Викладено результати досліджень з оцінки особливостей та розробки тактики розбудови структур систем керування рівнями електроспоживання приймачів залізорудних підприємств з підземним способом видобутку залізорудної сировини (ЗРС). Показано, що перевагами запропонованої структури в порівнянні з існуючими варіантами є втілення в її функціональне наповнення управляючих рішень, котрі обумовлюються специфікою технології функціонування електроприймачів електричної енергії (ЕЕ) даних видів підприємств. Рішення стало можливим на основі форматизації електроенергетичного комплексу даних видів підприємств в єдину структуру: системи електропостачання – приймачі ЕЕ. Встановлено перелік споживачів, котрі формують форму добових графіків електричних навантажень залізорудного підприємства – так звані стаціонарні установки, котрі споживають більш ніж 80 % від загального обсягу споживання ЕЕ. Саме ці споживачі і були включені до розряду приймачів-регуляторів ЕЕ. Індивідуальна оптимізація режимів функціонування даних приймачів в годинах доби покладена в основу логіки керування рівнями споживання ЕЕ. Така структура оптимізації виглядає доцільною також виходячи з того, що ціна за спожиту підприємством ЕЕ протягом доби формується генеруючою організацією диференційованою в функції зонних тарифів: пік, напівпік, ніч. В подальшому, визначивши залежність рівнів енергоспоживання, саме приймачів-регуляторів від керуючих і збурюючих змінних, встановлено і рекомендовано до реалізації доцільність керування рівнем споживання ЕЕ за обґрунтованим та встановленим критерієм, який полягає в мінімізації цього показника.

В роботі синтезовано математичну модель, виходячи з якої розроблено алгоритм керування. Це дозволяє не тільки мінімізувати рівні електроспоживання шляхом врахування зонних тарифів цін за спожиту ЕЕ, а й управляти потоками у випадках можливих обмежень рівнів електропостачання з боку живлячої енергосистеми

Ключові слова: алгоритм керування, оптимізація електроспоживання залізорудних підприємств, функціонально-технологічна структура, зонні тарифи

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DEVELOPMENT OF THE FUNCTIONAL MODEL TO CONTROL THE LEVELS OF ELECTRICITY CONSUMPTION BY UNDERGROUND IRON-ORE ENTERPRISES

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1. Introduction

Iron ore mining industry takes an important place in the economy of many countries in the world. Iron consumption per capita is one of the most important industrialization indices of any country. For example, in Japan, consumption of iron per capita is about 1,000 kg, in Germany, 510 kg, in China, 218 kg. An average iron consumption in the world at present is about 182 kg per capita. Given the modern level of iron-ore production, the current static iron ore reserves will last for 140 years [1].

Production and market of iron ore in the world have evolved quite stable until the beginning of the 21st century. However, this stability was disrupted at the beginning of the 21st century by two factors – the unprecedented growth of need in the iron ore by China and the global economic crisis in 2008.

The world constantly witnesses competition for markets to sell iron-ore raw materials (IOR). The iron ore market is undergoing enormous changes. Especially noticeable over recent decades has become the rapid rise of the economy of China, India, Vietnam, and Taiwan, with an increasing annual demand in this kind of raw materials. These changes have shifted accents in this sector of world production and trade of IOR: a seller's market has become a buyer's market, with rapidly developing various methods and tools of exchange trade of IOR.

Recent years have seen a steady tendency of growth in the production volumes, however the growth in the production of this kind of minerals outperforms a growth in consumption, which has led to a long decline in prices for IOR in the world market. Since the end of 2011, a decrease in world prices for IOR reached about 60 % (to the level of quarters 1–2 in 2011) [1, 2]. Such a surplus of IOR has resulted in the gradual transition from a seller's market to a buyer's market for IOR. Along with this, geopolitical factors have greatly influenced the priorities and the economical state of the world's mining and metallurgical companies.

A raw material base for iron-ore enterprises is the deposits of ferrous quartz and naturally-rich ores. A commodity product from these enterprises is the ores from underground mining (non-agglomerated iron ore), concentrate, agglomerate, and pellets [1].

Most iron-ore enterprises in Europe have been in operation for more than 20 years. IOR mining depths deepen over the years, which logically entails an increase in the cost of production of this kind of minerals.

Meanwhile, the system-forming feature of iron-ore enterprises has been, and still is, significant energy consumption. It should also be noted that more than 30 % of the IOR mining cost component at modern enterprises employing underground mining techniques account for energy consumption, in where, in turn, a share of electric energy is 90 % [3, 4].

It is obvious that it is not appropriate to confine ourselves to controlling the levels of EE consumption – at present, it is required to manage this process. In this case, control system should adaptively-preemptively respond to the emergence of respective disturbing factors in the technology of change in the operation modes of electricity receivers and primarily receivers-regulators of EE, which under conditions of iron-ore enterprises are the stationary installations.

2. Literature review and problem statement

Results of studies [5–7] allow us to argue about the existence of many alternatives for determining feasible approaches to improving energy efficiency at mining enterprises. However, these studies demonstrated an approach limited to the selection of structures for the systems that supply electricity to the underground mining enterprises. The reason for this is that such an approach under conditions of their time was logical and straightforward.

A different perspective underlies studies [9, 10], their emphasis being the choice of rational structures for power supply systems as the base for reliability of electricity supply systems particularly at iron-ore enterprises. However, this search ended with the optimization of power supply systems; the operational modes of EE receivers were not analyzed either.

Therefore, taking into consideration the new time trends, in an attempt to expand research frontiers, paper [8] considered and investigated the task related to the need to estimate and control energy fluxes at mining enterprises. At the same time, this study lacked specific solutions. Thus, work [11] focuses only on the optimization of levels of consumption in a function of volumes of extracted materials. Paper [12] proposed a financial model for estimating the level of efficiency of the mining industry in general. Study [13] analyzed global energy problems of mining enterprises. Paper [14] reports a study into energy efficiency of a number of coal mines in the eastern and central regions of China, where the technology of minerals extraction has its own specificity, which affects the process of energy consumption. An analysis of the energy concept of mining-metallurgical industry is given in work [15]. Paper [16] examined the issues of autonomous EE generation under conditions of mines in Poland. However, the logical deterioration of technological conditions related to the fact of increasing the depth of IOR mining emphasizes the task to improve energy efficiency of extraction of these kinds of mineral resources.

This is further confirmed by the fact that most well-known studies [5–16] were conducted for the conditions of IOR mining at depths down to 1,000 meters. At present, the boundaries of 1,500–2,100 m have been crosses. It is clear that the levels of EE consumption at such depths, and, accordingly, their effect on general cost indicators of IOR extraction, have a tendency to grow. This is a pressing issue not only in Ukraine, but also for the mining enterprises worldwide.

The above allows us to assert that it is a relevant task to develop a functional-technological structure for the system of control over levels of power consumption by iron-ore enterprises that employ the underground technique for IOR extraction.

3. The aim and objectives of the study

The aim of this study is to develop a functional-technological structure for the system of control over levels of electricity consumption by iron-ore enterprises that employ the underground technique for IOR extraction. This will make it possible to construct a mathematical model that would provide a possibility to investigate the dependence of daily levels of electricity consumption by receivers-regulators in a function of zonal tariffs for daily prices for the consumed electricity.

To accomplish the aim, the following tasks have been set:

– to formalize the components of the electrical power system at iron-ore enterprises that employ the underground technique for IOR extraction, to define the consumers-regulators of electric energy, and to decompose a general objective function into the local objective function in order to control these objects;

– to construct a mathematical model of the optimal control over levels of electricity consumption in order to devise an algorithm for system operation.

4. Materials and methods to study levels of electricity consumption by iron-ore enterprises

4. 1. Analysis of properties of control object

Underground iron-ore enterprises in different countries have a typical structure of the electricity supply system and a typical composition of electricity receivers. Therefore, hereafter we shall address the set aim on the basis of research under conditions of iron-ore enterprises in Ukraine.

Ukraine possesses large mineral resources of iron ore, represented by 80 deposits, 23 of which are under operation (58 % of proven reserves).

Specific share of export in total deliveries in Ukraine increased in 2017 and reached 53.6 % against 51.9 % in 2012.

The geographical structure of IOR export from Ukraine to other countries as of 2017 is shown in Fig. 1.

Over the analyzed period, the mining enterprises of Ukraine exported iron-ore products to 10 European countries, as well as to Turkey, China, India, Japan, and Russia. Over the analyzed time, the geographical areas of export of products, in the total structure of export of iron ore products in Ukraine, were dominated by China.

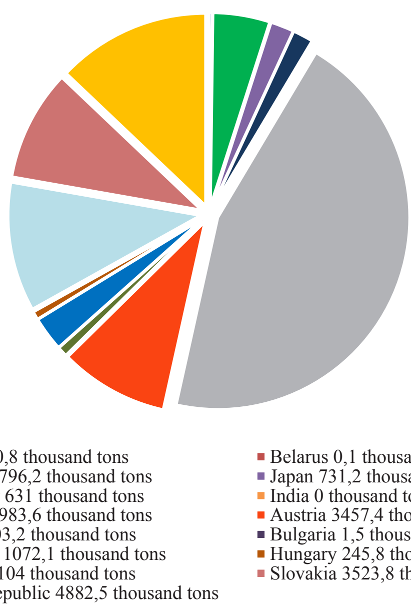

Fig. 1. Geographical structure of export of iron ore products from Ukraine, 2017

In this aspect, a positive experience for producers of IOR worldwide is the practice of Ukrainian iron-ore enterprises that are actively engaged in the search for stemming the growth of energy consumption for IOR mining [4]. Thus, over the past 5–7 years, iron-ore mining enterprises in Ukraine modified, for the first time of their operation, their energy-consuming EE receivers, transferring them to specially-priced zones of the day, which are differentiated as peak hours, half-peak hours, and night hours.

Such "splitting" defines appropriate tariffs in terms of the price for EE consumed by an enterprise during different hours of the day. It is interesting the difference between the levels of these tariffs, for example between a "peak" and a "night", amount to almost 8 times.

Given the current situation, the "organizational" measures taken by enterprises, despite their simplicity, enabled the enterprises that implemented them to significantly save material costs when paying for the consumed electric energy – about 20 %. This was also contributed to by the implementation at mining enterprises of systems to control the levels of electricity consumption (CLCS). At the same time, as reported in study [3, 4], the potential of effective measures to enhance the energy efficiency of these types of enterprises both in Ukraine and in the world is far from over. It appears appropriate to address the task on energy efficiency of iron-ore enterprises within the framework of existing technologies. This approach seems feasible because no construction of the new underground iron-ore enterprises in a number of countries is planned in the next 20 to 30 years.

This direction has been negatively affected by the current differentiation of the electricity power system at an enterprise as the entire complex. At present, the complex is divided into two parts: electricity supply systems and receivers of electrical energy [1, 2]. In this case, the fact that has become a dogma is that electricity supply to enterprises is the first component of the above complex, while centralized is provided by an energy system. Such a "division" is not the best option for management strategy and even not the optimal solution both for scientific research and the enterprises themselves.

In order to start a research into substantiation and selection of a tactic to work out a structure of the system to control the levels of electricity consumption, we adopted a holistic electricity energy complex of the form: power supply system – electricity receivers.

Regarding a second above-mentioned component, the fact that is of great importance for the further research has been confirmed on that the most electricity-intensive EE receivers at underground iron-ore enterprises are the so-called stationary installations. These consumers include the skip lifting, drainage and ventilator installations. The share of these installations in the total electricity consumption at these enterprises (Fig. 2) amounts to more than 80 % (Fig. 2), so they can be categorized as EE receivers-regulators.

When considering an iron-ore enterprise in the form of a topological structural diagram (Fig. 3), it is possible to highlight the input control and disturbing variables for the most energy-intensive EE receivers-regulators, as well as the output variables – the total electric load of a mine. Control variables are the intensity of operation and the functioning modes of EE consumers-regulators; disturbing variables are the total performance efficiency of underground extracting areas at an enterprise.

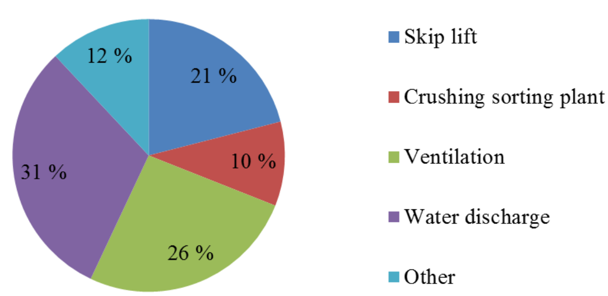

Fig. 2. Averaged indicators for the levels of electricity consumption by power plants at underground iron-ore enterprises in Ukraine

Thus, the total load on EE receivers at underground iron-ore enterprises is the implementation of various combinations of input variables and power consumption by stationary installations and depends on the controlling disturbing variables, according to the operational technology for these EE receivers-regulators. Therefore, it is appropriate, at sufficient level of efficiency, to control the work of stationary installations according to the assigned criterion, which implies the minimization of electricity consumption. Meanwhile, minimization of a criterion in general is a rather difficult task, even when computers are employed. In order to simplify the implementation of this task, it is advisable to decompose the overall objective function into local objective control functions of the most powerful stationary installations. The adequacy of such a decomposition is defined by the technological independence of electricity consumption by each consumer on the controlling variables of other consumers. The general structure of control system over the levels of electricity consumption by receivers-regulators at underground iron-ore enterprises is shown in Fig. 3, 4.

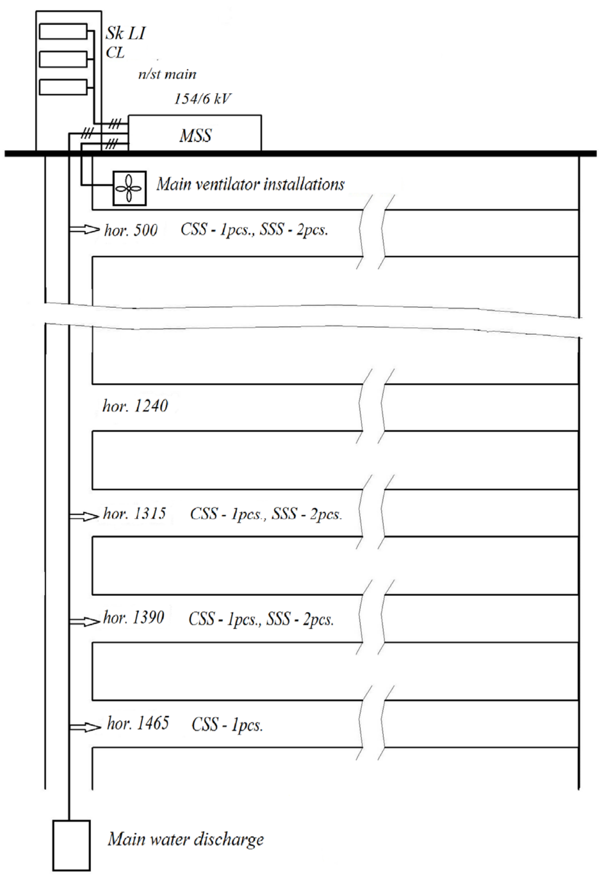

Fig. 3. Topology of electricity complex: electricity supply system — receivers of electric energy at an underground iron-ore company (a mine, an iron-ore mine): MSS — main step-down substation; CSS — central step-down substation; SSS — section step-down substation, SkLI — skip lifting installation, CL cage lift; hor. 500-1465 (underground horizons of respective depths (m) at the mine Ternivska (Ukraine)

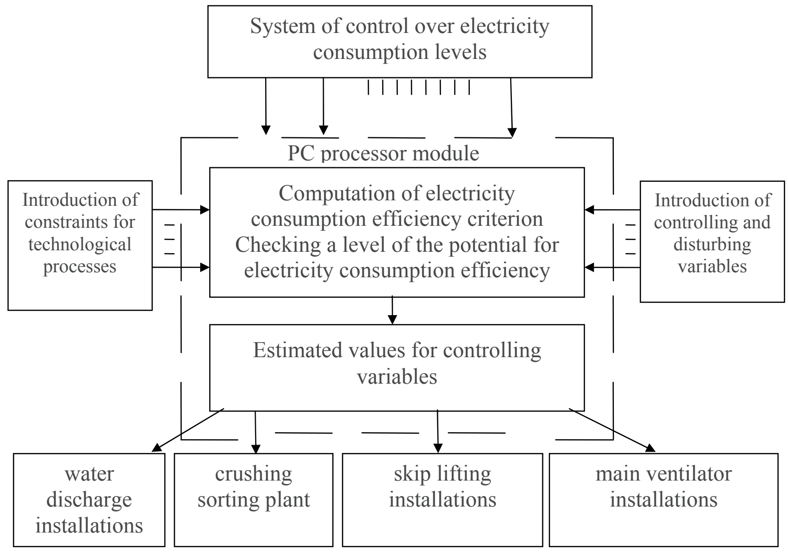

Fig. 4. Structural diagram of the system to control the level of electricity consumption by a typical underground iron-ore enterprise (a mine, an iron-ore mine)

This structure (Fig. 4) is essentially the base for working out a holistic complex of control over the levels of EE consumption by iron-ore enterprises that employ the underground IOR-extracting techniques. The fact that would unequivocally prove the efficiency of functioning of such a complex is its functional content.

4. 2. Construction of a mathematical model for the optimal control over the levels of electricity consumption by an underground iron-ore enterprise

In a general case, electricity consumption by EE receivers at an underground iron-ore enterprise can be determined in the form of the required electricity consumption over a specified period, which are related to manufacturing tasks on extraction, processing of IOR, etc. If one knows the power of electricity that is consumed by enterprise receivers over a specified period $[0;T]$, the required electricity consumption is then calculated from formula

$$\int_0^T W(t)\mathrm{d}t = Q_0, \tag{1}$$

where $W(t)$ is the power of electricity, kW; $[0;T]$ is the duration of electricity consumption, hours; Q_0 is the volume of power consumption, kW·h.

A criterion that determines the efficiency of electricity consumption by an object is recorded in the form

$$C = \int_0^T c(t)W(t)\mathrm{d}t, \tag{2}$$

where $c(t)$ is the cost of electricity consumption, UAH/kW·h.

In addition, it is necessary to determine the limitation on the magnitude of electricity power that is predetermined by the characteristics of the examined object,

$$W_{\min} \le W(t) \le W_{\max}, \tag{3}$$

where $W_{\min}$, $W_{\max}$ are the minimum and maximum powers of electricity, respectively, kW.

The purpose of control over electricity consumption by a stationary installation is the minimization of criterion (2) for the consumed power of electricity with respect to constraints (1) and (3).

A special feature of the recommended method for solving a problem is that the dependence of electricity price on time is assigned in the form of a piecewise-constant function. If one considers the duration of power consumption per day, then there are the so-called zonal tariffs. These tariffs define the price for electricity depending on the time of day. In practice, the three-zone tariffs are typically employed, that is, the price for electricity accepts three values during 24 hours: a peak, a half-peak, economy-time (night). The result is that the price of electricity is assigned by a piecewise-constant function that has three values

$$c(t)=\begin{cases} c_n,\ 0\le t<t_1 \\ c_{hp,}\ t_1\le t<t_2 \\ c_p,\ t_2\le t<T \end{cases} \tag{4}$$

where c_{n}, c_{hp}, c_{p} are the price of electricity consumption in the zones of tariffs "night" $[0;\ t_1)$; "half-peak" $[t_1;\ t_2)$, and "peak" $[t_2;\ T)$, respectively, UAH/kW·h.

Formula (4) employs the prices of electricity consumption, which are accepted at these types of enterprises. The gaps in the application of respective prices of electricity are combined into common intervals for convenience.

To solve the problem (1) to (3), we shall use the form of function (4). By using the linearity of integral, we obtain

$$\int_0^T c(t)W(t)\mathrm{d}t = c_n\cdot\int_0^{t_1} W(t)\mathrm{d}t + c_{hp}\times$$
$$\times\int_{t_1}^{t_2} W(t)\mathrm{d}t + c_p\cdot\int_{t_2}^{T} W(t)\mathrm{d}t. \tag{5}$$

Introduce designations

$$\int_0^{t_1} W(t)\mathrm{d}t = Q_n,\ \int_{t_1}^{t_2} W(t)dt = Q_{hp},\ \int_{t_2}^{T} W(t)\mathrm{d}t = Q_p, \tag{6}$$

where Q_n, Q_{hp}, Q_p is the electricity consumption over intervals that match the zonal tariffs "night", "half-peak" and "peak", respectively.

The objective function (2) is written then in the form

$$C = c_n\cdot Q_n + c_{hp}\cdot Q_{hp} + c_p\cdot Q_p. \tag{7}$$

In its turn, condition (1) can be recorded in the form

$$\int_0^T W(t)\mathrm{d}t = \int_0^{t_1} W(t)\mathrm{d}t + \int_{t_2}^{t_2} W(t)\mathrm{d}t + \int_{t_2}^{T} W(t)\mathrm{d}t. \tag{8}$$

With respect to (6), equation (8) takes the form

$$\int_0^T W(t)dt = Q_n + Q_{hp} + Q_p,$$

or, according to condition (1),

$$Q_n + Q_{hp} + Q_p = Q_0. \tag{9}$$

Constraint (3) will be represented in the following form through integration:

$$\int_0^{t_1} W_{\min}\mathrm{d}t \le \int_0^{t_1} W(t)\mathrm{d}t \le \int_0^{t_1} W_{\max}\mathrm{d}t,$$

$$W_{\min}\int_0^{t_1}\mathrm{d}t \le \int_0^{t_1} W(t)\mathrm{d}t \le W_{\max}\int_0^{t_1}\mathrm{d}t,$$

$$W_{\min}\cdot t_1 \le \int_0^{t_1} W(t)\mathrm{d}t \le W_{\max}\cdot t_1. \tag{10}$$

Considering (6), constraint (10) takes the form:

$$\underline{Q_n} \le Q_n \le \overline{Q_n}, \tag{11}$$

where $\underline{Q_n} = W_{\min}\cdot t_1$, $\overline{Q_n} = W_{\max}\cdot t_1$ are the constraints for the consumption of electricity over a period corresponding to the tariff "night".

Similarly, we obtain

$$\underline{Q_{hp}} \le Q_{hp} \le \overline{Q_{hp}}, \tag{12}$$

where

$$\underline{Q_{hp}} = W_{\min}\cdot(t_2 - t_1),\ \overline{Q_{hp}} = W_{\max}\cdot(t_2 - t_1)$$

are the constraints for the consumption of electricity over a period corresponding to the tariff "half-peak"

$$\underline{Q_p} \le Q_p \le \overline{Q_p}, \tag{13}$$

where

$$\underline{Q_p} = W_{\min}\cdot(T - t_2),\ \overline{Q_p} = W_{\max}\cdot(T - t_2)$$

are the constraints for the consumption of electricity over a period corresponding to the tariff "peak".

According to the results derived from formulae (1) to (3), a problem on the electricity consumption optimization is recorded in the form

$$C = c_n\cdot Q_n + c_{hp}\cdot Q_{hp} + c_p\cdot Q_p \to \min_{Q_n;Q_{hp};Q_p}, \tag{14}$$

$$Q_n + Q_{hp} + Q_p = Q_0, \tag{15}$$

$$\underline{Q_n} \le Q_n \le \overline{Q_n}, \tag{16}$$

$$\underline{Q_{hp}} \le Q_{hp} \le \overline{Q_{hp}}, \tag{17}$$

$$\underline{Q_p} \le Q_p \le \overline{Q_p}. \tag{18}$$

An analysis of problem (14) to (18) reveals that this is a problem on linear programming, which can be solved using the simplex method [17]. Solution to problem (14) to (18) produces the optimal magnitudes of electricity consumption over intervals where the zonal price tariffs of energy consumption are constant. The results of calculations are the magnitudes of electricity consumption for time periods with the zonal tariffs "night", "half-peak" and "peak", $\hat{Q}_n$, $\hat{Q}_{hp}$, $\hat{Q}_p$.

It must be emphasized that the magnitudes of electricity power for each time period with constant price tariffs for electricity consumption are not defined, but must satisfy constraints (3). As one of the possible ways to derive the magnitudes of electricity power over time intervals with different tariffs for electricity consumption is the application of a theorem on the mean value for integrals [17]. We consistently find the mean values for electricity power over time intervals where the price of electricity consumption is constant.

$$\overline{W_n} = \frac{\hat{Q}_n}{t_1}, \ \overline{W_{hp}} = \frac{\hat{Q}_{hp}}{t_2 - t_1}, \ \overline{W_p} = \frac{\hat{Q}_p}{T - t_2}. \quad (19)$$

For the zonal tariffs “night”, “half-peak”, and “peak”, the electricity power averages are, respectively, calculated from formulae (19).

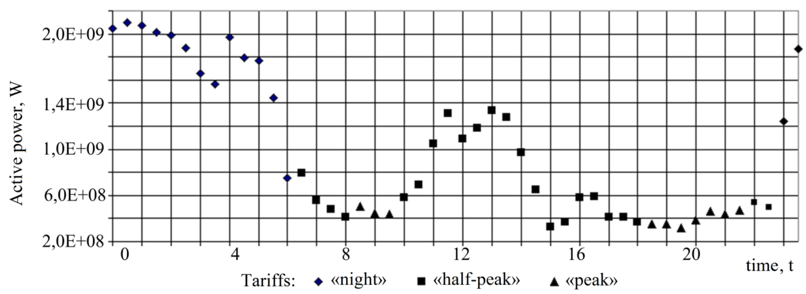

Fig. 5. Daily schedule of electricity consumption by the receiver-regulator at the underground enterprise, the mine Ternivska at PAT “Kryvyi Rih iron ore plant”

5. Results of a study into development of a functional model to control the levels of electricity consumption by underground iron-ore enterprises

As an example, for the sake of clarity, we present a study into EE consumption by underground enterprises at PAT “Kryvyi Rih iron ore plant”, Ukraine. Energy generating companies (oblast electric utilities), aiming at perfect alignment of the daily volume of EE “production-consumption”, stimulate their consumers. The pricing policy of energy generating enterprises regarding the EE consumers matches the time periods that form zonal tariffs rates of electricity consumption. Table 1 gives respective data on the three-zonal tariffs of electricity consumption.

Table 1

Zonal tariffs of electricity consumption

Zonal tariffs	Price, conditional units/kW·h	Tariff limits
night	0.01	23:00 to 6:00
half-peak	0.04	6:00 to 8:00, 10:00 to 18:00, 22:00 to 23:00
peak	0.06	8:00 to 10:00, 18:00 to 22:00

An analysis of data from Table 1 reveals that the price of electricity consumed changes during 24 hours. The highest price for electricity consumed is during business hours, which, of course, is due to the large number of electricity consumers that causes a shortage of electricity. On the contrary, at night the price for electricity consumed is the lowest, due to the number of working electricity consumers and the existence of excess electricity. Thus, enterprises in general, and the iron-ore-mining ones, in particular, face the task on solving a dual problem on the distribution of EE consumption on an hourly basis while simultaneously maintaining the continuity of manufacturing processes.

Fig. 4 shows a daily schedule of electricity consumption at the enterprise under consideration.

We compute integrated characteristics of actual electricity consumption, according to the schedule in Fig. 4. The cost of electricity over 24 hours is the following magnitude

$$Q_0 = \int_0^{24} W(t)\mathrm{d}t = 23395812950, \ \text{kW·hours}. \quad (20)$$

Next, we compute expenses on electricity consumption, according to the form of objective function (7). Prior to that, we find, according to (6), electricity consumption of electricity for the zonal tariffs “night”, “half-peak” and “peak”, respectively,

$$Q_n = \int_0^6 W(t)dt + \int_{23}^{24} W(t)dt = 13079298278, \text{kW}\cdot\text{h},$$

$$Q_{hp} = \int_6^8 W(t)\mathrm{d}t + \int_{10}^{18} W(t)\mathrm{d}t + $$
$$+ \int_{22}^{23} W(t)\mathrm{d}t = 8238538044, \text{kW}\cdot\text{h},$$

$$Q_p = \int_8^{10} W(t)\mathrm{d}t + \int_{18}^{22} W(t)\mathrm{d}t = 2077976628, \ \text{kW}\cdot\text{h}.$$

We substitute the results obtained above in formula (7) and, employing data from Table 1, we find the total cost of electricity consumption over 24 hours in the normalized units, n. u.

$$C = 0{,}25\cdot 0{,}559 + 1{,}02\cdot 0{,}352 + 1{,}8\cdot 0{,}089 = 0{,}659, \ \text{n.u.} \quad (21)$$

To solve problem (14) to (18), we determine the required parameters.

We find, according to the schedule in Fig. 1, the minimum and maximum magnitudes of electricity power over 24 hours

$$W_{\min} = 318229921 \ \text{kW}, \ W_{\max} = 2098281249 \ \text{kW}. \quad (22)$$

It is clear that these magnitudes of electricity power are predetermined by both the special features of IOR processing and the capacity of technological equipment.

The constraints for the magnitudes of electric energy consumption, according to formulae (11) to (13), are, respectively,

$$\underline{Q_n} = W_{\min}\cdot 7 = 2227609447, \text{kW}\cdot\text{h},$$
$$\overline{Q_n} = W_{\max}\cdot 7 = 14687968743, \text{kW}\cdot\text{h}, \quad (23)$$
$$\underline{Q_{hp}} = W_{\min}\cdot 11 = 3500529131, \text{kW}\cdot\text{h},$$
$$\overline{Q_{hp}} = W_{\max}\cdot 11 = 23081093739, \text{kW}\cdot\text{h}, \quad (24)$$
$$\underline{Q_p} = W_{\min}\cdot 6 = 1909379526, \text{kW}\cdot\text{h},$$

$$\overline{Q_p} = W_{\max} \cdot 6 = 12589687494, \text{kW} \cdot \text{h}. \quad (25)$$

Thus, problem (14) to (18) takes the form:

$$C = 0,25 \cdot Q_n + 1,02 \cdot Q_{hp} + 1,8 \cdot Q_p \to \min_{Q_n; Q_{hp}; Q_p}, \quad (26)$$

$$Q_n + Q_{hp} + Q_p = 23395812950, \quad (27)$$

$$2227609447 \le Q_n \le 14687968743, \quad (28)$$

$$3500529131 \le Q_{hp} \le 23081093739, \quad (29)$$

$$1909379526 \le Q_p \le 12589687494. \quad (30)$$

To solve problem (26) to (30) as a problem on linear programming, we have applied the simplex-method, implemented using the spreadsheet processor MS Excel [18]. The result of solving a problem takes the form

$$\hat{Q}_n = 14687968743 \text{ kW} \cdot \text{h},$$

$$\hat{Q}_{hp} = 6798464681 \text{ kW} \cdot \text{h},$$

$$\hat{Q}_p = 1909379526 \text{ kW} \cdot \text{h}. \quad (31)$$

The minimum magnitude of objective function (26), considering (31), is equal to:

$$C_{\min} = 0,600, \text{ n.u.} \quad (32)$$

According to (19), we find the mean power of electricity consumption over time intervals with zonal tariffs, "night", "half-peak" and "peak", respectively,

$$\overline{W_n} = \frac{\hat{Q}_n}{7} = 2098281249 \text{kW},$$

$$\overline{W_{hp}} = \frac{\hat{Q}_{hp}}{11} = 618042244 \text{ kW},$$

$$\overline{W_p} = \frac{\hat{Q}_p}{6} = 318229921 \text{ kW}. \quad (33)$$

Thus, we have established that it is efficient to maintain the average power of electricity consumption over time intervals with zonal tariffs "night", "half-peak" and "peak" at the levels defined by formulae (33). Given such an approach to controlling the receivers-regulators, expenses for electricity consumption over 24 hours would be minimal, equal to the magnitude derived from formula (32).

6. Discussion of results obtained in the study of a mathematical model

The application of an algorithm for minimizing the levels of electricity consumption by receivers-regulators at iron-ore enterprises, which is represented by formulae (14) to (18), has demonstrated that these types of enterprises have reserves in terms of the optimization of electricity consumption levels, based on the efficient employment of tariffs. That can be confirmed by comparing actual expenditures with optimal expenses for electricity consumption using the example considered above.

Given (21) and (32), we find the magnitude of relative decrease in electricity consumption by the enterprise PAT "Kryvyi Rih iron ore plant" over 24 hours

$$\frac{C - C_{\min}}{C} \cdot 100\,\% = 8,9\,\%. \quad (34)$$

Thus, electricity consumption by stationary installations at a single iron ore mine within 24 hours could be reduced by 8.9 %, while maintaining the total volume of electricity consumption. In this case, we note that this "percentage" complement the effect, which is obtained at preventive optimization of operation of energy-intensive installations over 24 hours [2, 18].

One of the basic principles to control energy consumption is the principle of optimality. The complexity of a power system fundamentally excludes the complete formalization of such systems, which is why they are divided into two subsystems: the first one is mainly formalized, the second is predominantly non-formalized. A second one specifies external parameters for the formalized subsystem and registers the legitimacy of its specific procedures.

A special feature of the recommended method to solve a problem is that the dependence of electricity price on time is assigned in the form of a piecewise-constant function. Consequently, a price for electricity is assigned by a piecewise constant function with three values.

Compared with existing practice to estimate the levels of EE consumption, we have created the base for ensuring the applicability of analytical methods for analysis of cost-objective characteristics of electricity consumption levels at iron-ore enterprises. In this case, constraints are defined by the magnitude of electricity power, predetermined by the characteristics of the examined object. It should also be noted that a change in zonal tariffs requires reformatting the objective function.

Advancement of the proposed research could include resolving the tasks on predicting EE consumption.

7. Conclusions

1. It is established that the sufficient efficiency in the functioning of an electricity consumption system at underground iron-ore enterprises necessitates determining a series of EE receivers-regulators, specifically: skip lifting, fans of the main ventilation, water discharge. The monitoring over EE consumption has made it possible to draw a conclusion on that the listed receivers consume more than 80 % of the total volume of EE consumption by underground iron-ore enterprises, which identified them as consumers-regulators. That has formed the basis for decomposing a general objective function of the electricity complex at an iron-ore company. We have devised a structural scheme of the system to control the level of power consumption by a typical underground iron-ore enterprise (a mine, an iron-ore mine).

2. Proceeding from the actual operating conditions of iron-ore enterprises, a mathematical model has been proposed, which makes it possible to investigate the dependence of daily levels of power consumption by receivers-regulators

in a function of zonal tariffs for daily prices for electricity consumed. A special feature of the proposed mathematical model is that the dependence of price for electricity on time is assigned in the form of a piecewise-constant function. Formal-theoretical results are implemented in a practical solution with actual data, which allowed us to draw a conclusion about the existence of an appropriate reserve for the optimization of levels of electricity consumption based on the efficient accounting of tariffs. That can be confirmed by comparing actual expenditures with optimal expenses for electricity consumption based on the given example, which is about 8.9 %.

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