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Simulation of power consumption control of receivers at underground iron ore mining enterprises

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ABSTRACT

The article presents the results of developing a concept for controlling the process of power consumption by electrical receivers with a voltage of up to 1000 V at underground mining enterprises in the function of hourly tariffs, which are characterized by variable pricing for the day ahead in current market conditions. The following parameters are considered: limitations on operation duration of a separate electrical unit during the day, the maximum load on underground substation transformers, and the amount of power ordered by the enterprise, the excess of which leads to the application of penalties. To solve the control problem, it is proposed to apply a heuristic optimization method based on a genetic algorithm. System efficiency is studied by determining settings of the evolutionary search algorithm that would ensure the lowest cost of power purchase. In particular, the crossover function (one-point, two-point, or Laplace) and the number of elite individuals in the population are modified. The experiments are carried out on the basis of the Global Optimization Toolbox in the MATLAB software package. Simulation of system efficiency through different settings of the genetic algorithm demonstrates that the minimum power cost can be ensured by using the Laplace crossover method with 10 individuals in a population of 100, of which 10 are elite and pass to the next generation unchanged. This option allows obtaining an average of 2.62 % lower daily power cost than the other parameters studied. The proposed method of power consumption control allows us to identify the achievable potential for reducing the energy component in the final product cost of iron ore mining at underground mining enterprises. It can be recommended for practical implementation at both operating and projected enterprises.

Keywords: Underground mine power system; up to 1000 V loads; power price; optimization; mixed-integer linear programming; heuristic control system; genetic algorithm

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INTRODUCTION

The state of a country's energy sector is a systemic component that determines the level of its economic and political independence, and creates preconditions for joining progressive blocs of economically advanced countries. One of the most important features of such independence level is energy intensity of the gross domestic product [1].

Currently, this indicator is far from optimal in Ukraine. This is primarily due to the fact that generalized energy indicators of the state as a whole are determined by the state of domestic energy of consumers and especially their energy-intensive types [2]. This class of production includes metallurgical enterprises and mining as their raw material base.

The total installed power capacity of these enterprises reaches hundreds of MW (Fig. 1).

Despite sufficient volumes of power generation at power plants to meet the country's needs, Ukraine's power problem has worsened in recent decades, which is a result of a number of factors [3, 4], including the relationship between generating and distributing power structures on the one hand, and the Ukrainian power market and power consumers on the other. And while the former need to ensure the stability of power consumption levels by customers, including in terms of hours of the day, the latter need transparent pricing, preferably predictable, to enable them to optimize power consumption and costs.

Under the existing Law [5], neither the first nor the second scenario can be fully implemented. That is, both parties need to find effective ways to function together.

In this research, the authors focus their search on the possibilities of solving the power problem on the part of the power consumer, or rather, mining enterprises with underground methods of iron ore mining.

One of the main ways to improve energy efficiency of iron ore mining is to reduce the volume of power consumption by relevant enterprises [5]. It is also logical that with available iron ore mining technologies, this can be achieved by replacing outdated energy inefficient equipment with the new energy efficient one. However, according to the results of [1, 2] and [4], such measures to improve their energy efficiency are not enough for the conditions of underground mining enterprises. Moreover, as iron ore mining depths naturally increase over time, within the framework of existing technology, the energy savings achieved by this method are offset by the need for potential increased power consumption. That is, it is necessary to search for new and mostly non-standard energy-oriented ways.

This requires a new vision of the energy efficiency improvement format and, above all, a reduction in the material burden on iron ore mining costs.

One of these potentially effective ways to reduce energy costs is to manage the distribution of power flows among consumers by hours of the day, since the existing tariffs, i.e. the price per kW*h of power consumed by hours of the day, are not constant and essentially characterized by 24-hour tariffs [5]. Moreover, these tariffs are not constant from day to day, but variable and unpredictable in time, which is a derivative of fluctuations of the market price of power.

However, the analysis shows that according to the logic of its structure, the existing format of daily tariffs consists of “economic” and “non-economic” prices for power supplied by generating companies. At the same time, the difference between “economic” and “non-economic” tariffs is several times greater, so there is logic to research in this direction.

Fig. 1 provides information on the levels of power consumption and the cost of power at iron ore underground mines of Kryvyi Rih.

In other words, speaking of energy efficiency in mining in this modern vision, it is correct to understand it in terms of a multilateral or multifactorial concept and the corresponding search format.

The above emphasizes that, according to the testing of the relevant Law [5] in the practice of mining enterprises, these enterprises themselves should intensify their activities to implement modern systems controlling power supply and consumption of electrical receivers.

In this case, an equally important criterion for the development of such control systems is the need and ability of the system to adapt to stochastic conditions of changes in consumption parameters caused by changes in the nature of mineral resource extraction.

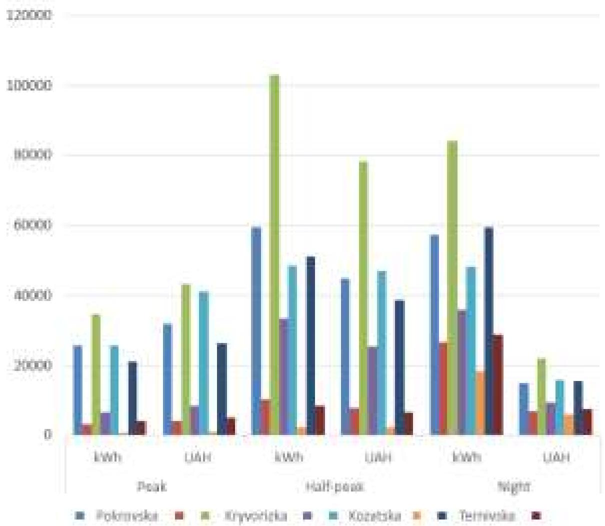

Fig. 1. **Daily power consumption levels and power costs at iron ore underground mines in Kryvyi Rih iron ore basin (2021)**

Source: **compiled by the authors**

LITERATURE REVIEW

The logistics of load control in power grids of industrial enterprises, cities and local facilities has been the subject of a number of scientific studies.

For example, [7, 8], [9, 10] and [11] provide a detailed analysis of the methods used to control power consumption in the internal power grid. In this case, they consider different optimization criteria that can be used. The authors compare effectiveness of specific optimization algorithms. According to the research analysis, there are several approaches to solving the load control problem. Methods of linear [12], nonlinear [13], and quadratic programming are classical [14].

Heuristic methods [15, 16], [17, 18], [19, 20], and tools similar to the processes of adaptation and evolution of biological organisms are used to make decisions about controlling power consumption [21].

These methods are often applied to solving complex optimization problems when exact analytical solutions are not applicable.

Methods based on the principles of machine learning, artificial intelligence, and fuzzy logic are mentioned in [22, 23], [24, 25], [26]. These methods can use machine learning, intelligent algorithms, and other artificial intelligence technologies to control power consumption.

At the same time, the peculiarities of optimizing power consumption at iron ore underground mines using these methods, in particular, heuristic ones, have not been studied sufficiently. More attention is paid to the use of more classical methods [27, 28] or individual technological objects are considered [29, 30].

Therefore, this paper aims to develop a system for controlling power consumption by receivers of underground mining enterprises in the function of hourly tariffs for the power cost using a genetic algorithm, as the most proven one for solving optimization problems of this nature. It also aims to analyze the influence of parameters of this algorithm on the system's efficiency by modeling. Underground mine consumers with voltage up to 1000V are considered.

MAIN PART
FORMULATION OF THE MINE LOADS POWER CONSUMPTION OPTIMAL CONTROL PROBLEM

Fig. 2 shows the structure of a part of the mine power grid with a heuristic power consumption control system. It consists of two components. On the one hand, it is the equipment of the power supply system and the electrical equipment of the underground mine level, and on the other hand, it is a unit for optimizing the power load schedule and managing the connection of consumers to the grid. The power supply system itself consists of a 6 (10) kV switchgear located on the surface, to which sections of the central underground substation (CUS) are connected through the reactors. The substation supplies power to consumers in the trunk yard and underground distribution points (UDPs). Mobile site underground substations (MSUSs) are connected to the underground distribution points and then to the consumers of ore mining blocks. The main part of the industrial power supply system, the DP-CUS – DP-MSUS, to simplify the analysis, combines a substation with concentrated parameters – a "virtual substation" similar to a wind power plant, but without generating capacity [31].

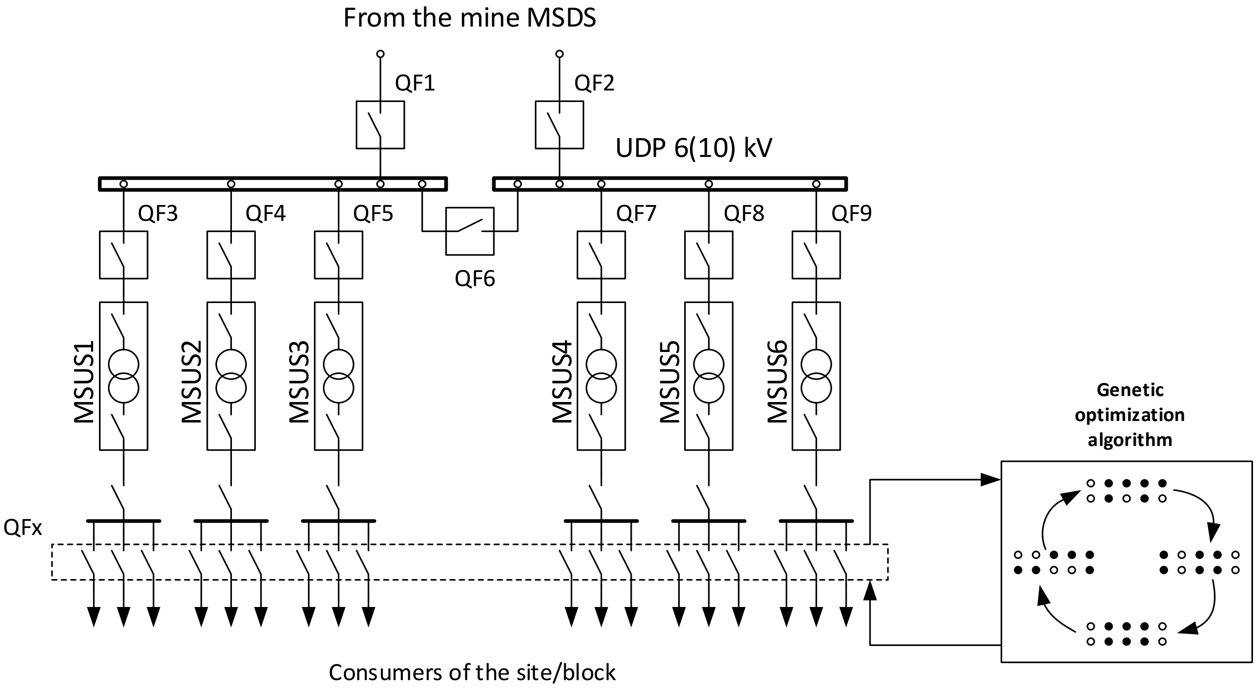

Fig. 2. **Block diagram of a part of the mine power system with the heuristic power consumption control system**
Source: **compiled by the authors**

Next, we consider the direct connection of the electrical equipment of preparatory and stopping workings to this power plant through a group of QFx switches that have digital interfaces for remote control. The heuristic system switches them at time intervals determined by the genetic algorithm, thereby directly controlling the load.

Controlling power consumption at an underground mine is a single or multi-criteria optimization problem. It can include minimizing power consumption, reducing costs, and other goals. To represent the control of each process unit, a binary coding is used, where 1 indicates connection to the power grid and 0 indicates disconnection. This means that there are two possible states for each unit – connected or disconnected. The optimization problem turns into a binary mixed integer programming problem because there are both integer (binary) variables (connection state) and ordinary numeric variables, such as power or costs. A genetic algorithm is one of the optimization methods that can be used to solve the following problems. A genetic algorithm models an evolutionary process where individuals (solutions) evolve, interbreed, and mutate to find the optimal solution. One gene in a chromosome can be either 0 or 1, which is a two-bit encoding. This is a typical encoding method for binary genetic algorithms, where each variable is encoded as a single bit. Genetic algorithms can be efficient for solving optimization problems, especially when the solution involves a combinatorial aspect (for example, choosing between connecting and disconnecting different units). However, it is important to correctly define the fitness function and other parameters of the genetic algorithm to achieve the desired results in the optimization problem. The generalized form of an optimization problem with constraints is as follows:

$$\begin{aligned}
&\min: && J\left(x_{ij}\right)=\sum_{i=1}^{N_T} C_i \sum_{j=1}^{N_L} P_{ij}\cdot x_{ij}, \\
&\text{subject to:} && \sum_{i=1}^{N_T} x_{ij}=n_j; \\
& && \sum_{i=1}^{N_T}\sum_{j=1}^{N_L} P_{ij}\cdot x_{ij}\le P_{РДН}; \\
& && \sum_{j=1}^{N_L} P_{ij}\cdot x_{ij}\le P_{ном\ ПДПП},
\end{aligned} \tag{1}$$

where N_L is the number of electrical receivers; N_T is the number of time intervals; x_{ij} is the state of connection of the j-th mining electrical receiver at a specific i-th time of day; C_i is the price of kW*h of power, UAH/kW*h; P_{ij} is the power of the mining electrical receiver at a particular time of day; n_j is the total operating time of the mining electrical receiver, hours.

The objective function (1) allows you to distribute the operating time of individual power consumers in such a way as to minimize the total daily cost of purchased power.

The process of power control optimization of an underground mine is affected by constraints that should be taken into account when determining the fitness function in a genetic algorithm. Therefore, the first limitation is the time limits when the electrical unit operates. The next limitation is the daily power consumption spent on mining operations, which should not exceed the ordered daily volumes. Finally, the load factor of underground transformers should not exceed 100%. These constraints and the objective function can be used in a genetic algorithm to find the optimal distribution of power among consumers while minimizing the cost or other optimization criteria. The genetic algorithm can search for optimal combinations of binary variables (connect or disconnect) to achieve these goals and constraints.

A procedure for modeling the operation of a power consumption control system in an underground mine using a genetic algorithm is carried out.

To do this, let us use the Global Optimization Toolbox of the MATLAB software package. Three crossover functions are used to model the control system – one-point, two-point, and Laplace [32]. The time interval of the electrical receiver is 1 hour [33]. For comparison purposes, let us also consider several options for setting up the population of the genetic algorithm. All settings options are shown in Table 1.

Table 1. **Setting up a genetic algorithm**

Option	Population size	Number of elite individuals	Crossover function
A	100	10	One-point
B			Two-point
C			Laplace
D		5	One-point
E			Two-point
F			Laplace

Source: **compiled by the authors**

The research object is the part of the industrial power supply system that supplies electrical equipment of several mining blocks of iron ore underground mine levels in Kryvyi Rih. The number of power receivers is 82 units with a total power of 1662 kW.

MODELING THE POWER CONSUMPTION CONTROL SYSTEM BASED ON A GENETIC ALGORITHM

Fig. 3 and Fig. 4 show the results of modeling the operation of the power consumption control system of electrical receivers of an underground mine when using the setting of the genetic algorithm according to option A.

Fig. 3 shows the distribution of hours of production operations performed by electrical equipment for conducting stoping and preparatory workings during the day. Power costs in this option amount to 42.5 thousand UAH. It is typical for consumers whose work is related to ensuring safe working conditions, such as main ventilation fans and mine drainage pumps, to operate around the clock. For others, there is a natural tendency for maximum power consumption to occur during hours when the cost of power is minimal. Peak loads occur at 5 a.m. At other periods, power consumption is approximately equally distributed throughout the day.

In Fig. 4, we can see how the quality of the populations changes after every 40 generations of the genetic algorithm. In the starting population, one phenotype gives the objective function value between 43680 UAH/day and 43754 UAH/day. This is the best result in the first generation. The largest number of genes in the first generation, namely 8 units, gives the value of the objective function between 45678 UAH/day and 45752 UAH/day.

After generation 40, the population is divided into two groups: the larger number of 86 individuals yields values between 43470 UAH/day and 47110 UAH/day, and the smaller number of 14 individuals yields values between 42560 and 43015 UAH/day. Moreover, the largest number of individuals - 8 - gives values between 42742 UAH/day and 42833 UAH/day. This division persists until recent generations.

Fig. 5 reveals the distribution of consumers' operation when using option B of the genetic algorithm parameters setting. In this case, the operation hours of the loads are less scattered throughout the day than in option A. Moreover, there are clearly defined peak hours at 5, 14 and 21. There is also a period with minimum power consumption at 16. In this case, the level of daily power costs is reduced compared to option A to 42.6 thousand UAH. That is, the decrease is only 0.23 %.

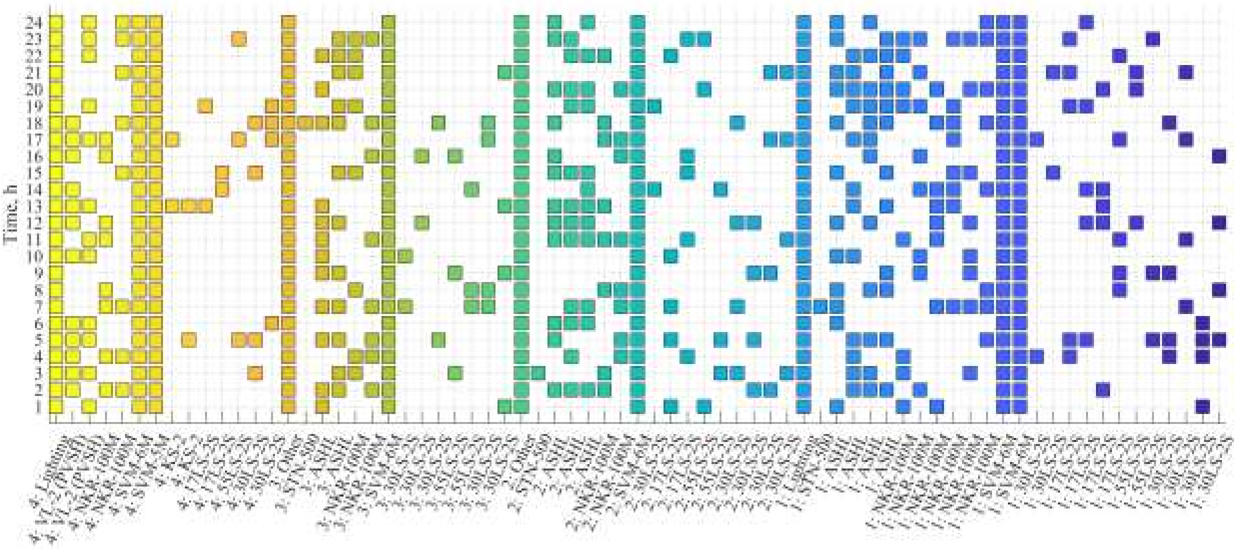

Fig. 3. **Daily operation schedule of consumers for conducting stopping and preparatory workings of the mine level when using a genetic algorithm with settings according to option A**
Source: **compiled by the authors**

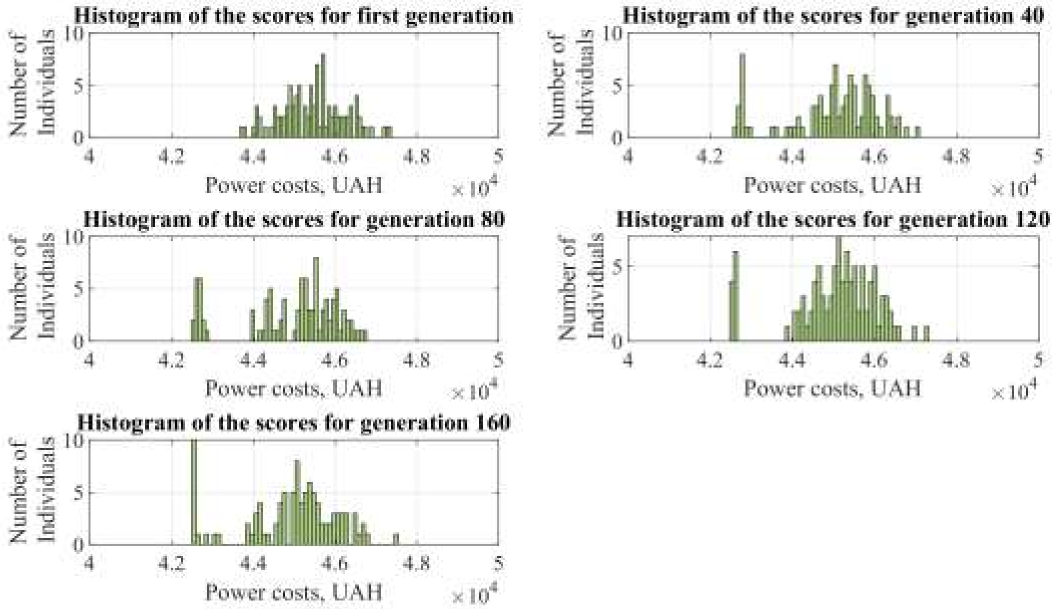

Fig. 4. **Evolution of populations in optimizing the operation schedule of mine level consumers using a genetic algorithm with the setting according to option A**
Source: **compiled by the authors**

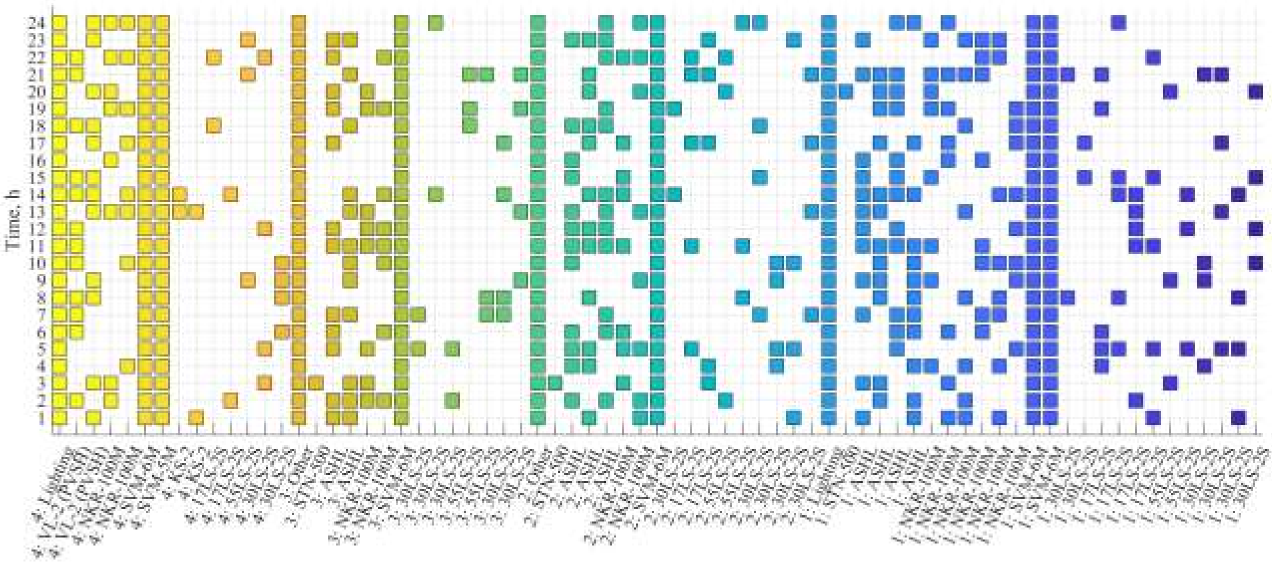

Fig. 5. **Daily operation schedule of consumers of stoping and preparatory workings of the mine level when using a genetic algorithm with the setting according to option B**
Source: **compiled by the authors**

It can be argued that both the one-point and two-point crossover variants give approximately the same results when optimizing the consumer's load schedule. Let us analyze the quality of populations in the process of evolutionary search for an extremum of the objective function (1).

The bar graphs of population quality (Fig. 6) in the evolutionary search for option B indicate similar patterns as in the one-point crossover. In the starting population, individuals are grouped by quality between the values of the objective function 43680 UAH/day and 47380 UAH/day.

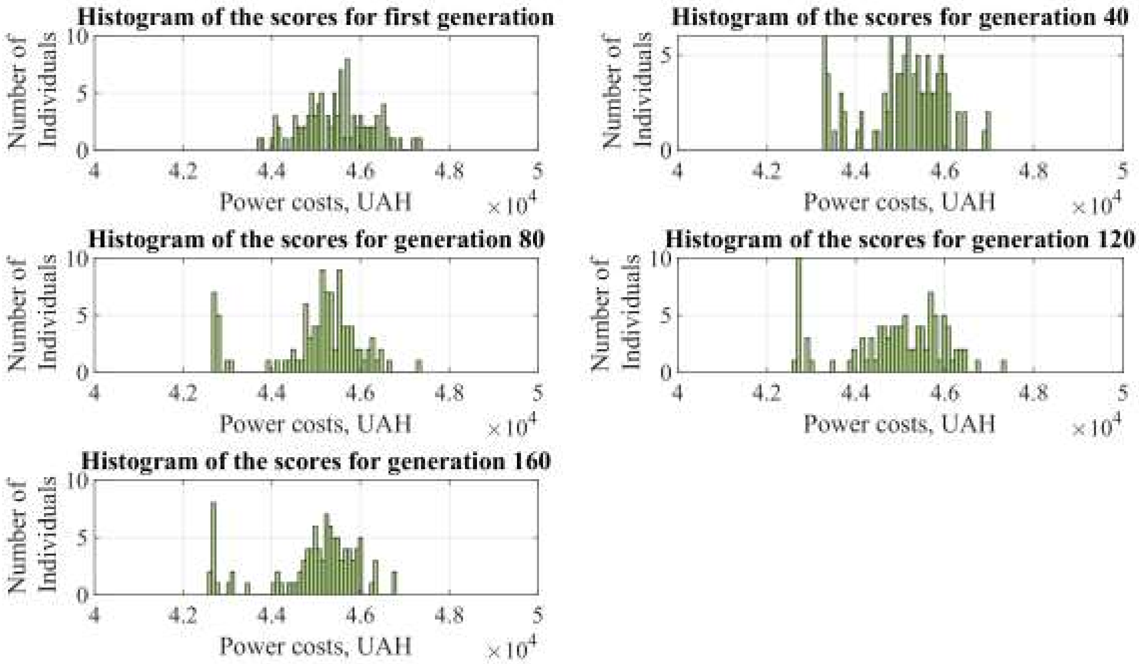

Fig. 6. **Evolution of populations in optimizing the operation schedule of mine level consumers using a genetic algorithm with the setting according to option B**
Source: **compiled by the authors**

The initial and final intervals include one phenotype from each population. The largest number of individuals is 8, taking values of at least 45678 UAH/day and 45752 UAH/day. In case of generation 40, the population is still quite grouped in terms of quality, but the range is more evenly distributed. After generation 80, the population is divided into two groups: the main group (86 individuals per 80th generation and 85 individuals per 160th generation) and the elite group (14 individuals per 80th generation and 15 individuals per 160th generation), which is of higher quality. Moreover, in generation 120, 10 individuals give values of the objective function in the range of 42666 UAH/day and 42762 UAH/day, and in generation 160, 8 individuals gave values from 42645 UAH/day to 42730 UAH/day. That is, even with the random nature of selection, crossover and mutation, the number of elite units of the population varies slightly.

Fig. 7 shows the results of the genetic optimization algorithm when applying the Laplace crossover function, 100 individuals in the general population with a ratio of the number of elite units to their total number of 1/10 (option C of Table 1). In this option, there is a high fluctuation in power consumption. Peak loads vary for hours with minimal power consumption and vice versa. At the same time, the cost of purchasing power in a heuristic system with these settings during the day is 41.4 thousand UAH, which is 2.6 % less than in option A and 2.8 % less than in option B. This combination of parameters demonstrates the best results in the experiments.

Fig. 8 indicates that in the course of evolutionary optimization, the entire population begins to shift from generation to generation to the region of lower values of the objective function, i.e. the whole population becomes more qualitative, and not only a small group of elite individuals is distinguished, as in other crossover functions. Thus, the starting population fully gives the value of the objective function between 43680 UAH/day and 47380 UAH/day. By generation 40, the bulk of the population (94 individuals) yields power costs between 42210 UAH/day and 43746 UAH/day. Moreover, with evolution, the shift continues and the area in which the main individuals are located becomes more grouped. Thus, for generation 160, this area is 1020 UAH/day (from 41500 UAH/day to 42520 UAH/day), and for generation 40, it was 1536 UAH/day (50.588% higher).

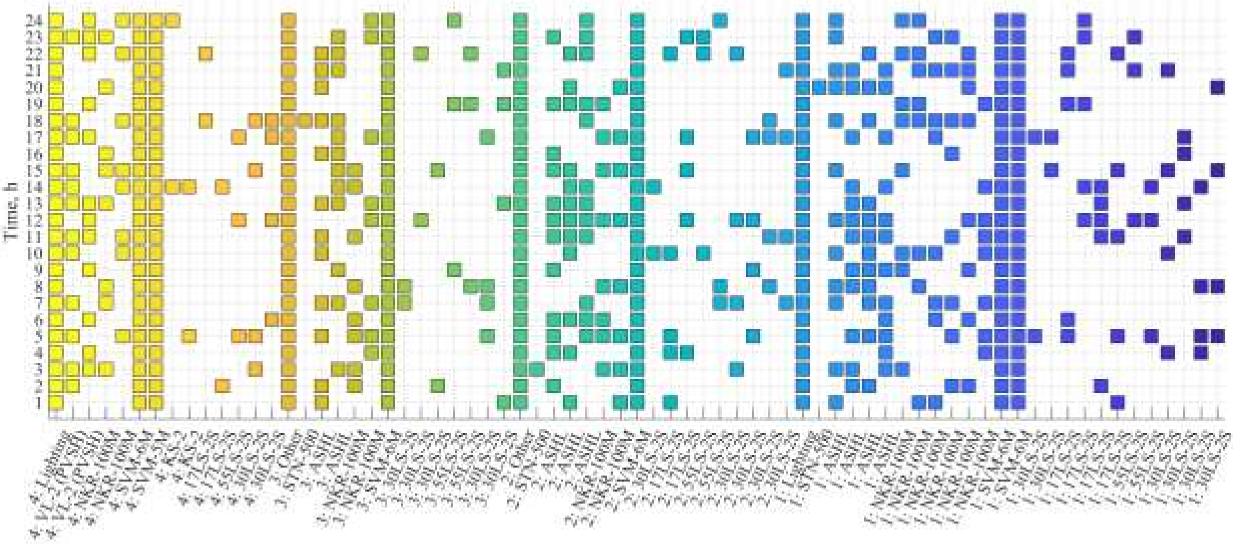

Fig. 7. **Daily operation schedule of consumers of stoping and preparatory workings of the mine level when using a genetic algorithm with settings according to option C**
Source: **compiled by the authors**

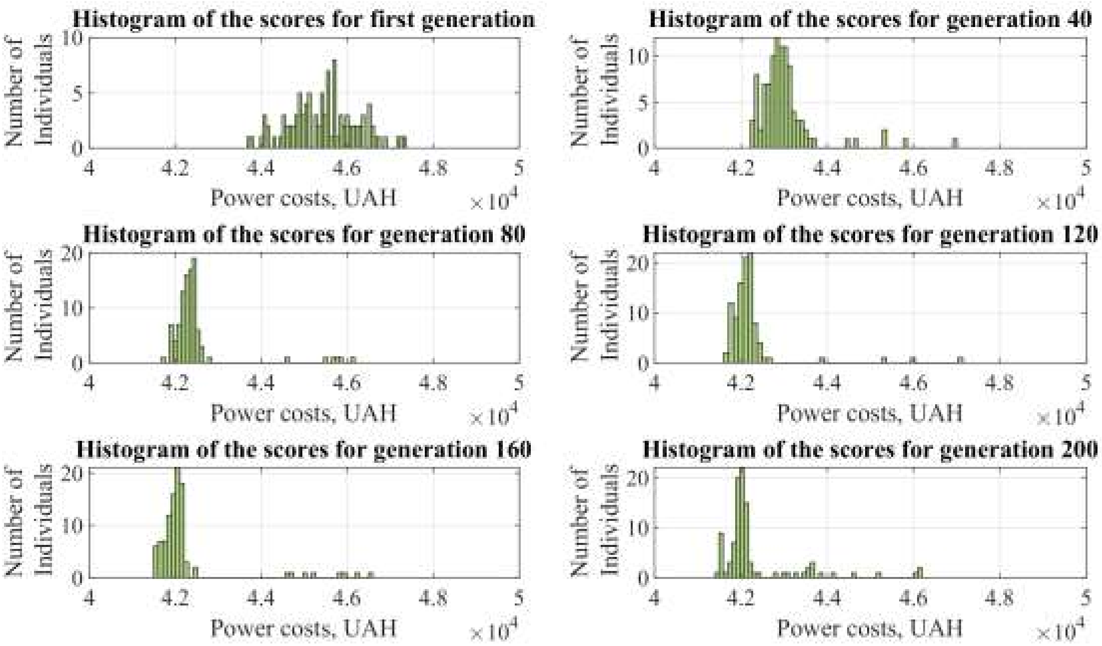

Fig. 8. **Evolution of populations in optimizing the operation schedule of mine level consumers using a genetic algorithm with the setting according to option C**
Source: **compiled by the authors**

In Fig. 9 shows the distribution of consumers' working hours during the day obtained as a result of the optimization algorithm with the setting of evolution parameters according to option D. The highest levels of power consumption in this experiment are observed at 14 and 5. The minimum is at 16. In total, power costs amount to 42.3 thousand UAH. It is advisable to compare them with the system that gives the best result with the previous population settings, i.e. option C. As a result, option C demonstrates 2.1 % lower daily costs than option D.

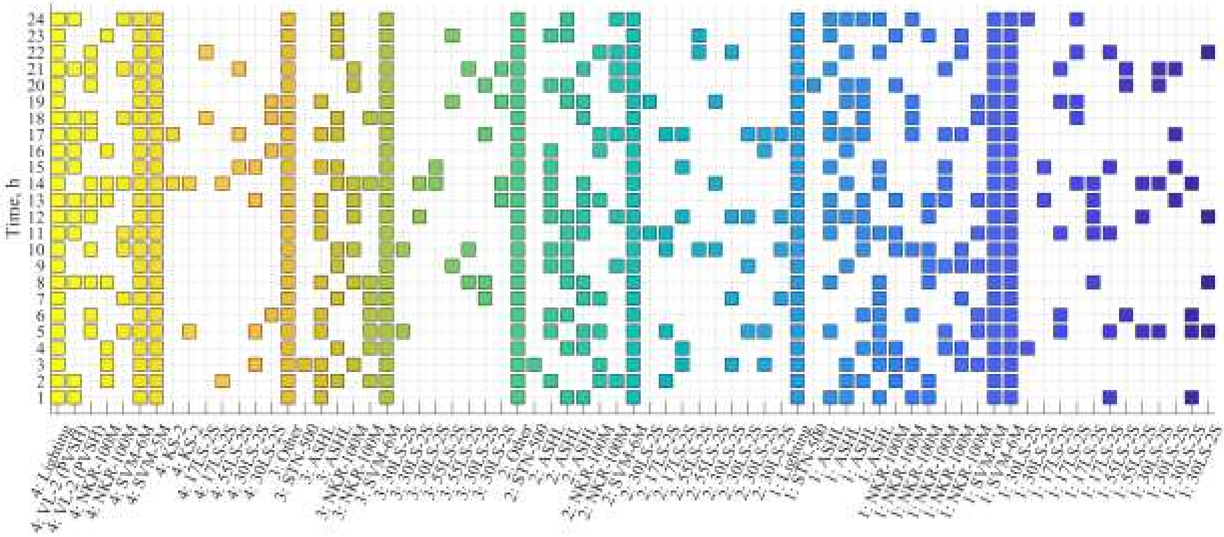

Fig. 9. **Daily operation schedule of consumers of stoping and preparatory workings of the mine level when using a genetic algorithm with settings according to option D**
***Source:* compiled by the authors**

Setting up the control system algorithm according to options E and F (Table 1) ensures the power cost of 42.7 thousand UAH and 42.5 thousand UAH, respectively. In other words, option C provides 3 % and 2.6 % less value of the optimization criterion compared to E and A. The consumers' schedules for these two options are not shown in the article.

The change in population quality has the same trends as in cases where the number of elite individuals is 10 %. In the case of one- and two-point crossovers, evolution results in the division of the population into two groups (Fig. 10 and Fig. 11).

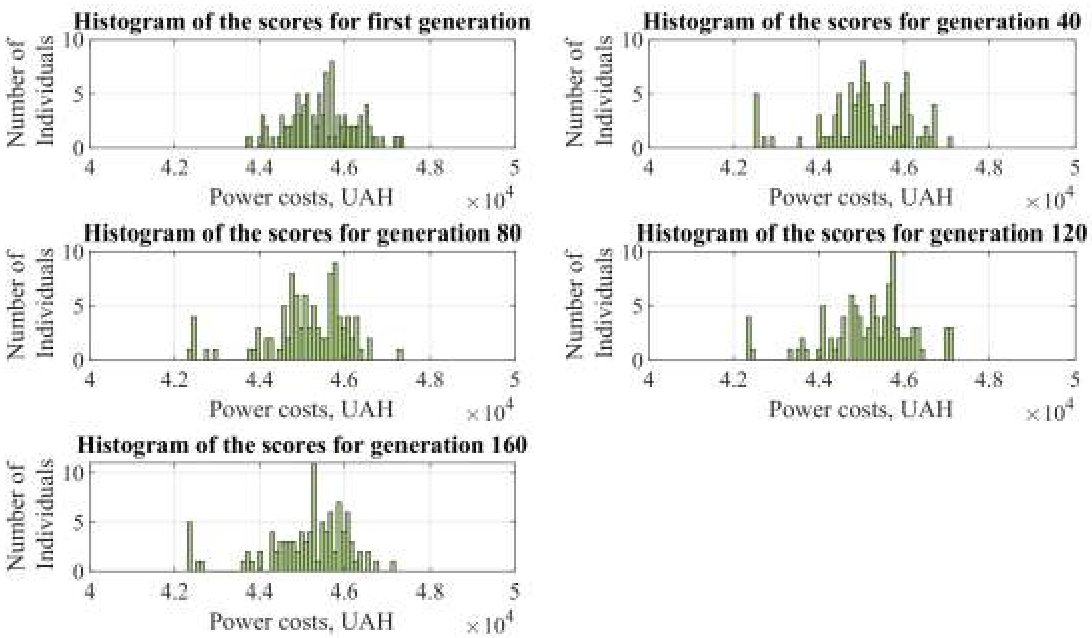

Fig. 10. **Evolution of populations in optimizing the operation schedule of mine level consumers using a genetic algorithm with the setting according to option D**
***Source:* compiled by the authors**

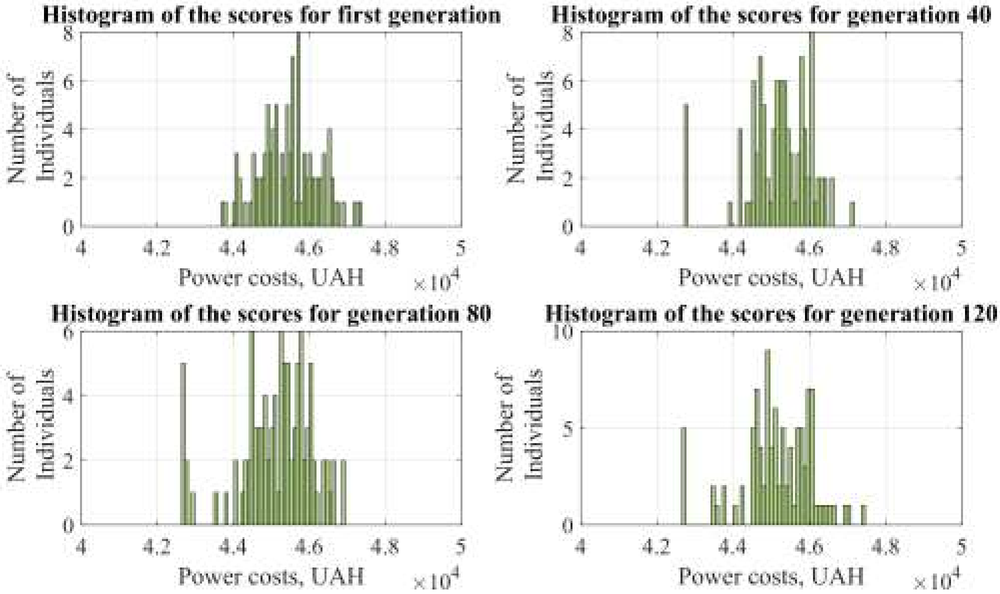

Fig. 11. **Evolution of populations in optimizing the operation schedule of mine level consumers using a genetic algorithm with the setting according to option E**
***Source:* compiled by the authors**

With the Laplace crossover function, the entire population becomes more qualitative (Fig. 12). Individuals are grouped around the value of the optimization criterion of about 43 thousand UAH.

Thus, after analyzing all the results of modeling the operation of the heuristic system for controlling power consumption of mine electric receivers, it can be argued that the best efficiency in terms of power costs is demonstrated by a system of 100 individuals in the population with 10 elite individuals, and the Laplace crossover method. On average, option C allows providing a 2.62 % lower value of the optimization criterion than the other considered options (see Table 1).

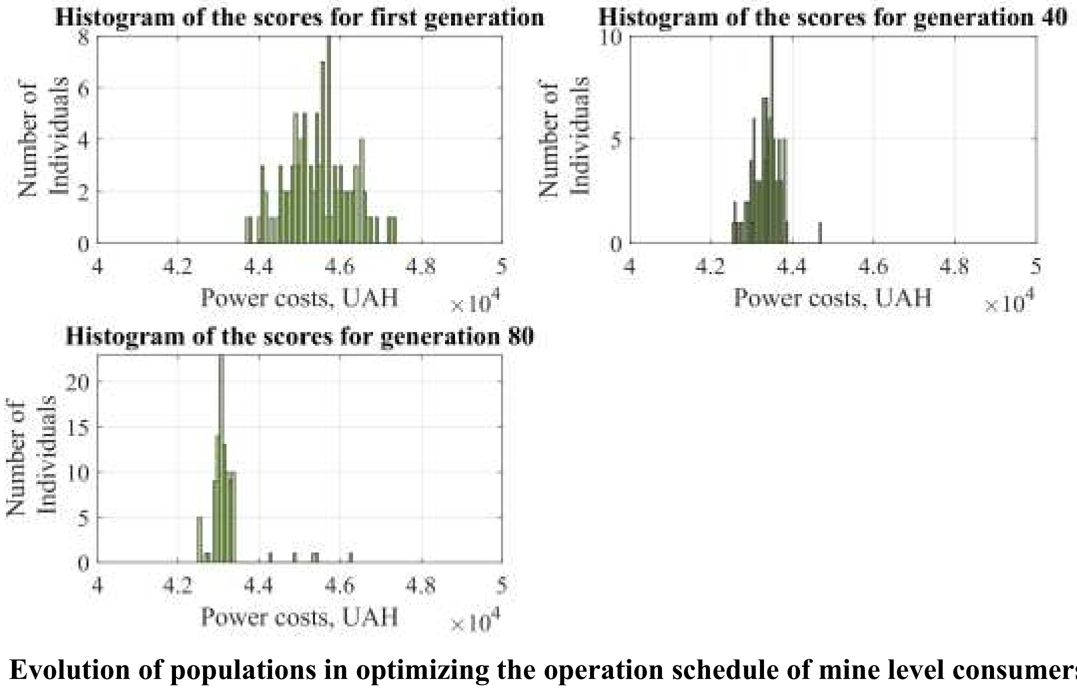

Fig. 12. **Evolution of populations in optimizing the operation schedule of mine level consumers using a genetic algorithm with the setting according to option F**
***Source:* compiled by the authors**

CONCLUSIONS

The research develops an option for controlling power consumption at underground mining enterprises on the example of electrical equipment with a voltage of up to 1000 V, considering hourly power tariffs and their variable pricing for the day ahead in the power market. It considers limitations on the operation duration of certain technological electrical units, maximum loads on transformer substations and the amount of power the company can order, considering odious factors such as penalties for deviations from the declared power consumption level.

To solve this problem, we propose a genetic algorithm as a method of heuristic optimization. Experiments indicate that the best results are achieved by using the Laplace crossover method. At the same time, a population of 100 individuals with 10 elite individuals that pass unchanged to the next generation is used. This approach allows for lower power costs by an average of 2.62% per day compared to the other parameters studied.

The proposed method of controlling power consumption allows us to identify the potential for reducing power costs in the final product cost at underground mining enterprises. The concept is recommended for practical implementation in power supply control systems of both operating and projected mining enterprises specializing in iron ore underground mining.

Further research will be aimed at building a system that solves a multi-criteria optimization problem with additional objective functions, such as minimizing labour costs due to higher power costs during nighttime hours.

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Моделювання процесу керування електроспоживанням приймачів підземних залізорудних підприємств

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АНОТАЦІЯ

У статті представлені результати розробки концепції формату керування процесом споживання електричної енергії електроприймачами підземних гірничорудних підприємств напругою до 1000 В в функції погодинних тарифів на вартість електроенергії, які характеризуються плаваючим ціноутворенням на добу наперед в умовах існуючого ринку. Також враховуються обмеження на тривалість роботи окремої гірничої електроустановки протягом доби, максимальне навантаження на трансформатори підземної підстанції та допустимий замовлений підприємством обсяг електроенергії, перевищення якого призводить до застосування штрафних санкцій. Для рішення задачі керування запропоновано застосувати евристичний оптимізаційний метод, що базується на генетичному алгоритмі. Дослідження ефективності роботи системи здійснювалося шляхом визначення налаштувань алгоритму еволюційного пошуку, які б забезпечували найнижче значення витрат на придбання електроенергії. Зокрема, змінювалася функція схрещування (приймалися одноточкова, двоточкова або Лапласа) та число елітних фенотипів у популяції. Експерименти проводилися на базі пакету Global Optimization Toolbox програмного комплексу MATLAB. Проведене моделювання ефективності роботи системи з різними налаштуваннями генетичного алгоритму продемонструвало, що мінімальні витрати на придбання електроенергії можуть бути забезпечені при залученні методу схрещування Лапласа, кількості фенотипів у популяції 100 з яких елітними, що переходять у наступне покоління без змін, є 10 особин. Такий варіант дозволяє отримати в середньому на 2,62 % меншу добову вартість придбання електроенергії протягом доби ніж інші досліджені параметри. Запропонований метод керування електроспоживання дозволяє виявити на підземних залізорудних підприємствах досяжний потенціал зі зниження енергетичної складової в собівартості кінцевого продукту видобутку. Він може бути рекомендований для практичної реалізації як в умовах діючих, так і проєктуємих підприємств.

Ключові слова: система електропостачання шахти; електроприймачі напругою до 1000 В; вартість електроенергії; оптимізація; змішане цілочисельне програмування; евристична система керування; генетичний алгоритм

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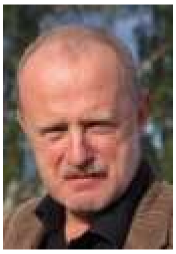

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