Transformation Justification of types of filter compensating devices in 6 kV mine networks with powerful nonlinear electric receivers

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Abstract. In this paper presents the features and disadvantages of networks of mining enterprises with a voltage of 6 kV with high-power thyristor DC electric drives of hoisting installations, made according to the TP-D system. In most of these networks, negative phenomena are observed due to the presence of powerful nonlinear electrical receivers. Various power filters are widely used to eliminate negative phenomena and reduce additional power losses in mine networks. Moreover, the choice of a specific type of filter and its design is a complex multi-criteria task. The paper presents an in-depth analysis of various types of power filters, and considers factors that influence the choice of FCD. The disadvantages of various existing methods of selecting FCD are revealed. Justification of the types of filter-compensating devices is based on the application of a multi-criteria approach and optimization of the structure of the FCD using the fuzzy set apparatus. The optimal design of FCD for use in 6 kV mine networks with powerful thyristor DC electric drives of hoisting installations, made according to the TP-D system, has been determined. At the same time, the use of the developed FCD design in 6 kV mine networks will allow to compensate for the most pronounced HH currents and voltages, significantly reduce additional power losses, improve the quality of electrical energy and improve the overall electromagnetic environment.

1. Introduction

A feature of power supply systems and electric networks of industrial enterprises is the presence of powerful nonlinear electric receivers, which significantly disrupt the electromagnetic environment and negatively affect many electrical parameters.

For example, distribution networks of medium voltage 6-10 kV are problematic for almost all mining enterprises. This is due to the peculiarities of the technological process of ore extraction by open or closed methods. When mining iron ore in an underground (closed) way, the mine field is opened with skip and crate vertical shafts equipped with hoisting installation (HI). At many operating mining enterprises, electric drives made according to the system of thyristor Converter – DC motor with independent excitation (TP-D) are used as HI drives [1-3], which are powerful nonlinear electric receivers (figure 1). Powerful thyristor electric drives are the reason for generating higher harmonics (HH) of currents and voltages in the high-voltage mine network and create non-sinusoidal dynamic modes of operation. Such an impact on the mine supply network is the cause of the disturbance of the general electromagnetic environment and deterioration of the quality of electrical energy.
Figure 1. The power supply circuit of the power consumers PU.
2. Power loss study
For the power supply system of the Yakovlev’s mine in the Belgorod region, experimental studies, simulation modeling and analytical calculations were carried out, which showed that the most pronounced are the 11, 13, 23, 25, 35 and 37 harmonics of currents and voltages (figure 4). At the same time, the total coefficients of harmonic components of stresses in the 6 kV mine network reach an average of KU=10-17% per hoisting cycle and exceed the normalized values. At the same time, the reliability of the data obtained is confirmed by a high correlation of measurement results, simulation modeling, and analytical calculations, the degree of discrepancy of which does not exceed 10-12 % [1-4].

The presence of higher harmonics of current and voltage in the mine network leads to many negative consequences, one of which is additional loss of power and electricity in the elements of the power supply system.

Additional losses of power and electrical energy in the elements of the power supply system are defined as the sum of additional losses in cable and overhead lines, reactors and transformers from a single HH source. Additional power losses in power transmission lines, reactors, and power transformers of the power supply scheme were determined using the methods presented in [5-7].

In a result of the assessment, the additional power losses caused by the action of HH currents and voltages in the power supply system of the ore mining enterprise amounted to the values shown in figure 2. At the same time, additional power losses in non-sinusoidal modes in comparison with the total losses, respectively, were: for skip HI δadd = 16.99%; for cage HI δadd = 44.3%.

![Figure 2. Histograms of additional power losses in the mine power supply system at non-sinusoidal modes.](image_url)
3. Technical devices for reducing power losses

Now, to compensate for HH currents and voltages, the main distribution is organizational, technical measures and measures to improve the systems of calculation and technical accounting of electricity, as well as various types of technical means.

Various types of power filters are widely used to compensate for HH currents and voltages and reduce additional power losses [8-13]:

- passive harmonic filters (PHF);
- active harmonic filters (AHF);
- hybrid filters (GF or active-passive filters);
- passive filters with special settings (PFSN).

In addition to attenuating the higher harmonics of currents and voltages, power filters can perform the functions of reactive power compensation and voltage regulation at the connection point.

To compensate for the HH in the 6 kV mine network with thyristor converters made according to the 12-pulse rectification scheme, the installation of a FCD consisting of:

- PHF tuned to 11, 13, 23 and 25 harmonics can be provided;
- AHF tuned to the entire harmonic series;
- combinations of PHF tuned to 11, 13 harmonics, and AHF tuned to other harmonics (HF – hybrid filter).

An important feature is that due to the technical features of mine power supply systems and the low quality of electricity, the installation of FCD is necessary in the 6 kV network directly near non-linear loads. This leads to a significant cost of the FCD design.

Based on the analysis of numerous works, the specific average cost of PHF is about 380.9 rubles/kvar, AHF – 7162.6 rubles/kvar, HF – 6994.2 rubles/kvar [14 – 18].

Taking into account the significant power of electric drives of HI, as well as the specific average cost of power filters, the most appropriate and cost-effective option for compensating HH currents and voltages in the 6 kV mine network is to install filter-compensating devices consisting of passive harmonic filters.

In the electric power industry, the following PHF configurations are used (figure 3): first, second, and third order filters and C-type filters. A comparative analysis of passive harmonic filters, their main characteristics, scope and purpose, advantages and disadvantages are presented in table 1.

![Figure 3](image-url)

**Figure 3.** Configurations of passive harmonic filters: a – first order PHF; b – resonant or narrowband PHF; c – second order PHF; d – third order PHF; e – C-type PHF.
To compensate for HH currents and voltages in the 6 kV mine network, almost equivalent versions of FCD can be used, consisting of various configurations of PHF in their composition. To select the best version of the FCD, a number of important criteria were determined, which each proposed type of FCD must meet to some extent. The choice of a specific variant of the FCD was determined by solving a multi-criteria optimization problem, which means choosing the best option simultaneously according to many criteria.

4. Selection of the optimal configuration of technical devices

Many existing methods for selecting the location and parameters of the FCD in power supply systems are based on minimizing active power losses and reduced costs [3, 19-21]. The proposed solutions have a number of disadvantages: not taking into account the properties of the frequency characteristics of the "filter – external network"; power losses in the FCD. The calculations use deterministic values of parameters of power supply systems and empirical formulas for accounting for changes in network resistance depending on the HH numbers. A more accurate justification for the use of a specific type of FCD is provided by a multi-criteria approach and optimization of the FCD structure.

The following important criteria are applied to each specific type of FCD installed in a 6 kV mine network with high-power thyristor electric drives for compensation of HH currents and voltages:

- capital expenditures, including installation and installation of FCD and operating costs;
- properties of the "filter – external network" frequency characteristics in terms of compensation of canonical harmonics and amplification of interharmonics and subharmonics;
- minimization of additional power losses in the network;
- power losses in the elements of FCD;
- ability to compensate for reactive power on the main harmonic.

Capital expenditures depend on the number and configuration of PHFs in the FCD, on the capacity and total capacity of capacitors, and on the manufacturer.

Properties of the frequency characteristics of the "filter – external network" significantly expand the idea of its operating modes with different composition and variations of the load at higher harmonics. This criterion allows us to evaluate not only the efficiency of compensation of HH currents and voltages, but also warns about possible resonances of current and voltage, amplification of interharmonics and subharmonics [4, 6, 9, 22, 23].

All other things being equal, it is important to consider the power loss in the FCD, consisting of various configurations of the PHF. Power loss estimation at the fundamental and harmonic frequencies for the SHPF can be performed similarly to a resonant PHF tuned to a single frequency.

The ability to compensate for the reactive power of the FCD on the main harmonic is taken into account at the design stage. The parameters of the PHF configurations in the FCD were calculated taking into account reactive power compensation in accordance with the required power factor.

To compensate for HH currents and voltages in the 6 kV mine network, four alternative equivalent types of FCS were proposed and calculated, consisting of various PF configurations:

- resonant PHFs tuned to the 11th and 13th harmonics, and second-order SPF tuned to compensate for the HH, starting from the 23rd;
- Dual tuning PHF for the 11th and 13th harmonics and second-order SPF tuned for HH compensation, starting from the 23rd;
- A C-type PHF tuned to the 11th and 13th harmonics, and a second-order SPF tuned to compensate for the HH, starting from the 23rd;
- resonant PHFs tuned to 11, 13, 23, 25, 35, and 37 harmonics.

The problem of choosing the optimal type of FCD is solved using the fuzzy set apparatus with the same and different importance of the proposed criteria. The results of solving the problem showed that the most optimal type of FCD is the first alternative (resonant PHFs tuned to the 11th and 13th harmonics, and a second-order PHF tuned to compensate for the SH, starting from the 23rd).
Table 1. Comparative analysis of passive harmonic filter configurations.

| Types of filter          | PFG First load | Resonant or narrowband PFG | PFG Second load | PFG Third load | C-type PFG |
|--------------------------|----------------|----------------------------|-----------------|----------------|------------|
| Brief description        | A parallel resonant circuit with the inductance of the external network. | Simultaneous suppression of several harmonics. | Simultaneous suppression of several harmonics. | Inclusion in the cross branch of the second-order filter of the capacitor C2. The capacitance of the capacitor C2 must be such that the resonant frequency of the oscillating circuit LC2 coincides with the frequency of the main harmonic. |
| Quality factor           | –              | 0.5-5                      | 0.5-5           | 3-5            |
|                          | 30–50          | Higher values are used when it is necessary to attenuate closely spaced harmonics. The quality factor is chosen such as to ensure that a given characteristic is obtained in a certain frequency range. | Higher values are used when it is necessary to attenuate closely spaced harmonics. The quality factor is chosen such as to ensure that a given characteristic is obtained in a certain frequency range. | The quality factor is chosen such as to ensure that a given characteristic is obtained in a certain frequency range. |
| Advantages               | Simplicity     | Effectively weakens harmonic components whose frequencies are close to the resonant frequency. Simplicity, economy and reliability. It is widely used in networks with non-linear loads. | It is convenient in operation, in comparison with the first order filter, it has lower losses at the fundamental frequency. Provides a reduction in the values of harmonic voltage components in electrical networks in a wider frequency range. | Small (lower) losses at the fundamental frequency in comparison with a second-order filter, provides a decrease in the values of harmonic components of voltage in electrical networks in a wider frequency range. | Lower power loss at the fundamental harmonic frequency compared to narrow-band filters of the second and third orders. Providing reduction of values of harmonic components of voltage in electric networks in a wider frequency range. Provide reactive power compensation at the frequency of the main harmonic and attenuation of higher harmonics. |
| Disadvantages            | It has high losses at the fundamental frequency due to the use of a high power capacitor, which limits its use. | Efficiency decreases when the harmonic composition of currents and voltages and network parameters change. The possibility of resonance in a parallel oscillatory circuit formed by the filter and the inductance of the supply network, at frequencies close to the frequencies of higher harmonics. | It is widely used in industry. The losses at the fundamental frequency are large compared to a narrow-band filter. | Reducing the possibility of obtaining the required frequency response in the attenuation band. It is rarely used in industry due to its high cost and complexity. | Fine tuning to the fundamental frequency, a wide range of capacitor ratings and, accordingly, a large total capacitance. High sensitivity to changes in fundamental frequency and deviations of parameters of elements. The degree of attenuation of harmonics, the frequencies of which exceed the resonant frequency, are small. |
The parameters of all resonant PHFS were determined on the basis of canonical schemes of reactive bipolar circuits using a matrix of hybrid circuit parameters through the system resistance and filter [9]. For the obtained optimal type of FCD, the parameters of resonant PHFS were calculated for the most pronounced canonical 11th and 13th higher harmonics. The SPFS were tuned to the 23rd harmonic component, the most pronounced harmonic in the high-frequency region after the 13th harmonic. The results of calculations of the parameters of resonant and broadband PHF are presented in table 2.

| HI type            | P, kW | QK, kvar | H   | HH number | ki | Li, mGΩ | Ci, mkF | Qi, kvar | Q       | R, Om   |
|--------------------|-------|----------|-----|-----------|----|---------|---------|---------|---------|---------|
| Skip HI            | 1381  | 807.89   | 0.274 | 11        | 1.752 | 1.817   | 46.09   | 193.1    | 0.1047  |
|                    |       |          |      |           |     |         |         |          |         |         |
|                    | 13    | 1.904    | 1.672 | 35.87     |     |         |         | 150.0    | 60      | 0.1138  |
| Cage HI            | 2246  | 788.35   | 0.312 | 11        | 1.537 | 2.071   | 40.43   | 169.5    | 0.1193  |
|                    |       |          |      |           |     |         |         |          |         |         |
|                    | 13    | 1.674    | 1.905 | 31.47     |     |         |         | 131.6    | 0.1297  |
| Broadband PF 2nd order |  |         |      |  |     |         |         |          |         |         |
| Skip HI            | –     | 807.89   | –    | 0.268     | 71.43 | 1.937  |
|                    | –     | 788.35   | –    | 0.275     | 69.71 | 1.985  |
| Cage HI            | –     | 788.35   | –    | 0.268     | 71.43 | 1.937  |

Note: H – normalization coefficient; Q – q factor

Installation of the FCD is supposed to be in the SG-6 kV of the building of hoisting machines, on the side of the higher voltage of matching transformers in the form of separate additional cells (figure 1).

![Figure 4. Spectra of harmonic voltages in the underground network of 6 kV: a – Skip HI; b – Cage HI.](image)

As follows from the simulation results, the currents and voltages in the phases of power supply systems of HI take forms close to sinusoidal, and the total coefficients of the harmonic components of the voltage are equal: for skip HI: $K_U = 0.61\%$; for cage HI: $K_U = 1.2\%$. 
The histogram of additional power losses in the elements of the power supply systems of skip and cage HI when installing the FCD is shown in figure 5 a – skip HI; b – cage HI.

![Histogram of additional power losses](image)

**Figure 5.** Histogram of additional power losses in the power supply systems of skip and cage HI during installation of FCD.

As follows from the simulation results, additional power losses caused by non-sinusoidal operating modes during the installation of the FCD decreased by more than 90% and amounted to \( \Delta P = 0.51 \) kW. Thus, compensation of HH currents and voltages helps to reduce additional power losses in the elements of power supply systems for skip and cage HI under non-sinusoidal operating modes.

5. Conclusions

Most networks of mining enterprises with a voltage of 6 kV are characterized by a violation of the General electromagnetic environment, low quality of electric energy in terms of non-sinusoidal currents and voltages, and significant additional power losses in non-sinusoidal modes. The reason for these phenomena are powerful thyristor DC electric drives of hoisting installations, made according to the TP-D system.

Various power filters are widely used to compensate for HH currents and voltages and reduce additional power losses in mine networks. Moreover, the choice of a specific type of filter and its design is a complex multi-criteria task.

The choice and justification of FCD types in 6 kV mine networks is based on a deep analysis of various types of power filters, taking into account a large number of factors and studying the methods of selecting FCD. In addition, a multi-criteria approach was applied to optimize the structure of the FCD, using the fuzzy set apparatus. As a result, the optimal design of the FCD was determined for use in 6 kV mine networks with powerful thyristor DC electric drives of hoisting installations made using the TP-D system (resonant PHFS tuned to the 11th and 13th harmonics, and second-order SHPF tuned to compensate for the HH, starting from the 23rd).

The use of the optimal design of the FCD in 6 kV mine networks with powerful thyristor DC electric drives of hoisting installations will allow you to compensate for the most pronounced HH currents...
and voltages, significantly reduce additional power losses, improve the quality of electrical energy and improve the overall electromagnetic environment.

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