactive power, it was proposed to use a capacitor unit with harmonic filters. The proposed measures effectively reduce power and electrical energy losses and, as a result, the bills for the electrical energy, increase the service life of electrical equipment. An economic evaluation of the proposed measures was carried out.

Key words

Electrical energy quality, voltage deviation, voltage unbalance, reactive power compensation, relay protection, energy savings, net present value, equivalent annual annuity, sensitivity analysis.

Contents

List of abbreviations

Abbreviation	**Russian**	**English**
AC		Alternating current
AFCD		Active filter-compensating devices
CAPM		Capital asset pricing model
CC		Current cutoff
DC		Direct current
EAA		Equivalent annual annuity
EE		Electrical energy
FCD		Filter compensating device
GOST	Gosudarstvennyy standart	Russian technical standard
NPV		Net present value
SM		Synchronous machine
SC		Short circuit
OCP		Overcurrent protection

Introduction

Electrical energy (EE) is the main type of energy used in gas condensate fields. Basically, EE is transmitted to the consumer through electric networks from distribution grid companies or autonomous power plants for their own needs. The supplied EE must comply with the requirements of GOST 32144-2013, which prescribes the norms and parameters of EE quality in electrical networks of general-purpose power supply systems of three-phase and single-phase alternating current with a frequency of 50 Hz at points to which electrical networks located in property of various gas condensate enterprises [1].

The quality of work of distribution systems has a direct impact on the technological process of the consumer of the country, so the main task of power supply to the consumer is providing the consumer with EE uninterruptedly in the right amount and quality.

In this work, EE quality of a drilling rig, which is part of the Kazanskoye gas condensate field, is investigated. Electric drives of drilling rigs are characterized by intense and difficult operating conditions (climatic and mechanical influences, remoteness of service bases). At the same time, drilling rigs are subject to high requirements for uninterrupted operation, since equipment shutdowns can lead to accidents in the well and large economic losses. Drilling rigs are often characterized by the following problems: low power factor, increased distortion of the sinusoidality of the voltage curve, voltage drop when powered from a relatively weak line, voltage unbalance [4]. Therefore, normal operation of the drilling rig is difficult unless special measures are taken.

Thus, the purpose of this work is to assess the quality of EE of the gas condensate field and develop measures to improve it.

The following tasks have been set:

1. Describe electrical energy quality problems at gas condensate field and methods to improve it.
2. Analyze electrical energy quality parameters.
3. Propose measures to improve electrical energy quality for the analyzed network.
4. Evaluate economic efficiency of proposed investments.
5. Perform sensitivity analysis.

1. Potential electrical energy quality problems for the gas condensate field and solutions

The purpose of this chapter is to provide an overview of potential electrical energy quality problems for the gas condensate fields and suggest ways to solve them.

Electrical energy (EE) is the main type of energy used in oil and gas production enterprises. EE is mainly transmitted to the consumer via power grids from distribution grid companies or autonomous auxiliary power plants. The quality of electrical energy is the degree to which the characteristics of electrical energy comply with the set of standardized EE quality parameters at a given point of the electrical system. The electrical energy quality parameters include: voltage deviation, voltage fluctuation, voltage non-sinusoidal voltage, voltage unbalance of the three-phase system, frequency deviation, random events, which can be represented as electromagnetic interference [1].

Supplied electrical energy must comply with the requirements of GOST 32144-2013 (Russian technical standard on quality norms for electrical energy in power supply systems) [1]. Non-compliance with the requirements leads to deterioration of operating conditions of electrical equipment, significant losses in the industry, technological and electromagnetic damage.

EE consumers of gas condensate field are subdivided into drilling rigs, direct oil production mechanisms, pumping units, gas collection and pumping facilities, gas treatment facilities, gas compressor stations, and formation pressure maintenance facilities at gas condensate fields. In this work, measurements of the EE quality parameters at the inlet of the drilling rig are used as initial data, so I will consider more specifically the equipment of the drilling rig.

The drilling rig consists of main and auxiliary electrical equipment. The main equipment includes winch, rotor and mud pump, the auxiliary equipment - compressed air compressors, crane beam, water pump, automatic lowering, and lifting device. The drilling rig consumes active power depending on the operating mode, hardness of the drilled rock, length, and weight of the drill pipes. Often its load schedule has a sharp character for a long period of operation (10-15 days) [2].

The most common problems are voltage dips and distortions of current and voltage sinusoidal curves due to the significant length of the networks, uneven load distribution along long lines and wide introduction of non-linear consumers in distribution networks. A possible solution to these problems is influence limitation of starting modes of the main drives of the drilling rig. It can be achieved by compensation of voltage loss by using of booster transformers or using starting control devices, for example, frequency converters or thyristor starting devices [3].

Electric drives of drilling rigs are characterized by intense operating modes and harsh operating conditions (climatic and mechanical influences, comparable power of power supplies, remoteness of service bases, etc.). At the same time, rigs are subject to high requirements for uninterrupted operation, since equipment shutdowns can lead to accidents in the well and large economic losses. For thyristor electric drive, the following problems are typical: low power factor (0.5-0.6), an increase in the distortion of the sinusoidality of the voltage waveform (voltage harmonic component of the voltage may exceed 20%), decrease in voltage when it is supplied from a relatively weak line (voltage deviation can reach 15-20% at the bushing of the drilling rig). Consequently, the operation of the drilling rig is difficult in normal mode without special measures. For example, the solution can be the use of filter compensating devices [4].

DC valve drives (as part of drilling rigs), receiving energy from a power source whose power is comparable to the power of electric drives, often become the reasons for the deterioration of EE quality. They cause a decrease in the power factor, deviation of the mains voltage from the nominal, distortion of the sinusoidal voltage waveform. As a result, this leads to energy losses, insulation aging and equipment service life is shortened. To eliminate the described problems, filter compensating devices are also used [4].

To improve EE quality and reduce losses, there are the following ways to eliminate the asymmetry of three-phase currents and voltages: transverse compensation of reactive power, the use of closed and semi-closed circuits, equalization of single-phase loads in the phases of a three-phase network [5].

To reduce the voltage deviation, voltage regulation in the power center is used, for example, by changing the transformation ratios, changing the longitudinal and transverse components of the voltage drop due to the regulation of reactive power flows in the supply, and distribution lines using compensation devices. Another method is local regulation using controlled reactive power sources [5].

Thus, the main problems of the quality of electrical energy at the gas condensate field and the solutions were considered. In the next chapter, I will analyze the initial data.

2. Description of initial data

In this chapter, I will describe the supply of a gas condensate field and analyze the initial data - measurements of parameters of electrical energy quality.

Kazanskoye gas condensate field belongs to Tomskgazprom company and is located 325 km northwest of Tomsk (Parabelsky region, Russia) [6]. The Parabelsky region is characterized by a flat relief, the climate is continental-cyclonic, severe and heterogeneous due to its long length (about 450 m), the average annual temperature ranges from 1.4 ºC in the south-west and up to 2.8 ºC in the northeast [7].

The gas condensate field is powered by gas turbine units and automated diesel power plants. The field consists of four 35 kV substations - "Bolotnoye", "BKNS-2", "Energokompleks-2", and "Kazanskaya", which transmit power to 6 kV indoor switchgears and then to transformer substations of oil clusters. In this work, I study electrical energy quality of drilling rig as a part of the cluster No. 39, which receives power from indoor switchgears of "Energokompleks-2" by overhead line.

According to the electrical scheme of the drilling rig, its power supply is carried out by a 6 kV overhead line (self-supporting insulated conductor with cross section of 95 mm^2). A reserve power supply is provided - a diesel power plant with a capacity of 200 kW at 0.4 kV. The drilling rig complex consists of two 6 kV synchronous motors, designed for winch and pump drives and started by soft starters, automatic reactive power compensation capacitor unit, accumulator batteries, and a step-down transformer. Equipment is protected by circuit breakers and voltage suppressors. Converted voltage from transformer is transmitted to power distribution cabinets and control cabinets, the main electrical consumers of which are electric motors. To protect the electrical receivers, circuit breakers are provided against short-circuit currents and modular contactors against overloads.

Parameters of electrical energy quality can be obtained using recording devices that register changes in the corresponding parameter over time [8]. Measurements of quality parameters of the electrical energy transmitted through the overhead line were carried out at the input of the drilling rig and were provided by Tomskgazprom company for analysis.

The following initial data will be used for calculations: values of frequency, line voltages and phase currents, and average values of active and reactive powers. For convenience, the numerical values of the parameters are converted into the dependencies presented in Figure 1-5 below.

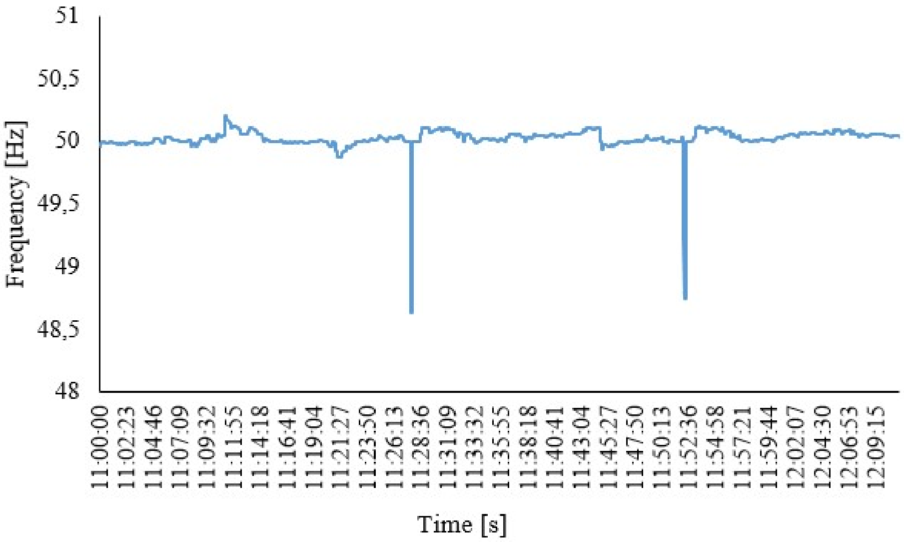

Figure 1. Graph of frequency change over time, based on initial data [9]

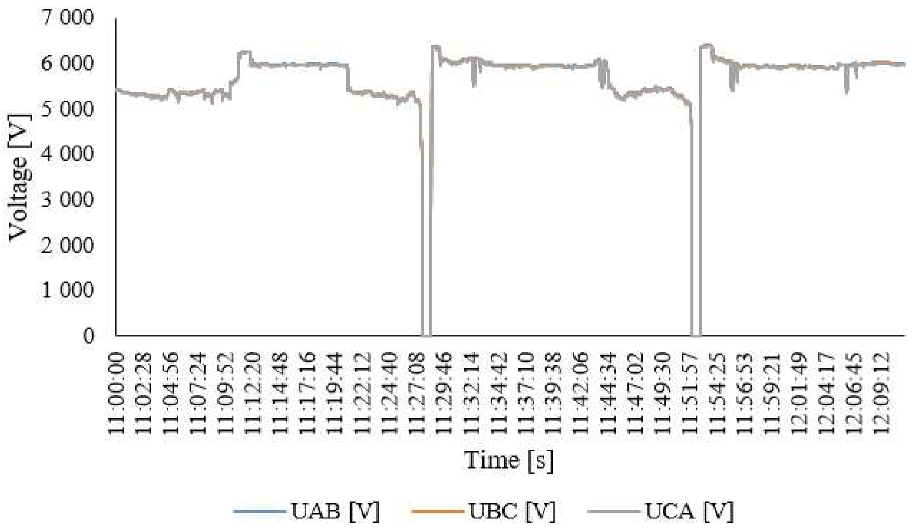

Figure 2. Graph of line voltages over time, based on initial data [9]

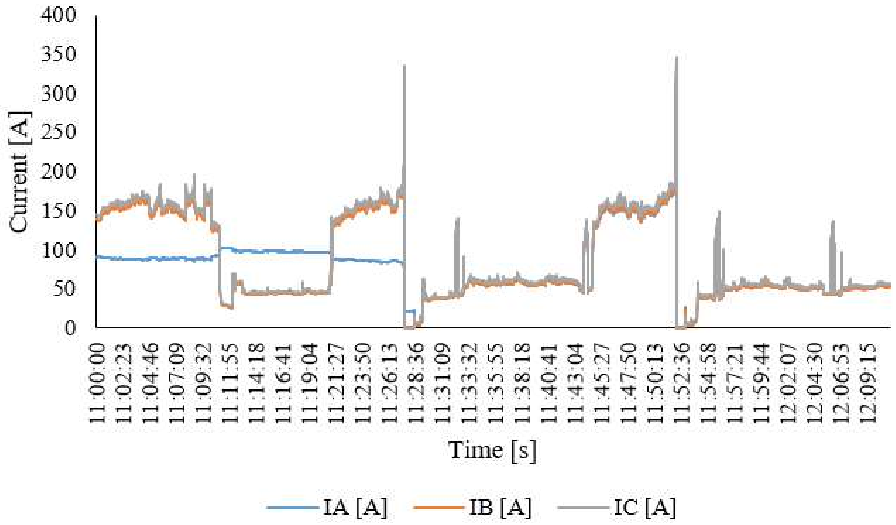

Figure 3. Graph of phase currents over time, based on initial data [9]

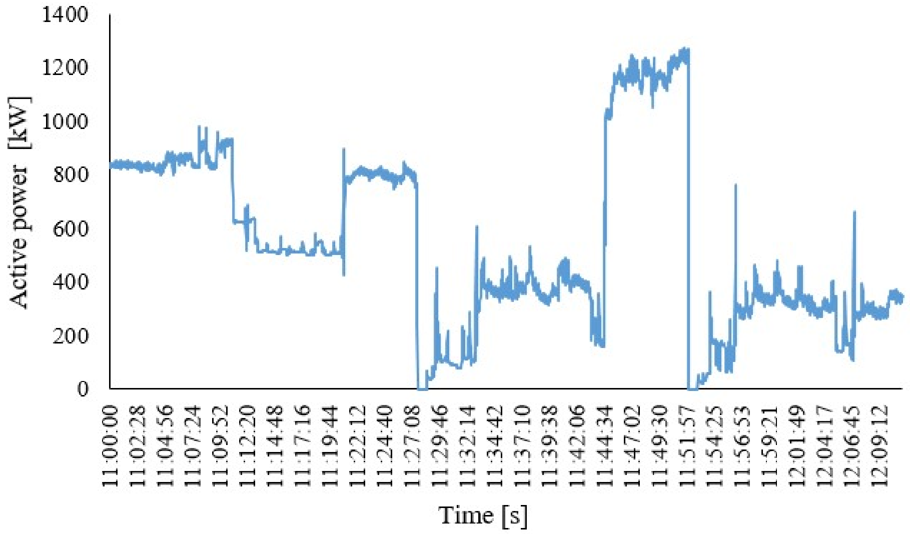

Figure 4. Graph of active power consumption over time, based on initial data [9]

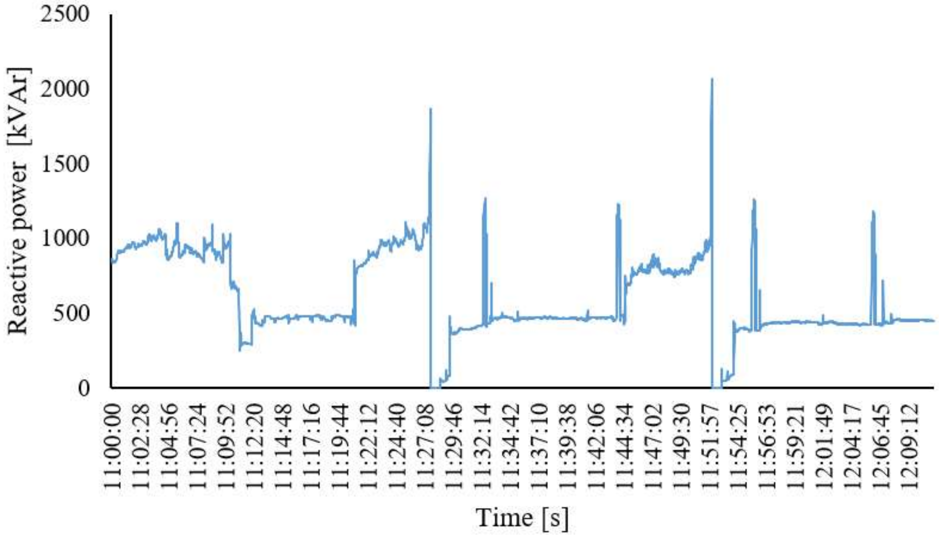

Figure 5. Graph of active power consumption over time, based on initial data [9]

From the obtained dependences, a sharp drop in voltage is observed at certain points in time. The reason can be the connection of additional consumers, as a result of which an overload occurs in the network. Consequently, the current increases and slightly exceeds the setting of relay protection, then the maximum current protection is triggered. Such shutdowns lead to voltage dips and thus distort the quality of the electrical energy. In this case, it can be recommended recalculation of short-circuit currents and selection of new relay protection settings to eliminate voltage dips.

2.1. Selection of power transformer

Low quality of electrical energy causes additional losses in the transformer windings, which lead to an increase in overall temperature and local overheating. As a result, the service life of the insulation is reduced [10]. To assess the losses of power and electrical energy in a transformer caused by low quality of EE, it is necessary to know its passport data. Due to the fact that these data are unknown, it was decided to select the transformer based on the total load of drilling rig.

The selection of the transformer is based on the formulas 2.1-2.2 according to [11].

The power of the transformer can be found by the formula:

$$S_{rated} = \frac{S_{calc}}{\beta} = \frac{2\ 309.79}{0.7} = 3\ 300\ [kVA], \tag{2.1}$$

where S_{calc} – the full calculated power of the enterprise on the high voltage side, [kVA]; $\beta = 0.7$ – the load factor of the transformer.

Based on the calculated power of the transformer I chose a transformer type TMN with rated power S_{rated} =4000 kVA. Checking the selected transformer to ensure the required power, taking into account the possible permissible overload of the transformer:

$$S_{calc} < 1.4 \cdot S_{rated}, \tag{2.2}$$

$$3\,300\ [kVA] < 1.4 \cdot 4\,000 = 5\,600\ [kVA].$$

Power transformer TMN 4000/35 has been tested. Its passport data are shown in the Table 1.

Table 1. Passport data of the TMN 4000/35 transformer [12]

Rated power [MVA]	Losses [kW]		Off-load current [%]	Short-circuit voltage [%]	Resistance [Ohm]	
	Off-load	Short circuit			Active	Reactive
4	6.7	33.5	1	7.5	2.6	23

3. Analysis of power and electrical energy losses in the 6 kV distribution grid

This chapter is dedicated to the analysis of the power and electrical energy losses in the distribution grid for the voltage level of 6 kV that are caused by the transmission of electrical energy to the end consumers.

According to [13], the power and electrical energy losses in each element of electrical networks can be calculated by one of two methods, depending on the information availability: the method of operational calculations and the method of average loads. According to [13], the method of operational calculations is more accurate than the method of average loads. However, most enterprises engaged in the sale of electrical and thermal energy to consumers prefer to use the method of average loads (for example AO «Tomskenergosbyt» company [27]). So, it is possible to apply the result of calculating by any method. I will use the method of average loads in this work. It is necessary to know the daily load graph as shown in Figures 6-7 for calculation of power and EE losses.

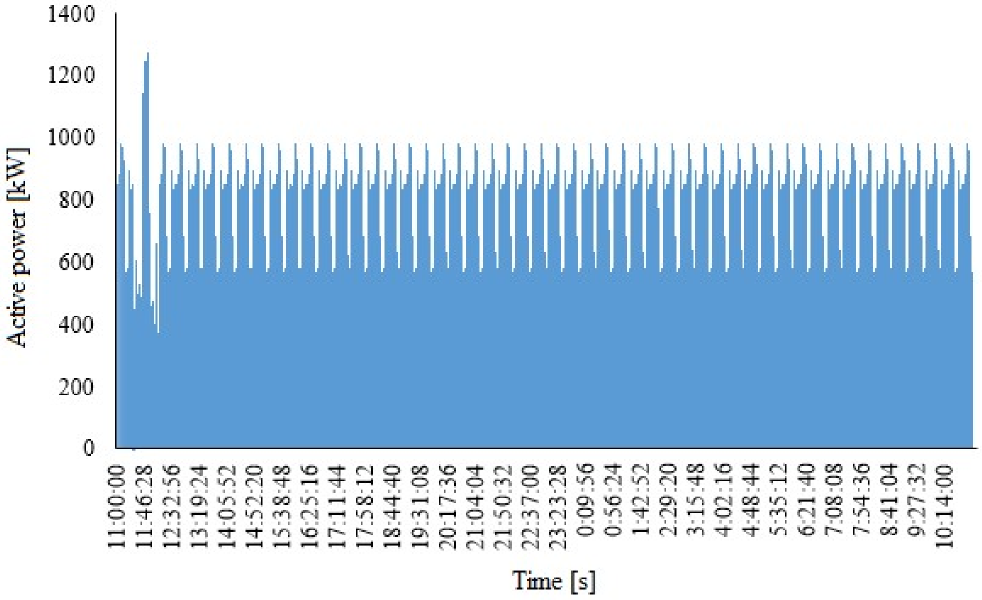

Figure 6. The daily load graph of active power [9]

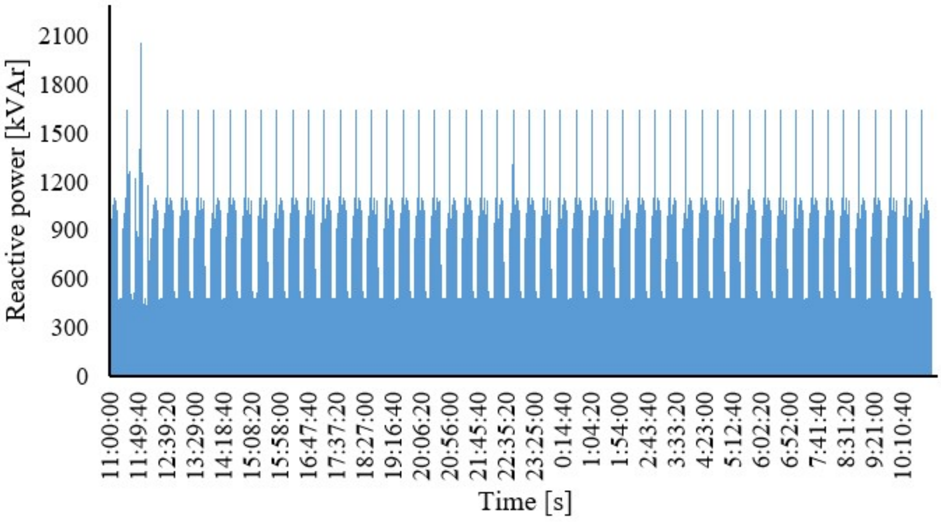

Figure 7. The daily load graph of reactive power [9]

I can calculate the losses of electrical energy and power in an overhead line of 6 kV and a power transformer, using the formulas presented in [13].

- **Calculation of losses of electrical energy in overhead line**

Firstly, it is necessary to calculate the average current transmitted through the overhead line:

$$I_{av} = \frac{\sum_{i=1}^{n} I_i}{n} = \frac{(114.86 + 115.524 + \cdots + 65.99)}{86400} = 99.95\ [A], \tag{3.1}$$

where I_i – the current for i-th moment of time, [A], n – the total number of measurements.

Average active power losses

$$\Delta P_{av} = 3 \cdot R \cdot I_{av}^2 \cdot 10^{-3} = 3 \cdot 0.028 \cdot 99.95^2 \cdot 10^{-3} = 0.84\ [kW], \tag{3.2}$$

where R – the active resistance of a 6 kV overhead line, [Ohm].

Load curve shape factor is equal to:

$$k_{c.s.} = \frac{\sqrt{(\sum_{i=1}^{n} P_i{}^2 \cdot \Delta t_i)/86\,400}}{(\sum_{i=1}^{n} P_i \cdot \Delta t_i)/86\,400} = \frac{\sqrt{0.99}}{0.9} = 1.1, \tag{3.3}$$

where P_i – the active power for i-th moment of time Δt_i, [kW].

Then losses of electrical energy can be found as:

$$\Delta W_{av} = k_k \cdot \Delta P_{av} \cdot T_{year} \cdot k_{c.s.}{}^2 = 0.99 \cdot 0.84 \cdot 8\,760 \cdot 1.1^2 =$$

$$= 8\,814.63\ [kW \cdot h], \tag{3.4}$$

where k_k – coefficient taking into account the difference in the configurations of the graphs of active and reactive load, T_{year} – the number of hours per year, [h].

- **Calculation of losses of electrical energy in transformer**

Transformer load factor is at average load:

$$\beta_{av} = \frac{S_{av}}{n \cdot S_{rat.tr.}} = \frac{1\,038.719}{4\,000} = 0.26, \tag{3.5}$$

where S_{av} – the total average power, [kVA], n – the number of transformers, $S_{rat.tr.}$ – the rated power of transformer, [kVA].

Losses of electrical energy for the year are equal to:

$$\Delta W_{av.year} = n \cdot \Delta P_{off-load} \cdot T_{year} + n \cdot k_k \cdot k_{c.s.}{}^2 \cdot \Delta P_{sh.c.} \cdot \beta_{av}{}^2 \cdot \tau_{max} =$$

$$= 6.7 \cdot 8\,760 + 0.99 \cdot 1.1^2 \cdot 33.5 \cdot 0.26^2 \cdot 3\,336.05 = 67\,719.64\ [kW \cdot h], \tag{3.6}$$

where n – the number of transformers,
$\Delta P_{off-load}$ – off-load losses, [kW],
T_{year} – the number of hours per year, [h],
$\Delta P_{sh.c.}$ – short-circuit losses, [kW],
k_k – coefficient taking into account the difference in the configurations of the graphs of active and reactive load,
$k_{c.s.}$ – load curve shape factor,

T_{max} – the number of hours of use of the maximum load can be found as:

$$T_{max} = \frac{W_{year}}{P_{max}} = \frac{P_i \cdot t_i \cdot 365}{1273.815} = 4931.12\ [h], \tag{3.7}$$

where W_{year} – the total amount of electrical energy for a year, [kW·h], P_{max} – the maximum active power according to the load graph, [kW], P_i – the active power for i-th moment of time Δt_i, [kW],

τ_{max} – maximum loss hours:

$$\tau_{max} = (0.124 + \frac{T_{max}}{10000})^2 \cdot 8760 = \left(0.124 + \frac{4931.12}{10000}\right)^2 \cdot 8760 = 3336.05\ [h]. \tag{3.8}$$

According to calculations, the annual electrical energy losses in the overhead line are equal to 8 814.63 kW·h and in power transformer are 67 719.64 kW·h, the power losses in the overhead line are equal to 0.84 kW and in power transformer are 15.41 kW as a sum of off-load and short-circuit losses multiplied on load factor.

To minimize the losses of power and EE in the electrical network, it is possible to perform reactive power compensation. The most efficient way to reduce the reactive power consumed from the network is the use of reactive power compensation units or capacitor units. A capacitor unit is a set of capacitor banks equipped with switching equipment, protection and control equipment. Since the load changes, the capacitor unit should be adjustable with the smallest possible control step.

4. Assessment of power quality parameters

The purpose of this chapter is to calculate parameters of electrical energy quality: voltage deviation, negative sequence voltage unbalance factor, zero sequence voltage unbalance factor, and perform an analysis for compliance with the requirements of GOST 32144-2013 [1].

4.1. Calculation of steady-state voltage deviation

The steady-state voltage deviation is the voltage deviation from its nominal value in the steady-state operation of electrical networks, averaged over the calculated interval. Slow changes in power supply voltage (more than 1 minute) are usually caused by changes in the load of the electrical network [14].

The voltage deviation from the nominal (δU) is the difference between the actual (U) and the nominal voltages (U_{rated}) values for the given network [14]:

$$\delta U = \frac{U - U_{rated}}{U_{rated}} \cdot 100\% \tag{4.1}$$

The positive sequence voltage of the fundamental frequency can be determined by an approximate expression in three-phase networks [15]:

$$U_{1(1)i} = \frac{1}{3}\left(U_{AB(1)i} + U_{BC(1)i} + U_{CA(1)i}\right) [kV], \tag{4.2}$$

where $U_{AB(1)i}, U_{BC(1)i}, U_{CA(1)i}$ – rms values of phase-to-phase voltages of the fundamental frequency, [kV].

The initial data for the calculation will be the values of the phase-to-phase voltages presented in Figure 2.

An example of calculating the positive sequence voltage at time 11.00, based on the formula 4.1:

$$U_{1(1)i} = \frac{1}{3}(5.418 + 5.415 + 5.401) = 5.41 \; [kV].$$

The steady-state voltage value is calculated as a result of averaging the voltages over *N* observations over an averaging interval of 60 seconds [15]:

$$U = \sqrt{\frac{\sum_{i=1}^{N}(U_{1(1)i})^2}{N}} = \sqrt{\frac{\sum_{i=1}^{N}(5.39^2 + 5.33^2 + \cdots)}{71}} = 5.65 \; [kV]. \tag{4.3}$$

Now I can calculate the voltage deviation from the nominal using the formula 4.1:

$$\delta U = \frac{5.65 - 6}{6} \cdot 100\% = -5.8 \; [\%].$$

The calculation results according to formulas 4.1-4.3 are presented in the form of a graph shown in Figure 8.

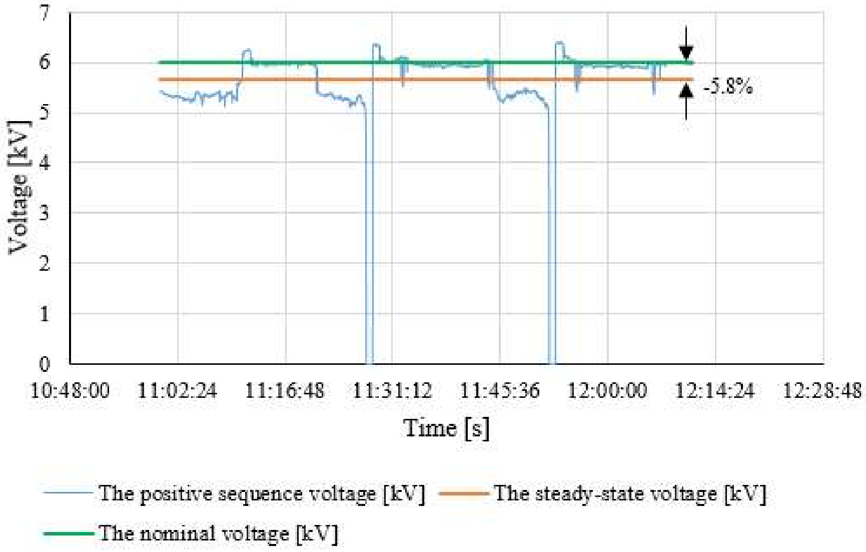

Figure 8. Graphs of positive sequence voltage, steady-state and nominal voltages

According to GOST 32144-2013 [1], the following norms have been established for EE quality parameters: positive and negative voltage deviations at the point of electric energy transfer should not exceed 10% of the nominal or agreed voltage value for 100% of the time interval of one week. The resulting value (-5.8%) is included in the range of ±10%.

4.2. Calculation of negative sequence voltage unbalance factor

One of the factors that increase losses in networks and elements of electrical energy distribution is the unbalance of currents and voltages. Unbalance, or three-phase unbalance, is the phenomenon in a three-phase system, in which the rms value of the voltages or the phase angles between consecutive phases are not equal [16].

Voltage unbalance, according to [1], is characterized by two parameters: the negative sequence voltage unbalance factor (K_{2U}) and the zero sequence voltage unbalance factor (K_{0U}).

The value of the negative sequence voltage unbalance factor (K_{2Ui}) is determined as a percentage in each i-th observation [15]:

$$K_{2Ui} = \frac{U_{2i}}{U_{1i}} \cdot 100\ [\%], \tag{4.4}$$

where:

U_{2i} – the rms value of the negative sequence voltage of the fundamental frequency of the three-phase voltage system in the i-th observation, [V]. It is found by the formula:

$$U_2 = \sqrt{\frac{1}{12}\left(\left(\sqrt{3} \cdot U_{AB} - \sqrt{4 \cdot {U_{BC}}^2 - \left(\frac{{U_{BC}}^2 - {U_{CA}}^2}{U_{AB}} + U_{AB}\right)^2}\right)^2 + \left(\frac{{U_{BC}}^2 - {U_{CA}}^2}{U_{AB}}\right)^2\right)}\ [V], \tag{4.5}$$

U_{1i} – the rms value of the positive sequence voltage of the fundamental frequency of the three-phase voltage system in the i-th observation, [V]. It is found by the formula:

$$U_1 = \sqrt{\frac{1}{12}\left(\left(\sqrt{3} \cdot U_{AB} + \sqrt{4 \cdot {U_{BC}}^2 - \left(\frac{{U_{BC}}^2 - {U_{CA}}^2}{U_{AB}} + U_{AB}\right)^2}\right)^2 + \left(\frac{{U_{BC}}^2 - {U_{CA}}^2}{U_{AB}}\right)^2\right)}\ [V], \tag{4.6}$$

where U_{AB}, U_{BC}, U_{CA} – the rms values of the phase-to-phase voltage between phases A and B, B and C, C and A, respectively, of the fundamental frequency, [V].

The initial data for the calculation will be the values of the phase voltage presented in Figure 2.

Calculation example of the negative sequence voltage, positive sequence voltage and negative sequence voltage unbalance factor at time 11.00 is presented below and based on formulas 4.4-4.6:

$$U_{2(1)} = \sqrt{\frac{1}{12}\left(\left(\sqrt{3}\cdot 5\,418 - \sqrt{4\cdot 5\,415^2 - \left(\frac{5\,415^2 - 5\,401^2}{5\,418} + 5\,418\right)^2}\right)^2 + \left(\frac{5\,415^2 - 5\,401^2}{5\,418}\right)^2\right)} =$$

$$= 10.47\ [V],$$

$$U_{1(1)} = \sqrt{\frac{1}{12}\left(\left(\sqrt{3}\cdot 5\,418 + \sqrt{4\cdot 5\,415^2 - \left(\frac{5\,415^2 - 5\,401^2}{5\,418} + 5\,418\right)^2}\right)^2 + \left(\frac{5\,415^2 - 5\,401^2}{5\,418}\right)^2\right)} =$$

$$= 5\,411.32\ [V],$$

$$K_{2U(1)} = \frac{10.47}{5\,411.32}\cdot 100 = 0.19\ [\%].$$

The value of the negative sequence voltage unbalance factor is calculated as a result of averaging N observations according to the formula [15]:

$$K_{2U} = \sqrt{\frac{\sum_{i=1}^{N} K_{2Ui}{}^2}{N}} = \sqrt{\frac{0.19^2 + 0.19^2 + 0.18^2 + \cdots}{4\,273}} = 11.06\ [\%]. \qquad (4.7)$$

The calculation results according to formulas 4.4 and 4.7 are presented in the form of a graph shown in Figure 9.

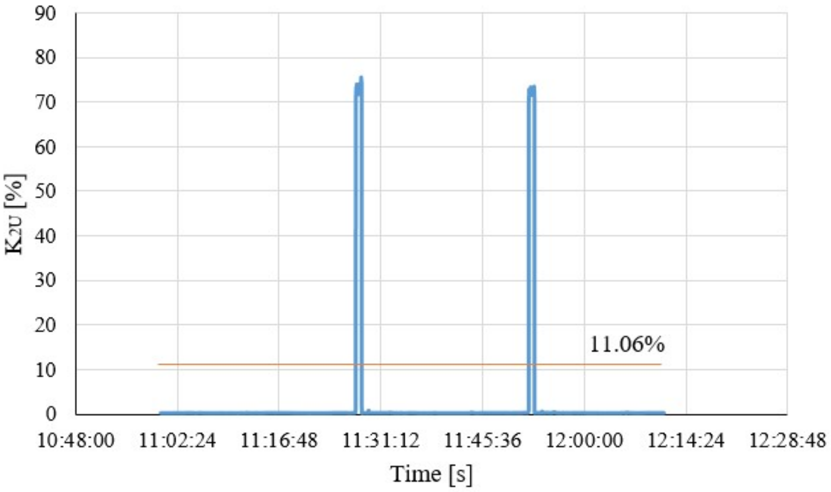

Figure 9. The graph of the change in the negative sequence voltage unbalance factor K_{2U}

Normal and maximum permissible values of the negative sequence voltage unbalance factor are 2% and 4% respectively in the points of connection to the power grids [1]. The obtained value (11.06%) is not within the permissible range.

4.3. Calculation of zero sequence voltage unbalance factor

The zero sequence voltage unbalance factor is a value equal to the ratio of the zero-sequence voltage to the nominal phase voltage. The value of the zero sequence voltage unbalance factor K_{0Ui} in each i-th observation is determined as a percentage [15]:

$$K_{0Ui} = \frac{U_{0i}}{U_{phase}} \cdot 100\ [\%], \tag{4.8}$$

where U_{0i} – the rms value of the zero sequence voltage of the fundamental frequency of the three-phase voltage system in the i-th observation, [V]. It is found by the formula:

$$U_0 = \frac{1}{6}\sqrt{\left(\frac{U_{BC}{}^2 - U_{CA}{}^2}{U_{AB}} - 3\cdot\frac{U_B{}^2 - U_A{}^2}{U_{AB}}\right)^2 + \left(\sqrt{4\cdot U_{BC}{}^2 - \left(\frac{U_{BC}{}^2 - U_{CA}{}^2}{U_{AB}} + U_{AB}\right)^2} - 3\sqrt{4\cdot U_B{}^2 - \left(\frac{U_B{}^2 - U_A{}^2}{U_{AB}} + U_{AB}\right)^2}\right)^2}\ [V], \tag{4.9}$$

U_{phase} – rated value of phase voltage, [V],

U_{AB}, U_{BC}, U_{CA} – the rms values of the phase-to-phase voltage between phases A and B, B and C, C and A, respectively, of the fundamental frequency, [V].

The initial data for the calculation will be the values of the phase voltage presented in Figure 2.

Calculation example of the zero sequence voltage and the zero sequence voltage unbalance factor at time 11.00 is presented below and based on formulas 4.8-4.9:

$$U_0 = \frac{1}{6}\sqrt{\left(\frac{5415^2 - 5401^2}{5418} - 3\cdot\frac{3126.35^2 - 3128.08^2}{5418}\right)^2 + \left(\sqrt{4\cdot 5415^2 - \left(\frac{5415^2 - 5401^2}{5418} + 5418\right)^2} - 3\sqrt{4\cdot 3126.35^2 - \left(\frac{3126.35^2 - 3128.08^2}{5418} + 5418\right)^2}\right)^2} = 6.04\ [V],$$

$$K_{0U(1)} = \frac{6.04}{6\,000/\sqrt{3}} \cdot 100 = 0.174\ [\%].$$

The value of the zero sequence voltage unbalance factor is calculated as a result of averaging *N* observations according to the formula [15]:

$$K_{0U} = \sqrt{\frac{\sum_{i=1}^{N} K_{2Ui}{}^2}{N}} = \sqrt{\frac{0.174^2 + 0.179^2 + 0.167^2 + \cdots}{4\,273}} = 0.198\ [\%]. \tag{4.10}$$

The calculation results according to formula 4.8 and 4.10 are presented in the form of a graph shown in Figure 10.

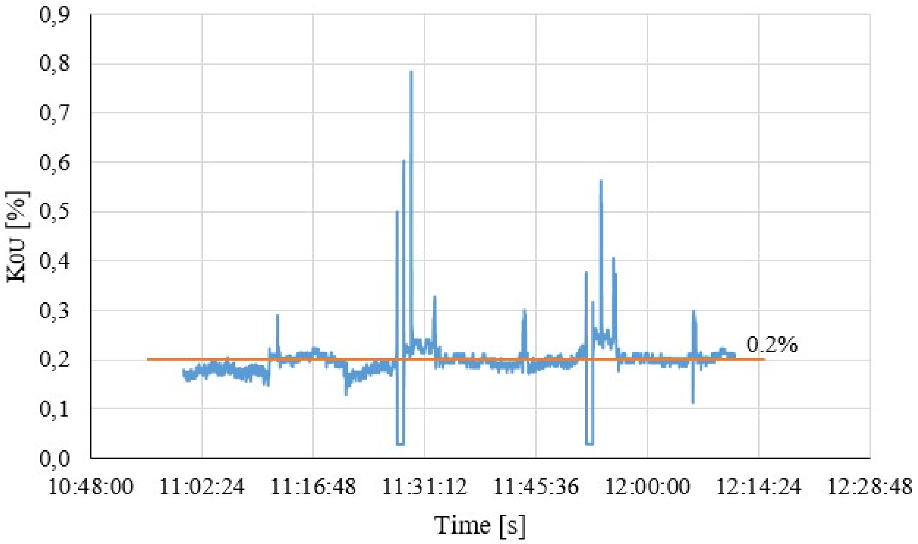

Figure 10. The graph of the change in the zero sequence voltage unbalance factor K_{0U}

According to GOST 32144-2013:

– “the values of the voltage unbalance factors in the negative sequence and in the zero sequence, averaged over a time interval of 10 minutes, should not exceed 2% during 95% of the time interval of one week at the point of transfer of electrical energy”;

– “the values of the voltage unbalance factors in the negative sequence and in the zero sequence, averaged over a time interval of 10 minutes, should not exceed 4% during 100% of the time interval of one week at the point of transfer of electrical energy” [1, p. 16].

The obtained value of the zero-sequence voltage unbalance factor (0.198%) is included in the permissible range.

5. Additional losses of power and electrical energy, caused by low electrical energy quality

One of the reasons for the deterioration of EE quality parameters is the asymmetry (unbalance) of currents and voltages, leading to an increase in losses and consumption of electrical energy, a decrease in the service life of equipment. In this chapter, I will calculate additional power losses in the power supply system due to the asymmetry of currents and voltages.

The additional power losses in the overhead line can be found in symmetrical mode using the following formula [19]:

$$\Delta P_{add.line} = \Delta P_{line} \cdot k_{add.loss} \; [kW], \tag{5.1}$$

where $k_{add.loss}$ – the coefficient of additional losses, ΔP_{line} – the power losses in overhead line in symmetrical mode, [kW]:

$$\Delta P_{line} = 3{I_{av}}^{2} \cdot R\ [kW], \tag{5.2}$$

where R – phase wire resistance equal, [Ohm], I_{av} – symmetrical mode current, [A]:

$$I_{av} = \frac{I_A + I_B + I_C}{3}\ [A]. \tag{5.3}$$

where I_A, I_B, I_C – measured phase currents, [A].

The coefficient of additional losses for networks with isolated neutral is found by the formula [19]:

$$k_{add.loss} = 3\frac{{I_A}^2 + {I_B}^2 + {I_C}^2}{(I_A + I_B + I_C)^2} = \frac{{I_A}^2 + {I_B}^2 + {I_C}^2}{3{I_{av}}^2}, \tag{5.4}$$

where I_A, I_B, I_C – measured phase currents, [A].

An example of calculation for the time 11:00, using formulas 5.1-5.4:

$$I_{av} = \frac{90.61 + 139.6 + 145}{3} = 125.07\ [A],$$

$$\Delta P_{line} = 3 \cdot 125.07^2 \cdot 0.028 \cdot 10^{-3} = 1.31\ [kW],$$

$$k_{add.loss} = \frac{90.61^2 + 139.6^2 + 145^2}{3 \cdot 125.07^2} = 1.038,$$

$$\Delta P_{add.line} = 1.31\ \cdot 1.038 = 1.36\ [kW].$$

The average value of additional losses of active power in overhead line is equal to 0.78 kW, the average coefficient of additional losses is 1.068.

The graph of changes in additional losses of active power in 6 kV overhead line is presented in Figure 11 and was obtained based on calculations using formula 5.1.

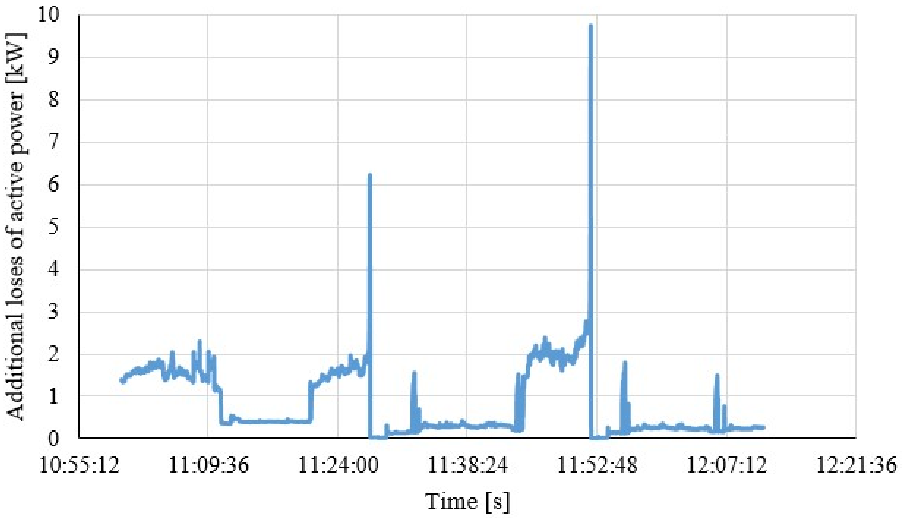

Figure 11. The graph of changes in additional losses of active power in 6 kV overhead line

According to the graph in Figure 11, the greatest power losses occur during periods of voltage dips. The next step is to analyze the power losses, increasing the coefficient of additional losses $k_{add.loss}$ to 1.5 and using the formula 5.1. I summarized the calculations of additional power losses $\Delta P_{add.line}$ depending on $k_{add.loss}$ in Table 2.

Table 2. Average value of additional power losses of active power in overhead line taking into account the change in $k_{add.loss}$

$k_{add.loss}$	1.068	1.1	1.15	1.2	1.25	1.3	1.35	1.4	1.45	1.5
$\Delta P_{add.line}$ [kW]	0.78	0.83	0.86	0.90	0.94	0.98	1.01	1.05	1.09	1.13

Based on the results in Table 2, I can construct a graph of changes in the average additional losses of active power depending on $k_{add.loss}$ shown in Figure 12.

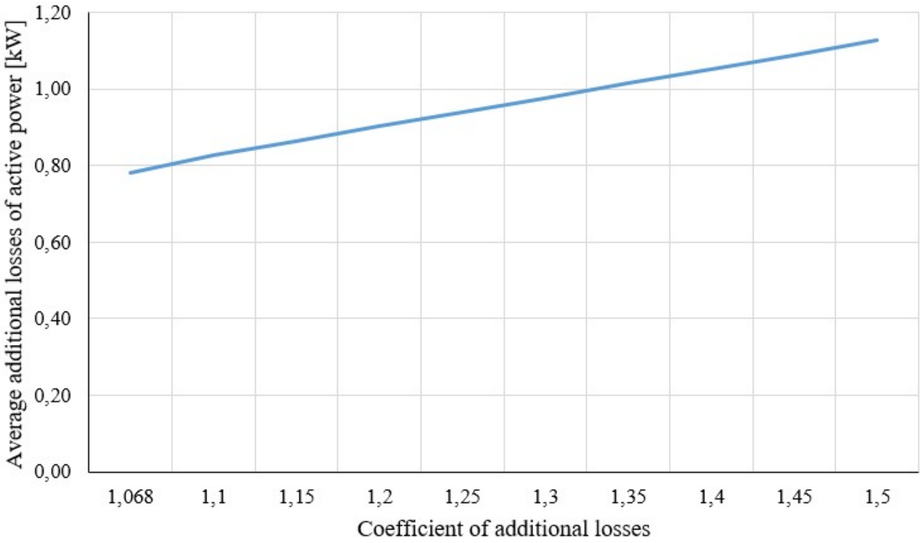

Figure 12. The graph of changes in the average additional losses of active power depending on $k_{add.loss}$

With an increase in the coefficient of additional losses $k_{add.loss}$ up to 1.5, additional losses of active power in the overhead line increase by 1.45 times relative to $\Delta P_{add.line}$ with a steady $k_{add.loss}$ equal to 1.068, and reach a maximum of 14.38 kW at the moment of voltage dip. An increase in additional losses of active power occurs as a result of an increase in the asymmetry of currents caused by the inclusion of consumers in the power supply system that distorts the quality of electricity, or in the case of uneven connection of the load.

I can analyze the change in active power losses depending on the voltage deviation using the following formulas [15]:

$$I = \frac{P}{\sqrt{3} \cdot U \cdot cos\varphi} \; [A], \tag{5.5}$$

$$\Delta P_{line} = 3I^2 \cdot R \; [kW], \tag{5.6}$$

where I – the current transmitted through the overhead line, [A], U – the steady state voltage depending on the voltage deviation, [V], P – the active power transmitted through the overhead line, [W], R – the active resistance of the overhead line, [Ohm], $cos\varphi$ – power factor.

An example of calculating with a voltage deviation of -10 % from the rated voltage for a time of 11:00, using the formulas 5.5-5.6:

$$I = \frac{828\ 037}{\sqrt{3} \cdot 5\ 400 \cdot 0.69} = 128.31 \; [A],$$

$$\Delta P_{line} = 3 \cdot 128.31^2 \cdot 0.028 \cdot 10^{-3} = 1.38 \; [kW].$$

The average value of power losses is 0.90 kW for the voltage deviation of -10 %. I summarized all calculations of active power losses in the overhead line in Table 3.

Table 3. Average values of active power losses taking into account voltage deviation

Voltage deviation [%]	-10	-8	-6	-4	-2	0	2	4	6	8	10
ΔP_{line} [kW]	0.90	0.86	0.82	0.79	0.76	0.73	0.70	0.67	0.65	0.62	0.60

Based on the results in Table 3, I can construct a graph of the dependence of active power losses in the overhead line on the voltage deviation shown in Figure 13.

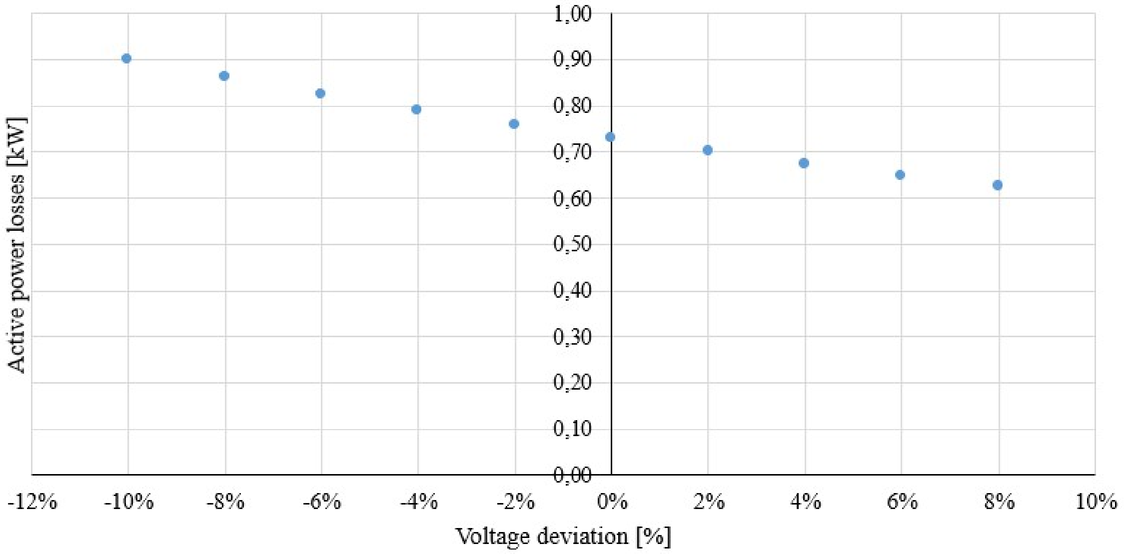

Figure 13. The graph of the dependence of active power losses on the voltage deviation in the overhead line

According to the obtained dependence, the active power losses in the overhead line ΔP_{line} decrease at positive voltage deviation and increase at negative voltage deviation. ΔP_{line} change approximately 1.2 times relative to ΔP_{line} at a nominal voltage without deviation. Therefore, it is necessary to increase the voltage to reduce losses in overhead line.

There are also additional losses in electric machines: basic and additional. The basic losses are losses arising in electric machines due to electromagnetic processes occurring in them: losses from the main power flow in the copper of the windings and in steel, losses from friction in bearings, brushes and ventilation [15].

In synchronous machines (SM), additional losses of active power caused by asymmetry of the operating mode are present both in the stator and in the rotor at the same time, in contrast to the asynchronous machines. At the same time, the value of losses in the stator from voltage unbalance is much lower than the losses in the rotor winding, so it is recommended to neglect them. Therefore, additional power losses for SM are determined depending on the voltage unbalance factor according to the formula [15]:

$$\Delta P_{add.SM} = k_{SM} \cdot {k_{2U}}^2 \cdot P_{rated} = 0.68 \cdot 0.1106^2 \cdot 710 = 5.906\ [kW], \qquad (5.7)$$

where $k_{SM} = 0.68$ – coefficient determined depending on the type of synchronous machine [15], k_{2U} – calculated negative sequence voltage unbalance factor, P_{rated} – rated active power of the SM, for SDBM 99/49 is equal to 710 kW [34].

Power transformers are static devices in which the order of phase rotation does not change the nature of the processes taking place in them. The asymmetry of the input voltages of the transformer, as well as of its load currents, leads to the appearance of the asymmetry of its output voltages, caused by the components of the negative and zero sequence, respectively. Transformers with a star-star with zero winding connection are especially sensitive to unbalanced loads, which have a large zero sequence resistance, which causes an unbalanced system of their output voltages.

Additional power losses occur during long-term asymmetric operation in power transformers due to the flow of negative sequence currents, which can be determined by the following formula [15]:

$$\Delta P_{add.tr} = {k_{2U}}^2 \cdot \left(\Delta P_{off-load} + \frac{\Delta P_{sh.c.}}{{u_{sh.c}}^2}\right) = 0.1106^2 \cdot \left(6.7 + \frac{33.5}{(\frac{7.5}{100})^2}\right) = 0.81\ [kW], \qquad (5.8)$$

where $\Delta P_{off-load}$ – off-load losses in the transformer, [kW], $\Delta P_{sh.c.}$ – short-circuit losses, [kW], k_{2U} – negative sequence voltage unbalance factor, $u_{sh.c}$ – the short-circuit voltage, [%].

6. Measures to improve the quality of electrical energy

According to the analysis of EE quality parameters and power and EE losses, the following problems were found: the necessity of reactive power compensation and the high value of the negative sequence voltage unbalance factor. Thus, the chapter will be devoted to the study of measures aimed at eliminating these problems.

6.1. Analysis of measures for improving EE quality. Reactive power compensation

Voltage unbalance leads to additional power losses in power lines, transformers, and electrical machines. For example, the negative sequence voltage unbalance factor induces additional double-frequency currents in the rotors of the electrical machines. These currents lead to additional losses in the windings of the rotors of machines, their overheating and a reduction in service life [15]. The service life of a loaded engine is halved with a voltage unbalance of 4%, the available motor power is reduced by 5-10% with a voltage unbalance of 5%. In addition, braking torques arise, which affects the operation of mechanisms driven by electrical machines [5]. Thus, it is necessary to take measures to eliminate the unacceptable asymmetry.

The following methods can be a solution to reduce asymmetry: uniform distribution of single-phase loads in phases, an increase in the cross-section of the power line, the use of booster transformers, or the use of filter-compensating devices.

One of the methods for reducing voltage unbalance is to evenly distribute single-phase loads in phases so that the voltage unbalance factor does not exceed the permissible limits. However, this method is not always effective, moreover, it is expensive and less reliable due to the construction of special transposition supports [5].

Another method is the reduction the active resistance (by increasing the cross-section of wires and cores of the electrical network) and the reactance of the elements of the power supply system. A decrease in inductive resistance is achieved by splitting the phases of current conductors and using longitudinal capacitive compensation. But this method has drawbacks: after the implementation of longitudinal compensation, short-circuit currents increase, overvoltages appear on capacitor banks [5].

The installation of booster transformers should be considered on lines in operation, in which voltage losses significantly exceed the permissible values of the established requirements and on lines to which technological connection is planned, as well as during new construction of power transmission lines. The use of booster transformers has the following advantages in distribution networks of 6-20 kV: increasing and stabilizing the voltage in the network, compensating for the asymmetry of phase voltages, promptly responding to consumer complaints about the quality of electrical energy and reducing the volume and urgency of capital investments. Also, the installation of booster transformers should be used as a measure to ensure the quality of electrical energy, along with other measures (increasing the cross-section of conductors on power lines, transferring power lines to another voltage class) [20]. The disadvantages of application of booster transformers: they are more expenses than transformer with on-load tap-changes, less efficient due to losses in boosters and requires more space [21].

Filter compensating device (FCD) is an asymmetrical filter that is connected to the line voltage of the network. The choice of line voltages to which the control unit is connected, included in the filter phases, is determined by the conditions for balancing the voltage. FCDs are a special type of capacitor units, the task of which is to filter harmonics together with reactive power compensation. FCD is mainly used in industries where the energy-intensive equipment with a non-linear nature of electricity consumption are widely used. It is economically feasible to use a FCD for a voltage of 6 (10) kV due to the fact that high-voltage consumers create a smaller spectrum of harmonic distortions (where 3, 5, 7 harmonics are strongly expressed and, to a lesser extent, harmonics of higher orders) in comparison with low-voltage consumers [22].

Since the unbalance of voltages is observed in this work, it will be better to select filter-compensating devices. However, I have decided to replace FCD by capacitor unit with harmonic filters due to the lack of information on the FCD with necessary power and technical parameters from the manufactures and literature sources. This equipment is usually installed for reactive power compensation and filtering harmonics of high-voltage consumers as well as FCD. Also, capacitor unit with harmonic filters is designed to:

- increase and maintains the value of the power factor at a given level;
- reduce current consumption by 30-50 %;
- reduce the influence of higher harmonics;
- minimize reactive energy bills.

The principle of operation of a capacitor unit with harmonic filters is as follows: capacitor unit consist of capacitors and reactors that form a series resonant circuit. The use of series-connected reactors and capacitors prevents the network from resonating at the largest harmonic by shifting the resonant frequency below its frequency. Since harmonics below the fifth are usually small or absent in a three-phase network, there is no possibility of resonance. In this case, distortion is reduced to an acceptable level. The built-in power factor controller turns the stages on and off to obtain the required reactive power values [23].

To determine the power of the capacitor unit with harmonic filters, I will apply the technique developed in [24]:

$$Q_{CU} = (0.26P_{DC} + 0.318P_{AC})k \ [VAr], \qquad (6.1)$$

where P_{DC} is the power of the DC drive, [W], P_{AC} is the power of the AC drive, [W], k is a factor depending on the initial and desired unbalance factor of the supply voltage, selected according to the diagram below in figure 14.

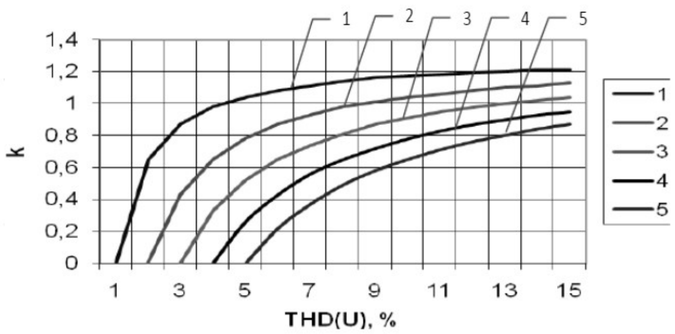

Figure 14. Diagram for the selection of the coefficient k, curves 1–5 correspond to the unbalance factor (THD) of the supply voltage after installing capacitor unit [24]

The calculated negative sequence coefficient voltage unbalance is 11.06%. After installing the capacitor unit with harmonic filters, it is necessary to take the coefficient voltage unbalance in the negative sequence equal to 0.9%, since the rated motor load is allowed at less than 1%. Therefore, according to the diagram, we take k is equal to 1.2. Then the power of the capacitor unit with harmonic filters using the formula 6.1:

$$Q_{CU} = 0.318(710 + 710)1.2 = 541.872\ [kVAr].$$

Based on the previous calculation, I chose the capacitor unit UKRMF-6.3-550-50 with harmonic filters at 189 Hz. The advantage of capacitor unit over FCD is the presence of automatic control steps of reactive power, that is necessary for the enterprise with changeable load. Also, it provides the capacitors with harmonic overload protection and partially filters the network itself. The technical parameters of installation are presented in Table 4 below [25].

Table 4. The technical parameters of capacitor unit UKRMF-6.3-550-50 with harmonic filters [25]

Rated power [kVAr]	Control step [kVAr]	Rated current [A]	Rated voltage [kV]	Settable power factor	Step configuration [kVAr]
550	50	50.40	6.3	0.8-0.99	2*50+1*100+1*150+1*200

Thus, this installation can reduce the negative sequence coefficient voltage unbalance from 11.06% to 0.9% in the case of voltage dips. If there are no emergency situations at the enterprise, the capacitor unit UKRMF-6.3-550-50 with harmonic filters only regulates the reactive power. The necessary power of the capacitor unit is selected according to the maximum active power and the difference between the actual and recommended reactive power factors [17]:

$$Q_{CB} = P_{max}(tg\varphi_1 - tg\varphi_2) = 1273.815 \cdot (0.73 - 0.4) = 420.36\ [kVAr], \tag{6.2}$$

where P_{max} – the maximum active power [9], [kW], $tg\varphi_1$ – the actual reactive power factor [9], $tg\varphi_2$ – the recommended reactive power factor. According to [26], the recommended reactive power factor should not exceed 0.4 for the voltage level of 1-20 kV.

I can install the power of the capacitor unit with harmonic filers equal to $Q_{CB} = 450$ kVAr. As the load diagram is of a sharply variable nature at the gas condensate field there is an additional possibility of reactive power regulation in case of its increase. The checking is:

$$tg\varphi_1 = \frac{Q - Q_{CB}}{P_{max}} = \frac{934.999 - 450}{1273.815} \approx 0.4.$$

Further, I can evaluate the power losses in the power transformer and 6 kV overhead line after the introduction of the capacitor unit according to formulas presented in [18]. Firstly, I should find the value of the active component of the total average current:

$$I_{a.av} = \frac{P_{av}}{\sqrt{3}U_r} = \frac{717\,047.5}{\sqrt{3} \cdot 6\,000} = 69.08\ [A], \tag{6.3}$$

where P_{av} – the average active power according to load diagram, [W], U_r – the rated voltage, [V].

The value of the reactive component of the total average current:

$$I_{r.av} = \frac{Q_{av}}{\sqrt{3}U_r} = \frac{744\,345.1}{\sqrt{3} \cdot 6\,000} = 71.71\ [A], \tag{6.4}$$

where Q_{av} – the average reactive power according to load diagram, [VAr].

Now I can determine the reactive component of the total load current at the measurement point before $I_{r.1}$ and after compensation $I_{r.2}$:

$$I_{r.1} = \frac{P_{av} \cdot tg\varphi_1}{\sqrt{3}U_r} = \frac{717\,047.5 \cdot 0.73}{\sqrt{3} \cdot 6000} = 50.43\ [A], \tag{6.5}$$

$$I_{r.2} = \frac{P_{av} \cdot tg\varphi_1}{\sqrt{3}U_r} = \frac{717\,047.5 \cdot 0.4}{\sqrt{3} \cdot 6\,000} = 27.63\ [A] \tag{6.6}$$

Then the reactive component of the total current consumed by the enterprise, after consumption, will be equal to:

$$I_{r.av2} = I_{r.av} - (I_{r.1} - I_{r.2}) = 71.71 - (50.43 - 27.63) = 48.91\ [A] \tag{6.7}$$

The total current consumed by the enterprise, after compensation, will be equal to:

$$I_{2av} = \sqrt{{I_{a.av}}^2 + {I_{r.av2}}^2} = \sqrt{69.08^2 + 48.91^2} = 84.64\ [A] \tag{6.8}$$

Then the power and EE losses in overhead line after compensation according to formula 3.2-3.3:

$$\Delta P_{av} = 3 \cdot 0.028 \cdot 84.64^2 \cdot 10^{-3} = 0.60\ [kW],$$

$$\Delta W_{av} = k_k \cdot \Delta P_{av} \cdot T \cdot k_{c.s.}{}^2 = 0.99 \cdot 0.60 \cdot 8760 \cdot 1.1^2 = 6\,296.16\ [kW \cdot h].$$

The power and EE losses in power transformer after compensation according to formulas 3.5-3.6:

$$\beta_{av} = \frac{I_{2av} \cdot \sqrt{3}U_r}{n \cdot S_{rat.tr.}} = \frac{84.64 \cdot \sqrt{3} \cdot 6}{4\,000} = 0.22,$$

$$\Delta P_{tr} = \Delta P_{off-load} + \Delta P_{sh.c.} \cdot \beta_{av}{}^2 = 6.7 + 33.5 \cdot 0.22^2 = 8.32\ [kW],$$

$$\Delta W_{av} = 6.7 \cdot 8\,760 + 0.99 \cdot 1.1^2 \cdot 33.5 \cdot 0.22^2 \cdot 3\,336.05 = 65\,171.53\ [kW \cdot h].$$

According to calculations, the difference between annual electrical energy losses before and after compensation in the overhead line are equal to 2 518.47 kW·h and in power transformer are 2 548.11 kW·h, the difference between power losses before and after compensation in the overhead line are equal to 0.24 kW and in power transformer are 7.09 kW.

6.2. Elimination of voltage dips

Based on the analysis of the calculations of the electrical energy quality parameters of the gas condensate field, it was noted that the main reason for the deterioration of the voltage unbalance factor was a sharp voltage drop due to the activation of the maximum current protection due to the connection of a new load. Therefore, it is necessary to calculate the short-circuit currents depends on new load, select protective devices, and recalculate the overcurrent protection settings.

6.2.1. Calculation of short-circuit currents in a 6 kV network

The calculation of short-circuit (SC) currents in installations with voltages above 1 kV has a number of features:

- the active resistances of the elements of the power supply system are not taken into account if the condition $x/r > 3$ x / r> 3 is satisfied, where *r* and *x* are the total active and reactive resistances of the elements of the power supply system to the point of short-circuit;
- the make-up from high-voltage synchronous motors is taken into account in the shock and the cut-off short-circuit currents [11].

To calculate the short-circuit currents, a design diagram of the power supply system for 6 kV is presented in appendix A.

Average voltage of a step with short-circuit points is 6.3 kV. The parameters of the supply system is $Z_{cmin} = 0.015 + j0.85$ Ohm in the minimum mode and $Z_{cmax} = 0.005 + j0.83$ Ohm in the maximum mode. All necessary data from [27] are shown in appendix A.

I can calculate the values of the currents from the high-voltage motors feeding the short-circuit location.

SM rated current [11]:

$$I_{nomSM} = \frac{P_{nom}}{\sqrt{3} \cdot U_{nom} \cdot \eta_{nom} \cdot cos\varphi} = \frac{710}{\sqrt{3} \cdot 6 \cdot 0.947 \cdot 0.9} = 80.15 \text{ [A]}, \quad (6.9)$$

where $P_{nom} = 710\ kW$, $U_{nom} = 6\ kV$, $\eta_{nom} = 0.947$, $cos\varphi = 0.9$ – nominal parameters of SM of power, voltage, efficiency and power factor respectively [28].

Short-circuit current and shock current are found by the formulas [11]:

$$I_{SC\_SM} = \frac{E_0'' \cdot I_{nomSM}}{x_d''} = \frac{1.07 \cdot 80.15}{0.15} = 0.572\ [kA], \quad (6.10)$$

$$i_{shock\_SM} = \sqrt{2}k_{shock} \cdot I_{SC_{SM}} = \sqrt{2} \cdot 1.9 \cdot 0.572 = 1.54\ [kA], \quad (6.11)$$

where E_0'' – value of supertransient EMF, x_d'' – supertransient resistance of SM, k_{shock} – shock of coefficient [11].

The initial value of the periodic component of the short-circuit current in the minimum and maximum modes is [11]:

$$I_{max}{}^{(3)} = \frac{U_{nom}}{\sqrt{3} \cdot z_{max}}\ [A], \quad (6.12)$$

$$I_{min}{}^{(3)} = \frac{U_{nom}}{\sqrt{3} \cdot z_{min}}\ [A], \quad (6.13)$$

where U_{nom} – the nominal voltage, [V], z_{max}, z_{min} – total active and reactive resistances of the elements of the power supply system to the point of short-circuit, [Ohm].

Two-phase short-circuit current is [11]:

$$I_{min}{}^{(2)} = \frac{\sqrt{3}}{2} I_{max}{}^{(3)}, [A]. \quad (6.14)$$

The shock current in the minimum and maximum modes is [11]:

$$i_{shock} = \sqrt{2}k_{shock} \cdot I_{max}{}^{(3)}, [A]. \quad (6.15)$$

I summarized the calculation results for every point of SC in the Table 5.

Table 5. The results of the calculation of SC currents

The point of short circuit	Excluding make-up of SM			Including make-up of SM		
	$I_{max}^{(3)}$, [A]	$I_{min}^{(2)}$, [A]	i_{shock}, [A]	$I_{max}^{(3)}$, [A]	$I_{min}^{(2)}$, [A]	i_{shock}, [A]
1	2 302	1 968	6 348	3 446	2 959	9 428
2	2 277	1 948	6 183	3 421	2 938	9 263
3	2 246	1 921	5 599	3 390	2 912	8 679
4	2 246	1 921	5 559	3 390	2 912	8 679
5	1 166	1 003	2 968	2 310	1 994	6 048

6.2.2. Selection of protective devices

High-voltage circuit breaker is a switching device designed for operational switching on and off of individual circuits or electrical equipment in the power system. There are oil, air, vacuum and SF_6 circuit breakers. The reliability of power supply to consumers depends on the quality and reliability of the circuit breakers. The most preferable are vacuum and SF_6 circuit breakers, since they are the most efficient, reliable, characterized by a high speed of operation and a higher breaking capacity and preferable from the point of view of fire safety and ecology [29].

Before choosing the parameters of high-voltage circuit breakers, I will compare the electrical characteristics of vacuum (VVU-SEShch-10 [30], BB/TEL-10(6) [31]) and SF_6 (LF-1 [32]) circuit breakers in Table 6.

Table 6. Electrical characteristics of circuit breakers [30-32]

Comparative values	VVU-SEShch-10	BB/TEL-10(6)	LF-1
Nominal voltage, [V]	10 000	10 000	6 000
The highest operating voltage, [V]	12 000	12 000	7 200
Nominal current, [A]	1 000	630	630
Nominal breaking current, [kA]	20	20	25
Short-circuit through current, [kA]:			
- the largest peak	50	32	64
- initial effective value of the periodic component	20	20	25
Full shutdown time, [s]	0.035	0.09	0.07
Own shutdown time, [s]	0.025	0.015	0.048
Full turn-on time, [s]	0.05	0.1	0.065
Switching resource	50 000	50 000	10 000
Weight, [kg]	78	35	124
Service life, [years]	30	25	25
Price, [ths. RUB]	171	198	185

Where:

VVU-SEShch-10 – V – circuit breaker, V – vacuum, U – unified, SEShch – drive type is electromagnetic, 10 kV – the nominal voltage;

BB/TEL-10(6) – B – circuit breaker, B – vacuum, TEL – the series name, 10(6) kV – the nominal voltage;

LF-1 – SF_6 circuit breaker with LF-1 series.

The improved characteristics among the considered circuit breakers are shown by the vacuum VVU-SEShch-10. VVU-SEShch-10 circuit breaker is cheaper and has less full shutdown time and full turn-on time, however BB/TEL-10(6) is lighter and has less own shutdown time, but it is inferior in full shutdown time to LF-1 circuit breaker. To choose the optimal variant it is necessary to conduct the economic comparison.

I can temporarily choose vacuum circuit breaker VVU-SEShch-10 due to a high speed of operation and cheaper price. After an economic comparison, it will be possible to replace this type of circuit breaker with another one of the considered circuit breakers since the technical parameters of the circuit breakers differ slightly.

I will select high-voltage circuit breakers for every sections of 6 kV and summarize the selection in a Table 7. The selection of high-voltage switches is made according to the following parameters [11]:

- by the voltage of the electrical installation (network) $U_{set} \leq U_{nom}$, where U_{set} – the voltage of network, [V], U_{nom} – the nominal voltage of circuit breaker, [V];
- for continuous current $I_{max} \leq I_{nom}$, where I_{max} – the maximum current passing through the considered section of the circuit, [A], I_{nom} – the nominal current of circuit breaker, [A];
- by breaking capacity $I_{sc} \leq I_{br.c.}$, where I_{sc} – the initial value of the periodic component of the short-circuit current for the considered section of the circuit, [kA], $I_{br.c.}$ – the nominal breaking current of circuit breaker, [kA];
- by electrodynamic resistance $I_{sh} \leq I_{el}$, $i_{shock} \leq i_{el}$, where I_{sc} – the initial value of the periodic component of the short-circuit current for the considered section of the circuit, [kA], I_{el} – the initial value of the periodic component of the short-circuit current of circuit breaker, [kA], i_{shock} – the shock current for the considered section of the circuit, [kA], i_{el} – the argest peak through current of circuit breaker, [kA];
- by thermal resistance $B_{th} \leq I_{th}^2 \cdot t_{th}$, where B_{th} – the thermal resistance for the considered section of the circuit, [$kA^2 \cdot s$], I_{th} – the current thermal resistance of circuit breaker, [kA], t_{th} – the thermal current flow time, [s].

Table 7. Circuit breaker selection

Design data of 6 kV network			Nominal parameters VVU- SEShch-10-20/1000
For a section with an overhead line SIP-95 (Q1)	For sections with cable lines KGE 3x70+1x16 (Q2, Q3)	For section with cable line ASB 3x70 (Q4)	
U_{set} = 6 kV	U_{set} = 6 kV	U_{set} = 6 kV	U_{nom} = 10 kV
I_{max} = 233.57 A	I_{max} = 80.15 A	I_{max} = 154.14 A	I_{nom} = 1000 A
I_{sc} = 3.42 kA	I_{sc} = 3.39 kA	I_{sc} = 2.31 kA	I_{el} = 20 kA
I_{sc} = 3.42 kA	I_{sc} = 3.39 kA	I_{sc} = 2.31 kA	I_{el} = 20 kA
i_{shock} = 9.26 kA	i_{shock} = 8.68 kA	i_{shock} = 6.05 kA	i_{el} = 50 kA
B_{th} = 1.8 kA^2 ·c	B_{th} = 0.91 kA^2 ·c	B_{th} = 0.47 kA^2 ·c	$I_{th}^2 \cdot t_{th}$ = 1200 kA^2 ·c

Thus, I chose vacuum circuit breakers of the VVU- SEShch-10-20/1000 type to protect the lines and the transformer 6 kV. To assess the selectivity of operation of circuit breakers with higher-level protections, it is necessary to build a selectivity map. To do this, it is necessary to calculate the relay protection settings.

6.2.3. Calculation of relay protection settings and construction of selectivity map

According to [33], two-stage overcurrent protection should be provided on lines with one-way power supply from multiphase short circuits. The first stage is performed in the form of a current cutoff (CC), the second stage in the form of overcurrent protection (OCP) with an independent or dependent time delay characteristic.

The purpose of the current cutoff is the fastest elimination of short circuits that occur at the beginning (at least about 20% of the length) of the working zone. CC should be carried out without time delay on non-reactivated lines with one-way power supply, departing from the substation buses supplying large synchronous motors. The zone of their action should be selected from the condition of quick short circuit shutdown. To ensure this requirement, it is allowed to perform non-selective maintenance [34].

The next step is to calculate the CC settings. According to the condition of detuning from three-phase short-circuits at the end of the line, the operating current is calculated by the formula [34]:

$$I_{\mathrm{CC}} = k_r \cdot {I_{max}}^{(3)}, [kA], \tag{6.16}$$

where ${I_{max}}^{(3)}$ – the three-phase SC current in maximum mode, [kA], k_r – the coefficient of reliability, is equal to 1.1-1.2 for rele RT-40.

To calculate the CC setting for the protection of cable line, through which the transformer is powered, formulas 6.16 and 6.17 are used. As a result, the largest of the obtained values should be selected as the operating current of the CC [33]:

$$I_{CC} = k_m I_{nom.tr}, [kA], \tag{6.17}$$

where $k_m = 7$ – the coefficient of magnetizing in-rush current, $I_{nom.tr}$ – nominal current of transformer, [kA].

Overcurrent protection setting should provide:

- lack of OCP operation during post-emergency overloads;
- coordination of current and time actions with the protections of the previous elements;
- the required sensitivity for all types of short circuits in the main zone and in the redundancy zone [34].

To calculate the OCP, it is necessary to calculate the setting current, the time delay and detune from the neighboring protections. The setting current of OCP is [34]:

$$I_{OCP} \geq \frac{k_r \cdot k_{ss}}{k_{rr}} I_{op.max}, [A], \tag{6.18}$$

where $k_r = 1.15$ – the coefficient of reliability, $k_{ss} = 2$ – the coefficient of self-starting, k_{rr} – the return coefficient, $I_{op.max}$ – the maximum operating current of the protected selection, [A].

The condition of coordination with previous protection [34]:

$$I_{OCP}[A] \leq \frac{{I_{OCP}}^{pr}}{k_{r.c.}} [A], \tag{6.19}$$

where I_{OCP} – the setting current of considered protection, [A], ${I_{OCP}}^{pr}$– the setting current of previous protection, [A], $k_{r.c.}$ – the coefficient of reliability of coordination, the value of which depends on the type of current relays, is equal to 1.3-1.4 for RT-40.

Checking of OCP is by sensitivity [34]:

$$k_s = \frac{{I_{min}}^{(2)}}{I_{OCP}}, \tag{6.20}$$

where ${I_{min}}^{(2)}$ – the two-phase SC current, [A], k_s should me more 1.5 in the main zone and more 1.2 in the redundancy zone.

Example of calculation for section with an overhead line:

$$I_{\text{CC}} = 1.15 \cdot 3.421 = 3.93\ [kA],$$

$$I_{OCP} \geq \frac{1.15 \cdot 2}{0.8}(80.15 + 80.15 + 154.14) = 904\ [A],$$

checking of OCP is by sensitivity in main zone:

$$k_s = \frac{2\,938}{904} = 3.25 > 1.5$$

in the redundancy zone:

$$k_s = \frac{2\,912}{904} = 3.22 > 1{,}2$$

or

$$k_s = \frac{1\,994}{904} = 2.2 > 1{,}2.$$

Calculation of the operating current of the relay

$$I_{CCr} = \frac{k_{sc} \cdot I_{CC}}{n}, [\mathrm{A}], \tag{6.21}$$

$$I_{OCPr} = \frac{k_{sc} \cdot I_{OCP}}{n}, [\mathrm{A}], \tag{6.22}$$

where n – the current transformer ratio, k_{sc} – the coefficient of scheme, is equal to 1 for incomplete star scheme.

Example of calculation for section with an overhead line:

$$I_{CCr} = \frac{1 \cdot 3\,930}{\frac{400}{5}} = 49.13\ [\mathrm{A}],$$

$$I_{OCPr} = \frac{1 \cdot 904}{\frac{400}{5}} = 11.3\ [\mathrm{A}].$$

I should round the obtained values of the operating current of the relay to 50 and 12.5 A and recalculate the current settings of protection:

$$I_{CC} = 50 \cdot 80 = 4\,000\ [\mathrm{A}],$$

$$I_{OCP} = 12.5 \cdot 80 = 1\,000\ [\mathrm{A}].$$

I summarized the results of calculation in Table 8.

Table 8. The protection settings

The name of value	Calculated settings for sections		
	Section with an overhead line SIP-95	Sections with cable lines KGE 3x70+1x16	Section with cable line ASB 3x70
Current cutoff:			
operating current I_{CC}, [A]	4 000	3 900	2 660
response time t, [s]	0	0	0
current transformer ratio	400/5	100/5	200/5
Overcurrent protection:			
operating current I_{OCP}, [A]	1 000	250	500
response time t, [s]	1,0	0,4	0,6
current transformer ratio	400/5	100/5	200/5

A 6 kV network with indicated protection settings and currents reduced to 6 kV is presented in appendix B.

A map of selectivity is constructed, which is presented in appendix C. The disconnection time of the outgoing connection of the ASB 3x70 cable line and the TSL-1600/6 transformer will be 0.6 s (should be less 4 s) at a three-phase short circuit on the 0.4 kV. The characteristics of the overcurrent protection on the selectivity map do not intersect, their selectivity is ensured by different response times. The intersection of current cutoff of adjacent protections is allowed since their selectivity is ensured by the choice of the operating current.

6.3. Result of proposed measures

Based on calculations of EE quality parameters a significant deviation of the negative sequence voltage unbalance factor from the permissible values was noted. However, such high value of negative sequence voltage unbalance factor (11.06 %) is related with the occurrence of a temporary emergency at the enterprise. We can observe the voltage dips in figure 2, which appear when the rms voltage decreases between 10 and 90 percent of nominal voltage for one minute due to the connection of the new load and then the tripping of the overcurrent protection. For elimination of this emergency, I recalculated the short-circuit currents depends on new load, selected the protective devices and recalculated the overcurrent protection settings. Thus, it was possible to recalculate the parameters of EE quality in accordance with formulas from paragraphs 4.1-4.3. The initial data for the calculation were the values of voltages presented in Figure 2 without intervals of voltage dips. I obtained the following results, which are presented in the Table 9.

Table 9. Comparison of parameters of EE quality before and after eliminating the voltage dips

Parameter	Before	After	Norms [1]
Voltage deviation [%]	-5.8	-4.08	±10
Negative sequence voltage unbalance factor [%]	11.06	0.21	2
Zero sequence voltage unbalance factor [%]	0.198	0.197	2

As we can see from the Table 9, all recalculated parameters of EE quality are included in the permissible range according to [1] after elimination of voltage dips.

If the enterprise prefers to change the network configuration, for example, to connect a new non-linear load in the future, and the relay protection trips again, then the capacitor unit with harmonic filters will be able to operate in the harmonic suppression mode and reduce the unbalance factor to the required value (to 0.9%). In normal operation, the function of the capacitor unit is reactive power compensation. As a result, the capacitor unit with harmonic filters reduces the EE losses by 2 518.47 kW·h in the overhead line and by 2 548.11 kW·h in power transformer, power losses by 0.24 kW in the overhead line and by 7.09 kW in power transformer. Also, it maintains the value of power factor $cos\varphi$ at 0.8 (reactive power factor $tg\varphi$ at 0.4).

7. Economic efficiency of proposed investments

In this chapter, I will evaluate the economic efficiency from the introduction of measures for reduction of power and EE losses and voltage unbalance. A description of the investments is presented below:

- The capacitor unit with harmonic filters was chosen as an equipment for reduction of the power losses, energy bills and as a backup plan in the case of occurring of voltage unbalance if the enterprise decide to change the load in the future, for example, to connect new equipment.
- The following actions were completed for elimination of voltage unbalance due to the voltage dips which occurred due to the operation of overcurrent protection: calculation of short circuit current depending on the maximum and minimum load, selection new circuit breakers and recalculation of relay protection settings. For these measures, only high-voltage circuit breakers will be investment because the rest of the steps just require calculation. I will compare the following types of circuit breakers: vacuum VVU-SEShch-10 and BB/TEL-10(6) circuit breakers and SF_6 one of types LF-

1. Proposed measures allow to decrease the energy bills due to the reduction of EE losses caused by the voltage unbalance and decrease the number of overhauls for synchronous motors.

Thus, I will consider the following configurations:

A. The capacitor unit with harmonic filters and SF_6 circuit breakers LF-1
B. The capacitor unit with harmonic filters and vacuum circuit breakers VVU-SEShch-10
C. The capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6)

7.1. Initial data for economic evaluation

I will describe the following parameters for economic evaluation in this subchapter:

- Investments
- Depreciation
- Inflation
- Discount rate
- Taxes
- Energy savings after proposed measures
- Extending the service life of SM after proposed measures

7.1.1. Investments

Table 10 presents the prices for the equipment, its costs of installment and technical maintenance. Price for the equipment were taken according [25, 35-37].

The installment cost and cost of technical maintenance were calculated based on territorial rates, including the cost of labor and materials, and taking into account indices for conversion to current prices [38]. Technical maintenance is carried out every 10 years for circuit breakers and annually for capacitor unit with harmonic filter.

Table 10. The costs for equipment

	Capacitor unit with harmonic filter UKRMF-6.3-550-50	SF_6 circuit breaker LF-1	Vacuum circuit breaker VVU-SEShch-10	Vacuum circuit breaker BB/TEL-10(6)
Price for 1 unit [RUB]	2 610 000	185 000	171 000	198 000
Installment cost for 1 unit [RUB]	12 169	58 539	58 539	58 539
Technical maintenance for 1 unit [RUB]	2 662	8 434	8 434	8 434
Lifetime [years]	20	25	30	25
Number of units	1	4	4	4

7.1.2. Depreciation

Depreciation is the process of gradually transferring the value of fixed assets to costs to cover depreciation. There are 4 main methods of depreciation calculation for accounting for fixed assets in Russia:

- Linear method - deductions are made evenly throughout the entire period of use. Deductions are found as the initial cost divided by the useful life.
- Declining balance method - when a company needs to recognize more expenses in the early years than in subsequent years, this method is appropriate.
- The method based on the write-off of value in proportion to the volume of products - this method allows to take into account wear relative to actually produced products.
- The method of writing off value according to the sum of the digits of the years of useful lifetime - an accelerated method that writes off most of the cost of the fixed assets in the first years of use.

I will use variable declining balance method, in which the cost of an asset is reduced by a large amount during the first period of its lifetime and by smaller amounts in subsequent periods. According to this method, depreciation is determined as the double-declining balance method:

$$VDB = \frac{2}{Lifetime} \cdot (Cost - Accumulated\ depreciation)\ [RUB] \tag{7.1}$$

The variable declining balance method will switch to straight line calculation when the depreciation value calculated with straight line method is greater than the depreciation value calculated with the double decline balance method.

For example, for the capacitor unit with harmonic filters:

- for the first year:

$$VDB_1 = \frac{2}{20} \cdot (2\,622\,169\ - 0) = 262\,217\ [RUB],$$

- for the second year:

$$VDB_2 = \frac{2}{20} \cdot (2\,622\,169\ - 262\,217) = 235\,995\ [RUB],$$

- for the third year:

$$VDB_3 = \frac{2}{20} \cdot \big(2\,622\,169\ - (262\,217 + 235\,995)\big) = 212\,396\ [RUB].$$

The result of calculating the depreciation for the equipment are presented in the appendixes D-G.

7.1.3. Inflation

Inflation is a steady increase in the general price level of goods and services in an economy. In 2015, the Bank of Russia set the goal of monetary policy as reducing annual inflation to 4% in 2017 and maintaining it near this level in the future. In 2021, there was a sharp jump to the level of 8.4% per year [39]. Historical data are presented in Table 11.

Table 11. Historical data of inflation for previous 10 years [39]

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Inflation [%]	6.58	6.45	11.36	12.91	5.38	2.52	4.27	3.05	4.91	8.39
Geometric average [%]	6.5									

According to analysts' forecast [40], inflation will increase to 22% by the end of 2022 and slow down to 7.6% and 5% in 2023 and 2024. Also, the Bank of Russia's monetary policy will promote conditions to return of annual inflation to 4% in 2024.

With regard to the historical development of inflation (geometric average 6.5%), the current development and with regard to the forecast, I assume the long-term level of inflation at 6.5% as it is difficult to predict further development and the rate of inflation.

7.1.4. Escalation of electrical energy price

According to historical data of electrical energy price presented in Table 12, I assume that EE price will be not too different from previous values. Thus, the escalation of EE price can be calculated as a geometric average and equal to 5%.

Table 12. Historical data of electrical energy price for previous 8 years [41]

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021
EE price [RUB/MW·h]	2 745.40	3 089.54	3 112.75	3 215.51	3 628.96	3 506.80	4 123.25	3 948.64	4 351.72
Geometric average [%]	5								

7.1.5. Taxes of Russian Federation

A tax rate is percentage of income that must be paid in taxes to the government. According to the tax code of the Russian Federation, tax rate is equal to 20% [42]. This tax rate includes two parts:

- the amount of tax calculated at a tax rate of 2% is payable to the federal budget;
- the amount of tax calculated at the tax rate of 18% is payable to the budgets of the constituent entities of the Russian Federation [42].

7.1.6. Discount rate

Discount rate is an opportunity cost, as it is the return that can be received by investing in the project, rather than investing in financial markets. For the determination of discount rate, I will use capital asset pricing model (CAPM). CAPM describes relations between risk and expected return. Discount rate can be calculated by following formula [43]:

$$r = r_f + \beta(r_m - r_f) = 8.73 + 1.13 \cdot 8.1 = 17.88\ [\%], \tag{7.2}$$

where:

r_f – risk-free rate, is equal to 8.73 % for 30 years [44],

β – beta ratio of stocks, is equal to 1.13 for oil and gas production [45],

$(r_m - r_f)$ – market risk premium, is equal to 8.1 % [46].

7.1.7. Energy savings

Improvement the EE quality leads to reduction of power and electrical energy losses, increase in the service life of electrical equipment and reduction in payment of electricity bills. Firstly, I can evaluate the reduction of power losses [47]:

$$\varepsilon = 100 - \frac{\Delta P'_{av} + \Delta P'_{add.}}{\Delta P_{av} + \Delta P_{add}} \cdot 100\% =$$

$$= 100 - \frac{0.6 + 8.32 + (0.62 + 2 \cdot 0.002 + 0.024)}{0.84 + 15.41 + (0.78 + 2 \cdot 5.906 + 0.81)} \cdot 100\% = 67.73\ [\%], \tag{7.3}$$

where ΔP_{av} – average power losses before proposed measures, [kW], $\Delta P'_{av}$ – average power losses after proposed measures (using capacitor unit with harmonic filters for reactive power compensation), [kW], ΔP_{add} - additional power losses without proposed measures, [kW], $\Delta P'_{add.}$ – additional power losses after proposed measures (elimination of voltage unbalance), [kW]:

$$\Delta P_{add} = \Delta P_{add.line} + \Delta P_{add.SM} + \Delta P_{add.tr}, [kW],$$

where $\Delta P_{add.line}, \Delta P_{add.SM}, \Delta P_{add.tr}$ – are the additional losses of active power caused by asymmetry of the operating mode in the overhead line, two synchronous motor and the power transformer calculated by formula 5.1, 5.7 and 5.8 respectively, using the coefficient voltage unbalance in the negative sequence 11.06%. The same formulas were applied for $\Delta P'_{add.}$ using the accepted coefficient voltage unbalance in the negative sequence 0.21 % after elimination of voltage dips in the grid.

Thus, the power losses due to the decrease in voltage unbalance decreased by 67.73 %.

The annual economic effect of reducing losses is determined by the formula [47]:

$$\Delta W_{add} = \left(\sum_{j=1}^{n} t_j \cdot T_j \cdot (\Delta P_{av} + \Delta P_{add}) - \sum_{j=1}^{n} t_j \cdot T_j \cdot (\Delta P'_{av} + \Delta P'_{add.}) \right) \cdot C \left[\frac{RUB}{year} \right], \tag{7.4}$$

where $t_j = 24$ [h] – operating time of the electric receiver with a given load and a certain value of unbalance per day, $T_j = 365$ – days of work with a given load and a certain value of unbalance per year, units, C – cost of electricity, [RUB/(MW·h)].

To determine the cost of energy efficiency in monetary terms, it is necessary to choose the optimal price category. From January 1, 2012, the Government Decree No 442 introduced the concept: price categories of electricity. Pricing categories are tariff options for the consumer. There are six price categories, which are subdivided into integral (1st and 2nd) and interval (from 3rd to 6th). At the same time, consumers are also divided into two groups: with a maximum power of more than 670 kW and less than 670 kW. The drilling rid belongs to consumers with a maximum power of over 670 kW. Consumers whose maximum capacity exceeds 670 kW cannot choose price categories of the integral type, so price categories from the 3rd to the 6th will be considered [48].

For the calculation, a daily schedule will be used (in Figure 6), I will take 365 days (year) for the calculation period. Also, it is necessary to use the rates for the actual hourly volumes of electricity purchases for the month from the forecast limit levels of unregulated prices for electricity (capacity) [41]. The results of the electricity payment to the wholesale market are presented in the Table 13.

Table 13. The results of the payment for electricity for every price category

Price category	3	4	5	6
Total payment, [RUB/year]	22 679 436	35 837 940	23 857 580	35 826 632

Example of calculation for third price category:

The calculation is carried out according to [48]. Electricity is charged every hour at a different price, so hourly electricity metering is required. The payment for EE for each hour, taking into account the rate for the actual hourly volumes of electricity purchases per month, is determined by the formula:

$$\Pi_{mEE} = \sum_{i=1}^{n} (P_i \cdot t_i \cdot T_{EEi})\ [RUB], \tag{7.5}$$

where P_i – the active power according to daily load graph (Figure 6), [MW], during the time t_i, [h], T_{EEi} – the rate for the actual hourly volumes of electricity purchases for the month, it will be taken from the predicted marginal levels of unregulated prices for electricity (capacity) used for the calculation for July 2020 by TomskEnergosbyt, [RUB/(MW·h)] [41].

For convenience, I summarized the calculations in the Table 14.

Table 14. The calculation of $P_i \cdot t_i$ according to daily load graph, [MW·h]

Time [h]	0:00-1:00	1:00-2:00	2:00-3:00	3:00-4:00	4:00-5:00	5:00-6:00	6:00-7:00	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00
$P_i \cdot t_i$, [MW·h]	0.5855	0.5106	0.5586	0.5682	0.5340	0.4879	0.5786	0.5665	0.5050	0.5964	0.5163	0.5872
Time [h]	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-0:00
$P_i \cdot t_i$, [MW·h]	0.5521	0.5185	0.5893	0.5214	0.5024	0.5530	0.5926	0.4820	0.5820	0.5374	0.5249	0.5128

Thus, the payment for EE for each hour per month is equal to:

$$\Pi_{mEE} = \sum_{i=1}^{n} (0.5855 \cdot 3\,881.66 + 0.5106 \cdot 3\,919.94 + \cdots) = 1\,599\,271\ [RUB].$$

Thus, the payment for EE for each hour per year is equal to:

$$\Pi_{yearEE} = \Pi_{mEE} \cdot 12 = 1\,599\,271 \cdot 12 = 19\,191\,252\ [RUB].$$

To determine the power to be paid for the wholesale market, it is necessary to know the hours of maximum cumulative electricity consumption. Table 15 provides a monthly peak hour report.

Table 15. Monthly peak hour report according to daily load graph

Day	Time, [h]	P_i, [MW]
1	12 (from 11 to 12)	0.587
2	11	0.516
3	10	0.516
6	11	0.516
7	12	0.587
8	11	0.516
9	11	0.516
10	10	0.516
13	11	0.586
14	12	0.586
15	11	0.516
16	11	0.517
17	10	0.517

Continuation of Table 15

20	11	0.517
21	12	0.586
22	11	0.517
23	11	0.517
24	10	0.517
27	11	0.518
28	12	0.585
29	11	0.518
30	11	0.518
31	10	0.518

Power paid to the wholesale market:

$$P_{Wh.} = \frac{\sum P_i}{N_w} = \frac{12.304}{30} = 0.41\ [MW], \tag{7.6}$$

where N_w – the amount of work day per month.

Power payment to the wholesale market per month:

$$\Pi_{Wh.m.} = P_{Wh.} \cdot T_{Wh.} = 0.41 \cdot 708\,981.27 = 290\,682\ [RUB], \tag{7.7}$$

where $T_{Wh.}$ – the rate for the power payment to the wholesale market per month, [RUB/MW] [41].

The total payment for the third price category for the year will be:

$$\Pi = \Pi_{yearEE} + 12 \cdot \Pi_{Wh.m.} = 19\,191\,252 + 12 \cdot 290\,682 = 22\,679\,436\ [RUB]. \tag{7.8}$$

From the obtained calculations (Table 13), it follows that it will be cheaper to apply the third price category. The average rate for the power purchased by the consumer is the ceiling level of unregulated prices for the third category is equal to 3 948.64 RUB/(MW·h) [41].

According to formula 7.4, annual economic effect of reducing the EE losses is:

- using capacitor bank with harmonic filters:

$$\Delta W_{add} = \frac{(67\,719.64 + 8\,814.63 - 65\,171.53 - 6\,296.16)}{10^3}) \cdot 3\,948.64 = 20\,006\ \left[\frac{RUB}{year}\right],$$

- after elimination the voltage unbalance:

$$\Delta W_{add} = \left(\frac{\left(24 \cdot 365 \cdot (0.78 + 2 \cdot 5.906 + 0.81) - 24 \cdot 365 \cdot (0.62 + 2 \cdot 0.002 + 0.024)\right)}{10^3}\right) \cdot$$

$$\cdot\, 3\,948.64 = 441\,162\ \left[\frac{RUB}{year}\right].$$

Economic effect of reducing power and electrical energy losses is equal to 461 168 RUB/year.

7.1.8. Increasing the service life of a synchronous motor

Voltage unbalance creates a significant current unbalance in the motor windings. This leads to additional heating in the windings, a decrease in the useful moment and available power of the machines, and a reduction in the service life. I can estimate the extending the service life of two high-voltage synchronous motors due to improving the EE quality.

The overhaul of SM should be carried out at least once every 3 years [49]. However, based on the literature [50], SM should be overhauled once a year due to non-compliance with the voltage unbalance factor if negative sequence voltage unbalance factor is more 4%. The lifetime of SM is 20 years [51].

The cost of overhaul is equal to 60% of the cost of equipment (6 000 000 RUB), so it will be 3 000 000 RUB for one SM [51].

7.2. Economic evaluation

In this chapter, I will conduct the economic estimation of proposed measures: installing the capacitor bank and the high-voltage circuit breakers. The following parameter will be determined:

- Net present value (NPV)
- Equivalent Annual Annuity (EAA)

7.2.1. Net present value

Net present value (NPV) is present value plus any immediate cash flow. It shows the amount of cash that the investor expects to receive from the project [43]:

$$NPV = -Inv + \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} \; [RUB], \qquad (7.9)$$

where:

Inv – initial investments, [RUB],

CF_t – cash flow for the period *t*, [RUB],

r – the discount rate,

T – the lifetime of the project.

Cash flow is determined for this work as:

$$CF_t = EAT_t + Depr_t\ [RUB], \tag{7.10}$$

where EAT_t – earnings after taxes for the period *t*, [RUB],
$Depr_t$ – depreciation for the period *t*, [RUB].

Earnings after taxes can be found as:

$$EAT_t = EBT_t - tax\ [RUB], \tag{7.11}$$

where EBT_t – earnings before taxes for the period *t*, [RUB],
$tax = EBT_t \cdot 20\%$ – deduction on taxable income for the period *t*, [RUB].

Earnings before taxes can be calculated as revenue minus expenses excluding tax.

For this work, revenue consists of energy savings due to the reduction of EE losses and, consequently, energy bills for capacitor unit with harmonic filter. For case of reduction of voltage unbalance, where the investments are circuit breakers, the savings due to the increasing the service life of SM (decreasing the number of overhauls) are also taken into account. Expenses includes depreciation and technical maintenance.

The result of calculation of cash flow and NPV are shown in the appendices D-G. Table 16 presents the result of NPV calculations.

Table 16. The result of NPV calculations

Equipment	NPV [RUB]
Capacitor unit with harmonic filters	-2 334 811
SF_6 circuit breaker LF-1	28 857 830
Vacuum circuit breaker VVU-SEShch-10	29 737 579
Vacuum circuit breaker BB/TEL-10(6)	28 809 083

Since all equipment has the different service life, it is impossible to compare NPV. To compare them, it is necessary to calculate equivalent annual annuity.

7.2.2. Equivalent annual annuity

Equivalent annual annuity (EAA) is used to compare mutually exclusive projects with unequal lifetimes provided that the economic effects of the projects are repeatable. It is determined as:

$$EAA = NPV \cdot \frac{(1+r)^T \cdot r}{(1+r)^T - r}\ [RUB], \tag{7.12}$$

where r – the discount rate, T – the lifetime of the project.

The results of EAA calculations are shown in the Table 17.

Table 17. The result of EAA calculations for different options

Configuration	EAA [RUB]
A. Capacitor unit with harmonic filters and SF6 circuit breaker LF-1	4 812 022
B. Capacitor unit with harmonic filters and vacuum circuit breaker VVU-SEShch-10	4 921 973
C. Capacitor unit with harmonic filters and vacuum circuit breaker BB/TEL-10(6)	4 971 938

According to results, the best option is to install capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6) due to the highest EAA. However, despite on the negative NPV, the installment of capacitor unit with harmonic filter is necessary because it:

- reduces the power and EE losses,
- decreases energy bills,
- serves as a backup plan in the case of occurring of voltage asymmetry in this work,
- maintains the reactive power factor at 0.4 according to order of the Ministry of Energy [26].

8. Sensitivity analysis

Sensitivity analysis examines how input parameters of project (EE price, discount rate, inflation etc.) affect the result. For the sensitivity analysis, I will use the following list of input parameters:

- EE price
- discount rate
- escalation of EE price
- inflation

Dependence of EAA on the EE price is presented in Figure 15. The dependance shows that as EE price increases, EAA increases because energy savings rise and increase the cash flow. However, changing the EE price has no impact on the decision, configuration C: capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6) remains the best option.

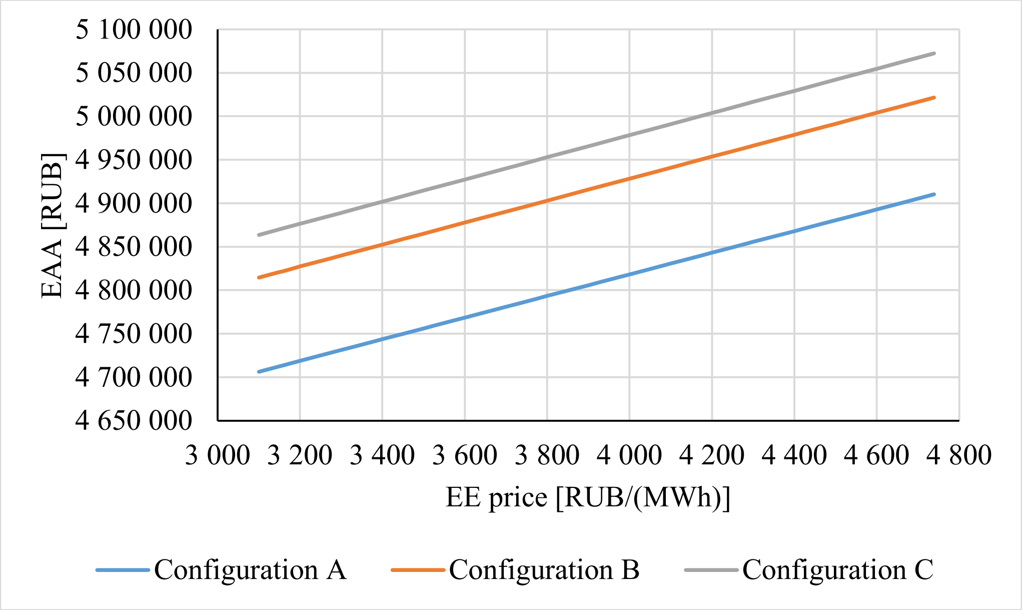

Figure 15. The graph of the dependence of EAA on investments

Dependence of EAA on the discount rate is presented in Figure 16. The discount rate should be higher than inflation rate. The dependance shows that as discount rate increases, EAA decreases. It is explained by formulas 7.9 and 7.12. Configuration C will remain the best alternative with the increase in the discount rate.

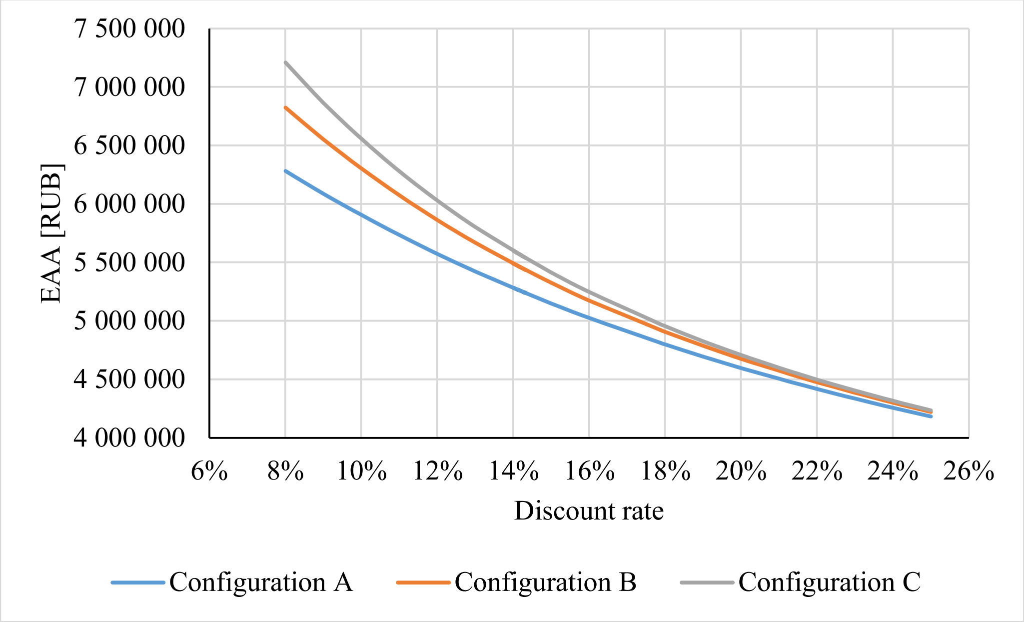

Figure 16. The graph of the dependence of EAA on the discount rate

Dependence of EAA on the escalation of EE price is presented in Figure 17. According to the graph, EAA increases with the EE price escalation increases. It is logical, since the higher the price is, the greater the energy savings are in cash flow, consequently the greater the NPV and EAA are according to formulas 7.9 and 7.12. Changing the escalation of EE price has no impact on the decision.

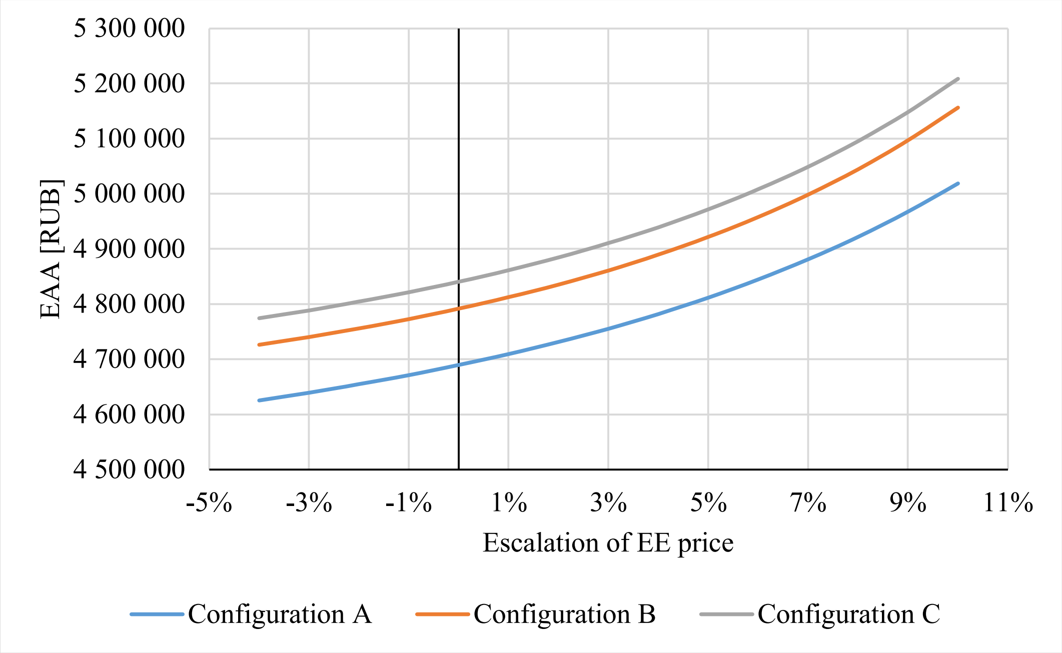

Figure 17. The graph of the dependence of EAA on escalation of EE price

Dependence of EAA on the inflation is shown in Figure 18. According to the graph, EAA increases with the inflation increases, because the increasing the lifetime of synchronous motors have a significant impact on NPV due to the big cost of overhaul savings in cash flow.

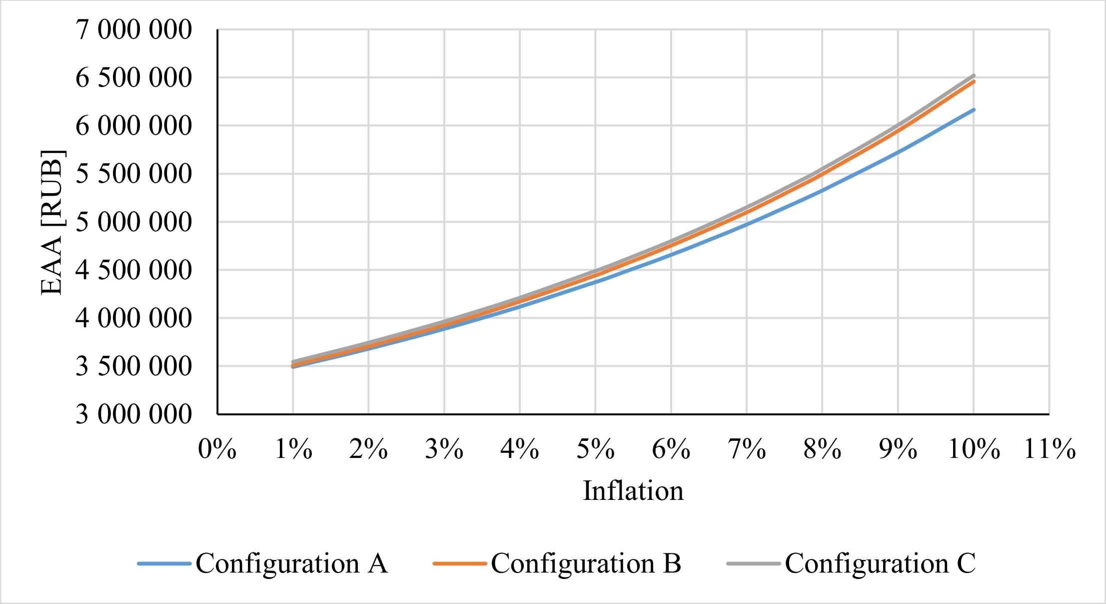

Figure 18. The graph of the dependence of EAA on the inflation

According to the result of sensitivity analysis, the change of any input parameters has no impact on the final decision. Configuration C: capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6) remains the best option for all changes.

Tornado diagram for capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6) configuration is presented in Figure 19. Tornado diagram is used to perform sensitivity analysis, comparing the relative importance of initial data of the project. All input parameters changed by 20%.

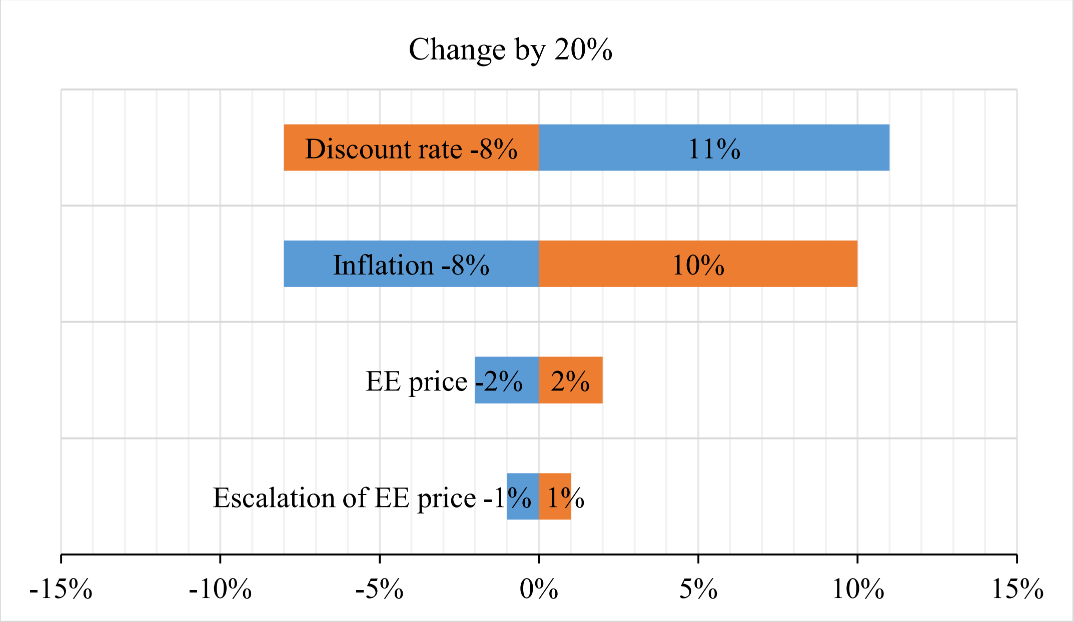

Figure 19. Tornado diagram

According to Tornado diagram, the EAA of the project is most affected by the discount rate and inflation. Such a high impact of inflation is explained by the large amount of savings overhaul of synchronous motors. EE price and escalation of EE price is also influenced but in less amount.

Conclusion

The goal of this work was to assess the quality of electrical energy of a drilling rig located at the Kazanskoye gas condensate field and propose measures to improve it.

The first step was to collect data of measurements of voltages, currents, active and reactive powers of the overhead line at the input to the drilling rig to calculate the parameters of EE quality. The measurements were obtained in the form of Excel datasheet [9] and presented in the work in the form of graphs.

The second step was to calculate the power and electrical energy losses in the distribution grid for the voltage level of 6 kV by the method of average loads. These losses are caused by the transmission of electrical energy to the end consumers and lead to an increase in overall temperature and local overheating in the windings of transformer, reduction in the service life of the insulation. Thus, the electrical energy losses in the overhead line were equal to 8 814.63 kW·h and in power transformer were 67 719.64 kW·h, the power losses in the overhead line were equal to 0.84 kW and in power transformer were 15.41 kW. To minimize the losses of power and EE in the electrical network, it was necessary to perform reactive power compensation.

The third step was to assess the voltage parameters of EE quality such as voltage deviation, negative sequence voltage unbalance factor, zero sequence voltage unbalance factor, and perform an analysis for compliance with the requirements of GOST 32144-2013 [1]. Based on calculations of EE quality parameters a significant deviation of the negative sequence voltage unbalance factor from the permissible values was noted. Such high value of negative sequence voltage unbalance factor (11.06%) was related with the occurrence of a temporary emergency at the enterprise due to the connection of the new load and then the tripping of the overcurrent protection.

Voltage unbalance leads to additional power losses in power lines, transformers, and electrical machines. Thus, the fourth step was to estimate the additional power losses caused by negative sequence voltage unbalance factor. Based on calculations, the additional power losses in the overhead line were equal to 0.78 kW, in synchronous motors were 5.91 kW, in power transformers were 0.81 kW. The total additional power losses 7.5 kW.

Finally, the following problems were identified: the necessity of reactive power compensation and the high negative sequence unbalance factor. To compensate the reactive power, it was proposed to use a capacitor unit with harmonic filters. A capacitor unit with harmonic filters:

- increases and maintains the value of the reactive power factor $tg\varphi$ at a given level 0.4 (power factor $cos\varphi$ at 0.8);
- decreases power and electrical energy losses: the difference between annual EE losses before and after compensation is 5 066.58 kW·h, between power losses is 7.33 kW;
- minimizes reactive energy bills, energy savings equal to 20 006 RUB/year.

If the enterprise prefers to change the network configuration, for example, to connect a new non-linear load in the future, and the relay protection trips again, then the capacitor unit with harmonic filters will be able to operate in the harmonic suppression mode and reduce the unbalance factor to the required value (decrease the voltage unbalance in the negative sequence up to 0.9%). In normal operation, the function of the capacitor unit is only reactive power compensation.

The second problem, high negative sequence voltage unbalance factor, was due to voltage dips. The solution was applied to recalculate short-circuit currents in dependence on minimum and maximum loads, select new high-voltage circuit breakers and recalculate relay protection settings. For these measures, high-voltage circuit breakers will be investment because the rest of the steps just require calculation. Such measures allowed:

- to decrease power and electrical energy losses caused by voltage unbalance: the difference between annual EE losses before and after measures is 111 725 kW·h, between power losses is 12.75 kW;
- to increase energy savings equal to 441 162 RUB/year due to the decrease in EE losses;
- to increase the service life of synchronous motors due to the decrease in the number of overhauls. The overhaul is carried out once a year due to non-compliance with the voltage unbalance factor according to norms and once every 3 years after proposed measures. Overhaul cost of one SM is equal to 3 000 000 RUB/year.

Also, the technical and economic comparison of three types of circuit breakers was completed: SF_6 circuit breaker of LF-1 type, vacuum circuit breakers VVU-SEShch-10 and BB/TEL-10(6). From the technical point of view, the improved characteristics among the considered circuit breakers are shown by the vacuum VVU-SEShch-10. VVU-SEShch-10 circuit breaker has less full shutdown time and full turn-on time, however BB/TEL-10(6) is lighter and has less own shutdown time, but it is inferior in full shutdown time to LF-1 circuit breaker. The vacuum circuit breakers VVU-SEShch-10 were chosen as the best option due to a high speed of operation.

The economic evaluation for proposed investments has been completed. From the economic point of view, the best option is to install capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6) due to the highest EAA. The sensitivity analysis was performed for this configuration. According to its result, the change of any input parameters has no impact on the final decision, configuration C: capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6) remains the best option for all changes. The project is most affected by the discount rate and inflation according to Tornado diagram.

Despite the negative NPV, the installing of capacitor unit with harmonic filters is necessary due to the requirements to maximum reactive power factor according to order of the Ministry of Energy [26]. The technical characteristics of the circuit breakers are slightly different, so it is possible to choose the profitable option: the installing BB/TEL-10(6) circuit breakers. In conclusion, I will recommend installing the capacitor unit with harmonic filters and vacuum circuit breakers BB/TEL-10(6).

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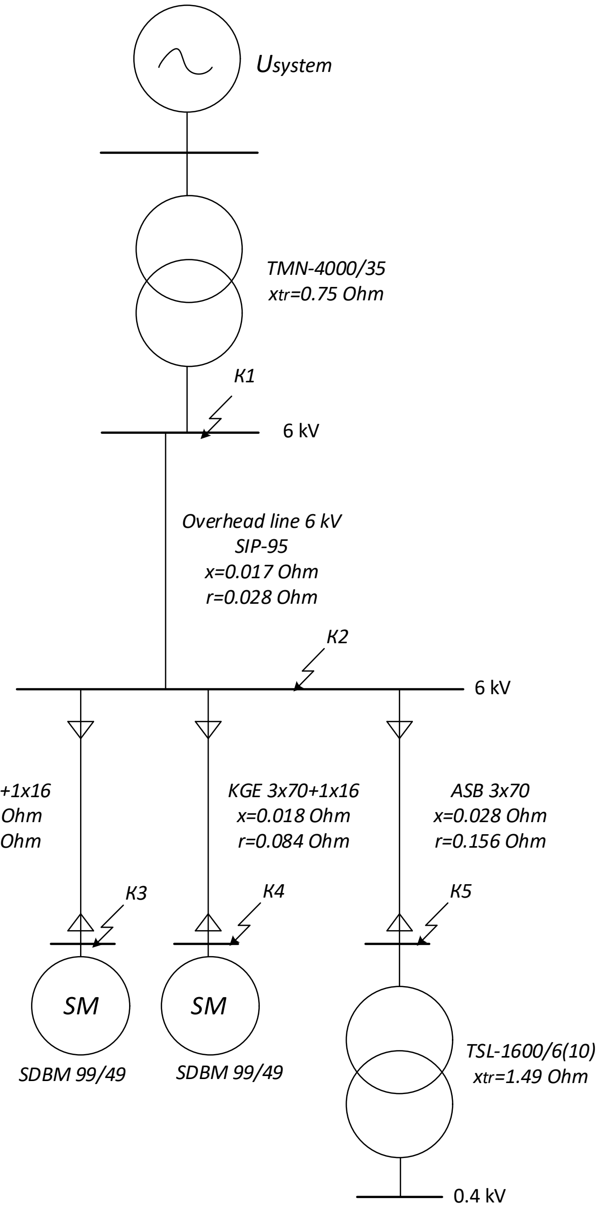
Appendices

Appendix A. The design diagram of the power supply system for 6 kV



According to scheme: K1-K5 – the points of short circuit;

TMN-4000/35 – T – transformer, M – oil, N – voltage regulation under load, 4000 kVA – rated capacity, 35 kV – primary voltage;

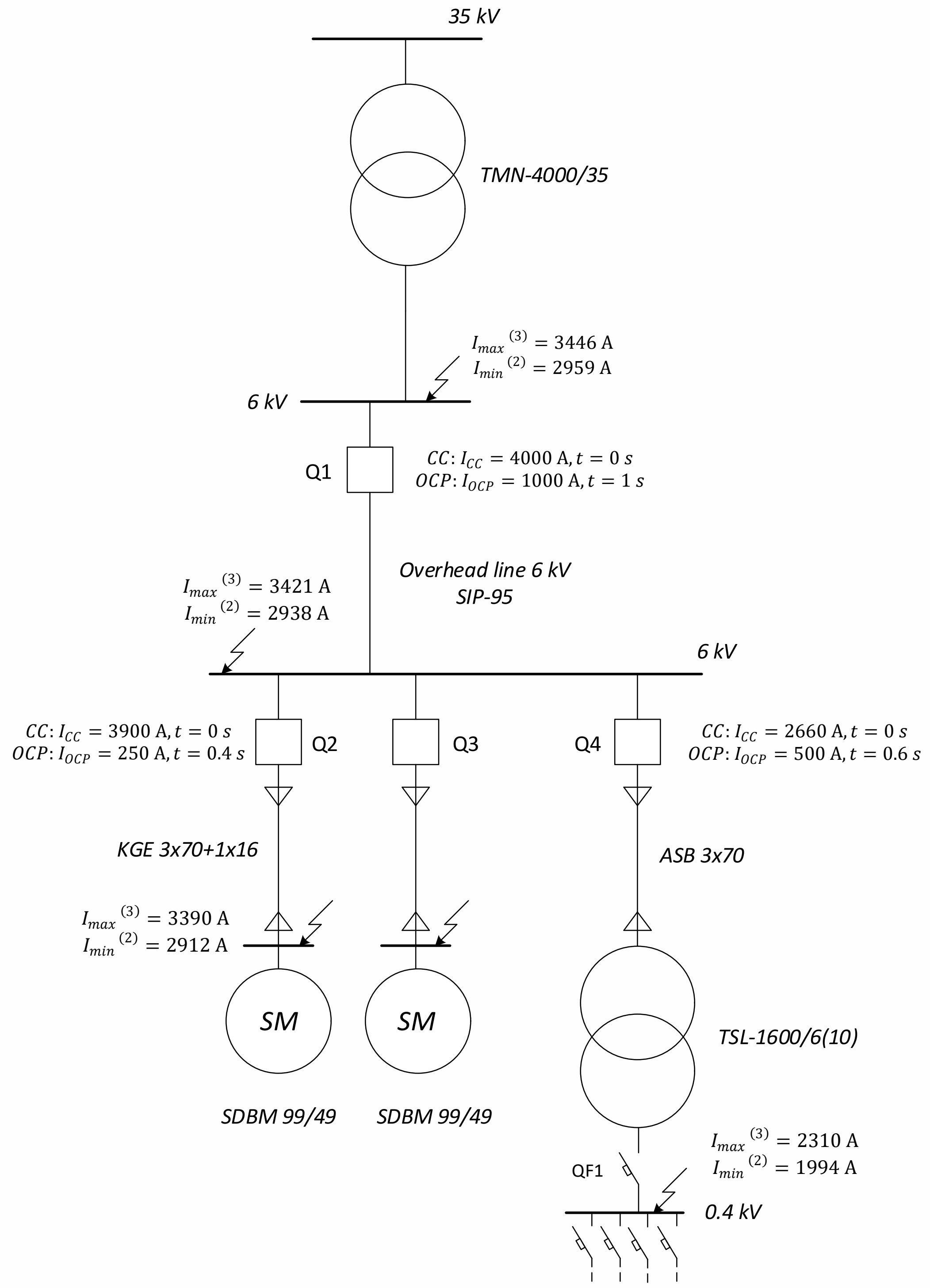
SIP-95 – self-supporting insulated wire with cross-section 95 mm^2;

KGE 3x70+1x16 – K – cable, G – flexible, E – shielded, 3 – number of main cores, 70 mm^2 – cross-section of main cores, 1 – additional core, 16 mm^2 – cross-section of additional core;

ASB 3x70 – cable, A - aluminum conductive core, S - lead sheath, B - armor of two steel strips, 3 – number of main cores, 70 mm^2 – cross-section of main cores;

TSL 1600/6(10) – T – transformer, S – dry, L – cast resin, 1600 kVA – rated capacity, 6(10) kV – primal voltage.

Appendix B. A network with indicated protection settings and currents reduced to 6 kV



According to scheme: CC– current cutoff protection,

OCP – overcurrent protection,

I_{CC} – the tripping current of current cutoff, [A],

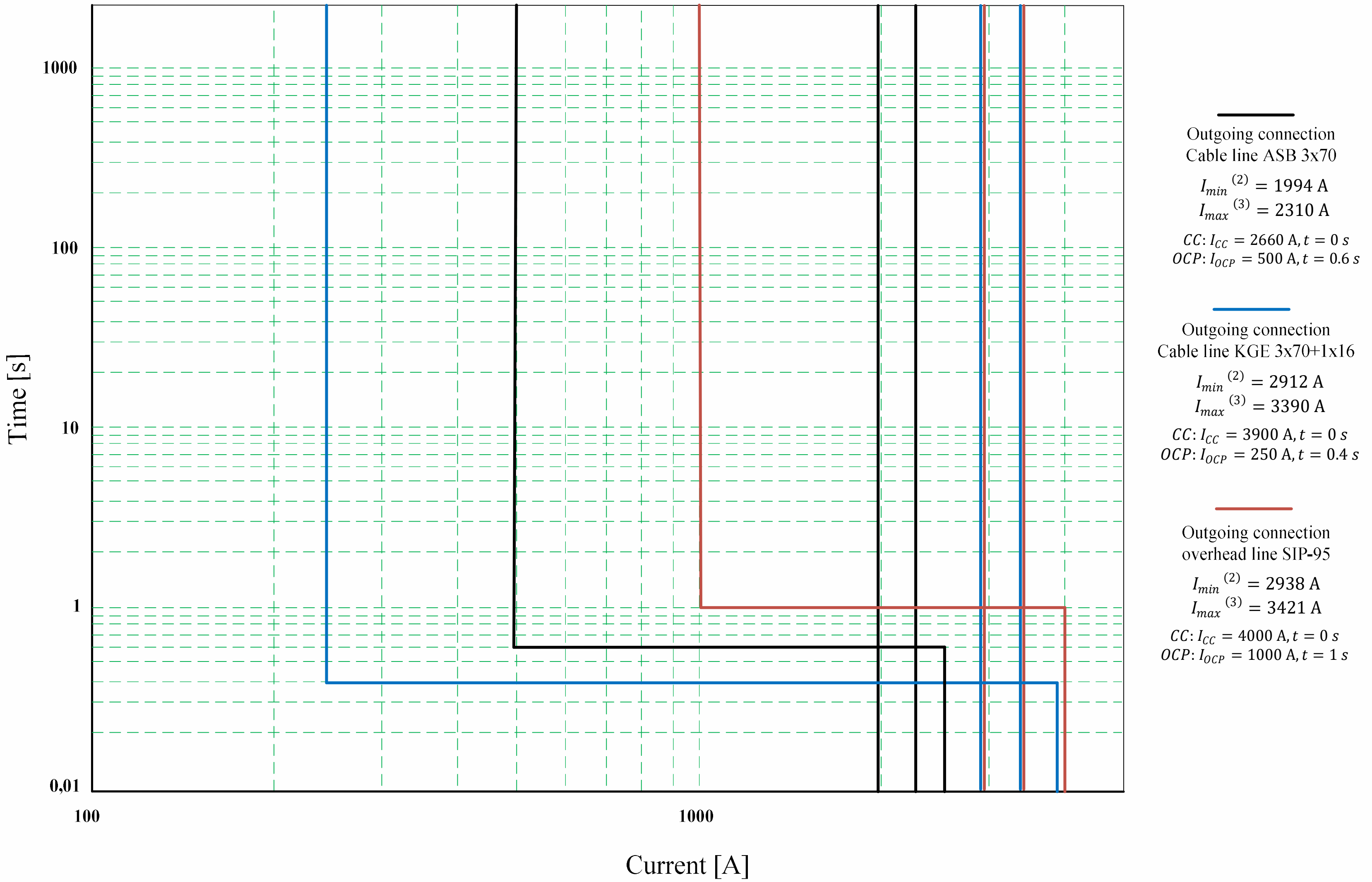
I_{OCP} – the tripping current of overcurrent protection, [A],

t – the response time, [s],

Q – the high-voltage circuit breaker,

QF – the low-voltage circuit breaker.

Appendix C. Selectivity map



According to map: CC– current cutoff protection, OCP – overcurrent protection, I_{CC} – the tripping current of current cutoff, [A], I_{OCP} – the tripping current of overcurrent protection, [A], t – the response time, [s], $I_{min}^{(2)}$ – two-phase minimum short circuit current, [A], $I_{max}^{(3)}$ – the three-phase maximum short-circuit current, [A].

Appendix D. Economic evaluation: the capacitor unit with harmonic filters

Year	0	1	2	3	4	5	6	7	8	9
Investment [RUB]	2 622 169									
Technical maintenance [RUB]		2 662	2 835	3 019	3 216	3 425	3 647	3 884	4 137	4 406
Depreciation [RUB]		262 217	235 995	212 396	191 156	172 041	154 836	139 353	125 418	112 876
Energy savings+Escalation [RUB]		20 006	21 006	22 057	23 160	24 318	25 533	26 810	28 151	29 558
EBT [RUB]		-244 873	-217 824	-193 358	-171 212	-151 148	-132 950	-116 427	-101 404	-87 723
Tax shield [RUB]		-48 975	-43 565	-38 672	-34 242	-30 230	-26 590	-23 285	-20 281	-17 545
EAT [RUB]		-195 898	-174 259	-154 687	-136 970	-120 918	-106 360	-93 142	-81 123	-70 179
Cash flow [RUB]	-2 622 169	66 319	61 736	57 709	54 186	51 122	48 476	46 211	44 295	42 697
DCF [RUB]		56 259	44 428	35 231	28 063	22 460	18 067	14 611	11 880	9 715

Year	10	11	12	13	14	15	16	17	18	19	20
Investment [RUB]											
Technical maintenance [RUB]	4 692	4 997	5 322	5 668	6 036	6 428	6 846	7 291	7 765	8 270	0
Depreciation [RUB]	101 588	91 429	91 429	91 429	91 429	91 429	91 429	91 429	91 429	91 429	91 429
Energy savings+Escalation [RUB]	31 036	32 588	34 217	35 928	37 724	39 611	41 591	43 671	45 854	48 147	50 554
EBT [RUB]	-75 244	-63 838	-62 534	-61 169	-59 741	-58 247	-56 684	-55 050	-53 340	-51 552	-40 875
Tax shield [RUB]	-15 049	-12 768	-12 507	-12 234	-11 948	-11 649	-11 337	-11 010	-10 668	-10 310	-8 175
EAT [RUB]	-60 195	-51 071	-50 027	-48 935	-47 793	-46 598	-45 347	-44 040	-42 672	-41 242	-32 700
Cash flow [RUB]	41 393	40 359	41 402	42 494	43 637	44 832	46 082	47 390	48 757	50 188	58 729
DCF [RUB]	7 990	6 608	5 751	5 007	4 362	3 802	3 315	2 892	2 524	2 204	2 188

NPV=-2 334 811 [RUB]

Appendix E. Economic evaluation: SF_6 circuit breakers LF-1

Year	0	1	2	3	4	5	6	7	8	9
Investment [RUB]	974 156									
Technical maintenance [RUB]										
Depreciation [RUB]		77 932	71 698	65 962	60 685	55 830	51 364	47 255	43 474	39 996
Increasing the service life of SM [RUB]		6 000 000	6 390 000	0	7 247 698	7 718 798	0	8 754 854	9 323 919	0
Energy savings+Escalation [RUB]		441 162	463 220	486 381	510 700	536 235	563 047	591 199	620 759	651 797
EBT [RUB]		6 363 229	6 781 522	420 419	7 697 713	8 199 203	511 683	9 298 798	9 901 204	611 801
Tax [RUB]		1 272 646	1 356 304	84 084	1 539 543	1 639 841	102 337	1 859 760	1 980 241	122 360
EAT [RUB]		5 090 584	5 425 218	336 335	6 158 170	6 559 362	409 346	7 439 039	7 920 963	489 441
Cash flow [RUB]	-974 156	5 168 516	5 496 916	402 297	6 218 855	6 615 193	460 710	7 486 293	7 964 438	529 437
DCF [RUB]		4 384 557	3 955 841	245 599	3 220 698	2 906 309	171 707	2 366 933	2 136 162	120 463

Year	10	11	12	13	14	15	16	17	18
Investment [RUB]									
Technical maintenance [RUB]	59 462								
Depreciation [RUB]	36 797	33 853	31 145	28 653	27 459	27 459	27 459	27 459	27 459
Increasing the service life of SM [RUB]	10 575 422	11 262 825	0	12 774 577	13 604 925	0	15 431 046	16 434 064	0
Energy savings+Escalation [RUB]	684 387	718 606	754 537	792 264	831 877	873 471	917 144	963 001	1 011 151
EBT [RUB]	11 163 551	11 947 578	723 392	13 538 188	14 409 342	846 011	16 320 731	17 369 606	983 692
Tax [RUB]	2 232 710	2 389 516	144 678	2 707 638	2 881 868	169 202	3 264 146	3 473 921	196 738
EAT [RUB]	8 930 840	9 558 063	578 714	10 830 550	11 527 474	676 809	13 056 585	13 895 685	786 954
Cash flow [RUB]	8 967 637	9 591 916	609 858	10 859 203	11 554 933	704 268	13 084 044	13 923 144	814 413
DCF [RUB]	1 730 919	1 570 594	84 712	1 279 606	1 155 063	59 722	941 239	849 680	42 162

Year	19	20	21	22	23	24	25
Investment [RUB]							
Technical maintenance [RUB]		111 618					
Depreciation [RUB]	27 459	27 459	27 459	27 459	27 459	27 459	27 459
Increasing the service life of SM [RUB]	18 639 926	0	21 141 870	22 516 092	0	25 538 314	27 198 305
Energy savings+Escalation [RUB]	1 061 709	1 114 794	1 170 534	1 229 061	1 290 514	1 355 039	1 422 791
EBT [RUB]	19 674 176	975 717	22 284 945	23 717 693	1 263 054	26 865 895	28 593 637
Tax [RUB]	3 934 835	195 143	4 456 989	4 743 539	252 611	5 373 179	5 718 727
EAT [RUB]	15 739 341	780 573	17 827 956	18 974 155	1 010 444	21 492 716	22 874 910
Cash flow [RUB]	15 766 800	808 033	17 855 415	19 001 614	1 037 903	21 520 175	22 902 369
DCF [RUB]	692 438	30 104	564 322	509 457	23 607	415 224	374 867

NPV= 28 857 830 [RUB]

Appendix F. Economic evaluation: vacuum circuit breakers VVU-SEShch-10

Year	0	1	2	3	4	5	6	7	8	9
Investment [RUB]	918 156									
Technical maintenance [RUB]										
Depreciation [RUB]		61 210	57 130	53 321	49 766	46 449	43 352	40 462	37 764	35 247
Increasing the service life of SM [RUB]		6 000 000	6 390 000	0	7 247 698	7 718 798	0	8 754 854	9 323 919	0
Energy savings+Escalation [RUB]		441 162	463 220	486 381	510 700	536 235	563 047	591 199	620 759	651 797
EBT [RUB]		6 379 952	6 796 090	433 060	7 708 632	8 208 585	519 695	9 305 591	9 906 914	616 550
Tax [RUB]		1 275 990	1 359 218	86 612	1 541 726	1 641 717	103 939	1 861 118	1 981 383	123 310
EAT [RUB]		5 103 961	5 436 872	346 448	6 166 905	6 566 868	415 756	7 444 473	7 925 531	493 240
Cash flow [RUB]	-918 156	5 165 172	5 494 002	399 769	6 216 672	6 613 316	459 108	7 484 935	7 963 296	528 487
DCF [RUB]		4 381 720	3 953 744	244 056	3 219 567	2 905 485	171 109	2 366 503	2 135 855	120 247

Year	10	11	12	13	14	15	16	17	18
Investment [RUB]									
Technical maintenance [RUB]	59 462								
Depreciation [RUB]	32 897	30 704	28 657	26 746	24 963	23 299	21 746	21 746	21 746
Increasing the service life of SM [RUB]	10 575 422	11 262 825	0	12 774 577	13 604 925	0	15 431 046	16 434 064	0
Energy savings+Escalation [RUB]	684 387	718 606	754 537	792 264	831 877	873 471	917 144	963 001	1 011 151
EBT [RUB]	11 167 450	11 950 727	725 880	13 540 094	14 411 838	850 171	16 326 444	17 375 319	989 405
Tax [RUB]	2 233 490	2 390 145	145 176	2 708 019	2 882 368	170 034	3 265 289	3 475 064	197 881
EAT [RUB]	8 933 960	9 560 582	580 704	10 832 076	11 529 471	680 137	13 061 155	13 900 256	791 524
Cash flow [RUB]	8 966 857	9 591 286	609 361	10 858 822	11 554 434	703 436	13 082 901	13 922 001	813 270
DCF [RUB]	1 730 768	1 570 491	84 643	1 279 561	1 155 013	59 652	941 157	849 610	42 103

Year	19	20	21	22	23	24	25	26	27
Investment [RUB]									
Technical maintenance [RUB]		111 618							
Depreciation [RUB]	21 746	21 746	21 746	21 746	21 746	21 746	21 746	21 746	21 746
Increasing the service life of SM [RUB]	18 639 926	0	21 141 870	22 516 092	0	25 538 314	27 198 305	0	30 848 997
Energy savings+Escalation [RUB]	1 061 709	1 114 794	1 170 534	1 229 061	1 290 514	1 355 039	1 422 791	1 493 931	1 568 628
EBT [RUB]	19 679 889	981 430	22 290 659	23 723 407	1 268 768	26 871 608	28 599 350	1 472 185	32 395 879
Tax [RUB]	3 935 978	196 286	4 458 132	4 744 681	253 754	5 374 322	5 719 870	294 437	6 479 176
EAT [RUB]	15 743 911	785 144	17 832 527	18 978 725	1 015 014	21 497 286	22 879 480	1 177 748	25 916 703
Cash flow [RUB]	15 765 657	806 890	17 854 273	19 000 471	1 036 760	21 519 032	22 901 226	1 199 494	25 938 449
DCF [RUB]	692 388	30 062	564 286	509 427	23 581	415 202	374 848	16 655	305 535

Year	28	29	30
Investment [RUB]			
Technical maintenance [RUB]			0
Depreciation [RUB]	21 746	21 746	21 746
Increasing the service life of SM [RUB]	32 854 182	0	37 264 035
Energy savings+Escalation [RUB]	1 647 059	1 729 412	1 815 882
EBT [RUB]	34 479 495	1 707 666	39 058 171
Tax [RUB]	6 895 899	341 533	7 811 634
EAT [RUB]	27 583 596	1 366 133	31 246 537
Cash flow [RUB]	27 605 342	1 387 879	31 268 283
DCF [RUB]	275 848	11 765	224 854

NPV=29 737 579 [RUB]

Appendix G. Economic evaluation: vacuum circuit breakers BB/TEL-10(6)

Year	0	1	2	3	4	5	6	7	8	9
Investment [RUB]	1 026 156									
Technical maintenance [RUB]										
Depreciation [RUB]		82 092	75 525	69 483	63 924	58 810	54 106	49 777	45 795	42 131
Increasing the service life of SM [RUB]		6 000 000	6 390 000	0	7 247 698	7 718 798	0	8 754 854	9 323 919	0
Energy savings+Escalation [RUB]		441 162	463 220	486 381	510 700	536 235	563 047	591 199	620 759	651 797
EBT [RUB]		6 359 069	6 777 695	416 898	7 694 473	8 196 223	508 941	9 296 276	9 898 883	609 666
Tax [RUB]		1 271 814	1 355 539	83 380	1 538 895	1 639 245	101 788	1 859 255	1 979 777	121 933
EAT [RUB]		5 087 256	5 422 156	333 518	6 155 579	6 556 978	407 153	7 437 021	7 919 107	487 733
Cash flow [RUB]	-1 026 156	5 169 348	5 497 681	403 001	6 219 503	6 615 789	461 259	7 486 798	7 964 902	529 864
DCF [RUB]		4 385 263	3 956 392	246 029	3 221 033	2 906 571	171 911	2 367 092	2 136 286	120 560

Year	10	11	12	13	14	15	16	17	18
Investment [RUB]									
Technical maintenance [RUB]	59 462								
Depreciation [RUB]	38 761	35 660	32 807	30 183	28 925	28 925	28 925	28 925	28 925
Increasing the service life of SM [RUB]	10 575 422	11 262 825	0	12 774 577	13 604 925	0	15 431 046	16 434 064	0
Energy savings+Escalation [RUB]	684 387	718 606	754 537	792 264	831 877	873 471	917 144	963 001	1 011 151
EBT [RUB]	11 161 586	11 945 771	721 729	13 536 658	14 407 877	844 545	16 319 265	17 368 140	982 226
Tax [RUB]	2 232 317	2 389 154	144 346	2 707 332	2 881 575	168 909	3 263 853	3 473 628	196 445
EAT [RUB]	8 929 269	9 556 617	577 384	10 829 327	11 526 301	675 636	13 055 412	13 894 512	785 781
Cash flow [RUB]	8 968 030	9 592 277	610 191	10 859 509	11 555 226	704 561	13 084 337	13 923 437	814 706
DCF [RUB]	1 730 995	1 570 653	84 759	1 279 642	1 155 092	59 747	941 260	849 697	42 177

Year	19	20	21	22	23	24	25
Investment [RUB]							
Technical maintenance [RUB]		111 618					
Depreciation [RUB]	28 925	28 925	28 925	28 925	28 925	28 925	28 925
Increasing the service life of SM [RUB]	18 639 926	0	21 141 870	22 516 092	0	25 538 314	27 198 305
Energy savings+Escalation [RUB]	1 061 709	1 114 794	1 170 534	1 229 061	1 290 514	1 355 039	1 422 791
EBT [RUB]	19 672 710	974 251	22 283 479	23 716 228	1 261 589	26 864 429	28 592 171
Tax [RUB]	3 934 542	194 850	4 456 696	4 743 246	252 318	5 372 886	5 718 434
EAT [RUB]	15 738 168	779 401	17 826 783	18 972 982	1 009 271	21 491 543	22 873 737
Cash flow [RUB]	15 767 093	808 326	17 855 709	19 001 907	1 038 196	21 520 468	22 902 662
DCF [RUB]	692 451	30 115	564 332	509 465	23 613	415 230	374 872

NPV= 28 809 083 [RUB]