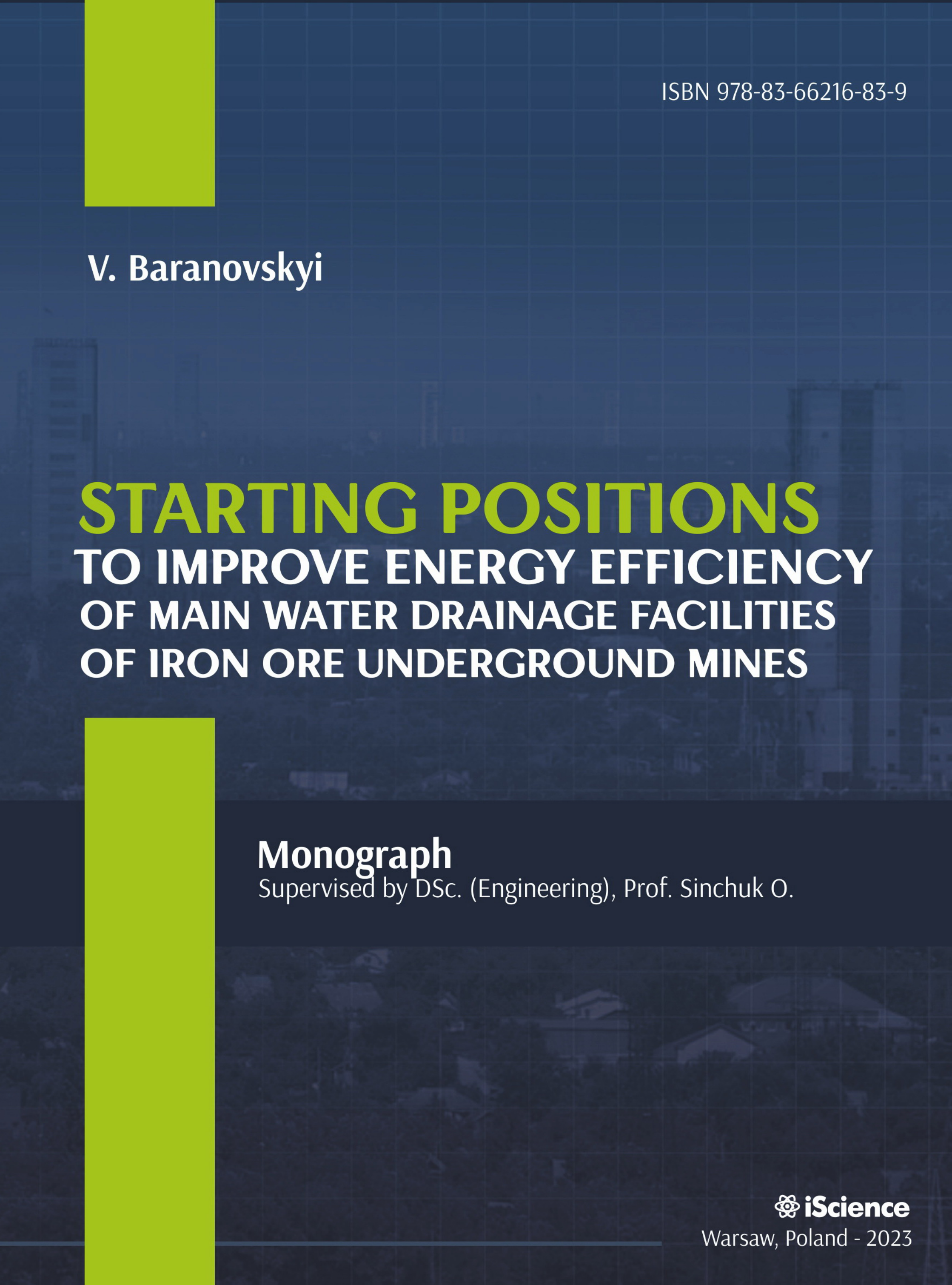

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V. Baranovskyi

STARTING POSITIONS TO IMPROVE ENERGY EFFICIENCY OF MAIN WATER DRAINAGE FACILITIES OF IRON ORE UNDERGROUND MINES

Monograph

Supervised by DSc. (Engineering), Prof. Sinchuk O.

iScience
Warsaw, Poland - 2023

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MONOGRAPH

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Author: V. Baranovskyi

Recommended for publication by the Academic Council of Kryvyi Rih National University of the Ministry of Education and Science of Ukraine
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Starting positions to improve energy efficiency of main water drainage facilities of iron ore underground mines / Monograph / V. Baranovskyi. Supervised by Doctor of Sciences (Engineering), Professor Sinchuk O. – Warsaw: iScience Sp. z.o.o. – 2023. – 135 p.

Materials presented in this monograph contain the results of researches by the scientific school headed by Doctor of Sciences (Engineering), Professor Sinchuk O. from Kryvyi Rih National University. The issue of increasing energy efficiency of main water drainage facilities at iron ore underground mines is discussed. There are developed theoretical aspects and practical recommendations for obtaining an automated system for multi-criteria control of operating modes for electromechanical systems of pumping units.

The author continues researches of power engineering scientists from Kryvyi Rih National University. A system of technical and analytical indices of energy efficiency of the iron ore mining enterprise is formed. Methodological principles of studying power consumption by water drainage facilities as a stochastic process are determined. A mathematical model of power consumption by water drainage facilities is developed. Input parameters of the ACS for studying electromechanical processes and determining power consumption levels using a fuzzy logic inference algorithm are determined. The book consists of 135 pages and consists of anintroduction, a review of the literature, chapters, research methods used, own research results, their discussion, conclusions, practical recommendations.

The book is illustrated with 16 tables and 53 figures.

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INTRODUCTION

Ukraine's development strategy, and its component energy security strategy, foresee a reduction in the energy intensity of GDP in a combined trend. The "roadmap" of this study is to solve the problem of reducing the energy intensity of products produced in energy-intensive industries.

One of the local and rather effective trends here can be the use of the available potential of energy resources of such types of industrial enterprises. Among various state-owned energy-intensive enterprises, metallurgical and mining ones are of great importance.

These enterprises, which are the backbone of the state's economic industry, have significant energy potential that has yet to be tapped [1, 2].

Almost 200 ferrous metallurgy enterprises are operating in Ukraine, accounting for more than 40% of its industrial potential and about 70% of annual financial and foreign currency receipts into the state budget [2].

Among the enterprises of the mentioned industry, a significant number are mining enterprises, including iron ore mining ones producing the basic type of raw material.

The answer to whether Ukraine can remain in the world's top 10 in iron ore production and sales to metallurgy will depend on whether it can solve the problem of energy efficient production and processing of this type of mineral, which is a national strategy.

Credit of trust pending the solution to the problem of energy efficiency increase of the national mining industry is almost exhausted in today's realia.

Meanwhile, almost 90% of modern mining enterprises consume electric power [1, 2]. Moreover, according to studies, power costs are a negatively dominant factor with a steady trend to constant growth in the economy of these enterprises.

Following the research findings, the most obvious solution, which implies reducing the amount of electric power consumption, is not effective enough, since the technology of mining minerals in general, including iron ore, involves a constant increase in mining depths, which respectively leads to a problem of increasing levels of power consumption.

According to the method of iron ore mining, the types of enterprises are divided into open-pits, with further ore concentration at specific processing factories to produce concentrate or pellets, and underground mines, where ore, as a rule, does not require further concentration.

All the above-mentioned methods of mining both this and other types of minerals are inherent in the need to drain natural water that accumulates in mine workings to be pumped to the surface into water drainage sumps. The very fact of this water emergence lies in the structure of subsoil hydrogeology, which, as is known, contains aquifers, including rivers and lakes.

The process of underground water drainage is an energy-intensive process. Thus, underground iron ore mining accounts for more than 30% of the total amount of power consumed by these types of enterprises[1].

The drama of this process lies in the fact that underground water inflows, both actual and projected, are independent of production, and are not subject to a forecast assessment, but the level of power consumption by relevant facilities increase as mining deepens.

This raises the problem of reducing energy intensity of water drainage facilities to the level that is of primary importance in the complex of other measures for increasing energy efficiency of mining enterprises.

Trivial engineering measures to localize this process have extremely limited effectiveness.

Among the well-known and constantly developed researches to increase overall energy efficiency of iron ore underground mines, the most relevant are associated with the most energy-intensive component of these enterprises - the main water drainage facility [1].

An important addition to the above is the fact that the portfolio of scientific solutions to such measures has accumulated quite a few interesting and viable directions. Among them are both traditional trivial directions and very modern ones. Nevertheless, there is uncertainty about the tactics of their practical implementation, or rather the logistics of solving the problem. However, in the complex of multivariability, the basic and still unrealized canonical option is still urgent, namely the increase of electric power efficiency of electrical engineering systems of pumping units of the main drainage facility.

Undoubtedly, the above in no way calls into question the necessity and expediency of implementing these and other measures to increase energy efficiency of iron ore mining. It is also clear that the maximum effect of increasing energy efficiency of mining can be, and will be, achieved only with the comprehensive implementation of all possible and available at the current moment measures.

In order to operate the main water drainage system in general, and its electromechanical units in particular, taking into account the stochastic nature of fluctuations and reading the current parameters and corresponding conditions, it is necessary to respond to these changes as quickly,

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[1] The statement is based on the actual performance of Ukraine's iron ore mining enterprises until February 2022.

appropriately and creatively as possible by means of appropriate management decisions, that is, signals for the control system to react. This management format can only be implemented by an AI-based control system.

Meanwhile, to structure the system and ensure its stable and comfortable operation, it is required to verify and format a set of input parameters and possible fluctuations.

For this, it is considered necessary to carry out a number of relevant proactive studies in this direction.

SECTION 1

ANALYSIS AND FORMATIZATION OF SYSTEM-FORMING ASSESSMENT COMPONENTS OF POWER CONSUMPTION FLUCTUATIONS AT IRON ORE MINING ENTERPRISES

1.1 Proactive assessment of energy efficiency problems and their solutions at underground iron ore enterprises

Iron ore mining enterprises in Ukraine apply the following mining methods: underground mining (underground mines), open-pit or surface mining (open pits, mining and processing plants), and mixed mining. In Kryvyi Rih region, the main iron ore mining region of Ukraine, where more than 80% of the national mining volume is extracted, there are five enterprises engaged in surface mining (including the one with mixed mining) and eight in underground mining. In 2021, the latter produced about 30% of the total iron ore production in Ukraine. In addition, an important fact for the mining and metallurgical industry and Ukraine as a whole is that since 2000, the process of increasing iron ore extraction by underground mining methods has resumed in Ukraine[2]. This is a positive trend for both the power industry in general and environmental safety, since mines consume significantly less power and energy intensity of mining is 2-3 times lower here than at mining and processing plants, which is no less important [1, 2].

According to the studies, iron ore underground mining is currently conducted at deeper levels. This determines an increase in annual power consumption of more than 1 kWh/t of iron ore mined, regardless of the power cost. Thus, those elements of energy efficiency that can be achieved (are achieved) by implementing a number of trivial measures are absorbed [3-15].

Undoubtedly, the above in no way calls into question the necessity and expediency of implementating certain measures to increase energy efficiency of iron ore mining.

At the same time, it is understood that the efficient power consumption in electrotechnical complexes and systems of underground mining enterprises is characterized, in qualitative terms, by machinery, degree of productivity, suitability and other properties.

Of interest for the development of the research methodology is the fact that the structure of the power supply scheme, even if somewhat

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[2] The work analyzes real statistics of operating mining enterprises up to 2022, as this year is not typical for known reasons, and the indicators are temporary

modernized, is only in terms of the extension of cable lines in the underground portion of the general power supply scheme (Fig. 1.1 - 1.4). To a large extent, this also applies to most types of electrical equipment.

It stands to reason that the way to achieve a real level of energy efficiency improvement should not only be based on purely technological solutions, but also on modern management of the entire power consumption process of the enterprise, which today is very relevant and effective.

As proven [5, 15], potential and still little-exhausted sources of increasing the operating efficiency of the main water drainage facility at iron ore underground mines in general and energy efficiency in particular are such components of this hydropower complex as: water pumps, electromechanical facilities of pumps, pipelines and tanks. However, in order to evaluate all of the above components and determine the level of energy efficiency of the main drainage facility, the electromechanical component of the pump unit (electrical drive) will be the subject of study.

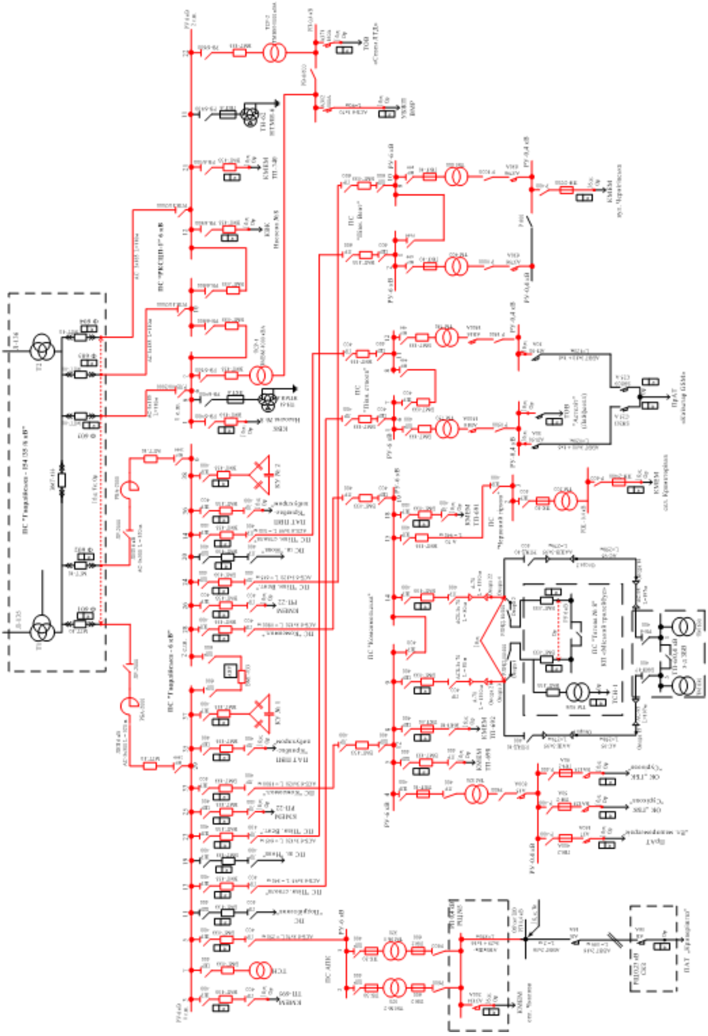

Figure 1.1 – One-line power supply diagram of Pokrovska mine

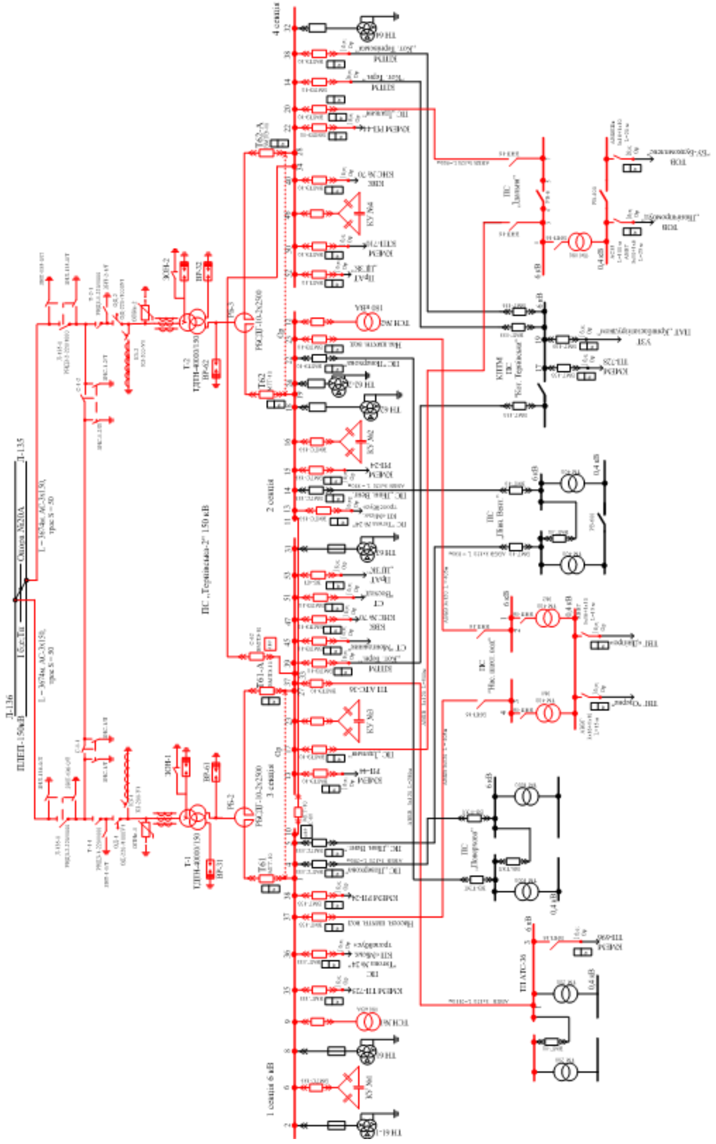

Figure 1.2 – One-line power supply diagram of Ternivska mine

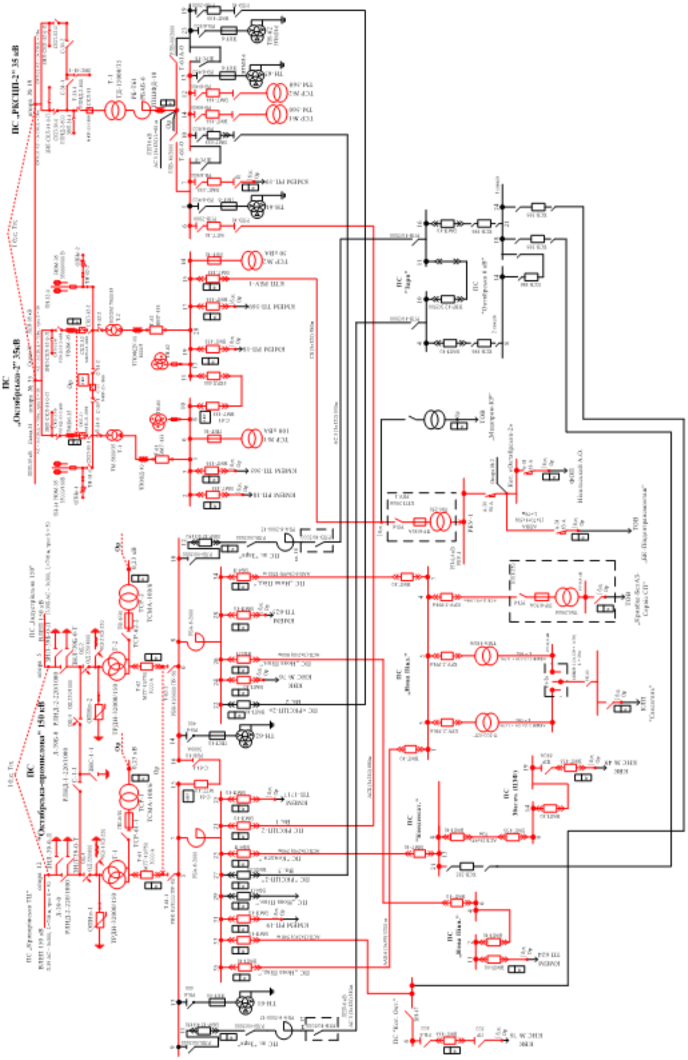

Figure 1.3 – One-line power supply diagram of Kozatska mine

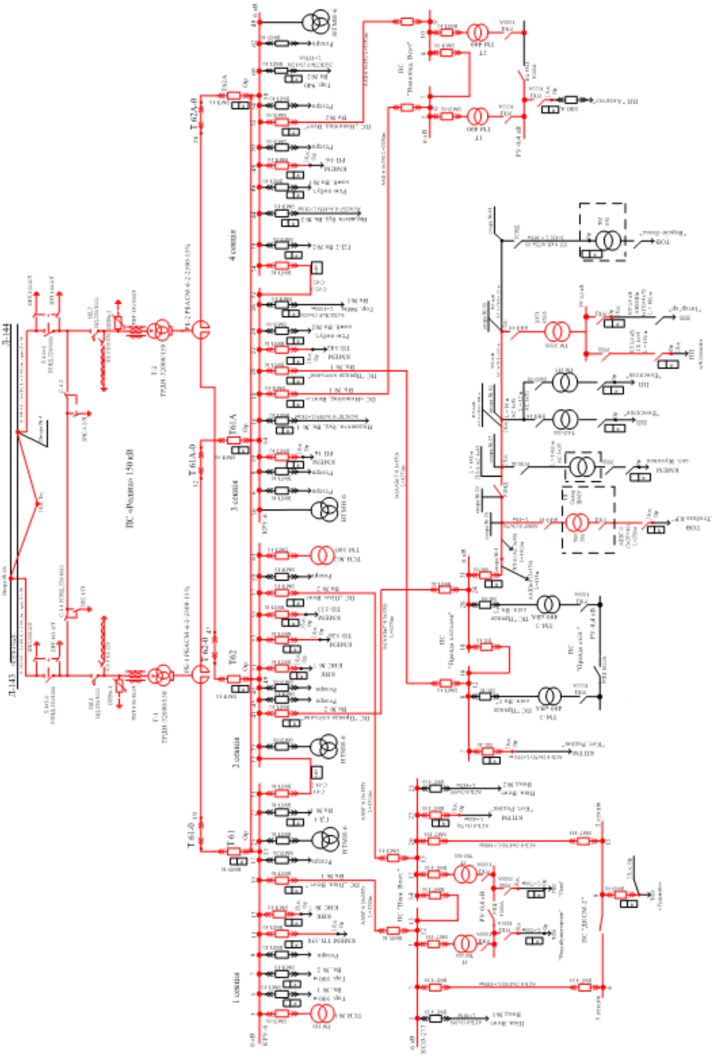

Figure 1.4 – One-line power supply diagram of Kryvorizka mine

1.2 Basic imperatives of energy intensity analysis of iron ore mining

Most modern scientific researches single out one or another energy-intensive power consumer of the iron ore enterprise as an object, which significantly narrows the possibility to uniform the use of these studies for underground mines of various kinds and types, including national iron ore ones with their specific technologies [1, 3, 5-6, 10, 15]. To a certain extent, this limitation does not allow applying the methods and appropriate methodology of system analysis to solving energy efficiency tasks of these enterprises in a complex way (Fig. 1.5).

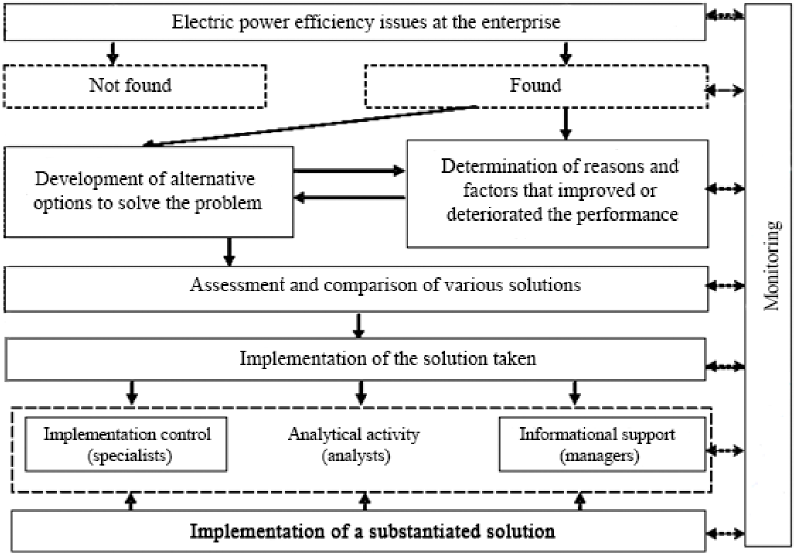

Figure 1.5 – Main empirical directions of increasing electric power efficiency of mining enterprises

The positive role of the system approach can be reduced to the following main points. First, the concepts and principles of the system approach reveal a broader cognitive reality compared to the one fixed in previous knowledge. Secondly, the system approach contains a new, compared to the previous, explanatory scheme based on the search for specific mechanisms of the object integrity and identification of a fairly complete typology of its connections. Thirdly, a complex object assumes not one but several breakdowns. At the same time, the extent to which it is possible to build an operational "unit" of analysis can serve as a criterion for a justified choice of breakdown of the object under study.

The system approach plays the most important role not only in the analysis of operating complex systems, but also in the implementation of systems engineering tasks, i.e. designing large technical systems. In practice, the system approach is a system coverage, a system presentation, a system orientation of research. The system coverage requires considering a problem in different aspects from different points. The system representation is achieved by building a single model capable of replacing a real object and providing relevant information about the object being modeled. The system organization of research means continuous planning and management of development with the help of methods and means of work coordination.

Iron ore mining enterprises are quite specific in terms of power consumption, and therefore the analysis of energy intensity of iron ore mining is a difficult task. It is practically impossible to carry out energy intensity analysis on the basis of the existing methodological support without its thorough refinement, since it is aimed at the application of simplified analytical and empirical dependencies calculated for the same initial data, regardless of conditions. The analysis of energy intensity of iron ore mining is a necessary stage for providing appropriate management of power consumption.

As is known, an integral and decisive component of performance of industrial enterprises, in general, and mining enterprises, in particular, is reduction of their energy intensity. Naturally, energy intensity of every industrial enterprise is influenced by natural and climatic factors, fixed and working capital, intangible assets, and personnel activity.

It is energy intensity of iron ore mining that determines efficiency of the actions taken by management in the field of distribution, direction, planning and analysis of all available resources of an iron ore enterprise, which niche is occupied and will be occupied in the future by this enterprise in the market of iron ore raw materials, taking into account the influence of its competitive environment. An important place in this issue belongs to the impact of current trends in the field of technology development on dynamics of production process components. Investigating these processes and conducting an appropriate analysis is an important and urgent issue for national mining and iron ore mining enterprises.

The specifics and individual features of the operating technology of mining enterprises, in particular with regard to the problem of increasing energy efficiency, are covered in detail in the works by national and foreign scientists: B.N. Avilov-Karnaukhov, N.L. Alamakha, T.M. Beridze, S.I. Vypanasenko, S.A. Volotkovsky, M.V. Hraisukh, Ye.S. Huzov, V.V. Dehtiarov, A.A. Driomin, M. Durnev, L.I. Zhivov, V.T. Zaika, V.F. Kalinichenko, Yu.H. Kachan, H.I. Kornilov, O.V. Liakhomsky, S.R. Maimin, M.V. Melnikov, L.I. Poltava, H.H. Pivniak, A.V. Prakhovnik, V.P. Rozen, I.T. Rozumny, I.S. Samoilovych, O.M. Sinchuk, I.O. Sinchuk, V.F. Shchitka, F.I. Shkrabets, M.I. Shulin, V.I. Shchutsky and many others. Without diminishing deep scientific analysis, which was carried out by predecessor scientists, we note that the issue of energy intensity for enterprises of the iron ore industry and for today's conditions requires further study and even rethinking the ways of achieving the goal. It should be emphasized that the analysis of the impact of scientific and technical progress on the mechanisms of interaction between constituents of production potential and efficiency of iron ore mining enterprises has not been sufficiently disclosed. That is why these issues need more thorough analysis and improvement.

The practical basis for improving the efficiency of power consumption at mining enterprises is, among other things, enhancement of methods for calculating power loads, establishing scientifically based specific power consumption, increasing the accuracy of forecasting and the level of planning power consumption parameters, reducing losses and saving power, etc. The rapid growth of energy consumption creates a danger of the imminent exhaustion of fossil energy resources. The risks associated with the development of the energy industry determine the increased interest in certain assessments of future dynamics of the energy industry and the consequences of its development. It should be taken into account that energy security is currently the cornerstone of the policy of many countries. It is appropriate to note that by 2030, according to the Ministry of Fuel and Energy of Ukraine, the country plans to reduce the consumption of energy resources by 12%, including in metallurgy, which traditionally comprises the iron ore subsector, by 30%. In contrast to these "plans", we note that until 2019, such a trend in the levels of power consumption was not actually observed. And if we look back a year, we will see that the level of power consumption in 2018 compared to 2013 in Ukraine practically did not decrease, in metallurgy as well, being stable for years (≈ 24.5%).

When performing a comprehensive assessment of power consumption, there is a question about the change in consumption from each power source in comparison with the previous period, as well as its reasons, namely: the depth of the underground mine, the amount of dehydration, the change in the quality of ore, the change in technology, etc. Elaboration of these issues and real assessment of the situation in the analyzed direction are essential grounds for the possibility of solving issues to shape a comprehensive approach to consideration of power consumption at iron ore mining enterprises as a systemic process [3-5].

It is obvious that the level of power consumption efficiency is a consequence of energy intensity reduction of mining iron ore raw materials, and for its management, it should be based on optimal planning and forecasting of power consumption with differentiation of power distribution among consumers. Optimum planning and forecasting of power consumption will give the desired effect if scientifically based rationing of power consumption for main and auxiliary processes of mining technology is applied.

Proactive rationing of power consumption largely depends on planning at iron ore enterprises. To identify the viable planned actions aimed at increasing power consumption efficiency, it is required to determine load modes of power receivers at iron ore mining enterprises.

According to the views on the iron ore mining strategy of iron ore as a basic product of the national economy [7-9], the methodology of research conducting should highlight two main areas of ensuring the optimal energy intensity of iron ore mining. These include the supply of physical volumes of energy resources in accordance with the needs of the economy, simultaneously reducing the influence of external factors on power supply stability, and the reduction of the growth rate of the economy's need in energy carriers while ensuring stable GDP growth by increasing the efficiency of power resources by the national economy. Moreover, these directions also contribute to strengthening the economic security of the state.

Each of the above directions has its own priorities. In general, the implementation of the solution to the task of ensuring the optimal energy intensity of iron ore mining, taking into account the listed factors, involves two directions. The first direction implies ensuring own energy resource maximization by intensifying own production volumes, improved processing, new energy conversion technologies, use of secondary energy resources, avoidance of monopoly dependence on supplies of energy carriers from Russia (almost total monopoly supplies of oil, gas, nuclear fuel) through diversification of import energy sources and transportation routes; modernization of fixed assets, primarily of the fuel and power enterprises (the level of wear and tear of their fixed assets is about 60%); development of actions ensuring the vital activity of the economy in case of unforeseen circumstances in the fuel and power complex or with resource supply.

Implementation of the second direction should ensure changing the industrial production structure by reducing the specific weight of energy- and resource-intensive industries; comprehensive modernization and re-equipment of Ukraine’s economy in general and iron ore enterprises in particular, considering energy-saving approaches, introduction of cutting-edge energy-saving technologies, modern telecommunications and computer networks; reduction of wasteful and unmanaged consumption of energy resources and secondary energy resources; expanding the use of alternative energy sources. The analysis of the priorities of both directions of providing optimal energy intensity of iron ore mining enterprises points to energy saving as a priority for the management apparatus. Currently, Ukraine is facing the problem of reducing energy intensity of its economy to ensure its security.

This can be done in several ways. Considering Ukraine's economic situation, the broad approach of increasing its own production and importing from various suppliers is the most acceptable. However, it is impossible to completely reject the consumption of alternative power sources. By replacing old equipment with new, Ukraine can cut the cost of heat and power almost in half.

In view of this, the main components of the approaches to comprehensive assessment of power consumption by iron ore mining enterprises should include theoretical justification of methodological provisions for monitoring power consumption by energy-intensive components, modeling, optimization, forecasting, substantiation and determination of informative signs and indicators of energy efficiency using factor analysis, etc. This is especially important under conditions of a limited data set.

Theoretical and methodological principles are the basis for evaluating energy intensity of iron ore mining, both theoretically and practical application. The issue of determining and forecasting energy-intensive components in the structure of iron ore mining technology is becoming topical.

1.3 Formatting methodological approaches to developing a system of technical and analytical indicators of ensuring energy efficiency at iron ore mining enterprises

The operational peculiarity of iron ore mining enterprises under market conditions is that the coordination of activities within the enterprise, carried out in the form of command and administrative control, replaces market coordination. This approach is based on the fact that, according to R. Coase's theory, every transaction in the market economy (voluntary market agreements) entails costs, and these costs must be considered in the market analysis.

In modern economic theories, considerable attention is paid to the analysis of of enterprises' activities by means of their mathematical modeling [5, 10, 15]. In particular, the neoclassical theory of a firm considers enterprise as a "black box". At the same time, initial resources are considered as input variables, while finished products are output variables. The enterprise is represented as something "given" in this theory. Like the consumer, the enterprise acts as a primary logical element of technical and economic system. The initial limitations of this model are unchanged prices for resources, constant growth of producer's budget, the use of two factors of production.

The category "enterprise" in modern science has an ambiguous interpretation. Most unorthodox theories, such as the neo-Austrian school, neo-institutionalism, Marxist political economy, consider it as one of the central technical and economic categories. However, even among unorthodox branches, differences in approaches to enterprise analysis are quite significant. The difference between the definitions reflects theory fundamentals and depends mainly on a type of enterprises or their manufacturing processes being prioritized.

This study proposes an approach to the analysis of energy efficiency of an iron ore mining enterprise as a "gray" box. With this approach, in addition to input and output variables, the elements of the enterprise's structure that are significant from the point of view of its production activity are taken into account.

The study of production systems of different levels using the modeling method is based on the assumption that the production system has the same set of characteristics, invariant as for research objectives, as ordinary complex systems, among which the main ones are integrity, complexity, emergence, dynamism, causality, adaptability, etc.

Some specific issues of stability of production systems also deserve attention. Considerable scientific results are obtained in the theory of economic equilibrium, which become one of the most important sections of mathematical economics. The main issue investigated in the theory of equilibrium is the problem of creating such conditions under which supply would fully satisfy demand, and producers and consumers of goods would not be interested in changing the established equilibrium situation. Stable systems, the equilibrium of which is maintained by the market process of price regulation, are a typical example of homeostasis.

The study of production systems of any level is conducted from the standpoint of a system approach, which is a scientific and applied methodology for solving major problems.

It should be emphasized that the importance and, at the same time, significant difficulties of the system approach in the study of production systems. In technical systems (in particular, in very complex stochastic systems), as a rule, it is relatively easy to trace the relevant connections between individual subsystems and, with greater or lesser probability, to predict the interconnectivity of events in such subsystems.

In this regard, technical and economic systems are much more sophisticated, as their leading component is people, who, thanks to their purposeful activity, implement both production and management processes. At the same time, there is such a complex and tight conglomerate of interactions of individuals, staff, finance and power distribution that its correct and effective analysis is possible only as a whole.

Production systems are distinguished by certain features:

1) their great complexity due to numerous and fairly strong material and informational connections between subsystems and system elements;

2) continuous, dynamic and unrepeated on a micro scale nature of development, methods of production, economic relations can change significantly and repeatedly.

Application of system analysis is not an end in itself for the study of complex production systems. On its basis, a system approach is developed to study the economy as a whole in a comprehensive manner. At the same time, the system approach ensures the implementation of the next important stage of creation, the synthesis of systems designed to achieve specific set goals.

The use of the system approach to production systems opens up ways to optimize the structure and functioning of both individual system elements and the system as a whole. The system approach, which includes system analysis and synthesis, means that when making any partial decision on solving a particular technical problem, all direct and indirect, present and distant consequences of this decision should be taken into account whenever possible.

One of the important tasks of improving structures controlling power consumption is the search for effective methods of assessing the existing ones. Production and organizational structures of control, along with the control technology and information management system, are an integral part of the energy efficiency control system, and the ultimate goal of improving management structures is to increase control efficiency as a whole. Therefore, the energy efficiency indicator should be considered as a criterion to optimize the enterprise's management structure.

The following points make the development of a methodology to define the concept of energy efficiency difficult:

– it is impossible to isolate the result of energy efficiency because it is revealed indirectly in the final product;

– the effect of improvement can be visible not only in the subdivision where this improvement was made, but also in adjacent ones;

– energy efficiency consists of various economic, social, organizational, scientific and technical, information and environmental results, many of which cannot be quantified.

Currently, there are different approaches to determining energy efficiency. There is an approach in which efficiency is equated to the overall efficiency of production and is assessed by such indicators as production costs, capital investments considering the time factor, annual economic effect, estimated profit, reduction of total labour costs, labour productivity, etc. Summarizing indicators that comprise various final performance indicators of an iron ore mining enterprise are also suggested.

There are different approaches and different indicators of energy efficiency assessment, each with its own advantages and disadvantages. When choosing one or another indicator, it is necessary to take into account the purpose of energy efficiency measurement, the specifics of the industry, as well as requirements that the energy efficiency determination method is designed to meet. The main requirements are as follows:

1. The energy efficiency measurement system should be comprehensive, using a set of indicators and reflecting all components of power consumption.
2. All indicators necessary for analysis and calculations should be taken from available reporting. The creation of new, additional forms of reporting is an extreme measure, because this increases the already enormous document flow of industrial and economic entities.
3. The measurement system should be uniform for all components of power consumption, not only for convenience, but primarily for comparability of assessment results. Indicators may be different, but not the methods of their calculation.
4. Energy efficiency indicators should carefully reflect the features of each structural element of the production system. For each structural unit, there should be a limited number of comparable indicators.
5. It is necessary to summarize all energy efficiency indicators.

Currently, the mining sub-sector has a tendency to increase the number of large enterprises. Optimization of enterprises and their production units contributes to the introduction of equipment with a larger unit capacity and its more effective use, the establishment of an adequate ratio between the main and auxiliary production, and better use of available resources. Concentration leads to an increase in energy efficiency, as the number of facilities is reduced due to optimization of production divisions and service departments, and elimination of duplicative functions. Administrative personnel are also reduced. This results in improved manageability and higher specialization of performing individual functions.

It is known that iron ore mining enterprises, like the entire mining and metallurgical industry, are energy-intensive, this fact greatly complicating their economic component. The operating technology at operating mining enterprises makes it impossible to have a positive prospect of reducing power consumption, at least now.

Thus, there is an urgent need for theoretical and methodological processing of power consumption analysis in order to optimize power consumption levels. The solution to this complex scientific problem should be based on the development of modern methodological approaches to forming a system of relevant energy efficiency indicators. The lack of such scientific and practical analysis narrows the possibility of applying research methods to iron ore mining enterprises.

National iron ore mining enterprises are quite specific with regard to power consumption, and therefore research into increasing their energy efficiency should be based on the appropriate technological and power-consuming components of these types of enterprises.

1.4 Energy balance of iron ore underground mining enterprises

The logistics of shaping the energy balance of industrial enterprises are governed by the relevant standards of Ukraine and the Power Market Law. Thus, in addition to energy policy, the "attention" of state agencies to this aspect can also be explained by the important fact that which components of production technology consume how much electricity can be assessed by the energy balance.

The main task of drawing up the energy balance of any industrial enterprise is to determine cost items and study the issues related to determining power consumption. Another aspect, which is no less important than the above, is annual compilation of energy balance that allows considering and monitoring the results of practical implementation of measures aimed at increasing the level of efficiency (including energy efficiency) of both the entire power management of the enterprise and its individual components.

According to the results of the research aimed to assess the levels of energy consumption at iron ore underground mines [1-15] (Fig. 1.6), the electric power consumption prevails. Therefore, further on, following the research aim, the power balance concept will be referred to.

Meanwhile, in addition to the above, we note that drawing up a power balance of the enterprise is a complicated and urgent engineering task. However, the task of this level of certainty is a starting point for scientific analysis and assessment of the state of power supply-power consumption process. In drawing up the power balance, there arise both natural and objective problems, such as definition of the type and area of application and the format of energy efficiency indicators of power consumption. There are also a number of subjective factors that determine a specific goal or goals that are necessary for further use of the results. According to the latter, this includes the composition of primary information for the development and analysis of the power balance of a specific enterprise or types of enterprises.

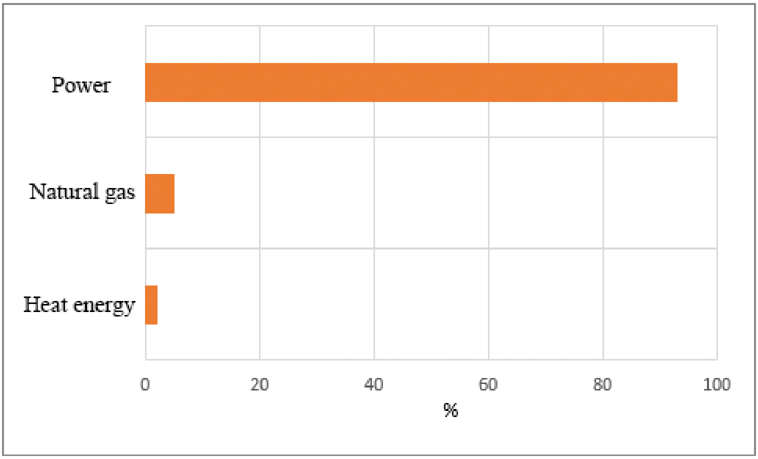

Figure 1.6 – Averaged components of power consumption of Ukraine’s iron ore underground mining enterprises

As a rule, primary information to develop and analyze power balances of industrial enterprises includes general information about the enterprise, design and reporting (actual) data on power consumption, technical and energy characteristics of technological processes and plants, technical and economic characteristics of energy carriers.

General information about the enterprise should include the data on its economic performance.

As a rule, the following is accepted as design and reporting (actual) data on power consumption:

– project documentation (specification and energy specification of the enterprise, feasibility study, etc.);

– statistical reporting arrangements.

Engineering and energy characteristics of technological processes and plants are the basis for developing analytical power balances and must contain the data necessary for assessing the efficiency of energy carriers use, including:

– material flows (material balance);

– costs and parameters of raw materials, fuel, energy, and wastes;

– design features of plants (overall dimensions, insulation, availability of recycling plants for secondary energy resources, instrumentation and automation, etc.);

– operating modes of equipment (frequency of use, duration of stand-by mode, etc.).

Engineering and energy characteristics are revealed for the most energy-intensive equipment.

Engineering and economic characteristics of energy carriers include:

– cost of energy carriers;

– parameters of energy carriers (voltage, frequency for electric power);

– annual and daily power consumption curves (for typical days of summer and winter periods).

Experimental studies of power consumption and load modes make it possible to compile power balances based on the most effective calculation and experimental method.

The power balance equation as a system of indicators for the supply and conversion of power reflects the equality of the sum of supplied and useful energy and its losses, which in the general case takes the form

$$W = W_{\mathrm{n}} + W_{\mathrm{l}} + W_{\mathrm{con}} + W_{\mathrm{m}} \tag{1.1}$$

where W is power supplied to a plant;

W_{n} is power consumed without losses;

W_{l} are power losses in power transmission lines;

W_{con} are power conversion losses (in an electric motor, a transformer, a rectifier, etc.);

W_m are losses in an operating machine

The values included in (1.1) can be expressed through the corresponding power indicators.

When using the calculation-experimental method, the calculation of power consumed by operations is carried out "from top to bottom", that is, by subtracting power losses in plants and networks from the total amount of own power provided for operations.

This type of analysis is carried out on the basis of statistics on power consumption both at the iron ore mining enterprise as a whole and at its sections in particular (Tables 1.1, 1.2).

Table 1.1 – Descriptive statistics of input statistical information on power consumption levels

Indices	Underground mine			
	Pokrovska	Kryvorizka	Kozatska	Ternivska
Mean	43247.99	65702.91	43897.76	43271.31
Standard error	721.45	4042.87	870.10	701.83
Median	42827.82	69166.24	43664.51	42972.90
Standard deviation	1767.18	9902.96	2131.31	1719.12
Sampling variance	3122924.49	98068648.27	4542485.34	2955389.66
Kurtosis	2.88	5.63	2.52	-1.60
Asymmetry	1.62	-2.35	1.02	0.31
Interval	4762.77	26001.20	6492.22	4443.21
Minimum	41783.45	45672.34	41181.33	41229.13
Maximum	46546.22	71673.54	47673.55	45672.34
Total	259487.93	394217.45	263386.55	259627.83

According to the analyzed methodological approaches to determining power balance, it is necessary to determine the amount of power consumed by less energy-intensive consumers of the iron ore enterprise, which is about 20% of the total amount consumed.

The most energy-intensive are the so-called stationary plants: water drainage facilities, skip hoists, ventilation plants and crushing and sizing plants.

Table 1.2 – Power consumption by plants of iron ore underground mines

Plants	Underground mines			
	Pokrovska	Kryvorizka	Kozatska	Ternivska
Total	137847.6	250997.4	156225.5	140063
Skip hoists	21878.72	25460.78	48390.59	25543.34

Ventilation	52903.78	73386.55	49885.08	56412.79
Water drainage	28153.85	113154.6	8944.53	42632.27
Crushing and sizing plant	7358.98	11274.15	11086.75	6976.8
Subtotal	110295.3	223276.1	118307	131565.2
Other	27552.28	27721.33	37918.55	8497.75

Table 1.3 shows calculations of statistical data for other consumers, which conditionally refer to less energy-intensive types.

Table 1.3 – Statistical data on less energy-intensive power consumers

Indices	Less energy-intensive power consumers of underground mines
Mean	25422.48
Standard error	6140.162
Median	27636.81
Standard deviation	12280.32
Sampling variance	1.51E+08
Kurtosis	2.107079
Asymmetry	-1.03492
Interval	29420.8
Minimum	8497.75
Maximum	37918.55
Total	101689.9

The kurtosis values indicate a bimodal distribution, which warrants further analysis. It is expedient to conduct a more thorough study, which involves the analysis of various losses during power consumption.

Figure 1.7 shows the ratio of power consumption at iron ore underground mines.

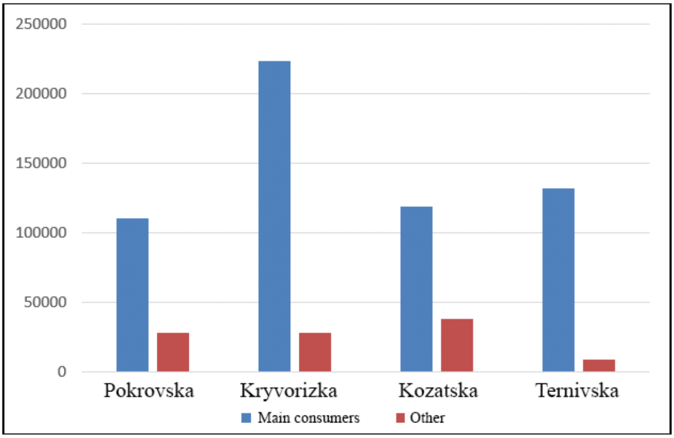

Figure 1.7 – Ratio of power consumption by iron ore underground mining enterprises

The quantitative ratio of what we called "other" consumers to power consumers that make up the system-forming component of power consumption (energy-intensive) at the iron ore mining enterprise is given in Table 1.4.

Table 1.4 – Quantitative ratio of power consumption

Underground mine	Pokrovska	Kryvorizka	Kozatska	Ternivska
Ratio %	25	12	32	6

According to Table 1.4, a significant share of power consumption by other consumers is observed at Kozatska underground mine – 32%, the smallest share, 6%, at Ternivska underground mine.

The analysis of Table 1.4 allows us to state that reducing power consumption by other consumers enables optimizing energy efficiency. Solving such an urgent problem is the basis for obtaining appropriate management decisions to ensure energy efficiency.

Thus, further research should involve development of appropriate methodological principles and approaches to solving specified problems based on the system approach.

1.5 Modes and specific features of power consumption at iron ore underground mining enterprises[3]

It is obvious that formatting the parameters of power consumption by enterprises, and the targeted evaluation of influence of their system-forming components on the existing algorithm of consumers' operations in general, and each one in particular, is the determination of directions for finding means to solve the problem of energy efficiency and develop the appropriate scheme for its implementation.

Analysis of experimental studies conducted by the researchers of the scientific school headed by Professor Sinchuk O.M. at iron ore underground mines of Ukraine for more than last 15 years, highlighted, or rather confirmed, the previously obtained results on power distribution among consumers of iron ore underground mines.

Thus, it is asserted that the main, and at the same time system-forming, feature of iron ore underground mining enterprises (underground mines) is that that about 60% of the total volume of power consumed by these types of enterprises refers to consumers that do not adjust to the enterprise's capacity, namely the condition and production of iron ore (Fig. 1.9). That is, the levels of power consumption by these enterprises are close to 50%, whether the enterprise operates at its maximum or minimum designed capacity and performance. To a large extent, this also applies to idle, i.e. non-operated underground mines, which, despite their current static state, consume on average about 40% of the power consumed during its normal (designed) operation (Fig. 1.8).

An important fact (see Table 1.5) about the power supply to underground mining enterprises, is the change or redirection of power consumption by energy-intensive consumers over the years.

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[3] The work uses the results of experimental studies carried out at Ukrainian iron ore underground mines until February 2022.

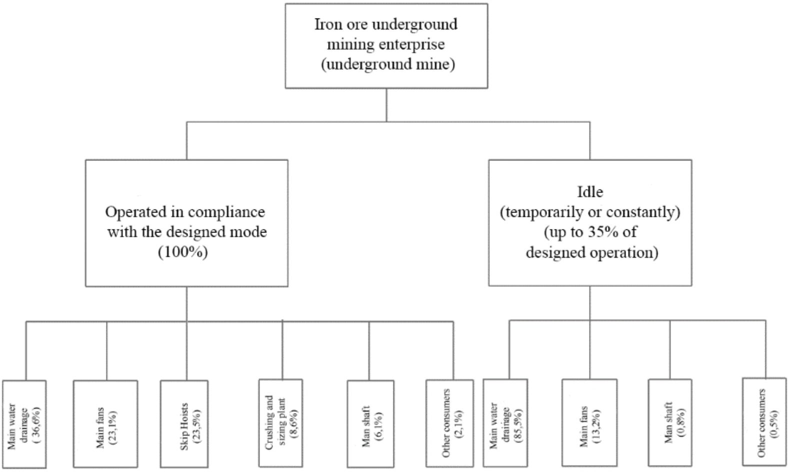


Figure 1.8 – Power distribution among energy-intensive consumers at national iron ore underground mines

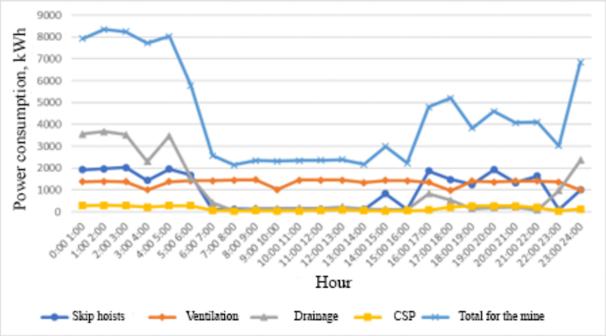
Table 1.5 – Averaged indicators of power consumption by iron ore underground mines of Kryvyi Rih iron ore region

#	Consumer type	Total power consumption, %		Yearly deviations, % (+/-)
		1990	2021	
1	Main water drainage facilities	11.1	36.6	+ 229.7
2	Skip hoists	34.8	23.5	- 32.5
3	Main fans	15.6	23.1	+ 21.2
4	Central (local) compressor stations	18.8	Removed from the register of power consumers of underground mines	
5	Intra-mine transport - electric ore haulage	6.5	3.8	- 71
6	Crushing and sizing plant	11.0	8.6	–
7	Other	2.2	4.4	

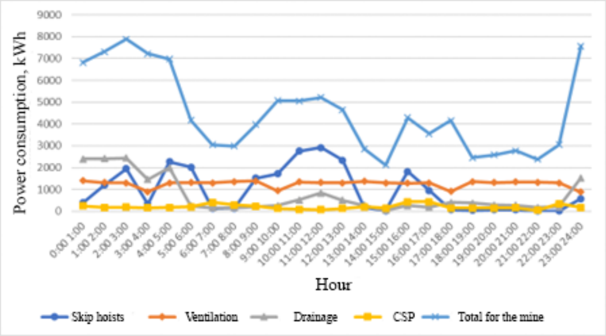
Meanwhile, the logic of changes in power consumption by energy-intensive consumers of iron ore mines over the years is clear, following simple considerations regarding the technology of iron ore mining. However, there is also a certain peculiarity - a specificity that borders with a system-forming factor in this process.

Compared to coal and shale mines, iron ore underground mines are noted for significant fluctuations in the levels of power consumption during hours of the day [5, 10, 15]. To a certain extent, in the last decade, in addition to the impact of mining technology on this process, there is also a corresponding reaction of the enterprises themselves - power consumers to hourly tariffs, which since 2019 have become hourly - 24 tariffs, replacing the existing three-tariff system.

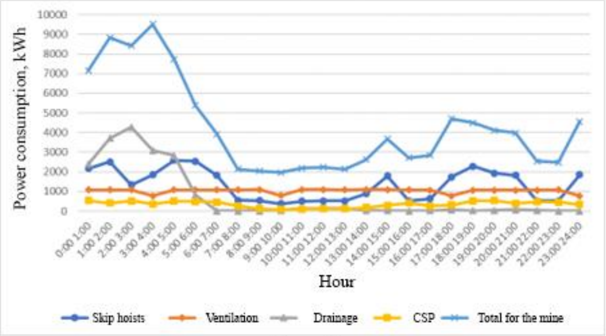
Fig. 1.9 shows daily curves of power consumed by iron ore underground mines on a monthly and yearly basis. As evidenced by Fig. 1.9, in recent years, the level of fluctuations has increased with the tendency of even more significant differences in hours of the day.



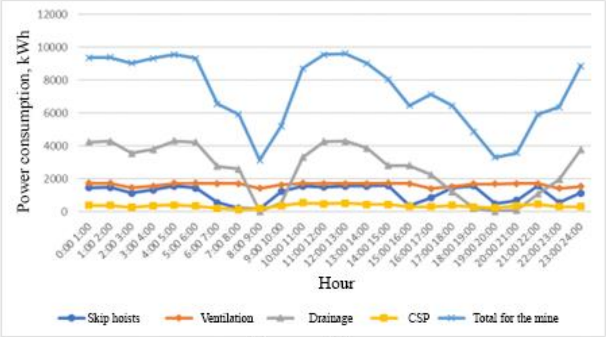
Ternivska



Pokrovska



Kozatska



Kryvorizka

Figure 1.9 – Daily curves of power consumption by underground mines

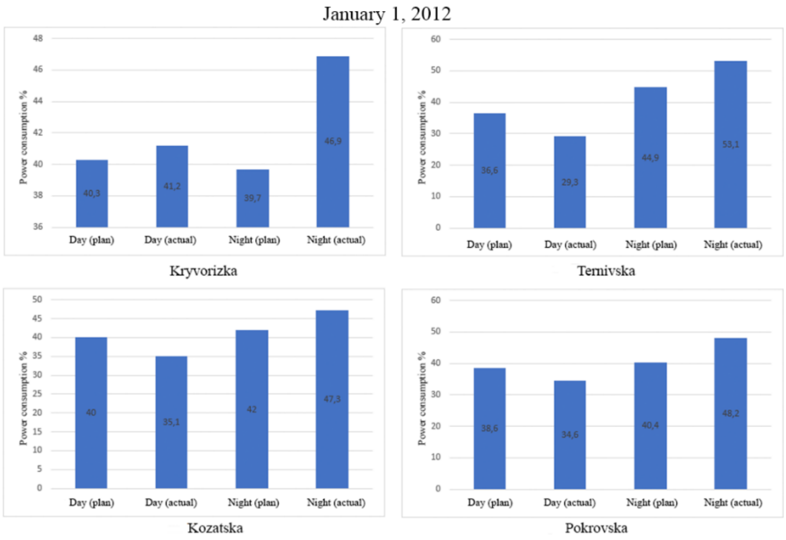
This local intervention of the energy services of enterprises in the process of artificial formation of power consumption schedules gives certain positive effect on payment levels for the power consumed according to the relevant tariffs. Nevertheless, it also creates new problems - a negative impact on reliability and service life of electrical equipment. This problem is the result of the "manual control" over operating modes, primarily of energy-intensive types of power consumers, since these modes fluctuate unpredictably from the minimum - when a consumer does not work for several hours, to the maximum - when it works at the maximum, and often in ultra-maximum mode. The latter is the cause of premature "aging" and failure of the corresponding electrical equipment [1, 3, 5, 6, 10].

Taking into account this specificity and the fact that the influence of its components on power consumption is unpredictable, which means that the determination of relevant control indicators in forming iron ore production cost has its own basis, enterprises are forced (and this is a good thing) to plan prospective power consumption by energy-intensive consumers. However, the level of this "planning" is not always sufficient (Fig. 1.10).

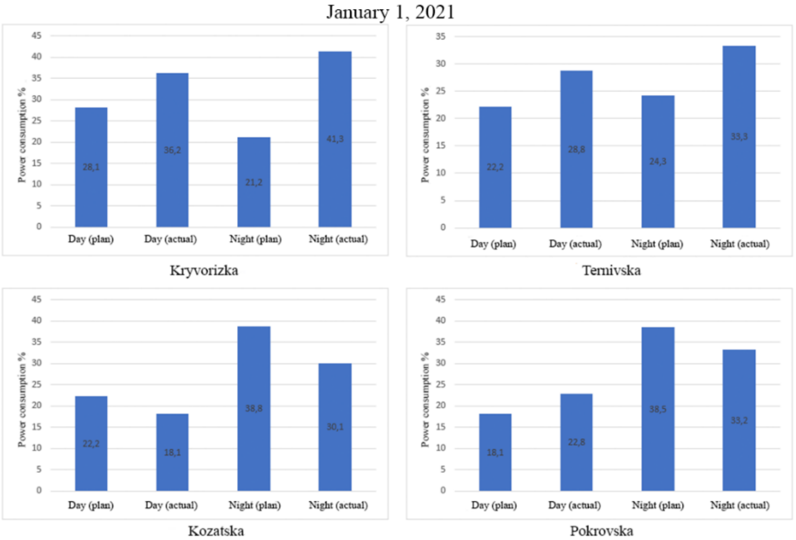
However, water drainage facilities of iron ore underground mines have always had significantly larger percentage of total power consumption compared to other consumers (Table 1.5).

Energy services of the enterprises are forced to constantly monitor and coordinate the hourly volume of water drainage to fall into the limit of the corresponding power costs. Such a "case" is made according to "plan instructions" which are received from planning departments.

However, plan and reality in this version of management do not always, or rather almost never, coincide (Fig. 1.10). This is a logical consequence of inefficient "manual management" of such a complicated process. As a result, the power component in the cost of iron ore mining continues its growth.



a)



b)

Figure 1.10 – Plan-actual graphs of daily specific power consumption indicators: a) January 1, 2012, b) January 1, 2021.

However, the algorithm controlling the ratio of plan and actual levels deserves attention, as it affects the iron ore production cost by reducing, or rather restraining within optimal limits, the power component of this baseline multifaceted indicator - profitability of the enterprise. Obviously, both the structure and the development of the technology of intelligent automated control of water drainage at iron ore underground mines in general, and power management of this local process in particular, should be based on the artificial maintenance of the zero difference of the aforementioned ratio.

As evidenced by the data (Fig. 1.11), water drainage facilities are again characterized by the highest level of deviations. Correspondingly, water drainage facilities are to be prioritized when deciding on energy efficiency improvements at iron ore underground mines.

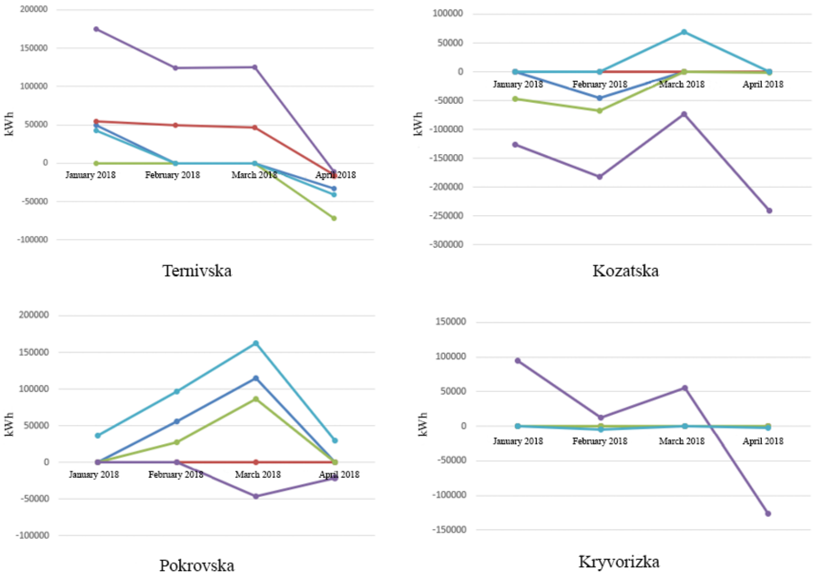


Figure 1.11 – Diagrams of absolute deviations of power consumption at a range of iron ore mines in Kryvyi Rih region

1.6 Practice of applying the theory of production systems to assessing power consumption at iron ore underground mining enterprises

Nowadays, scientists use the synergistic approach and the mathematical theory of active systems in their research with good reason, believing that synergetics is a theory of self-organization in systems of various natures. In complex production systems as a whole, properties may appear that none of the components of this system possesses. As for the mathematical theory of active systems, it provides a conceptual framework for describing mechanisms of functioning of production systems and allows solving the following tasks:

Analysis. The structure and functioning mechanism of the system are set. Based on reasonable hypotheses about the behaviour of active elements, the efficiency of the active system is determined.

Synthesis. The mechanism and laws of functioning of the active system, ensuring its maximum efficiency are determined.

Basic principles of synergetics and the mathematical theory of active systems are the basis for assessing power consumption at national underground mining enterprises.

When considering the main control functions of complex production systems, such as an iron ore mining enterprise, the functions of organization and planning are usually distinguished. These functions, in a broad sense, are generalized (integral) management functions. The planning function can be defined as the organization of human activity on the basis of establishing its criteria and goals, means and methods of their achievement. The function of organization can be defined as a special process that is orderly and purposeful in relation to certain actions, i.e. it can regulate implementation of all functions.

The issues of studying the system for assessing parameters of power consumption are directly related to the components of the theory of production systems.

To interpret such processes and mechanisms of the power consumption assessment system, the following features are essential:

1. A power consumption assessment system is a multilevel set of subsystems with limited independence and priority of subsystem actions.
2. In a production system, the main dimensions of subsystems should be controlled, and individual system components or subsystems should be given some autonomy in selecting solutions. Besides, system-wide and proprietary limitations should be taken into account (Fig. 1.12).
3. An elementary component of the system for assessing power consumption of an operating entity is the management subject. The subject embodies management decision-making. Such decisions cannot be formalized through management functions, but rather accumulate the elementary cycle of the management process.

Local goals cause intra- and inter-level conflicts in the system. Inter-level conflicts in a system arise when the global goal and local goals of subsystems are incompatible. Naturally, the structural elements of power consumption assessment at the lower level tend to provide false data or hide the share of resources of an iron ore mining enterprise from the levels above.

Intra-level conflicts arise when other subsystems prevent achieving local goals.

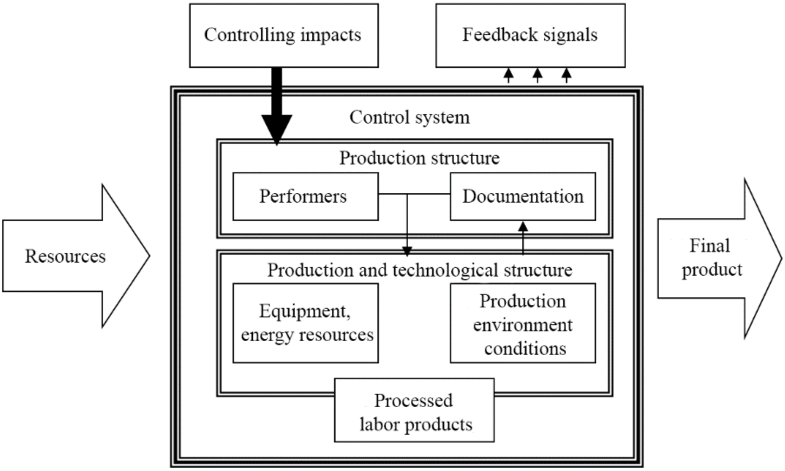


Figure 1.12 – Structure of power consumption assessment

Formalization of some of these features makes enables formulating methods and theories of active systems. Control objects of this theory are active elements. At the content level, an active element can be defined as a purposefully functioning one that has a feature of self-organization (self-development), generating with different efficiency depending on the goals of control (management) action in terms of assessing power consumption and making appropriate decisions. Such an active system can be an iron ore mining enterprise as a whole and its most energy-intensive components.

The behaviour of active elements of the system is to some extent determined by the given functioning mechanism.

The functioning mechanism contains:

1) methods for developing criteria, goals, and plans for assessing power consumption;

2) patterns of assessment, planning, and incentives;

3) organization of processes for assessing power consumption in accordance with the functions of planning, accounting, control, decision-making, and management actions.

There is a set of variables describing the state of the *i*-th active elements, with the input being x_i and the output being y_i. Based on the appropriate interpretation, the vector of inputs x_i is defined as certain resources of the *i*-th active element, and the vector of outputs y_i is defined as the result of the production system (an iron ore mining enterprise). The efficiency r_i of the active element i is determined by the correspondence between costs and results, i.e. $r_i = r_i (x_i, y_i)$ of the i-th active element, which is the realization vector, then $r_i = r_i (u_i)$.

The control center does not have accurate information about potential efficiency of the active element. When forming the plan, the control centre uses information about model parameters of the active element.

σ_i is assessment of the vector parameter r_i used by the planning centre. Moreover, although $\sigma_i \in \Omega_i$ are the areas of effective implementations, in general, $\sigma \neq r$. The procedure for forming a plan π_i for the active element i can be defined as a reflection of π_i: i.e. an analytical reflection of the planning law.

The plan vector $u_i^\pi = \left(x_i^\pi, y_i^\pi\right)$, set by the control centre to the active elements, defines the planned implementation for the i-th active element and characterizes the ‘desired’ values of the corresponding implementation components. The plan must be implemented, that is:

$$u_i^\pi \in U_i,$$

where U_i a set of implementations of active elements.

The dimensionality u_i in general is larger than the dimensionality u_i^π, since some of the active element variables are translated into free variables u_i^0. The vector u_i^0 is a set of variables formed by the exception from u_i the planned variables , i.e.

$$u_i = \left(u_i^0, u_i^\pi\right).$$

The centre controls the variables of the planning vector u_i^π, while the variables to be assessed are directly at the disposal of the active element.

The dimensionality u_i^0 for all active elements is assumed the same (they are brought to the same dimensionality by adding zero components). This is due to the need to represent the system as a group of functionally homogeneous subsystems. Homogeneity of active elements is the first condition for ensuring the principle of comparability of assessments.

The second condition necessary for assessment is related to the ratio of results and costs of the active element in achieving the results of the production system (the enterprise). Comparability of assessments is ensured by bringing each of implementation variables to the unit of resource use, for example, in the form of various specific indicators.

Efficiency depends to a large extent on how well the choice of production policy is made. Substantiation of management decisions is directly related to a comprehensive technical and economic analysis. The choice of the best option for controlling power consumption should be based on a comparative analysis of energy efficiency of solution options.

Production systems are, of course, appropriately complex production systems. Production systems are noted for their own specific features.

In the face of rapidly changing environments, adaptability of production systems is evident. Preserving crucial features in order to keep essential variables within certain limits is the main task of energy efficiency.

A significant difficulty in analyzing and assessing power consumption systems is the presence of emergent features. These properties are the least accessible to tracking and measurement. They can be identified and quantified only by analytical techniques.

The complexity of the technical condition of an iron ore mining enterprise makes it impossible to fully formalize systems for assessing power consumption. When modeling power consumption assessment systems, two subsystems are distinguished: mostly formalized and mostly informalized. External parameters are set with respect to the formalized subsystem and determine the legitimacy of certain procedures.

Effective formalization of power consumption assessment systems involves supplementing them with external data, which is determined by the achieved level of research of the production system and its respective interaction with the environment. This process is ensured by a systematic approach to describing objects of research. Naturally, formalization is a system of models interconnected by direct and reverse communication channels.

Given that an iron ore mining enterprise is a complex object, it is advisable to build a mathematical model of the enterprise's functioning to solve the problem.

At the same time, in order to expand the boundaries of perception and assessment of possible extraordinary directions in the field of improving energy efficiency of iron ore mining enterprises, we will consider the possibility of their own generation of power by these types of enterprises. In this case, the enterprise model will be interpreted as a dependency that connects input and output variables and can be written in the form

$$y = f\left(x\right) \tag{1.2}$$

where x is an input variable,

y is an output variable.

In general, the functional dependence (1.2) is unknown, so it is reasonable to consider an iron ore mining enterprise as a ‘black box’ whose internal content is unknown, and the model is represented by a multipole with an unknown structure. Fig. 1.13 presents a diagram of an iron ore mining enterprise as a ‘black box’.

Figure 1.13 – An iron ore mining enterprise (‘black box’)

In accordance with the problem under study, the assessment of power consumption at an iron ore mining enterprise due to its own power source is used as an additional possible contribution to the total power consumption by an iron ore mining enterprise.

Fig. 1.14 presents a diagram explaining the use of power consumption sources generated by an iron ore mining enterprise.

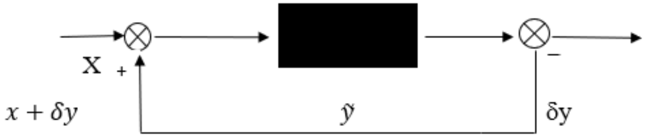


Figure 1.14 – Scheme of using power consumption resources by an iron ore mining enterprise

According to Fig. 1.14, the enterprise as a "black box" receives an input variable consisting of its own sources of power (x), part of which are formed by the contribution ($\delta\, y$). As a result, according to (1.1), the output variable will take the form:

$$\tilde{y} = f(x + \delta y).$$

Thus, we can propose the following methodi for assessing power consumption, given the time intervals of power consumption.

Let a given period of time be $\left[0; T\right]$.

In this case, we denote the daytime by $[0; T_1]$ and the night by $[T_1; T]$.

According to the condition, c_1 is the cost of active power during the day, i.e., for the period $[0; T_1]$, c_2 – is the cost of active power at night, i.e. for the period $[T_1; T]$.

According to the condition of the problem

$$c_1 > c_2. \tag{1.3}$$

Let c_0 be the cost of active power, which is independently generated by the enterprise.

According to the condition,

$$c_0 = \frac{1}{4} c_1 . \tag{1.4}$$

$W_0(t)$ is active power of the enterprise's own power consumed,

$W_1(t)$ is active power from external sources consumed by the enterprise.

Let Q_0 denote the specified amount of power consumption during $[0; T]$.

We consider power consumption during $[0; T]$, taking into account consumption of both the enterprise's own power and that from external sources:

$$\int_0^t W_0(t)dt + \int_t^T W_1(t)dt = Q_0 , \tag{1.5}$$

where $[0; t]$ is the period of the enterprise's power consumption,

$[t; T]$ is the period of consuming power from external sources.

Power consumption during the period $[0; T]$ is as follows:

$$Z(t)=\begin{cases} c_0\cdot\int\limits_0^t W_0(t)dt+c_1\cdot\int\limits_t^{T_1} W_1(t)dt+c_2\cdot\int\limits_{T_1}^{T} W_1(t)dt, & 0\le t\le T_1 \\ c_0\cdot\int\limits_0^t W_0(t)dt+c_2\cdot\int\limits_t^{T} W_1(t)dt, & 0\le t\le T \end{cases} \qquad (1.6)$$

Formula (1.6) determines the dependence of power costs on the time of consuming the enterprise's own electricity.

Considering (1.4), with an increase in the time of consuming the enterprise's own power for a period of $[0;T]$, power costs (1.6) will decrease. At the same time, the period for consuming the enterprise's own power is determined by condition (1.5).

Next, it is advisable to use average values according to the formulas:

$$\begin{gathered} \int\limits_0^t W_0(t)dt=\bar{W}_0(t)\cdot t;\ \int\limits_t^{T_1} W_1(t)dt=\bar{W}_1(t;T_1)\cdot(T_1-t); \\ \int\limits_{T_1}^{T} W_1(t)dt=\bar{W}_1(T_1;T)\cdot(T-T_1);\ \int\limits_t^{T} W_1(t)dt=\bar{W}_1(t;T)\cdot(T-t). \end{gathered} \qquad (1.7)$$

According to (1.9), formula (1.5) is written as:

$$\bar{W}_0(t)\cdot t+\bar{W}_1(t;T)\cdot(T-t)=Q_0. \qquad (1.8)$$

Using (1.6), we find the period of consuming the enterprise's own power to provide condition (1.3):

$$t=\frac{Q_0-\bar{W}_1(t;T)\cdot T}{\bar{W}_0(t)-\bar{W}_1(t;T)}=t_0. \qquad (1.9)$$

It is clear that in this case, the following condition should be met:

$$\frac{Q_0-\bar{W}_1(t;T)\cdot T}{\bar{W}_0(t)-\bar{W}_1(t;T)}>0,$$

or

$$\bar{W}_0(t)>\bar{W}_1(t;T). \qquad (1.10)$$

Considering (1.9), formula (1.8) will take the form:

$$Z(t)=\begin{cases} c_0\cdot\bar{W}_0(t)\cdot t+c_1\cdot\bar{W}_1(t;T_1)\cdot(T_1-t)+c_2\cdot\bar{W}_1(T_1;T)\cdot(T-T_1), & 0\le t\le T_1 \\ c_0\cdot\bar{W}_0(t)\cdot t+c_2\cdot\bar{W}_1(t;T)\cdot(T-t), & T_1<t\le T \end{cases} \qquad (1.11)$$

Then, according to (1.9), the minimum cost of power for a given period $[0; T]$ is:

$$Z(t_0)=\begin{cases} c_0\cdot\bar{W}_0(t_0)\cdot t_0+c_1\cdot\bar{W}_1(t_0;T_1)\cdot(T_1-t_0)+c_2\cdot\bar{W}_1(T_1;T)\cdot(T-T_1), & 0\le t_0\le T_1 \\ c_0\cdot\bar{W}_0(t_0)\cdot t_0+c_2\cdot\bar{W}_1(t_0;T)\cdot(T-t_0), & T_1<t_0\le T \end{cases}. \quad (1.12)$$

Consider separately the case when:

$$\bar{W}_0(t)=\bar{W}_1(t;T). \quad (1.13)$$

Substituting (1.13) in (1.8), we find:

$$\bar{W}_0(t)\cdot T=Q_0. \quad (1.14)$$

According to (1.14), the amount of power consumption does not depend on the time of consuming the enterprise’s own power. In its turn, equation (1.14) allows you to calculate the active power to ensure a given amount of power consumption during $[0; T]$, according to the formula:

$$\bar{W}=\frac{Q_0}{T}. \quad (1.15)$$

Then, taking into account (1.14), the specific cost of power for a given period $[0;T]$ per unit of active power is recorded as:

$$\hat{Z}(t)=\begin{cases} (c_0-c_1)\cdot t+(c_1-c_2)\cdot T_1+c_2\cdot T, & 0\le t\le T_1 \\ (c_0-c_2)\cdot t+c_2\cdot T, & T_1<t\le T \end{cases}, \quad (1.16)$$

where $\hat{Z}(t)=\dfrac{Z(t)}{\bar{W}}$.

As an example, consider the following numerical calculations.

Let us have the following initial data:

$$Q_0=520;\ W_1=20;\ W_0=30;\ T=24;\ T_1=12;\ c_0=1;\ c_1=8;\ c_2=4. \quad (1.17)$$

Then, according to (1.9), we find the necessary time to consume the enterprise’s own power for a given volume of power consumption:

$$t_0=4. \quad (1.18)$$

According to (1.12), taking into account (1.18), the minimum cost of power for a given period $[0; T]$ is equal to:

$$Z(t_0=4)=2270. \quad (1.19)$$

Using the above formulas, it is possible to study the dependence of the cost of power consumed on the duration of consuming the enterprise’s own power. Fig. 1.15 shows a graph of this dependence.

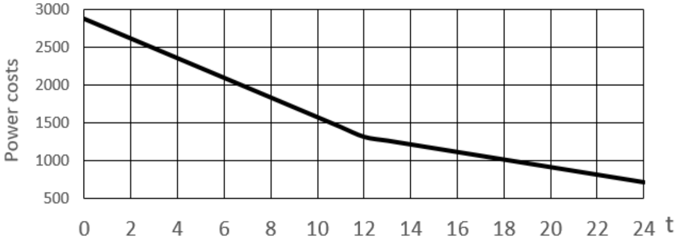


Figure 1.15 – Dependence of the cost of power consumed on the duration of consuming the enterprise’s own power

Analysis of the graph given in Fig. 1.15 shows that with an increase in the duration of power consumption due to the enterprise’s own potential, the cost of its consumption decreases. It should be emphasized that during \ transition from non-economic to economic periods (*t*=12) there is a break in the schedule, which is explained by a change in the cost of active power of electricity. In this case, the cost of active power of electricity in non-economic periods is greater than that in economic periods ($c_1 = 8 > c_2 = 4$). Further, after the break of the schedule, there is a lower rate of reduction in the cost of power consumed.

Figure 1.16 shows a dependence of the cost of power consumed on the volume of power consumption.

Analysis of the graph shows that with an increase in the consumption of the power generated by the enterprise itself, the cost of power consumed decreases.

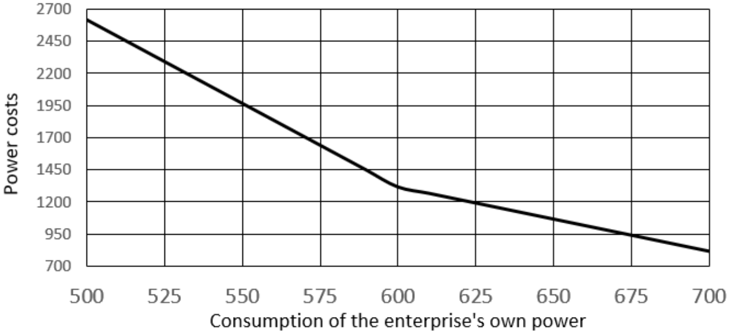


Figure 1.16 – Dependence of the cost of power consumed on the volume of the enterprise’s own power

Separately, it represents the case when the active power of electricity from external sources is equal to the active power of the enterprise's own electricity, i.e. (1.13). In this case, to ensure a given volume of power consumption during $\left[0;\,T\right]$, according to (1.14), the following active power of electricity is required:

$$\overline{W} = \frac{520}{24} = 21{,}67. \tag{1.20}$$

Figure 1.17 shows a dependence of the specific power cost on the period of consuming the enterprise's own power, calculated by (1.16). Analysis of the given graph indicates that with an increase in the duration of consumption of the enterprise's own power, the specific power cost decreases. Changes in the schedule are due to the above reasons, i.e. different costs of active power of electricity during non-economic and economic hours.

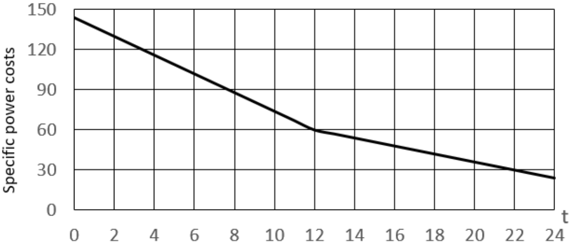


Figure 1.17 – Dependence of the specific cost of power consumed on the duration of consuming the enterprise's own power

CONCLUSIONS TO SECTION 1

1. It is confirmed that for the last 10-15 years, main water drainage facilities have been main power consumers among other energy-intensive consumers of national iron ore underground mines, in terms of volumes of power consumption. It is established that the percentage of power consumption by these types of receivers has been increasing over the years, and only over the past 5 years (until 2021), the average share of power consumption at the analyzed types of underground mines has increased to almost 37 %.

2. The conducted research suggests that simulation of evaluating corporate power consumption provides an opportunity to determine optimal time intervals with a minimum power cost. The authors summarize the data and propose an optimized synergistic model aimed at reducing costs of power consumed at different time intervals of the day. The obtained analytical ratios allow conducting an appropriate analysis of simulation results. The dependencies obtained provide the basis for studying the cost of power consumed on duration of power consumed and produced by the enterprise's own and external sources. Power produced by the enterprise allows reducing its cost, taking into account the operation technology adopted by a certain mining enterprise. Based on quantitative ratios of cost indices of power consumption resulted from the enterprise's own production and from external sources, it is advisable to use power produced by the enterprise itself during economic periods of the day, i.e. when the tariff is the highest. The period of time for consuming power generated by the enterprise is determined by the amount of power consumed. It is confirmed that consumption of the enterprise's own power can reduce the cost of power consumed by the enterprise. The cost of power consumed will be less if the enterprise consumes its own power at non-economic hours of the day, i.e. when the cost of active power is the highest. The period of consuming the enterprise's own power is determined by a given amount of power consumption during $\left[0;T\right]$. Thus, the use of corporate consumption allows to reduce the cost of electricity consumption by almost two times.

3. In order to optimize, rather than idealize the flow of energy efficiency improvements of main water drainage facilities of iron ore underground mines, it is necessary to consider that the biased but fundamental option of improving energy efficiency of the electromechanical system, including non-normative approaches to solving the energy efficiency

problem of main water drainage facilities, is a key point to achieve the final positive result of expected efficiency levels.

The main results of the research in this section are highlighted in the author's scientific works.

SECTION 2
STUDYING POWER CONSUMPTION BY MAIN WATER DRAINAGE FACILITIES AS A STOCHASTIC PROCESS

2.1 Objectives and general methodological principles of studying the process of power supply and consumption

When qualitatively assessing the state of the process of power consumption at mining enterprises, it is possible to identify its properties, advantages, degree of suitability, etc. The current level of electrification of mining production allows us to identify in a generalized way a number of properties of this process, the relevance of which is due to the increase in the efficiency of power use at mining enterprises. These properties undoubtedly include efficiency of power consumption.

Ensuring efficiency of power consumption requires the study of a number of problematic issues to identify new phenomena and on the basis of their analysis, synthesis and generalization, formulate regularities that interpret new facts obtained at the empirical level of knowledge in a deeper way, making forecast assessments of the development of power consumption at mining enterprises [1-7, 11-13, 15-32].

Industrial power consumption is characterized by consumption modes and power balances. In this regard, when studying power consumption of mining enterprises, it is advisable to establish regularities - relevant characteristics.

The process of power consumption at mining enterprises on a time scale can be characterized by variable, monthly and annual modes.

A set of dynamics of variable, monthly and annual power consumption has a close relationship between its components. Processes of power consumption at the analyzed time levels have a direction of action from the variable to the annual level. Changes in power consumption characteristics at lower time levels have a significant impact on the value and dynamics of power consumption at higher time levels.

In this regard, the study of power consumption in the temporal aspect should allow its assessment at the specified temporal levels.

The study contains a set of methods that investigate problematic issues of efficient power consumption at mining enterprises.

Increasing efficiency of power consumption at mining enterprises is inextricably linked to the problem of assessing power consumption modes, which is especially relevant due to the specifics of mining conditions. In this regard, it is advisable to put forward the following ideas:

1) Power consumption of mining enterprises depends on a large number of factors. The influence of factors on the power consumption process is complex and diverse, and its description within the framework of both deterministic and classical statistical methods is not always possible due to unpredictability of the conditions that determine the effect of factors. In this regard, it can be stated that the power consumption of mining enterprises is formed under the influence of factors, the prediction of the impact of which is not sufficiently reliable. A large number of different factors presents certain difficulties in assessing their impact on power consumption both in methodological and technical-economic aspects.

2) The information about the power consumption process contains various sets of empirical data and is characterized by multidimensional random features. A large number of features makes it difficult to identify relationships between them. In this case, it is necessary to describe the power consumption process by a smaller number of generalized characteristics that reflect internal objectively existing patterns not directly observable.

3) These features cause the need to use methods allowing us to obtain solutions in the conditions of random processes when assessing the states of power consumption modes of mining enterprises. In this case, the tasks of analyzing power consumption data arise, the solution of which is based on applying methods of the theory of random processes and establishing typology of the objects under study.

4) In this aspect, assessment of the power consumption state, despite the variety of analysis models, is based on the fact that in a survey or experiment, when the empirical material contains a large number of parameters, many of them are stochastic. This is because the observed ‘external’ parameters only indirectly characterize the power consumption process. Along with a large number of these ‘external’ parameters (factors), there is a small number of ‘internal’ (‘essential’) parameters that are difficult or impossible to measure, but which determine the behaviour of ‘external’ parameters.

Such parameters (factors) of the mining and technological group as depth of occurrence, size of deposits, temperature of rock masses, type of technology, parameters of stripping and development systems, types of machinery and equipment used, etc. affect power capacity and, accordingly, the cost of iron ore raw materials. Climatic and meteorological factors determine the seasonality of power consumption, forming an intra-annual trend in its change. Power factors - structural parameters of power circuits, the number, power, efficiency of electrical receivers, etc. - determine the formation of electrical load modes. Organizational and operational factors determine the degree of use of electrical receivers, the level of increased power losses due to deterioration of characteristics of power equipment, machinery and mechanisms.

Assessment of the states of the power consumption process under stochasticity determines power consumption modes, using the initial statistical information to obtain adequate mathematical models.

In this regard, it is advisable to consider the basic procedures for assessing the states of power consumption modes considering information compression.

A significant part of the technological electrical receivers of mining enterprises forms power modes that are heterogeneous in terms of probability distribution. In this case, probability distributions of values of features of the original statistical information and the transformed information about power consumption processes are polymodal. This circumstance introduces certain difficulties in modelling power consumption processes.

The use of power consumption statistics encourages a more thorough analysis of main provisions of statistics.

A statistical indicator is a generalized characteristic of a phenomenon or process that characterizes the entire set of research units and is used to analyses the set as a whole. With the help of statistical indicators, one of the main tasks of statistics is solved: the quantitative side of a phenomenon or process is determined in combination with the qualitative side. The quantitative side of an indicator is represented by a number with an appropriate unit of measurement to characterize: the size of phenomena, their levels, and ratios. The qualitative content of the indicator depends on the essence of the phenomenon (process) under study and is reflected in the name of the indicator.

According to the way they perform their functions, indicators reflect the volume of the phenomenon, its average level, intensity of manifestation, structure, change in time or comparability in space.

For statistical indicators to correctly characterize the phenomenon under consideration, the following requirements must be met:

1) to rely on statistical methodology and experience of statistical work in their construction;

2) to achieve completeness of statistical information both in terms of coverage of units of the object and in terms of comprehensive reflection of all aspects of the process under study;

3) to ensure comparison of statistical indicators due to the similarity of the source data in time and space;

4) to provide accuracy and reliability of the initial information for reliability of the content of the process under study.

When studying energy consumption, it is advisable to use the following static indicators:

– mean

$$\bar{y} = \frac{\sum y_i}{n}; \ \ \overline{x_i} = \frac{\sum x_{ij}}{n}$$

– dispersion

$$G_y^2 = \frac{\sum(y_i - \bar{y})^2}{n}; \quad G_{x_i}^2 = -\frac{\sum(x_{iy} - \bar{x})^2}{n};$$

– root-mean-square deviation

$$\sigma_y = \sqrt{\sigma_y^2}; \quad \sigma_{x_i} = \sqrt{\sigma_{x_i}^2};$$

– the standard error of the mean

$$\sigma_{\bar{y}} = \frac{1}{\sqrt{n}} \sigma_y; \quad \sigma_{x_i} = \frac{1}{\sqrt{n}} \sigma_{x_i};$$

– the variation coefficient

$$V_y = \frac{\bar{y}}{\sigma_y} * 100; \quad V_{x_i} = \frac{\overline{x_i}}{\sigma_{x_i}} * 100;$$

– asymmetry

$$A_y = \left\{ \frac{\sum(y_i - \bar{y})^3}{n} : \sqrt{\left[\frac{\sum(y_i - \bar{y})^2}{n}\right]^3} \right\} \frac{\sqrt{n(n-1)}}{n-2};$$

$$A_{x_i} = \left\{ \frac{\sum(x_i - \bar{x})^3}{n} : \sqrt{\left[\frac{\sum(x_i - \bar{x})^2}{n}\right]^3} \right\} \frac{\sqrt{n(n-1)}}{n-2};$$

– the standard error of asymetry

$$\sigma_E = \sqrt{\frac{6n \cdot (n-1)}{(n-2) \cdot (n+1) \cdot (n+3)}};$$

– excess

$$E_{x_i y} = \frac{n-1}{(n-1)(n-3)} \left[(n+1)\left(\frac{\mu_4}{\mu_2^2} - 3\right) + 6\right],$$

where, respectively

$$\mu_4 = \frac{\sum(x_i - \bar{x})^4}{n}; \ \mu_2 = \frac{\sum(x - \bar{x})^2}{n};$$

$$\mu_4 = \frac{\sum(y_i - \bar{y})^4}{n}; \ \mu_2 = \frac{\sum(y - \bar{y})^2}{n};$$

– the standard error of excess

$$\sigma_E = \frac{24n \cdot (n-1)^2}{(n-3)\cdot(n-2)\cdot(n+3)\cdot(n+5)}.$$

To identify and analyze power consumption processes at underground mines of Kryvyi Rih iron ore basin, a general statistical analysis is conducted using the Excel software (Tables 2.1, 2.2).

Table 2.1 – Input information on power consumption at underground mines of Kryvyi Rih iron ore basin

Year	Underground mine			
	Pokrovska	Kryvorizka	Kozatska	Ternivska
2014	41829.29	68037.22	43544.69	42161.45
2015	41783.45	69874.32	42983.44	44678.34
2016	42678.32	71673.54	43784.32	43784.35
2017	43673.34	45672.34	47673.55	45672.34

Dispersion is a measure of dispersing values of a random variable relative to the mean value of distribution. Larger dispersion values indicate greater deviations of random variable values from the center of the distribution.

The root-mean-square deviation of the arithmetic mean in mathematical statistics is a value that characterizes standard deviation of the sample mean calculated from a sample of the size of the general population. The term was first coined by Udney Yul in 1897. The value of the root-mean -square deviation of the arithmetic mean depends on the dispersion of the population and the sample size.

Table 2.2 - Descriptive statistics of input statistical information on power consumption

Indicator	Underground mines			
	Pokrovska	Kryvorizka	Kozatska	Ternivska
Mean	43247.99	65702.91	43897.76	43271.31
Standard error	721.45	4042.87	870.10	701.83
Median	42827.82	69166.24	43664.51	42972.90
Standard deviation	1767.18	9902.96	2131.31	1719.12
Sampling dispersion	3122924.49	98068648.27	4542485.34	2955389.66
Excess	2.88	5.63	2.52	-1.60
Asymmetry	1.62	-2.35	1.02	0.31
Interval	4762.77	26001.20	6492.22	4443.21
Minimum	41783.45	45672.34	41181.33	41229.13
Maximum	46546.22	71673.54	47673.55	45672.34
Amount	259487.93	394217.45	263386.55	259627.83

The sampling distribution of the sample mean is formed by repeating the experiments and recording the average obtained each time. This creates a distribution of different means, and this distribution has its own mean and dispersion. Mathematically, the dispersion of the resulting sample distribution is equal to the dispersion of the population divided by the sample size. This is because, as the sample size increases, the sample mean converges closer to the population mean.

Thus, the relationship between the standard deviation of the arithmetic mean and the standard deviation is such that for a given sample size, the standard deviation of the arithmetic mean is equal to the standard deviation divided by the square root of the sample size. In other words, the standard deviation of the arithmetic mean is a measure of dispersion of sample means around the center of the population distribution.

The standard deviation of the arithmetic mean is sometimes called the ‘standard error’. These terms are ambiguous and are not recommended as likely to lead to confusion.

The excess coefficient is a numerical characteristic of the probability distribution of a real random variable. The excess coefficient characterizes the ‘steepness’, i.e. the rapidity of the distribution curve as compared to the normal curve.

In case of a heterogeneous power mode of electrical receivers (with a polymodal distribution of electrical load values), it is advisable to model the power consumption process by introducing stable levels from the entire area of load change, about the average values of which vary separately with a certain degree of dispersion.

Thus, we can assert that power consumption by individual enterprises, namely underground mines in Kryvyi Rih region, is stochastic.

2.2 Experimental studies of the power consumption process

According to the nature of the distribution characterizing power consumption, the compliance of the process with stochasticity is established.

Random variables are widely used in solving various practical problems. A random variable is characterized by the fact that it takes on a single, unknown, but unique value as a result of experience.

Limiting the consideration by individual random variables, a random phenomenon is studied as if ‘in static’, in such fixed constant conditions of individual experience.

However, this approach to studying random phenomena in a number of practical problems is clearly insufficient. In practice, you have to deal with random variables that are constantly changing in the course of experience.

The study of power consumption at mining enterprises takes into account monthly and annual power consumption at variable levels. In this case, the analysis requires a time series of power consumption compiled from statistical data.

In order to identify the stochastic process of power consumption, the most energy-intensive components at iron ore mining enterprises are studied and identified [11-13]. This analysis is based on principles of system analysis. It is found that such components are water drainage facilities, ventilation units, skip hoists, and a crushing and sorting plant (CSP). Fig. 2.1 - 2.4 show power consumption at selected system components for each enterprise.

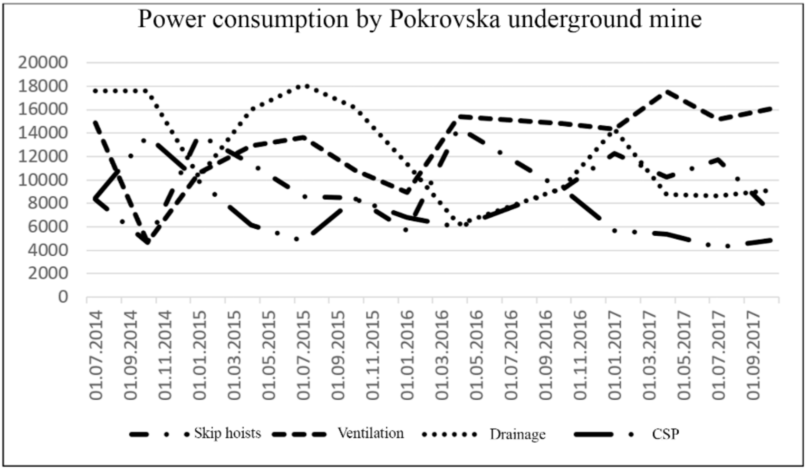


Figure 2.1 – Power consumption by Pokrovska underground mine

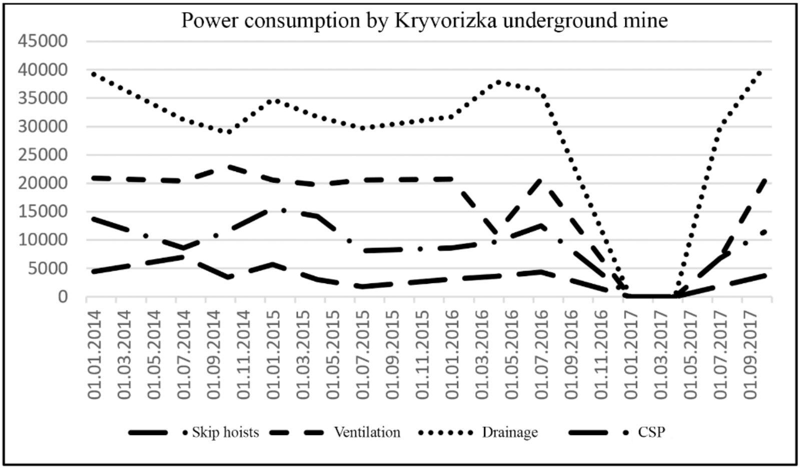


Figure 2.2 – Power consumption by Kryvokizka underground mine

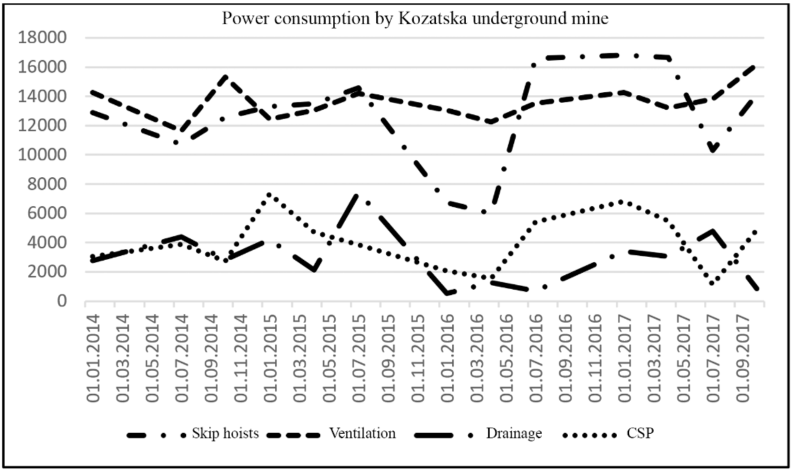


Figure 2.3 – Power consumption by Kozatska underground mine

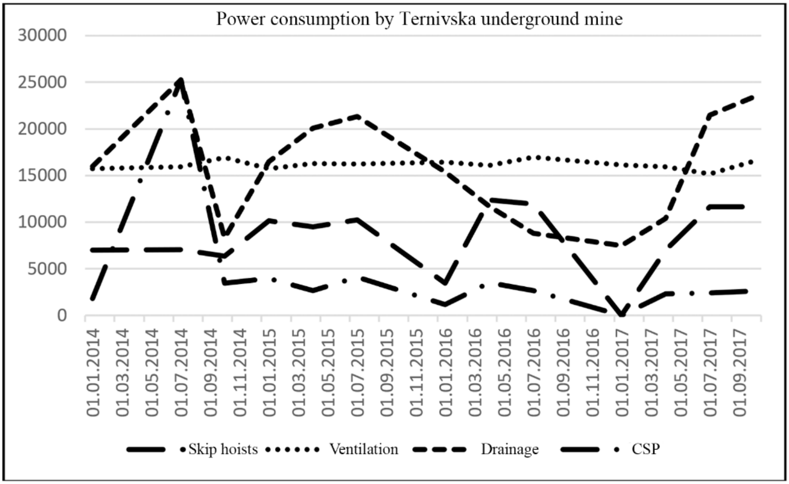


Figure 2.4 – Power consumption by Ternivska underground mine

A visual analysis of the provided time curves gives grounds to assert that the processes of power consumption by skip lifts, ventilation units and CSP are random. The stochastic nature of the process is explained by technological features of iron ore mining.

All processes observed and characterizing phenomena in general are classified in the most general way as deterministic and non-deterministic.

Deterministic processes are those that can be described by precise mathematical relations.

Non-deterministic processes are those that cannot be described by precise mathematical relations. It is impossible to predict the exact value of such a process at some point in the future. By their nature, these processes are not described by exact equations, but by random functions and statistical models.

When solving specific problems, it is necessary to remember that in practice, the decision on the deterministic or random nature of a process is usually made on the basis of the possibility or impossibility of reproducing it under given conditions. If multiple repetition of an experience produces the same results (within the measurement error), then, in general, there are reasons to consider the process deterministic. If the repetition of experience in identical conditions leads to a different result, then the nature of the process is random.

Experimental studies of power consumption, for the purpose of their further analysis, are based on the following provisions. Observable features that determine the process of power consumption are random variables, which implies appropriate planning of the experiment (survey), taking into account the sampling method. Among the main issues that arise in this case are formation of sampling frames and the determination of the number of members (number of observations) of samples.

The number of sample members is determined as in the case of an actual random repeated sample:

$$\eta = \frac{t^2 \delta_0^2}{\Delta^2},$$

where *t* is the value of a random variable.

Δ is the marginal sampling error characterized by the largest deviation of the sample mean from the general mean at a given probability.

There are recommendations on the number of measurements (observations) in studying power consumption. According to these recommendations, the accuracy in determining the calculated values should be within ±10%. In individual experimental studies, when dispersion is determined by statistical processing of the measurements, the recommended value of the relative error (± 15%) gives a tolerance of the designed load value of only 3+15%.

On the basis of statistical information, the relevant statistical characteristics of the indicated components of power consumption by iron ore mining enterprises are calculated.

A continuous random process is a process in which the argument *t* and the random function *x(t)* can take values on a segment or on the entire axis.

Accordingly, the calculated statistical characteristics using Excel software are presented in Table 2.3 - 2.6.

Table 2.3 – Statistical indicators of power consumption components at Pokrovska underground mine

Indicators	Skip hoists	Ventilation	Drainage	CSP
Mean	9698.077	12802.67	12577	7392.833
Standard error	825.2093	1016.629	1161.515	775.8809
Median	9148	13975.5	11362	6455
Mode	–	–	–	–
Standard deviation	2975.334	3521.707	4187.901	2687.73

Sample dispersion	8852615	12402420	17538514	7223894
Excess	-0.69336	1.395145	-1.70323	1.5053
Asymmetry	-0.01005	-1.14441	0.072024	1.189276
Interval	9800	12909	11918	9461
Minimum	4657	4657	6208	4264
Maximum	14457	17566	18126	13725
Amount	126075	153632	163501	88714

Table 2.4 – Statistical indicators of power consumption components at Kozatska underground mine

Indicators	Skip hoists	Ventilation	Drainage	CSP
Mean	12670,31	13626,31	2950,692	4066,846
Standard error	963,4267	345,2778	545,8176	536,6554
Median	13292	13534	2823	3880
Mode	–	–	–	–
Standard deviation	3473,684	1244,917	1967,974	1934,939
Sample dispersion	12066483	1549818	3872920	3743988
Excess	-0,04257	0,220913	0,830259	-0,85514
Asymmetry	-0,76507	0,470049	0,803559	0,112745
Interval	10826	4548	6927	6190
Minimum	5979	11625	526	1125
Maximum	16805	16173	7453	7315
Amount	164714	177142	38359	52869

Table 2.5 – Statistical indicators of power consumption components at Kryvorizka underground mine

Indicators	Skip hoists	Ventilation	Drainage	CSP
Mean	9293.538	15770.08	28610.77	3244.615
Standard error	1348.895	2308.19	3675.394	554.1602
Median	9696	20398	31733	3464
Mode	–	–	–	–
Standard deviation	4863.511	8322.297	13251.82	1998.053
Sample dispersion	23653743	69260620	1.76E+08	3992215
Excess	0.404605	0.022119	2.271752	0.058976
Asymmetry	-0.96056	-1.26843	-1.79113	-0.05016
Interval	15528	22964	40686	6970
Minimum	0	0	0	0
Maximum	15528	22964	40686	6970
Amount	120816	205011	371940	42180

Table 2.6 – Statistical indicators of power consumption components at Ternivska underground mine

Indicators	Skip hoists	Ventilation	Drainage	CSP
Mean	8458.417	16163.23	15850.25	4311.692
Standard error	1100.795	136.0387	1843.844	1773.009
Median	9844	16154	15948	2670
Mode	–	–	–	–
Standard deviation	3813.264	490.4945	6387.263	6392.675
Sample dispersion	14540983	240584.9	40797127	40866293
Excess	0.71787	0.164116	-1.66354	11.99727
Asymmetry	-1.11027	-0.05756	0.038325	3.403832
Interval	12376	1765	17771	25254
Minimum	0	15197	7483	0
Maximum	12376	16962	25254	25254
Amount	101501	210122	190203	56052

As you can see, a random function combines the features of a random variable and a function. If you fix the value of the argument, it turns into a regular random variable; as a result of each research, it is transformed into a regular (non-random) function.

Generally speaking, a random function can be characterized to some extent by specifying an ensemble of realizations, the law of distribution, and probability characteristics. The set of realizations of a random function characterizes its properties to some extent. However, just as a variation series only approximately characterizes a random variable, so a set of realizations of a random function can characterize its properties only to a certain degree of approximation.

Probabilistic characteristics such as mathematical expectation, dispersion, correlation function, spectral density characterize random processes with quite acceptable reliability for practical use.

In our opinion, it is advisable to analyze the clustering of power consumption by the components of an iron ore mining enterprise.

The measure of closeness is the within-group sum of squared deviations between each image and the cluster average. The quality of clustering is ensured by minimizing the selected proximity measure.

$$y = \sum_{i=1}^{n} \sum_{x \epsilon pj} \left\| x - m_i \right\|^2 = \min$$

where n is the number of clusters;

P_i is the set of images included in the i-th cluster;

X is the electrical load measurement vector;

m_i is the vector of sample averages for the set P_i.

Clustering of power consumption according to the above scheme allows you to get many stable consumption levels and their duration $t_{\text{п}}$:

$P=\{P_1,P_2,\ldots,P_n\}$

$t=\{t_1,t_2,\ldots,t_n\}$

The analysis of power consumption changes the traditional view of the nature of power consumption distribution in the form of a normal distribution, which is the basis of calculation methods. Therefore, we consider it appropriate to study the processes of power consumption as random. In connection with the non-traditional consideration, it is necessary to analyze general definitions of the values used in the calculations.

For power consumption for the analyzed period (for example, a shift), the calculation can be written as:

$$P_c \cdot t_{3M} = \sum_{i=1}^{n} P_i \cdot t_i$$

where P_c is the average load per shift t_{shift}.

By roughly dividing the left and right parts into $P_{\text{nom}}\ t_{\text{3M}}$, entering the notation:

$P_\mathrm{c} = P_\mathrm{c} / P_{\text{ном}}$; $P_i^* = P_i / P_{\text{ном}}; t_i^* = t_i / t_{CM}; K_r = P_i^* / P_i, (r = 2,3...,n)$

and taking P* as the maximum load level, we have:

$$P_c^* = P_1^* \cdot t_1^* + K_2 \cdot P_1^*(1 - \sum_{t=1t\neq 2}^{n} t_i) + \ldots + K_n \cdot P_1^*(1 - \sum_{t=1t\neq 2}^{n} t_i)$$

or

$$P_c^* = P_1\left[t_1 + \sum_{r=2}^{n} Kr \cdot P_1^*(1 - \sum_{t=1i\neq r}^{n} t_i \right] \cdot$$

The resulting expression allows us to describe power consumption for components with a heterogeneous nature of operation as a random process.

The described procedures make it possible to implement the basic ideas about the process of power consumption, which are accepted in the research and assessment of its states as a random process.

Thus, the research conducted make it possible to establish patterns of power consumption and calculate relevant statistical indicators. This allows us to analyze the procedures enabling to use statistical information to the fullest extent possible in conditions of low information content to obtain an adequate description of the process of electricity consumption. We can also build mathematical models that should have optimal properties that minimize the root mean square error when describing real processes, as well as reduce the degree of uncertainty under which the mathematical description is carried out.

2.3 Formatting a practical option of building a stochastic model of the water drainage process

As noted in the first section of this research, ancillary works are of great importance in iron ore underground mining to ensure the support of the mining process and the necessary working conditions, especially in terms of safety. Among the auxiliary works, it is natural to single out water drainage from underground horizons, which is most important in underground operations.

As a result, digital support for this process is of great importance in today's environment. Available methods for calculating water drainage characteristics are not accurate enough, as the calculations are based on average values without taking into account stochasticity of the processes. Considering stochasticity through mathematical modeling of water drainage using IT technologies makes it possible to improve calculation of its characteristics in iron ore mining. As an example, we consider mathematical modeling of water drainage at Ternivska mine in the Kryvyi Rih iron ore basin.

Analysis of publications shows that in order to increase iron ore production, it is necessary to carefully consider the specifics of auxiliary operations [1]. In recent years, Ukrainian iron ore enterprises have been experiencing a decline in productivity, which is primarily due to the complication of iron ore mining conditions [2]. The issues related to the decline in iron ore production can be resolved by developing digital methods to support auxiliary operations based on the use of modern IT technologies. This process is complicated by the fact that today the methods for calculating properties of auxiliary works in iron ore mining are outdated and far from perfect [3].

In order to eliminate the negative aspects in the methods of assessing properties of auxiliary works in iron ore mining, Ukraine is experiencing a revival of activity [4]. At the same time, there are shortcomings related to the specifics of auxiliary works in iron ore mining. This is especially true for such auxiliary works that are stochastic in nature [5]. It is clear that the assessment of features of auxiliary work, according to old methods, by average indicators does not meet modern requirements for the quality of calculations and requires new approaches. One of the important types of auxiliary works is water drainage [6].

As one of possible approaches, we propose mathematical modeling of auxiliary works on iron ore mining, in particular, water drainage, as stochastic processes in order to take into account their peculiarities.

Iron ore mining, especially underground mining, requires auxiliary operations. These works are related to ensuring conditions that allow for efficient and safe extraction of minerals. It is clear that we can cite a fairly extensive list of these works. At the same time, in accordance with the task, it seems important to highlight the work associated with the need to pump water from underground mine horizons. In practice, such works are called water drainage [7].

It should be emphasized that water drainage is quite significant in total costs of iron ore production.

However, in the authors' opinion, the ideology of the research structure development, the results of which are presented in this paper, should consider the rate of water accumulation in underground reservoirs as the main indicator (Fig. 2.5).

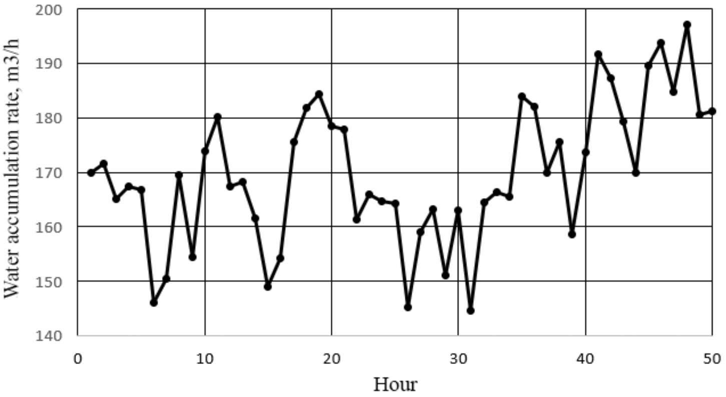


Figure 2.5 – Water accumulation rates in the underground reservoir of a standard iron ore underground mine (Kryvyi Rih)

As a result, it is of great importance to digitally track technological processes related to water drainage, which can be carried out by mathematical modeling using IT technologies [8]. To this end, let us consider building a mathematical model of water drainage. To do this, we apply the law of conservation of energy. To pump water from the underground horizon of a mine, it is necessary to perform elementary work [9]:

$$da = g \cdot h \cdot dm, \qquad (2.1)$$

where dm is the element of water mass, kg;
g is free fall acceleration, m/s^2;
h is the depth from which water is pumped, m.

If the volume of water is taken into account, then formula (2.1) takes the form:

$$da = \rho \cdot g \cdot h \cdot du, \qquad (2.2)$$

where ρ is water density, kg/m^3;
du is the element of water volume, m^3.

To convert energy to kW*h, we use the coefficient δ = 2.78·10-7 kWh/J. Then formula (2) will take the form:

$$da = \rho \cdot g \cdot h \cdot \delta \cdot du\,. \qquad (2.3)$$

In turn, taking into account the values of $\rho = 10^3$ kg/m^3 and $g = 9{,}8$ m/s^2 , formula (2.3) takes the form:

$$da = \beta \cdot h \cdot du\ , \qquad (2.4)$$

where $\beta = \rho \cdot g \cdot \delta = 0{,}002724$ H/m^3.

Formula (2.4) allows us to calculate the work required to lift an element of water volume du to a height h.

Considering that

$$du = v(t)dt\,,$$

where $v(t)$ is the rate of water accumulation at time t, m^3/h.

formula (2.4) will take the form:

$$da = \beta \cdot h \cdot v(t)dt\,. \qquad (2.5)$$

Then the dependence of power consumption on lifting water is determined by the formula:

$$n(t) = \beta \cdot h \cdot v(t)\,, \qquad (2.6)$$

where $n(t)=\dfrac{da(t)}{dt}$ is power, kW.

At the same time, it should be emphasized that in real conditions, the rate of water accumulation in the underground horizon of a mine is a stochastic function, since at each moment of time it is caused by different unknown reasons [10]. As a result, the power consumption required to provide water drainage will also be a random function. As a result, formula (2.6) will take the form:

$$N(t)=\beta\cdot h\cdot V(t), \tag{2.7}$$

where $V(t)$ is the random rate of water accumulation at time t, m^3/h,

$N(t)$ is the random power at time *t*, kW.

Let us say that the analysis of the water accumulation rate as a stochastic function allowed us to determine its numerical characteristics, such as the mean $\bar{v}(t)$ and dispersion $D(V(t))$. Then, according to formula (2.7), we have the following numerical characteristics of power as a stochastic function:

mean $\bar{n}(t)=\beta\cdot h\cdot\bar{v}(t)$ and dispersion

$$D\left[N(t)\right]=\beta^2\cdot h^2\cdot D\left[V(t)\right]. \tag{2.8}$$

The obtained results make it possible to consider the stochastic nature of changes in the rate of water accumulation in the underground mine horizon when calculating power consumption for water drainage from a given depth of the underground horizon. Thus, in order to characterize power consumption for drainage from a given depth of the underground mine horizon, it is necessary to take into account not only its average value but also dispersion.

In practice, questions arise related to the need to calculate the volume of accumulated water in the underground horizon of the mine for a given period of time, i.e. to calculate the integral of the water accumulation rate as a stochastic function

$$U(T)=\int_0^T V(t)dt, \tag{2.9}$$

where $\left[0;T\right]$ is the set period of water accumulation, hours.

In this case, the existence of a correlation function of the stochastic function $V(t)$, which we denote by [11], is necessary:

$$K_v(t',t''). \tag{2.10}$$

For integral (2.9) to exist in a given area of the upper boundary *T*, a double integral must exist in the same area:

$$\int_0^T\int_0^T K_v(t',t'')dt'dt''. \tag{2.11}$$

Assuming that the condition for the integral (2.11) existence is fulfilled, we determine the correlation function of the stochastic function (2.10):

$$K_u(t_1,t_2)=M\Big[\big(U(t_1)-M[U(t_1)]\big)\big(U(t_2)-M[U(t_2)]\big)\Big]=$$
$$=M\left[\int_0^{t_1}\int_0^{t_2}\big(V(t')-M[V(t')]\big)\big(V(t'')-M[V(t'')]\big)dt'dt''\right],$$

where $M[\cdot]$ is mathematical expectation.

By swapping the operations of integration and finding the mathematical expectation, we obtain:

$$K_u(t_1,t_2)=\int_0^{t_1}\int_0^{t_2} K_v(t',t'')dt'dt''. \tag{2.12}$$

In a special case, when the subintegral function in (2.9) is stationary, formula (2.12) takes the form [12]:

$$K_u(t_1,t_2)=\int_0^{t_1}\int_0^{t_2} K_v(t''-t')dt'dt''. \tag{2.13}$$

At the same time, the dependence of the subintegral function on the difference of variables allows you to get rid of the double integral, i.e. to simplify the calculations:

$$K_u(t_1,t_2)=\int_0^{t_2}(t_2-\tau)K_v(\tau)d\tau+\int_0^{t_1}(t_1-\tau)K_v(\tau)d\tau-\int_0^{t_2-t_1}(t_2-t_1-\tau)K_v(\tau)d\tau. \tag{2.14}$$

In particular, if $t_1=t_2=T$, formula (2.14) will determine the dispersion of integral (2.9):

$$D[U(T)]=2\int_0^T(T-\tau)K_v(\tau)d\tau, \tag{2.15}$$

and the standard deviation, taking into account (2.15), is determined by the formula:

$$\sigma[U(T)] = \sqrt{2} \cdot \sqrt{\int_0^T (T-\tau) K_v(\tau) d\tau} \cdot \tag{2.16}$$

In turn, when integrating the stochastic function (9), we apply the operation of finding the mathematical expectation to both parts of the equality:

$$M[U(T)] = M\left[\int_0^T V(t)dt\right].$$

Let us swap the operations of finding the mathematical expectation and integration:

$$M[U(T)] = \int_0^T M[V(t)]dt,$$

then

$$\bar{u}(T) = \int_0^T \bar{v}(t)dt. \tag{2.17}$$

The mathematical expectation of an integral of a stochastic function is equal to the integral of the mathematical expectation of that function. Thus, considering the water accumulation rate as a stochastic function, in particular, the use of its correlation function, allows us to determine such numerical characteristics of calculating the volume of accumulated water in the underground mine horizon for a given period of time as the mathematical expectation and standard deviation.

In its turn, in practice, questions arise related to the need to calculate the amount of power consumption for water drainage from a given depth of the underground mine horizon for a given period of time, i.e. to calculate the integral of the power for water drainage as a stochastic function:

$$A(T) = \int_0^T N(t)dt, \tag{2.18}$$

where $[0;T]$ is set period of water accumulation, hours.

If we use formulas (2.7) and (2.9), formula (2.18) will take the form:

$$A(T) = \beta \cdot h \cdot U(T) .$$

Considering the results obtained above for the integral (2.9), it is possible to write down the numerical characteristics for power consumption for water drainage from a given depth of the underground mine horizon for a certain period of time as a stochastic function. According to formula (2.17), the mathematical expectation of the amount of power consumption for water drainage from a given depth of the underground mine horizon for a certain period of time is written in the form:

$$\bar{a}(T)=\beta\cdot h\cdot\bar{u}(T)\,. \tag{2.19}$$

In turn, the dispersion of power consumption for such a water drainage system over a certain period of time will be written in the form:

$$D\left[A(T)\right]=2\beta^{2}\cdot h^{2}\cdot\int_{0}^{T}\left(T-\tau\right)K_{v}(\tau)d\tau\,, \tag{2.20}$$

and the standard deviation will take the form:

$$\sigma\left[A(T)\right]=\beta\cdot h\cdot\sqrt{2}\sqrt{\int_{0}^{T}\left(T-\tau\right)K_{v}(\tau)d\tau}\,. \tag{2.21}$$

The results obtained in the course of the research allow us to take into account the stochastic nature of changes in the water accumulation rate in the underground horizon of the mine when calculating power consumption, the volume of water accumulation and power consumption for water drainage from a given depth of the underground horizon of the mine for a given period of time. It is shown that in order to characterize power consumption, water accumulation, and power consumption for water drainage from a given depth of the underground mine horizon over a given period of time, it is necessary to take into account not only their average values but also standard deviations characterizing their spread.

If the water accumulation rate in the underground level of a mine is a normal stochastic process, then the power consumption for drainage from this horizon will also be a normal stochastic process, the properties of which are completely determined by its mean and dispersion [13]. To do this, it is enough to use the appropriate normal probability densities. Thus, for power consumption of water drainage from the underground level of the mine, taking into account (8), the probability density, is as follows:

$$f\left(n(t)\right)=\frac{1}{\beta\cdot h\cdot\sqrt{2\pi}\cdot\sigma\left[V(t)\right]}e^{-\frac{\left(n(t)-\beta\cdot h\cdot\bar{v}(t)\right)^{2}}{2\cdot\beta^{2}\cdot h^{2}\cdot D\left[V(t)\right]}}\,. \tag{2.22}$$

It should be noted that the stochasticity of power consumption for water drainage from the underground mine level makes it possible to solve the ‘emission problem’ [14]. If we assume that the process under study is stationary, then the formulas for the ‘emission problem’ are written as follows: the average time a random function stays above a given level for a given period of time, the average number of emissions during the same time, and the average duration of an emission, respectively,

$$\overline{t_a} = T \cdot \int_a^{\infty} f(n)dn, \tag{2.23}$$

$$\overline{m}_a = T \cdot \int_0^{\infty} w \cdot f(a,w)dw, \tag{2.24}$$

$$\overline{\tau}_a = \frac{\int_a^{\infty} f(n)dn}{\int_0^{\infty} w \cdot f(a,w)dw}, \tag{2.25}$$

where $w = \dfrac{dn}{dt}$ is the rate of change of power consumption for water drainage from the underground mine level, kW*h;

$f(n)$ is probability density of distributing power ordinates of power consumption for water drainage from the underground level of the mine;

$f(n,w)$ is two-dimensional probability density of distribution of power ordinates of power consumption for water drainage from the underground level of the mine and their velocities.

Next, it is advisable to consider the average number of emissions per unit of time:

$$\overline{v}_a = \frac{\overline{m}_a}{T}, \tag{2.26}$$

or according to (2.24),

$$\overline{v}_a = \int_0^{\infty} w \cdot f(a,w)dw \cdot \tag{2.27}$$

For a normal stationary stochastic process, the probability density of the power consumption for drainage from the underground mine horizon, according to (2.22), is as follows:

$$f(n) = \frac{1}{\beta \cdot h \cdot \sqrt{2\pi} \cdot \sigma_n} e^{-\frac{(n-\overline{n})^2}{2 \cdot \sigma_n^2}}, \tag{2.28}$$

де $\sigma_n = \beta \cdot h \cdot \sigma[V]$,
$\bar{n} = \beta \cdot h \cdot \bar{v}$.

The power ordinate of power consumption for water drainage from the underground mine level and its rate of change are independent values. The two-dimensional probability density of distributing power ordinates of power consumption for water drainage from the underground mine level and their rates decomposes into the product of the normal probability density of power ordinates of power consumption for water drainage from the underground mine level and the normal probability density of the change rate of the power ordinate of power consumption, that enabling to write:

$$f(n,w) = \frac{1}{\sqrt{2\pi} \cdot \sigma_n} e^{-\frac{(n-\bar{n})^2}{2\cdot\sigma_n^2}} \cdot \frac{1}{\sqrt{2\pi} \cdot \sigma_w} e^{-\frac{(w-\bar{w})^2}{2\cdot\sigma_w^2}}, \quad (2.29)$$

where σ_w is the standard deviation of the change rate of the ordinate of power consumption for water drainage from the underground mine level;

$\bar{w}$ is the average change rate of the ordinate of power consumption for water drainage from the underground mine level.

The dispersion of the change rate of the power consumption ordinate for water drainage from the underground mine level is calculated by the formula:

$$\sigma_w^2 = \left| \frac{d^2 K_n(\tau)}{d\tau^2} \Big|_{\tau=0} \right|. \quad (2.30)$$

At the same time, due to stationarity of the random process, the average change rate of the power consumption ordinate for water drainage from the underground mine level is zero:

$$\bar{w} = 0. \quad (2.31)$$

For the average number of emissions per unit of time, substituting (2.29) into (2.27), taking into account (2.31), gives the formula:

$$\bar{v}_a = \int_0^\infty w \cdot \frac{1}{\sqrt{2\pi} \cdot \sigma_n} e^{-\frac{(a-\bar{n})^2}{2\cdot\sigma_n^2}} \cdot \frac{1}{\sqrt{2\pi} \cdot \sigma_w} e^{-\frac{w^2}{2\cdot\sigma_w^2}} dw \cdot \quad (2.32)$$

We take the constant terms out of the integral sign in (2.32):

$$\bar{v}_a = \frac{\sigma_w}{2\pi \cdot \sigma_n} e^{-\frac{(a-\bar{n})^2}{2\cdot\sigma_n^2}} \cdot \int_0^\infty \frac{w}{\sigma_w} e^{-\frac{w^2}{2\cdot\sigma_w^2}} dw \cdot \quad (2.33)$$

Using the variable substitution, we calculate the integral in (2.33):

$$\int_0^{\infty} \frac{w}{\sigma_w} e^{-\frac{w^2}{2\cdot\sigma_w^2}} dw = \left| \begin{array}{l} x = -\dfrac{w^2}{2\cdot\sigma_w^2} \quad dx = -\dfrac{w}{\sigma_w^2} dw \\ w = 0 \to x = 0 \\ w = \infty \to x = -\infty \end{array} \right| = -\sigma_w \cdot \int_0^{-\infty} e^x dx = \sigma_w \cdot e^x \Big|_{-\infty}^{0} = \sigma_w \, . \quad (2.34)$$

Substituting (2.34) into (2.33), we finally find:

$$\overline{\nu}_a = \frac{\sigma_w}{2\pi \cdot \sigma_n} e^{-\frac{(a-\overline{n})^2}{2\cdot\sigma_n^2}} . \quad (2.35)$$

The average duration of the emission is found by substituting (2.35) into (2.25),

$$\overline{\tau}_a = \pi \frac{\sigma_n}{\sigma_w} e^{\frac{(a-\overline{n})^2}{2\cdot\sigma_n^2}} \int_a^{\infty} f(n) dn \cdot \quad (2.36)$$

Taking into account (2.28), we find:

$$\overline{\tau}_a = \pi \frac{\sigma_n}{\sigma_w} e^{\frac{(a-\overline{n})^2}{2\cdot\sigma_n^2}} \int_a^{\infty} \frac{1}{\sqrt{2\pi} \cdot \sigma_n} e^{-\frac{(n-\overline{n})^2}{2\cdot\sigma_n^2}} dn \cdot \quad (2.37)$$

To calculate the integral in (2.37), we use the Laplace function [14]:

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^{x} e^{-\frac{t^2}{2}} dt \cdot \quad (2.38)$$

We replace the variable in (2.37):

$$\int_a^{\infty} \frac{1}{\sqrt{2\pi} \cdot \sigma_n} e^{-\frac{(n-\overline{n})^2}{2\cdot\sigma_n^2}} dn = \left| \begin{array}{l} x = \dfrac{n-\overline{n}}{\sigma_n} \quad dx = \dfrac{1}{\sigma_n} dn \\ n = a \to x = \dfrac{a-\overline{n}}{\sigma_n} \\ n = \infty \to x = \infty \end{array} \right| = \frac{1}{\sqrt{2\pi}} \int_{\frac{a-\overline{n}}{\sigma_n}}^{\infty} e^{-\frac{x^2}{2}} dx \, . \quad (2.39)$$

We use the integral linearity over the integration interval:

$$\frac{1}{\sqrt{2\pi}} \int_{\frac{a-\overline{n}}{\sigma_n}}^{\infty} e^{-\frac{x^2}{2}} dx = \frac{1}{\sqrt{2\pi}} \int_{\frac{a-\overline{n}}{\sigma_n}}^{0} e^{-\frac{x^2}{2}} dx + \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-\frac{x^2}{2}} dx = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-\frac{x^2}{2}} dx - \frac{1}{\sqrt{2\pi}} \int_0^{\frac{a-\overline{n}}{\sigma_n}} e^{-\frac{x^2}{2}} dx \quad (2.40)$$

According to (2.40), integral (2.39) is written in the form:

$$\int_a^{\infty} \frac{1}{\sqrt{2\pi} \cdot \sigma_n} e^{-\frac{(n-\overline{n})^2}{2\cdot\sigma_n^2}} dn = \Phi(\infty) - \Phi\left(\frac{a-\overline{n}}{\sigma_n}\right) = \frac{1}{2} - \Phi\left(\frac{a-\overline{n}}{\sigma_n}\right) \quad (2.41)$$

Taking into account (2.41), formula (2.37) is written in the form:

$$\overline{\tau}_a = \pi \frac{\sigma_n}{\sigma_w} e^{-\frac{(a-\overline{n})^2}{2\cdot\sigma_n^2}} \left(\frac{1}{2} - \Phi\left(\frac{a-\overline{n}}{\sigma_n}\right)\right). \qquad (2.42)$$

We note that the issue is considered when the average value deviates, i.e:

$$a = \overline{n},$$

formula (42) is simplified and takes the form:

$$\overline{\tau}_a = \frac{\pi}{2}\frac{\sigma_n}{\sigma_w}. \qquad (2.43)$$

The operation of integrating a stochastic function is reduced to summing the ordinates of the stochastic function and then moving to the boundary. On the other hand, from the general course of probability theory, it is known that the sum of any number of terms forming a system of normal values gives a normal value. Therefore, it can be argued that the integral of a normal stochastic process is also a normal process that can be fully characterized by its mathematical expectation and correlation function, since it is set by the normal probability density, which is fully determined by the mathematical expectation and standard deviation.

Thus, if the rate of water accumulation at the underground mine level is a normal stochastic process, the volume of water accumulation and the amount of power consumption for water drainage from this level will also be normal stochastic processes, the properties of which are completely determined by their mathematical expectations and variances. Thus, for the amount of water accumulation at the underground mine level over a certain time, the probability density has the form:

$$f(u(T)) = \frac{1}{\sqrt{2\pi}\sqrt{\int\limits_0^T (T-\tau)K_v(\tau)d\tau}} e^{-\frac{(u-\overline{u}(T))^2}{4\int_0^T (T-\tau)K_v(\tau)d\tau}}. \qquad (2.44)$$

In turn, for power consumption for water drainage from the underground mine level, the probability density has the form:

$$f(a(T)) = \frac{1}{\beta\cdot h\cdot\sqrt{2\pi}\sqrt{\int\limits_0^T (T-\tau)\cdot K_v(\tau)d\tau}} e^{-\frac{(u-\beta\cdot h\cdot\overline{u}(T))^2}{4\beta^2\cdot h^2\cdot\int_0^T (T-\tau)\cdot K_v(\tau)d\tau}}. \qquad (2.45)$$

As an example of modeling water drainage as a stochastic process, let us consider Ternivska underground mine in Kryvyi Rih iron ore basin. Fig. 2.5 shows the water accumulation rate on the 1000 m mine level over 50 hours (the first part of the implementation in 100 hours). Analysis of the graph in Fig. 2.5 indicates the water accumulation rate being a stochastic process. The average water accumulation rate over a certain period of time (100 hours) is as follows:

$$\bar{v} = \frac{1}{100}\sum_{i=1}^{100} v_i = 170 \text{ м}^3/\text{год}. \qquad (2.46)$$

The dispersion is equal to:

$$D[V] = \frac{1}{99}\sum_{i=1}^{100} (v_i - \bar{v})^2 = 196 \ (\text{м}^3/\text{год})^2. \qquad (2.47)$$

To check the normality of the stochastic process of the water accumulation rate at the 1000m mine level, the Pearson criterion is applied [16], with relevant calculations made and presented in Table. 2.6.

Table 2.6 – Input data on the water accumulation rate

#	Rate interval	Average rate	Empirical frequencies of falling into the interval	Probability of falling into the interval	Theoretical frequencies of falling into the interval	Discrepancy between theoretical and empirical frequencies
1	138-145	141.5	1	0.03	3	0.98
2	145-152	148.5	2	0.06	6	2.86
3	152-159	155.5	7	0.12	12	1.87
4	159-166	162.5	15	0.17	17	0.27
5	166-173	169.5	22	0.20	20	0.26
6	173-180	176.5	21	0.18	18	0.59
7	180-187	183.5	14	0.13	13	0.17
8	187-194	190.5	11	0.07	7	2.42
9	194-201	197.5	6	0.03	3	3.05
10	201-209	205	1	0.02	2	0.50
Σ			100	1.00	100	12.98

To apply the Pearson criterion, we divide the statistical data on the water accumulation rate at the underground mine level into groups, which are presented in the second column. The third column contains the midpoints of the intervals. According to the statistical data, the *Histogram* function, which is part of the *Data Analysis* complex of *Excel* spreadsheets, builds a histogram, the values of which are shown in the fourth column. The fifth column shows the calculations of the probability of occurrence of the water accumulation rate in the underground mine level for the normal distribution law for the average water accumulation rate (m^3/h) and the standard deviation (m^3/h).

The sixth column shows theoretical frequencies of the water accumulation rate in the underground mine level falling within a given interval. The last column shows calculations of differences between theoretical and empirical frequencies according to the Pearson criterion. The sum of the elements of the last column gives the observed value of the Pearson criterion $\chi_c^2 = 12{,}98$. For the number of freedom degrees $k = 10 - 3 = 7$ and the significance level $\alpha = 0{,}05$ from the table of critical points, we find $\chi_{кр}^2(0{,}05;7) = 14{,}067$. As $\chi_c^2 = 12{,}98 < \chi_{кр}^2(0{,}05;7) = 14{,}067$, we can say that at the confidence level of 0.95 there is a normal distribution law with parameters $\overline{v} = 170$ and $\sigma_v = 14$.

Fig. 2.6 presents statistical data on the water accumulation rate in the underground mine level.

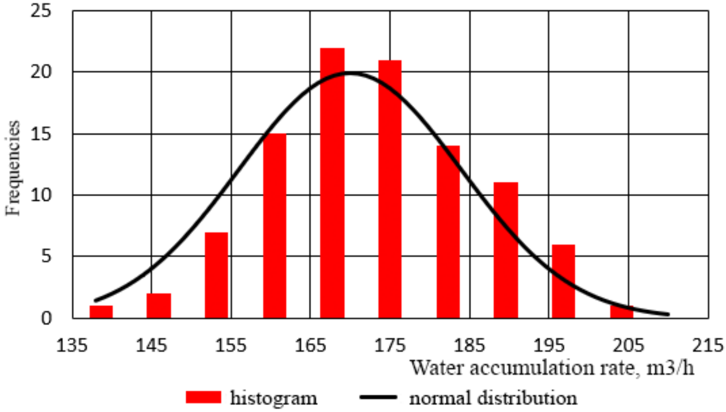


Figure 2.6 – Statistical data on the water accumulation rate at the underground level of Ternivska underground mine

Analysis of the data in Fig. 2.6 shows a fairly good approximation of the histogram to the normal distribution curve, which confirms the results found using the Pearson's criterion.

Since the water accumulation rate at the underground mine level is a normal stochastic process, the formula for the normal probability density of power consumption for water drainage from a given underground mine level is described by the formula according to (2.28), (2.46) and (2.47):

$$f(n) = 0,0105 \cdot e^{-3,4 \cdot 10^{-4}(n-463)^2} \tag{2.48}$$

Formula (2.48) allows for a complete study of power consumption for water drainage from a given mine underground level as a stochastic process.

The correlation function of the water accumulation rate is defined by the formula:

$$K_v(l) = \frac{1}{100-l+1} \sum_{j=0}^{100-l} (v_j - \bar{v})(v_{j+l} - \bar{v})(м^3/год)^2, \quad (l = 0,1,...,5) \; . \tag{2.49}$$

Fig. 2.7 presents graphs of the normalized correlation function calculated by the formula:

$$\tilde{K}_v(l) = \frac{K_v(l)}{D[V]}, \tag{2.50}$$

and approximation of this function with the formula:

$$\tilde{K}_v^a(\tau) = e^{-\alpha \cdot |\tau|} \; . \tag{2.51}$$

The application of the least squares method to the ordinates of the statistical normalized correlation function (2.50) allowed us to find the value of the parameter in formula (2.51), which is equal to:

$$\alpha = 0,55. \tag{2.52}$$

As a result, formula (2.51) takes the form:

$$\tilde{K}_v^a(\tau) = e^{-0.55 \cdot |\tau|} \; . \tag{2.53}$$

Analysis of graphs in Fig. 2.7 shows a fairly satisfactory approximation. To confirm this conclusion, the determination index is calculated using the formula:

$$R^2 = 1 - \frac{S_a^2}{D\left[\tilde{K}_v\right]}, \tag{2.54}$$

where $S_a^2 = \frac{1}{5} \sum_{l=0}^{5} (\tilde{K}_v(l) - e^{-0.55 \cdot l})^2$.

Considering the numerical results, calculation by formula (2.54), results in:

$$R^2 = 1 - \frac{0,0015}{0,1459} = 0,990 \cdot \tag{2.55}$$

The value of the determination index (2.55) suggests that there is a very high strength of relationship between the variables according to the Chaddock scale [17].

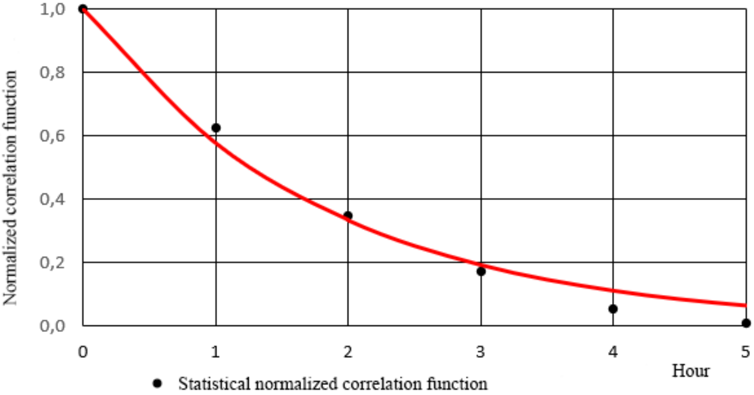


Figure 2.7 – Statistical normalized correlation function and its approximation

Considering (2.7), the normalized correlation function of power consumption for water drainage from a given underground mine level coincides with the normalized correlation function of the water accumulation rate in the underground mine level, i.e. it is possible to use the corresponding approximation (2.53). Thus, given that the power dispersion of power consumption for water drainage from a given underground mine level is:

$$\sigma_n^2 = 1105,6, \tag{2.56}$$

and the correlation function of power consumption for water drainage from a given underground mine level:

$$K_n^a(\tau) = 1105,6 \cdot e^{-0.55 \cdot \tau} \; . \tag{2.57}$$

According to formula (2.30), one can write:

$$\sigma_w^2 = 334,5 \cdot \tag{2.58}$$

Then, according to (2.35), the average number of emissions per unit time beyond the limit, which is equal to n_0, is

$$\bar{v}_{n_0} = 0,0875 \cdot e^{-4,52 \cdot 10^{-4} (n_0 - 457,47)^2} \; . \tag{2.59}$$

In turn, according to (2.42), the average duration of the emission beyond the limit is equal to

$$\overline{\tau}_{n_0} = 1,728 \cdot e^{-4,52 \cdot 10^{-4} (n_0 - 457,47)^2} \left(0,5 - \Phi\left(0,03 \cdot (n_0 - 457,47)\right)\right). \quad (2.60)$$

If

$$n_0 = \overline{n},$$

according to (2.43), the average duration of the emission will be:

$$\overline{\tau}_{\overline{n}} = 1,728.$$

Let us use formula (2.17) to find the volume of accumulated water in the selected level of Ternivska mine as a function of time:

$$\overline{u}(T) = \int_0^T \overline{v} dt = \overline{v} \cdot T = 167,94 \cdot T, м^3 \quad (0 \le T \le 100) \cdot \quad (2.61)$$

To find the dispersion of the accumulated water volume, we apply formula (2.14), which, taking into account (2.28), takes the form:

$$D[U(T)] = 2D[V] \int_0^T (T - \tau) \cdot e^{-0.55 \cdot \tau} d\tau \cdot \quad (2.62)$$

Calculating the integral in formula (2.60) by parts provides the following result:

$$\int_0^T (T - \tau) \cdot e^{-0.55 \cdot \tau} d\tau = -\frac{1}{0,55}(T - \tau) \cdot e^{-0,55 \cdot \tau} \Big|_0^T - \frac{1}{0,55} \int_0^T e^{-0,55 \cdot \tau} d\tau = \frac{T}{0,55} +, (e^{-0,55 \cdot T} - 1)’$$

or, after ordering,

$$\int_0^T (T - \tau) \cdot e^{-0,55 \cdot \tau} d\tau = \frac{e^{-0,55 \cdot T} + 0,55 \cdot T - 1}{0,55^2}. \quad (2.63)$$

Taking into account (2.63), formula (2.62) will take the form:

$$D[U(T)] = 985,12 \cdot \left(e^{-0,55 \cdot T} + 0,55 \cdot T - 1\right), м^6 \quad (0 \le T \le 100) \cdot \quad (2.64)$$

In turn, the standard deviation is determined by the formula:

$$\sigma[U(T)] = 31,39 \cdot \sqrt{e^{-0,55 T} + 0,55 \cdot T - 1}, м^3 \quad (0 \le T \le 100) \cdot \quad (2.65)$$

To calculate the average power consumption for water drainage, we use formula (2.19), which, taking into account the numerical values of the parameters, will take the form:

$$\overline{a}(T) = 456,8 \cdot T, \text{ kW*h, } (0 \le T \le 100) \quad (2.66)$$

The dispersion of power costs for water drainage is calculated by formula (2.20), which, taking into account the numerical values of the parameters, will take the form:

$$D\left[A(T)\right] = 7288{,}34 \cdot (e^{-0{,}55 \cdot T} + 0{,}55 \cdot T - 1) \text{ (kW*h)}^2, \ (0 \le T \le 100). \quad (2.67)$$

In turn, the standard deviation of power consumption for water drainage is determined by the formula:

$$\sigma\left[A(T)\right] = 85{,}37 \cdot \sqrt{e^{-0{,}55 \cdot T} + 0{,}55 \cdot T - 1} \text{ kW*h}, \quad (0 \le T \le 100). \quad (2.68)$$

If the water accumulation rate in the underground mine level is a normal stochastic process, then the volume of water accumulation at the underground mine level for a certain time is described by the formula of the normal probability density as:

$$f(u(T)) = \frac{0{,}013}{\sqrt{e^{-0{,}55 \cdot T} + 0{,}55 \cdot T - 1}} e^{-\frac{5{,}1 \cdot 10^{-4} (u - 167{,}94 \cdot T)^2}{e^{-0.55 \cdot T} + 0{,}55 \cdot T - 1}}. \quad (2.69)$$

In turn, the formula for the normal density of the volume of power consumption for water drainage from a given depth of the underground mine level for a certain time is described by the formula:

$$f(a(T)) = \frac{4{,}67 \cdot 10^{-3}}{\sqrt{e^{-0{,}55 \cdot T} + 0{,}55 \cdot T - 1}} e^{-\frac{6{,}9 \cdot 10^{-5} (a - 456{,}8 \cdot T)^2}{e^{-0{,}55 \cdot T} + 0{,}55 \cdot T - 1}}. \quad (2.70)$$

Formulas (2.48), (2.69) and (2.70) allow for a complete study of power consumption for water drainage, the volume of water accumulation in the underground mine level and power consumption for water drainage from a given depth of the underground mine level for a certain time as stochastic processes.

The study of water drainage as a stochastic process allowed us to build a mathematical model using statistical data on the water accumulation rate at the underground level of Ternivska mine.

The synthesized model made it possible to determine such stochastic characteristics of the water drainage process as the mean and dispersion of power consumption for water drainage, the volume of water accumulation at the underground mine level, and power consumption for water drainage from a given depth of the underground mine level for a certain time. Moreover, if the ordinates of the water accumulation rate in the underground mine level have a normal distribution law, i.e. the distribution density is known, the normal distribution law also is applicable to the capacity of power consumption for water drainage, the volume of water accumulation at the underground mine level and the power consumption for water drainage from a given depth of the underground mine level for a certain time, i.e. they are fully characterized as random variables.

Thus, the results obtained make it possible to characterize water drainage not only by average values, as was done before and is being done now, but also by dispersions, i.e. by their spread. If it is known that the ordinates of the water accumulation rate the underground mine level have a normal distribution law, then it is possible to fully characterize water drainage as a stochastic process.

CONCLUSIONS TO SECTION 2

1. The study of water drainage at iron ore underground mines considered as a stochastic process, based upon actual experimental data and statistics on the water accumulation rate at the underground mine level enables developing a mathematical model.

2. The synthesized model has made it possible to identify such stochastic characteristics of the water drainage process as averages and dispersions of power consumption capacity, the amount of water accumulation at the underground mine level, and corresponding power consumption for water drainage out from the specified mine depth for the given period. Moreover, if ordinates of the water accumulation rate in an underground mine belong to a normal distribution law (i.e. its distribution density is known), it also covers the model-based capacity of power consumption, amounts of water accumulation and water drainage out from the specified mine depth for the given period, i.e. they are characterized as completely random values.

3. Consequently, the findings help characterize water drainage from the underground mine levels not only using average values (as it has been done before and is being done now) but also applying dispersions, i.e. their distribution. If one knows that ordinates of water accumulation belong to a normal distribution law, it is possible to characterize water drainage as a stochastic process.

4. Mathematical modelling of water drainage from the underground mine levels as a stochastic process has made it possible to identify its deeper characteristics connected with a natural randomness factor. The water drainage parameters, early developed with the use of only average values, are complemented by new factors characterizing their dispersion. In addition, certain drainage features, being determined through the normal distribution law of ordinates of water accumulation rates, may involve a complete expectation characteristic and water accumulation amount as well as power consumption capacity to pump out water from the specified mine depth for the given period as random processes.

5. The developed methods to analyze water drainage from the underground mine levels as a stochastic are applicable to other auxiliary activities in the functioning technology of mining enterprises.

SECTION 3

DEVELOPMENT OF THE STRUCTURE AND DETERMINATION OF PARAMETERS OF AUTOMATED ENERGY-EFFICIENT CONTROL OF ELECTROMECHANICAL COMPLEXES OF MAIN WATER DRAINAGE FACILITIES AT IRON ORE UNDERGROUND MINES

3.1 Introductory references to the vision of effectiveness of technical means of improving energy efficiency of main water drainage facilities

In the previous sections of this study, the main directions for improving energy efficiency of main water drainage facilities at iron ore underground mines are considered and proactively substantiated. The list of ways to solve the problem under analysis also highlights basic technical directions of ways to solve this problem.

To determine and make effectiveness of projected measures more visible, certain technical and economic calculations of technical solutions are presented to format the logistics of further research.

Summarizing the range of possible technical solutions to improve energy efficiency of water drainage systems, there are two global trends.

Technical and economic indicators of power consumption include two ways to improve them: either using more advanced equipment to reduce power consumption per unit of output or improving efficiency of the old one. This paper uses the second way. As you know, mine drainage pumps themselves have low, and more importantly, non-linear efficiency. Pump drive asynchronous motors also have a non-linear efficiency that depends on the load. The parameters of the water drainage system are also ambiguous. Up to 6-7 pumps are installed in the underground levels of national iron ore underground mines. There are 2-3 pumps in operation simultaneously.

Moreover, the mine levels are interconnected by two or three parallel lines of pipelines (columns). It is clear that the use of different numbers of pumps for different numbers of parallel pipelines (which leads to different values of hydraulic resistance) causes different modes of operation of the hydraulic system, including energy inefficient ones. Hence, to a first approximation, it follows that operating mode control (switching the number of parallel pumps to different numbers of parallel pipeline branches) can provide significant energy savings. This can mainly be achieved by maximizing the efficiency of electric motors and pumps to their maximum operating points.

In the future, this paper will use computer modeling to test this idea and possible practical ways of its implementation according to the existing structure of groundwater drainage at Kozatska undergorund mine (Kryvyi Rih), as the one with the largest water inflow [1-8].

3.2 Investigation into the initial option of developing the structure of energy efficient management of operation modes for water drainage facilities

Analysis of operating modes and parameters of main water drainage facilities of iron ore underground mines carried out in Section 1 of this research and theoretical aspects of assessing the levels of their power efficiency highlighted in Section 2 allow us to move on to the final solution of the problem of improving energy efficiency of these most energy-intensive types of power consumers at the analyzed types of mining enterprises and develop their structure and management system.

According to the structure for improving energy efficiency of main water drainage facilities outlined in Section 1, the key areas of focus are changing the technology of water drainage from underground mine levels, replacing all or part of the equipment with more modern ones, and developing and implementing automated control. In accordance with the purpose of the research, we will focus on the latter of the above ways. The logistics in the development of the ACS of main water drainage facilities implies:

analysis of electric power parameters of electromechanical systems functioning as group electric drives of main water drainage facilities → selection of the scheme for applying smooth speed control systems of pump electric drive motors →
selection of an algorithm for energy-efficient control of the group electric drive of main water drainage facilities → development of a generalized algorithm and an appropriate program for the functioning of main water drainage facilities as a subsystem of the overall structure of the power consumption ACS →
development of an algorithm for the ACS in the option of the power consumption with a composite structure - peak HPPs for main water drainage facilities.

In its turn, at the assessment stage, the process of building such a subsystem complex (not to mention the system as a whole) is not simple in technical vision and long-term in its implementation.

When justifying and choosing ways to achieve the goal, one should clearly assess and realize that the timeframe for overcoming these problems should not cross the line when the entire expected result is 'eaten up by inflation'.

Nevertheless, the implementation of the entire complex for improving energy efficiency of main water drainage facilities can and should be modular with mandatory final integration in the ACS version. The first step in solving the problem of energy efficiency of main water drainage facilities is energy efficiency of electromechanical systems, which are the basic components of these complexes.

This starting point is relevant and basic in the logistics of ACS development, since the existing control systems for electromechanical complexes of main water drainage facilities are far from energy-efficient options. In addition, it is necessary to take into account the fact that electromechanical structures of main water drainage facilities are modular multi-engine complexes, which, in the energy-efficient direction of developing control algorithms, remain a significant potential for obtaining positive solutions in power consumption of mining enterprises.

In the context of such a solution, the mandatory logistical necessity of expected complex solutions within the ACS development should involve availability of energy-intensive energy-efficient speed controllers of water pump drive motors enabling to automate their operation modes according to a generalized algorithm.

In today's realities, choosing the type of energy-efficient supply voltage converter to regulate the speed of water pump drives in order to control operating modes of both individual process modules and the main water drainage facility as a whole is not a scientific task, let alone a scientific problem. The problem in this aspect concerns selection and optimization of their functioning parameters in accordance with energy efficiency criteria of the entire multi-module electromechanical complex of main water drainage facilities.

It is possible to assess the expected and desired modes of operation of the electromechanical systems of main water drainage facilities to develop an appropriate control algorithm on the basis of mathematical modeling with subsequent verification on physical models or at operating main water drainage facilities.

3.3 Development of a simulation model of main water drainage facilities

The first purpose of building a simulation model is to automatically determine parameters of the operation mode of the main water drainage facility. Technical literature [9-12] provides a number of methods for calculating static modes of hydraulic systems of pipelines, but they are all highly complicated. To avoid this negative aspect and obtain final results as close to the real-life ones as possible, you can automatize the calculation process using the Matlab package. This allows you to visualize static modes of the main water drainage facility, and, under some assumptions, some dynamic modes as well [13-17].

When modeling the process, the authors consider the following arguments. Available schemes and electromechanical equipment of the main water drainage facilities at national iron ore underground mines, which with the appropriate number of pumping units are located on the underground levels of these types of industrial enterprises, are used as input data.

Drive motors of the MWDC pumps, which are asynchronous (AM), have a nonlinear efficiency, depending on the load level. On each of the underground levels of national iron ore underground mines (stages of the MWDC), as a rule, 6-7 pumps are installed [3]. 2-3 pumps are in operation at the same time, the rest are either in the ‘hot’ or in the ‘cold’ reserve. Underground pipelines of water drainage at iron ore underground mines are interconnected by two or three parallel branches of pipelines (pump columns) with a diameter of 325 mm.

This option of using a different number of pumps for a different number of parallel branches of pipelines (which provides different hydraulic resistances) leads to appropriate variations in the operation modes of the hydraulic system, including energy-inefficient ones.

Hence, already in the first approximation, it is expected that the control of operation modes (switching parallel pumps to a different number of parallel branches of the pipeline) can potentially provide energy savings. To a large extent, this can be achieved due to the maximum approximation of operating points of efficiency of electric motors and pumps to their maximum.

Despite the fact that pumps can theoretically operate with a fairly wide range of the flow rate, the permissible range of their effective operation is significantly narrowed to certain boundaries stipulated by the manufacturer. For example, for a pump of the CPS type 300-600, this range lies in the range of 220-360 m^3/h. In order to study the real operation modes of pumps for lifting water from the 500 m level of Kozatska underground mine (Kryvyi Rih), a detailed simulation scheme is developed in Matlab (Fig. 3.1).

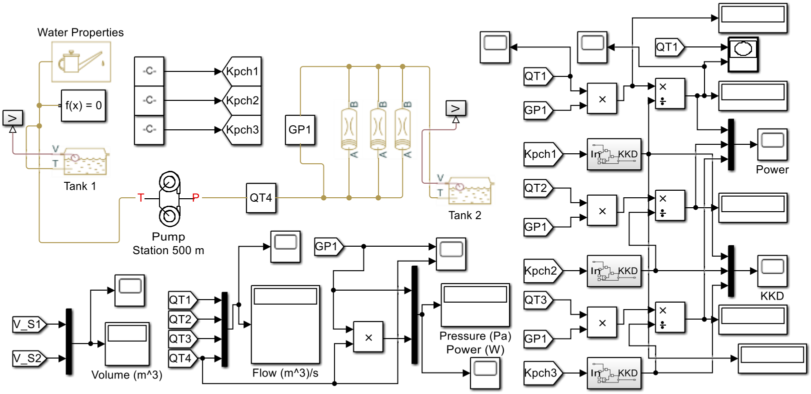


Figure 3.1 – Model for studying energy modes of pump operation at the main drainage complexes (the 500 m level of Kryvorizka underground mine in Kryvyi Rih)

The core of the model consists of *Tank1*, which together with the pumping station is on the 500 m level, three parallel columns (pipelines), which connect the sewer of the pumping station with the conditional water storage facility – *Tank2* (it is on the surface, yet may be absent). All the other blocks of the model perform measuring and other auxiliary functions. Thus, the *Water Properties* block sets parameters of water (density, temperature, viscosity). In block *f(x)=0*, parameters of the model calculation are set (integration step, integration method, rounding errors, etc.). The blocks named with *QT* are flow sensors, and with *QP* – pressure sensors. Such blocks as *Volume (m^3)*, *Flow (m^3)/s* and *Pressure (Pa) Power (W)* are multichannel digital measuring instruments that measure two channels of water volume (for *Tank1* and *Tank2*), four water flow channels (separately through each pump and total flow rate), two measuring channels (pressure on the lifting pipeline from *Tank1* to *Tank2*, and facilities for pumping water on the specified pipeline). Blocks *V* near the tanks measure the current volume of water in them. The right side of the model consists of three identical power measurement channels and the current flow rate (for each of the three pumps separately). The flow rate of the pumps changes when control signals change, according to the Moody formula:

$$\eta_1 = 1 - \frac{1-\eta_2}{\left(\frac{n_1}{n_2}\right)^{0,36}}, \tag{3.1}$$

here n_2 and η_2 are pump revolution frequency and efficiency according to natural characteristics (based on specifications for pumps); n_1 is the pump revolution frequency at a reduced power supply frequency.

Considering efficiency of the pump and without doing so, the power model of Fig. 3.1 provides the result calculated both in digital form and as graphs.

The model additionally implements an option of separate control of the frequency converter (FC) of three pumps (which are located in the subsystem of the *Pump Station 500 m*). The control signals of the FC (*Kpch1*÷*Kpch3*) vary in the range of 0 ÷ 1, which corresponds to the range of change in revolution frequency of the drive motors from 0 to 1470 rpm. The absence of parameters of specific types of real asynchronous motors in the model can be neglected, because under the nominal mode, their power losses will be only 51 kW, and with frequency control, they are almost unchanged.

If necessary, without errors affecting the final result, you can add this constant value of 51 kW to power consumption indices of the pumps, considering the same insignificant losses in frequency converters.

The actual structure of the 500 m *Pump Station* block is shown in Fig. 3.2. Due to the fact that only 2-3 pumps are constantly involved under the conditions of the technological process, 3 pumps are accepted in the model of the pumping station, the other 3-4 pumps, which are in the ‘hot’ or ‘cold’ reserve, are not considered in simulation. It is necessary to pay attention to *Check Valve 1*÷*Check Valve 1*. They are very important. The fact is that elementary models of *Tank1* and *Tank2* water storage facilities, connected by vertically arranged pipelines, are implemented as if they are communicating vessels. That is, raising *Tank2* to a height of 500 m will automatically lead to the leakage of water from it to *Tank1* below (when all the pumps are stopped). This is not true, because water is poured into the tanks from above; there is no way for water to leak everywhere at the bottom of the storage facility. Therefore, the check valves, as soon as the pumps, when adjusting their rotational speed, become unable to lift the water to 500 m, cut off the reverse flow of water.

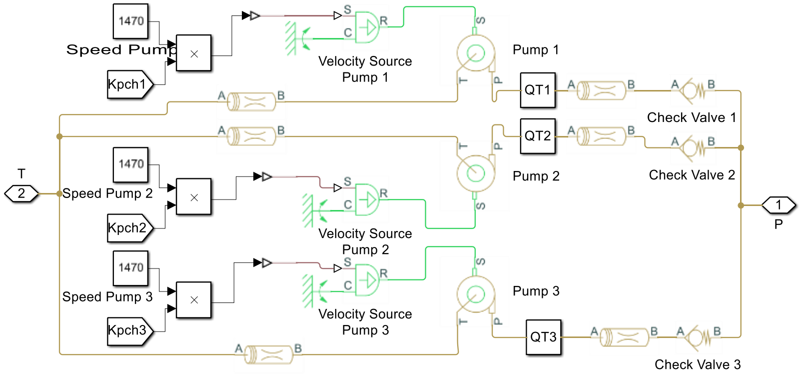


Figure 3.2 – Model of the MWDC block of the 500 m underground level (Kryvorizka underground mine in Kryvyi Rih) developed in Matlab

In the context of the research technology, we check the balance of lifting from the specified underground level of 500 m by means of simulation. We study operation of all three pumps in parallel for all three pipeline columns in different configurations, under nominal operating conditions, without speed control. Simulation results are presented in Table 3.1.

The following conclusions can be drawn from Table 1.3:

1. The designers of the hydraulic system initially designed a high-quality system – all pumps in any configuration operate in an admissible range.

Table 3.1 – Results of multi-optional studies

Mode	Flow of Pump 1, m^3/h	Flow of Pump 2, m^3/h	Flow of Pump 3, m^3/h
1 pump per 1 column	0.09678	$-7.288 \cdot 10^{-11}$	$-7.288 \cdot 10^{-11}$
1 pump per 2 columns	0.09729	$-7.275 \cdot 10^{-11}$	$-7.275 \cdot 10^{-11}$
1 pump per 3 columns	0.09738	$-7.272 \cdot 10^{-11}$	$-7.272 \cdot 10^{-11}$
2 pumps per 1 column	0.09483	0.09483	$-7.337 \cdot 10^{-11}$
2 pumps per 2 columns	0.09678	0.09678	$-7.288 \cdot 10^{-11}$
2 pumps per	0.09715	0.09715	$-7.278 \cdot 10^{-12}$

3 columns				
3 pumps per 1 column	0.09182	0.09182	0.09182	
3 pumps per 2 columns	0.09595	0.09595	0.09595	
3 pumps per 3 columns	0.09677	0.09677	0.09677	
Mode	Power consumption of Pump 1, W	Power consumption of Pump 2, W	Power consumption of Pump 3, W	Total flow, m^3/h
1 pump per 1 column	691400	0	0	0.09678
1 pump per 2 columns	692300	0	0	0.09729
1 pump per 3 columns	692500	0	0	0.09738
2 pumps per 1 column	687500	687500	0	0.18966
2 pumps per 2 columns	691400	691400	0	0.19356
2 pumps per 3 columns	692100	692100	0	0.1943
3 pumps per 1 column	680100	680100	680100	0.27546
3 pumps per 2 columns	689800	689800	689800	0.28785
3 pumps per 3 columns	691400	691400	691400	0.29073

2. No significant changes in the mode of the hydraulic system when turning on a different number of pumps for a different number of columns occurred as water flow of each pump changes by a maximum of 5.7%, and the power consumed by a single pump - by a maximum of 1.8%.

3. When operating one, two or three pumps for a different number of pipelines, the water flow rate changed in the range of 0.6%, 2.4% and 5.5% respectively. These are insignificant indicators to consider in further development of the automation system for the MWDC.

3.4 Investigation into the acs of pumps of main water drainage complexes in dynamics

Let us use a simulation model of Fig. 1 to study dynamics of the MWDC on the example of the above-mentioned level of 500 m of the operating underground mine. Suppose arbitrarily that the FC control signals change as shown in Fig. 3.3 (the first grows parabolic, from 0.84 to 1 p.u. (or from 42 to 50 Hz), the second also decreases parabolic, from 0.9 to 0.84 p.u. (from 50 to 42 Hz).

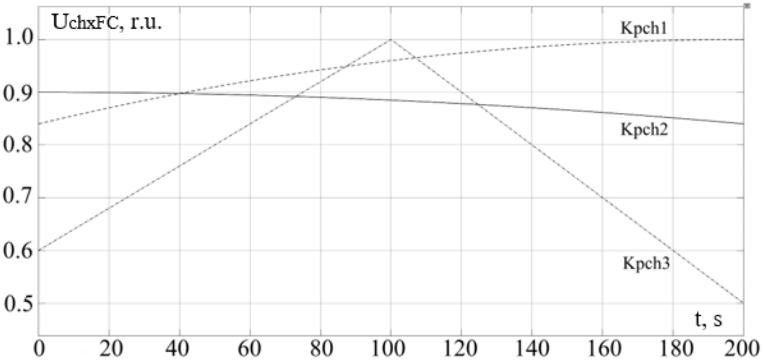


Figure 3.3 – Control signals of frequency converters of pump motors

Such control signals of the FCs of pumps cause subsequent changes in pump performance (Fig. 3.4).

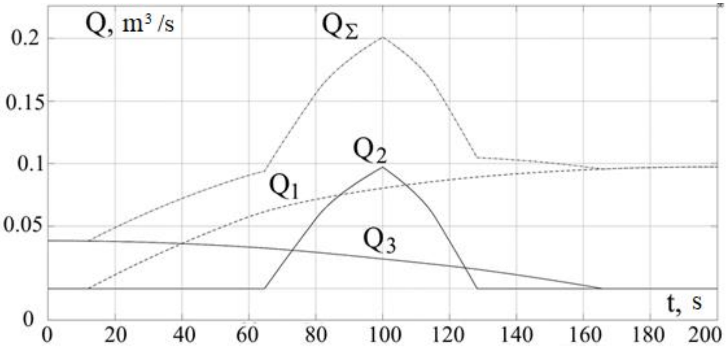


Figure 3.4 – Total flow rate (QΣ) and that of individual pumps ($Q_1 \div Q_3$)

As you can see, the pump flow rate for each of the pumps varies in a nonlinear way, so the first pump turns on to the water supply at ≈ 12 seconds (at 43 Hz), the second pump turns off at ≈ 166 seconds (at 43 Hz), and the third pump generally turns on sequentially at ≈ 65 seconds. (at 43 Hz), and then turns off at 128 seconds (also at 43 Hz). As you can see, at the power supply frequency of the drive pumps exceeding 43 Hz, water is pumped upward, and if the power supply frequency of the pumps drops below 43 Hz, the pressure developed by the pumps is no longer able to apply the pressure of the water barrel, and the pump stops as a technological mechanism, continuing to work on the ‘thrust’ mode. The power consumption and flow rate of the pumps change as follows (Fig. 3.5, Fig. 3.6).

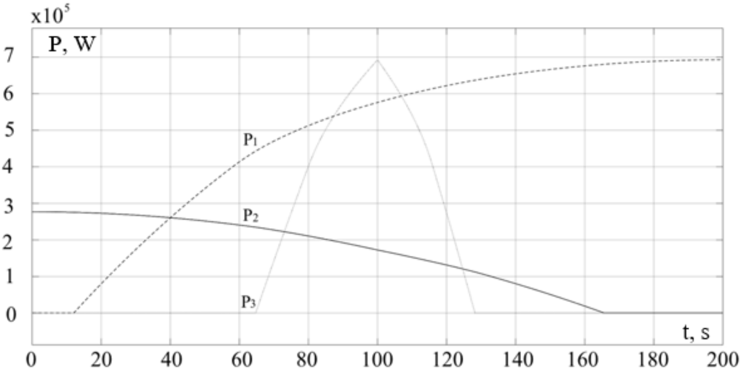


Figure 3.5 – Power consumption of individual pumps of the mine water drainage facility

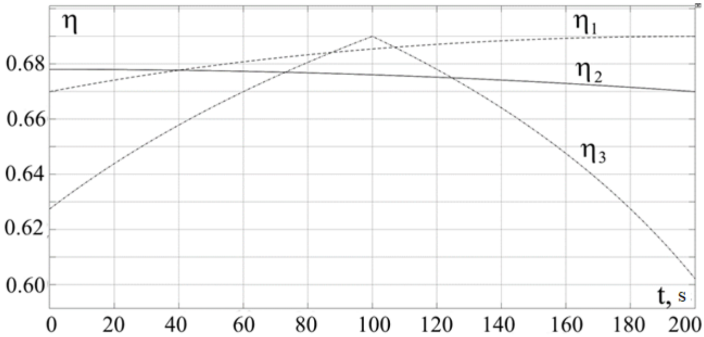


Figure 3.6 – Efficiency of the pumps for different control signals of the supply voltage frequency converters

In this case, efficiency of the pumps is calculated according to (1). It can be noted that for all the pumps the initial efficiency for the nominal rotation frequency is the same and equal to 0.69 (corresponds to the initial operating point on pump specifications).

As you can see, the active power of the pumps varies from 0 to the maximum value, which is different for each. The power value of 0 with the pump running is natural, since no pumping upwards occurs. It is also established that despite nonlinearity of Q-H characteristics of the pumps, the dependence of power consumption on the flow rate is linear, i.e. any pump of this type (CPS 300-600) can be characterized by a coefficient of 7128.9 kW/m^3/s. The specified coefficient can be useful as a necessary constant for building a mathematical support for the ACS of pump operation modes.

Fig. 3.7 shows graphs of the column head and total pump capacity. It can be seen that the total productivity varies in a significant range from 0.04 m^3/s to 0.2 m^3/s (by 80%), while the pressure in columns varies in a smaller range - from 4904 kPa to 4916 kPa (by 0.2%). Obviously, as soon as all three pumps stop supplying water, the pressure in the column will be equal to the pressure of a trunk of still water.

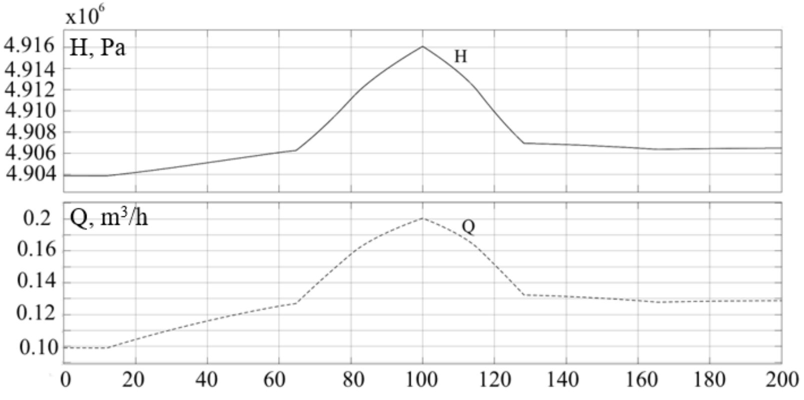


Figure 3.7 – Head in the ponds and total water consumption

Let us assess the dependence of power consumption of one pump on its performance. Let us set a signal of the frequency converter as shown in Fig. 3.8 (linear change).

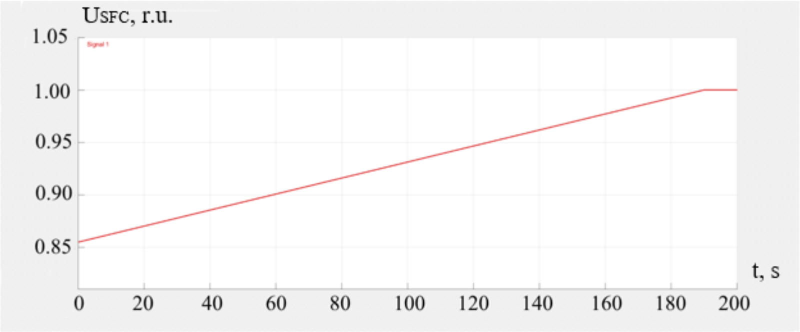


Figure 3.8 – Setting a signal of a single frequency converter (43-50 Hz)

In the frequency range of 43-50 Hz, the active power consumed by the pump varies from 0 to 691.5 kW (Fig. 3.9) and the pump capacity varies from 0 to 0.097 m3/s (Fig. 3.10).

In the frequency range of 43-50 Hz, the active power consumed by the pump varies from 0 to 691.5 kW (Fig. 3.9) and the pump capacity varies from 0 to 0.097 m3/s (Fig. 3.10).

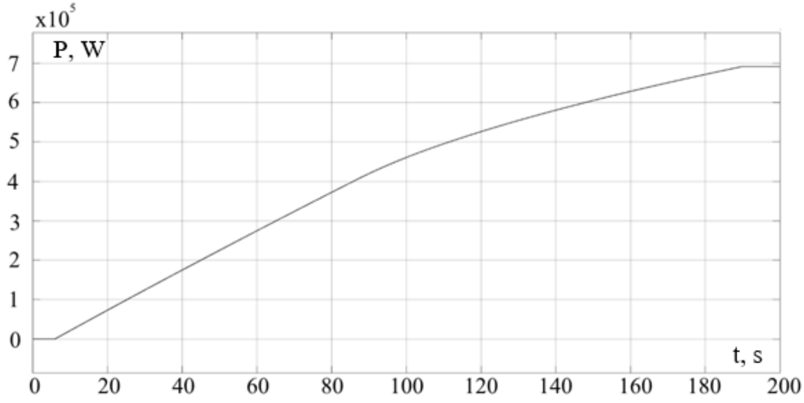


Figure 3.9 – Active power consumption of the pump when changing the frequency range of 43-50 Hz

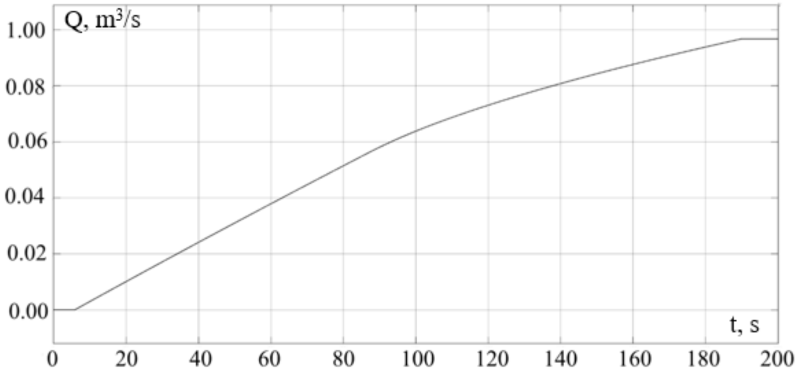


Figure 3.10 – Pump performance when the frequency changes from 43 to 50 Hz

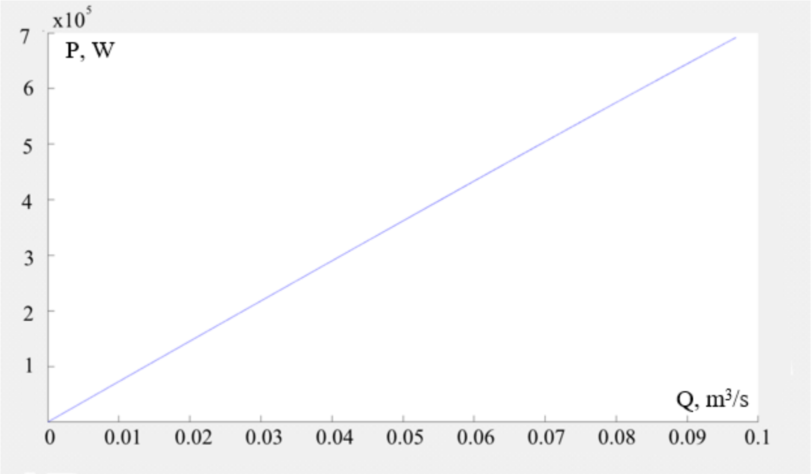


Figure 3.11 – Dependence of pump power consumption on its performance

The dependencies obtained show that despite the nonlinearity of the *Q-H* characteristic of pumps, the dependence of power consumption on flow is linear, i.e. any pump of this type can be characterized by a coefficient of 7128.9 kW/m^3/s. This coefficient can be useful as a necessary constant for building mathematical support for the automated control system of pump operating modes.

3.5 Assessment of the impact of power losses of drive motors on the power balance of main water drainage facilities

Let us assess the impact of power losses of pump drive motors on the total power losses of main water drainage facilities. As you know, the 500-m level pumping station uses 800 kW high-voltage motors with a synchronous speed of 1500 rpm. For further research, let us take an A-13-46-4 engine with the following parameters:

P_n = 800 kW; U_n=6 kV; n_n =1485 rpm; s_n = 1 %; η_n = 94 %; cosφ_n = 0.91; I_{start}/I_n = 6,4; M_{start}/M_n = 1.0; M_{max}/M_n = 2,1; J = 200 kg·m^2.

Unfortunately, for this motor, as well as for many other motors, there are no detailed parameters of the substitution scheme necessary for calculating static and dynamic characteristics. Therefore, they are determined by calculation and experimentation. With the help of multivariate studies conducted on the model of Fig. 3.12, the parameters of the substitution scheme are determined:

- stator phase active resistance 0.8946 Ohm;
- stator phase inductance 0.01456 H;
- total active rotor impedance of 1.152 Ohms;
- total inductance of the rotor phase is 0.01456 H;
- mutual inductance 0.57582 H.

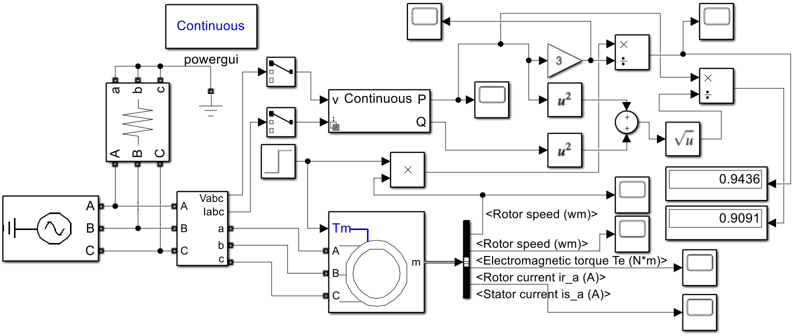


Figure 3.12 – Model of an asynchronous pump motor with efficiency measuring circuits and cosφ

A direct start of the asynchronous motor with the corresponding parameters of the substitution scheme is carried out and transient graphs are obtained, according to which compliance with the passport data of the motor type A-13-46-4 is checked (Figs. 3.13 - 3.15).

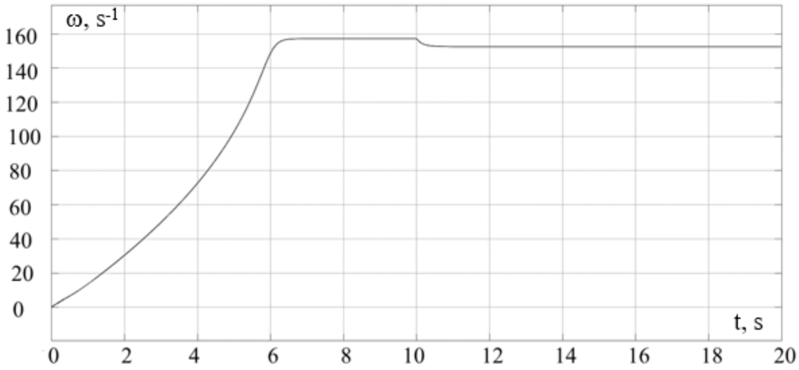


Figure 3.13 – Speed of the asynchronous pump motor (direct start)

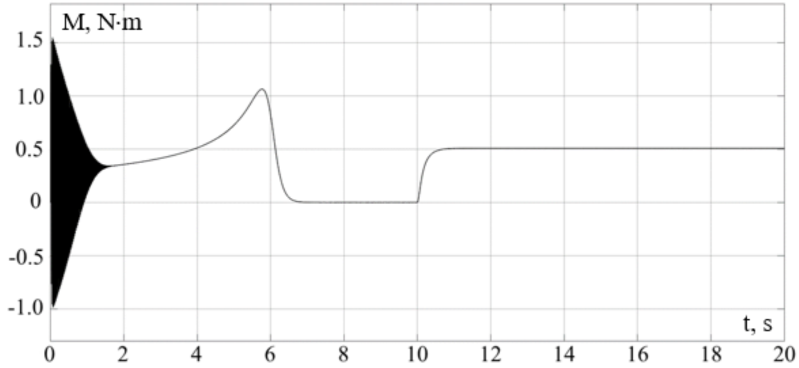


Figure 3.14 – Electromagnetic torque of an asynchronous pump motor (direct start)

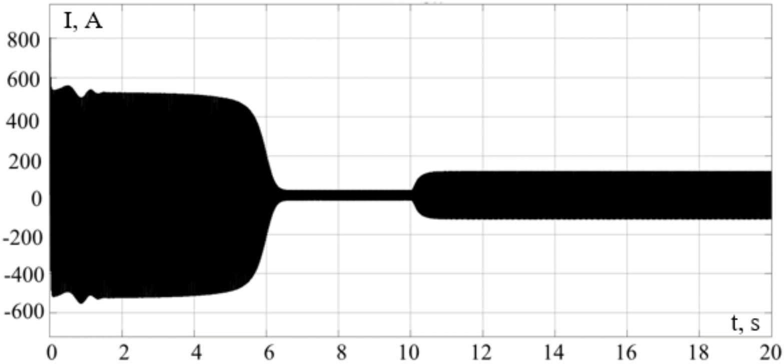


Figure 3.15 – Stator phase current of an asynchronous pump motor

The electromagnetic torque graph shows that the ratio of the maximum (critical) torque to the rated torque corresponds to the passport value $M_{max}/M_n = 2.1$.

The rated current from the graph in Fig. 3.6 corresponds to the nominal passport value:

$$I_n = \frac{P_n}{3 \cdot U_{fn} \cdot \cos\varphi_n \cdot \eta_n} = \frac{800000}{3 \cdot 3464 \cdot 0{,}91 \cdot 0{,}94} = 89{,}99 \text{ A},$$

the amplitude value of the current: $I_{nampl} = I_n \cdot \sqrt{2} = 89{,}99 \cdot \sqrt{2} = 127{,}3$ A.

The result shows that the steady-state values of the rated current are equal.

The overcurrent capacity is less: 4.5 from the current graph vs. $I_{\text{start}}/I_{\text{n}} = 6.4$. This is because the Matlab model of the asynchronous motor (according to the mathematical description) does not take into account the influence of the skin effect when it is started directly. The nominal efficiency and power factor in the simulation reach values almost identical to the passport values (efficiency 0.9436 vs. nominal 0.94; power factor 0.9091 vs. nominal 0.91). It follows that the parameters of the substitution scheme are determined with satisfactory accuracy.

Using the model of Fig. 3.3, we determine the dependence of efficiency on load for the studied asynchronous motor of the A-13-46-4 type (Table 3.2, Fig. 3.16).

Table 3.2 – Dependencies $\eta = f(m)$

$m = M/M_n$, r.u.	0.05	0.1	0.2	0.3	0.4	0.5	0.6
Efficiency, r.u.	0.9359	0.9622	0.9769	0.9735	0.9733	0.9683	0.9653
$m = M/M_n$, r.u.	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Efficiency, r.u.	0.9611	0.9556	0.9505	0.9436	0.9383	0.9322	0.9255

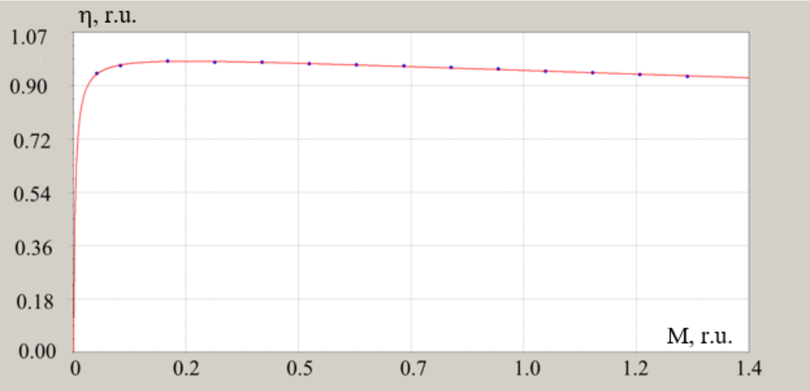


Figure 3.16 – Dependence of efficiency on the relative load on the shaft of an asynchronous pump motor

The expression for approximation is as follows:

$$\eta(m) = \frac{-0,0000028995 + 273,132 \cdot m}{1 + 271,393 \cdot m + 17,073 \cdot m^2}. \tag{3.1}$$

Fig. 3.16 shows that efficiency at the rated load is minimal and increases with a decrease in load, i.e. it can be assumed that for the A-13-46-4 asynchronous motor efficiency practically does not change and is equal to 0.9683 (for the average load on the motor shaft). Thus, the additional losses of the engine are:

$$\Delta P_{eng} = \left(\frac{1}{\eta} - 1\right) \cdot P_n = \left(\frac{1}{0,9683} - 1\right) \cdot 800 = 26,19 \text{ kW}$$

3.6 Assessment of limits of controlling the power consumed by pumps using frequency converters

In practice, the appropriate hydraulic resistance is set by partially closing the valves to bring the pump into rated operation. Today, this method is irrational because it wastes a lot of power.

If you set the minimum permissible water flow rate of 0.061 m^3/s by adjusting the speed of the 500 m level pumps (which will be possible if you set K_{pch} = 0.927), the power consumed by the pump will be 443600 W, making 35% less than when the same pump operates with the water flow rate of 0.1 m^3/s.

That is, if in the previous option (without the frequency converter) we had the possibility of almost discrete switching of the leakage of the 500 m pumping station with an interval of about 0.1 m^3/s (0, 0.1, 0.2 and 0.3 m^3/s) with discrete switching of consumption power with an interval of about 692 kW, then using frequency converters we have more flexible ranges of power consumption:

$$443{,}6 \leftrightarrow 692; \quad 1135{,}6 \leftrightarrow 1384; \quad 1827{,}6 \leftrightarrow 2076 \text{ kW.}$$

As you can see, there are still so-called ‘blind spots’ in regulating power consumption of the pumping station: from 692 to 1135.6 kW, from 1384 to 1827.6 kW, each of which is 443.6 kW.

The following substantive evidence is also established. Energy efficiency of pumps at different rotor speeds varies significantly. So, if the pump operates with a maximum flow rate, power consumption for pumping 1 m^3/s per hour is as follows:

$$E_1 = \frac{P_1}{Q_1} = \frac{692}{0.1} = 6920 \text{ kW}\cdot\text{s/m}^3.$$

If the pump operates with a minimum flow rate of 0.061 m^3/s, power consumption for pumping 1 m^3/s of water per hour is different:

$$E_2 = \frac{P_2}{Q_2} = \frac{443.6}{0.061} = 7272 \text{ kW}\cdot\text{s/m}^3.$$

As we can see, adjusting the speed of the pump wheels not only reduces power consumption of the pump, but also deteriorates the process water drainage, making it less energy efficient.

3.7 Controlling pump switching on and off processes

It is established (clause 3.5) that the most energy-efficient mode of pump operation is operation at maximum speed, i.e. pumping water at maximum modes. However, due to the limited volume of the reservoir, the pumps will have to be turned on and off periodically (possibly several times a day).

Let us assess negative effects of switching a powerful pump motor on and off. It is known that starting, for example, synchronous motors with highly inertial mechanisms on their shafts is a difficult process due to overheating of the stator windings and starting winding cores. Overheating of the stator windings leads to accelerated aging of the winding wire insulation and groove insulation, with the subsequent prospect of sudden motor failure due to insulation breakdowns. Overheating of rotor starting winding cores leads to uneven heating of the entire structure, and thus to its deformation with disruption of electrical contacts of the cores with the connecting rings.

An asynchronous motor also has stator windings and rotor squirrel cage rods. Let us evaluate the possibility of heating the AM stator winding to temperatures above the nominal, and the rods to cage deformation temperatures when the AM pump is started.

For this study, we will use the model of Fig. 3.12. It is known that the moment of inertia of the engine is 200 kg-m^2, the moment of inertia of the pump is unknown, but the total weight of the pump is 2470 kg, the pump is multi-stage (the number of pump wheels is 5 pcs.).

Let us assume that the moment of inertia of the pump wheels is 50 kg-m^2. In this case, the total moment of inertia will be 250 kg-m^2 (1.25 times greater than the engine), which is consistent with most pairs of the engine-mechanism system. It should also be noted that the pump drive is usually started with the valve closed, and the torque on the drive shaft is determined solely by mechanical friction in the pump unit and fluid losses in the pump casing. Let us assume that the torque on the shaft will be 10% of the nominal torque.

Using this model (Fig. 3.12), it can be determined that, first, the direct start time increases to 9.5 s, and second, the total amount of energy consumed to start the unit is 11.16 MJ.

Let's determine the energy that was directly spent on accelerating the unit to steady state. After acceleration, the kinetic energy of the unit will be:

$$E_k = \frac{J \cdot \omega^2}{2} = \frac{250 \cdot 157^2}{2} = 3{,}08 \text{ MJ.}$$

Energy consumption to form the magnetic field of the AM is not taken into account, since this energy is related to reactive power rather than active power.

This means that the difference between the total starting active energy and the kinetic energy of the accelerated unit will be exclusively thermal energy, which will be supplied to the induction motor in 8 seconds:

$$E_{thermal} = E_{\Sigma} - E_k = 11{,}16 - 3{,}08 = 8{,}08 \text{ MJ.}$$

This thermal energy is generated exclusively by the flow of stator currents through the stator windings and rotor currents through the rods of the squirrel cage. Let us assess how much the temperature in the windings and cores will rise. We assume that during startup, the thermal energy is distributed equally between the stator and rotor:

$$8{,}08/2 = 4{,}04 \text{ MJ.}$$

Let us use the heat balance equality known from physics for solid bodies:

$$Q = c \cdot m \cdot (T_2 - T_1),$$

where Q is the amount of heat (energy) transferred to the body (J);

c is the heat capacity of the body;

m is body weight;

T_2, T_1 are the temperatures after heating and before heating, respectively.

The specific heat capacity of copper in stator windings is 0.385 kJ/(kg/K), and the heat capacity of squirrel cage aluminum is 0.897 kJ/(kg/K). Let us assume the initial temperature of the engine before startup is 25 °C.

On average, the heating time constant of the conductors is 30 minutes, so it can be assumed that the heat generated in the conductors during 9.5 seconds of the AM startup will not begin to escape the surrounding masses of the motor. In other words, almost all of the heat energy will initially be concentrated exclusively in the copper of the stator windings and the aluminum of the cage. To determine the temperature of conductors, you need to know the active masses of copper and aluminum:

$$T_2 = \frac{Q}{c_{Al} \cdot m_{Al}} + T_1 \text{ – aluminum;}$$

$$T_2 = \frac{Q}{c_{Cu} \cdot m_{Cu}} + T_1 \text{ – copper.}$$

Unfortunately, the active masses of copper and aluminum in the AM are unknown and are determined approximately.

Here is another approach to solving this problem.

Let us assume that the motor heats up to 155 °C at startup (permissible temperature for insulation class F). This requires 80 kg of copper and 34.7 kg of aluminum. At first glance, these figures are too low for an asynchronous motor weighing 3910 kg. However, in any case, it is highly likely that the A-13-46-4 engine with a CNS 300-600 pump will not overheat during one direct start. However, restarting or starting from the initial hot state will no longer be acceptable, as the engine will heat up to 155 + 130 = 285 °C.

Given that the cooling time constants are quite large, the motor can cool down from a temperature of 285 °C to a temperature of 155 °C, which causes irreversible damage to the stator winding insulation. It is known that constant overheating of the motor windings by every 10°C will reduce its service life by 2 times.

Therefore, the designed automation system must correctly select motors for reconnection to the hydraulic system when controlling the energy flows of the main water drainage facility. The best option would be to implement a lightweight start-up of pumping units, which can be realized using the same frequency converters. This will allow any pumping unit to be put into operation an unlimited number of times. Thus, the capabilities of frequency converters are expanding.

3.8 Influence of power tariffs on energy performance of main water drainage facilities

Previously, the main focus was on only one area of energy saving - reducing power consumption by adjusting the speed of the pump wheels downward. Let us consider the possibility of saving money due to the difference in power costs during the day. As you know, the cost of power varies during the day: during the daytime, it is 1.9 UAH/kW, and at night, it is 2.1 UAH/kW.

Energy savings can be achieved by:

1) maximizing the use of pumps of all levels exclusively at night; or
2) consuming power during the day and saving it from at night.

The first option is possible by increasing the volume of reservoirs to the required minimum level, and the second option is possible by using power storage devices.

3.8.1 Increasing the volume of mine level tanks/reservoirs

Previously, attention was paid to just one direction of energy saving – reducing power consumption by ‘lowing’ the speed of pump wheels. Let us consider the possibility of energy saving due to the difference in payment for power consumption during the day, when each hour of the day has its own fixed tariff. However, conditionally, without significant errors for the final result, we break the 24-hour tariffs into ‘night’ (economical) and ‘daytime’ (non-economical). In this case, savings can be achieved if the most of pumps of all levels are used exclusively at night. Moreover, the economic effect can be enhanced by increasing the capacity of intermediate level tanks to the required level, which is achievable. The following procedure is required.

In order for the pumps not to work in the daytime, it is necessary that the natural water inflow at least at the lowest tank of the same typical Kozatska underground mine (the 1240 m level) does not overflow the tank during 16 hours. That is, the tank should have a capacity of at least 476 m^3 · 16 = 7616 m^3 (where 476 m^3 is the average daily inflow of groundwater in the underground mine). Currently, on the 1240 m level the total capacity is 4800 m^3. We calculate the economic effect of the night operation due to expanding the tank capacity to 7616 m^3. In the initial version, when the pumps worked regardless of the time of day, in order to pump up the entire daily volume of water (i.e. 476 m^3/h · 24 h = 11424 m^3), a minimum of 36.5 pump-hours should be consumed per day (with a capacity of each pump ≈ 313 m^3/h and power consumption of 371 kW). In other words, 1-2 pumps should work during the day. Suppose that one pump is constantly running and the other is running from time to time, all night and part of the day. Then at night, this pump works for 8 hours, and during the day – for 4.5 hours. Let us calculate the cost of power consumed during the day:

C_{power1} = 371 kW · 16 h · 2.1 UAH/ kW + 2 · 371 kW · 8 h · 1.9 UAH/ kW + 371 kW · 4.5 h · 2.1 UAH/ kW = UAH 32889.

Let us consider another option – all the water accumulated in 16 hours of the day is pumped out during 8 night hours. In this case, to pump out the accumulated 4800 m^3, as well as 476·8 = 3808 m^3, which is added overnight (in total making 9408 m^3), we need 4 pumps to work at night for 7.5 night hours and the tank will be completely empty. Also, 1 pump is needed during the 0.7 night hours (to pump out an additional 476· 0.5 h = 238 m^3), and 1 pump during 9 daytime hours to completely fill the tank at night. Let us calculate the power cost during the day when operation of the pumps is ‘shifted’ to the night period as much as possible:

C_{power2} = 371 kW · 4 pcs · 7.5 h · 1.9 UAH/kW +
+ 371 kW · 1 pcs 0.7 h · 1.9 UAH/kW + 371 kW · 1 pcs 9 h · 2.1 UAH/kW = =UAH 28652.

The difference in power costs during the day is:

$$\Delta C = C_{\text{power1}} - C_{\text{power2}} = 32889 - 28652 = 4237 \text{ UAH.}$$

As can be seen, 'shifting' pump operation to the night period causes an additional economic effect making an even greater yearly value:

$$365 \cdot 4237 = 1546505 \text{ UAH} = \text{UAH } 1.5 \text{ mln.}$$

3.8.2 Additional increase in energy efficiency of main drainage facilities by increasing the tank capacity to the required minimum

Suppose that no pump works in the daytime. This is possible only if the mine waters fill the tank completely with a self-flow. It turns out that in the 16-hour self-flow, we will need to have a tank with a capacity of 16 · 476 = 7616 m^3.

Then at night, to pump the whole volume, 3 pumps should work for 8.11 hours (almost all night). We calculate the power cost for this option:

$C_{\text{power3}} = 371 \text{ kW} \cdot 3 \text{ pcs} \cdot 8.11 \text{ h} \cdot \text{UAH } 1.9 = \text{UAH } 17150.$

The economic effect compared with the primary version will be:

$\Delta C = C_{\text{power1}} - C_{\text{power3}} = 27250 - 17150 = \text{UAH } 10100.$

Total yearly savings will make 10100 · 365 = UAH 3686500 = 3.7 UAH mln. This economic effect can be achieved solely by increasing the capacity of the tank from 4800 m^3 to 7616 m^3, i.e. by 60%.

3.8.3 Assessing efficiency by power storage devices

Assuming that it will not be possible to expand the water drainage sump to the required 7616 m^3 at the 1240 m level, it is still possible to use power storage to supplement the pumps during the day. Naturally, the storage devices should contain power purchased at the night price.

Earlier, it was determined that pumping 11424 m^3 per day could be achieved if 1-2 pumps per day (more precisely, 36.5 pump-hours) are operated, with 1 pump operating day and night, and the other pump operating at night and 4.5 hours at the daytime.

Let us determine the economic effect of such a reduction in power costs:

$$C_{\text{power4}} = 371 \text{ kW} \cdot 4.5 \text{ h} \cdot (2.1 - 1.9 \text{ UAH}) = 333.9 \text{ UAH.}$$

The yearly amount will be:

$$C_{\text{power4year}} = 333.9 \cdot 365 = 121873.5 \text{ UAH} = 121.8 \text{ K UAH}$$

Thus, the following energy is required for power storage devices during 4.5 hours:

$E = t_{\text{wor}} \cdot P_{\text{cons}} \cdot 3600 = 4{,}5\ \text{h} \cdot 371000\ \text{V} \cdot 3600 = 6010200000\ \text{J}.$

According to the formula of potential energy of the capacitor, it is necessary to have the following total capacity of supercapacitors:

$$C = \frac{2E}{U^2} = \frac{2 \cdot 6010200000}{8100^2} = 183\ \text{F},$$

where 8100 is the rated DC link voltage of the frequency inverter:

$$U_\text{d} = U_{2\text{l}} \cdot 1{,}35 = 6000 \cdot 1.35 = 8100\ \text{V}.$$

If we use Korean LSUC 2.8 V supercapacitors with the 3000 F capacity as an option, their number should be calculated. When the DC link voltage of the frequency inverter of 8100 V with a supercapacitor battery installed for convenience, 8100/2.8 = 2892 supercapacitors will be required in series connection. For simplicity, let us assume that we have 3000 super capacitors connected in series.

The current purchase cost is 1000 UAH/unit, so the direct cost for supercapacitors will be:

$$549000 \cdot 1000 = 549000000 = 549\ \text{mln UAH}.$$

Thus, with the economic effect of 121873.5 UAH/year, the payback period will be unacceptable

$$549000000 / 121873{,}5 = 4504{,}7\ \text{years}.$$

As an option, let us consider using storage batteries instead of ultra-expensive supercapacitors. With the rated stator current of induction motors of 90 A, the current of the DC link in front of the inverter is

$$90 / 0.817 \approx 110\ \text{A}.$$

Using the obtained DC value of 110 A, we determine the value of the battery capacity:

$$110 \cdot 4.5\ \text{h} \approx 495\ \text{A·h}$$

The number of consecutively in-series batteries will be:

$$8100\ \text{V} / 12\ \text{V} = 675\ \text{units}.$$

Thus, in order to create an electrochemical power storage device (storage battery), it is necessary to use 675 in-series connected batteries of 495 A·h capacity each. The most common batteries are from 55 A·h to a little over 100 A·h. If 5 batteries of 100 A·h capacity are connected in parallel, we can obtain the required total capacity of 100 · 5 = 500 A·h.

Thus, the electrochemical cell battery will consist of 675 · 5 = 3375 batteries. With their average cost of 3000 UAH per unit, the total cost will be:

Total cost = 3375 · 3000 UAH = 10125000 UAH.

Provided that direct savings of 121873, 5 UAH are obtained, we will receive an unacceptably long payback period of 83 years.

3.9 Substantiation of the automation system for controlling mine water drainage modes

Hydraulic systems with centrifugal pumps are mechanisms with very low efficiency, which, together with significant unit power values, results in very large power losses when pumping any fluids. The issue of replacing centrifugal pumps with more energy-efficient types of pumps is not yet being considered.

Any hydraulic system is a system with a rigid structure and configuration and is highly sensitive. Therefore, any changes in any point of the hydraulic system will immediately affect the operation of the entire hydraulic system.

However, the operation of the hydraulic system can change over time without human intervention due to wear of pump wheels, changes in roughness of internal surfaces of pipes due to the abrasive effect of mine water on them, and siltation in the bends of pipelines. These conditions change the parameters of the steady-state mode of the hydraulic system.

The above reasons are taken into account when designing. Nominal parameters of the pumps are matched to those parameters of the nominal mode of the hydraulic network so that the pump operating point is within the permissible range specified by the manufacturer. However, this is not always achieved, because in practice, it is necessary to coordinate the operation of pumps with that of the network.

To avoid unnecessary power losses when adjusting the hydraulic system's operating mode and to ensure precise control of water pumping volumes, frequency converters are installed.

If there is a need for deep regulation of water pumping, frequency converters, perform their direct task - they change the rotation speed of centrifugal pump wheels. The above illustrates power savings that can be realized with a small adjustment of the operating point at the nominal pump performance.

Frequency converters can also be used as starting and accelerating devices to connect one pump to the system. Then the frequency converter switches to start or regulate the motor of the next pump.

This field of application significantly improves technical and economic performance of equipment. Firstly, it eliminates water hammer in the system, and secondly, it prevents direct starts of asynchronous motors. All of these phenomena reduce the service life of equipment.

For asynchronous motors, not only overheating of stator windings and squirrel cages is dangerous, but also electrodynamic shocks in motor windings, which contribute to the destruction of conductor insulation and cause inter-turn short circuits.

However, using single frequency converters (to save initial capital investment) solely to facilitate starting modes is a bad idea.

Having analyzed static characteristics of central pumping station pumps, it is clear that the permissible capacity range is 220 - 360 m^3/h at the nominal impeller speed, the efficiency changes significantly (from 62% to 70%) and the useful pumping power is hundreds of kilowatts (the range increases with increasing fluid pressure).

By shifting the pump's operating point within the permissible performance range, you can change power consumption of the pump motor. This can be achieved by shifting the operating point on efficiency characteristic of the pump drive asynchronous motor.

The constant change in parameters of the hydraulic system (slow due to natural causes and fast due to daily fluctuations in water inflow) necessitates the use of a water drainage automation system.

The automated control system involves the use of sensors and regulators of process parameters. In this case, the main task of the water drainage system is to pump out water with a minimum of power consumption.

The feedback signals, given the configuration of the water drainage system at Kryvorika underground mine, are:

1) current water levels in intermediate water collectors;
2) current intensity of filling water collectors of different levels;
3) current performance of each pump.

The latter parameter should also be controlled based on the fact that the wheel speed can be reduced to such an extent that the generated head may not be sufficient to overcome the resistance of a multi-meter column of water, and the water simply will not go up, i.e. the pump will operate at a "thrust". Having all these parameters, we can strive to reduce the N_2 power as much as possible, while accepting the limitations associated with the ultimate capacity of water collectors and intensity of their filling.

The structure of the water drainage automation system is shown in Fig. 3.18.

Fig. 3.19 depicts a fragment of the structure diagram of the automated control system aimed at minimizing power consumption while maintaining all the remaining water drainage parameters at the proper level.

The considered ACS is part of a multi-hierarchical ACS, which also performs many other tasks besides water drainage. Therefore, in the algorithm block diagram, in addition to the signals from the sensors that are directly related to the water drainage, it is also necessary to constantly poll the control signal from a higher level of the control system.

If the sensors show that the sump has a low water and is filling up rather slowly, it is possible to reduce the intensity of water flowing upward. However, to avoid any surprises, forecast calculations are made to determine whether and when the sump will overflow in the near future. If the forecast is favourable, the control signal of the pump frequency converter is corrected.

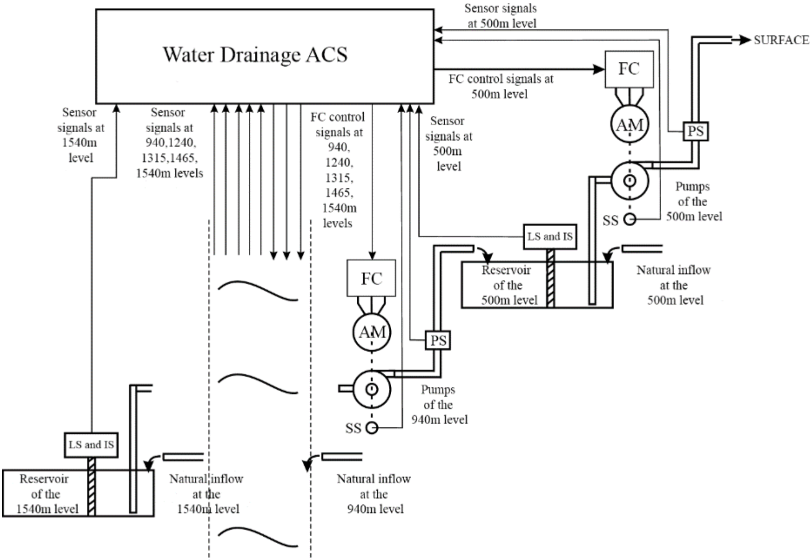


Figure 3.18 – Structure of the water drainage ACS: ACS - automatic control system, LS - level sensor, IS - intensity sensor (water level rise), SS - pump rotor speed sensor, PS - performance sensor, FC - frequency converter, AD - asynchronous motor

It also controls whether the water flow upwards is interrupted (this can happen when the water pressure drops below the maximum permissible level and is not enough to overcome the height of the column to the upper sump). If the flow is interrupted, the previous value of the pump control signal is returned. If the pumping capacity becomes too low compared to the inflow of water into the sump, and calculations show that there is a danger of overflowing, the frequency converter control signal is calculated to accelerate the water darinage from the sump.

However, to further save energy, the pump speed increase should be based on the forecast of the sump capacity. There should not be any haste pumping the water upward if there is a possibility that the water inflow may decrease, which will again reduce power consumption.

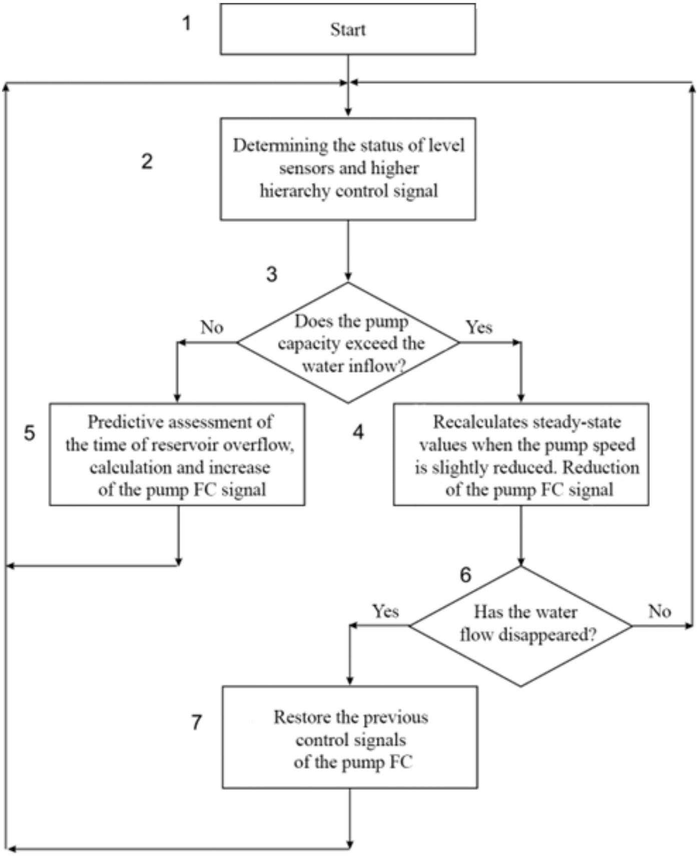


Figure 3.19 – Algorithm for the water drainage ACS

In any case, as a result of the calculations, it should always be possible to force the outflow process from the sump, taking into account probabilistic peak values of water inflow.

CONCLUSIONS TO SECTION 3

1. The starting option for improving technical and economic indicators of mine water drainage is the use of frequency converters as part of their electromechanical complexes. This possibility appears due to successful combination of two points: a positive inclination of characteristics of the active power consumption of asynchronous motors and a negative inclination of the Q-H characteristics of the pumps.

2. The previous advantage is leveled by the fact that energy efficiency of pumping decreases with a decrease in the rotational speed of the pump wheel: the lower the wheel speed, the worse the current energy efficiency of pumping.

3. On the example of the operating Kryvorizka underground mine (Kryvyi Rih) for pumping stations of 500 m, 940 m and 1240 m levels, it is established that the designers of the hydraulic system performed their work ‘perfectly’, the pumps work within the permissible technological ranges set by the manufacturer. Almost all the pumps operate at the maximum flow rate. This allows you to convert the Q-H operating point of pump characteristics from the increased water flow to the reduced one, achieving energy savings sufficient for quick payback of introduction of frequency converters for pump motors.

4. To fully regulate the pump performance from 0 to the maximum value, the minimum range of regulation of the initial frequency of converters (practically from 40 to 50 Hz) is sufficient. At the same time, it is necessary to consider that the dependence of power consumption of a pump on its flow rate is constant, so for a LM 300-600 pump it is characterized by a coefficient of 7128.9 kW·m^3/s.

5. Expectation of significant changes in the operation mode of the hydraulic system when turning on a different number of pumps for a different number of columns turns out to be irrelevant. Water consumption by each pump changes by a maximum of 5.7%, and the power consumed by a single pump – by a maximum of 1.8%. When one, two or three pumps operate for a different number of pipelines, the water flow rate varies in the range of 0.6%, 2.4% and 5.5% respectively. These are insignificant indices. However, they should also be taken into account when developing automation of the MWDC.

6. If the payment for night and daytime periods for power consumed by the MWDC reaches even the minimum difference (in our case, 0.2 UAH/kW), it is still possible to achieve an economic effect of UAH 1.5 mln per year due to the maximum possible shift of pump operating hours in

8 economical (night) hours. However, during these periods four pumps should work.

7. If it is possible to expand the capacity of the tank at the 1240 m level from the initial 4800 m^3 to 7616 m^3, then due to the complete shift of the pump operating hours at night (no pump will work during the day), savings of 3.7 million UAH/year will be achieved only due to the difference of UAH 0.2 at night and daytime tariffs.

8. Considering all of the above, as well as constant variability of parameters of the operation mode of the MWDC, it becomes obvious that the complex requires an ACS to be introduced. Naturally, it should be based on the signals of the system sensors, and, depending on its condition, one should decide whether to turn on one or another of the pumps or adjust them in an appropriate way. Obviously, given the probabilistic nature of the mine water flow, the control system should be based at least on either expert systems or artificial intelligence, which will require further research.

SECTION 4

DEVELOPMENT OF A SYSTEM FOR CONTROLLING POWER CONSUMPTION BY ELECTROMECHANICAL EQUIPMENT OF MAIN WATER DRAINAGE FACILITIES BASED ON THE MAMDANI FUZZY LOGIC INFERENCE ALGORITHM

According to the conclusions outlined in the previous sections of this research, the system for controlling power consumption levels by main water drainage facilities of underground mines should have two inputs: water inflow and power cost (or power production cost in case of distributed generation sources)[4]. The output coordinate in this approach is the power of electromechanical complexes of pumping units that are simultaneously in operation, i.e. their total power.

As mentioned earlier, the power control system of main water drainage facilities of the underground mine can be represented by a MISO-structure with two input (water inflow and power cost) and one output (the power of pumps) variables. Moreover, all three coordinates are subject to expert evaluation. As a result, it is advisable to develop a smart power control system for main water drainage facilities using the Mamdani fuzzy logic inference algorithm.

The research paper aims to synthesize a system for controlling power consumption levels by electromechanical equipment at main water drainage facilities based on the Mamdani fuzzy logic inference algorithm to reduce power costs of an industrial enterprise for the power supplied by an external distribution operator.

4.1 General characteristics of main water drainage facilities of the underground mine as a fuzzy control object

The synthesis of a fuzzy control system for power consumption by main water drainage facilities as part of a mining enterprise can be clearly demonstrated on the example of the Kryvorizka underground mine (Kryvyi Rih). Fig. 1.1 shows main water drainage facilities of the mentioned underground mine, which are placed on appropriate levels and include several

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[4] To effectively implement the research results described in this section into the practice of iron ore underground mines, a number of preventive measures should be taken to ensure that the current structures and parameters of drainage meet their design requirements

pumps, usually of the same type and power. On the same levels, there are additional water reservoirs, the size of which allows accumulating required volumes of mine water entering a specific level from others (deeper ones).

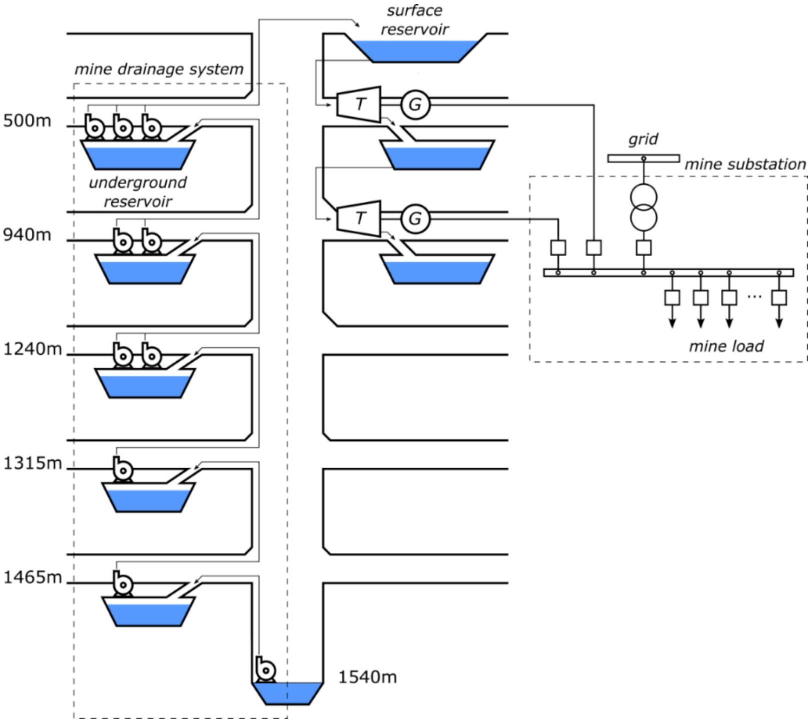

Figure 4.1 – Water drainage of mine water from the internal space of the Kryvorizka underground mine

A 500 m water drainage level is adopted as a control object. Given that this level is the final stage before pumping water to the surface, where water from the entire internal space of the underground mine enters, it is equipped with the largest water reservoir and consequently the most powerful pumps. As a result, it is one of the most energy-intensive consumers of water drainage and the entire underground mine as a whole. The water drainage section of the 500m level contains seven pumps of the CPS-300x600 type with a nominal power of 800 kW each. Due to the reduced production volumes, compared to the design ones observed in recent years, there is a decrease in water inflow to the underground mine (Table 1.1). This caused the need to simultaneously use only three pumps at the maximum water inflow into the working spaces and one or two under normal conditions.

Table 4.1 – Annual groundwater inflow into the Kryvorizka underground mine for 2016-2021

#	Year	Water inflow, m^3/year
1	2016	3281132
2	2017	3709753
3	2018	4416601
4	2019	4619121
5	2020	4784339
6	2021	4673021

After taking into account the above features during fuzzification of the fuzzy system for controlling power consumption by electrical equipment of the 500 m level, let us consider this procedure in more detail.

4.2 Development of a smart expert system for controlling power consumption by main water drainage facilities of the underground mine

4.2.1 Fuzzification of linguistic variables of a fuzzy control system

Each coordinate of the fuzzy logic inference MISO-structure, namely "water inflow", "power tariff" and "pump power" are represented by corresponding linguistic variables.

A finite set *Q*, used to form the membership functions of the linguistic variable "water inflow", is defined on the interval $\{q_i \in \mathbb{R} \,|q_{min} \le q_i \le q_{max}\}$, where $q_{\min}$ and $q_{\max}$, are the minimum and maximum levels of groundwater inflow into the underground mine. We assume that the linguistic variable includes three fuzzy sets: "low inflow" (Q_L), "normal inflow" (Q_N), and "high inflow" (Q_H). Membership functions to the above-mentioned fuzzy sets are formed by piecewise linear functions. This reduces computational complexity while implementing a fuzzy logic inference algorithm. The membership function for the fuzzy set "normal water inflow" is defined as triangular, for the set "high water inflow" as *S*-shaped, and for the set "low water inflow" as *Z*-shaped.

When parametrizing membership functions, the average value of water inflow over 6 years (Table 1.1) is taken as the mean value, which is $q_m = 484{,}85$ m^3/h. We assume that the high water inflow exceeds 2.5 times the normal one, while the low water inflow is twice smaller, and make

$q_l = 1212{,}13$ m^3/h and $q_h = 242{,}43$ m^3/h, respectively. At the same time, we set the minimum value at the level of $q_{\min} = 0$ m^3/h, а максимальне – $q_{\max} = 1500$ m^3/h.

The membership function to the fuzzy set Q_N is defined by the following expression:

$$\mu_{Q_N}(q) = f(q; q_l, q_m, q_h) = \max\left[\min\left(\frac{q-q_l}{q_m-q_l}, \frac{q_h-q}{q_h-q_m}\right), 0\right],$$

while:

$$\mathrm{core}(Q_N) = \{q_m\} = 484{,}85 \text{ m}^3\text{/h},$$
$$supp(Q_n) = \{q \in \mathbb{R} \mid q_l \le q \le q_h\} = 969{,}71 \text{ m}^3\text{/h}.$$

Here is an expression for determining the membership function to the fuzzy set Q_L:

$$\mu_{Q_L}(q) = f(q; q_{\min}-1, q_{\min}, q_l, q_m) = \max\left[\min\left(\frac{q-(q_{\min}-1)}{q_{\min}-(q_{\min}-1)}, 1, \frac{q_m-q}{q_m-q_l}\right), 0\right],$$

while:

$$core(Q_L) = \{q \in \mathbb{R} \mid 0 \le q \le q_l\} = 242{,}43 \text{ m}^3\text{/h},$$
$$supp(Q_L) = \{q \in \mathbb{R} \mid 0 \le q \le q_m\} = 484{,}85 \text{ m}^3\text{/h}.$$

Here is the expression for determining the membership function to a fuzzy set Q_N:

$$\mu_{Q_H}(q) = f(q; q_m, q_h, q_{\max}, q_{\max}+1) = \max\left[\min\left(\frac{q-q_m}{q_h-q_m}, 1, \frac{q_{\max}+1-q}{q_{\max}+1-q_{\max}}\right), 0\right],$$

while:

$$core(Q_H) = \{q \in \mathbb{R} \mid q_h \le q \le q_{max}\} = 287{,}86 \text{ m}^3\text{/h},$$
$$supp(Q_H) = \{q \in \mathbb{R} \mid q_m \le q \le q_{max}\} = 1015{,}15 \text{ m}^3\text{/h}.$$

Given the membership functions to the fuzzy sets Q_L and Q_H both the upper and lower reference values go beyond the limits of the finite set Q, that is, they increase and decrease by one respectively. This is done to avoid dividing by zero cases.

A diagram representation of membership functions to the fuzzy sets of the linguistic variable "water inflow" is shown in Figure 4.2.

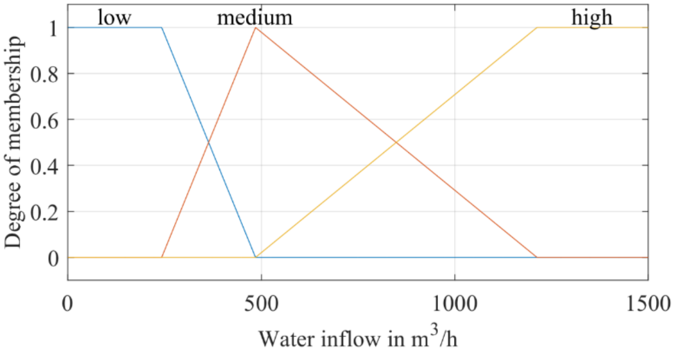

Figure 4.2 – Membership functions to the fuzzy set "water inflow"

The fuzzification of the linguistic variable "power tariff" is performed on the basis of the following considerations. In compliance with the Law of Ukraine *On the Electric Power Market* [1] as of January 07, 2019, a new power cost system for industrial enterprises and distributors was established. This system involves the introduction of an hourly tariff mode, where power cost changes every hour depending on the market condition. What is more, one day in advance, an enterprise orders from a distributor the amount of power that is expected to be consumed during each hour of the following day. This approach is fundamentally different from payments according to tariffs differentiated by time periods, which were in effect before, when the power cost was fixed. At the same time, the analysis of the hourly payment structure allows us to state that it is appropriate to distinguish three zones based on power cost, when its level is high, medium or low. Moreover, the day periods when the specified zones are virtually active coincide with peak, half-peak and night periods. This is explained by the nature of the power load schedule, namely, a high level of power consumption in morning and evening hours, a low level at night and a medium level during daylight hours. Thus, in order to formalize the fuzzy control algorithm, we differentiate the power cost in the "peak", "half-peak" and "night" zones.

As reference values for assigning membership functions for the linguistic variable "power tariff", we will use the tariff values set by the power distributor DTEK Dniprovski Elektromerezhi [2]. Also, we use the data for the case of centralized power supply and for the case of the installed distributed generation facilities. In the latter case, this variable is equivalent to the cost of power production.

For the consumers of the first voltage type, namely from 35 kW and higher, at the limit of balance distribution, which includes the Kryvorizka mine, the tariff of $c_{HP} = 0{,}13788$ UAH/kW·h has been effective since January 01, 2022. This value will determine the power cost in the "half-peak" zone. Accordingly, the "peak" tariff is 1.5 times higher than the "half-peak" one, and the "night" tariff is 0.4 times lower. They are $c_{PK} = 0{,}20682$ UAH/kW·h and $c_{NT} = 0{,}055152$ UAH/kW·h respectively. These three values are used as references when forming membership functions and their further parameterizing.

The linguistic variable "power cost" is defined by a finite set on the interval $\{c \in \mathbb{R} | c_{min} \le c \le c_{max}\}$, and $c_{\min} = 0$ UAH/kW·h, $c_{\max} = 0{,}3$ UAH/kW·h. Let us represent the variable as three fuzzy sets - "night zone", "half-peak zone" and "peak zone".

The membership function to the fuzzy set "night zone" is defined as *Z*-shaped:

$$\mu_{C_{NT}}(c) = f\left(c; c_{\min}-1, c_{\min}, c_{NT}, c_{HP}\right) = \max\left[\min\left(\frac{c-\left(c_{\min}-1\right)}{c_{\min}-\left(c_{\min}-1\right)}, 1, \frac{c_{HP}-c}{c_{HP}-c_{NT}}\right), 0\right],$$

where:

$core(C_{NT}) = \{c \in \mathbb{R} \mid 0 \le c \le c_{NT}\} = 0{,}055152$ UAH/kW·h,
$supp(C_{NT}) = \{c \in \mathbb{R} \mid 0 \le c \le c_{HP}\} = 0{,}13788$ UAH/kW·h.

The membership function to the fuzzy set "half-peak zone" is triangular and has the following characteristics:

$$\mu_{C_{HP}}(c) = f\left(c; c_{NT}, c_{HP}, c_{PK}\right) = \max\left[\min\left(\frac{c-c_{NT}}{c_{HP}-c_{NT}}, \frac{c_{PK}-c}{c_{PK}-c_{NT}}\right), 0\right],$$

while:

$\mathrm{core}\left(C_{HP}\right) = \left\{c_{HP}\right\} = 0{,}13788$ UAH/kW·h,
$supp(C_{HP}) = \{c \in \mathbb{R} \mid c_{NT} \le c \le c_{PK}\} = 0{,}151668$ UAH/kW·h.

The membership function to the fuzzy set "peak zone" is S-shaped and has the following characteristics:

$$\mu_{C_{PK}}(c) = f\left(c; c_{HP}, c_{PK}, c_{\max}, c_{\max}+1\right) = \max\left[\min\left(\frac{c-c_{HP}}{c_{PK}-c_{HP}}, 1, \frac{c_{\max}+1-c}{c_{\max}+1-c_{\max}}\right), 0\right],$$

while:

$core(C_{PK}) = \{c \in \mathbb{R} \mid c_{PK} \le c \le c_{max}\} = 0{,}09318$ UAH/kW·h,
$supp(C_{PK}) = \{c \in \mathbb{R} \mid C_{HP} \le c \le c_{max}\} = 0{,}16212$ UAH/kW·h.

A diagram representation of membership functions to the fuzzy sets of the variable "power tariff" is in Fig. 4.3.

The output coordinate of the fuzzy power consumption control system is the total output power consumed by the drainage pumps. Moreover, it is advisable to focus on the value of this electrical parameter, and not on the number of units that are operated at a time as modern electric drives of pumps are equipped with semiconductor frequency inverters making it possible to adjust the output power of flow-generation mechanisms over a wide range.

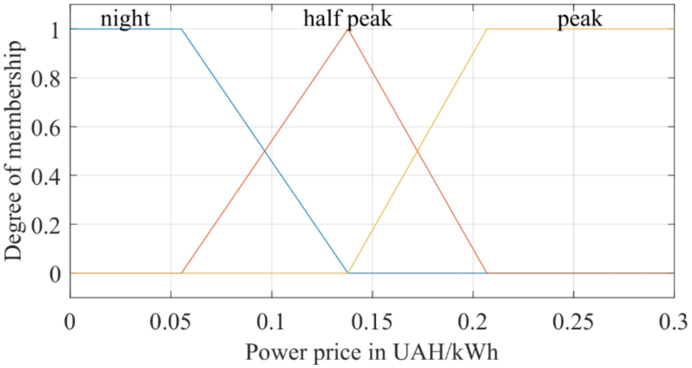

Figure 4.3 – Membership functions to the fuzzy set "power tariff"

According to the static characteristics $P = f(Q)$ of the CNS-300x600 pump, its operating performance for the nominal angular rotation frequency of 1485 rpm is within efficiency limits of 220-360 m^3/h with a power change range of 625-825 kW. Taking into account the fact that one to three pumps are used for water drainage, the final set for the linguistic variable "pump power" should be determined on the interval $\{p \in \mathbb{R} \mid p_{min} \le p \le p_{max}\}$, where $p_{\min} = 625$ kW is a lower level of drainage capacity, which corresponds to the minimum power of one CNS (centrifugal) pump, $p_{\max} = 2475$ kW, i.e. when all three pumps work with the highest performance and at maximum power.

During fuzzification, we represent the linguistic variable "pump power" as three fuzzy sets corresponding to the total power consumed by one, two or three pumps. All three membership functions to the fuzzy sets are defined as triangles and the fuzzification procedure is performed.

The membership function to the fuzzy set "power of one pump" is defined by the following expression:

$$\mu_{P_{OP}}(p) = f(p; p_{\min}, p_{nom}, p_{\max} + p_{\min}) = \max\left[\min\left(\frac{p - p_{\min}}{p_{nom} - p_{\min}}, \frac{p_{\max} + p_{\min} - p}{p_{\max} + p_{\min} - p_{nom}}\right), 0\right],$$

while:

$\operatorname{core}(P_{OP}) = \{p_{nom}\} = 800$ kW,

$supp(P_{OP}) = \{p \in \mathbb{R} \mid p_{min} \leq p \leq p_{max} + p_{min}\} = 825$ kW.

The peculiarity of this function is that the upper reference value is taken in such a way that one pump is supposed to work at maximum power, while the second one additionally drains water with the minimum permissible power consumption, i.e. $q_{\max} + q_{\min} = 1425$ kW.

The following membership function to the fuzzy set "power of two pumps" is formulated from the following considerations. The reference value of the lower limit is taken considering the fact that both pumps will work simultaneously at the minimum of their operating characteristics, so their power will be $2 \cdot p_{\min} = 1250$ kW. The reference value of the upper limit is set assuming that two pumps will work simultaneously at the maximum working section of the static characteristics, and the third is put into operation at the minimum, i.e. $2 \cdot p_{\max} + p_{\min} = 2275$ kW. As a result, the membership function is as follows:

$$\mu_{P_{TP}}(p) = f(p; 2p_{\min}, 2p_{nom}, 2p_{\max} + p_{\min}) =$$

$$= \max\left[\min\left(\frac{p - 2p_{\min}}{2p_{nom} - 2p_{\min}}, \frac{2p_{\max} + p_{\min} - p}{2p_{\max} + p_{\min} - 2p_{nom}}\right), 0\right],$$

while:

$\operatorname{core}(P_{TP}) = \{2p_{nom}\} = 1600$ kW,

$supp(P_{OP}) = \{p \in \mathbb{R} \mid 2p_{min} \leq p \leq 2p_{max} + p_{min}\} = 1025$ kW.

Similarly, the membership function to the fuzzy set "power of three pumps" is given. At the same time, it is assumed that the reference value for the lower limit involves the operation of three pumps with the minimum power consumption of $3 \cdot p_{\min} = 3 \cdot 625 = 1875$ kW, and for the upper limit - three pumps with the maximum power $3 \cdot p_{\max} = 3 \cdot 825 = 2475$ kW:

$$\mu_{P_{TRP}}(p) = f(p; 3p_{\min}, 3p_{nom}, 3p_{\max}) =$$

$$= \max\left[\min\left(\frac{p-3p_{\min}}{3p_{nom}-3p_{\min}}, \frac{3p_{\max}-p}{3p_{\max}-3p_{nom}}\right), 0\right],$$

while:

$\mathrm{core}(P_{TRP}) = \{3p_{nom}\} = 2400$ kW,

$supp(P_{TRP}) = \{p \in \mathbb{R} \mid 3p_{min} \le p \le 3p_{max}\} = 600$ kW.

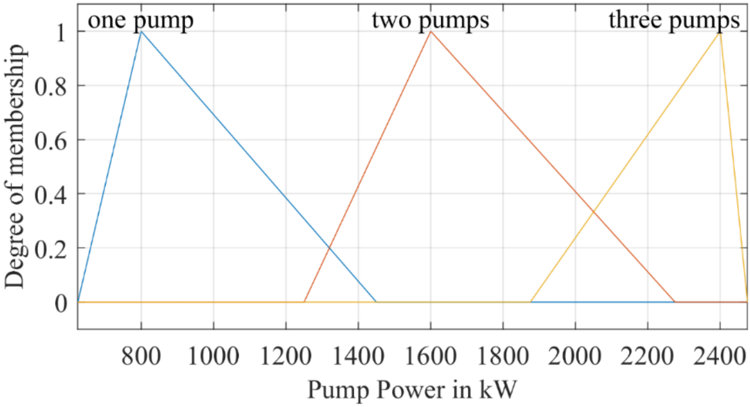

Figure 4.4 – Membership functions to the fuzzy set "pump power"

For the first two membership functions, the upper limit includes an extra pump operation with a minimum power consumption, when intervals that do not belong to any fuzzy set defined for the linguistic variable emerge in the system of fuzzy logic inference in the domain of the finite set. For example, the upper reference value for the membership function to the fuzzy set "power of one pump" should be given at $q_{\max} = 825$ kW. However, the lower limit of the function to the fuzzy set "power of two pumps" is $2q_{\min} = 1250$ kW. As a result, the power range from 825 kW to 1250 kW does not belong to any fuzzy set, which greatly reduces control flexibility.

4.2.2 Synthesis of the rule base for the fuzzy inference system

On completing the fuzzification phase, it is necessary to form the rule base of the Mamdani fuzzy inference system. This procedure is carried out taking into account technological requirements for operating modes of mine water drainage. The key requirement is to ensure the efficient groundwater pumping, depending on intensity of its inflow into the underground mine. This is done to avoid flooding a shaft and mine levels, as it creates a danger to human life and makes it impossible to carry out technological operations of rock mass mining. Therefore, the highest level of significance is given to those comprising the fuzzy set "high inflow".

Since the system has two inputs, the conditional part of the base rules uses fuzzy AND conjunction operators to establish a logical relationship between the input variables of the fuzzy inference system.

Let us formalize the rules.

In all cases, if there is a high water inflow into the underground mine, all three pumps must be put into operation, regardless of the current power tariff. Moreover, the significance of this block of rules is 1, which determines the highest importance of these rules. As a result, they have the following form:

$$\text{R1}: \textbf{IF}\left(q \text{ is } H\right) \textbf{AND} \left(c \text{ is } NT\right) \textbf{THEN } p \text{ is } TR;$$

$$\text{R2}: \textbf{IF}\left(q \text{ is } H\right) \textbf{AND} \left(c \text{ is } HP\right) \textbf{THEN } p \text{ is } TR;$$

$$\text{R3}: \textbf{IF}\left(q \text{ is } H\right) \textbf{AND} \left(c \text{ is } PK\right) \textbf{THEN } p \text{ is } TR.$$

Given a normal water inflow, the output power consumption of pumps depends on the current tariff. It is expedient to pump out water with maximum efficiency at the "night" tariff with all three pumps of a level, at the "half-peak" tariff with two, and at the "peak" tariff with only one. The significance of this block of rules is 0.75. As a result, the rules have the following form:

$$\text{R4}: \textbf{IF}\left(q \text{ is } M\right) \textbf{AND} \left(c \text{ is } NT\right) \textbf{THEN } p \text{ is } TR;$$

$$\text{R5}: \textbf{IF}\left(q \text{ is } M\right) \textbf{AND} \left(c \text{ is } HP\right) \textbf{THEN } p \text{ is } TW;$$

$$\text{R6}: \textbf{IF}\left(q \text{ is } M\right) \textbf{AND} \left(c \text{ is } PK\right) \textbf{THEN } p \text{ is } ON.$$

Regardless of power costs, it is advisable to drain water with only one pump at low water inflow, so the following set of rules looks like this:

$$\text{R7}: \textbf{IF}\left(q \text{ is } L\right) \textbf{AND} \left(c \text{ is } NT\right) \textbf{THEN } p \text{ is } ON;$$

$$\text{R8}: \textbf{IF}\left(q \text{ is } L\right) \textbf{AND} \left(c \text{ is } HP\right) \textbf{THEN } p \text{ is } ON;$$

$$\text{R9}: \textbf{IF}\left(q \text{ is } L\right) \textbf{AND} \left(c \text{ is } PK\right) \textbf{THEN } p \text{ is } ON.$$

The significance of this block of rules is 0.75 as well.

Table 4.2 summarizes the fuzzy rules.

Table 4.2 – AND-type rule base of the fuzzy system controlling power consumption by water drainage facilities

	NT	HP	PK
L	ON	ON	ON
M	TR	TW	ON
H	TR	TR	TR

The output surface of the Mamdani fuzzy inference system with nine **AND** rules is shown in Fig. 4.5.

For comparison, let us synthesize the rule base using the fuzzy disjunction operator OR. Water drainage facilities will consume the maximum power either at high water inflow or during the "night" tariff, and the minimum power either at low water inflow or at the "peak" tariff. Similarly, we formulate the rule for normal water inflow and the "half-peak" tariff.

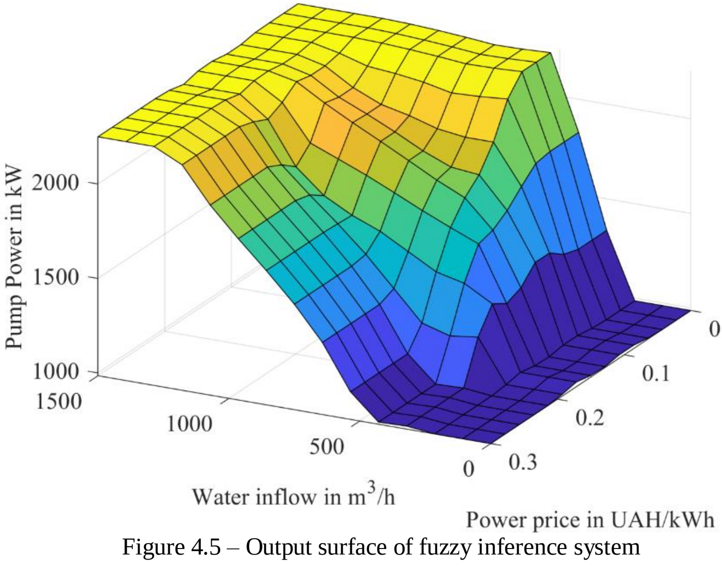

Figure 4.5 – Output surface of fuzzy inference system

The resulting rule base is as follows:

$$\mathrm{R1:}\,\mathbf{IF}\,(q\ \text{is}\ L)\,\mathbf{OR}\,(c\ \text{is}\ PK)\,\mathbf{THEN}\ p\ \text{is}\ ON;$$

$$\mathrm{R2:}\,\mathbf{IF}\,(q\ \text{is}\ M)\,\mathbf{OR}\,(c\ \text{is}\ HP)\,\mathbf{THEN}\ p\ \text{is}\ TW;$$

$$\mathrm{R3}: \mathbf{IF}\ (q \text{ is } H)\ \mathbf{OR}\ (c \text{ is } NT)\ \mathbf{THEN}\ p \text{ is } TR.$$

The first rule R1 has the significance of 1 and the other two – 0.75.

It should be noted that this approach does not cover all possible combinations of value pairs of input variables.

The output surface of the Mamdani fuzzy inference system with three OR-type rules is shown in Figure 4.6.

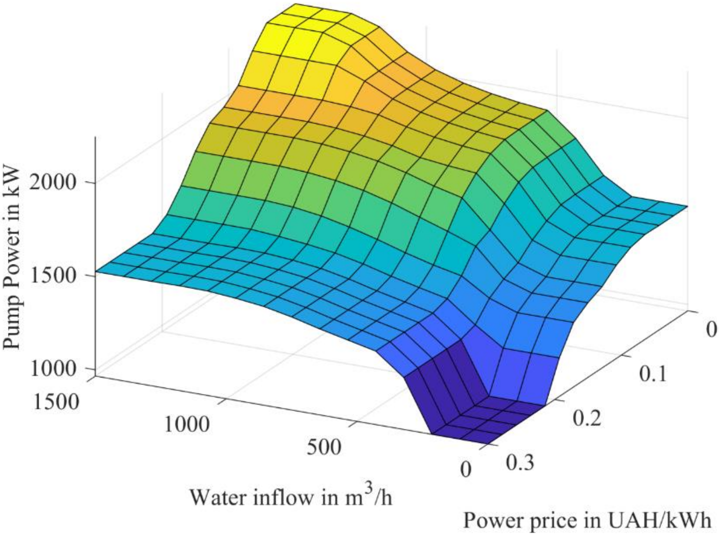

Figure 4.6 – Output surface of the fuzzy inference system

4.3 Modelling the expert system for controlling power consumption by main water drainage facilities of the underground mine

Let us analyze the efficiency of the fuzzy power consumption control system of the 500 m level. To do this, we will implement the system in MATLAB/FuzzyLogicToolbox and simulate its operation.

As a test signal for the input coordinate "water inflow", we use a stochastic process of a random variable. The law of probability distribution is assumed to be normal with mathematical expectation $\mathrm{E}[Q]=500$ m^3/h and variance $\sigma^2 = D[Q] = 200$ m^3/h. The state of the pseudorandom number generator is recorded by the software to ensure representativeness when comparing several control systems. Therefore, the stochastic process implementation will be conditionally constant for all experiments.

The test signal for the input variable "power tariff" is generated by distributing tariff zones during the day. That is, the "night" zone is effective for 8 hours from 23.00 to 7.00, the "half-peak" zone - 11 hours from 7.00 to 8.00, from 11.00 to 20.00 and from 22.00 to 23.00, the "peak" zone - 5 hours from 8.00 to 11.00, from 20.00 to 22.00. To simplify, we assume that the underground mine is supplied with electric power in a centralized way by an external distributor, so the test signal has a stable periodic nature.

A comparative analysis will be performed for fuzzy logic inference systems with AND- and OR-type rule bases, as well as with a system without power consumption control, in which two pumps with nominal performance and power are simultaneously operated on the level throughout the day.

The system operation is modeled during a week and a month.

The results of the experiments are summarized in Tables 4.3 and 4.4 and presented in Fig. 4.7-4.10.

Table 4.2 – Modelling results of power consumption fuzzy control by the water drainage facilities of the level over 7 days

Power consumption control type	Medium power, kW	Maximum power, kW	Power consumption, kW*h	Power cost, UAH
No control	1600	1600	268800	33510.36
With fuzzy logic inference system and OR-type rule base	1646.1	2078.18	276545.37	32878.18
With fuzzy logic inference system and AND-type rule base	1644.23	2243.57	276230.13	32125.55

The obtained results of the water drainage modelling over a week (Table 4.3) demonstrate that when using fuzzy power consumption control systems, power costs decrease, compared to the system without such control.

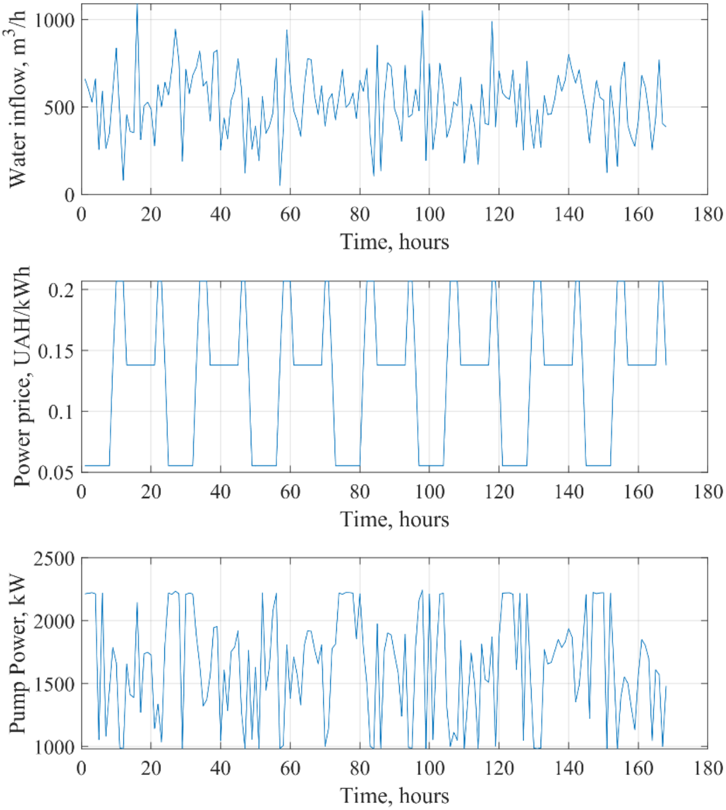

Figure 4.7 – Results of modelling the operation of the water drainage power consumption control system based on the Mamdani fuzzy logic inference algorithm with the AND-type rule base over 7 days

The controlled system that uses the fuzzy logic inference algorithm with the OR-type rule base provides 1.89% (or UAH 632.18 in monetary value) lower level of power cost over a week than the uncontrolled one, and the use of the AND-type rule base - by 4 .13% (or by UAH 1.384). If we compare smart expert systems with each other, the system with the AND-type rule base is more cost-effective. It provides 2.29% (UAH 752.63) lower power costs than the system with the OR-type rule base.

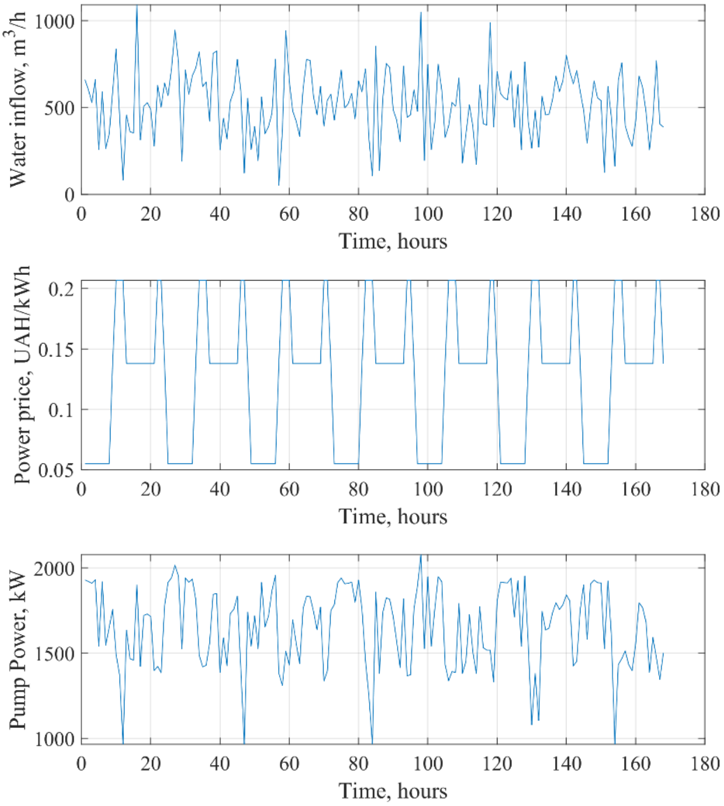

Figure 4.8 – Results of modelling the operation of the water drainage power consumption control system based on the Mamdani fuzzy logic inference algorithm with the OR-type rule base over 7 days

This trend persists if we consider a longer period, for example, a month (Table 4.4). Moreover, the level of savings on power costs is only increasing. Thus, the fuzzy system with the OR rule base allows reducing power costs by 2.28% (by UAH 3379.66), the system with the AND-type rule base – by 5.43% (by UAH 8058.36). That is, the percentage ratio increases for both systems by 0.39% and by 1.3% compared to the week's operation. The cumulative nature of the economic effect is observed. At the same time, the AND-type rule base system provides 3.23% (or UAH 4,678.7) lower total cost of the produced power compared to the OR-type rule base system.

Table 4.3 – Modelling results of power consumption fuzzy control by the water drainage facilities of the level over 31 days

Power consumption control type	Medium power, kW	Maximum power, kW	Power consumption, kW*h	Power cost, UAH
No control	1600	1600	1190400	148403
With fuzzy logic inference system and OR-type rule base	1639.03	2078.18	1219441.7	145023.34
With fuzzy logic inference system and AND-type rule base	1623.65	2243.57	1207996.01	140344.64

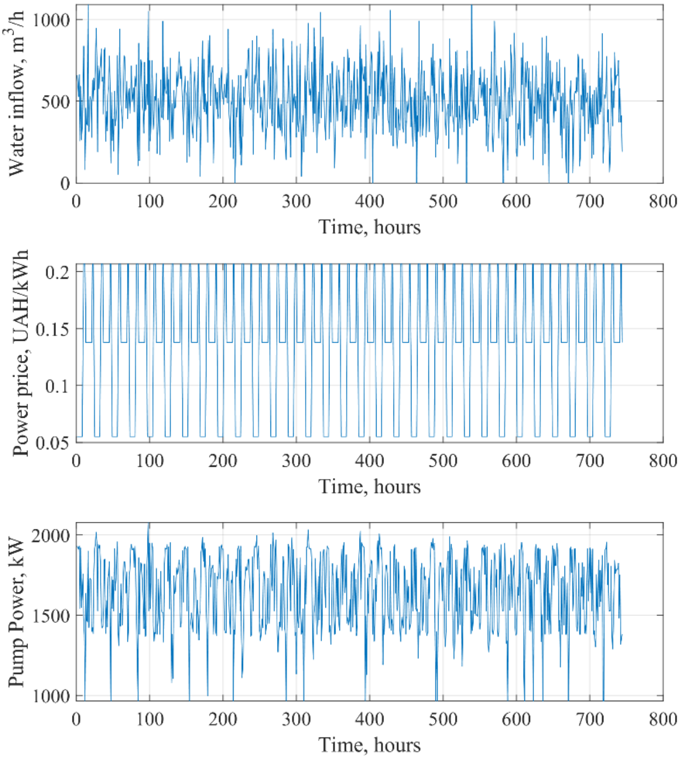

Figure 4.9 – Results of modelling the water drainage power consumption control system based on the Mamdani fuzzy logic inference algorithm with the OR-type rule base over 31 days

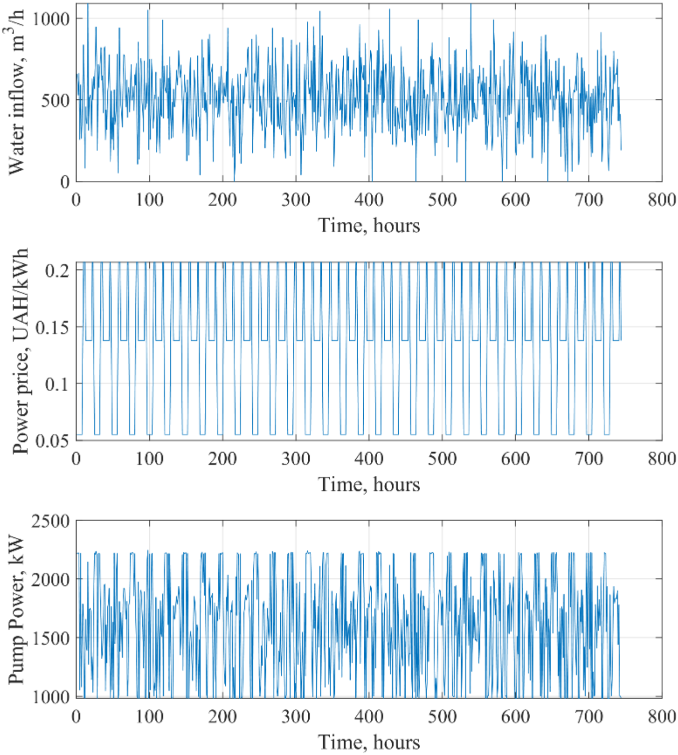

Figure 4.10 – Results of modelling the the water drainage power consumption control system based on the Mamdani fuzzy logic inference algorithm with the AND-type rule base over 31 days

Two characteristic features of fuzzy control systems of water drainage power consumption at underground mines should be noted. The average power of the facilities at the mine level almost does not deviate from 1600 kW during the considered periods of operation. What is more, the power consumption level of uncontrolled systems is lower. This is due to the fact that in fuzzy control systems, power is consumed unevenly and there are long periods when the water inflow is high and three pumps are running at the same time, which leads to an increased level of power consumption. However, the fuzzy control algorithm allows increasing economic efficiency of the system due to the transfer of the high power consumption period to the "night" tariff time, thereby reducing the total cost of produced power.

CONCLUSIONS TO SECTION 4

1. The proposed expert control system of power consumption by main water drainage facilities of the underground mine based on the Mamdani fuzzy logic algorithm demonstrates its expected economic efficiency. Correspondingly, it is to be recommended for implementation at the relevant facility of iron ore underground mines.

2. The higher quality of control is demonstrated by the system with a conjunction-type fuzzy rule base. The level of power consumption in the uncontrolled system is lower due to uniformity of output power distribution by electromechanical drainage facilities during the day.

3. Further improvement of fuzzy control systems consists in increasing energy efficiency, i.e. reducing power consumption by main water drainage facilities of underground mines, which can be achieved by introducing an additional limitation for the power level of pumps running simultaneously during fuzzification of the corresponding linguistic variable. The developed fuzzy algorithm can be applied to controlling a peak pumped-storage power plant of main water drainage facilities of underground mines.

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Scientific publication

Vladyslav Baranovskyi

STARTING POSITIONS TO IMPROVE ENERGY EFFICIENCY OF MAIN WATER DRAINAGE FACILITIES OF IRON ORE UNDERGROUND MINES

MONOGRAPH

Supervised by DSc. (Engineering), Prof. Sinchuk O.

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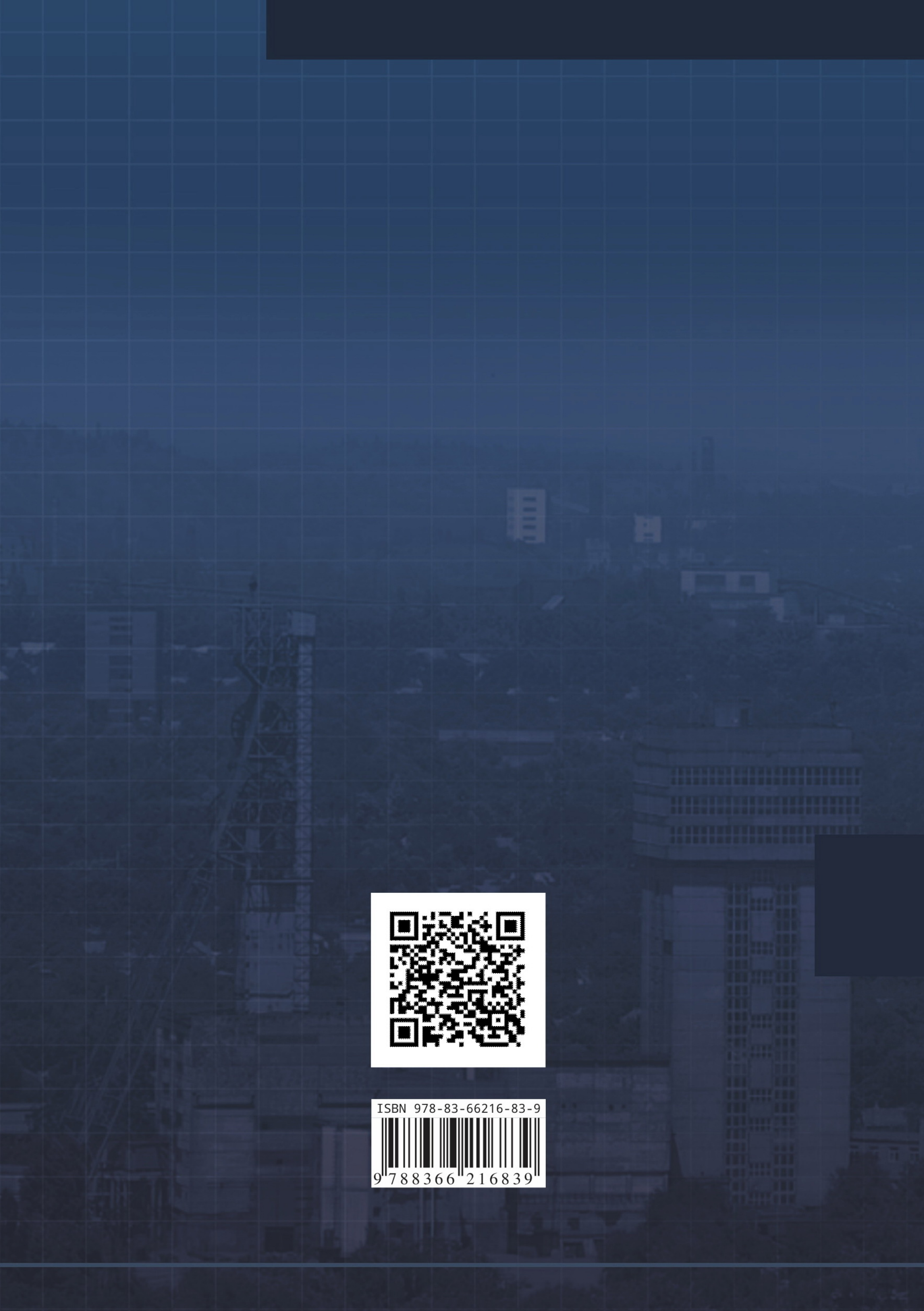

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