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Optimization of the structure of filter-compensating devices in networks with powerful non-linear power consumers based on fuzzy logic

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ABSTRACT

The article presents a solution to the problem of optimizing the structure of filter-compensating devices (FCD) when installed in high-voltage mine networks with powerful nonlinear electrical receivers. The urgency of the problem of choosing a rational structure of the FCD. The problem of choosing the design and installation location of the FCD is presented. The main technical means of compensation of higher harmonics of currents and voltages in high-voltage networks with powerful nonlinear electrical receivers are considered. Analysis of different types of passive filters (PF) and their frequency properties showed that the choice of specific types of PF refers to the multi-criteria optimization problem. The main methods of optimization of FCD design are considered. The variant of FCD construction based on the solution of multi-criteria optimization problem with the use of fuzzy sets is proposed and justified. To this end, the calculation of PF parameters and frequency characteristics of equivalent systems of the "filter-external network" type for four possible combinations of PF is performed. The optimal is a FCD with two resonant PF tuned to the 11^{th} and 13^{th} harmonics, and a second-order broadband PF tuned to compensate harmonics starting from the 23^{rd} and above. The analysis of simulation results showed effective compensation of higher harmonic currents and voltages.

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1. INTRODUCTION

At modern operating industrial enterprises for the extraction of iron ore by the underground method, powerful lifting units (PLI) are used for lifting the mined rock to the surface, lowering and lifting personnel, mining equipment and materials along vertical shafts. As a rule, such enterprises use skip and cage PLI with powerful regulated direct current (DC) electric drives, made according to the system thyristor converter-motor of independent excitation (TC-M). Therefore, the main feature of high-voltage mining networks is the presence of powerful and power consuming non-linear electrical receivers.

The use of powerful converting equipment, such as thyristor converters or controlled rectifiers, leads to the generation of higher harmonic (HH) components of currents and voltages into the high-voltage supply network. A number of works describe the negative influence of the HH components of currents and voltages on the elements of general-purpose power supply systems, [1]–[5] in general and of mines with a powerful nonlinear load in particular [6]–[10]. The main negative consequences of the action of higher harmonics include: i) the deterioration of indicators of the quality of electrical energy [1]–[5], [7], [9]; ii) additional losses of active power and electricity in the elements of power supply systems, such as supply lines, reactors, power and matching transformers [3], [5], [6]; iii) the influence of non-sinusoidal voltage on industrial electrical equipment is expressed in a reduction in its service life due to accelerated aging of insulation [5], [10]; iv) high probability of disruption of the normal performance of electrical equipment and its failure with low quality of electricity [5], [7], [8], [10]; v) impact on the operating modes of the entire system, as well as on consumers of electrical energy in particular [1], [2], [4], [5].

2. RESEARCH METHOD

At the same time, the results of experimental studies, simulation modeling and analytical calculations confirm that in high-voltage mine networks with powerful thyristor DC drives, the most pronounced are the canonical 11th, 13th, 23rd, 25th, 35th and 37th harmonics of currents and voltages [6], [11]–[14]. The magnitude of non-canonical harmonics and interharmonics is much lower than the level of canonical harmonics, starting from the 11th. In 6-10 kV networks with isolated neutral, there are no physical prerequisites for generating the 3rd harmonic into the network due to the high requirements for phase symmetry. The low level of the 5th and 7th harmonics is ensured by their compensation in the valve windings of the matching transformers. The significant negative influence of higher harmonics caused by the operation of powerful nonlinear electrical receivers, especially in high-voltage mining networks, makes the problem of their compensation especially urgent.

To compensate for HH currents and voltages in high-voltage mine networks with powerful non-linear loads, various types of technical means can be used such as passive filters (PF), active filters (AF), and hybrid filters [12]–[22]. One of the most widespread, convenient and practically applicable technical means of compensation of HH components of currents and voltages in high-voltage mining networks are passive filters, which, despite the appearance of active filters, remain in demand [15]–[19]. It is one of the most affordable, cheap and effective means of compensating for higher harmonics and improving the quality of electricity.

Passive filters have low cost, economy, rather simple design, do not require regular maintenance, simultaneously perform functions of attenuation of higher harmonics and compensation of reactive power, and differ in a variety of configurations and implemented frequency characteristics. They are static devices, but can be installed as part of an automated control system as separate stages, tuned to the corresponding harmonics under dynamically changing load. In this case, the efficiency of the PF application will be much higher with an approximately constant harmonic composition of currents and voltages, as well as with a "rigid" structure of the supply network. The disadvantage of using the PF is the possibility of resonance in the parallel oscillatory circuit formed by the filter and the inductance and capacity of the supply network, at frequencies close to the frequencies of higher harmonics. It must be taken into account when choosing specific PF structures by analyzing the frequency characteristics of the filter-external network systems.

Based on the foregoing, to compensate for HH currents and voltages, to ensure electromagnetic compatibility (EMC) in high-voltage mine networks with powerful non-linear consumers, it is advisable to use three-phase three-wire passive filters of various orders, mainly with parallel connection, tuned to one or more frequencies of higher harmonics. Also, the use of passive harmonic filters is based on the analysis of technical and economic indicators of the efficiency of compensation of HH currents and voltages in high-voltage mine networks in the presence of powerful nonlinear consumers [12]–[14].

Passive filters as part of filter compensating devices (FCD) are usually installed directly near non-linear loads to compensate for the HH components of currents and voltages. But at most of the operating facilities there is no technical possibility of installing a FCD directly in front of a non-linear load, for example, in front of thyristor converters. In this regard, FCDs are installed in a high-voltage network-in switchgears 6-10 kV on the HV side of the matching transformer in Figure 1.

In power supply systems to compensate for HH currents and voltages, the following types of PFs are used: first, second, third order and C-type filters [15]–[19], [23]. The suppression of several harmonics can be provided by structures formed by the parallel connection of several sections. Each section is an oscillatory circuit tuned to the frequency of one of the harmonics. Installing such filters near a non-linear load also provides a ground fault for higher harmonic currents through the corresponding oscillating circuit.

The composite filter contains a resonant branch that suppresses the lowest order harmonics. It will eliminate the possibility of amplifying this harmonic due to parallel resonance. Almost all of the considered types of passive filters are used to compensate for HH in power supply systems, but the choice of specific types of filters as part of the FCD, their parameters are determined by the nature of the nonlinear load, the power supply system, frequency properties and other parameters.

Analysis of various types of PFs, their combinations in the composition of the FCD, the frequency characteristics of the filter-external network systems showed that to compensate for the most pronounced harmonics at frequencies up to the 20th order, it is rational to use resonant PFs, PFs of double tuning and C-type filters. To compensate for harmonics, starting from the 20th, it is more efficient to use wideband filters of the second and third orders. Combined filters FCD, containing resonant and wideband PFs, provide deep compensation for harmonics at low and medium frequencies (up to the 20th) and a significant reduction in the level of harmonics at high frequencies (starting from the 20th).

Thus, the choice of specific types of PFs to create the most optimal structure of the FCD requires solving a multicriteria optimization problem, which means choosing the best option simultaneously according to many criteria. At the same time, solving optimization problems using classical objective functions and minimizing them due to 2–3 parameters may not give the best solution, turn out to be too difficult to solve, not cover all criteria and constraints, or may not have solutions at all. Therefore, in recent years, the theory of fuzzy sets has been widely used to optimize the modes of electric power systems [24]–[26]. From a mathematical point of view, solving a multicriteria optimization problem allows you to choose the best option with criteria of equal and different importance.

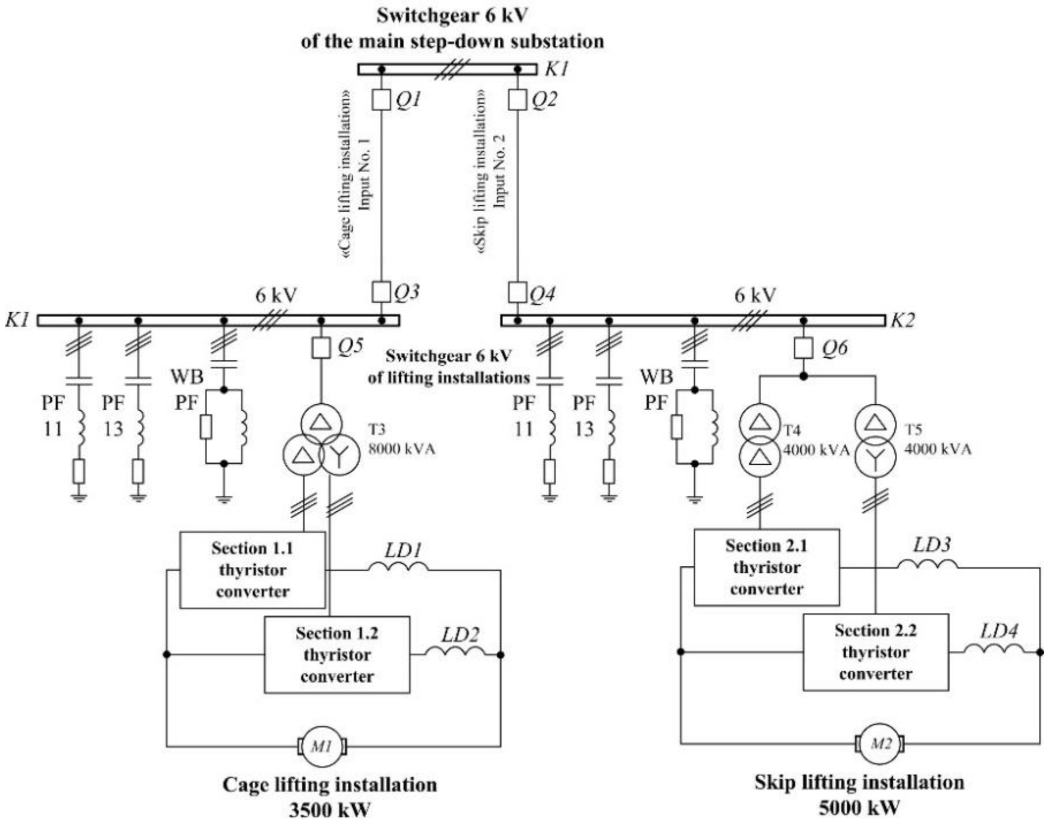

Figure 1. Scheme of FCD installation in a high-voltage mine power supply system

3. RESULTS AND DISCUSSION

On the basis of the analysis carried out to compensate for HH currents and voltages in a mine high-voltage network with powerful nonlinear electrical receivers, several equivalent combinations of PFs can be proposed as FCD:

- Resonant PF, tuned to the 11th and 13th harmonics, and a second-order PTI, tuned to compensate for the HH, starting from the 23rd–F1;
- PF of double tuning to the 11th and 13th harmonics and the second order PTI, tuned to compensate for the HH, starting from the 23rd–F2;
- PF of C-type, tuned to the 11th and 13th harmonics, and the second order PTI, tuned to compensate for VH, starting from the 23rd–F3;
- Resonant PF, tuned to 11th, 13th, 23rd, 25th, 35th and 37th harmonics–F4.

The existing methods of compensation of HH currents and voltages, the choice of the size and location of FCD in power supply systems are based on minimizing active power losses and reduced costs [12], [27], [28]. The proposed solutions have a number of disadvantages such as failure to take into account the properties of the frequency characteristics of the "filter-external network"; power losses in the FCD. The calculations have the deterministic values of the parameters of power supply systems and empirical formulas to take into account the change in the network resistance depending on the HH numbers. The use of methods based on fuzzy sets allows making decisions by formalizing the human ability to reason.

From a mathematical point of view, with the same importance of criteria, the problem of choosing the optimal option can be presented in the following form. For example there is a set of k alternatives $A=\{a_1, a_2, ..., a_k\}$. Then, for the criterion (requirement) T, a fuzzy set can be considered:

$$\mathrm{T} = \{= \{\mu_T(a_1)/a_1, \mu_T(a_2)/a_2, \dots, \mu_T(a_k)/a_k\}, \tag{1}$$

where: μ_T (a_i) [0, 1] is the assessment of the alternative a_i according to the criterion (requirement) T, which characterizes the degree of compliance of the alternative with the concept determined by the criterion (requirement) T.

If there are n criteria (requirements): T_1, T_2, ..., T_n, then the best alternative is considered to satisfy both the criterion (requirement) T_1, and T_2, and …, and T_n. Then the rule for choosing the best alternative can be written as the intersection of the corresponding fuzzy sets:

$$D = T_1 \cap T_2 \cap \dots \cap T_n. \tag{2}$$

The operation of intersection of fuzzy sets corresponds to the operation of minimization performed on their membership functions. The alternative a* with the largest value of the membership function is chosen as the best.

In our case, it is required to select the FCD so that they meet the following requirements: T_1 - capital costs, taking into account the installation and mounting of the FCD and operating costs; T_2 - properties of frequency characteristics "filter-external network" from the point of view of compensation of canonical harmonics and amplification of interharmonics and subharmonics; T_3 - power losses in the FCD elements; and T_4 - the ability to compensate for reactive power at the fundamental harmonic.

The assessments of alternatives according to the presented criteria are presented as values of expert assessments in Table 1. Expert assessments were obtained based on the analysis of publications and the experience of leading scientists, taking into account experimental data, analytical calculations and the results of simulation. The quantitative values of the parameters are given on the basis of statistical processing of the graphs of loads by currents of the fundamental frequency and currents of the HH.

Table 1. Evaluation of alternatives in accordance with the presented criteria

Alternative	Assessments of alternatives (expert assessments)			
	μ_1	μ_2	μ_3	μ_4
	Criterion (requirement) T_1			
Φ_1	0,6	0.8	0.9	0.95
Φ_2	0.5	0.6	0.65	0.7
Φ_3	0.4	0.5	0.6	0.8
Φ_4	0.6	0.7	0.8	0.9
I_u, A	0–5	5–10	10–20	20–50
	Criterion (requirement) T_2			
Φ_1	1	0.9	0.85	0.7
Φ_2	0.8	0.75	0.7	0.65
Φ_3	0.85	0.8	0.75	0.7
Φ_4	0.9	0.8	0.7	0.6
I_u, A	0–5	5–10	10–20	20–50
	Criterion (requirement) T_3			
Φ_1	0.9	0.85	0.8	0.7
Φ_2	0.9	0.8	0.75	0.6
Φ_3	0.75	0.8	0.85	0.9
Φ_4	0.8	0.75	0.7	0.6
I_u, A	0–5	5–10	10–20	20–50
	Criterion (requirement) T_4			
Φ_1	0.85	0.8	0.7	0.6
Φ_2	0.7	0.75	0.8	0.85
Φ_3	0.8	0.85	0.9	1
Φ_4	0.85	0.7	0.6	0.5
I_u, A	0–5	5–10	10–20	20–50

The Table 1 shows the assessment of alternatives with the same importance of criteria (requirements) in Figure 2(a), from which the degree of influence of each criterion on the choice of the optimal FCD version is clearly visible. As a result, the following data were obtained characterizing the degree of belonging of the DIA to the specified requirements:

$$\begin{aligned} T_1 &= \{0.9/F_1;\ 0.65/F_2;\ 0.6/F_3;\ 0.8/F_4\}; \\ T_2 &= \{0.85/F_1;\ 0.7/F_2;\ 0.75/F_3;\ 0.7/F_4\}; \\ T_3 &= \{0.8/F_1;\ 0.75/F_2;\ 0.85/F_3;\ 0.7/F_4\}; \\ T_4 &= \{0.7/F_1;\ 0.8/F_2;\ 0.9/F_3;\ 0.6/F_4\}., \end{aligned} \tag{3}$$

There are several rules for choosing solutions. In accordance with one of them, the corresponding minimum values are first found, from which the maximum is then selected, it indicates the result:

$$\begin{aligned} D &= max\begin{Bmatrix} min(0.9;\ 0.85;\ 0.8;\ 0.7/F_1)\,;\ min(0.65;\ 0.7;\ 0.75;\ 0.8/F_2)\,; \\ min(0.6;\ 0.75;\ 0.75;\ 0.8/F_3)\,;\ min(0.8;\ 0.7;\ 0.7;\ 0.6/F_4)\,; \end{Bmatrix} = \\ &= max\{0.7/F_1;\ 0.65/F_2;\ 0.6/F_3;\ 0.6/F_4\}. \end{aligned} \tag{4}$$

Thus, the most optimal option for using a PF as a FCD is the first alternative option F_1 - resonant PFs tuned to the 11th and 13th harmonics, and a second-order PTI tuned to compensate for the HH, starting from the 23rd: F_1={0.9; 0.85; 0.8; 0.7}.

In practice, T_i requirements can be of varying importance. It depends on the configuration of power supply systems, the nature of the loads, the ratio of the short failure power from the side of the system and the converter. The requirements T_i have different importance, then each of them is assigned a degree of importance $\alpha_i \geq 0$ (the more important the criterion, the more α_i), and the selection rule takes the form:

$$D = T_1^{\alpha_1} \cap T_2^{\alpha_2} \cap \ldots \cap T_n^{\alpha_n}, \tag{5}$$

where: $\alpha_i > 0;\ i = 1 \ldots n;$

The coefficients of relative importance are determined based on the procedure of paired comparison of criteria. First, a matrix of paired comparisons M is formed, the elements of which are found from a scale of relative importance and satisfy the following conditions: $m_{ii}=1;\ m_{ij}=1/m_{ij}$:

$$M = (m_{ij}) = \begin{pmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{pmatrix} \tag{6}$$

For the purposes of expert assessment, a 9-point scale was adopted in accordance with the Saaty hierarchy analysis method. The scale of relative importance also contains all inverse numbers 1/9, 1/7, 1/5, 1/3, as well as intermediate values 1/8, 1/6, 1/4, 1/2. Then the parameter w is determined - the eigenvector of the matrix *M*, corresponding to the maximum eigenvalue Zmax.

The target values of the coefficients α_i are obtained by multiplying the elements *w* by *n* to satisfy the condition:

$$\alpha_i = n \cdot w_i. \tag{7}$$

In accordance with the scale of relative importance, a matrix of paired comparisons of the above requirements for FCD was formed:

$$M = (m_{ij}) = \begin{pmatrix} 1 & 1 & 3 & 2 \\ 1 & 1 & 5 & 3 \\ 0.33 & 0.2 & 1 & 1 \\ 0.5 & 0.33 & 1 & 1 \end{pmatrix}$$

Equal importance of T_1 and T_2 requirements (capital costs and frequency response properties "filter-external network") is accepted; moderate superiority of the T_1 requirement over the T_3 and T_4 requirements (the superiority of capital costs over power losses in the FCD elements and the ability to compensate for reactive power at the fundamental harmonic); more significant superiority of the requirement T_2 over the requirements of T_3 and T_4 (significant superiority of the property of frequency characteristics over the power losses in the

FCD elements and the ability to compensate for reactive power at the fundamental harmonic); as well as the equal importance of the requirements T_3 and T_4 (power losses in the elements of the FCD and the ability to compensate for reactive power at the fundamental harmonic)

Eigenvector of pairwise comparison matrix and the coefficients of the relative importance of the requirements:

$$w = \begin{pmatrix} 0.591 \\ 0.745 \\ 0.192 \\ 0.241 \end{pmatrix}$$

$$\alpha_1 = n \cdot w_1 = 4 \cdot 0.591 = 2.364;$$
$$\alpha_2 = n \cdot w_2 = 4 \cdot 0.745 = 2.98;$$
$$\alpha_3 = n \cdot w_3 = 4 \cdot 0.192 = 0.768;$$
$$\alpha_4 = n \cdot w_4 = 4 \cdot 0.241 = 0.964.$$

Modification of sets of requirements:

$$T_1^{\alpha_1} = T_1^{2.364} = \{0.9^{2.364}/F_1;\ 0.65^{2.364}/F_2;\ 0.6^{2.364}/F_3;\ 0.8^{2.364}/F_4\} = \{0.78/F_1;\ 0.361/F_2;\ 0.299/F_3;\ 0.59/F_4\};$$
$$T_2^{\alpha_2} = T_2^{2.98} = \{0.85^{2.98}/F_1;\ 0.7^{2.98}/F_2;\ 0.75^{2.98}/F_3;\ 0.7^{2.98}/F_4\} = \{0.616/F_1;\ 0.345/F_2;\ 0.424/F_3;\ 0.345/F_4\};$$
$$T_3^{\alpha_3} = T_3^{0.768} = \{0.8^{0.768}/F_1;\ 0.75^{0.768}/F_2;\ 0.85^{0.768}/F_3;\ 0.7^{0.768}/F_4\} = \{0.843/F_1;\ 0.802/F_2;\ 0.883/F_3;\ 0.76/F_4\};$$
$$T_4^{\alpha_4} = T_4^{0.964} = \{0.7^{0.964}/F_1;\ 0.8^{0.964}/F_2;\ 0.9^{0.964}/F_3;\ 0.6^{0.964}/F_4\} = \{0.709/F_1;\ 0.806/F_2;\ 0.903/F_3;\ 0.611/F_4\}.$$

Figure 2(b) shows the assessment of alternatives with different importance of the requirements T_i, from which the degree of influence of each criterion on the choice of the optimal variant of the FCD is clearly visible. The set containing the minimum values F_1, F_2, F_3, F_4: D={0.616/F_1; 0.345/F_2; 0.299/F_3; 0.345/F_4}. The maximum membership value has the alternative F_1 - FCD, consisting of resonant PFs tuned to the 11th and 13th harmonics, and a second-order PTI tuned to compensate for the HH, starting from the 23rd: F_1={0.78; 0.616; 0.843; 0.709}.

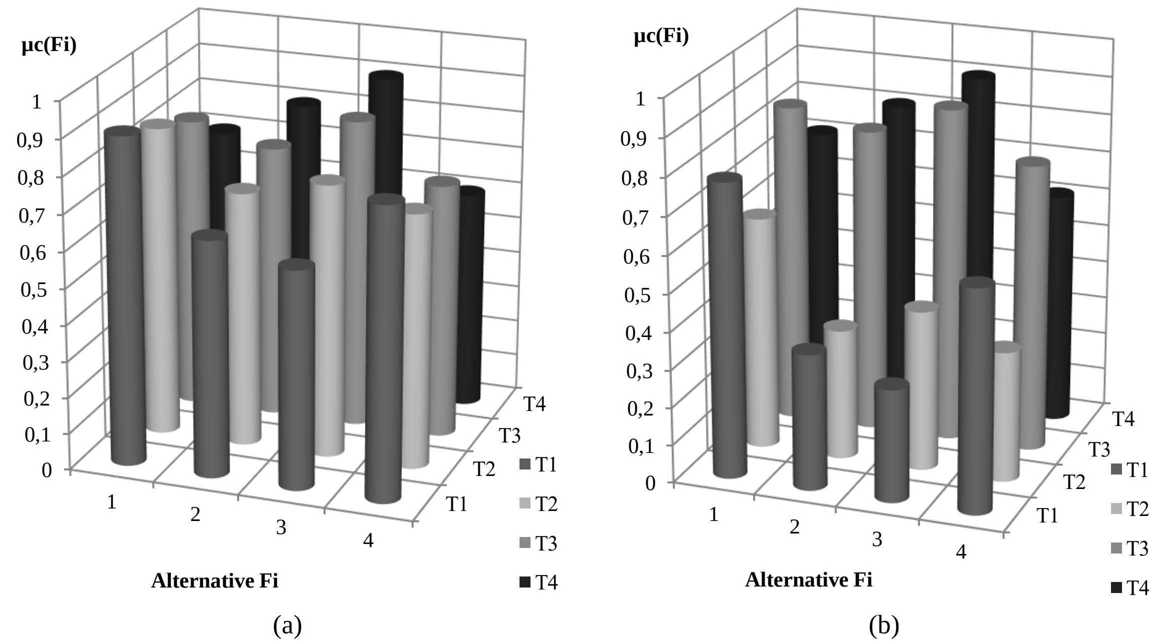

Figure 2. Assessment of alternatives with the same (a) and different (b) importance of criteria (requirements)

4. CONCLUSION

The solutions to the problems of choosing the optimal variant of using a PF as a FCD with the same and different importance of the criteria (requirements) showed that the most optimal version of the FCD is the use of resonant PFs tuned to the 11th and 13th harmonics, and a second-order PTI tuned to compensation HH, starting from the 23rd. The installation of the FCD of the obtained structure allows ensuring electromagnetic compatibility and improving the quality of electricity in the high-voltage mine network by compensating for HH currents and voltages. At the same time, the total coefficients of harmonic components of current and voltage decreased significantly and amounted to: K_I=3.72%, K_U=0.61% for the high-voltage network of the skip PLI; K_I=2.66%, K_U=1.2% for the cage network. At the same time, additional total power losses caused by the action of higher harmonics, when installing the FCD, decreased by more than 90% and amounted to ΔP=0.51 kW.

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