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Optimization approach to reduce the negative impact of high harmonic components of currents and voltages in high-voltage mine networks

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Abstract. The article presents an analysis of the work of the high-voltage mine network, which confirms the presence of higher harmonic components of currents and voltages of significant magnitude and their negative impact on the elements of the power supply system. The most pronounced higher harmonics of currents and voltages in the high-voltage mine network, as well as the most probable ranges of load currents and distortion currents are revealed. It is proved that the load change in the mine network as a function of time refers to random processes. The mathematical apparatus of the theory of random processes was used to study and predict load currents and distortion currents. The obtained quantitative values of trends of load currents and distortion currents were used in the estimation of power losses and in the calculation of parameters of filter compensating devices. An optimization approach is proposed to reduce the negative influence of higher harmonic components of currents and voltages, based on minimizing the target function of additional active power losses from the action of higher harmonics. To reduce the negative impact of higher harmonic components of currents and voltages in the high-voltage mine network, it is proposed to use two resonant passive filters tuned to the 11-th and 13-th harmonics, and a second-order broadband filter tuned to compensate harmonics, starting from the 23-rd and above.

1. Introduction

An important task in the power supply systems of ore mining enterprises in particular and in modern energy in General is to ensure electromagnetic compatibility (EMC) in electrical networks and reduce power losses and electricity due to the presence of powerful electrical receivers with nonlinear voltage characteristics. The most energy-intensive electric receivers in such systems are cage and skip lifting installations (LI) (Figure 1). As electric drives of LI the adjustable electric drive executed on system the thyristor Converter – the DC motor with independent excitation (TP-D) is used. LI, as a rule, work in repeatedly-short - term modes of rise-lowering on the set diagrams of movement. The time of movement of skips per cycle is 160 s, stands-170 s. in the cycles of LI operation, dynamic processes prevail, the duration of which is 46-50 % of the total cycle time [1].

In thyristor converters of electric drives LI used 12-pulse rectifier circuit. Electric drives of lifting units have a deep range of speed control due to changes in the voltage at the output of thyristor converters. During operation, the electric drives of LI generate higher harmonic (HG) components of currents and voltages into the supply network. Harmonics of the 11th, 13th, 23rd, 25th, 35th and 37th or-

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ders appear in the supply voltage [1-3]. This leads to a decrease in the quality of electricity and violation of electromagnetic compatibility, to additional power losses in the elements of high-voltage power supply systems of mining enterprises [4-8]. Therefore, minimizing power losses due to the presence of higher harmonic components of currents and voltages is an important and urgent task for both mine electric networks and general purpose power supply systems.

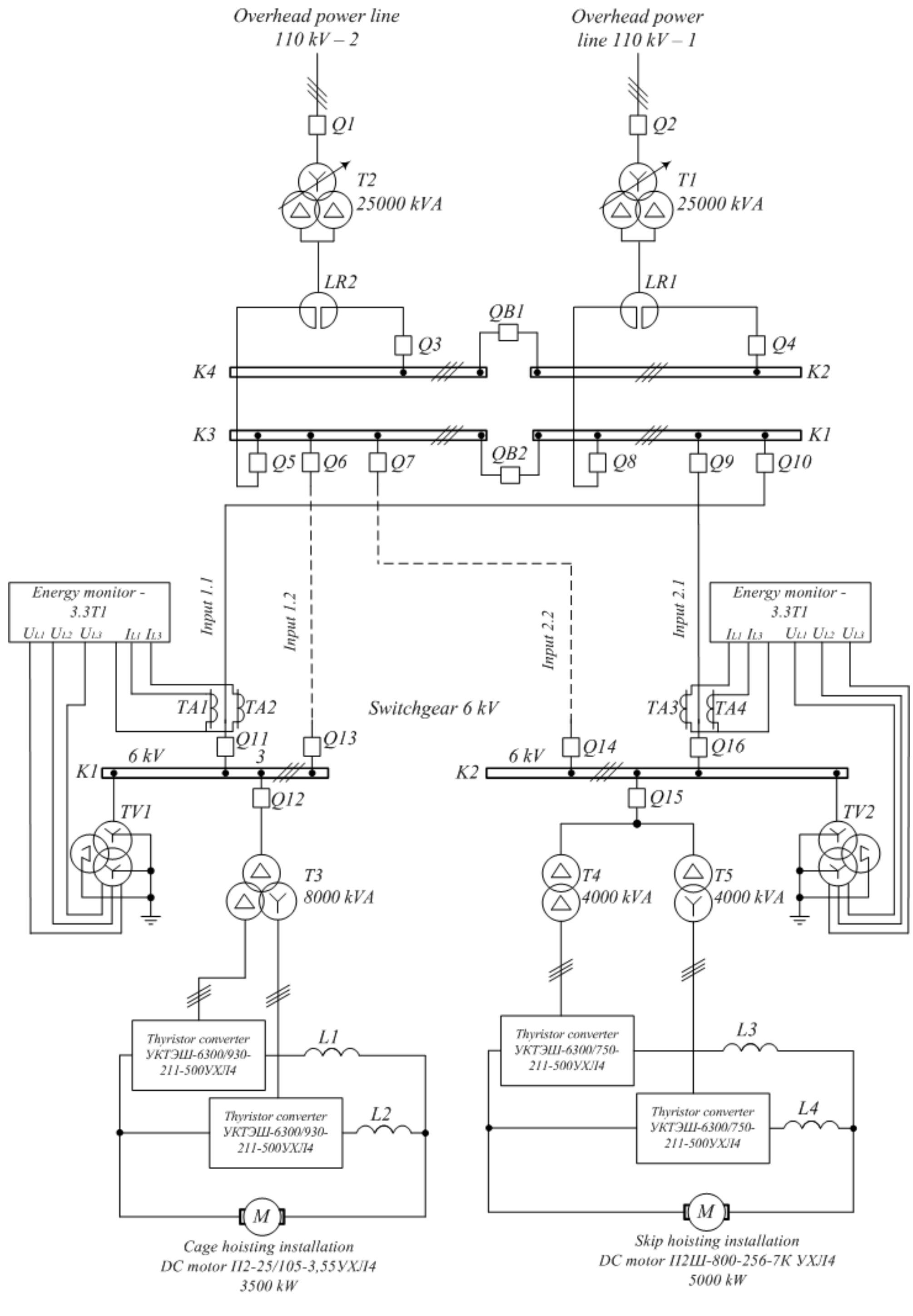

Figure 1. A fragment of the mining enterprise power supply scheme.

2. Materials and Methods

The estimation of EMC and power losses in the high-voltage mine network was carried out with the help of experimental studies, engineering calculation and simulation in the Matlab system with the Simulink extension package and the SimPowerSystems library [9, 10]. The measurements were carried out in a 6 kV switchgear on the busbar sections of a transformer substation providing power supply to the hoisting units. The location of the measurements is shown in fig. 1. Measurements are made in accordance with the requirements of GOST 30804.4.7–2013, continuously for a specified period of time for an average of three days, certified devices "Energomonitor-3.3 T1" and C. A 8335 [1, 2, 4, 9].

The fragment of results of measurements of values of parameters during operation of drives of skip and cage LI is resulted in table 1.

Table 1. Parameters of modes and indicators of EMC current.

Time	I, A	K_I, %	$I_{(1)}$, A	$K_{I\,(11)}$, %	$K_{I\,(13)}$, %	$K_{I\,(23)}$, %	$K_{I\,(25)}$, %	$K_{I\,(35)}$, %	$K_{I\,(37)}$, %
Skip LI (Energy r monitor - 3.3T1)									
17:33	311.44	8.58	308.51	5.57	4.22	2.14	2.05	1.03	1.07
17:55	332.93	8.57	329.57	5.64	4.3	2.15	2.04	1.02	1.01
18:34	323.76	9.92	269.26	5.56	4.28	2.26	1.97	1.1	0.81
18:37	370.94	8.81	321.04	5.51	4.35	2.06	2.08	0.95	1.02
18:41	311.44	8.1	369.86	5.76	4.4	2.1	2.14	0.97	1.15
Cage LI (Energy monitor - 3.3T1)									
17:43	287.03	7	288.46	5.57	1.58	2.08	0.9	0.96	0.75
17:44	447.83	9.21	439.80	7.1	2.69	2.85	1.04	1.32	0.81
17:44	435.17	9.37	438.84	7.18	2.83	2.92	1.08	1.38	0.81
17:44	408.48	9.51	409.92	7.1	2.79	2.89	1.1	1.38	0.85
17:44	310.80	8.53	323.47	6.28	2.2	2.45	1.04	1.17	0.86

As a result of measurements spectra of HG of currents and voltages in a high-voltage mine network are received. For figure 2 the spectra of harmonics of currents in the networks of 6 kV cage and skip LI of the operating ore mining enterprise are presented.

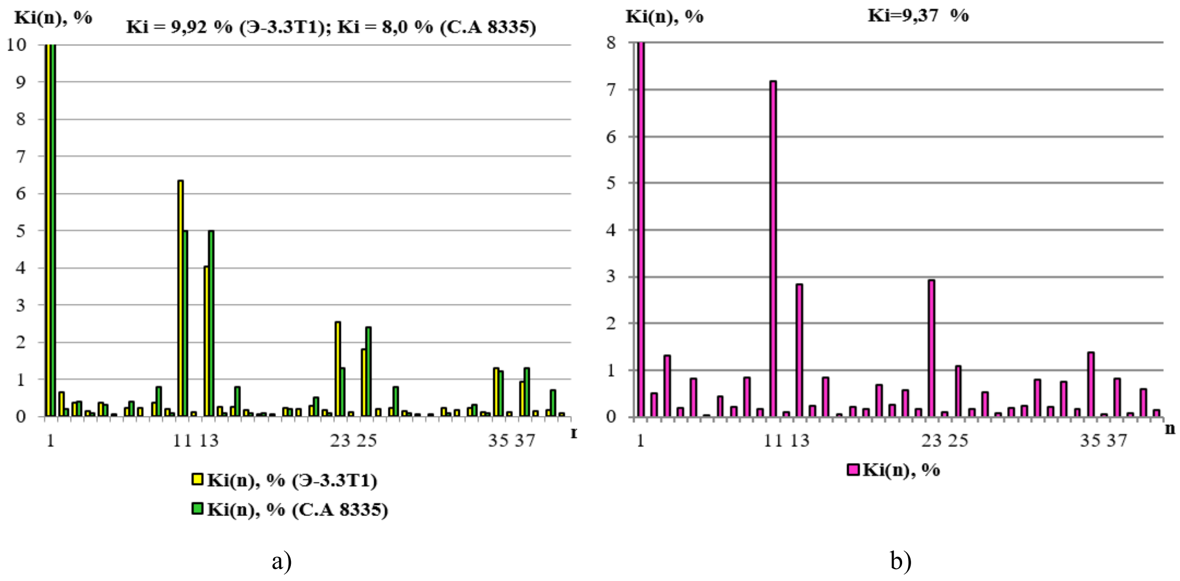

Figure 2. Spectra of current harmonics in high-voltage mine power supply system: a) – skip LI; b) – cage LI.

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The results of the measurements confirm that the most pronounced are the 11, 13, 23, 25, 35 and 37 harmonics of current and voltage in the high-voltage mine power supply system. The values of the coefficients of these harmonic components of the current, respectively, were:

Energy monitor-3.3T1:

Skip LI: $K_{I(11)}$ = 5,56 %, $K_{I(13)}$= 4,28 %, $K_{I(23)}$= 2,26 %, $K_{I(25)}$= 1,97 %, $K_{I(35)}$= 1,1 %, $K_{I(37)}$= 0,81 %;
Cage LI: $K_{I(11)}$= 7,18 %, $K_{I(13)}$= 2,83 %, $K_{I(23)}$= 2,92 %, $K_{I(25)}$= 1,08 %, $K_{I(35)}$= 1,38 %, $K_{I(37)}$= 0,81 %;

C.A 8335:

Skip LI: $K_{I(11)}$= 5,0 %, $K_{I(13)}$= 5,0 %, $K_{I(23)}$= 1,3 %, $K_{I(25)}$= 2,4 %, $K_{I(35)}$= 1,2 %, $K_{I(37)}$= 1,3 %.

The maximum values of the total coefficients of the harmonic components of the current in the high-voltage mine network of skip and cage lifting units, respectively, were K_I= 9,92 % and K_I= 9,37 %. The values of the coefficients of the 11-th and 13-th harmonic components of the current have the highest level (fig. 2). The maximum values of the total coefficients of the harmonic components of the voltage were K_U= 11,32 % and K_U= 17,87 % for skip and cage LI, respectively [1, 2, 9].

The reliability of the experimental results is confirmed by the results of simulation and engineering calculations. They showed that the total coefficients of harmonic components of currents and voltages in the high-voltage mine network reach on average K_I= 8-10% and K_U= 12-17%, respectively. The reliability of the results is confirmed by a good correlation between the results of experimental studies, simulation and engineering calculations, the degree of discrepancy did not exceed 10-12 %.

The load in the high-voltage power supply system is random, which is associated with the loading of LI, with the time of day. The change in load as a function of time refers to random processes. The mathematical model of a random stationary process of load current change is given in the form of a ratio:

$$I_{(1)j} = \varphi(t_j) + \Delta_j \tag{1}$$

where $I_{(1)j}$ – values reflecting a number of observations (j = 1, 2,..., n); $\varphi(t_j)$ – some deterministic function reflecting the General trend of $I_{(1)j}$ (sometimes called "deterministic component" or "trend"); Δ_j – random deviations occurring during the process $I_{(1)j}$.

Random processes of changing the parameters of load graphs proceed uniformly and have the form of continuous random oscillations around a certain average value. Different implementations of the main frequency current load graphs have a high correlation. It follows from the results that the changes in the parameters of the load graphs correspond to stationary random processes. Often a deterministic function is represented by a polynomial of K-th degree:

$$I_{(1)}(t) = C_0 + C_1 t + C_2 t^2 + \ldots + C_k t^k = \sum_{j=0}^{k} C_j t^j \tag{2}$$

The mathematical apparatus of the theory of random processes was used to study and predict load currents and distortion currents. Several implementations of daily load schedules with a time interval per minute during the period of operation of the LI for a working shift are arbitrarily selected (fig. 3). The results of the study and processing of load graphs confirmed that the changes in the parameters of the load graphs correspond to stationary random processes.

In order to obtain deterministic functions reflecting the General trend of load graphs in the high-voltage mine network according to the considered parameters, their approximation by polynomials of the 6-th order is performed. For example, the fundamental frequency current and distortion current trend equations are as follows:

$$I_{(1)} = -3\cdot10^{-10}\cdot t^6 - 6\cdot10^{-8}\cdot t^5 + 3\cdot10^{-5}\cdot t^4 - 0.0025\cdot t^3 + 0.0653\cdot t^2 + 0.3552\cdot t + 255.5 \tag{3}$$

$$I_D = 6\cdot10^{-11}\cdot t^6 - 3\cdot10^{-8}\cdot t^5 + 5\cdot10^{-6}\cdot t^4 - 0.0004\cdot t^3 + 0.0107\cdot t^2 - 0.0745\cdot t + 17.657 \tag{4}$$

The values of the constant coefficients of the deterministic functions of the load graphs of the high-voltage mine network for the considered parameters are presented in table 2.

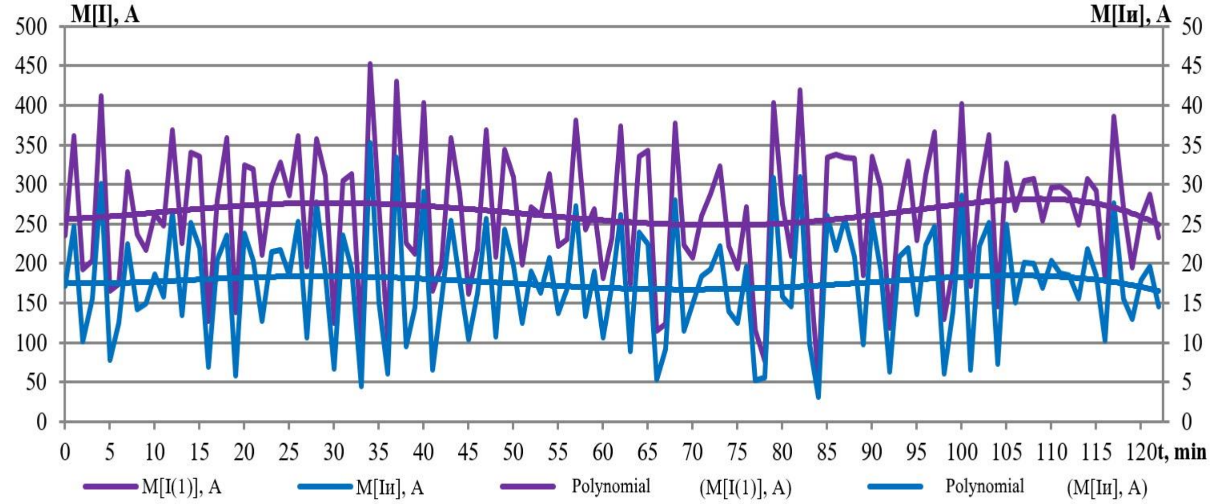

Figure 3. Graphs of current changes in the high-voltage mine power supply system and distortion current during the period of operation of the LI with graphs of deterministic functions.

Graphs of trends of the fundamental frequency currents and distortion are shown in figure 3. The obtained quantitative values of load current trends and distortion currents are used to estimate power losses. Also, these values can be used to calculate the parameters of filter-compensating devices (FCD) used to provide compensation of HG currents and voltages in the high-voltage mine network.

Table 2. The value of the constant coefficients of the deterministic function.

$I_{(1)}$, A	I_D, A	$I_{(11)}$, A	$I_{(13)}$, A	$I_{(23)}$, A	$I_{(25)}$, A	$I_{(35)}$, A	$I_{(37)}$, A
Skip LI							
255.5	17.66	12.93	9.57	4.76	4.52	2.14	2.07
Cage LI							
265.6	18.49	13.43	7.75	4.87	1.99	2.13	1.56

Additional power losses in non-sinusoidal regimes, taking into account the obtained trend values, were determined as the sum of losses in cable and overhead lines, reactors and transformers [4, 7, 8]. Thus losses from currents of the most expressed 11-th, 13-th, 23-rd and 25-th highest harmonic components were considered. To minimize active power losses in non-sinusoidal modes in high-voltage mine networks, an optimization problem based on minimizing the loss function is solved [9, 11, 12]. The target function was minimized:

$$\Delta P_{\Sigma add} = \sum_{j=1}^{p}\left(\Delta P_{PLj} + \Delta P_{Rj} + \Delta P_{Tj}\right) \to \min \tag{5}$$

Power losses in power lines:

$$\Delta P_{PL} = 3 \cdot \sum_{n=2}^{p} I_n^2 \cdot R_{PL} \cdot k_{rn} \tag{6}$$

where n is the number of harmonics; p – number of considered harmonics; I_n – current n-th harmonic; R_{PL} – active line resistance at the fundamental frequency; k_{rn} – coefficient of increase of resistance in transmission lines, taking into account the influence of surface effect.

Power losses from HG currents in reactors:

$$\Delta P_R = 3 \cdot \sum_{n=2}^{p} I_n^2 \cdot R_R \cdot k_{rn} \tag{7}$$

Power losses in transformers:

$$\Delta P_T = \Delta P_{NL} \cdot \sum_{n=2}^{p} \left(\frac{U_n}{U_{nom}} \right)^2 + 0,607 \cdot \frac{\Delta P_{SC}}{u_{SC}^2} \cdot \sum_{n=2}^{p} \frac{1 + 0,05 \cdot n^2}{n\sqrt{n}} \cdot \left(\frac{U_n}{U_{nom}} \right)^2 \tag{8}$$

where ΔP_{NL} – transformer idling losses; n – harmonic number; p – number of considered harmonics; ΔP_{SC} – transformer short-circuit losses; u_{SC} – transformer short-circuit voltage; U_n – voltage of the n-th harmonic; U_{nom} – rated voltage.

The target function has the following limitations:

$$\begin{cases} I_{11} + I_{13} + I_{23} + I_{25} \le I_{\mathrm{D}}, \\ \delta U < \delta U_{allow}, \\ K_U \le K_{U\,\mathrm{allow}}, \end{cases} \tag{9}$$

where I_D is the value of the distortion current created by the higher harmonic components. The limitations are due to the fact that voltage deviations in the power supply system should not exceed the permissible value, and compensation of higher harmonics currents is carried out to the permissible level of non-sinusoidal supply voltage.in this case the target function has the following limitations.

3. Results

Additional power losses in the elements of the mine network in non-sinusoidal modes, taking into account the trends of HG currents, respectively amounted to: for skip LI ΔP_{add}= 9,16 kW, for cage LI ΔP_{add}= 24 kW. Total additional power losses in the high-voltage mine network amounted to $\Delta P_{\Sigma add}$= 33,16 kW. The obtained values of additional power losses have a significant value and are approximately from 16,5 to 44 % of the main losses. The optimization problem was solved by the method of indefinite Lagrange multipliers, as a result of its solution the following values of higher harmonic currents were obtained:

$$I_{11} = 6{,}476\ \mathrm{A};\ I_{13} = 5{,}957\ \mathrm{A};\ I_{23} = 4{,}479\ \mathrm{A};\ I_{25} = 4{,}296\ \mathrm{A}.$$

In this case, the coefficients of the most pronounced harmonic components of the currents take the following values:

$$K_{I_{11}} = 2{,}319\%;\ K_{I_{13}} = 2{,}133\%;\ K_{I_{23}} = 1{,}604\%;\ K_{I_{25}} = 1{,}538\%.$$

The results of solving the optimization problem show that for minimizing of the objective function and reduce the total additional active power losses caused by higher harmonic components, it is necessary to compensate for the 11-th and 13-th harmonics and to reduce the level of 23-rd and 25-th harmonics.

An effective way to compensate for HG currents is the use of various types of passive filters (PF) [5, 6, 8, 12-15]. In this case, it can be proposed to install film-compensating devices with two resonant PF tuned to the 11-th and 13-th harmonics, and a second-order broadband filter tuned to compensate harmonics starting from the 23-rd and above [6, 8, 15]. The place of installation of FCD – on tires of 6 kV of the switchgear of lifting machines. Calculation of parameters of FCD is offered to be carried out according to the techniques offered in [6, 8, 12, 16-20].

When installing the proposed FCD on 6 kV tires of the switchgear of lifting machines and when compensating the higher harmonics of currents to the values obtained as a result of solving the optimization problem, the total loss of active power is reduced to the value $\Delta P_{\Sigma add}$= 12,59 kW, that is, more than 60 % (figure 4).

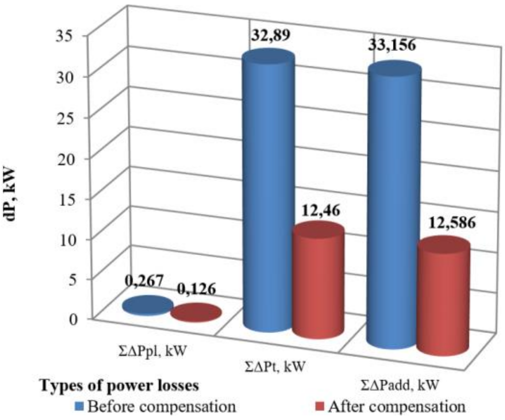

Figure 4. Histogram of additional power losses in high-voltage mine power supply system before and after compensation of HG.

4. Conclusion

The results of experimental studies, simulation and engineering calculations in the high-voltage mine network of lifting units of the ore-producing enterprise confirmed the presence of higher harmonic components of currents and voltages. At the same time, the results of measurements, simulation and engineering calculations showed good convergence. The degree of discrepancy did not exceed 10-12 %. It is confirmed that the most pronounced are the 11, 13, 23, 25, 35 and 37 harmonics of currents and voltages. The total coefficients of harmonic components of currents and voltages in the high-voltage mine network reach on average K_I= 8-10% and K_U= 12-17%, respectively.

Identification of parameters and determination of probabilistic characteristics of load currents and distortions is carried out. The identification results show that changes in load currents and distortions refer to random stationary processes. Quantitative characteristics of random processes allowed to reveal the most probable range of change of values of currents of loadings and distortions.

On the basis of the carried out identification the estimation of additional power losses in elements of high-voltage power supply systems at non-sinusoidal modes is carried out and the optimization problem of minimization of power losses is solved. At the received values of currents of the highest harmonics and taking into account the set restrictions of loss of power in mine system of power supply will be minimal. When compensating the HG to the found values, the total loss of active power in non-sinusoidal modes in the high-voltage mine network will decrease to the value $\Delta P_{\Sigma add}$= 12,59 kW, that is, more than 60 %.

It is proposed to perform compensation of HG currents by means of FCD with two resonant PF tuned to the 11-th and 13-th harmonics and a second-order broadband filter tuned to compensate harmonics starting from the 23-rd and above. Application of FCD allows to reduce losses of active power from currents of the higher harmonics and also to achieve decrease in value of total coefficient of harmonic components of tension in a high-voltage network to admissible value K_U= 4,86 %. In this case, a deeper compensation of the currents of higher harmonics is possible.

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