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Ensuring sustainability of the power supply system of mining enterprises in the conditions of war risks

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Abstract. In the work, a study of the conditions of normal operation of the power supply system of mining enterprises with limited capacity of the power system was carried out. Based on complex studies, conclusions were drawn about the structure of electrical loads in coal mines, which are characterized by a non-linear and non-symmetric nature. The problem of higher harmonics and interharmonics with limited short-circuit power, which is characteristic of an autonomous power supply system, is highlighted. Stable operation of the power supply system and main consumers is achieved by matching the mode of the generator set with the mode parameters of the load. New dependencies of regime parameters were obtained, which evaluate energy efficiency in complex situations caused by military risks. Experimental studies of voltage quality indicators and energy efficiency in the conditions of power supply systems of coal mines of Ukraine confirmed the adequacy of the proposed analytical models.

1 Introduction

Ukrainian energy today faces the harsh realities of military aggression by the Russian Federation, necessitating the implementation of an entirely new paradigm for the functioning and development of power systems [1]. The conflict has imposed severe disruptions, challenging the resilience and stability of the national energy infrastructure. Adapting to these unprecedented conditions requires innovative strategies and robust measures to ensure the continuity and reliability of the power supply amid ongoing hostilities [2].

The main challenges posed to the Ukrainian energy system include technical constraints caused by frequent blackouts and infrastructure damage [1,3]. These disruptions necessitate the rapid development and integration of renewable energy sources, which are redefining the principles of decentralization and autonomy through the creation of energy islands [4]. These self-sufficient energy units can operate independently of the main grid, providing a more resilient and flexible power supply, crucial in conflict zones where traditional power infrastructure is vulnerable to attack [5].

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The structure of electrical loads has undergone drastic changes in frontline and occupied regions. The electromagnetic compatibility of power supply systems is increasingly tested by the presence of powerful asymmetric and non-linear loads, all within the limited capacity of the existing energy system [6]. These loads can cause significant fluctuations and inefficiencies, further complicating the management of the grid [7]. Addressing these issues is vital for maintaining stability and ensuring that both civilian and military operations can continue to function effectively under these challenging conditions [8].

The main tasks for the government in addressing the energy challenges involve several key initiatives. Firstly, the implementation of the electricity market with accurate forecasting of electricity consumption is crucial [9]. This step ensures that supply meets demand efficiently, reducing waste and optimizing resource use. Additionally, the formation of a unified model of the Integrated Energy System is essential [10]. This model should incorporate distributed generation, which leverages smaller, localized power sources. Compatibility with European system models is another priority, facilitating integration and cooperation with broader energy networks. Ensuring the stability and reliability of power supply in this evolving landscape is paramount. This comprehensive approach not only enhances energy efficiency but also strengthens the resilience of the national power infrastructure [11].

The current situation in the Ukrainian electric power industry is characterized by an excessively high level of energy losses during transmission, reaching up to 20%. This figure is significantly higher than those observed in economically developed countries. In Western European nations, energy losses during transmission are typically around 4 – 5%. In the United States, this figure stands at approximately 6% [12]. The stark contrast highlights inefficiencies within the Ukrainian power infrastructure. Addressing these losses is crucial for improving the overall efficiency and sustainability of the country's electric power industry [13]. The high level of losses in Ukraine’s electrical grids is associated with several critical issues. Significant damage to the energy infrastructure, often due to conflict and inadequate maintenance, plays a major role. Additionally, there is a low level of compensation for reactive power, which leads to inefficiencies in power transmission [14]. Outdated key assets of electricity generation facilities further exacerbate these losses [15]. Furthermore, there is an insufficient use of modern optimization tools for operating modes and voltage regulation, which are essential for efficient grid management. Unresolved issues related to the quality of electrical energy, such as fluctuations and interruptions, also contribute to the high loss levels. Addressing these multifaceted challenges is crucial for enhancing the efficiency and reliability of Ukraine's electrical grids [16]. The low quality of electrical energy in systems with limited capacity leads to a significant decrease in the energy efficiency of electrical grids across a range of indicators [17]. The problem of electrical energy quality is a crucial component of the comprehensive concept of electromagnetic compatibility within the power supply system (PSS). This issue is widely recognized by leading global scholars and industry experts [18]. It is considered one of the most critical challenges in modern electric power engineering. Poor electrical energy quality can lead to inefficiencies, equipment damage, and increased operational costs [19]. Addressing this problem is essential for improving the overall performance and reliability of power supply systems. Moreover, it forms a significant part of the broader challenge of enhancing the energy efficiency of electrical grids. Efforts to improve energy quality are integral to achieving more sustainable and resilient power infrastructures worldwide [16, 18, 20].

Ensuring the sustainability of the power supply system for mining enterprises under war risks is a multifaceted challenge that involves technical, logistical, and strategic considerations. The first step is thorough risk assessment and mitigation planning [21]. This involves identifying specific risks associated with the conflict, such as physical attacks on infrastructure, cyber-attacks, supply chain disruptions, and workforce safety [22]. Once threats are identified, their probability and impact are assessed through scenario planning and modeling. This helps in developing comprehensive plans to mitigate risks by fortifying infrastructure, diversifying energy sources, and creating redundancies in the power supply system .

A critical aspect of this strategy is the protection of infrastructure. This includes strengthening the physical security of critical power supply facilities, such as power plants, substations, and transmission lines, through barriers, surveillance systems, and security personnel [24]. Cybersecurity is equally important, requiring robust measures to defend against cyber-attacks that could disrupt the power supply. Regular updates, monitoring, and incident response planning are essential to maintain cybersecurity [25].

Diversification of energy sources and the development of backup systems are also crucial. By incorporating renewable energy sources like solar, wind, and biomass, mining enterprises can reduce dependence on centralized power plants that may be vulnerable to attacks [26]. The implementation of microgrids and distributed generation systems allows local areas to maintain power independently from the main grid [27]. Installing backup generators and investing in energy storage solutions, such as batteries and pumped hydro storage, ensure a reliable power supply during outages.

Effective supply chain management is essential to sustain the power supply. This involves diversifying suppliers to reduce vulnerability to supply chain disruptions and maintaining adequate reserves of essential supplies, including fuel and spare parts [28]. Workforce safety and training are also vital, with safety protocols in place to protect workers from the dangers associated with conflict zones and regular training on emergency response procedures.

Finally, collaboration and continuous monitoring are key to sustaining the power supply system. Mining enterprises must work closely with government and military agencies to align on security measures and response plans [29]. Collaboration with other mining enterprises and industry bodies allows for sharing best practices and resources. Continuous monitoring of the power supply infrastructure and the external environment enables real-time detection and response to threats [30]. By adopting these strategies, mining enterprises can enhance their resilience and maintain operations even in the most challenging conditions.

Given the strategic importance for the energy security and defence capabilities of Ukraine's mining and extraction enterprises, it is necessary to emphasize the relevance of conducting comprehensive research on energy efficiency, electromagnetic compatibility, and the reliability of power supply for mining enterprises. This consideration considers the non-stationary conditions of technical and legal functioning of power systems, as well as the requirements for implementing the future smart energy system.

The idea of this work is to analyse the conditions for the stable operation of the power supply system for coal mines in both “weak” power system modes and autonomous modes without any connection to the grid. In doing so, it is essential to meet the requirements of electromagnetic compatibility, consider individual harmonic and interharmonic profiles of powerful stationary installations, while maintaining optimal reactive power flux and monitoring system reliability indicators.

2 Literature review

The operating conditions of mining enterprises’ power supply systems are determined as a set of climatic and mechanical factors that affect the operation modes of the main electrical equipment [12]. In underground mining operations, humidity, temperature, dust, and corrosive substances have the most significant impact among the climatic factors [13 – 16]. All these factors affect the insulation of electrical equipment and reduce its reliability.

The operating conditions of mining equipment have formed a special class of electrical “mining” networks, to which standard approaches to designing and modelling electrical regimes in the presence of non-linear loads cannot be applied [15, 16]. To introduce justified assumptions and initial conditions in mathematical modelling, let's consider the peculiarities of this class of electrical grids [12]:

– high reliability requirements for the power supply system for mines prone to gas and dust hazards;

– separate power supply for underground consumers;

– complexity of organizing reactive power compensation in conditions of instability in underground workings;

– extensive power cable lines with voltages of 6 – 10 and 0.66 – 1.14 kV;

– high power of stationary installations (up to 5 MW);

– specifics of coal underground mining technology leading to cyclic operation of machines and mechanisms with frequent stops and idle running;

– difficulty in meeting voltage quality standards for surface and underground electrical receivers.

These factors form the basis for new models of calculating the quality and reliability of power supply for mining enterprises to achieve maximum energy efficiency.

Analyzing the components of the energy balance of coal mines by technological sections (Fig. 1), it was found that stationary installations account for up to 60% of the total expenses and form the power consumption mode with specific repetitive short-term cycles [12, 15, 16].

Over the past 10 years, there has been a large-scale modernization of technological electrical equipment in all production areas of mining enterprises using frequency converters of various types and capacities.

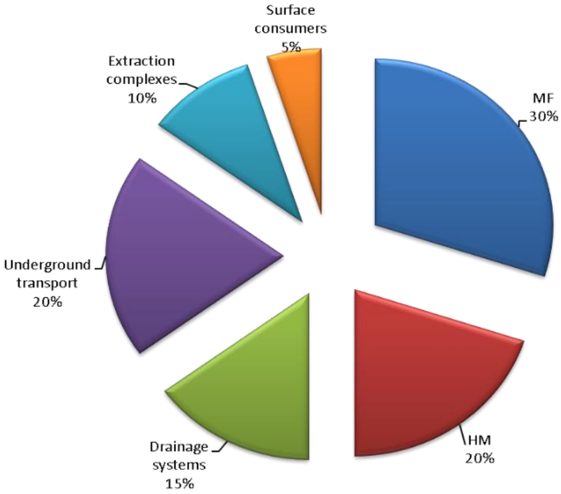

Fig. 1. The energy balance of a coal mine by technological stages [31].

Fig. 2 illustrates the dynamics of the growth of non-linear load in the energy balance of mining enterprises:

Main fans (MF) use asynchronous thyristor cascades and frequency converters with a direct current link with a power of 1.6 – 5.0 MW;

Hoisting machines (HM) (coal and rock) primarily employ rectifiers with a 6 or 12-phase valve commutation scheme with a power of 0.8 – 4.0 MW;

Extraction complexes have an installed power of approximately 1 MW for one section, with almost all electric motors equipped with a frequency drive;

Underground transport includes battery-powered and contactless electric locomotives, and modern conveyor lines are equipped with converters, almost completely displacing the so-called "clean" electric drive in underground electrical grids;

Drainage systems currently do not use frequency converters due to technical characteristics of pump equipment.

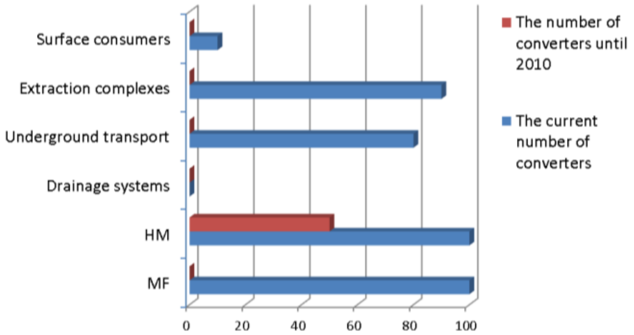

Fig. 2. The dynamics of non-linear load growth in the energy balance [31].

Therefore, existing methodologies for the design and analysis of electrical loads and modes of mining enterprises are outdated and do not meet modern requirements. The energy efficiency of the operation of this class of electrical grids with non-linear loads should be ensured. So, the development of new comprehensive criteria for the quality and reliability of power supply, taking into account the modes of converters, is necessary.

3 Research methods

The equivalent electrical load for the 6 – 10 kV section of the mining enterprise (cable lines (CL), transformers, asynchronous motors (AM) and synchronous motors (SM)) is represented by the following equivalent circuit (Fig. 3).

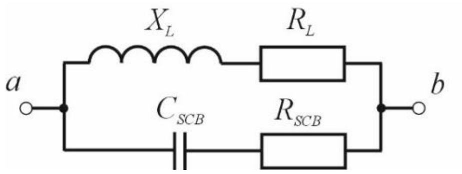

Fig. 3. Equivalent circuit of the generalized load [32, 33]: X_L – inductive reactance of CL, transformers, AM and SM; R_L – active resistance of CL, transformers, AM and SM; R_{SCB} – active resistance of the capacitor battery (CB) circuit; C_{SCB} – capacity of the CB.

The equivalent load complex impedance is determined from the equivalent circuit (Fig. 3):

$$\dot{Z}_{L1} = \frac{\left(R_L + jX_L\right)\left(R_{SCB} - jX_{SCB}\right)}{R_L + jX_L + R_{SCB} - jX_{SCB}}. \tag{1}$$

When modelling, the following assumptions are made:

1. The equivalent circuit of FC consists of two parallel-connected current sources. The justification for this assumption lies in the fact that the distortion of the input current curve of the converter is determined by canonical higher harmonics of the rectifier and interharmonics of the inverter, the level of which depends on the output frequency. In certain cases, a zero background of interharmonics is possible [13, 16, 33].
2. The voltage on the FC terminals deliberately considered are as non-sinusoidal:

$$u(t)=U_1\left[\sin\omega t+U_\nu\sin\left(\nu\omega t+\varphi_\nu\right)\right], \tag{2}$$

where U_1 is the fundamental frequency voltage; U_ν is the higher harmonics voltage.

Based on the adopted assumptions and using the general laws of electrical engineering, the parameters of the equivalent circuit of the load centre with frequency converters are determined:

1) Grid current:

$$i_c(t)=i_{FC}(t)+i_{Load}(t), \tag{3}$$

where $i_{FC}(t)$ is the current consumed by the frequency converter; $i_{Load}(t)$ is the current of the complex load.

2) FC load current:

$$i_{FC}(t)=i_{n\nu}(t)+i_{nh}(t), \tag{4}$$

where $i_{n\nu}(t)$ is the total higher harmonics current; $i_{nh}(t)$ is the total interharmonics current.

3) Rectifier current (switching function):

$$i_b(t)=\sum_{\nu=1}^{\infty}I_{m\nu}\sin\left(\nu\omega_1 t+\varphi_\nu\right). \tag{5}$$

4) Inverter pulsating current:

$$i_n(t)=\frac{1}{2}I_d\left[\cos\alpha_b+\cos\left(\alpha_b+\gamma_b\right)\right]+2\sum_{n=1}^{\infty}\left[\begin{array}{l}\dfrac{U_{d\nu b}\cos\left(np_2\omega_1 t+\varphi_{\nu b}\right)}{\sqrt{R_d^2+\left(np_2X_d\right)^2}}+\\+\dfrac{U_{d\nu u}\cos\left(np_2\omega_2 t+\varphi_{\nu u}\right)}{\sqrt{R_d^2+\left(np_2\chi X_d\right)^2}}\end{array}\right]\cdot(-1)^{n+1}, \tag{6}$$

where ω_1 and ω_2 are FC input and output frequency; p_2 is the number of inverter pulsations; χ is the relative frequency; n is the harmonic number.

5) Equivalent impedances of the FC are expressed as:

$$z_{H\nu}(t)=\frac{u(t)}{i_b(t)},\quad z_{Hh}(t)=\frac{u(t)}{i_n(t)}. \tag{7}$$

The analytical representation of the frequency converter as an element of the power supply system and the proposed equivalent circuit allows considering the initial phases of higher harmonics and interharmonics, the output frequency of the inverter, the control angles of the rectifier and the inverter, and the harmonic distortions of the power grid. The aforementioned has not been previously addressed in scientific literature.

Analysis of the technical characteristics and schemes of frequency converters currently present in the power electronics market has shown that virtually all manufacturers use the "rectifier-inverter" scheme with various connections of semiconductor switches. Therefore, the FC equivalent circuit, which includes two parallel current sources modelling distortions from canonical higher harmonics and interharmonics, is proposed.

In electrical devices, the most common and impactful disturbances are the so-called interharmonic interferences.

There is a known gradation of various harmonic components [13]:

Harmonic: $f=hf_1$, here $h>0$ (h – whole number);

Interharmonic: $f\neq hf_1$, here $h>0$ (h – whole number),

Subharmonic: $0\cdot Hz<f<f_1$.

where f_1 is the fundamental frequency of the supplying grid.

Let's assess and predict the levels of interharmonics (IH) as components of the distorted spectrum with frequencies that are not multiples of the supplying grid frequency. In the amplitude-frequency spectrum, they are located between canonical (higher) harmonics, including the fundamental, as well as between the DC component and the fundamental harmonic. Non-canonical harmonics and subharmonics are considered as separate cases of IH [13, 35, 36].

Sources of interharmonics are consumers that operate in a transient mode either permanently or for a short time. This mode is caused either by a load change related to the technological process or by the features of electromagnetic processes when electric devices operate (for example, the sequential operation of FC valves). In the first case, the processes of current (voltage) changes are random, meaning they are non-periodic. In the second case, neglecting the influence of various random disturbances, the processes of current (voltage) changes from IH sources can be considered periodic. This determines the approach to the analysis and calculation of IH generated by various sources.

Interharmonics in power supply system's arise as a result of modulation of the fundamental frequency and higher harmonics by other frequency components. They are observed when static power converters operate (cycloconverters, asynchronous motors (AM), asynchronous conversion cascades, controlled rectifiers, etc.). In general, interharmonics (IH) act similarly to higher harmonics (HH), and their influence may be stronger than that of HH [13, 36].

The presence of interharmonics (IH) leads to additional losses of active power and electrical energy. If the non-linear load with impedance Z_0, which is a source of both higher harmonics and interharmonics, is connected to a sinusoidal EMF source $e_1(t)$ with impedance Z_S (R_S, L_S), then the current $i(t)$ can be represented as:

$$i(t) = i_1(t) + i_{hh}(t) + i_{ih}(t), \tag{8}$$

where $i_1(t)$, $i_{hh}(t)$, $i_{ih}(t)$ is the currents of the fundamental harmonic (HH and IH, respectively).

Alternatively,

$$i(t) = i_1(t) + \sum_{k=2}^{\infty} i_{hh\,k}(t) + \sum_{n=2}^{\infty} i_{ih\,n}(t). \tag{9}$$

Voltage at load terminals [13, 36]:

$$u_L(t) = e_1(t) + i(t)R_S + L_S\frac{di}{dt}. \tag{10}$$

Thus, it is possible to perform mathematical modelling of the interharmonics impact on the parameters of the operation mode of electrical grids at mining enterprises when powerful non-linear loads are in operation.

4 Research results

The modelling results were validated for adequacy by comparing them with experimental values of interharmonics levels in various operating modes of the FC (Figs. 4 and 5).

To establish the principles of ensuring energy efficiency in the conditions of an operating enterprise, it is necessary to conduct a comprehensive study and develop technical solutions to the issue. One of the most crucial stages is the optimization of electrical modes while ensuring a rational flux of reactive power [14 – 16, 35]. Based on scientific and experimental studies of the electrical modes in coal mines, the following sequence of actions is performed:

1) calculation of electrical loads for stationary installations, underground loads, and the enterprise as a whole;

2) verification of voltage conditions up to the furthest electrical receivers;

3) verification of voltage quality indicators when operating powerful nonlinear loads, taking into account the cyclic nature of operation;

4) selection of configurations for circuits and intersections of cable lines (CL) in electrical grids;

5) selection of reactive power compensation devices (RPC) and their distribution among 0.4, 0.66 kV, and 6 kV grids (Fig. 6).

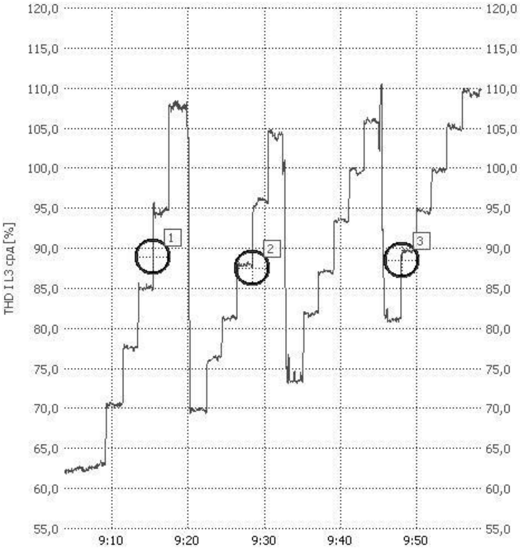

Fig. 4. The value of THD_I during experimental studies of the FC energy performance with a direct current link at a frequency $f_2 = 50 – 20$ Hz.

During the modernization of production and the implementation of energy converters in various technological stages, it is evident that the power of transformers, as well as the cross-section of cable lines, may need refinement. Electromagnetic compatibility of underground and surface electrical receivers with the power supply system also requires normalization. When formulating the research task, it was indicated that the limited power of the power system affects specific modes of stationary installations in coal mines. In a comprehensive approach to solving the problem of energy efficiency, these installations create unique correspondence between the parameters of electromagnetic processes of electrical energy transmission and transformation. As shown, the specificity of operation lies in the fact that the reactive power consumption and generation of higher harmonics have a variable nature, and the degree of reactive power consumption depends on the consumed active power.

Compensation of reactive power in the electrical grids of mining enterprises, in the presence of powerful non-linear loads and higher harmonics, requires the justification of new algorithms for finding the optimal distribution of capacitance compensating devices in the grids of 0.4, 0.66, and 6 – 10 kV. In doing so, it is necessary to consider the features of load variations in stationary installations, non-stationary and unstable loads of underground consumers, and the possibility of limiting the power of the power system in decentralized power supply.

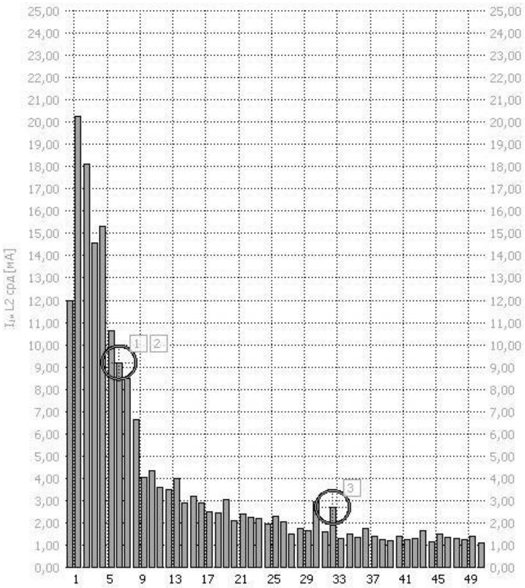

Fig. 5. The values of current interharmonics during experimental studies of the FC energy performance at a frequency $f_2 = 50 - 20$ Hz.

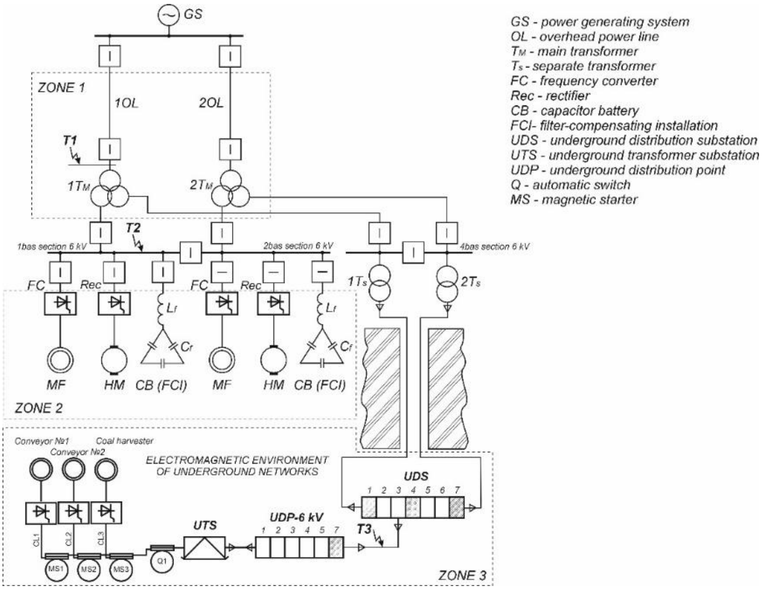

Fig. 6. Distribution of reactive power compensation devices in the power supply system of a coal mine.

The idea of reactive power compensation itself involves reducing active power losses in the elements of electrical grids as the source of reactive power approaches its consumption point [12, 35]. To obtain the optimization target function for reactive power compensation, two components of active power losses will be considered. They are losses due to reactive power flux at the fundamental frequency and additional losses due to the flux of higher harmonics components. The objective is to minimize the active power loss function. The function has the following form [20, 34, 35]:

$$\Delta P=\sum_{i=1}^{n}\left(Q_i-Q_{ki}\right)^2\cdot\frac{R_i}{U^2}+\sum_{i=1}^{n}\sum_{\nu=2}^{m}\left(\left(Q_{\nu i}-Q_{ki}\right)^2\cdot\frac{R_{\nu i}}{U_\nu^2}\right)\to\min, \tag{11}$$

where Q_i, $Q_{\nu i}$ is the reactive power of the electrical grid section at the fundamental frequency and at the frequency of higher harmonics, respectively; Q_{ki} is the total power of compensating devices at the fundamental frequency and at the frequency of higher harmonics; R_i, $R_{\nu i}$ is the resistances of the power supply system elements at the fundamental frequency and at the frequency of higher harmonics, respectively; U_ν is the voltage of the ν-th harmonic.

The specificity of this form of loss dependency lies in considering only the reactive component, which varies depending on the degree of compensation. The fraction of active losses in this issue formulation remains constant and is not considered in the dependencies.

Given the complexity of the electrical regimes of underground and surface consumers, the task of optimal distribution of compensating devices in the power supply system belongs to the issues of constrained optimization. It is solved using the Lagrange method [20, 34, 35].

Regarding the 6 – 10 kV load center, the electrical grid of the mining enterprise can be represented in a radial form (Fig. 7). In this case, circle 1 characterizes the connection of the 6 – 10 kV capacitor bank, circle 2 represents the electrical loads and compensating devices at 0.4 kV on the surface, and circle 3 represents the electrical loads and compensating devices at 0.66 kV in the underground part of the scheme.

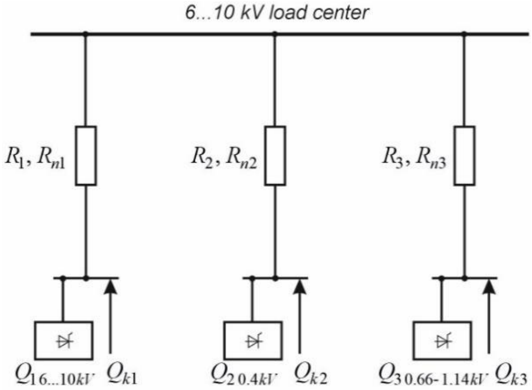

Fig. 7. Radial scheme of compensating devices distribution in the electrical grid of a mining enterprise.

Relative minimum of the objective function is determined under the condition of preventing the generation of reactive energy in the power grid of the energy system [35, 36]:

$$\sum_{i=1}^{n}Q_{ki}=Q_k, \qquad \text{or} \ \sum_{i=1}^{n}Q_{ki}-Q_k=0. \tag{12}$$

The Lagrangian for the derived objective function takes the form of [35, 36]:

$$L=\sum_{i=1}^{n}\left(Q_i-Q_{ki}\right)^2\cdot\frac{R_i}{U^2}+\sum_{i=1}^{n}\sum_{\nu=2}^{m}\left(\left(Q_{\nu i}-Q_{\nu ki}\right)^2\cdot\frac{R_{\nu i}}{U_\nu^2}\right)+\lambda\left(\sum_{i=1}^{n}Q_{ki}-Q_k\right)\to\min. \tag{13}$$

The minimum of the Lagrangian occurs when the partial derivatives of the primary function are equated to zero [35, 36, 37]:

$$\begin{aligned}
&\frac{\partial L}{\partial Q_{k1}} = \frac{-2R_1\left(Q_1 - Q_{k1}\right)}{U^2} - \frac{2R_{v1}\left(Q_{v1} - Q_{k1}\right)}{U_v{}^2} + \lambda \to \min, \\
&\frac{\partial L}{\partial Q_{k2}} = \frac{-2R_2\left(Q_2 - Q_{k2}\right)}{U^2} - \frac{2R_{v2}\left(Q_{v2} - Q_{k2}\right)}{U_v{}^2} + \lambda \to \min, \\
&\frac{\partial L}{\partial Q_{k3}} = \frac{-2R_3\left(Q_3 - Q_{k3}\right)}{U^2} - \frac{2R_{v3}\left(Q_{v3} - Q_{k3}\right)}{U_v{}^2} + \lambda \to \min, \\
&\frac{\partial L}{\partial \lambda} = \sum_{i=1}^{n} Q_{ki} - Q_k = 0.
\end{aligned} \tag{14}$$

Analysing the system of equations (14), the correlations for the optimal distribution of capacitor banks capacitance across the three levels of power distribution in the mining enterprise are obtained. They consider the requirements of electromagnetic compatibility:

$$\begin{aligned}
&R_1\left(Q_1 - Q_{k1}\right) + R_{v1}\left(Q_{v1} - Q_{k1}\right) = R_2\left(Q_2 - Q_{k2}\right) + R_{v2}\left(Q_{v2} - Q_{k2}\right) = \\
&= R_3\left(Q_3 - Q_{k3}\right) + R_{v3}\left(Q_{v3} - Q_{k3}\right).
\end{aligned} \tag{15}$$

Thus, in a comprehensive assessment of the energy efficiency of the power system of mining enterprises, dependencies for the optimal distribution of compensating devices across the hierarchy levels of power distribution have been obtained. With reliable information on the technical parameters of the autonomous power system and the operating modes of non-linear loads, it is possible to derive new correlations for the quantity and power of reactive power compensation devices and determine the optimal points of their connection.

5 Conclusions

The differences in the obtained objective function and its solution lie in simultaneously considering power losses at the fundamental frequency and at higher harmonics frequencies. Considering the high value of the non-linear load fraction and the prospect of transitioning to a decentralized principle of power system construction, it is necessary to introduce a series of variables that consider non-sinusoidality into all fundamental electrical calculations (selection of grid elements, short-circuit current calculations, relay protection settings, etc.). Reliable operation and the ability to operate power systems of large enterprises can be ensured only through comprehensive research with the derivation of correction coefficients for the given parameters.

The perspective development of the created approaches to optimizing reactive power flux parameters includes considering interharmonic components of the distorted current and voltage spectra. This involves developing a reliable mathematical tool for assessing and analysing interharmonics in the operation of energy converters.

Analysis of the electrical modes of typical electrical receivers of mining enterprises has allowed to identify their unique features: cyclicity of operation, a significant part of time operating in the unloaded mode. Considering the mandatory compliance with high requirements for the reliability and explosion safety of the power supply systems of coal enterprises, special requirements are defined for the structure of electrical grids and the control of power consumption modes. The combination of reliability and power supply quality indicators has allowed to offer comprehensive performance indicators for the power supply system obtained under specific combinations of the coal enterprises and power system modes.

Developments have been made in the methods of mathematical modelling of physical processes related to the transmission and distribution of electrical energy in the power supply systems of mining enterprises with non-linear electrical loads. These methods are used as a basis for predicting levels of electromagnetic compatibility.

The new theoretical bases for conducting research in modern power supply systems, considering the increasing power of non-linear loads, have allowed the development of scientific principles for the analysis and synthesis of energy processes in multiphase electrical systems. Additionally, methods for correction have been offered considering the complex interaction of electromagnetic interference sources, which are typical for mining enterprises. These approaches aim to assess their impact on the reliability and efficiency of the main electrical technological equipment.

The methodology for compensating reactive power in electrical grids has been developed based on a comprehensive analysis of individual higher harmonics distortion profiles and coordinated control of the parameters of filter-compensating devices. This approach, along with the justification of preventive measures and mitigation of abnormal modes in power supply systems, allows for optimizing reactive power fluxes and reducing electrical energy losses.

References

1. Kulahina-Stadnichenko, H. (2024). Religiosity of Ukrainian believers in the realities of Russian military aggression. *InterConf*, *41*(185), 165-171. https://doi.org/10.51582/interconf.19-20.01.2024.016
2. Dychkovskyi, R., Saik, P., Sala, D., & Cabana, E.C. (2024). The current state of the non-ore mineral deposits mining in the concept of the Ukraine reconstruction in the post-war period. *Mineral Economics*. https://doi.org/10.1007/s13563-024-00436-z
3. Fihurnyi, Y. (2017). Military and Information Aggression of the Russian Federation against Ukraine and Ukrainians and Its Modern Social Consequences. *Ukrainian Studies*, *3*(64), 42-56. https://doi.org/10.30840/2413-7065.3(64).2017.120301
4. Beshta, O., Fedoreyko, V., Palchyk, A., & Burega, N. (2015). Independent power supply of menage objects based on biosolid oxide fuel systems. *Power Engineering, Control and Information Technologies in Geotechnical Systems*, 33-39. https://doi.org/10.1201/b18475-6
5. Chmura, D., Jagodziński, A. M., Hutniczak, A., Dyczko, A., & Woźniak, G. (2022). Novel Ecosystems in the Urban-Industrial Landscape–Interesting Aspects of Environmental Knowledge Requiring Broadening: A Review. *Sustainability*, *14*(17), 10829. https://doi.org/10.3390/su141710829 4
6. Pedchenko, M., Pedchenko, L., Nesterenko, T., & Dyczko, A. (2018). Technological Solutions for the Realization of NGH-Technology for Gas Transportation and Storage in Gas Hydrate Form. *Solid State Phenomena*, (277), 123-136. https://doi.org/10.4028/www.scientific.net/ssp.277.123
7. Levinsohn, M.W., & Guertin, R. (1983). Hyperosmolarity Complicating Management of Intracranial Hypertension. *Intracranial Pressure V*, 866-870. https://doi.org/10.1007/978-3-642-69204-8_154
8. Snigyr, O. (2020). Time to Focus on Building European Security Resilience: Move Form Deterring Russian Agression to Overcoming the Core Problems. *Horizon Insights*, *3*(4), 1-4. https://doi.org/10.31175/hi.2020.04.01
9. Schor, J.B., & Fitzmaurice, C.J. (2017). Complicating conventionalisation. *Journal of Marketing Management*, *33*(7-8), 644-651. https://doi.org/10.1080/0267257x.2017.1311118
10. Rizkalla, M., El-Sharkawy, M., & Sun, P. (2015). Integrated Sensor Wireless System for Alternative Energy Applications. *Journal of Clean Energy Technologies*, *4*(1), 72-77. https://doi.org/10.7763/jocet.2016.v4.256
11. Xue, T., Yanming, J., Shanshan, F., Jianing, Y., & Zhaoyang, X. (2023). Assessment of Rural Energy Supply System Sustainability Based on Energy Cooperatives. *2023 Power Electronics and Power System Conference (PEPSC)*. https://doi.org/10.1109/pepsc58749.2023.10395475

12. Polyanska, A., Pazynich, Y., Mykhailyshyn, K., Babets, D., & Toś, P. (2024). Aspects of energy efficiency management for rational energy resource utilization. *Rudarsko-Geološko-Naftni Zbornik*, *39*(3), 13-26. https://doi.org/10.17794/rgn.2024.3.2
13. Wang, C.-H., Huang, C.-H., & You, D.-G. (2022). Condition-Based Multi-State-System Maintenance Models for Smart Grid System with Stochastic Power Supply and Demand. *Sustainability*, *14*(13), 7848. https://doi.org/10.3390/su14137848
14. Kolb, A., Pazynich, Y., Mirek, A., & Petinova, O. (2020). Influence of voltage reserve on the parameters of parallel power active compensators in mining. *E3S Web of Conferences*, (201), 01024. https://doi.org/10.1051/e3sconf/202020101024
15. Zakrzewska-Bielawska, A., & Lewicka, D. (2021). A company's relational strategy: Linkage between strategic choices, attributes, and outcomes. *PLOS ONE*, *16*(7), e0254531. https://doi.org/10.1371/journal.pone.0254531
16. Polyanska, A., Savchuk, S., Dudek, M., Sala, D., Pazynich, Y., & Cicho, D. (2022). Impact of digital maturity on sustainable development effects in energy sector in the condition of Industry 4.0. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 97-103. https://doi.org/10.33271/nvngu/2022-6/097
17. Seheda, M.S., Beshta, O.S., Gogolyuk, P.F., Blyznak, Yu.V., Dychkovskyi, R.D., & Smoliński, A. (2024). Mathematical model for the management of the wave processes in three-winding transformers with consideration of the main magnetic flux in mining industry. *Journal of Sustainable Mining*, *23*(1), 20-39. https://doi.org/10.46873/2300-3960.1402
18. Beshta, O., Cichoń, D., Beshta, O., Khalaimov, T., & Cabana, E.C. (2023). Analysis of the Use of Rational Electric Vehicle Battery Design as an Example of the Introduction of the Fit for 55 Package in the Real Estate Market. *Energies*, *16*(24), 7927. https://doi.org/10.3390/en16247927
19. Pivnyak, G.G., & Beshta, O.O. (2020). A complex source of electrical energy for three-phase current based on a stand-alone voltage inverter. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (1), 89-93. https://doi.org/10.33271/nvngu/2020-1/089
20. Beshta, A., Beshta, A., Balakhontsev, A., & Khudolii, S. (2019). Performances of Asynchronous Motor within Variable Frequency Drive with Additional Power Source Plugged via Combined Converter. *2019 IEEE 6th International Conference on Energy Smart Systems (ESS)*. https://doi.org/10.1109/ess.2019.8764192
21. Pivniak, G., Aziukovskyi, O., Papaika, Yu., Lutsenko, I. & Neuberger, N. (2022). Problems of development of innovative power supply systems of Ukraine in the context of European integration. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 89-103. https://doi.org/10.33271/nvngu/2022-5/089
22. Pivnyak, G., Azukovskiy, O., Papaika, Yu., Cabana, E.C., Olczak, P., & Dyczko, A. (2021). Assessment of power supply energy efficiency by voltage quality criterion. *Rynek Energii*, *4*(155). 75-84.
23. Bardas, A., & Parshak, O. (2013). Formation principles of the scientific system of ecological management at industrial enterprises. *Annual Scientific-Technical Collection – Mining of Mineral Deposits 2013*, 99-104. https://doi.org/10.1201/b16354-18
24. Beshta, O.S., Kuvaiev, V.M., Mladetskyi, I.K., & Kuvaiev, M.V. (2020). Ulpa particle separation model in a spiral classifier. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (1), 31-35. https://doi.org/10.33271/nvngu/2020-1/031
25. Pivnyak, G., Dychkovskyi, R., Cabana, E.C., & Smoliński, A. (2018). *Non-Traditional Technologies in the Mining Industry. Solid State Phenomena*. Zurich, Switzerland: Trans Tech Publication Ltd., 280 p.
26. Pivnyak, G., Dychkovskyi, R., Bobyliov, O., Cabana, E.C., & Smoliński, A. (2018). Mathematical and Geomechanical Model in Physical and Chemical Processes of Underground Coal Gasification. *Solid State Phenomena*, (277), 1-16. https://doi.org/10.4028/www.scientific.net/ssp.277.1
27. Shcherba, M.A. (2016). Multi-physical processes during electric field disturbance in solid dielectric near water micro-inclusions connected by conductive channels. In *2nd International Conference on Intelligent Energy and Power Systems (IEPS)*. https://doi.org/10.1109/ieps.2016.7521842

28. Shcherba, M., Shcherba, A., & Peretyatko, Y. (2020). Mathematical Modelling of Electric Current Distribution in Water Trees Branches in XLPE Power Cables Insulation. Proc. *IEEE 7th International Conference on Energy Smart Systems (ESS)*, 353-356. https://doi.org/10.1109/ESS50319.2020.9160293
29. Dusza, D., & Kosobudzki, G. (2018). Reactive power measurements based on its geometrical interpretation. *14th Selected Issues of Electrical Engineering and Electronics (WZEE)*, 8749118. https://doi.org/10.1109/WZEE.2018.8749118
30. Yang, D., Zhao, J., Suhail, S. A., Ahmad, W., Kamiński, P., Dyczko, A., Salmi, A., & Mohamed, A. (2022). Investigating the Ultrasonic Pulse Velocity of Concrete Containing Waste Marble Dust and Its Estimation Using Artificial Intelligence. *Materials*, *15*(12), 4311. https://doi.org/10.3390/ma15124311
31. Papaika, Y., Lysenko, O., Koshelenko, Y., & Olishevskyi, I. (2021). Mathematical modelling of power supply reliability at low voltage quality. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 97-103. https://doi.org/10.33271/nvngu/2021-2/097
32. World Energy & Climate Statistics – Yearbook. (2022). *Total energy consumption*. Retrieved from https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html
33. Ihnatov, A., Haddad, J.S., Koroviaka, Y., Rastsvietaiev, V., & Dmytruk, O. (2023). Study of rational regime and technological parameters of the hydromechanical drilling method. *Archives of Mining Sciences*, *68*(2), 285-299. https://doi.org/10.24425/ams.2023.146180
34. Janik, P., Kosobudzki, G., & Schwarz, H. (2017). Influence of increasing numbers of RE-inverters on the power quality in the distribution grids: A PQ case study of a representative wind turbine and photovoltaic system. *Frontiers in Energy*, *11*(2), 155-167. https://doi.org/10.1007/s11708-017-0469-3
35. Papaika, Yu., Lysenko, O., Rodna, K., & Shevtsova, O. (2020). Information technologies in modeling operation modes of mining dewatering plant based on economic and mathematical analysis. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 82-87. https://doi.org/10.33271/nvngu/2020-4/082
36. Pivnyak, G., Zhezhelenko, I., & Papaika, Y. (2016). Estimating economic equivalent of reactive power in the systems of enterprise power supply. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 62-66
37. Pivnyak, G., Zhezhelenko, I., Papaika, Y., & Lysenko, A. (2017). Interharmonics in power supply systems. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 109-114.