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INCREASING THE EFFICIENCY OF UNDERGROUND MINING COMPLEXES APPLICATION BY IMPROVING THE POWER SUPPLY SYSTEM

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Abstract. The aim of the study is to improve the quality of electricity and reliability of power supply systems of underground mining complexes of deep-level and power-intensive mines based on determining the optimal voltage class of high-voltage power lines.

The subject of the research is the methods of quality indicators ensuring, reliability and safety of power supply systems of underground mining complexes of deep-level and power-intensive mines.

Research methods. Analytical and calculation methods were used to solve the scientific problem to assess the nature and level of electricity consumption in modern deep-level and power-intensive mines; scientific generalization was used in determining the state of development of power supply systems of underground mining complexes of modern ore and coal mines; mathematical modeling was used in the description of processes in grids.

The result of the study. The paper analyzes the current situation when choosing a rational voltage class in the underground power supply system of modern mining complexes was analyzed. Factors that have a direct impact on the efficiency of electricity consumers of deep horizons are identified. The method of power quality indicators calculation at definition of a voltage class of a certain mining horizon or the enterprise as a whole is offered. Prospects of application of voltage classes 6, 10 and 35 kV for power supply of shaft cables in the conditions of deep-level and power-intensive mines are considered.

Conclusion. According to the obtained research results, it was established that the normalized voltage levels are far from the voltage values used today for the power supply lines of the underground power supply system, namely 6 and 10 kV.

Keywords. Voltage class, underground power supply system, mining complex, mining horizons, power quality indicators, voltage deviation.

Introduction

The high degree of mechanization and electrification of modern coal and ore mines leads to an increase in the level of electrical loads and electricity consumption, which significantly exceeds the growth rate of mining in the underground way. This is due to both production and organizational factors (tendency to intensify mining, consolidation and merging of mines, increasing the daily load on the longwall, etc.) and a significant complication of mining and technological conditions in connection with the transition to deeper horizons. The need for mining in deep horizons reduces the reliability and efficiency of underground power supply systems of mining complexes by increasing the total length of high and low voltage distribution grids, imbalance of load curve and more. According to the mentioned factors, the requirements to the level of equipment and safety of power supply systems of mining complexes increase, the principles of construction and economic indicators of which depend on the production capacity of the largest electricity receivers, maximum calculated values of electric loads, consumption levels (equipment for coal-face work, transport, lifting, drainage, etc.), distribution of loads between surface consumers and underground installations, as well as from the mining and geological features of the field – gas, water inflow, etc.

Underground power supply systems of mining complexes of mining enterprises have developed and continue to develop on the basis of the principles laid down in them when designing at the initial stage of their electrification. Constant improvement of technology, mechanization and increase of power equipment in the conditions of mining works, promoted increase of capacity and increase in number of underground electric receivers, complexity of designing of underground power supply systems was grown. [1-3]. In this case, the main aspect that was taken into account in the design was compliance with, in addition to the requirements of safety rules, various standards and indicators necessary for the effective functioning of the designed system. In some cases, some options were considered on the basis of technical and economic comparison and the most desirable of those that did not always correspond to reality was accepted. Accordingly, the quality and efficiency of design largely depend on the experience and engineering intuition of the designer.

The purpose of research is to analyze the factors influencing the choice of a rational voltage class in the conditions of changing the parameters of the underground power supply system; search for technical solutions aimed at improving the efficiency of its operation of underground mining complexes.

Presentation of the main material. When choosing the approximate voltage class at the initial stage of design, in domestic and foreign practice, the following formulas are used [4]

Germany. According to Weikert's formula, the rational voltage level (kV) is

$$U = 3\sqrt{S} + 0,5l\,, \qquad (1)$$

where S is transmitted power, MVA; l is distance, km.

USA. Still's formula is used

$$U = 4,34\sqrt{l + 16P}\,, \qquad (2)$$

where P is transmitted power, MW; l is distance, km.

Sweden. The formula is used

$$U = 17\sqrt{\frac{l}{16} + P}\,. \qquad (3)$$

Expression (2) was transformed by Nikogosov and became widespread in domestic practice in the form

$$U = 16\sqrt[4]{Pl}\,. \qquad (4)$$

These expressions allow us to determine the value of the optimal voltage, based on power and length. According to the recommendations [5], the Still-Nikogosov’s formula is used in approximate calculations, when the total length of the lines is less than 250 km with a power of less than 60 MVA, which is typical for most modern mining enterprises. If the total power is known and the number of power lines is resolved, the voltage can be determined from the expression [6]

$$U_{calk} \geq 0,05\sqrt{\frac{Sl}{n}}\ , \qquad (5)$$

where n is the number of power lines.

Underground power supply systems of mining complexes are becoming increasingly complex and take the form of a complex dynamic system that covers a set of numerous factors and objects. These factors include such as: the method of opening and preparation of the minefield, the exploitation system, the number of developed seams, their depth and angle of stratification, the level of mechanization of coal-face and preparatory work, the reliability of certain types and elements of electrical equipment, patterns formation of loads of mining machines, applied voltage in grids, quality of the electric power, operating conditions, etc. Moreover, in the technical and economic comparison of the developed power supply scheme, it is necessary to strive for a minimum of transformations and the maximum approximation of high voltage to the consumer. The choice of any general variant of the power supply system on the basis of technical and economic comparison with others is already insufficient, as well as the choice of individual variants of the general power supply system.

Currently, a voltage of 6 kV is used for underground high-voltage distribution grids. With the increase in the power of the mines under construction, and especially with the increase in the total power of electric motors in tunneling and mining areas, the shaft and underground cable grid becomes more complicated (it is necessary to increase the cross-sectional area of cable cores and lay parallel lines). into the underground power supply system and electricity losses. In the conditions of power-intensive mines it is necessary to lay a large number of parallel cables in the shaft, the number of which in some mines is up to 4-5 and more [7].

Given the existing limitations of regulations [8], the maximum cross-sectional area of the cores of laid cables (to stationary distribution points is 240 mm^2, to mobile distribution substations (DS) is 95 mm^2), power transmission at level of 5 MVA with an operating voltage of 6 kV, is up to difficult task. This is primarily due to the implementation of the requirements to ensure the necessary indicators of electricity quality for consumers of deep horizons. These circumstances lead to the use of unreliable and dangerous in multiple sectioning operation of underground substations. According to [9], increasing the number of shaft cables to 8-14 causes difficulties not only in building reliable power supply schemes of the Main underground substation (MUS) and laying cables, but also significantly reduces the reliability of power supply and complicates operating conditions. Examples of implementation of power schemes are shown in Fig. 1.

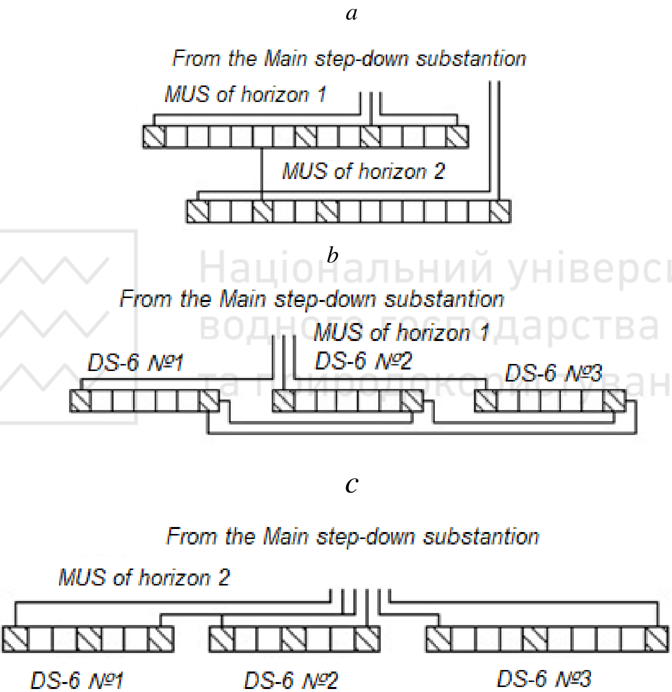

Fig. 1*a*. Power supply scheme when using three cables with a core cross-sectional area of 95 mm^2; *b* – Power supply scheme when using three cables with a cross-sectional area of 185 mm^2; *c* – Power supply scheme when using six cables with a cross-sectional area of 150 mm^2

When using three shaft cables, different variants of MUS power supply schemes are possible, which differ significantly in the number of input and sectional complete switchgears (CSG) used. When designing MUS power supply schemes, including for deep-level mines, it is necessary to use a circuit with two inputs for each CSG. According to the requirements [10], all power cables of the Main underground substation, laid in the shaft, must be constantly under load. To supply the MUS, it is necessary to lay at least two working cables, laying of spare cables is prohibited (in case of failure one of the cables, the other cables must ensure the operation of the mine without reducing its productivity). The implementation of these requirements needs separate power supply to the sections of the MUS busbar with an even distribution of load between them. Drainage pump motors must be connected to different busbar sections, and other high-voltage consumers must be distributed between the MUS busbar sections depending on the load current. This principle of construction of the MUS scheme is expedient if we assume that the main type of damage that causes interruptions in the power supply is the failure of one of the cables.

Also in the conditions of deep-level mines, when transmitting electricity over a long distance (the length of individual lines reaches 5 km), it is necessary to take measures to increase the capacity of the grid, which should be increased in two ways: by using double cable lines and increasing the maximum cross-sectional area. The use of these methods allows to increase the transmission capacity of the lines approximately twice, to simplify the existing scheme of the MUS by reducing the number of input and section switches. The number of backup switches, which are installed at the rate of one switch for each section of busbar, is also reduced. The disadvantage of such a system is that the line is considered as one, and therefore must have 100% backup. In addition, the probability of damage to the double lines increases. The increase in transmission capacity due to the change in the cross-sectional area of the cable is limited by the types of existing complete switchgear and complicates the installation of cables in the shaft due to the growth of their weight. Due to the increase in the total length of cable lines there is a significant number of failures in the high-voltage distribution grid – the frequency of failures in a cable line with a voltage of 6-10 kV with a length of 6 km is 0.6 h^{-1} [11]. These indicators can be increased only through the development of new principles for the construction and reconstruction of power supply systems for deep-level and power-intensive industries.

According to the requirements of [8], in the underground grid with a voltage of 6 kV at a grounding circuit resistance of 2 Ohms and a touch voltage of 30 V, the maximum allowable capacitance should not exceed 4.6 μF per phase. Therefore, the total length of the high-voltage cable grid, which is made of СБ, СБГ, ЦСКН, ЦСКл cable types under the condition of safe operation, should not exceed 24 km. Widespread recent use of the ЭВТ cable type, which has twice the capacity [11] compared to existing samples, in additional reduces the overall length of the grid.

The efficiency of supply lines transition to higher voltage rate can be explained that at the same loads, power factor, material and cross-sectional area of current-carrying cores with increasing line voltage from U_{r1} to U_{r2} the ratio of voltage losses [9] is

$$\frac{\Delta U_2}{\Delta U_1} = \frac{U_{r1}}{U_{r2}}, \tag{6}$$

and the power losses ratio

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{U_{r1}}{U_{r2}}\right)^2, \tag{7}$$

where ΔU_1, ΔP_1 are voltage and power losses at rated voltage U_{r1}; ΔU_2, ΔP_2 are voltage and power losses at rated voltage U_{r2}.

The calculated valuesof the ratios of voltage losses and power in the mine cable grids with constant parameters of the system are given in the table.

Table

The calculated values of the ratios of voltage losses and power in the mine cable grids with constant parameters of the system

U_{r1}, kV	U_{r2}, kV	$\frac{\Delta U_2}{\Delta U_1}$, %	$\frac{\Delta P_2}{\Delta P_1}$, %
6	10	60	36
	35	17	3

From the table, we can conclude that in case of transition the 6 kV lines to higher voltage rate, particularly 10 or 35 kV, the losses are 40 and 83% cut respectively, the power losses are 64 and 97% reduced.

Technical and economic comparative analysis of power supply options at different voltage classes should be performed taking into account quality indicators that do not have a cost estimate. Qualitative indicators of the option are better if:

- when working in the mains there are smaller voltage fluctuations;
- total voltage losses decrease;
- installation and operation of underground power supply grids simplify;
- grid reconstruction is simplified if necessary (if it is necessary to increase production capacity).

In papers [7, 13] the necessity of application of voltage class 10-20 kV for high-voltage distribution grid of mines under construction is noted. This allows to reduce the number of shaft cables, to improve the start-up conditions of powerful electric motors of stationary installations (primarily drainage), to increase the quality of voltage in the underground power supply system, efficiency and reliability of equipment. A special advantage of such a technical solution is the achievement of voltage stability even in the most remote sections of the distribution grid. The starting torque of powerful stationary motors is significantly increased (by about 20%), which does not cause a decrease in voltage when they are started under load and the associated shutdown of control and protection devices.

To date, there are design developments for the construction of a step-down transformer substation, which provides power supply to underground consumers of the unit with a voltage class of 10 kV in the conditions of PJSC " Pokrovskoye Mine Management". The total power of underground consumers of this unit is 22.8 MVA, and the total current is 1268 A, while when using a voltage class of 6 kV, it is 2194 A. Reducing current loads at a voltage of 10 kV instead of 6 kV, contributes to the corresponding reducing the voltage drop in the cables (1.73 times) [14]. The use of a voltage class of 10 kV instead of 6 kV for underground distribution grids requires the development of a complex of equipment in explosion-proof design (cables, switchgear, transformers, powerful motors, etc.). The transition to 10 kV can be effective only by increasing the allowable short-circuit power from 50-75 to 100-150 MVA, which requires a fundamentally new approach in the development of protection. Crucial in this case is the coordination of rated voltages of the power supply system of the mine and its consumers. For example, the use of 10/6 kV transformers in the pits for power supply of powerful consumers significantly reduces the field of use of the voltage class 10 kV.

The use of deep-level input of 35 kV voltage in underground mine workings also deserves additional attention, when there are no significant restrictions on the level of grid transmission capacity. The main problems are the development of underground substations in explosion-proof design and appropriate protection devices to ensure the established level of safety. Additional advantages of using this approach are the provision of independent power supply to consumers of the underground power supply system without the installation of separate transformers, as well as the transfer of the distribution boundary from the main step-down substation to the MUS, which reduces the total length of power cables by several kilometers. In addition, the use of 35/6 kV transformers at the Main underground substation will limit the short-circuit current to an acceptable level and abandon current-limiting reactors, which will increase the reliability and safety of underground grid maintenance.

When performing the relevant research, it is necessary to choose a mine with average productivity, depth of mining, water inflow, etc. When performing the analysis, it is necessary to take into account that to select the supply grid voltage, it is advisable to use the classes of the corresponding standard series: 6, 10 and 35 (110) kV. The use of a voltage class of 20 kV [15,16] is not appropriate due to the lack of necessary equipment of domestic production (primarily motors and transformers).

In the conditions of deep-level and power-intensive mines, the urgent problem is to provide the necessary indicators of electricity quality at the stage of design and development of a certain working horizon. First, the assessment of the impact of voltage quality indicators in consumers of electricity of the underground grid, the reliability of the power supply system, the analysis of the capacity of the respective distribution grids are performed [17-20]. The main indicator of the transmission capacity of cable lines is the value of the transmitted total power at a given level of voltage losses and rated voltage. The voltage losses in the line is determined by the expression, *V*

$$\Delta U = \sqrt{3}I\left(R\cdot\cos\varphi + X\cdot\sin\varphi\right), \qquad (8)$$

where *I* is current in line, A; f is phase shift angle between current and voltage; *R* and *X* are active and inductive resistance of cable cores respectively, Ohm.

More often the allowable voltage losses are expressed in %

$$\Delta u = \frac{\Delta U}{U_r}100, \qquad (9)$$

where U_r is rated voltage, V.

Taking into account (9), and assuming that the total power transmitted is equal to $S = \sqrt{3}IU_r$, the expression will take the form

$$\Delta u = \frac{S\left(R\cdot\cos\varphi + X\cdot\sin\varphi\right)}{10U_r^2}, \qquad (10)$$

then total power *S*, MVA is

$$S = \frac{\Delta u U_r^2}{\left(R\cdot\cos\varphi + X\cdot\sin\varphi\right)}\cdot 10^{-2}. \qquad (11)$$

Based on expressions (10-11), the appropriate voltage depending on the grid parameters and the allowable level of losses is determined by the formula

$$U = \sqrt{\frac{100S\left(R\cdot\cos\varphi + X\cdot\sin\varphi\right)}{\Delta u}}, \qquad (12)$$

Δu is set voltage deviation level, c.u.

The proposed expression allows the analysis of the allowable voltage level, with appropriate restrictions on its deviation (up to 5%). When performing the calculation, the parameters of real deep-level and power-intensive mines with a working load of S = 2..10 MVA and a horizon depth of 1000 m were used. The best operating conditions are considered: power factor is 0.95; 4 cable lines with the maximum possible cross-sectional area of cable cores of 240 mm^2.

The results of the calculation are shown in Figure 2. From the above graph it can be concluded that according to the established criteria, the normalized voltage levels are far from those used today for the voltage values for power lines of the underground power supply system, namely 6 and 10 kV.

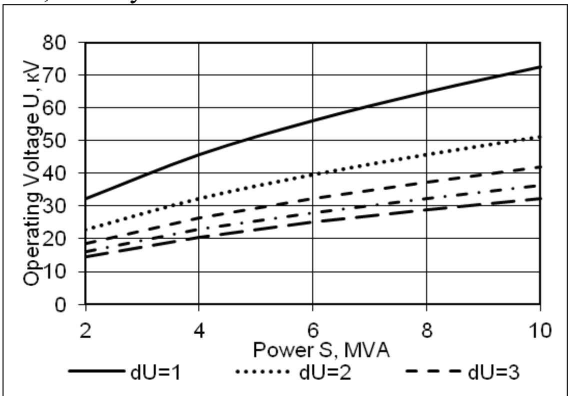

Fig. 2 Rational voltage classes in deep-level mines at restrictions on the allowable voltage deviation at the end of the line

Conclusion. These indicators clearly show the technical efficiency of the use of underground mining complexes by increasing the voltage class for distribution grids in conditions of insufficient transmission capacity of underground cable lines. Therefore, it is advisable to use voltage deviation indicators to assess its prospective class. This measure allows you to plan in advance the use of a certain voltage class in terms of changes in the cost of electrical equipment and electricity.

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