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ELECTRIC ENGINEERING OF IRON ORE UNDERGROUND ENTERPRISES. CURRENT STATUS AND PROSPECTS

Multi-authored monograph

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Electric engineering of iron ore underground enterprises. Current status and prospects. Multi-authored monograph / I.O. Sinchuk, F.I. Karamanyts, Yu.G. Osadchuk, M.L. Baranovska, S.M. Boiko, Yu.B. Filipp, I.V. Kasatkina, A.M. Yalova, V.O. Fedotov, T.M. Beridze; Edited by DSc., Prof. O.M. Sinchuk. – Warsaw: iScience Sp. z o. o. – 2019. – 122 p.

The monograph provides assessment of energy efficiency of Ukrainian iron ore mining enterprises. Load curves and ways to increase energy efficiency in mining are under consideration. Updating and development of advanced methods of calculating power loads of iron ore underground enterprises are substantiated.

The monograph targets electric engineering and mining students, specialists working in the mining industry, research institutes and design bureaus.

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This book is dedicated to
PETRO SAVORSKYI,
a famous Ukrainian miner and innovator,
a great and sincere person, who created
the entire epoch of Kryvyi Rih iron
ore mining.

A word to the Reader

Another monograph. How many of them? Honestly, I did not count. There were too many. The authors of this one are mostly my pupils including my colleagues and friends. What is the purpose of writing this book? What is the target audience? As authors, we did not consider these issues while working at this paper. We target a wide range of specialists - electricians, mining technologists, students, postgraduates, etc. We also hope to be satisfied by the work done and would be glad if someone finds this work useful.

I want both our friends and foes to read this book. People may either praise it or criticize. In any case we hope our readers to appreciate our efforts.

The main thing is it is worth reading.

O. Sinchuk

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LIST OF ABRIVIATIONS

MRP	Mechanical-repair plant
SHP	Skip hoisting plant
CSP	Crushing and sizing plant
RCPCMD	Regional compressor plant of central mine drainage
CUS	Central underground substation
MSDS	Main step-down substation
SUS	Site underground substation
KZRK	Kryvyi Rih Iron Ore Works
HVL	High-voltage line
MSS	Main step-down substation
CS	Central substation
CDCP	Central distribution control point
SUS	Site underground substation
L	Line
M	Motor
HVL	High-voltage line
CDCP	Central distribution control point
LDD	Line disconnecting device
BDD	Busbar disconnecting device
IS	Isolating switch
SC	Short-circuitor
ER	Earth rod
S	Switch
PDC	Power distribution cabinet
HVL	High-voltage line
SDC	Section disconnecting device
BS	Busbar section
IM	Induction motor
DCM	DC motor
SM	Synchronous motor
CLE	Caunen-Loeve expansion
MPC	Method of principal components
GM	Generator-motor
TC-M	Thyristor converter-motor
FC-SM	Frequency converter-synchronous motor

INTRODUCTION

The commodity sector of Ukraine's economy is a basic element in forming the country's foreign exchange reserves with iron ore materials prevailing [1–3].

Constant increase of iron ore costs is expected judging from the state's current strategy of raising power tariffs for iron ore mining enterprises as well. This will raise doubts about this industry's potential and prospects of its competitiveness on the world market of raw materials [1–3]. For example, in 2014-2015, power tariffs increased by a factor of 1,5 causing the growth of iron ore costs by more than 40 % on average [1–3].

Another important factor indicates that in spite of its recent decreasing tendency, Ukraine's industry consumption makes 42 % of the country's total power volume. The national industry comprises 51 metallurgical, mining, oil and gas enterprises consuming almost 32 % of all the power among other power-intensive enterprises under the supervision of "Derzhenerhonagliad" (the State Electric Inspection Service). It has a crucial impact on forms of daily load curves of national power systems and efficiency indices of energy transportation from the systems to consumers.

While increasing energy consumption efficiency, it is essential to engage all enterprises, especially power-intensive ones, in forming load curves of power systems.

The problem of increasing energy efficiency at mining enterprises including ore mining ones is to be considered in the context of developing knowledge on qualitative properties of this complex process of power supply and consumption. This is inseparably associated with the issue of assessing power consumption modes, which is topical for specific conditions of mining operations.

Available methods of assessing power consumption modes follow from theoretical models, which are not quite relevant for describing the process under study. It leads to considerable errors in determining designed power loads and future levels of power consumption. Problems of planning power consumption and saving are typically solved by desktop approaches which ignore cost accounting and application of scientifically grounded indices of power-intensity and -balances of processes and dependencies of power consumption modes on ore mining factors.

The above aspects of energy consumption at mining enterprises call for developing the theory of electrification of these production types on the basis of improved research methods, assessment of power modes and electrical safety conditions.

Research works by V.V. Alekseiev, E.B. Altshuller, Y.H. Badeliov, B.P. Belykh, V.A. Bunko, S.I. Vypanasenko, S.A. Volotkovskyi, L.V. Hladilin, P.F. Kovaliov, N.N. Maksymenko, M.I. Ozernyi, H.H. Pyvniak, A.V. Prakhovnik, H.I. Razhildeiev, V.P. Rozen, O.M. Sinchuk, V.G. Sobolev, N.F. Shyshkin, B.I. Shchutskyi, B.M. Yahudaiev and others created theoretical foundations of efficient and safe power consumption at mining enterprises.

Meanwhile, constant increase of power consumption and mining intensification demand further development of the electrification theory of the mining industry with the improved scientific level of research methods, assessment, simulation, forecasting and calculation of power consumption modes in view, especially under conditions of information ambiguity and deficiency.

Practical aspects of increasing energy efficiency at mining enterprises are also based on improvement of methods of determining designed loads, establishment of a scientifically grounded level of power consumption, increased accuracy of forecasting and planning power consumption indices, decreased losses and power saving, improved safety of electrical complexes and systems of mining enterprises [4, 5].

Thus, theoretical substantiation, assessment and development of methods of ensuring necessary and possible available energy efficiency aimed at maximum realization of power-saving potential within current and designed power-supply and consumption systems of underground iron ore mining enterprises are urgent and timely scientific tasks

SECTION 1 ASSESSMENT OF ENERGY EFFICIENCY AT OPERATING IRON ORE MINING ENTERPRISES

1.1 Initial statements and key ideas

Iron ore mining enterprises are considered specific when mining conditions dictate severe requirements to the quality of power transported by power-supply systems and associated with a complex of problems [4, 6–11].

Production intensification, which has become evident in the recent decade due to complicated mineral mining and technical conditions, calls for constant increase of power consumers' capacity causing further decrease in electric power quality, which does not meet accepted standards. According to the above mentioned, there arises a necessity to develop theoretical aspects and a complex of practical measures to increase power quality of iron ore underground mining enterprises' mains to reach optimal values.

It is evident that under current conditions, a shared desire of both designers and consumers to create high-quality technical mining facilities makes no sense if corresponding efficiency of power-supply and consumption is not provided. Besides, power supply should be considered one of the basic systemically important elements of any modern industrial complexes, which is particularly true for mining ones. Thus, requirements to energy efficiency should meet some standards [7–9].

Quality increase is a priori associated with extra expenses. It is evident that under current conditions of society and technology development, economic factors are crucial in solving the problems of increasing quality. In designing and operating power-supply systems, it is necessary to meet GOST (national standards) requirements and achieve efficiency indices of power supply which are reasonable in economic terms. There might be some exceptions when entities with minimum acceptable indices of energy efficiency are determined to avoid accidents and other adverse consequences. Even in this case, quality is achieved by economically grounded methods.

As is known, issues of energy efficiency became of particular importance in the late 1960s after the introduction of 13109-67 GOST for "Standards of energy efficiency indices for receivers connected to general service electricity mains". It indicated acceptable values and limits of changing indices of energy efficiency. It was the first official document of national electric engineering which standardized energy efficiency indices.

In the recent two decades, the number of similar legislative acts has increased, yet, without any positive consequences on a practical level.

It was the problem of low energy efficiency at iron ore mining enterprises itself that provided one of the clues for solving it. Application of 660 V at underground mines became a solution providing some advantages and a considerable technical end economical effect. Introduction of 660 V is one of the most important tasks to solve at industrial enterprises calling for creative efforts of both electrical engineering and designing organizations.

The main way to solve the tasks of 660 V transition is to generalize practices of designing 660 V enterprises and prepare advanced designs of electrical equipment and power cables.

Yet, this solution, which was urgent many years ago, has not been applied to designing power-supply systems of iron ore underground mines unlike similar coal mining enterprises.

Moreover, the modern approach to mineral mining at national enterprises owned by various, mostly foreign, companies does not encourage any optimism about this component of increased efficiency to be realized. Due to this abhorrent plan, the issue of choosing economical variants of industrial enterprises' power-supply schemes is the matter of public debates, this confirming their topicality when applied to power-supply systems of deep iron ore mines. In this respect, the choice of an optimal scheme of electric power distribution at mining levels is of primary importance, as a great number of electric drives and their increased loads result in a considerable number of variants and possible great discrepancies between expenses of each variant.

Research reveals that available power consumption systems place limits upon technical potentials of mining machines because of low power quality.

Available schemes and elements of power consumption at underground mines without applying any specific methods and means do not allow increasing energy efficiency to necessary standards.

Considerable deviations of voltage from rated fluctuations are determined by operation of high-power electric drives with abruptly variable impact load, which causes excess power losses, overheating of electric motor windings and their short life.

Further increase of power consumption facilitates efficiency indices which are now above specified standards, affect performance of mining machines resulting in increased electromagnetic and technological components of losses. Due to this, it is of great economic importance to enhance power supply of underground mines according to efficiency criteria through developing steps and methods to control voltage modes according to 13109-97 DSTU.

Increasing energy efficiency of mineral mining by reducing specific consumption of electric power per ton of mined minerals, improving reliability and decreasing the number of current injuries simultaneously are not just ordinary problems, but the issues demanding sustainable solutions. Unfortunately, by 1990-1991, low energy efficiency of mining accompanied by increased levels of current injuries in the industry had been explained by increased growth rates of production. Since 1992, it has had no other reason but ignorance of safe power supply and consumption standards in operating power supply systems, which can be considered illegal in terms of working condition of miners.

Yet, it should be noted that conditions or, to be exact, the approach to solving this set of problems has changed. The necessity to increase volumes of supplied power had been the most essential before. Nowadays, researchers focus their attention on reduced application of established electric machine capacity including that of transformers at all levels of power transformation. This very fact being extremely odious results in a variety of problems ranging from reactive power “wandering” along communication mains to failures of residual current circuit breakers [12].

Analysis of electric power application to various types of mining enterprises has always been subjected to monitoring, which reveals its historical background and scientifically significant results.

It has been found that energy efficiency is determined by a number of factors among other things characterizing accuracy of designed loads, expenses for constructing, operating and updating power-supply systems, specific power-intensity of products, the rate of effective utilization of power, accuracy of forecasting and planning power consumption and power security in technological units of the whole mining cycle.

It has been proven that methods of assessing power consumption modes currently applied and characterized by electrical loads, power intensity of processes, power balances and consumption modes do not consider probability and statistics as well as numerous mining-technical, climatic, meteorological and other factors.

The method-related aspect of increasing energy efficiency calls for the necessity to develop mining enterprises and continue elaborating the theory of adjusting power-supply systems to new conditions. It can be achieved by enhancing the scientific level of methods of assessing, analyzing, simulating and forecasting power consumption, particularly under ambiguous and incomplete data conditions.

The scientific base of increasing energy efficiency of iron ore mining enterprises comprises improvement of methods of calculating electric loads, identification of scientifically grounded specific power expenses, increased accuracy of forecasting and planning of power consumption indices, reduced expenses and power saving, optimization of voltage levels of electric receivers, increased security of operating electric engineering complexes, systems, etc.

Therefore, to assess the status of power use and formulate research tasks it is reasonable to consider methods of assessment, analysis, simulation, forecasting and current security conditions of power consumption at mining enterprises.

Before considering methods applied to research strategy and tactics of studying the mentioned scientific problem, we would like to indicate the following.

Analysis of power consumption at synergetic industrial entities (complexes) of underground, open pit or combined (underground-open pit) mining such as underground mines or integrated works involving mines, open pits, concentration plants and auxiliary departments is unable to provide necessary levels of result validity as above mentioned industrial structures are undergoing constant objective and subjective changes (reorganization or restructuring) at the present time and in the nearest 15-25 years [1–3, 7, 11].

Analysis of power consumption at separate underground mines or open pits as main technological units of an iron ore mining complex is the most realizable and reliable step under current conditions.

The fact that this statement is true and justified is confirmed by real indices of specific power consumption for certain iron ore underground mines of one and the same industrial complex like the PJSC "Kryvyi Rih Iron Ore Works" ("KZRK") that differ much, sometimes by a factor of three (Fig. 1.1-1.6).

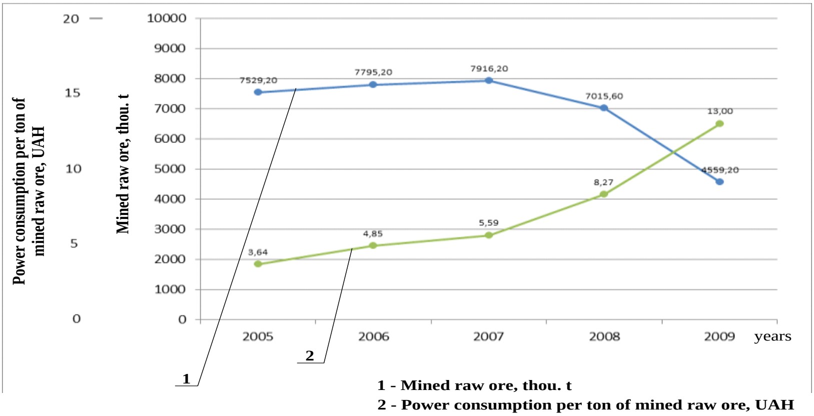


Fig. 1.1. Raw ore output and power consumption per ton of mined ore at the PJSC "Kryvyi Rih Iron Ore Integrated Works" (Kryvyi Rih)

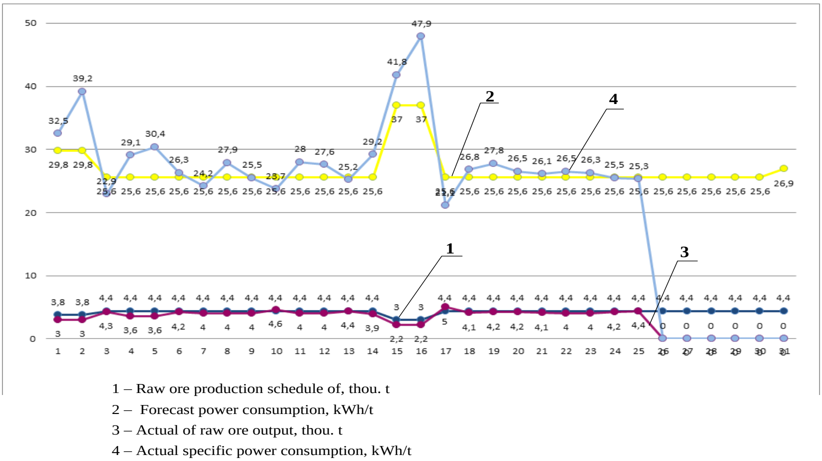
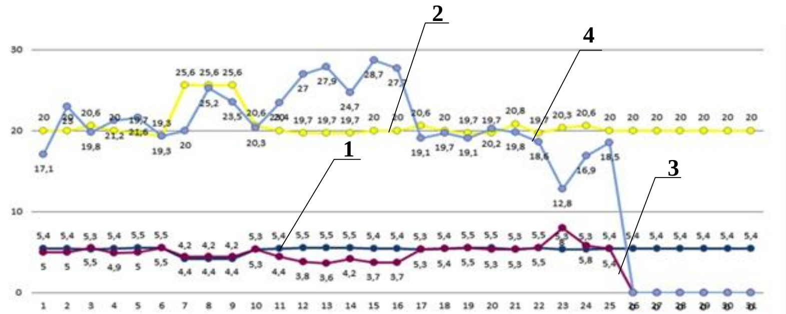


Fig. 1.2. Daily schedules of raw ore production and specific power consumption at Hvardiiska mine, the PJSC "Kryvyi Rih Iron Ore Integrated Works" (Kryvyi Rih)



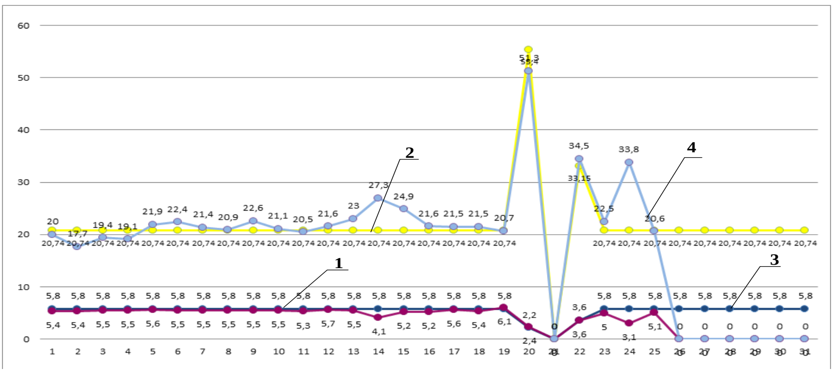
1 – Raw ore production schedule of, thou. t

2 – Forecast power consumption, kWh/t

3 – Actual of raw ore output, thou. t

4 – Actual specific power consumption, kWh/t

Fig. 1.3. Daily schedules of raw ore production and specific power consumption at Hvardiiska mine, the PJSC "Kryvyi Rih Iron Ore Integrated Works" (Kryvyi Rih)



1 – Raw ore production schedule of, thou. t

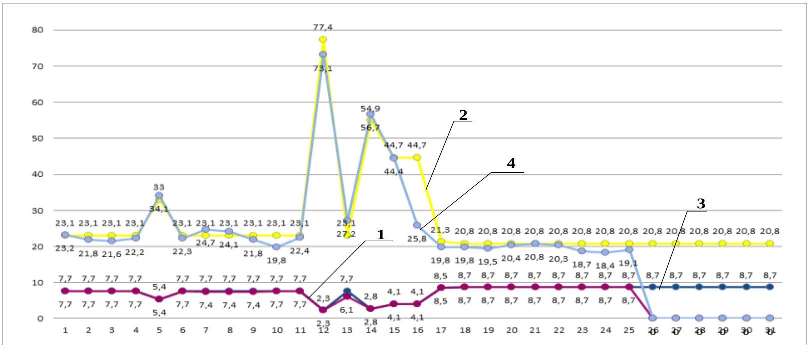
2 – Forecast power consumption, kWh/t

3 – Actual of raw ore output, thou. t

4 – Actual specific power consumption, kWh/t

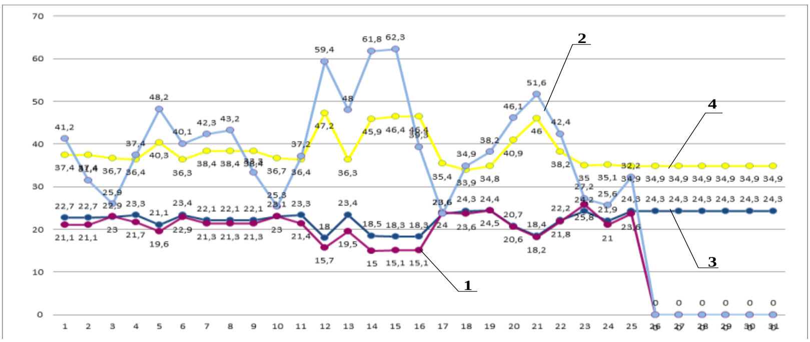
Fig. 1.4. Daily schedules of raw ore production and specific power consumption at Oktiabrska mine, the PJSC "Kryvyi Rih Iron Ore Integrated Works" (Kryvyi Rih)

* At present, Lenin mine is called Hvardiiska



1 – Raw ore production schedule of, thou. t
2 – Forecast power consumption, kWh/t
3 – Actual of raw ore output, thou. t
4 – Actual specific power consumption, kWh/t

Fig. 1.5. Daily schedules of raw ore production and specific power consumption at Rodina mine of the PJSC "Kryvyi Rih Iron Ore Integrated Works" (Kryvyi Rih)



1 – Raw ore production schedule of, thou. t
2 – Forecast power consumption, kWh/t
3 – Actual of raw ore output, thou. t
4 – Actual specific power consumption, kWh/t

Fig. 1.6. Daily schedules of raw ore production and specific energy consumption at the PJSC "Kryvyi Rih Iron Ore Integrated Works (KZRK)" (Kryvyi Rih)

This moment of truth confirms some specific features of national underground iron ore mining enterprises once again and determines designing and updating of their power supply systems (structures).

Unfortunately, there are no generalizing and distinct criteria of power supply and consumption efficiency that can be applied to iron ore mining enterprises. Yet, the following might be considered the basic ones:

– correspondence to and observance of electrical installation and safety codes and other regulatory documents;

– reliability of power supply of electric receivers;

– provision of necessary quality of electric power supplied to electric receivers;

– minimization of power losses during its transportation;

– automated control centralization and possible transition to decentralization in order to improve power modes;

– possible reduction of power consumption through:

– improvement of technological processes;

– application of improved equipment;

– application of controlled electric drives;

– monitoring of power consumption schedules;

– automation of subsystems of power metering both by group and individual electric receivers;

– creation of working capacity and selectivity of current relays, protections, including those for protecting miners against current injuries.

While conducting "framework", yet quite relevant for this research goal, investigation and analysis to determine levels of dependencies of iron ore output and power consumption, the authors indicate the following. Firstly, there are confirmed conclusions drawn by Kalinichenko, PhD (Engineering), and Sinchuk, DSc. (Engineering) in the 1960s and in the 2010s correspondingly as to difficulties in explaining these dependencies. It is definitely determined that reduced output of iron ore causes increase in specific power consumption. Thus, reduction of iron ore output of Oktiabrska mine in 2011 caused the increased consumption rate of electric power by 15.9 $kW \cdot h$/t as compared to the previous year. There are presented data on particular iron ore underground mines of the PJSC "KZRK". For better illustration of ratio levels between iron ore output and power consumption, the Chaddock scale is used [1]. Tables 1.1 – 1.2 provide data for each underground mine.

As to Ternivska underground mine, the strength of relationship between power consumption and marketable ore (0.382295) is noticeable as well as that between power consumption and raw ore (0.381373), which is noticeable as the Chaddock scale in this interval and indicates a noticeable relationship.

The strength of relationship between the consumption rate and marketable ore is 0.99638 (negative, reverse). This index determines a reverse dependency, i.e. increased consumption causes decreased quantity of raw ore, and according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between the consumption rate and salable ore is -0.98388 (negative, reverse).

Table 1.1. Ratio indices of power consumption and iron ore output at the PJSC "KZRK" in 2010-2014

Underground mine	**Power**	**Ore**	**Consumption rate**
		2010	
Oktiabrska	42577.655	1215.0	35.04
Rodina	62841.271	2008.0	31.30
Hvardiiska	38277.751	1648.0	23.23
Ternivska	39753.274	1840.0	21.61
Total	**183450.0**	**6711.0**	
PJSC "KZRK"	**292198,95**	**6711**	**43.54**
		2011	
Oktiabrska	43807.653	1149.0	38.13
Rodina	66385.458	2163.0	30.69
Hvardiiska	41033.967	1499.0	27.37
Ternivska	42224.988	1522.0	27.74
Total	**193452.1**	**6333.0**	
PJSC "KZRK"	**299223.214**	**6333**	**47.25**
		2012	
Oktiabrska	46546.222	2100.0	22.16
Rodina	70501.87	1329.0	53.05
Hvardiiska	44219.223	1608.0	27.5
Ternivska	42102.22	1276.0	33.0
Total	**203369.5**	**6313.0**	
PJSC "KZRK"	**300961.303**	**6313**	**44.67**
		2013	
Oktiabrska	42977.306	1348.0	31.88
Rodina	68458.157	2144.0	31.93
Hvardiiska	41181.327	1437.0	28.66
Ternivska	41229.128	1661.0	24.82
Total	**193845.9**	**6590.0**	
PJSC "KZRK"	**301738.288**	**6590**	**45.79**
		2014	
Oktiabrska	41829.29	1401	29.86
Rodina	68037.221	1905	35.72
Hvardiiska	43544.686	1654	26.33
Ternivska	42161.45	1840	22.91
Total	**195572.6**	**6800**	
PJSC "KZRK"	**307207.123**	**6800**	**45.18**

Table 1.2. Components of the correlation matrix of the PJSC "KZRK"

2010	**Index**	***Power***	***Ore***	***Consumption rate***
	Power	1	0.541478	0.48947327
	Ore	0.5414782	1	-0.4648887
	Consumption rate	0.4894733	-0.46489	1
2011	**Index**	***Power***	***Ore***	***Consumption rate***
	Power	1	0.877298	0.04730084
	Ore	0.8772976	1	-0.4379124
	Consumption rate	0.0473008	-0.437912	1
2012	**Index**	***Power***	***Ore***	***Consumption rate***
	Power	1	-0.313796	0.89080992
	Ore	-0.3137959	1	-0.7085557
	Consumption rate	0.8908099	-0.708556	1
2013	**Index**	***Power***	***Ore***	***Consumption rate***
	Power	1	0.911089	0.55926158
	Ore	0.9110886	1	0.16867867
	Consumption rate	0.5592616	0.168679	1
2014	**Index**	***Power***	***Ore***	***Consumption rate***
	Power	1	0.616275	0.84772942
	Ore	0.6162745	1	0.10536974
	Consumption rate	0.8477294	0.10537	1
PJSC "KZRK"	**Index**	***Power***	***Ore***	***Consumption rate***
	Power	1	0.11710711	-0.04097854
	Ore	0.117107113	1	0.55295915
	Consumption rate	-0.040978543	0.55295915	1
	Consumption rate	1	0.11710711	-0.04097854

This index indicates a reverse dependency, i.e. increased consumption causes decreased quantity of raw ore, and according to the Chaddock scale, the strength of relationship is high.

The strength of relationship between power consumption and marketable ore output at Hvardiiska underground mine is 0.655561, which can be characterized as good. The strength of relationship between power consumption and raw ore output of 0.74776 is high. The strength of relationship between power consumption and marketable ore is -0.98728 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make quantity of marketable ore decrease and according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between power consumption and marketable ore output is -0.96012 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make the quantity of raw ore decrease and according to the Chaddock scale, the strength of relationship is quite high.

For Oktiabrska mine, the strength of relationship between power consumption and marketable ore output is -0.12393 (negative, reverse), i.e. increased power consumption makes quantity of marketable ore decrease and, according to the Chaddock scale, the strength of relationship is weak.

The strength of relationship between power consumption and raw ore output is -0.09678 (negative, reverse), i.e. increased consumption makes the quantity of raw ore decrease and, according to the Chaddock scale, the strength of relationship is weak.

The strength of relationship between power consumption rates and marketable ore output is -0.97438 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make the quantity of marketable ore decrease and according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between energy consumption and raw ore production is -0.12393 (negative, reverse), which indicates a reverse dependency, i.e. increased energy consumption rates make the quantity of raw ore decrease and, according to the Chaddock scale, the strength of relationship is weak.

The strength of relationship between energy consumption and salable ore production is -0.30975 (negative, reverse), i.e. increased power consumption makes the quantity of marketable ore decrease and according to the Chaddock scale, the strength of relationship is noticeable.

The strength of relationship between power consumption and raw ore output is -0.28581 (negative, reverse), i.e. increased consumption makes the quantity of raw ore decrease and, according to the Chaddock scale, the strength of relationship is weak.

The strength of relationship between power consumption rates and marketable ore output is -0.99695 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make the quantity of marketable ore decrease and, according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between power consumption and marketable ore production is -0.9898 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make quantity of raw ore decrease and according to the Chaddock scale, the strength of relationship is quite high.

In general, the situation at the PJSC "KZRK" is the following. The strength of relationship between power consumption and marketable ore output is 0.923262 (direct, positive), i.e. increased power consumption makes the quantity of marketable ore decrease and according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between power consumption and raw ore output is

0.94705923262 (direct, positive), i.e. increased consumption makes the quantity of raw ore increase and according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between power consumption and marketable ore output is -0.99305 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make the quantity of marketable ore decrease and according to the Chaddock scale, the strength of relationship is quite high. The strength of relationship between power consumption and raw ore output is -0.8533 (negative, reverse), which indicates a reverse dependency, i.e. increased consumption rates make the quantity of raw ore decrease and according to the Chaddock scale, the strength of relationship is high.

1.2 Power supply systems of Ukrainian iron ore underground mines. Current status and prospects

Underground production consumes about 60% of the power in iron ore underground mining.

Interestingly, increased depth of mining operations makes established capacities of transformers at the main step-down substation (MSS) of an underground mine increase as well. While the transformer capacity of Rodina underground mine of the PJSC "KZRK" on the 527m level is 250 kVA, that of the 1350 m level makes 970 kVA, i.e. increasing by 4 times. The total capacity of transformers of all underground MSS made 20.66 mVA in 2015.

As indicated above, currently, iron ore underground mining is undergoing considerable changes. They are primarily conditioned by transition to deeper mining levels (> 1000 m). To solve more complicated tasks, the capacity of underground consumers increases concerning electric motors of water drainage facilities, electric haulage, ventilation, etc.

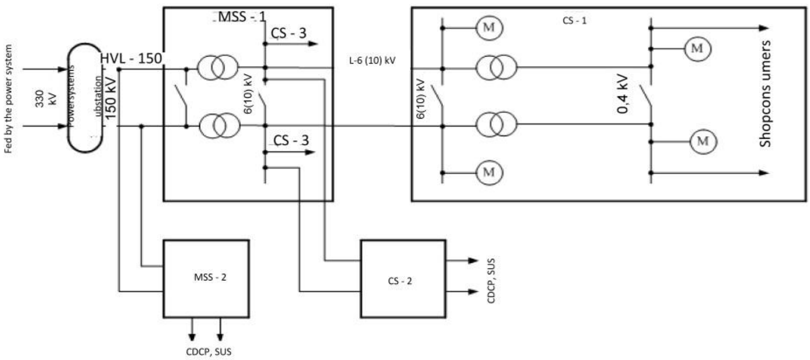
Basic demands to power-supply systems of iron ore underground mines include reliability, minimal investment terms, reduced losses of power and voltage levels in all sections of the system, efficient use of electric equipment.

Improvement of the power-supply systems of underground mines is aimed at establishing high-quality and reliable power supply of electric drives of mining equipment.

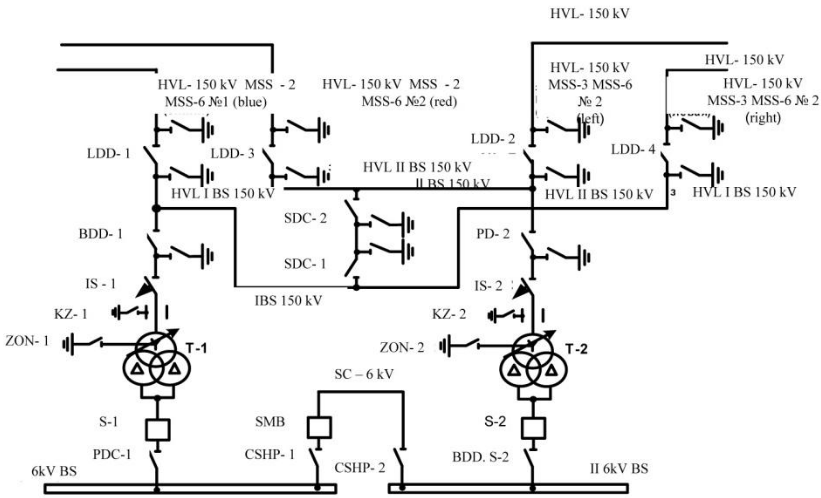
This task can be successfully fulfilled by means of substantiated and checked technical solutions and recommendations applied to determining designed loads, choosing a zone type of drives for mining mechanisms and machines, increasing the power factor, etc. Available methods of solving such tasks are mostly satisfactory, although some of them need further developing.

At deep underground mines, power supply costs will increase to a greater degree than efficiency of mining levels and mines as increased power consumption is primarily associated with the growing level of electrification and power availability per man. Considering this, the issue of creating an efficient power-supply system or updating the current one is topical. The system should provide high-quality power-supply with minimal construction and operation costs.

At iron ore mines including Kryvyi Rih basin ones, underground consumers are supplied with power under a radial scheme by the main step-down substation or by a 6 kV substation at the hoist house near the shaft mouth by means of cables along the shaft towards the central underground substation (CUS) typically located in the ore storage yard (Fig. 1.7). Part of the power received by the CUS is distributed by the same voltage to feed pumps of the main and intermediate drainages, transformer traction substations and power transformers of the shaft station consumers. The rest of the power (U_i = 6 kV) is used to feed electric receivers located directly in the mining area.



a)



b)

Fig. 1.7. The typical structural (a) and single-line (b) diagram of iron ore mine power-supply

In most cases, a traction substation is used to receive and distribute power. It is located at the end of the main haulage crosscut at the junction with fringe drifts and connected to one of the site underground substations. The substation construction is conditioned by long crosscuts (for example, the 1015m level of Rodina mine) and specific conditions of mine-take development.

The substation feeds site underground substations (SUS) according to the loop arrangement. The loads are mechanisms of mining and development operations, lighting and equipment for auxiliary cameras.

If there are high-pressure drainage plants, a separate power supply scheme is applied from the MSS with two 6 kV inputs. Power is distributed among 0.4 kV consumers from distribution boards of power distribution frames, central underground substations and site underground substations according to radial schemes.

The mentioned power-supply scheme of underground mines is characteristic for most or to be exact for all operating mines of the basin, and conditioned by mining technologies at deep levels with considerable distances from mine shafts. The technology is chosen according to reliability, economy and efficiency criteria of power-supply. Category I consumers are supplied with 100 % input reservation at the central distributing point, the CUS and CDP (central distribution point) operating for the whole production cycle. Plants composed of several operating or reserve aggregates (pumps of the main drainage, CUS transformers) are connected to different busbar sections. Under this scheme, the failure of one of the sections will cause the whole mine stoppage.

The drawback of the mine power-supply system is great length of low-voltage mains. As power losses are proportional to resistance, if the cable line length increases, power losses rise as well. Voltage losses occur with high-power electric drives and considerable length of intersection lines of 380 V.

Another problem is observed when electric drives and a feeding power system are united into a single electric system. Because of this, power quality becomes the problem of electromagnetic compatibility of the power-supply system and mines' electric receivers. Considering weak rigidity of mains, when total capacity of electric drives rises, it is impossible to provide necessary quality without applying special technical means. The issue of ensuring power quality in mine distributing mains is connected with compensation of reactive capacity.

1.3 Analysis of investigations of improving power-supply systems of mine electric receivers according to criteria of power quality

The quality of industrial output comprises consumer-related properties characterizing the degree of its compliance with the standard of a particular need under some industrial conditions [13]. Power quality refers to a complex of features determining power properties enabling consuming it to the fullest and most economical extent.

Electric power differs from other types of commodities by the fact that when of low quality, it is unprofitable to be used and less profitable for the power system itself. Along with operational reliability of power-supply, power quality is one of its primary indicators for consumers. It greatly affects both effective operation of an electric drive and technical-economic parameters of electric mains. The current state of national mains raises the issues of increasing quality indices of power-supply and electric drive operation.

A great number of scientific publications on this issue have appeared in recent 10–15 years. Most works deal with power quality in power-supplying mains, including the city ones. Fewer works are concerned with distributing mains in industrial power-supply systems. Power-supply efficiency studies are restricted to quality indices of voltage in distributing electric mains, which is conditioned by the necessity to develop steps depending on peculiarities of the process. Electric drive frequency does not influence much the quality indices and this problem is solved by enhancing the power system as a whole.

Ideas of voltage quality in power-supply systems of underground mine workings are evolving through studying regularities of its indices formation, developing control means and methods and substantiating steps to improve it. The issues of economic evaluation of voltage quality are understudied.

At the same time, Ukrainian miners' safety at underground mines is a disturbing question.

Many injuries in underground mining (more than 50 % of the total amount) occur in underground transport. More than 60 % of them happen when touching contact wires in orts at loading sites of electric locomotives.

Thus, the necessity is evident to conduct additional research and find a complex solution of the problem of developing efficient and safe energy systems.

1.4 Energy efficiency of Ukraine's iron ore mining enterprises

As mentioned in previous research works [14–19, 23, 26, 29–31], all national iron ore mining enterprises are notable for similar mining technologies, depths, haulage methods, equipment types, etc. (Fig. 1.8–1.9).

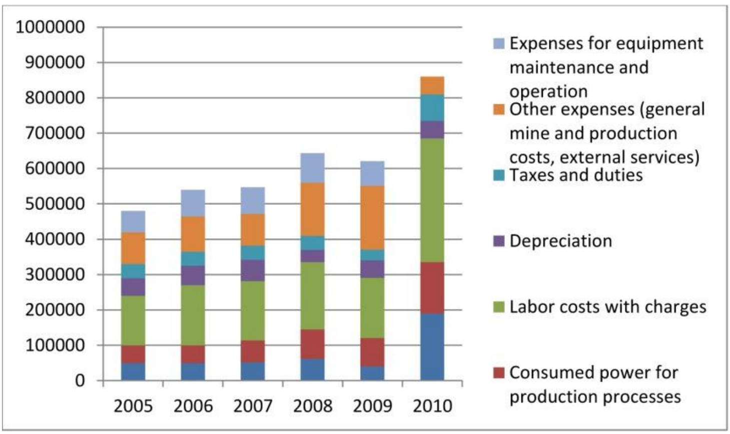


Fig. 1.8. Major components of raw ore costs at Ukraine's underground mines

All this causes natural similarity in power-supply schemes, modes of electric receiver functioning and other factors. Yet, they are only seemingly similar. If structures of creating power-supply schemes of iron ore underground enterprises are indeed similar, that does not concern functioning modes of electric receivers and power-consumption levels.

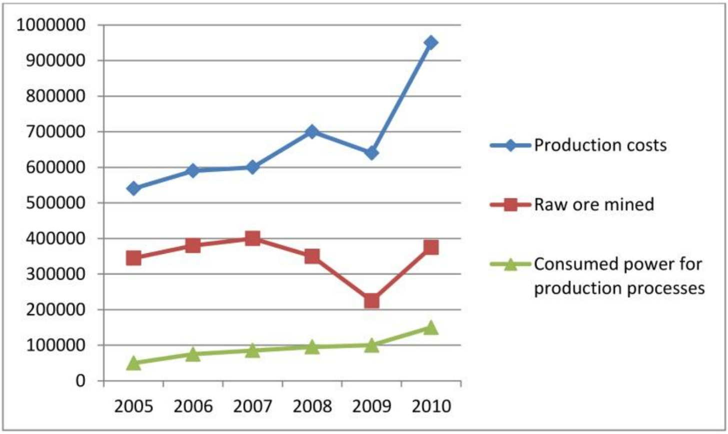


Fig. 1.9. Diagrams of changes of production costs and consumed Energy efficiency of Ukraine's iron ore mining enterprises at underground mines of the PJSC "KZRK"

Due to this, we are going to assess and analyze indices forming a complex indicator of the mass sector of underground mining enterprises' energy efficiency by means of data on several national enterprises including the power expenses fraction in the primary cost of 1.0 t of iron ore mined by a particular enterprise (production). It will allow providing an accurate assessment of this index comprising several segments and generalizing impacts on formation of its components for their further generalization at other Ukrainian iron ore underground enterprises.

Fig. 1.10 shows diagrams of power consumption of national iron ore underground mining enterprises. As is shown, the maximum difference of particular mines in the latest five years (2010-2014) is within 40 %. The maximum level of power consumption usually corresponds to the maximum iron ore output. At the same time, such conclusions cannot be applied to minimal iron ore output.

Moreover, attempts to determine the dependency level between iron ore output and power consumption concerning the PJSC "KZRK" and separate mines as typical iron ore mining enterprises reveal the following results. The generalized correlation factor of the PJSC "KZRK" in 2010–2014 made -0.43 determined by the Chaddock scale as a reverse relationship. As to structural departments of this integrated works (underground mines), the correlation factor of Rodina mine is 0.203 indicating a weak relationship, that of Oktiabrska mine is 0.09 indicating almost no relationship.

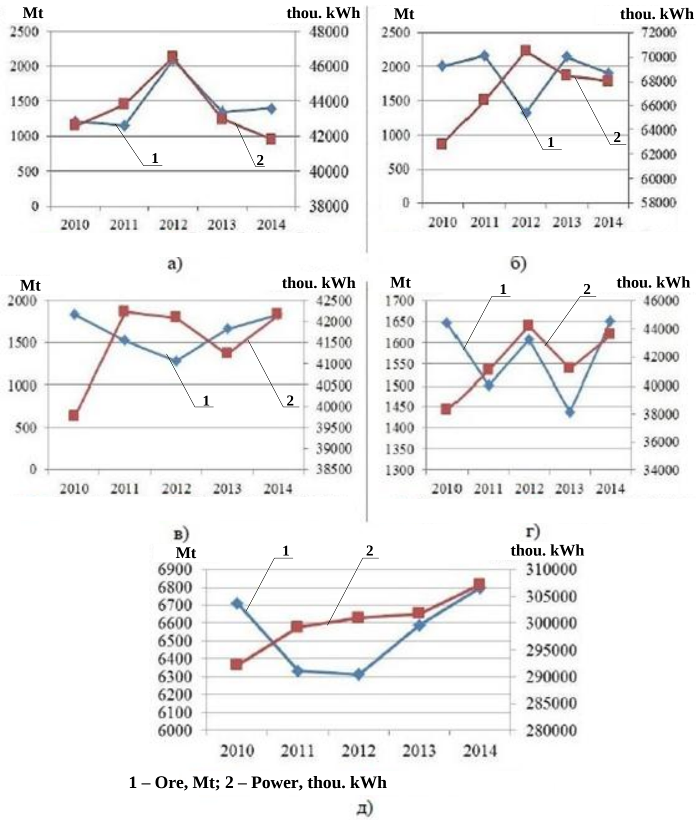


Fig. 1.10. Schedules of yearly iron ore output and energy consumption at the PJSC "KZRK": a) Oktiabrska mine, b) Rodina mine, c) Ternivska mine, d) Hvardiiska mine, e) the total of the PJSC "KZRK"

The correlation factor of Hvardiiska mine is 0.11 indicating a weak relationship, that of Ternivska mine is -0.53 corresponding to a good reverse relationship.

The highest correlation factor refers to the whole integrated works, the data on its structural components (mines) is shown below. It can be concluded that analysis and search for ways to increase energy efficiency of iron ore mining should be focused on an underground mine as a basic technological unit. Yearly analysis indicates that the relationship degree between iron ore output and power consumption is not high enough and that can be conditioned by both external (the technological component) and internal factors determining synergetic components of this process.

The connection indicating the dependency or its absence between iron ore output and power consumption is of certain practical and theoretical interest. Research results have shown that the more energy is spent, the less iron ore output is or there is no any relationship between power consumption and iron ore output. It is determined by several factors including volumes of water intake and drainage in underground mine workings, mining depths, electric capacity of receivers, their functioning modes, etc.

All this indicates inadequate assessment of power consumption levels at iron ore mining enterprises as for iron ore output. Power consumption at the PJSC "KZRK" in 2010–2014 increased no more than by 10 %. As for every separate underground mine of this integrated works, power consumption did not change more than by 7 % in the same period. This insignificant paradox in differences of power consumption at the integrated works and its structural units (mines) is explained not by iron ore output fluctuations, but by the increased conditionally constant component of the joined segment of power consumption by the integrated works itself.

At the same time, one can observe the difference in power consumption of underground mines (Fig. 1.11). Rodina mine consumed most energy, while Oktiabrska and Hvardiiska mines revealed minimum power consumption. The difference between the maximum and the minimum was up to 40 % on average. It allows us to conclude that there are levels or, to be exact, differences of primary costs of iron ore mined at these underground mines: the maximum primary cost and power expenses are observed at Rodina mine, the minimum ones – at Oktiabrska mine.

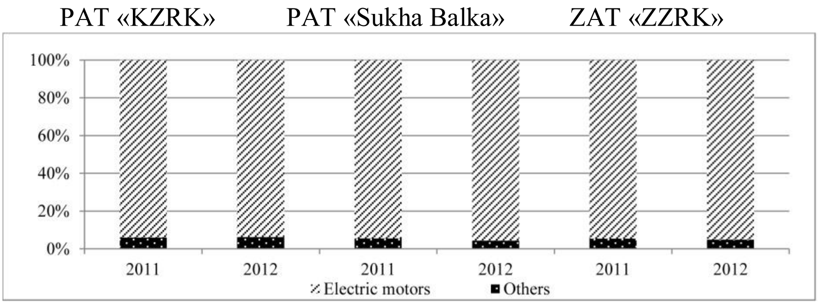


Fig. 1.11. Structure of electric balance at Ukraine's iron ore underground mines

In its turn, power balance of iron ore underground enterprises has not changed much for the recent 5-10 years (Fig. 1.11). Electric motors of technological equipment consuming up to 94 % of all the power dominate among other power consumers in iron ore underground mining.

Of all electric motors applied at iron ore underground mines, the synchronic ones are distinguished by consumption of about 60 % of all the power. As it is assumed from Fig. 1.12 the power consumption structure as to electric receiver types has not changed at these enterprises for the recent five years. Available insignificant fluctuations have not exceeded 2 % for the integrated works.

A similar trend is observed at separate underground mines of the integrated works, although fluctuations can reach 7 %, yet, they cannot be considered significant (Fig. 1.12-1.17). This conclusion is true for choosing an approach to planning power-saving steps.

Thus, a complex character of solutions is caused by the dual problem covering both assessment of the real level of achievable potential of energy efficiency and development of recommendations to achieve it.

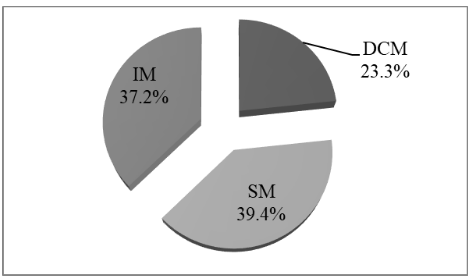


Fig. 1.12. Diagram of ratio of established capacities for electric motor types (the PJSC "KZRK", 2010-2014)

Such factors as iron ore mining technology and conditions, functioning modes of mining machines and mechanisms should be considered.

Besides, mining enterprises have started a new economic period and changed their attitude to electric power consumption. Moreover, the form of payment for consumed power has also changed greatly passing from double-rate tariffs to single-rate ones with differentiated payment depending on the time of day.

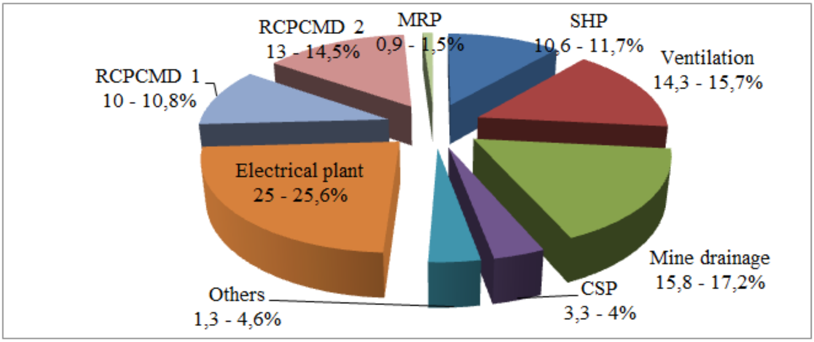


Fig. 1.13. Diagram of fluctuations of power consumption levels according to consumer types of Ukraine's iron ore mining integrated works in 2010-2014

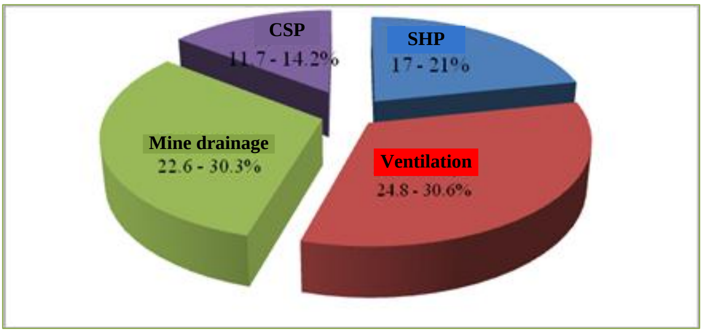


Fig. 1.14. Diagram of fluctuations of power consumption levels according to consumer types of Oktiabrska mine (the PJSC "KZRK") in 2010-2014

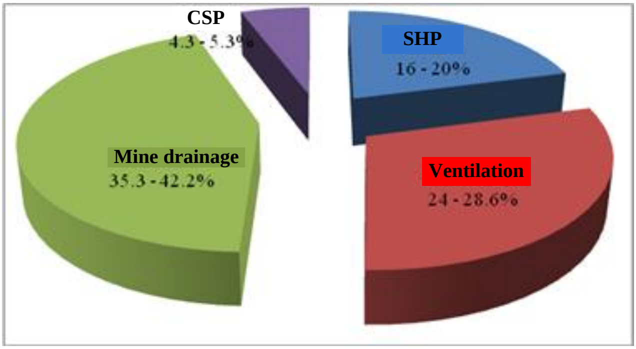


Fig. 1.15. Diagram of fluctuations of power consumption levels according to consumer types of Rodina mine (the PJSC "KZRK") in 2010-2014

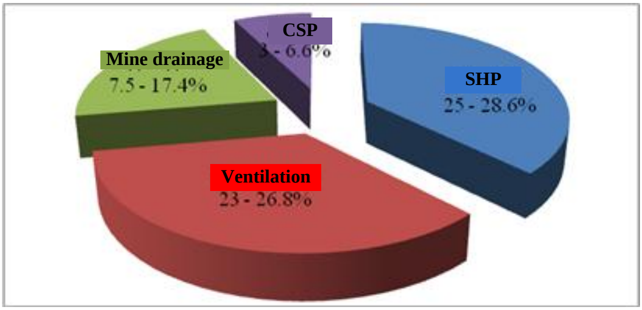


Fig. 1.16. Diagram of fluctuations of power consumption levels according to consumer types of Hvardiiska mine (the PJSC "KZRK") in 2010-2014

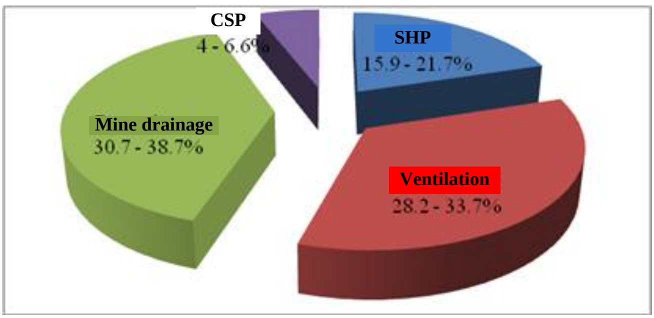


Fig. 1.17. Diagram of fluctuations of energy consumption levels according to consumer types of Ternivska mine (the PJSC "KZRK") in 2010-2014

Due to some managerial steps, the enterprises are trying to create a twenty-four-hour power-consumption schedule so that the most power-consuming aggregates (mine drainage and partially skip hoisting) operate at night. Other consumers work in off-peak hours.

Almost all major mine drainages of Kryvyi Rih iron ore basin mines operate from 11-12 p.m. to 6-7 a.m, except for the 940 m level of Rodina mine and the 1115 m level of Oktiabrska mine. They do not work at all other times. Water is pumped from underground levels by means of the electromechanical hydro-power complex which is not simple in its structure and operation modes. This complex character includes unstable water inflow to mines and water amounts for drainage. The so called "wet conservation" of dead pits involving breakthrough of levels of different mines into a single complex and sinking of mining operations raises the problems of choosing efficient modes of water pumps as electromagnetic complexes functioning under the multi-criteria algorithm with unclear forecasting. Fig. 1.18 shows the daily schedule of power consumption for a 30-minute interval at the PJSC "KZRK", which confirms the above mentioned.

Analysis of power consumption has confirmed that at both separate mines and the integrated works there is observed reduced power consumption at the beginning of the month and the increased one by about 30 % at the end of the month [25-33]. Pumps functioning in the nighttime result in power consumption of 40 %, although it lasts for 7 hours. Power consumption in shoulder periods of 11 hours made 38 % and that in peak periods – 22 % (Fig. 1.19).

The maximum power in peak and shoulder periods is consumed by main fans and hoists, the minimum one – by water drainage. It is on the contrary at night: the maximum power is consumed by water drainage reaching almost 90 % for some mines, the minimum power is consumed by fans. All MSS of iron ore mines and integrated works are typically equipped with power transformers of 32000-63000 kVA. Operation terms of almost all transformers have exceeded 40 years. Electric capacities of these transformers were chosen considering designed depths of iron ore mining reaching 1500 m. At the same time, these established capacities are sufficient enough for mining depths exceeding 1500 m. Moreover, quite the reverse happens. At the beginning of operation of current transformers, the load factor made about 70 %. It is much lower at the present time. Fig. 1.20 represents bar charts of the load factors of power transformers of some SUS of iron ore mines in the recent five years.

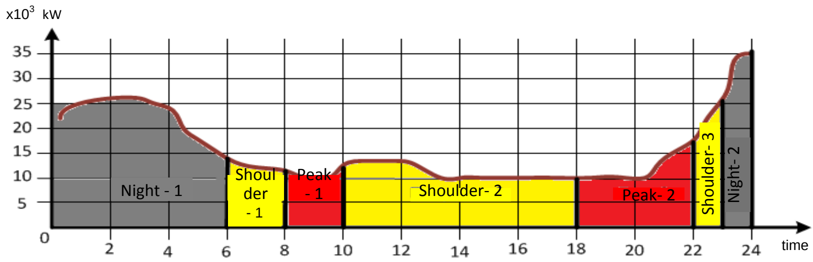


Fig. 1.18. Daily schedule of consumed power at the PJSC "KZRK"

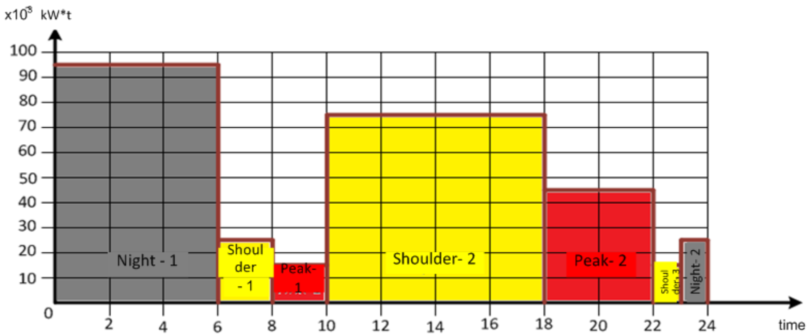


Fig. 1.19. Daily schedule of power consumption according to tariff zones at the PJSC "KZRK"

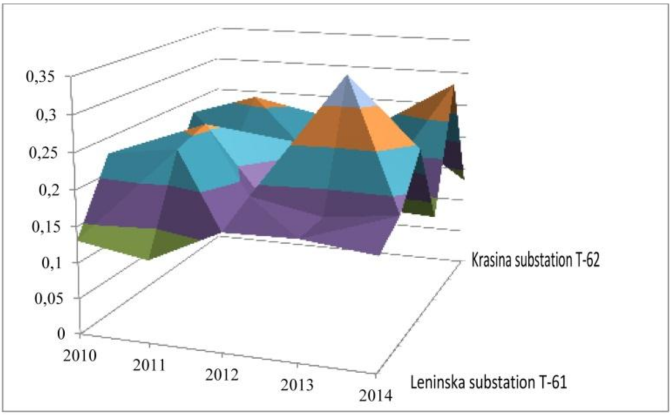


Fig. 1.20. Load factors of power transformers of main step-down substations of some Ukrainian iron ore underground mines

Only in two cases out of six, the load factor of transformers exceeded the level of 0.3 and in 17 cases it exceeded the level of 0.2, i.e. the load made 20 % of the rated one. Due to this, its mean indices did not exceed 0.20 and only in some transformers of the main step-down substations reached 0.25. It should be noted that substitution of available transformers by those with lower capacity is not possible under current economic conditions both at present and in the nearest 10-15 years [34-38].

SECTION 2
STATISTICS OF LOAD LEVELS AT IRON ORE MINING ENTERPRISES

2.1 Major procedures of assessing power modes

While assessing power consumption of mining enterprises, one can distinguish power properties, indices, applicability degrees, etc. Modern conditions of mining electrification allow distinguishing a number of properties of the process under study. Their topicality is conditioned by requirements to increase energy efficiency of mining enterprises. These properties include energy efficiency and safety.

Provision of energy efficiency requires studying a number of problems in order to establish new phenomena and through analyzing, synthesizing and generalizing them formulate regularities which interpret new facts obtained empirically, thus forecasting development of power consumption at mining enterprises.

Increased energy efficiency of iron ore mining enterprises is associated with the problem of adequate assessment of power modes which is especially acute in mining operations as:

1. Power consumption of mining depends on many factors of complicated and diverse nature. They can be described by means of deterministic and classical static methods. Yet, it does not always work because of ambiguity of conditions determining these factors. It can be noted that power consumption of iron ore mining enterprises is affected by factors that cannot be forecast accurately. A great number of various factors can complicate assessment of their influence on power consumption both in methodological and technical-economic aspects.

2. Information on power consumption contains various sets of empirical data and characterizes it by multi-dimensional occasional features. Multiple features complicate the process of finding connections between them. In this case, power consumption should be described by fewer generalizing characteristics reflecting internal objective regularities that cannot be directly observed.

3. While assessing conditions of power consumption at mining enterprises, indicated peculiarities call for the need to apply methods of solving problems under conditions of deficient information with reduced correspondence of input data ("contraction" of data). There arise problems of analyzing power consumption data that can be solved by applying

methods of factor analysis and defining typology of investigated objects [25, 31].

In this regard, assessment of power consumption using various models of analysis is based on the statement that in doing an experiment or examining empirical materials with a great number of parameters, many of them are connected by correlations with each other. It is explained by the fact that observed "external" parameters characterize power consumption indirectly. Along with a great number of "external" parameters (factors), there are a few "internal" ("essential") ones, which are difficult or impossible to measure, yet, they determine the behaviour of "external" parameters. Analysis of power consumption is aimed at finding these hypothetical essential parameters.

Grounding on the above mentioned, there are distinguished different sets of features (parameters) determining power consumption. Mining-geological, mining-technological, climatic-meteorological, electric-power and managerial groups of factors belong to these sets.

Such parameters (factors) of the mining-technological group as occurrence depth, deposit sizes, rock massif temperature, technology types, parameters of opening and mining systems, types of machines and equipment, etc. influence power intensity of products. Time of the year also influences power consumption. Electric-power factors (structural parameters of electric systems, the number, capacity, efficiency of electric receivers, etc.) condition formed power load modes. Managerial and operational factors determine the degree of application of electric receivers, the level of increased power losses because of deteriorated characteristics of power equipment, machines and mechanisms.

Power consumption in case of weak informational content of independent features determining power modes can be assessed through applying Caunen-Loeve expansion (CLE) and the method of principal components (MPC) to "contract" information. They use the initial statistic data in the most complete way in order to obtain adequate mathematical models. Thus, it is reasonable to consider basic procedures for assessing conditions of power modes, which are based on information "contraction".

Power modes under conditions of indefinite and incomplete data are assessed by methods of information "contraction" – CLE and MPC – finding essential features to determine the nature of power modes. These methods suppose that through orthogonal transformations, one finds the best projection of observation points in the space of smaller correspondence. The recently obtained vectors are distributed in the transformed space: in the MPC – according to the criteria of maximum dispersion, in the CLE –

according to the criteria of the minimum average square error. Thus, the CLE enable us to present the most stable condition of the system, which corresponds to the minimum square error. The MPC allows describing the maximum dispersion of the system using fewer vectors, in other words, providing more probable limits for changing the initial experiment matrix.

To apply the "contraction" method initial data on power consumption should be presented as a matrix:

$$X = [Xj] = \begin{bmatrix} X_{11} \ldots & X_{1j} \ldots & X_{1m} \\ X_{i1} \ldots & X_{ij} \ldots & X_{im} \\ \ldots & \ldots & \ldots \\ X_{n1} & X_{nj} & X_{nm} \end{bmatrix} \tag{2.1}$$

where $[X_j]$ is a vector-line reflecting the data on power consumption with *i*-value of the feature;

X_{ij} is the value of power consumption of the *i*-th feature of the *j*-th dimension (object);

$i = \overline{1,n}$ is the number of the feature values;

$j = \overline{1,m}$ is the number of dimensions (objects).

In this case, energy consumption can be characterized as the *n*-vector.

Simulation of power consumption by the CLE method provides for the following major transformations.

In real power consumption, there are distinguished some characteristic orthogonal (independent) components (representative vectors), which describe power consumption in the space of smaller correspondence while obtaining observation results based on the maximum data. This procedure is performed by means of a linear transformation of the coordinate system of the initial *n*-th vector of power consumption *X* according to the equation:

$$X = A \cdot Y \tag{2.2}$$

where *A* is a transformation matrix, $A = \{a_{ij}\}$, $i, j = \overline{1,n}$;

Y is a representative *n*-th vector describing power consumption in the space of new variables, $Y = \{Y_{ij}\}$, $i = \overline{1,n}$, $j = \overline{1,m}$.

The transformation matrix *A* is outside the initial matrix *X* and represents *n* of its own vectors of the covariance matrix C_x:

$$C_x = \begin{bmatrix} C_{11}\dots & C_{1l}\dots & C_{1m} \\ \dots & \dots & \dots \\ C_{i1}\dots & C_{il}\dots & C_{im} \\ \dots & \dots & \dots \\ C_{n1} & C_{nl} & C_{nm} \end{bmatrix} \quad (2.3)$$

where *Cij* are selective non-displaced assessments of the covariance matrix elements determined by

$$C_{il} = \frac{1}{m-1}\sum_{j=1}^{m}(X_{ij} - \overline{X}_j)(X_{lj} - \overline{X_l}) \quad (2.4)$$

where $\overline{X}_j, X_l$ are secondary average *i*-th and *l*-th components of the *n*-th measurable vector of power consumption *X*.

Eigenvectors U_i of the matrix C_x are found through eigenvalues λ_{Ki} from the equation

$$C_x \cdot U_i = \lambda_{Ki} \cdot U_i \quad (2.5)$$

The eigenvalues λ_{Ki} resulted from solving the equation:

$$C_x - \lambda_{Ki} \cdot I = 0 \quad (2.6)$$

where I is a unity matrix.

To observe orthonormalization of eigenvectors, they are to be normalized and then a transformation matrix is obtained:

$$A = [A] = \begin{bmatrix} a_{11}\dots & a_{1r}\dots & a_{1n} \\ \dots & \dots & \dots \\ a_{i1}\dots & a_{ir}\dots & a_{in} \\ \dots & \dots & \dots \\ a_{n1} & a_{nr} & a_{nn} \end{bmatrix} \quad (2.7)$$

When observing orthonormalization, the representative vector in the space of new variables is determined by the matrix equation:

$$Y = A^T X \quad (2.8)$$

In this, the following conditions are observed.

1. Representative vectors Y_i are non-correlated, i.e. the condition is observed

$$M\left\{(Y_{ij}-\overline{Y}_i)\cdot(Y_{lj}-\overline{Y}_l)\right\}=\begin{cases}\lambda_i & under\_l=i\\ 0 & under\_l\neq i\end{cases} \tag{2.9}$$

2. The mean square error is minimum, when used to provide *N* of the first representative vectors *Yi* *(N<n)* to represent vector *X*

$$\overline{\varepsilon}^2(N)_{min}=\sum_{i=N+1}^{n}\lambda_{Ki} \tag{2.10}$$

Thus, for the investigated power consumption, the model of “contracted” information looks like:

$$X_{ij}=\sum_{r=0}^{n}a_{ir}\cdot Y_{rj} \tag{2.11}$$

To simulate power consumption by means of the MPC, major transformations are the following:

Matrix values of the initial data on power consumption are standardized (2.1) and a standardized matrix is obtained

$$Z=\left\{Z_{ij}\right\} \tag{2.12}$$

The values of the standardized matrix are:

$$Z_{ij}=\frac{X_{ij}-\overline{X}_j}{\overline{\sigma}_j} \tag{2.13}$$

where $\overline{X}_j$ is an average value of the column *j*;

σ_j is a mean square deviation of values *X* in the column *j*.

New variables are found as non-correlated standardized linear combinations of initial features. In the matrix form we have:

$$F=B^T\cdot Z \tag{2.14}$$

where *F* is a matrix of new variables (major components),

$F=\left\{f_{ij}\right\}$, $i=\overline{1,n}$; $j=\overline{1,m}$;

B is a transformation matrix:

$$B = A \cdot \lambda^{1/2} \qquad (2.15)$$

where A is an orthogonal matrix, in which the r-th column is an r-th eigenvector corresponding to the r-th eigenvalue of the correlation matrix R_x;

λ is a diagonal matrix, on the diagonal of which there are eigenvalues λ_r of the correlation matrix R_x of the vector X.

Elements of the matrix λ are in the decreasing order:

$$\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \ldots \geq \lambda_n \geq 0 \qquad (2.16)$$

New variables are in the space of features in the decreasing order of their dispersion, i.e.:

$$\sigma^2(f_1) \geq \sigma^2(f_2) \geq \ldots \geq \sigma^2(f_n) \qquad (2.17)$$

where $f_1, f_2 \ldots f_n$ are the first, the second, the n-th major components.

For the studied process of power consumption, the 'contracted' information model will look like:

$$X_{ij} = \sum_{r=1}^{n} b_{ir} \cdot f_{rj} \qquad (2.18)$$

where n is the number of major components f_{rj} contributing to the total dispersion with sufficient set reliability.

While approximating the transformation vectors $(A_г, B_r)$ and the representative vectors Y_r (major components f_r) using analytic functions, we obtain adequate models of power consumption:

$$F_{Xij}(\gamma_a, \varphi_Y) = \sum_{r=1}^{n} \gamma_a, r_i(T) \cdot Y_{Y,rj} \qquad (2.19)$$

where γ_a, φ_Y are analytic functions, approximating vectors A_r and Y_r, which are included into the matrices A and Y; $i = \overline{1,n}$; $j = \overline{1,m}$.

The described procedures enable us to apply initial statistic data to assessments which adequately describe conditions of power modes under conditions of indefinite and weak information content of the observed features determining the process under study.

Many technological electric receivers of mining enterprises form power modes of heterogeneous character in terms of probabilities distribution. In this case, while distributing probabilities, values of features of initial statistic data and transformed ("contracted") information in power consumption are polymodal. This complicates simulation of power consumption to some degree.

If the power mode of electric receivers is heterogeneous (with polymodal distribution of electric loads), power consumption should be simulated by distinguishing stable levels among all variables of changed loads. Their mean values determine separate random load values with some degree of dispersion.

To perform this, it is reasonable to apply statistic classification based on selective observations, which allows transforming a great many observed values of loads into a system of ranged levels (classes).

Classification of electric loads is aimed at determining the number and properties of classes in the space of load images and identifying random load values, i.e. referring them to one of classes.

To distinguish classes among experimental data, one should generalize hypotheses through cluster analysis. Distinguishing the number and properties of clusters in the space of changed images of electric loads represented by polymodal samples is associated with ambiguity as clusters are not quite spaced. In this case, hypotheses should be generalized by the following scheme.

By the character of distribution and the number of sampling modes characteristic of electric loads, the number of clusters is determined. To identify random load values as a group measurement of proximity, an intergroup sum of squares of deviations between each image and the average one for the cluster is taken:

$$Y = \sum_{i=1}^{n} \sum_{x \in P_i} \left\| \dot{X} - \dot{m}_i \right\|^2 = min \tag{2.20}$$

where n is the number of clusters;

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

X is a vector of measuring electric loads;

m_i is a vector of sampling averages for the set P_i:

$$\dot{m}_i = \frac{1}{n_i} \sum_{x \in P_i} \dot{X} \qquad (2.21)$$

where n_i is the number of images included into the set P_i ;

Clusterization of electric loads according to this scheme allows obtaining a set of stable levels of loads and time of their operation t_n:

$$P = \{P_1, P_2, ..., P_n\} \qquad (2.22)$$

$$t = \{t_1, t_2, ..., t_n\} \qquad (2.23)$$

Determination of power modes in the form of (2.22) and (2.23) changes traditional ideas of electric loads distribution represented as standard electric loads determined by calculation methods.

Because of non-traditional representation of power modes, it is reasonable to consider general expressions to determine values used in calculating electric loads.

To determine power expenses for the considered period (for instance, a shift) bearing the obtained sets in mind, one can write down:

$$P_{av} \cdot t_{shift} = \sum_{i=1}^{n} P_i \cdot t_i \qquad (2.24)$$

where P_{av} is an average load per shift $t_{\text{shift.}}$

Performing alternate division of the left and right sides of (2.24) by $P_{nom} \cdot t_{shift}$, introducing: $P_{av}{}^{*} = P_{av} / P_{nom}$; $P_i^{*} = P_i / P_{nom}$; $t_i^{*} = t_i / t_{shift}$; $K_r = P_i^{*} / P_i$, (r=2, 3, … , n) and taking $P_1{}^{*}$ as the maximum load level, we have:

$$P_{av}{}^{*} = P_1^{*} \cdot t_1^{*} + K_2 \cdot P_1^{*}(1 - \sum_{\substack{i=1 \\ i \neq 2}}^{n} t_i^{*}) + ... + K_n \cdot P_1^{*}(1 - \sum_{\substack{i=1 \\ i \neq 2}}^{n} t_i^{*})$$

$$P_{av}^{*} = P_1^{*} \cdot \left[t_1^{*} + \sum_{r=2}^{n} K_r \cdot (1 - \sum_{\substack{i=1 \\ i \neq r}}^{n} t_i^{*}) \right]. \qquad (2.25)$$

The obtained expression (2.25) describes power loads for electric receivers with heterogeneous operation in the form of a multilevel additive model.

2.2 Load curves of underground mines and integrated works

A load curve is one of the basic integral indices of energy efficiency of an enterprise.

The character and form of a load curve is determined by a technological process. A group load curve results from totalizing curves of separate electric receivers of a group. Yet, even with similar electric receivers, their group curve can be of different forms depending on a number of random factors that causes changes in the operation time of electric receivers. To consider these possible changes in both group and individual curves and assess their influence on the maximum load of the group curve one can apply methods of the probability theory and mathematical statistics.

The heterogeneous day load curve reduces industrial energy efficiency, transfer and consumption. On each of these stages, there should be installed expensive equipment with improved characteristics, which operates under a standard mode for a limited period of time.

Another problem is increased power consumption in the mains because of irregular load curves. It affects the lifespan of electric mains, especially that of cable lines.

Iron ore mining enterprises' load curves are formed by totalizing separate load curves of surface and underground consumers of mines. Loads of electric receivers change in time regardless of their operation and result from random factors like:

– total duration of a cycle;

– duration of the operation part of a cycle;

– duration of a pause;

– power consumed in the operation part of a cycle and under the off-load, etc.

Depending on types of calculation and equipment there are different coefficients considering manifestations of the calculated maximum of loads and the form of the daily curve.

Total power consumption includes a constant component determined by operating mine installations and not resulting from mining directly (water drainage, ventilation, degasation, and other processes partly). This component makes 70 % of the total power expenses in the mining industry.

Fig. 2.1 presents the yearly curve of power consumption of the PJSC "KZRK".

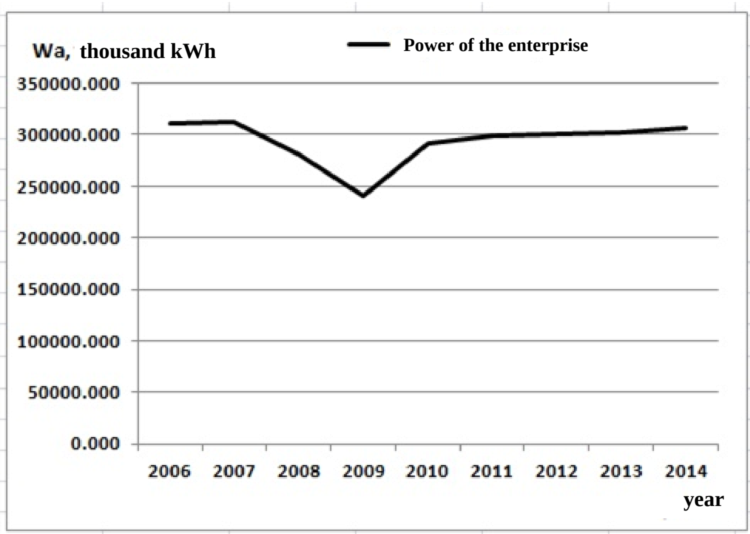


Fig. 2.1. Active power consumption at the PJSC "KZRK"

By 2007, power consumption of the PJSC "KZRK" had made over 310 mln $kW \cdot h$ in 2009, ore output considerably dropped at the two large mines of the works – Rodina mine and Oktiabrska mine, which caused reduction of total power consumption at the works. Since 2010, after some managerial and technical steps aimed at reducing downtimes and power losses, the load curve has been more stable. Insignificant growth of power consumption is caused by increased iron ore output.

Table 2.1 contains data on specific power consumption of some structural subdivisions of the PJSC "KZRK". As is shown, the mine with the greatest hoisting capacity of skip hoists has a greater fraction in the total power consumption (Rodina mine, 22.2 %). The total power consumption of the works' mines makes almost two thirds of the total consumption of the enterprise.

Table 2.1. Specific power consumption at the PJSC "KZRK" in 2014

#	Object	Specific power consumption, %
1.	Oktiabrska mine	13.5
2.	Rodina mine	22.2
3.	Hvardiiska mine	14.3

4.	Ternivska mine	13.8
	Total (mines):	63.8
5.	Power building	29.9
6.	Mechanical repair plant	1.1
7.	Other consumers	5.2
	Total (the PJSC "KZRK"):	100.0

About 30 % of power is consumed by the power department, which produces compressed air at the compression stations – RCPCMD 1 (Hvardiiska and Ternivska) and RCPCMD 2 (Oktiabrska and Rodina).

The repair plant consumes a bit over 1 % of the enterprise's power and other consumers – 5.2 %. Other consumers include various auxiliary subdivisions not engaged in iron ore mining and processing.

The following fixed installations are basic power consumers at mines:

– main fans (up to 20 % of the total power consumption),

– compressors (10-20 % at flat dipping mines and up to 60 % at steep dipping mines),

– hoists (up to 10 %) and water drainage (5-15 %).

Basic factor influencing power consumption include:

– air volume for ventilation installations (capacity *C* and dispersion *Q*);

– water volume to be pumped (capacity *C*) for water drainage installations;

– volumes of hoisted rocks (capacity *C*) for hoisting installations;

– volumes of produced compressed air for compression installations (capacity *C*).

Fig. 2.2 shows bar charts of the mines power consumption during 2014.

As is shown, power consumption at Rodina mine is greater by 65–70 % than at other mines. It is explained by greater capacity of the electric drive of hoisting installations and a greater volume of mine waters to be drained.

Figures 2.3-2.6 provide yearly curves of the PJSC "KZRK" structural subdivisions.

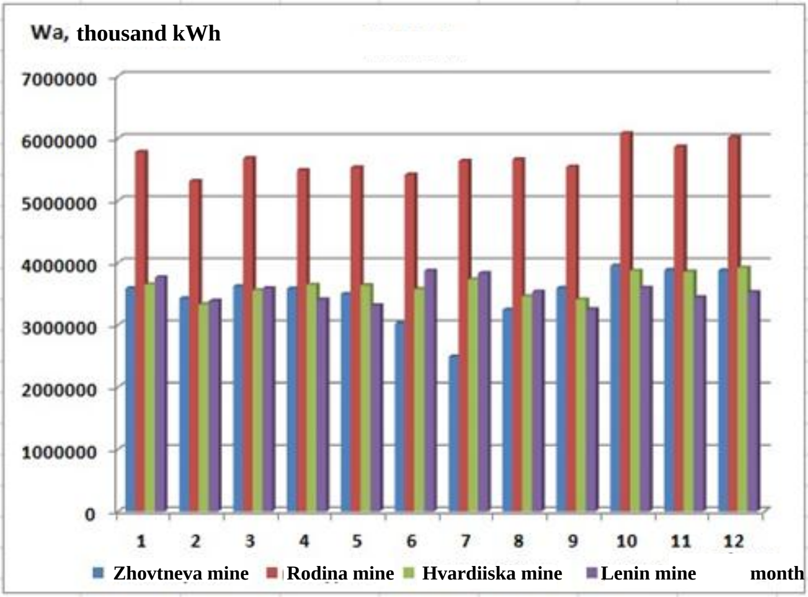


Fig. 2.2. Bar charts of the enterprise mines' power consumption in 2014

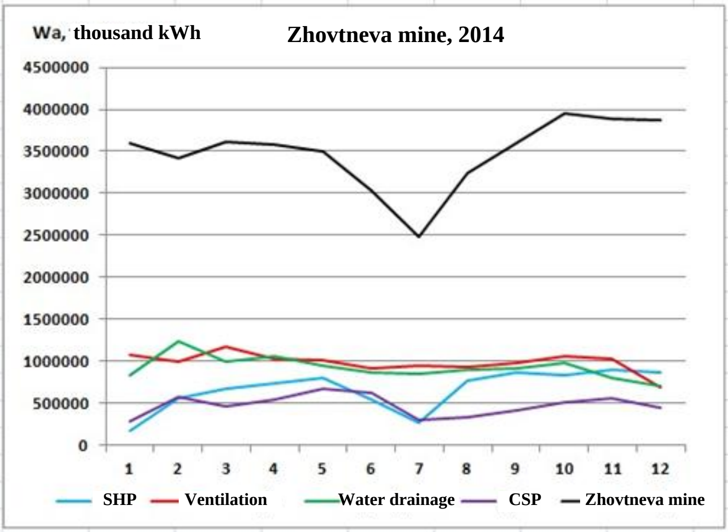


Fig. 2.3. Yearly curves of Oktiabrska mine subdivisions of the PJSC "KZRK"

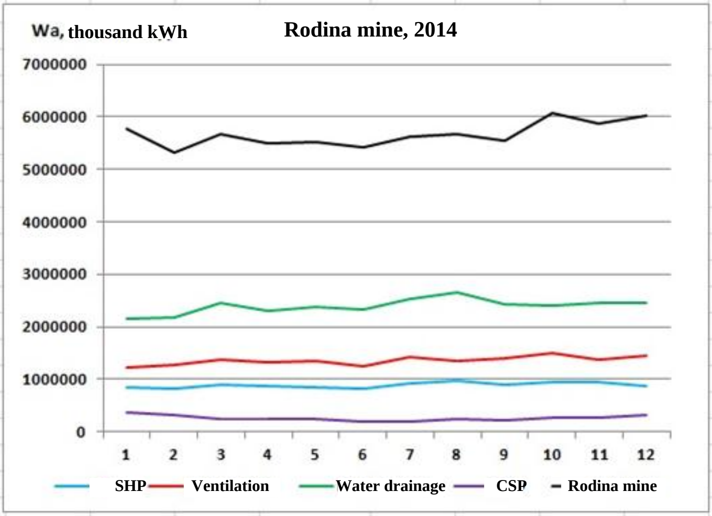


Fig. 2.4. Yearly curves of Rodina mine subdivisions of the PJSC "KZRK"

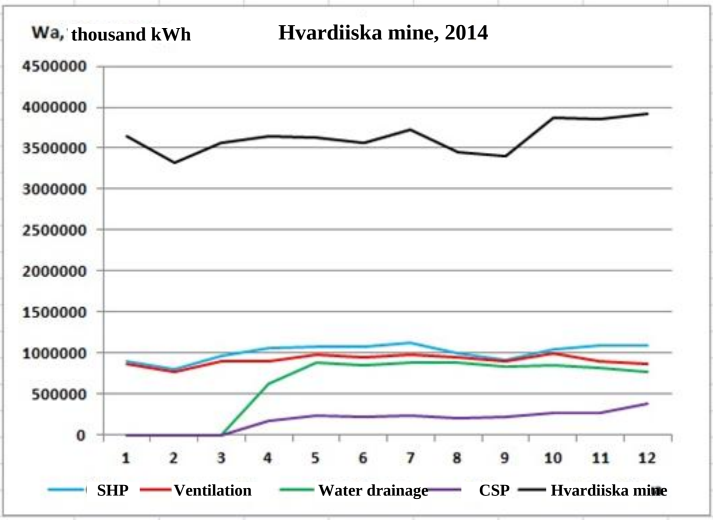


Fig. 2.5. Yearly curves of Hvardiiska mine subdivisions of the PJSC "KZRK"

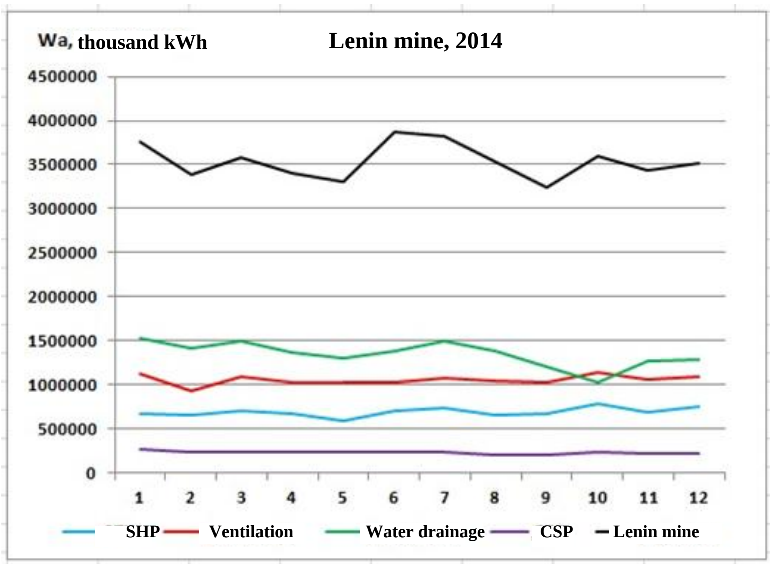


Fig. 2.6. Yearly curves of Ternivska mine subdivisions of the PJSC "KZRK"

As is shown, the total consumption of the mine is under the influence of changes in energy consumption the skip hoist drives and the crushing-sizing plant technologically connected with it. These technological units cause irregularity of the mine curves.

After analyzing monthly power consumption of water drainage installations, it can be concluded that water drainage is not associated with months and seasons as there is little precipitation in the region.

Monthly curves of active power are in Figures 2.7–2.9.

As is shown, Rodina mine consumes the most power as compared to other mines because of reasons mentioned above.

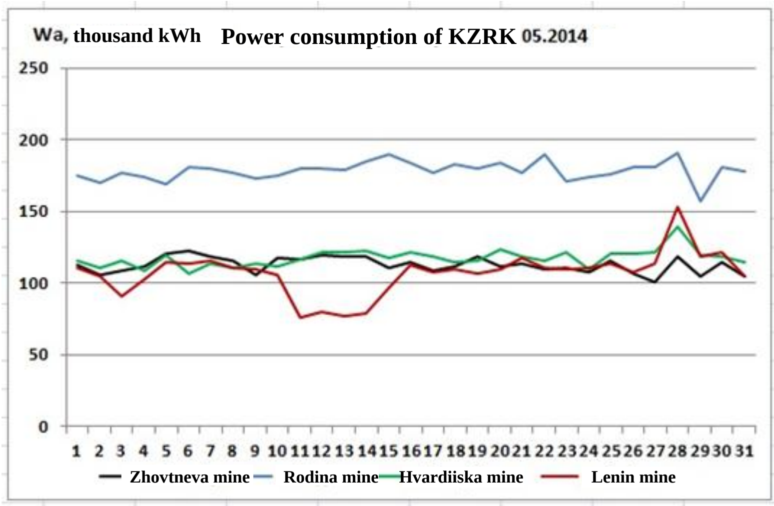


Fig. 2.7. Monthly curves of active power of the PJSC "KZRK" in May, 2014

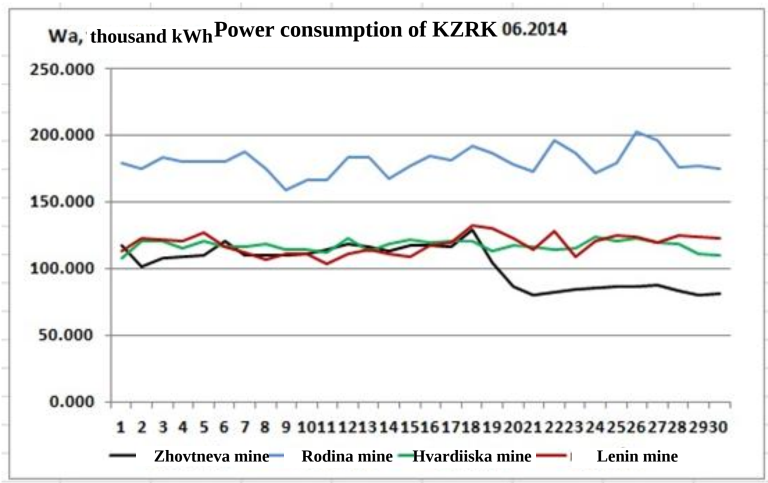


Fig. 2.8. Monthly curves of active power of the PJSC "KZRK" in June, 2014

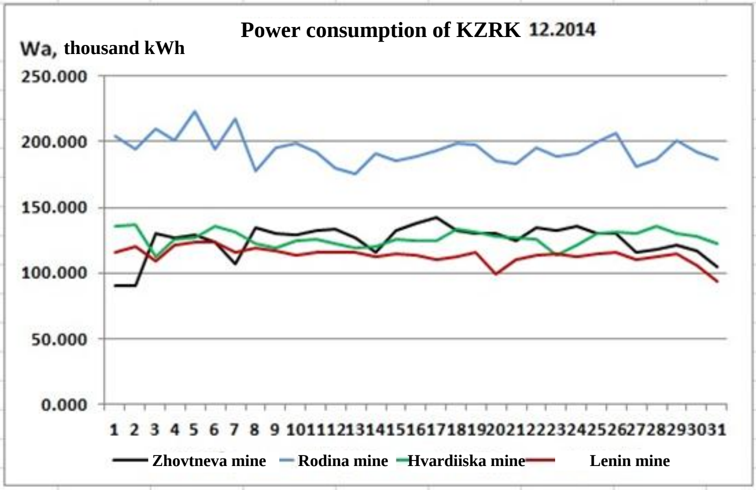


Fig. 2.9. Monthly curves of active power of the PJSC "KZRK"
in December, 2014

It should be noted that the monthly curves do not indicate evident periodicity. Level changes of power consumption are random and conditioned by mining intensity and iron ore hoisting as well as faults in functioning of some installations because of repair works and changes of modes.

Daily curves of electric equipment of some mine installations are of particular interest, it concerning both a separate mine and the works as a whole. Figures 2.10-2.18 reveal daily curves of active power of separate mine consumers in May 2, 2014.

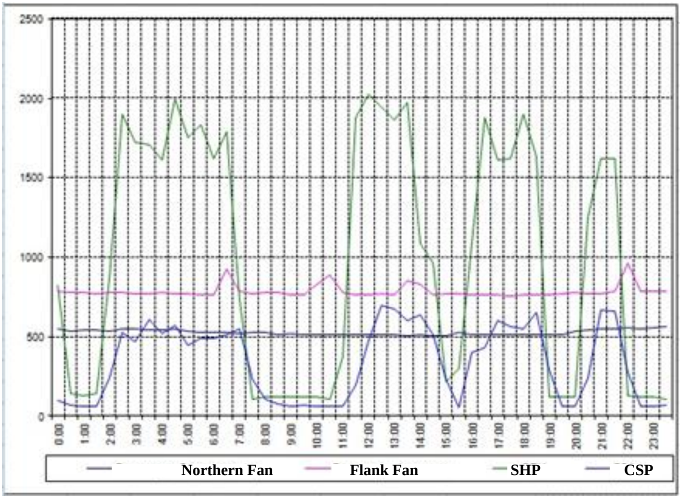


Fig. 2.10. Daily curves of ventilation, hoisting and the crushing-sizing plant at Ternivska mine of the PJSC "KZRK"

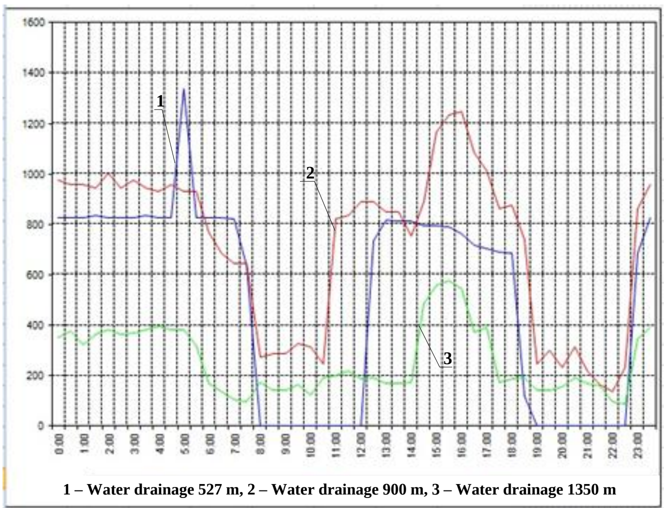


Fig. 2.11. Daily curves of water drainage at Ternivska mine of the PJSC "KZRK"

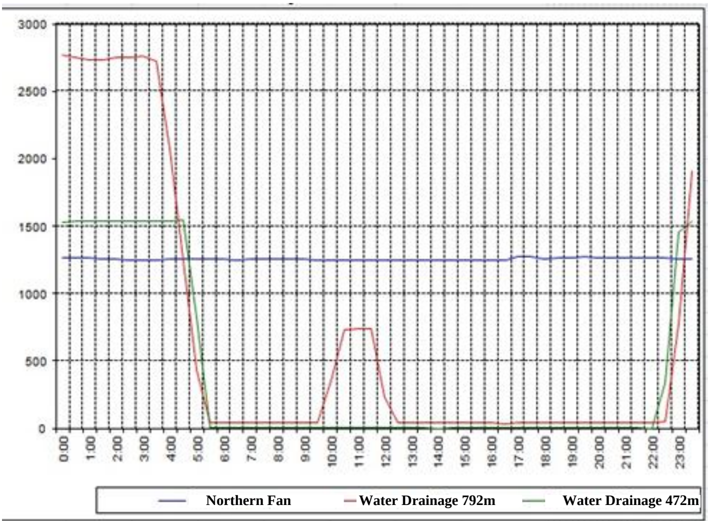


Fig. 2.12. Daily curves of ventilation and water drainage at Hvardiiska mine of the PJSC "KZRK"

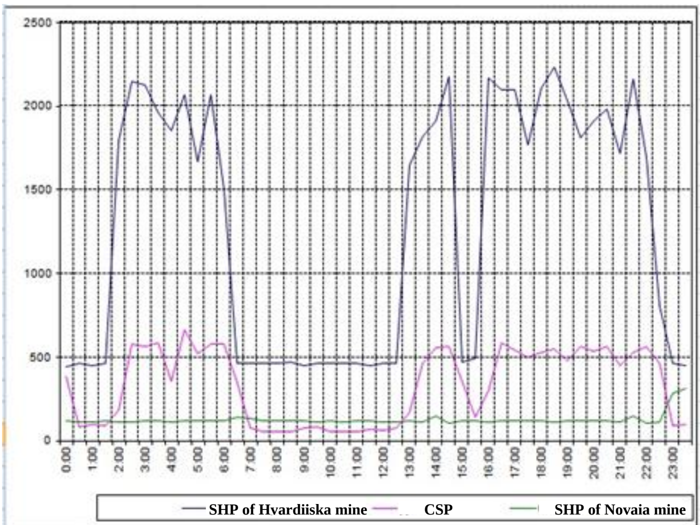


Fig. 2.13. Daily curves of hoisting and the crushing-sizing plant at Hvardiiska mine of the PJSC "KZRK"

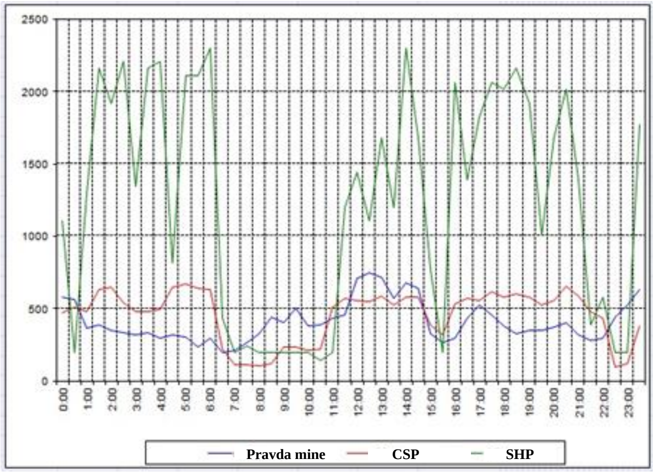


Fig. 2.14. Daily curves of hoisting and the crushing-sizing plant at Rodina mine of the PJSC "KZRK"

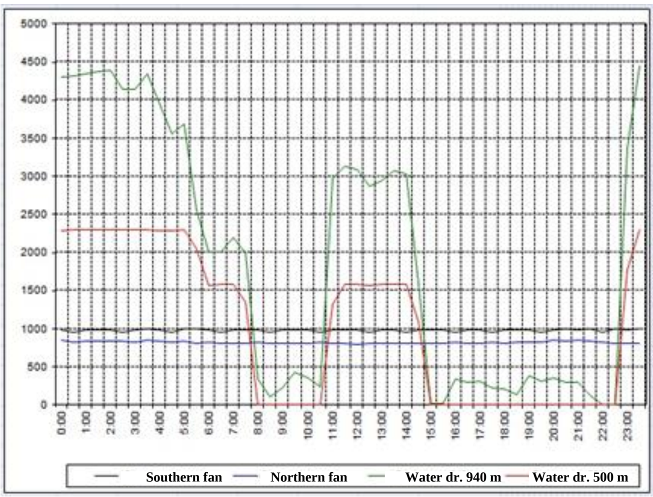


Fig. 2.15. Daily curves of ventilation and water drainage at Rodina mine of the PJSC "KZRK"

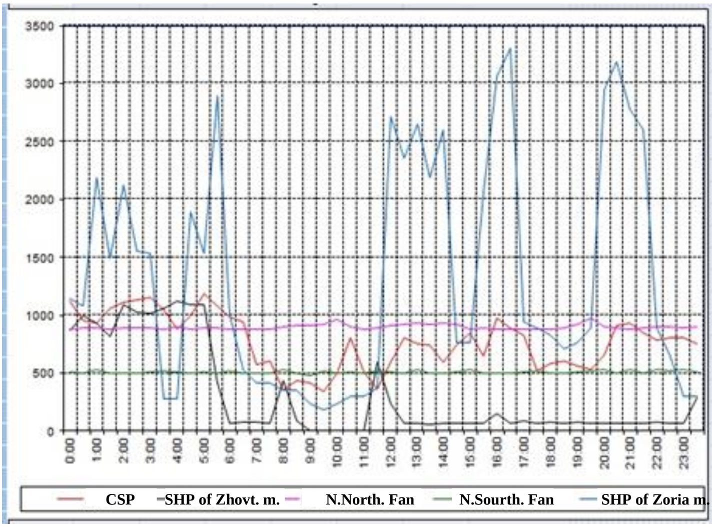


Fig. 2.16. Daily power curves of ventilation, hoisting and the crushing-sizing plant at Oktiabrska mine of the PJSC "KZRK"

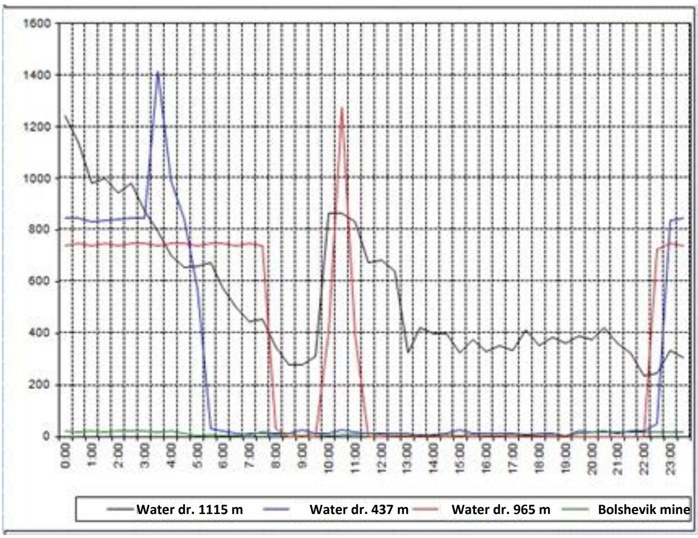


Fig. 2.17. Daily curves of water drainage at Oktiabrska mine of the PJSC "KZRK"

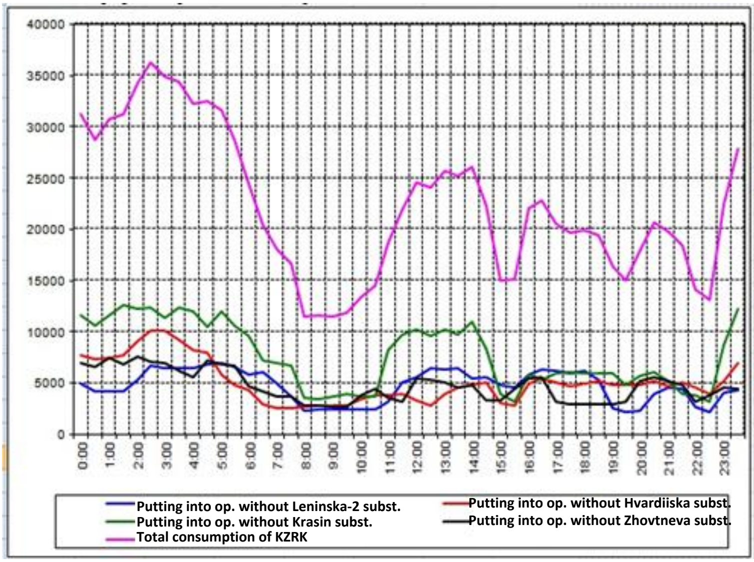


Fig. 2.18. Daily curves of the PJSC "KZRK" mines

The given curves indicate work intensity of water drainage installations at night. The curves of hoisting installations and crushing-sizing plants at night and evening hours are also seen. As full iron ore hoisting and processing cannot be provided at night, these operations are performed in the evening after routine repair works. One can also observe some associations of the curves of the crushing-sizing plant and those of skip-hoisting installations.

The curves of ventilation installations are fairly stable as there is need to ensure constant ventilation of underground mine workings. This stability is interrupted by ventilation shafts of hoisting installations as they can operate because of the necessity to transport people and cargo during repair works in mine workings [32, 33].

Analysis of the curves indicates the following:

– power consumers' curves can be probable with various degrees of changeability: a greater degree of changeability is observed in the curves of hoisting machines and crushing-sizing plants, the smaller degree – in the curves of ventilation and water drainage installations;

– power consumers' curves can be cyclic because of cyclic processes at the mines.

2.3 Load curves of power intensive installations

Compressed air is supplied to the PJSC "KZRK" mines by the region compression stations RCPCMD-1 and RCPCMD-2 located at Hvardiiska and Oktiabrska mine.

Compression installations with powerful synchronous engines (up to 3500 kW) are referred to power intensive ones (Table 2.2-2.3). Figures 2.19-2.22 provide daily curves of compression stations RCPCMD-1 and RCPCMD-2 in May 3-6, 2014.

Table 2.2. Technical characteristics of centered air compression machines

Compressor type	Capacity		Operating pressure, MPa	Consumption capacity, kW	Shaft speed, revolutions/ sec	Cooling water con-sumption, kg/s
	m^3/s	$m^3/$ min				
K-500-61-1	8.34	500	0.88	3400	50.2	50.0
K-350-61-1	5.83	350	0.72	2500	143	37.0
K-250-61-1	4.17	250	0.88	1500	183	25.0

Table 2.3. Parameters of compressor motors

Compressor type	Motor type	Indicated capacity, kW	Indicated shaft speed, rev/s	Indicated voltage, V
K-250-61-1	CTM-1500-2	1750	3000	6000
K-500-61-1	CTM-2500-2	3500	3000	6000

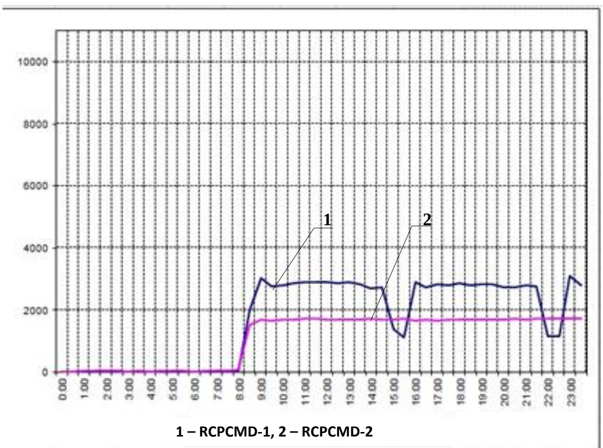


Fig. 2.19. Daily schedules of compressor plants RCPCMD -1, RCPCMD -2 of the PJSC "KZRK" on May 3, 2014

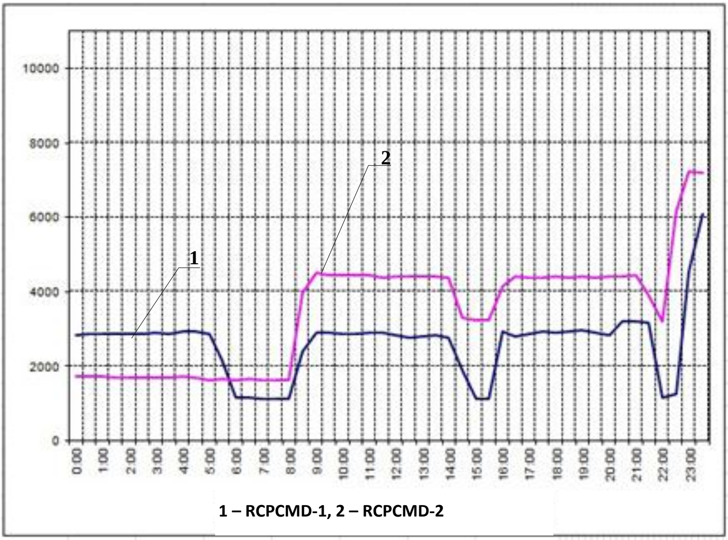


Fig. 2.20. Daily curves of compressor plants RCPCMD-1, RCPCMD-2 of the PJSC "KZRK" on May 4, 2014

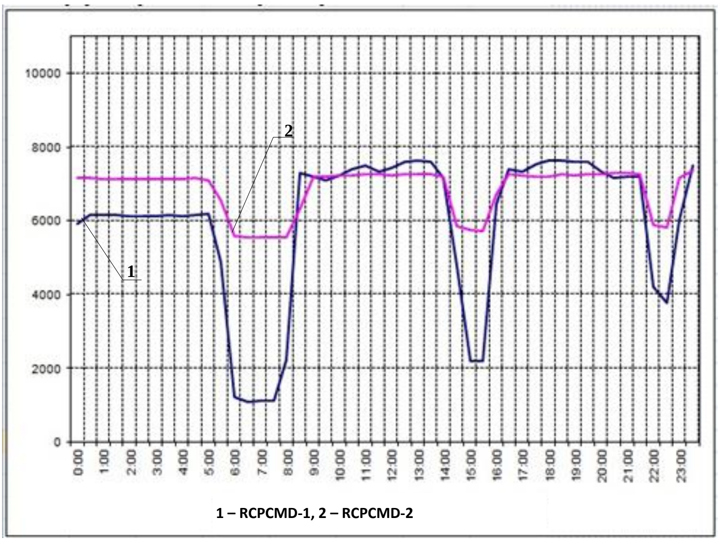


Fig. 2.21. Daily curves of compressor plants RCPCMD-1, RCPCMD-2 of the PJSC "KZRK" on May 5, 2014

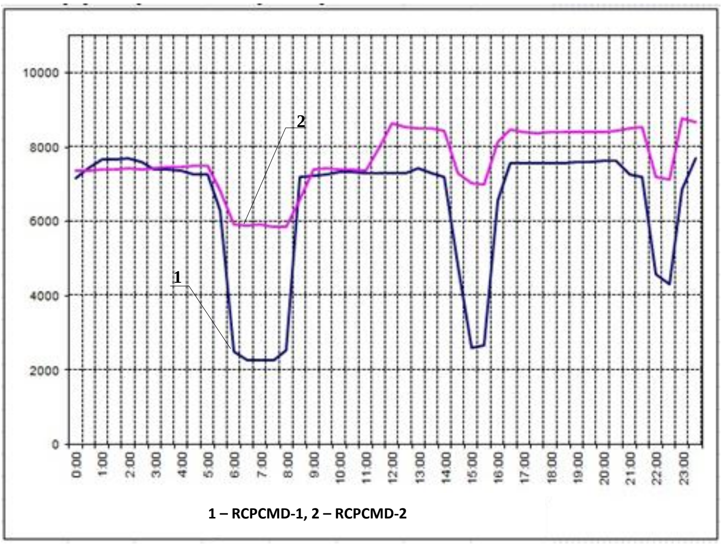


Fig. 2.22. Daily curves of compressor plants RCPCMD-1, RCPCMD-2 of the PJSC "KZRK" on May 6, 2014

As is shown, compressor plants did not operate on public holidays and came into operation on May 3, 2014 at 8 p.m. All day long, just one compressor was in operation at each station. The following days, in order to maintain pressure because of increased consumption of compressed air, another compressor was added for each plant.

The curves reveal periods of morning, daytime and evening unloading of compressor plants between shifts.

There is no soft-starter of synchronous motors at RCPCMD-2 and reduction of active capacity during unloading hours is smaller than that of RCPCMD-1 equipped with this device. Thus, soft-starter installation at RCPCMD-2 can save power due to unloading and increase reliability of synchronous motors when starting the compressor plant.

At Kryvyi Rih iron ore underground mines, various electric drive systems such as "generator-motor" (GM), "thyristor converter-motor" (TC-M), "frequency converter-synchronous motor" (FC-SM) are used. Table 2.4 provides data on generators, transformers and motors of the most powerful skip hoists.

Table 2.4. Technical characteristics of skip hoists

Equipment type	U_{nom}, V	I_{nom}, A	P_{nom}, kW	n_{nom}, rpm
DC generator П21-40	1000	6300	6300	375
DC motor П2-800-255	930	5740	5000	63/100
DC thyristor converter ТП3-6300/1050	1050	6300	6615	-
AC motor AMZ 2500 LL 16 (2 pcs)	3150	2x360	2x3750	47.7
AC thyristor frequency converter ACS 6109 A06 2s9	4160	2x360	2x3090	-

The "G-M" electric drive is installed at Rodina and Hvardiiska mines. The weight-carrying capacity of the skip hoist of Rodina mine is 50 t and that of Hvardiiska mine is 25 t.

The "FC-SM" electric drive made by ABB is installed and run at Ternivska and Zoria mines after updating. The weight-carrying capacity of the skip hoist of Ternivska mine is 30 t, that of Zoria mine is 35 t. Before updating, the mines had the "G-M" electric drive with the weight-carrying capacity of 25 t.

Fig. 2.23 shows daily curves of consumed active power of the mines' skip hoists at the PJSC "KZRK".

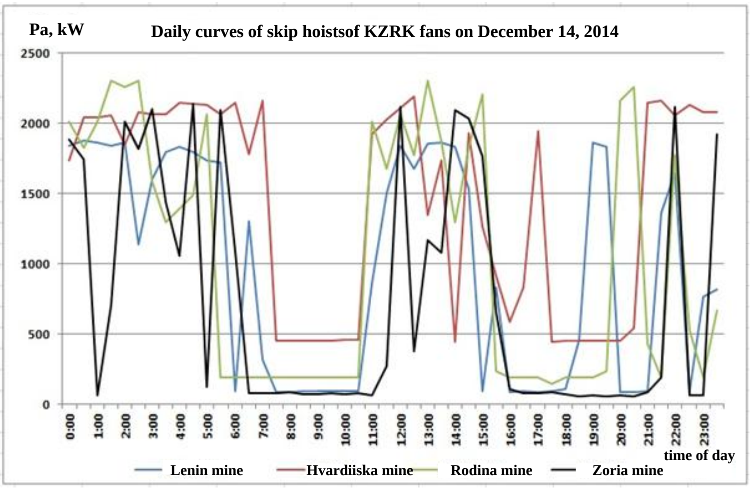


Fig. 2.23. Daily curves of consumed active power of skip hoisters at the PJSC "KZRK"

As the curves reveal, the maximum levels of consumed active power are seen at Rodina mine because of greater hoisting capacity of its skips. One should consider both the impact of pay load and the velocity of the skip or, to be exact, the sum of their impacts.

At Ternivska and Zoria mines, hoists are equipped with an electric drive (the "FC-SM" system) and in downtime periods the level of consumed power of the idling is much lower than that of the "G-M" system that is installed at Rodina and Hvardiiska mines (about 100 kW against 450 kW).

The yearly power losses at skip hoists with the "G-M" electric drives against the "FC-SM" one can be determined:

– for Rodina mine:

$$\Delta W_p = P_{xx} \cdot n_c \cdot m_r = 200 \cdot 24 \cdot 365 = 1752000 \text{ kW} \cdot \text{h};$$

– for Hvardiiska mine:

$$\Delta W_p = P_{xx} \cdot n_c \cdot m_r = 450 \cdot 24 \cdot 365 = 3942000 \text{ kW} \cdot \text{h},$$

where P_{ns} is losses of nonworking stroke;

n_{shift} is the number of hours in a shift;

m_{year} is the number of calendar days in a year число.

Ventilation takes the second place as to power consumption at the iron ore mines (Table 2.5). Unregulated electric drives with synchronous motors of the СДН (SDN) type are used for fan units.

Table 2.5. Technical characteristics of mine fans

Parameters	Fan unit size		
Axial-flow fans			
	ВОД-30М2	ВОД-40М	ВОД-50
1. Fan wheel diameter, mm	3000	4000	5000
2. Fan speed, rpm	600	375	300
3. Tip/blade speed, m/s	78.5	78.5	78.5
4. Fan capacity, m^3/s	60-270	85-380	110-580
5. Static pressure, Pa	1200-5800	600-3100	900-3200
6. Motor capacity, kW	1250	1600	2000
Aligned fans			
	ВЦД-31.5М2	ВЦД-42.5	ВЦД-47.5УМ
1. Fan wheel diameter, mm	3150	4250	4750
2. Fan speed, rpm	300-600	150-500	250-500
3. Tip/blade speed, m/s	100.5	112	120
4. Fan capacity, m^3/s	40-285	100-650	85-600
5. Static pressure, Pa	5200	6000	7500
6. Motor capacity, kW	1250	5000	4000

Fig. 2.24 provides daily curves of consumed active power of the PJSC "KZRK" mine fan units. As is shown, because of the length and geography of the mine workings, the minimum consumed power of a fan unit is observed at Hvardiiska mine (about 1000 kW).

Ternivska and Oktiabrska mines reveal a bit greater level of fan power – 1250 and 1400 kW. Rodina mine consumes even more power (2000 kW) because of greater depths and extensive networks of the mine workings.

Outbursts of active power at Ternivska, Hvardiiska and Oktiabrska mines result from operation of the mine hoist.

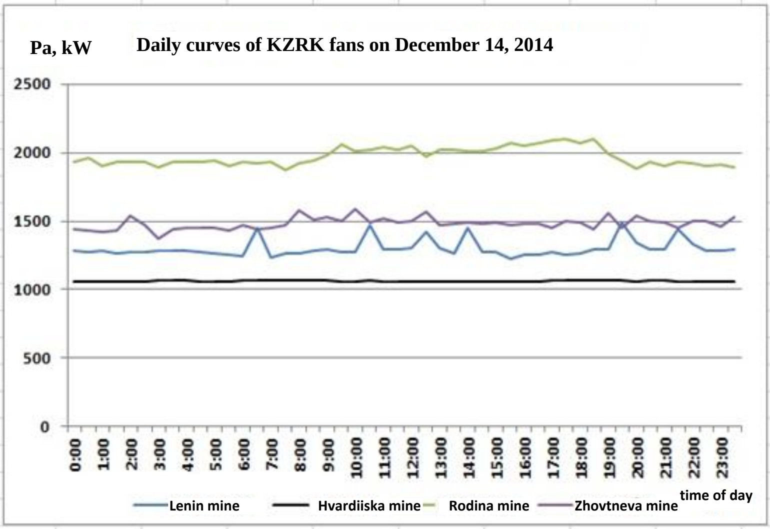


Fig. 2.24. Curves of active power consumption of mine fan drives at the PJSC "KZRK"

Water drainage is also power intensive. Aligned pumps (ЦНС type) are applied here (Table 2.6).

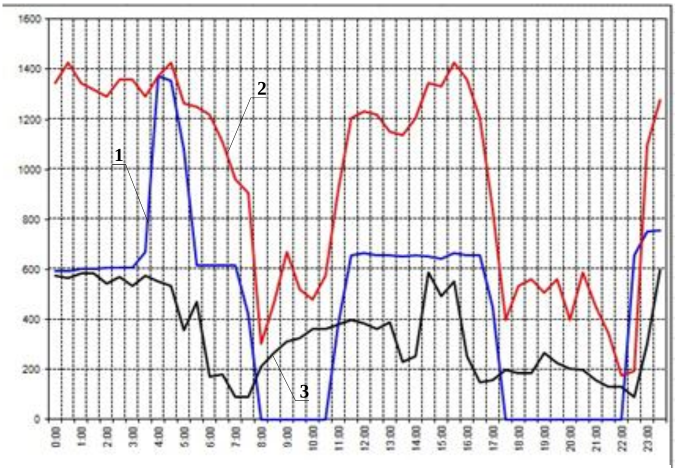
Table 2.6. Technical characteristics of mine aligned pumps

Parameters	Unit size	
	ЦНС 300-480	ЦНС 300-600
1. Pump capacity, m^3/h	300	300
2. Pressure, m	480	600
3. Motor type	А4-400Х-4М	А4-450Х-4М

4. Motor capacity, kW	630	800
5. Pump speed, rpm	1475	1475
6. Nominal voltage, kV	6	6

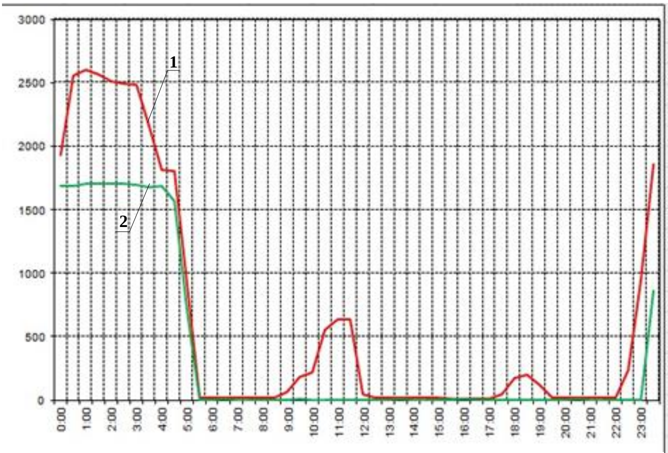
Figures 3.25-3.28 present power curves of pumps for various mine levels of the PJSC "KZRK".

As is shown, pumps drain mine waters mostly at nighttime when power costs are minimal. If pumps cannot drain the water fast enough, they do it in shoulder periods.



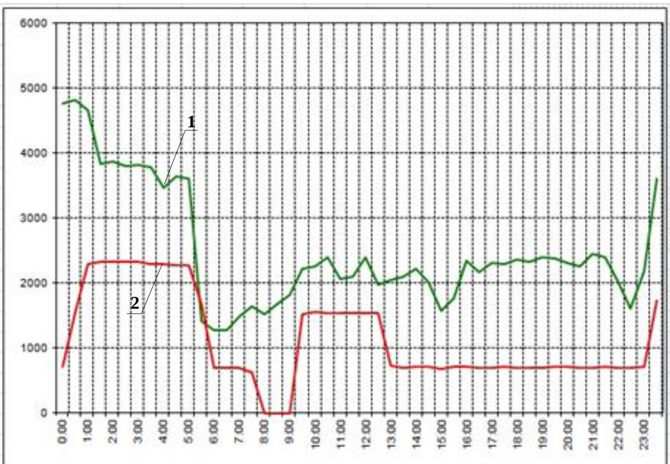
1 – Water drainage 527 m, 2 – Water drainage 900 m, 3 – Water drainage 1350 m

Fig. 2.25. Active power curves of mine water drainage drives at Ternivska mine of the PJSC "KZRK"



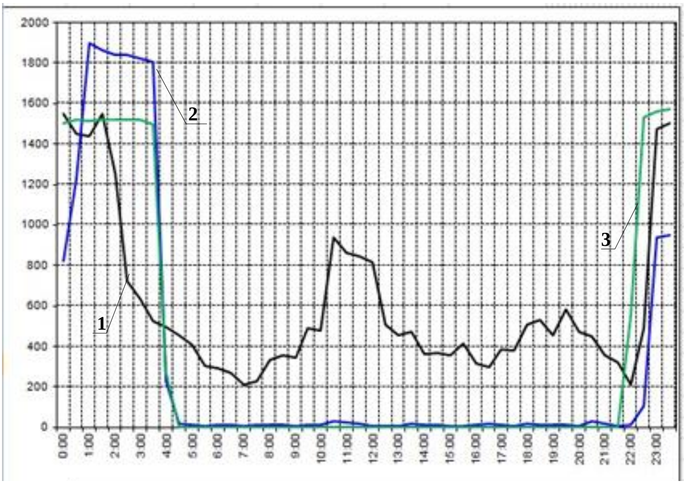
1 – Water drainage 792 m, 2 – Water drainage 472 m

Fig. 2.26. Active power curves of mine water drainage drives at Hvardiiska mine of the PJSC "KZRK"



1 – Water drainage 940 m, 2 – Water drainage 500 m

Fig. 2.27. Active power curves of mine water drainage drives at Rodina mine of the PJSC "KZRK"



1 – Water drainage 1115 m, 2 – Water drainage 437 m, 3 – Water drainage 965 m

Fig. 2.28. Active power curves of mine water drainage drives at Oktiabrska mine of the PJSC "KZRK"

Since, besides pumps, some other consumers operate at sections of substation busbars, they perturb regular power curves of these mine levels with pump electric drives being an exception.

2.4 Power resource consumption in iron ore mining

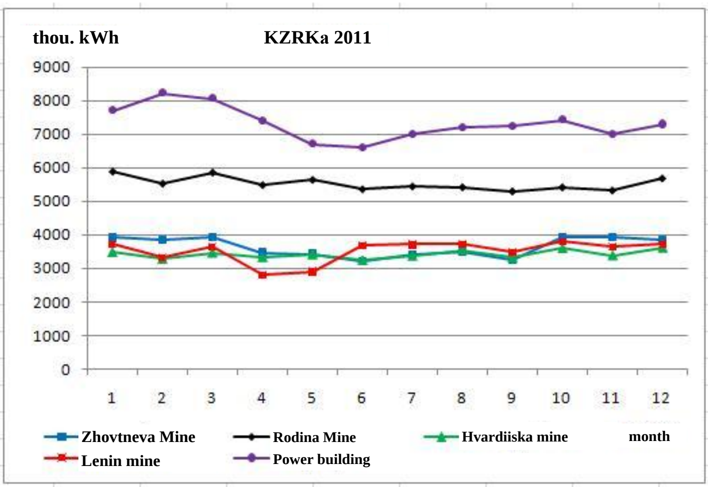
Underground mines of the PJSC "KZRK" are intensive power consumers. Among other units providing reliability, security and efficiency of a mining enterprise, fixed machines and installations are the major ones being characterized by complex structures and high energy-intensity (up to 70% of all power consumed by a mining enterprise). They are power-mechanical complexes engineered for hoisting minerals, wastes, people, materials and machines; draining mineral deposits and pumping water from mine workings (water drainage plants); ventilating mine workings and creating appropriate air conditions for mining (fan installation); producing blowing/pneumatic power (compressed air) used by continuous miners, mining and drilling picks, winding machines (compressor plants), local and section fans, etc. [37, 38] (Table 2.7).

Table 2.7. Indices of power consumption and costs at the PJSC "KZRK" (December, 2014)

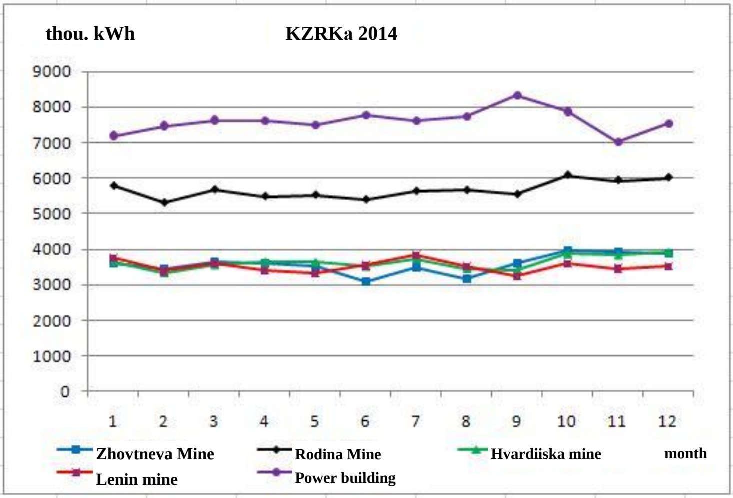
Structural unit	Power consumption	Specific fraction	Power costs	Specific fraction	Specific cost
	thou. kW·h	%	thou. UAH	%	UAH/ kW·h
Oktiabrska mine	3871.095	14.40	3510.437	13.04	0.90683
Rodina mine	6014.121	22.38	5541.670	20.59	0.92144
Hvardiiska mine	3919.249	14.58	4263.806	15.84	1.08791
Ternivska mine	3522.988	13.11	3291.708	12.23	0.93435
Power building	7554.571	28.11	8131.879	30.22	1.07642
Other consumers	1994.089	7.42	2172.935	8.08	1.08969
Total	26876.113	100.00	26912.435	100.00	1.00135

Table 2.7 reveals that power consumption of separate mines is different depending on a number of factors: current mineral output, mining depths, inflow volumes, mine working network, etc.

Fractions of consumed power costs are also different depending on steps aimed at improving power consumption as to tariff zones of payment and consumer classes. For example, Hvardiiska mine and RCPCMD-1 of the power building consume power supplied by Hvardiiska substation (154 kV) according to Class 2 which has a greater cost by 23 % than that of Class 1 as of March 2015 (Fig. 2.29-2.33).



a)



b)

Fig. 2.29. Yearly load curves of the PJSC "KZRK" mines and power building

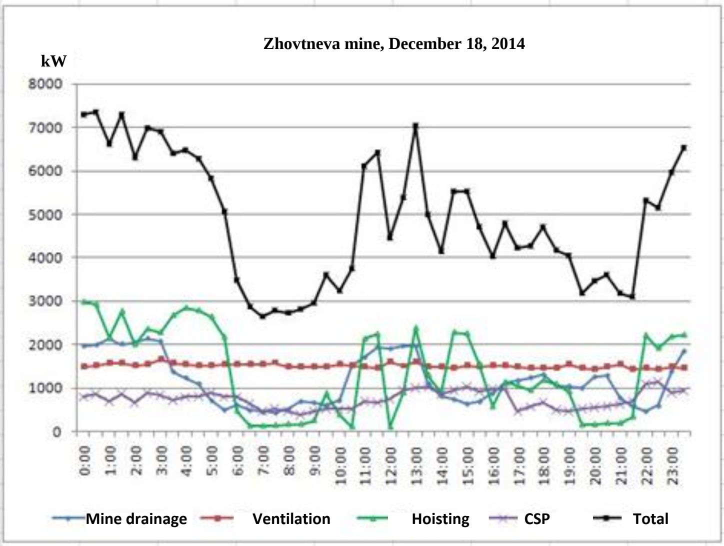


Fig. 2.30. Daily load curves of fixed installations of Oktiabrska mine

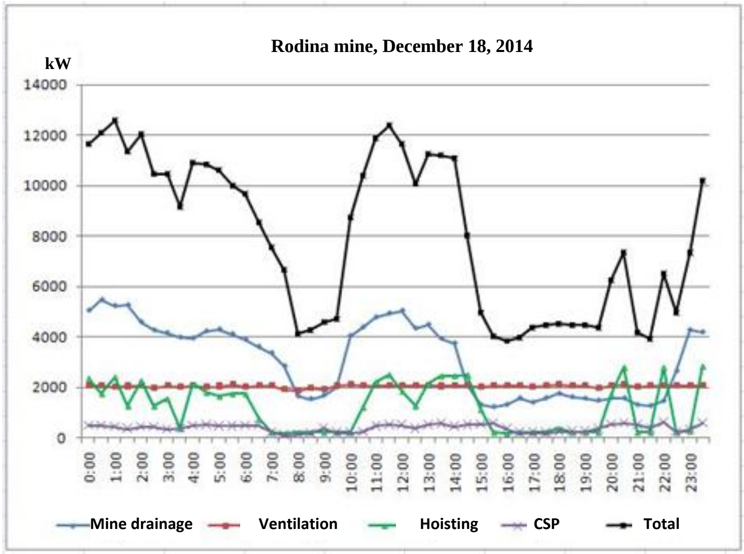


Fig. 2.31. Daily load curves of fixed installations of Rodina mine

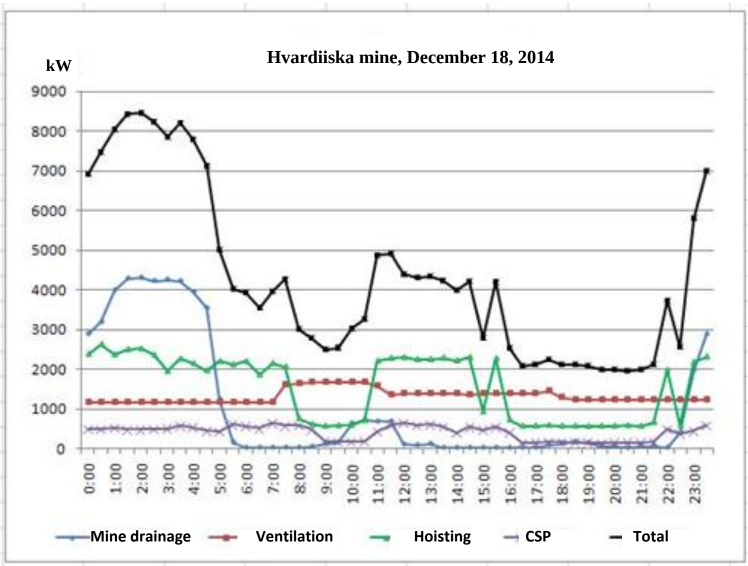


Fig. 2.32. Daily load curves of fixed installations of Hvardiiska mine

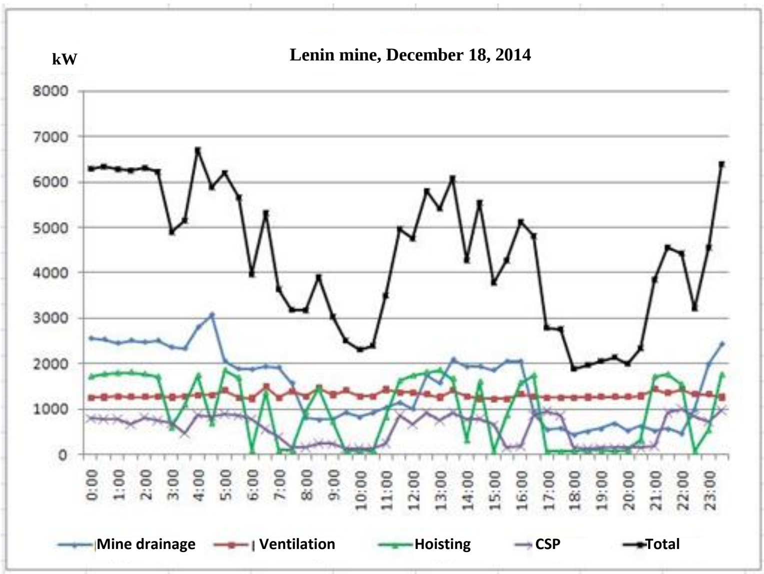


Fig. 2.33. Daily load curves of fixed installations of Hvardiiska mine

Figures 2.29 *a* and *b* show yearly load curves at the mines and the power building of the PJSC "KZRK" in 2011 and 2014. The power building produces compressed air by means of compressor plants for the mines' consumers.

The mines' load curves are formed by loads of structural consumers of theses mines (ventilation, water drainage, hoists and CSP). Corresponding load curves are in Fig. 2.30-2.33.

Analysis of the given curves enables the following conclusions:

1. Ternivska mine demonstrates the lowest levels of the total active power because of operation of the skip hoist equipped with the electric drive made by ABB. It is notable by high efficiency and the low level of reactive power consumption.

2. Ternivska mine waters are drained both at night and daytime. It reduces irregular power consumption as compared to that of Hvardiiska mine. These mines are similar in hoisting capacity of their hoists.

3. Rodina and Oktiabrska mines are also comparable due to the same hoisting capacity. Yet, Rodina mine has a greater active power because of the G-M electric drive as compared to that of FC-SM system made by ABB at Zoria mine which is similar to the system of the Ternivska

mine hoist. Zoria mine is part of Oktiabrska mine and iron ore is hoisted along the Zoria shaft.

4. Rodina mine has a considerable level of active power consumption conditioned by great capacity of water drainage plants because of high volumes of mine waters.

5. The level of active power of Rodina mine is higher than that of Oktiabrska mine because of complicated network of mine workings and greater power consumption of ventilation.

2.5 Ways of increasing energy efficiency

The capacity of hoist electric drives is the highest among electric drives of mine fixed installations.

Power consumption of hoists is determined by mining depth, weight of iron ore in the skip and power losses. Thus, power consumption can be reduced only by decreasing power losses.

Application of more modern AC electric drives with frequency transformers and AC motors enables reduction of power losses [38, 46].

Figures 2.34-2.37 show daily load curves of electric drives of skip hoists of crushing-sorting plants. They are interconnected technologically in the process of iron ore mining and processing.

The crushing and sorting plant (CSP) is another link of the technological chain along with the skip hoist. It is revealed in the graphs (Fig. 2.34-2.37) through load changes as ore goes to CSP conveyors and crushers after skip unloading.

As is shown the electric drives of skip hoists operate under the intensive mode at nighttime to save money for electricity. When sizeable volumes of iron ore are to be hoisted it occurs at daytime as well. In peak hours in the morning and in the evening, the skip hoist does not work because of the highest electricity tariffs at that time. A crushing and sorting plant is a mining enterprise designed to crush and screen (sort) rocks, minerals, slurries and other materials to obtain a product of the required granulometric size. A CSP can be both an autonomous enterprise and a shop within ore concentrating plants.

Crushing and grinding are processes of disintegrating and reducing sizes of mineral lumps under the action of external mechanical, thermal and electric forces aimed to overcome internal cohesion connecting particles of a solid body. In mining practices, external mechanical impacts are used for crushing in most cases.

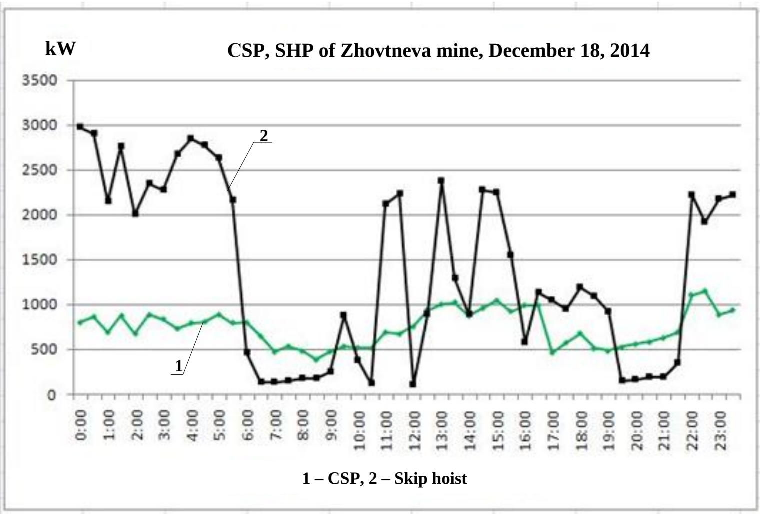


Fig. 2.34. Daily load curves of the CSP and SHP of Oktiabrska mine

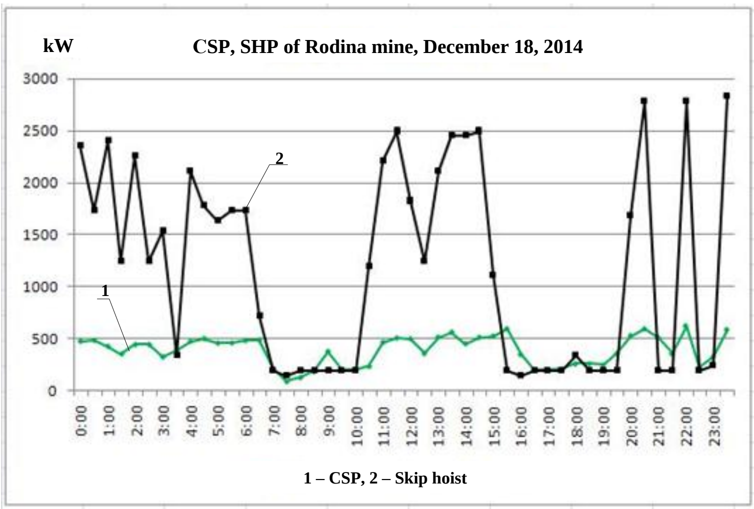


Fig. 2.35. Daily load curves of Rodina mine CSP and SHP

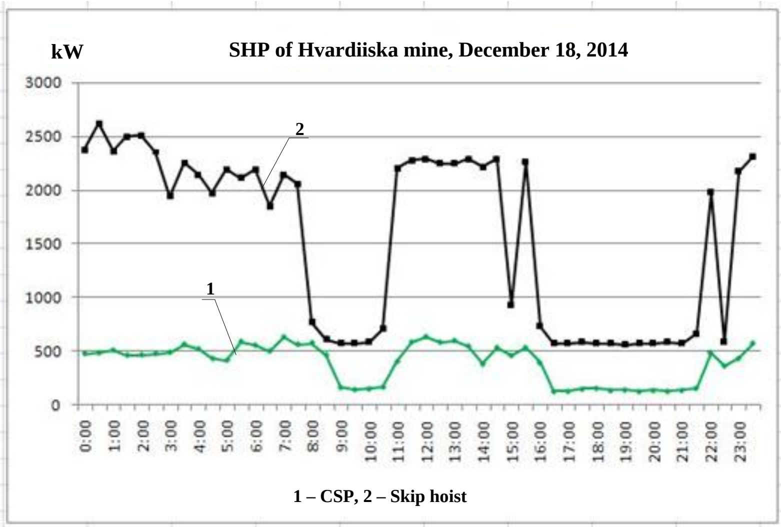


Fig. 2.36. Daily load curves of Hvardiiska mine CSP and SHP

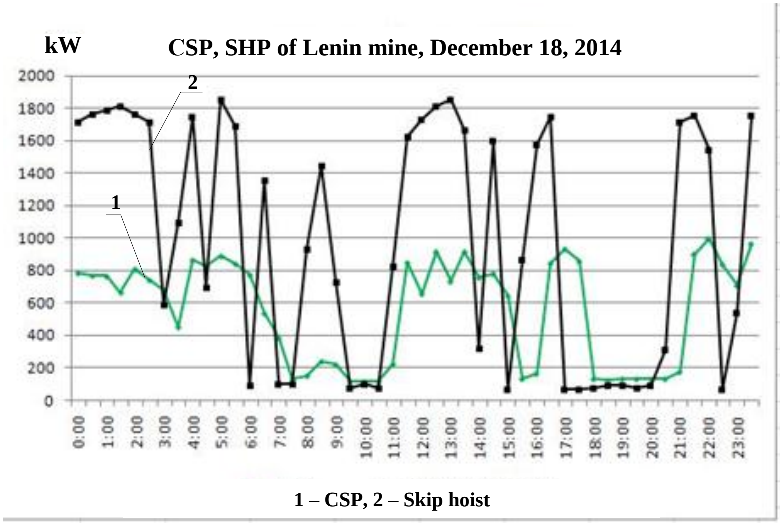


Fig. 2.37. Daily load curves of Hvardiiska mine CSP and SHP

Crushing and grinding are used to separate closely interlaced and merged mineral grains. The fuller mineral grains open in crushing and grinding, the more successful subsequent concentration is. Sizes of crushed and ground minerals depend on mineral composition, impregnation, concentration methods and the character of concentration product use.

Machines for ore crushing and grinding are called crushers and mills. Efficiency of crushers (mills) is assessed by the amount of crushed ground products per 1 kW/h of consumed power.

Screening (sorting) is division of bulk solids into sizes on screening surfaces.

Basic screening indices include efficiency and productivity which are inverse-related: the greater productivity, the smaller screening quality and vice versa. Screening efficiency depends on screening duration, the granulometric and material composition of initial materials and their humidity. The geometric form of grains is of primary importance. Round grains are most favourable. Design and mode parameters like screen design, opening forms and sizes, the ratio of the screening surface length to its width, the regular feed of materials, a slope angle, frequency and trajectory of vibrations have an impact on screening indices.

400 kW crushers and 280 kW conveyors to transport ore are used at the mines' CSP.

The CSP load curves repeat fluctuations in active power of the skip hoist, yet with smaller levels and with some delay because of continuous transportation of rocks.

Up-to-date electric drives designed for crushers and conveyors which are more efficient in technical and economic terms enable reduction of power consumption at the CSP.

Mine fans are designed to ventilate mine workings and maintain comfortable and safe labour conditions through adjusting air composition, speed and temperature to meet the industry safety rules.

The air passing through mine workings changes its composition. Its oxygen content falls while that of carbon dioxide rises. Besides, there are such gases as nitrogen, carbon oxide, sulfide, sulfur dioxide, nitrogen oxides, methane, as well as dust, vapour and other substances emitted from rocks and emerging during mining operations.

The content of gases in the air is characterized by their concentration which is a ratio of the volume (volume concentration) or mass (mass concentration) of the given gas to the total quantity of the gas-air mixture. The air coming from the surface into mine workings and undergoing some changes is called mine air.

The air flow from the air-intake shaft to faces is called inflowing, that one from faces to the return air shaft is called outflowing. The mine air consists of the following components:

– oxygen, the minimal content of which is not to be less than 20 % in volume according to safety rules;

– carbon dioxide, the maximum acceptable content of which should not exceed 0.5% at working places and the outflowing air at sites; 0.75 % at mine workings at mine workings with outflowing air of the mine-take wing, a level and a mine as a whole;

– carbon oxide not exceeding 0.0016 % in volume at mine workings that operate or are being constructed;

– nitrogen oxides formed during blasting and not exceeding 0.00025 % in volume in terms of nitrogen dioxide NO_2;

– sulfur dioxide not exceeding 0.00035 % in volume.

Considering the above, mine ventilation should provide for the required volume of oxygen and dissolve emitted harmful gases and substances to acceptable concentrations. Special fans designed for mining perform this operation.

According to their purpose, fans can be divided into main, auxiliary and local.

Main fans are designed to ventilate all workings of a mining enterprise (mines, open pits) or its part (wings, blocks, panels, etc.). Following mine safety requirements, they are installed on the surface of leakproof shafts, short holes, adits and boreholes.

Auxiliary fans typically located on the surface are designed to ventilate shafts and permanent workings as well as some sites of a mining enterprise.

Local fans ventilate dead headings, faces and some static zones. According to their aim, they are classified into main, auxiliary and local.

According to the ventilation type, main fans can be exhausting and forcing.

Aligned fans are used as both main and auxiliary ones. Local fans are mostly axial.

A fan design depends on its aim, location, the type of applied fans and the industrial requirements "Safety rules and Rules of technical operation".

Aligned main fans are designed according to GOST 11004–84 to be single-stage with double air supply, 1.6-4.75 m impellors, 25-630 m^3/s nominal feed and 2450-7000 Pa static pressure. The basic way to control the operating mode of main aligned fans is changing the angle of the inlet guide vane.

Main fans consist of a machine and a standby electric drive. Besides, they are equipped with reverse devices to reverse the air flow direction (fan flow) in all mine workings due to general shaft depression.

Operating and standby fans are connected to the mine shaft by fan channels (underwater, exhausting, forcing, bypass) and a fan diffuser with an exit. Channels are made in concrete foundations of fans.

Thus, main fans consist of two machines (fans with electric motors and controlling automated devices), auxiliary machines to change and reverse air flows and ventilation channels to provide direct and reverse operation of each fan.

Aligned fans are non-reverse. That is why, they have bypass channels to feed air into a mine under the reverse mode of fan operation.

Fans operate permanently with rare reduced or increased levels of power. It is revealed in active power curves in Fig. 2.38-2.39.

Power loads of fans can be decreased on public holidays when the number of miners working underground is reduced. Fig. 2.38-2.39 show curves of fan operation at Rodina, Oktiabrska and Hvardiiska mines.

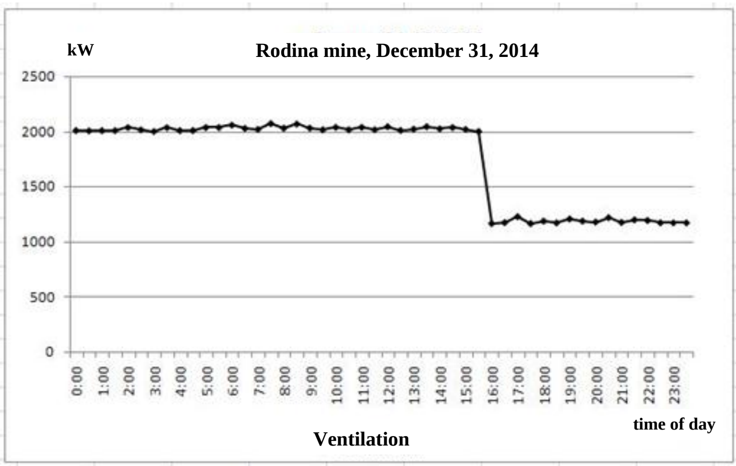


Fig. 2.38. Daily load curves of Rodina mine fans on public holidays

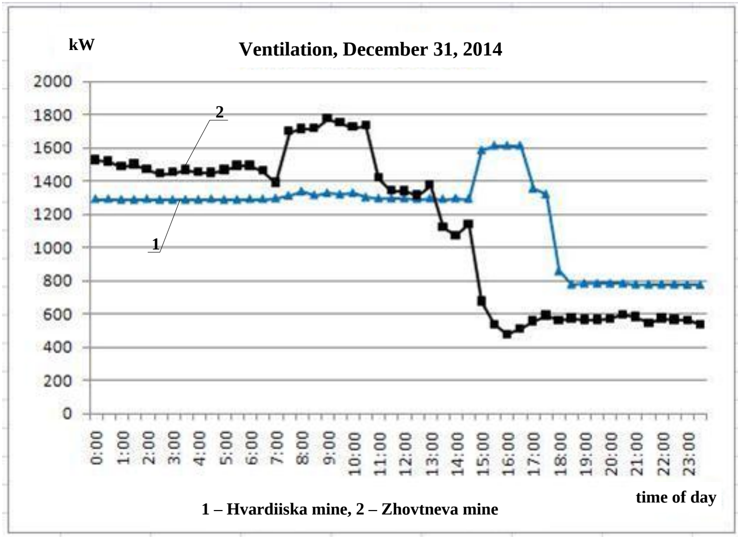


Fig. 2.39. Daily load curves of Oktiabrska and Hvardiiska mine fans on public holidays

As is shown in Fig. 2.39, a slight irregularity of load curves of Oktiabrska mine ventilation results from total consumption of its fan unit and cage hoist. Operation of the cage hoist changes the total load of the fan feeder. The mine's operational personnel uses all opportunities to save power.

Water contained in rocks and water inflows to mine workings make labour conditions complicated and in some cases affect physical properties of rocks resulting in rock instability and deterioration of mineral quality to be mined.

For this reason, open pit and underground mining call for steps aimed at full or partial drainage, elimination or reduction of water inflows into mine workings, water collection and management.

The steps taken at a mining enterprise being built or operating are realized by a special drainage system which includes a network of catchwater drains and technical means to collect and drain underground and surface waters.

An essential element of the drainage system is a drainage installation, a complex of power-mechanical machines to drain underground and surface waters from catchwater drains of underground mines.

As to the character of interaction with drained water, there are two elements of drainage facilities – a power pumping unit and a vacuum pumping unit.

As to their purposes, drainage installations are divided into main (central), auxiliary (sectional) and temporary (shaft-sinking). Main drainage installations are the units designed to catch and drain the whole or part of expected water inflow of mine workings. Long mine-takes may require several drainage installations. Two or three main drainage installations are used at two-three mine levels.

Auxiliary drainage installations are designed for water depression at separate faces and sections located lower than the main sump. Temporary drainage installations are used in shaft sinking of capital mine workings of an enterprise under construction or in case of emergency.

Drainage installations at mines are stationary, sump units notable for large sizes to accumulate water along drainage channels from mine workings.

Water reservoirs of mine sumps present a system of mine workings divided into sections separated from the main water-receiving sump by concrete crosspieces equipped with pass valves to turn off reservoir sections and clean them.

Pumps with 800 kW electric drives are used in water drainage installations. Two or three pumps of this type can function at mine levels. Daily curves of active power of pumps at the PJSC "KZRK" are in Fig. 2.40. Yearly load curves of the enterprise drainage installations are in Fig. 2.41.

Fig. 2.40 indicates that the pumps are not in constant operation as they are turned on only once or several times a day to drain water. When water reservoirs are large enough to accumulate water, it happens at nighttime only (Hvardiiska mine). When the volume is not enough to collect all the water, drain facilities have to function at daytime as well (Rodina and Oktiabrska mines).

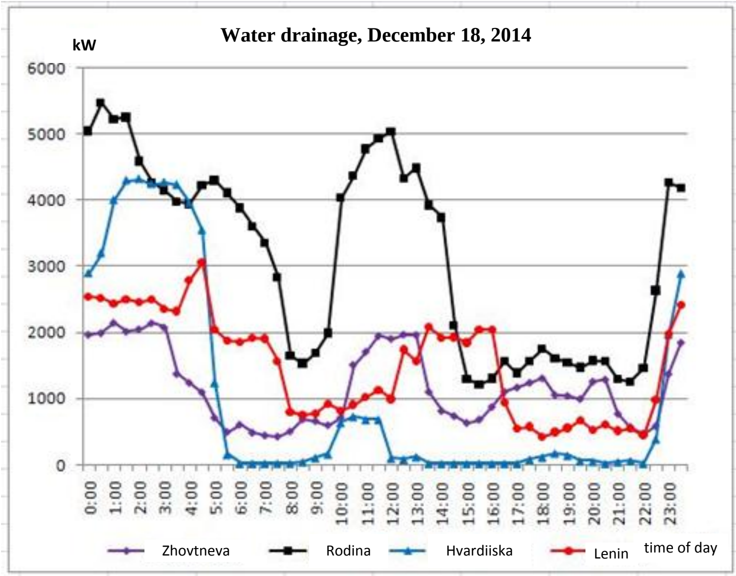


Fig. 2.40. Daily curves of active power of the PJSC "KZRK" water drainage installations

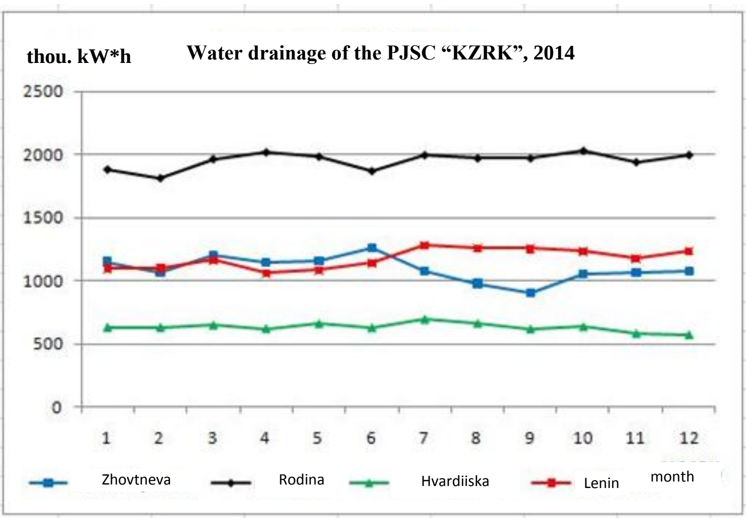


Fig. 2.41. Yearly load curves of the PJSC "KZRK" drainage installations

As is seen from Fig. 2.41, fluctuations of the load curves of water drainage are insignificant because of changes in water inflows.

Turbochargers or turbo-compressors are the most high-energy turbo-machines with capacity of up to 3200 kW. The machines are designed to raise gas pressure and transport it by pipelines. They are typically applied to generating blowing power, transporting gas by main gas pipelines, compressing air to receive oxygen by dividing air delivery and oxygen into blast furnaces. They are also used in refrigeration.

Currently, turbochargers are controlled by pressure throttling mainly. Turbocharger efficiency reduces proportionally to its capacity control.

Turbochargers are also peculiar for some critical machine feed corresponding to each revolution rate. Unstable operation can be caused by compressor blade slap leading to great pressure pulsations. In this case, it is necessary to transport the required quantity of gas with minimum power consumption. In response to reduced gas consumption, decreased feed is needed to avoid unnecessary pressure increase in pipelines. As turbochargers are united into stations of several compressors operating in successive or parallel order, the feed is controlled gradually by changing the number of machines in operation.

Turbochargers, superchargers and blowers are usually continuous load machines and their electric drives should be designed for continuous service of up to 8400 hours of operation. They are high-speed mechanisms with 3000-20000 RPM, this fact determining expediency of such motors. All turbochargers, except for turbo-blowers, operate for the main with resistance which means significant dependency of the resistant torque of the shaft on revolution rate. Changing RPM is the perfect way to control efficiency of turbochargers.

Turbochargers are put into operation with a machine unloaded by connecting the decreasing space and the atmosphere or increasing space due to which the starting peak torque does not exceed 0.4 of the nominal one.

Automation of such machines should meet the requirements including speed of operation, selectivity, sensitivity and reliability.

Selectivity of automation implies short-circuit switching-off a damaged section only or the closest one to the fault location.

Sensitivity of all types of automation is evaluated by the sensitivity factor and the minimum shot-circuit current. Reliability of automation provides safe operation in all provided cases.

There are five continuous operating compressors installed in the department. Three of them are running and the rest are under repair or on stand-by. The period between ordinary repairs is 8520 hours, the standing idle is 120 hours. Besides, compressors are stopped monthly for ordinary repairs of 8 hours.

Figures 2.42-2.46 depict load curves of the district compressors at RCPCMD-1 and RCPCMD-2 with different curve forms conditioned by different modes of compressed air consumption of mine consumers.

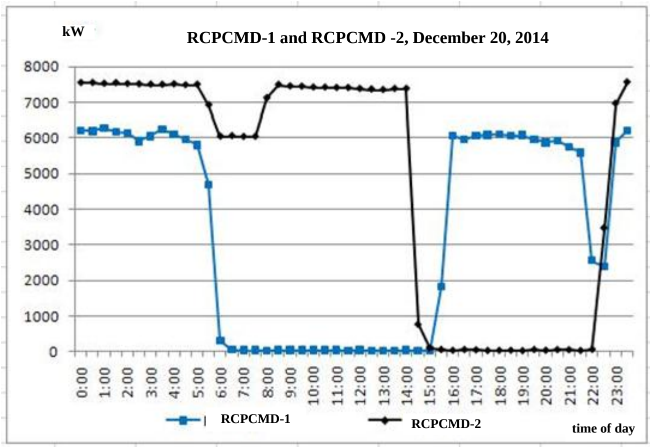


Fig. 2.42. Daily load curves of active power of district compressor stations RCPCMD-1 and RCPCMD-2 of the PJSC "KZRK", December 20, 2014

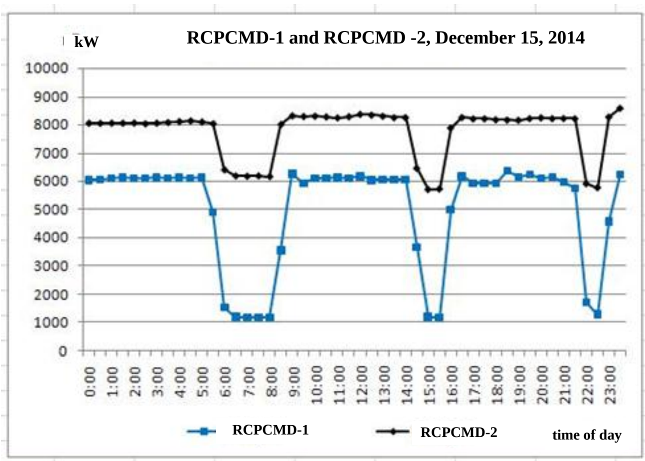


Fig. 2.43. Daily load curves of active power of district compressor stations RCPCMD-1 and RCPCMD-2 of the PJSC "KZRK", December 15, 2014

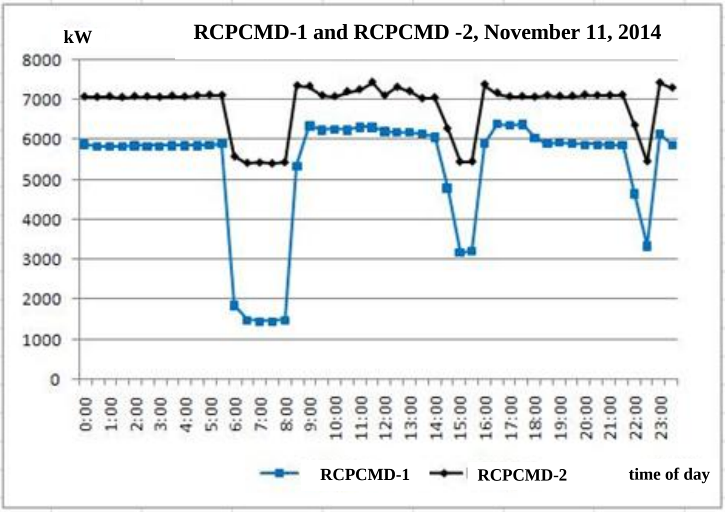


Fig. 2.44. Daily load curves of active power of district compressor stations RCPCMD-1 and RCPCMD-2 of the PJSC "KZRK", December 18, 2014

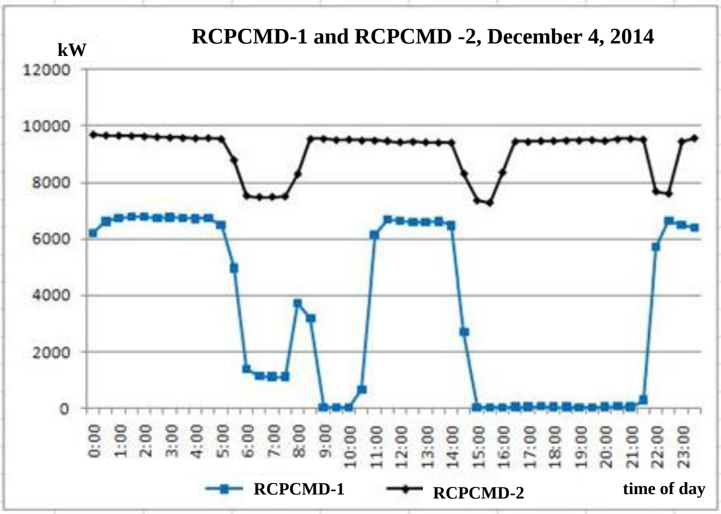


Fig. 2.45. Daily load curves of active power of district compressor stations RCPCMD-1 and RCPCMD-2 of the PJSC "KZRK", December 4, 2014

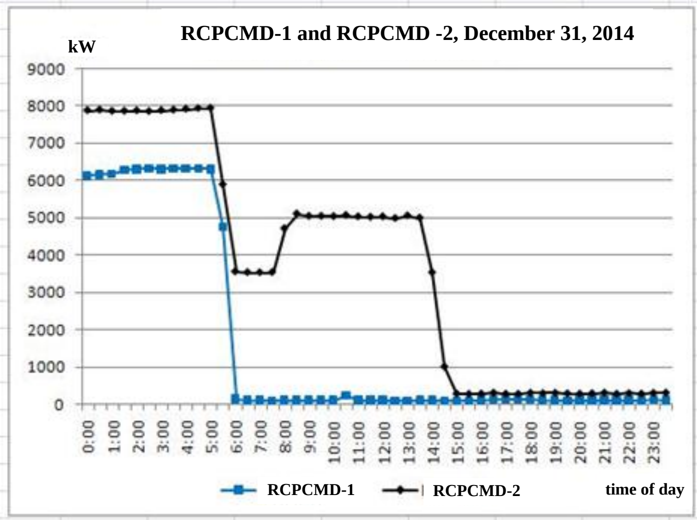


Fig. 2.46. Daily load curves of active power of district compressor stations RCPCMD 1 and RCPCMD 2 of the PJSC "KZRK", December 31, 2014

Reduction of active power is determined by the number of running compressors. As is seen from the load curves at the RCPCMD 2 that consumption of compressor stations RCPCMD-1 and RCPCMD-2 (December 4, 2014) in unloading periods decreases by 1500-2000 kW. Greater unloading (by 4500 kW) is observed at RCPCMD-1 as there are more non-operating compressors due to the soft start of synchronous motors installed to facilitate the starting mode. This device enables starting motors in succession at RCPCMD-1.

On public holidays (Fig. 2.42), all compressors are off during the standing idle of mining equipment.

Fig. 2.47 presents daily curves of the mines' reactive power. Hvardiiska mine reveals minimal levels of reactive power caused by adjusting the excitation mode of the synchronous motor of the transformation machine of the skip hoist feed.

Fluctuations of reactive power are conditioned by operating drainage and skip hoist installations both at night and daytime.

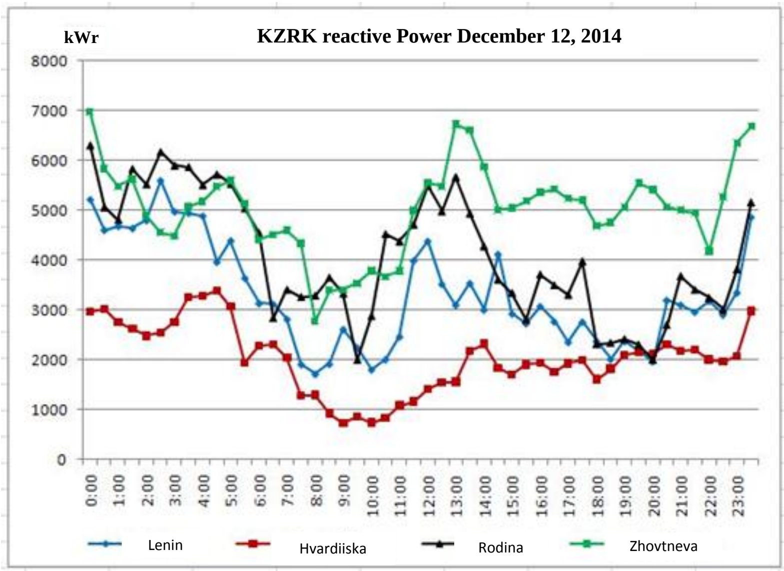


Fig. 2.47. Daily load curves of reactive power of the PJSC "KZRK" mines, December 18, 2014

A slightly greater consumption of reactive power is at Lenin mine that results from the skip hoist electric drive with the ABB transformer of high power factor and low levels of consumption of reactive power.

Oktiabrska and Rodina mines have much greater levels of reactive power because of much more powerful electric drives of skip hoists. Yet, Rodina mine is characterized by lower levels of reactive power as adjusting the excitation mode of the synchronous motor of the transformation machine of the G-M skip hoist feed enables a higher capacity factor.

Levels of reactive power at Oktiabrska mine are higher as skip hoists of Zoria and Oktiabrska mines are included into the presented curves. Here, the skip hoist is equipped with thyristor electric drive consuming more reactive power than the G-M system.

Power-saving is provided by managing metering and control of power consumption modes, introducing automated control systems of fuel-power resources, creating technical means to control power consumption and power-related characteristics of processes and installations.

The maximum power saving effect is achieved when using automated control and metering means of power consumption. There suggested automated systems of power monitoring (ASPM) to control and meter (active, reactive electric/thermal/blowing) power consumption at underground mines, basic indices of operating installations and sites, power consumption per unit produced, processing and analyzing data on an enterprise's power consumption and that of its departments as well as managing power resources consumption.

The system comprises a set of steps, hard- and software means aimed at managing an industrial process with minimal required power consumption to manufacture products or services. The current state of power consumption control in mining can be characterized, on the one hand, by active introduction of electricity metering means, accumulation of data on power consumption and, on the other hand, by a low-level analysis of these data. The system is aimed at automation of processing data on power consumption to make controlling decisions on reduction of specific consumption of power resources.

The suggested system includes:

– a device to collect data (meters of active and reactive power, underground meters of active and reactive power);

– a device to control depression and capacity of main fans;

– a device to control temperature in the shaft collar and air heater;

– a device to control heat carrier consumption;

– sensors of compressed air consumption and pressure;

– sensors of water pressure and consumption;

– a set of devices to transmit data including a distance control, data controllers, a computer.

The total reserve of power saving for iron ore mining enterprises can be defined as a sum of reserves of saved power resources of particular processes and facilities.

SECTION 3
SUBSTANTIATION OF UPDATING AND DEVELOPMENT OF ADVANCED METHODS OF CALCULATING POWER LOADS

3.1 Development of suggestions to improve methods of calculating power loads

Basic principles of creating structures of power-supply systems of industrial enterprises are based on the necessity to provide an enterprise with a required amount of electric power according to its order to the generating system.

This very principle as a crucial moment in designing or updating the system of power-supply is the most disputable because of accuracy of calculating expected loads and locating substations as well as choosing a structure of the power-supply system. Figures 3.1 and 3.2 provide examples of power-supply schemes at iron ore mines.

The theory of calculating power loads established in the 1930s determines a set of methods to find expected energy loads by means of assigned readings of power receivers and curves of expected power curves of enterprises. Practice shows insufficiency of this "down-up" method based on initial data of separate electric receivers or their groups [21-24, 45-47]. This theory makes sense in calculating the modes of a small number of receivers with known data and compiling a limited number of curves.

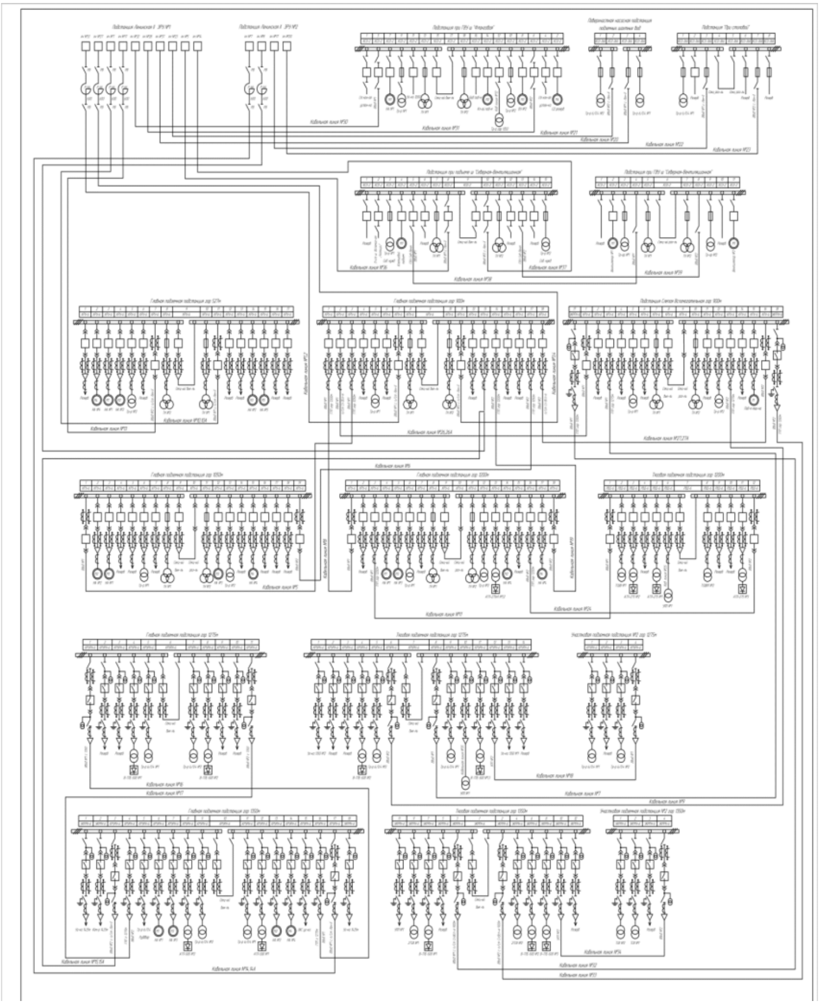


Fig. 3.1. Overview of power supply of the PJSC "KZRK" Rodina mine

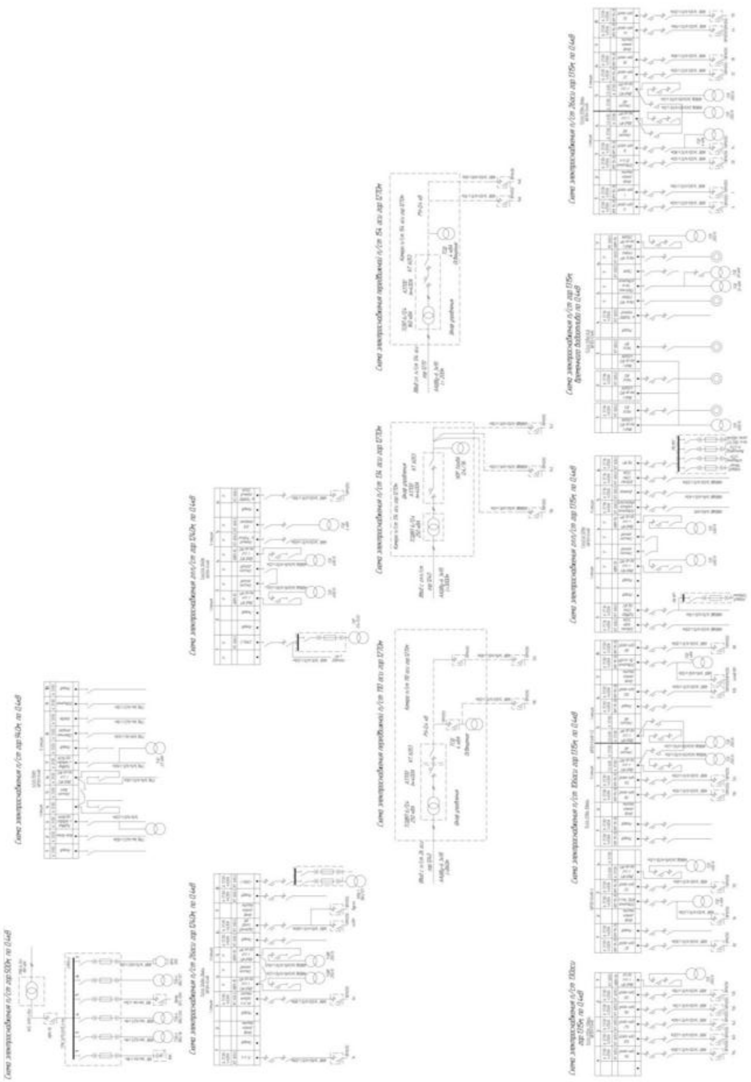


Fig. 3.2 – Overview of underground energy supply of the PJSC "KZRK" Rodina mine

In 1950-1960s, unsatisfactory results of designed calculations of power loads facilitated development of probabilistic-statistic methods based on ideas of loads as those caused by random processes. Loads were described by means of random values determined by mathematical statistics and resulted from Gaussian (normal) divisions. The following notions are used here: mathematical expectation of electric load MP_t (mean value); variance/dispersion DP_t (root-mean-square deviation as a load standard σ_{cal}); correlative $R_t(x)$ and auto-correlative functions [32, 39, 40]. For the normal division law, probability of the designed load yield P_{cal} beyond $MP_t \pm 3\sigma_{cal}$ equals 0.003 and enables neglecting values beyond $3\sigma_{cal}$. Separate works that set limits (1.5-2.0) σ_{cal}, did not become widespread.

In 1980-1990s, in the theory of calculating power loads, non-formalized methods prevailed, the complex one in particular [43]. Dealing with data bases of electric and technological indices, cluster-analysis and the theory of images recognition, probability and cenology distributions for expert and professionally logical evaluation can solve the problem of calculating power loads at all levels of power-supply and all stages of making engineering or investment decisions.

Calculation of power loads has evolved in several directions. Nowadays, the following are used:

1) empirical methods (factors of demand, binomial empirical expressions, specific power consumption and specific densities of load, a technological schedule);

2) the method of ordered flowcharts (calculation by the factor of designed active power);

3) statistical methods;

4) the method of stochastic modelling of load curves.

The method of demand factors is the simplest and the most widespread. It is used to start calculating loads by means of a known or set value P_{in} and table values of F_{dem}, given in reference books:

$$Q_{max} = P_{max} tg\varphi \tag{3.1}$$

The physical value F_{dem} is a quotient of a sum of nominal capacities of electric receivers. It statistically reflects the maximum mode of simultaneous operation and loads of some indefinite connection (realization) of installed receivers.

The given reference data on F_{dem} and F_{app} correspond to the maximum value, not the mathematical expectation. Summarizing maximum (not mean) values inevitably leads to increased loads. If we consider any group of modern electric entities, it becomes evident that "a homogenous group" is an abstract notion. Differences in the values of the factor 1:10 (up to 1:100 and higher) are inevitable and explained by techno-cenological properties of electric facilities of mining enterprises.

The method of specific densities of loads is close to the previous one. There is a set specific capacity (load density) γ and the area of the building F (a facility, a site, a department, a shop) is determined.

The method of a technological flowchart is based on that of an operating machine, a line or a set of machines. According to this, the operating schedule of an electric receiver is detailed by indicating items of its operation time. The flowchart is to define total power consumption per cycle (considering the time before the next cycle) and the maximum load to calculate the feeding system.

In 1960-1970s, the method of ordered flowcharts was a top-down **method for all levels** of the power-supply system on all design stages. In 1980s, it was transformed into calculation of loads according to the factor of calculated active power. With available data on the number of electric receivers, their capacity, operating modes, it is recommended for calculating elements of the power-supply system of Level 2, Level 3 (a wire, a cable, a bus wire, a low-voltage equipment) feeding the power load of up to 1 kV (it is simplified for the effective number of receivers of the whole shop, i.e. for the 6-10 kV Level 4 network). The method of ordered flowcharts and calculation by the factor of calculated active power differ by changing the factor of maximum F_{max}, which is always taken as a ratio of P_{max}/P_{av}, by the factor of calculated active power F_{cal}.

Statistical methods of determining electric loads. The calculated maximum loads of the group of electric receivers P_{max} can be found by means of the equation:

$$P_{max} = F_{max} F_{app} P_{nom} = F_{max} P_{av.shift}, \tag{3.2}$$

where F_{app} is the factor of application;

P_{nom} is group nominal power (a total of nominal powers except for spare ones to calculate loads);

$P_{av.shift}$ is average active power of the most loaded shift.

The mentioned method is bulky, difficult to understand and apply and it often has a twofold (or multifold) error. The non-Gaussian randomness, ambiguity and incompleteness of initial data can be overcome by the following assumptions:

– the same factors for electric receivers of the same name;

– standby cut-off motors providing loads;

– the capacity factor is considered independent of the number of electric receivers in a group;

– finding electric receiver with almost constant load curves;

– exclusion of the least powered electric receivers.

The method is not differentiated for various power-supply system levels and stages of design performance (approval). It is accepted that the value of the calculated factor of active power tends toward 1 when the number of receivers increases. It is not confirmed statistically. For a department with 300-1 000 motors and shops with up to 6 000 motors, this factor can make 1.2-1.4. Introduced market relations accompanied by automation and variety of products facilitates transition of electric receivers from one group to another.

Ambiguity reveals itself in measurements because of application to the administrative-regional structure. Restrictions of the power system cause the modes with the maximum load P_{max} in one shift and greater power consumption in the other. While determining P_{cal} it is necessary to give up $P_{av.shift}$, excluding intermediate calculations.

Each level accumulates further errors. Capacities and factors are added, yet, electric receivers come from different groups. However, simple adding is unacceptable as many receivers do not work in unison. Detailed consideration of the method drawbacks is aimed at revealing the fact that calculation of loads based on traditional ideas of electric chains and load curves cannot provide for sufficient accuracy from the theoretical point of view.

Some specialists persist in their points as to statistical methods of loads calculation. The methods take into account that even for one group of mechanisms operating in this section, factors and indices change greatly.

The aim of finding the maximum of function P_{cal} in some time period is complicated by the fact that electric receivers and consumers of various operating modes are powered by Level 2, Level 3, Level 4. Statistical methods are based on measuring loads of mains feeding certain groups of electric receivers without considering their operating modes and numerical characteristics of individual schedules.

The methods apply two integral characteristics – general mean load P_{av} and general mean square deviation $\sigma = \sqrt{DP_{max}}$, in which dispersion is taken for the same interval of averaging.

The maximum load is:

$$P_{max} = P_{av} + \beta\sigma, \tag{3.3}$$

where β is a statistical factor depending on the law of distribution and accepted exceeding probability according to the load curve $P(t)$ of level P_{max};

$\sigma = \sqrt{P^2_{m.sq.} - P^2_{av}} = \sqrt{DP}$ or $\sigma = P_{av}\sqrt{F^2_{form} - 1}$ while introducing the factor of $F_{form} = \dfrac{P_{m.sq.}}{P_{av}}$.

To build a group flowchart, data on load curves are required. To refuse flowcharts, measurements (recording) of maximum loads are taken daily or quarterly (or for other periods). Then mathematical methods determine P_{av} as mathematical expectation and dispersion as a central moment of the second order.

The value of β is taken as various. In the probability theory, the rule of three sigmas: $P_{max} = P_{av} \pm 3\sigma$ that under normal distribution equals the maximum probability 0.9973. Exceedance probabilities of loads by 0.5% corresponds to $\beta = 2.5$ and for $\beta = 1.65$ a 5 % probability of error is provided.

The statistical method can be referred to reliable methods of studying enterprises' loads as it provides a relatively correct value of the maximum load $P_{3(max)}$ stated by an enterprise at the time of its passing in the power system. The Gaussian distribution of operation of electric receivers (consumers) has to be admitted.

The method of stochastic modelling of load curves provides for direct study of a stochastic character of successive random changes of total load of electric receiver groups to obtain autocorrelative, reciprocal-correlative functions and other parameters. Investigation of load curves of electric receivers of great single capacity, shops' and enterprises' schedules determines the potential of the method of managing power-supply modes and curves adjustment.

The complex method of determining loads considered by Kudrin B.I. appears to be efficient as compared to other methods. But, in fact, it is an old method of ordered flowcharts, yet updated.

The complex method is centered on the idea that any object can be described by means of both numerical indices and verbally, i.e. by an image which is an object's model. Any two objects can be similar or different having or not having anything in common. An object is meant to be an enterprise, a shop, a department, a section, a facility, etc., in other words, any dimensional-spatial or administrative unit in terms of which power loads should be determined. Each object is verbally identified (described) and referred to any family (united cenologically by similarity, though not defined in terms of connections and dependencies). A family can be represented by all departments or shop sections of a mining enterprise, all enterprises of the same industry (sub-industry), etc.

Relying on electric and other indices, all family objects including that under analysis are ranged. To be exact, while identifying the quantity of objects by means of one's own professionally logical analysis (one's own qualification), experts' assessments, the theory of image recognition, each object is referred to this or that class of objects known as a cluster. If we refer an object under study to a cluster, it provides a range of solutions based on mathematical expectations and final errors (dispersion).

Computerization facilitated the theory of image recognition which deals with principles and methods of classifying and identifying objects, phenomena, processes, signals, in other words, all the objects that can be described by a finite set of properties. If two enterprises (underground mines) have the same maxima P_{max} , of power-supply A, average capacity of electric motors P_{av} and other indices, is it possible to conclude about equivalence of their electrical facilities? If they are different, which of them is better or more efficient? There are no explicit answers to these questions which are explained by cenological properties. Yet, awareness and professionalism enable a solution of the problem.

Available methods of determining loads are aimed at formalizing calculations. It means that power-supply is described (mathematically or graphically) casually without alternative (or probabilistically through mathematical expectation, dispersion and other characteristics), i.e. for set initial data, there suggested a calculation algorithm P_{max}, enabling us to obtain a simple result. In fact, this part of the theory of calculating loads has a restricted application area and is convenient for educational purposes only. It is not applicable to investment design, determining power capacity and consumption in operation or prospects of updating the power-supply system.

Investment design of a new enterprise, as well as expansion, reconstruction and updating of existing ones is grounded by pre-design solutions and feasibility studies. Pre-investment stages are obligatory for making any solutions associated with financial and other expenditures. On pre-investment stages, certain electric receivers are not known. Moreover, not all technological components (shops, facilities, shop sections and sites) are determined yet. Only the most essential shops (machines) are set. The issue of grid connection should be solved. Each electric receiver and its power-supply are considered in detailed design documentation only. At main underground substations and distributing points, pre-investment stages are not fulfilled separately from the technological part of the design.

When conducting a feasibility study of a large-scale facility (a launching complex), an enterprise is taken as a whole – Level 6 and Level 5 in detail. A modern mining enterprise's power layout involves determining the composition of main step-down substation, power-supply modes, the number of distributing points, voltage and power-supply of high-power motors, voltage and single capacity of 0.4 kV transformers.

The first principle defines up-down determination of loads. For Level 6, all shops, buildings and facilities are taken into account. Solutions on designing main step-down substations are made before those on distributing points and high-power motors and prior to all 10/0.4 kV transformers fed from them. Location and capacity of Level 3 transformers is determined before installing Level 2 cabinets and all electric receivers connected to the transformer. Only the choice of the Level 2 element produced on the documentation stage is determined by particular electric receivers. Although, for some flexible enterprises, shops and departments, there are projects in which Level 2 cabinets are determined by a construction module. Only bus ways and most distributing bus wires are designed and constructed before obtaining initial data on every Level 1 receiver.

Level 6, Level 5 and Level 4 characterizing the whole enterprise, production and a shop correspondingly remain stable in time. Because of changes of designs on the documentation stage, corrections are made in any design part and any time before the start-up and after it. They result in the fact that electric receivers "disappear, appear, change voltage, frequency, current type and capacity".

Another principle depicts quantitative increase of installed equipment and practical calculation of installed electric receivers. It raises the issue of factuality causing *H*-distribution implying potential availability of infinite numbers of properties subjected to further study.

The complex method involves:

1) creation of information support;

2) classification of power-supply objects, application of image recognition, expert systems and cluster-analysis;

3) application of forecasting to all system levels including those of construction (replacement) of large units.

The complex method of calculating maximal loads provides simultaneous application of several methods with the following parameters:

1) power intensive products E_i on Level 6:

$$P_{max} = E_i \cdot M_i / T_{max} , \tag{3.4}$$

where M_i is the volume of *i*-th technological products (crude ore, sinter);

2) yearly power-supply A or average yearly capacity $P_{av.year}$ on Level 6, Level 5, Level 4:

$$P_{max} = F_M \cdot A / T_{year} = F_M \cdot P_{av.year} , \tag{3.5}$$

where F_M is the average yearly factor of maximum;
T_{year} = 8760 h is the number of hours per year;

3) specific yearly power consumption A_{sp} on Level 5, Level 4, Level 3:

$$P_{max} = F_M \sum_{i=1}^{n} \left(\frac{A_{sp(t)} M_t}{T_t} \right), \tag{3.6}$$

where T_t is the number of operating hours of a shop (production, department) per year;

4) the average demand factor F_{dem} on Level 6-Level 2:

$$P_{max} = F_{dem} \cdot P_{in} , \tag{3.7}$$

where P_{in} is power of the installation;

5) specific load capacities on Level 6-Level 2:

$$P_{max} = \gamma \cdot F , \tag{3.8}$$

where γ is specific capacity (load density);
F is the area of an enterprise/region/shop/department/site;

6) forecasting of temporary lines on Level 6-Level 2:

$$P_{max} = f\left(W_j\right), \tag{3.9}$$

where W_i is a matrix of indices determined by the time line;

7) professional-logical analysis (including the CAD mode):

$$P_{max} = \left\{P_0, W_i\right\} , \tag{3.10}$$

where P_0 is the matrix of electrical indices characterizing an object's cluster (an electrical facility).

The nominal (set) capacity $P_{cal} = P_{max} = P_{nom} = P_{in}$ is taken as the rated one $P_{cal} = P_{max}$ for each Level 1 electric receiver of the continuous operating mode while choosing switchgears and conductors. Changed values of the efficiency factor and the power factor are neglected in changing loads. The calculation current is determined by:

$$I_{cal} = \frac{P_{max}}{\sqrt{3} U_{nom} \cos\varphi} , \tag{3.11}$$

For a multi-motor drive machine like an electric receiver, nominal capacity is a total of nominal capacities of all the motors. If two or three receivers form a group feeding by one conductor from one switchgear, $P_{cal}=P_{max}$ is a total of their nominal capacities. The rated load is accepted to be equal to capacity of two most powerful electric receivers.

Thus, for Level 1, electric loads are not calculated to determine power-supply. Electric equipment for this level is chosen by P_{nom}. The factors F_{app}, F_{dem}, F_{max}, F_{form} and differentiation of stand-by receivers are not necessary. The notion of the most load-intensive shift is not used.

Summarizing the mentioned above methods of calculating loads for mining enterprises, it should be noted that notwithstanding a great number of methods, this problem is not solved completely even in an acceptable variant.

This categorical assumption is determined by fact that there are discrepancies between rated and operating loads, this fact is a priori known and will be confirmed later.

At industrial enterprises including mining ones, loads are calculated by methods of the demand factor and ordered diagrams. Let us consider structures and peculiarities of these methods.

From the viewpoint of structure, the method of demand factor is the simplest with the maximum or rated active load calculated as:

$$P_{max} = \sum^{n} P_{nom} \cdot F_{dem}, \qquad (3.12)$$

where P_{nom} is the nominal capacity of a group of electric receivers with the same operational mode;

F_{dem} is the corresponding demand factor for a group of electric receivers with the same operational mode;

n is the number of groups of receivers.

In other words, loads are calculated for groups of consumers with the same operational mode, though there are technological groups of consumers with different operational modes like consumers of shops, sites and enterprises. The structure of the method of the demand factor does not comply with the structure of power-supply systems.

To determine demand factors at enterprises, one should divide consumers into groups according to the same operational mode and record maximum loads for these groups. To perform this, special equipment and many efforts are needed. No wonder that demand factors have not been renewed for more than 50 years and their results are far from being real.

Another drawback of the method is absence of a calculating mechanism of consumers' number. Although it is a well-known fact, that the more consumers are, the smaller probability of their simultaneous work is and the smaller values of electric loads are. To calculate the number of consumers, another factor is introduced. It is the factor of matching of maximums of consumer groups, but its value is rather arbitrary.

Given disadvantages of the demand factor method are partially eliminated in the method of ordered diagrams which is recommended by regulatory documents for calculating enterprises' loads [30–33]. This method involves two stages – mean loads and maximum ones.

Mean active loads are determined:

$$P_{av} = \sum^{n} P_{nom} \cdot F_{app}, \tag{3.13}$$

where F_{app} is a factor of application for groups of consumers with the same operational mode in the most load-intensive shift.

This method has the same drawbacks as the previous one. Consumers are divided into groups with the same operational mode, though real power layouts supply the groups with various operational modes. That is why, checking and specifying factors is also problematic.

Next, peak loads are determined:

$$P_{max} = P_{av} \cdot F_{max}, \tag{3.14}$$

where F_{max} is the peak-load factor determined by ordered diagrams as a general factor of application and the equivalent number of consumers.

It is worth noting that ordered diagrams are built for a situation when consumption is of random character and consumers are independent of each other.

As for industrial enterprises, it does not fall in line with reality – power consumption is determined by the production programme and consumers are almost always connected with some processes.

Some authors introduced corrections into their methods because of high accuracy of ordered diagrams. [14, 21, 22] suggest applying the peak-load factor $F_{max} = 1$ to consumers with regular load curves considering the peak-load equal to the mean one. For other consumers with irregular load curves, the peak-load factor is determined by ordered diagrams implying an extra distribution of consumers according to their operating modes.

Suggests [23] using a complex method of calculating loads which involves several calculating methods used simultaneously as well as the analogue database. It is noteworthy that application of the analogue database is feasible for any methods of calculating loads. Use of several methods simultaneously is not an innovation and does not make the task any simpler.

This seems to suggest that methods of calculating loads and corresponding calculation factors should target not separate consumers, but total evaluation of power consumption of groups of consumers, the operating modes of which are interconnected and conditioned by technological processes.

This is up to the structure of real-life power-supply systems, providing an opportunity to check calculations and correct calculation factors by applying operational devices.

In this respect, statistical methods are of interest, in particular, the variant considered with the peak-load determined as

$$P_{max} = \left(F_{app} + \frac{\beta\sigma_*}{\sqrt{n_e}} \right) \cdot \sum P_{nom}, \tag{3.15}$$

where σ_* is relative mean-square divergence of an equivalent consumer;

β is a confidential interval applied usually within the range of 1.5–2.5;

n is the equivalent number of consumers.

In (3.15) the expression in brackets is nothing but a demand factor:

$$F_{dem} = F_{app} + \frac{\beta\sigma_*}{\sqrt{n_e}}. \tag{3.16}$$

Yet, application of the demand factor in the form like this is problematic as there are no data on mean-square divergences as they are difficult to define in industry.

Thus, we are going to simplify the task. If we consider a well-known statement that for a single electric receiver one can take F_{dem}=1, this statement will occur under $\beta\sigma_* = 1 - K_{dem}$, and we can write:

$$F_{dem} = F_{app} + \frac{1 - F_{app}}{\sqrt{n_e}}. \tag{3.17}$$

This simple formula expresses rather complex logic of dependencies of power-supply parameters:

– the major disadvantage of the demand method is eliminated;

– the influence of the number of consumers is taken into account;

– when increasing the number of consumers $n_e \to \infty$, the demand factor is $F_{dem} \to F_{nom}$, the maximum capacity is $P_{max} \to P_{av}$;

– when reducing the number of consumers $n_e \to 1$, the demand factor is $F_{dem} \to 1$, the maximum capacity is $P_{max} \to P_{nom}$.

Neither ordered diagrams, nor mean-square divergences or the factor of application for each equipment type are needed for calculating loads by the suggested generalized method. The maximum volume of initial data includes general factors of application for groups of consumers with various capacities, numbers and operating modes.

The equivalent number of consumers is calculated by [21-24]:

$$n_e = \frac{\left(\sum_1^n P_{nom}\right)^2}{\sum_1^n P_{nom}^2} \tag{3.18}$$

When the number of consumers is more than 20, a simplified expression can be used:

$$n_e \approx \frac{2\sum_1^n P_{nom}}{P_{nom.max}}, \tag{3.19}$$

where $P_{nom.max}$ is the nominal capacity of the most powerful consumer.

Anyway, while calculating the number of consumers, it is worth considering the fact that a group of motors functioning simultaneously only is regarded as a single motor of total capacity. On the other hand, one should neglect standby and low-powered consumers.

When it comes to more than 100 consumers $F_{dem} = F_{app}$ [21-24]. So, while calculating loads of 6-10 kV mains, the mean peak-load should be taken as the rated one:

$$P_{max} = \sum_1^n P_{av} = \sum_1^n P_{nom} \cdot K_{app}. \tag{3.20}$$

The reactive power is determined in the same way as the method of ordered diagrams:

$$Q = P_{av} \cdot tg\varphi, \tag{3.21}$$

where $tg\varphi$ are power factors for corresponding groups of consumers.

To specify the suggested generalized method and determine particular rated factors of the design, some detailed experiments have been conducted for site loads of the "KZRK" iron ore mines.

Daily load curves were registered and analyzed at the site transformer substations of the three mines. Meters of active and reactive power were used. The power was determined by the number of impulses per time unit

$$P = \frac{N \cdot a}{t}, \qquad (3.22)$$

where N is the number of impulses in the considered interval t; a is power counted out per impulse.

Fig. 3.3 presents one of the typical daily load curves of the site transformer substation that feeds mining and development sites with the total capacity of consumers of $\sum P_{н} = 215$ kW.

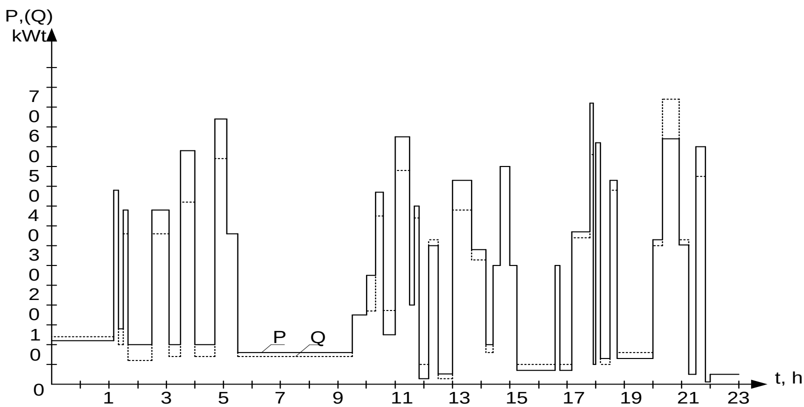


Fig. 3.3. Daily load curves of the site transformer substation

Here, three-shift operation of consumers with variable loads is presented. In some intervals, reactive power (lining) exceeds the active one indicating equipment overload which is short-term. The mean power factor is $tg\varphi = 0.9$.

For all 18 load curves, the following characteristics are determined: peak loads and their duration, mean and mean-square loads, factors of form, filling, demand, application and power.

Analysis of load curves reveals that the load of transformers at the site substations is less by 30 % than the installed power. It indicates inaccuracy of applied methods of calculating loads and calculating factors.

Experimental data and statistical characteristics of daily curves were determined and processed by mathematical statistical methods ensuring necessary accuracy and adequacy of calculations with confidential probability of 0.98 [37-43]. According to the experimental data, the group factor of application varies from 0.1 to 0.2 in different conditions. The maximum value $F_{app} = 0.2$ is taken as a rated value.

While calculating, one should consider that the factor of a single consumer loading is less than 1 and makes 0.7-0.9. It allows correcting the demand factor (3.6) and presenting it as:

$$F_{dem} = F_{app} + \frac{0.8 - F_{app}}{\sqrt{n_e}}. \tag{3.23}$$

If we consider the real maximum of the application factor as $F_{app} = 0.2$, it is better to use the following demand factor to calculate loads of mining sites:

$$F_{dem} = 0.2 + 0.6\frac{1}{\sqrt{n_e}}. \tag{3.24}$$

During the experiments, the power factor $tg\varphi$, was determined within 0.8-0.9 for various sites. The maximum of $tg\varphi = 0.9$ was taken as a rated value.

To evaluate different methods of calculating loads, the method of ordered diagrams and the suggested generalized method were used. The generalized method produces the rated peak power by 30–40 % smaller than that calculated by the ordered diagram method and much closer to the real values.

Another noticeable detail of designing involves designed values of the aggregate established capacities greatly exceed actual ones, i.e. by 1.6 times at the sites under analysis. Providing inaccurate calculations, the transformer capacity appears to be twice overestimated and it is observed in reality.

The suggested generalized method of calculating loads is universal and acceptable for any enterprises and power systems.

To apply this method it is necessary to know values of group factors of application in the most loaded shift. These values can be calculated, yet it is more accurate to define them at operating enterprises. With limited numbers of experiments to fix possible deviations, maximum measured values of the application factor should be increased by 0.005, i.e. the rated value of the application factor

$$F_{app} = F_{app.meas} + 0.05 \cdot \qquad (3.25)$$

Available power metering systems enable efficient measurements of mean loads to determine current factors of application for different groups of consumers, shops and enterprises. It allows increasing accuracy of calculations and decreasing power expenditures.

3.2 Analysis of power-consumption of site underground substations

Analysis of operation of Ukrainian iron ore mining enterprises presented in the previous section would be incomplete for general assessment of power consumption without considering site underground substations feeding most consumers. According to the classification mentioned above it is the 3rd or the 4th level of the general structure of power-supply.

Among various mining systems, the most applicable are those with scraper ore haulage. Mining systems with ore vibration drawing are seldom applied, power consumption is smaller here than that of scraper haulage. That is why, this section focuses on power consumption of sites with scraper haulage.

Scraper hoists with 10 kW-100 kW electric motors can be used. Although in most cases, ЛС-30 scraper hoists of 10 kW are used to meet the requirements of both mining and development operations.

Along with mining, development operations are in progress with new scraping drifts driven. Rocks are removed by scraper hoists the number of which is of the same order as that of mining operations, yet it is greater on the initial stage of block working. Scraper hoists of development operations are fed from the same main as those of mining operations. It is clear that these loads should be considered together. Next, total capacity of scraper hoists installed in a block is studied. Ore is loaded into trucks by vibro-chutes with 1-14 kW electric motors. Irrespective of the total number of chutes at the loading drive, just one of them is switched on as a rule. The switching lasts not more than 0.5.

Local fans are rarely used at mining sites. As a rule, ventilation is due to mine depression or by pneumatic ejectors.

Lighting, welding transformers, drilling machines, kettles also consume power but they do not influence peak-loads.

Tables 3.1-3.2 provide data on power consumers of the site underground substations at which loads have been measured. Only one vibro-chute per loading drive which is in operation is taken into account.

Three-phase transformers (ТКШВ) of 320 kVA are used at all substations, from 1 to 3 transformers per substation.

To achieve greater accuracy and adequacy in building load curves, a series of experiments have been conducted at Kryvyi Rih underground mines. A measuring set of equipment enabling us to register active and reactive power in the time function has been developed.

More than 500 readings have been received from various mine substations. According to table data, actual load curves of the sites and transformers are built and the following characteristics are defined: peak-loads, their duration, mean/ mean-square loads, load/power factors, specific power consumption, etc

Table 3.1. Consumers of Artem mine substation-3

line #	What is fed	Consumers	Power, kW	Number, units	Total power, kW
Section 1					
2	Site 12, block 7	Scraper hoist ЛС – 55	55	1	55
		Scraper hoist ЛС – 30	30	5	150
		Scraper hoist ЛС – 10	10	1	10
		Transformer ТОР – 1.5	1.5	1	1.5
		Transformer ТС - 300	20	1	20
		Chute ВПР	13	1	13
Total			249.5		
3	Block 16 drift lighting	Chute ВПР	13	1	13
		Transformer ТОР – 1.5	1.5	7	10.5
Total			23.5		
Section 1 total					273
Section 2					
6	Block 8	Chute ВПР	13	1	13
		Transformer ТОР – 1.5	1.5	1	1.5
		Fan СВМ – 6 Fan	14	1	14
Total			28.5		
8	Site 1, block 6	Scraper hoist ЛС – 55	55	1	55
		Scraper hoist ЛС – 30	30	3	90
		Scraper hoist ЛС – 10	10	2	20
		Transformer ТОР – 1.5	1.5	1	1.5
		Transformer ТС - 300	20	1	20
Total			186.5		
Section 2 total					215

Table 3.2. Consumers of Artem mine substation-5

Line #	What is fed	Consumers	Power, kW	Number, units	Total power, kW
Section 1					
1	Site 4, block 47	Scraper hoist ЛС-30 Scraper hoist ЛС-55 Scraper hoist ЛС-17 Transformer ТОР-1.5 Transformer ТС - 300	30 55 17 1.5 20	6 1 1 1 1	180 55 17 1.5 20
Site 4 total					273.5
3	Drift lighting	Transformer ТОР – 1.5	1.5	4	6
4	Substation’s needs, dispatcher, lighting	Transformer ТОР – 1.5 Transformer АП - 4	1.5 4	3 4	4.5 16
Section 1 total					300
Section 2					
	Research Institute’s site block 47	Chute ВПР Scraper hoist ЛС – 10 Fan СВМ – 6 Transformer ТОР – 1.5	13 10 14 1.5	1 2 3 2	13 20 42 3
Total					78
	Site 5 block 48	Scraper hoist ЛС – 30 Scraper hoist ЛС – 55 Transformer ТОР – 1.5 Transformer ТС – 300 Chute ВПР (775 m)	30 55 1.5 20 13	8 2 2 1 1	240 110 3 20 13
Total					386
	Block 5	Chute ВПР Transformer ТОР – 1.5	13 1.5	1 1	13 1.5
Section 2 total					478

Table 3.3 – Consumers of combined SUS of Oktiabrska mine

Name	Type	Power	Number and capacity per block						
			Block 0	Block 4	Block 7	Block 10	Block 16	Block 22	Total
Lighting	ТОС-1,5	1,5 kVA	1x1,5=1,5	1x1,5=1,5	31x1,5=41,5		1x1,5=1,5	1x1,5=1,5	10,5
	ТОС-2,5	2,5 kVA			1x2,5=2,5				2,5
	ТОС-4	4 kVA				1x4=4			4,0
Scraper hoist	ЛС-10	10 kW			1x10=10		1x10=10		20,0
	ЛС-17	17 kW		1x17=17		1x17=17	1x17=17		51,0
	ЛС-30	30 kW	4x30=120		2x30=60	2x30=60	3x30=90	4x30=120	450,0
Fan	ВМП	22 kW	1x22=22		3x22=66				88,0
Vibro-chute	ВПР	10 kW				1x10=10	1x10=10	1x10=10	30,0
Total power			143,5	18,5	143	91	128	131,5	656

To illustrate values and the character of loads, transformers and sites' daily curves in the most loaded shift are built (Fig. 3.4-3.10).

Table 3.4. Consumers of Yuvileina mine substation #10

Line #	What is fed	Consumers	Power, kW	Number, units	Total power, kW
Section 2					
	Access crosscut 213	Vibro-feeder ВПР Transformer ТОР-1.5	14 1.5	1 1	14 1.5
	Access crosscut 217	Vibro-feeder ВПР Scraper hoist ЛС–30 Transformer ТСШ Transformer ТОР – 1.5	14 30 4.5 1.5	1 2 1 1	14 60 4.5 1.5
Section 2 total					95.5
Section 3					
0	Access crosscut 209	Scraper hoist ЛС–30 Vibro-feeder ВПР Transformer ТОР – 1.5 Transformer ТС – 300	30 14 1.5 20	8 1 4 1	240 14 6 20
Total					280
1	Access crosscut 205	Scraper hoist ЛС–30 Vibro-feeder ВПР Transformer ТОР – 1.5 Transformer ТС – 300 Boiler	30 14 1.5 20 3	10 1 3 1 1	300 14 4.5 20 3
Total					341.5
2	Lighting	Transformer ТСШ	4.5	2	9
Section 3 total					630

Table 3.4 provides some characteristics of the daily load curves presented in Fig. 3.1-3.10, namely:

– average power, P_{av};

– mean-square power, $P_{m.sq.}$;

– maximum 30-minute power, P_{max};

– the load factor of the daily curve (F_{load}):

$$F_{load} = \frac{P_{av}}{P_{max}}; \qquad (3.26)$$

– the form factor (F_{form}):

$$F_{form} = \frac{P_{m.sq.}}{P_{av}} . \qquad (3.27)$$

Analysis of the load curves indicates that only about 30% of transformer capacity is used as compared to the forecast one at substations including the underground substation.

The form factor is within 1.12-1.5 indicating great irregularity of loads.

The load factor of the daily curve varies within 0.27-0.56; duration of the maximum load is 4-8 hours. Depending on combination of these values, the load diagram can indicate the acceptable overload of a transformer above the rated capacity. In case of the worst combination under the load factor of 0.6 and overload duration of 8:00, acceptable overload makes 15 %.

To determine primary initial data for designing site transformer substations, about 50 traces of daily load curves of transformers from four site transformer substations at Artem, Tsentralna and Saksahan mines are processed. Processing experiment data and determining statistical characteristics of daily load curves are performed by mathematical statistics methods to ensure necessary accuracy and adequacy of the results.

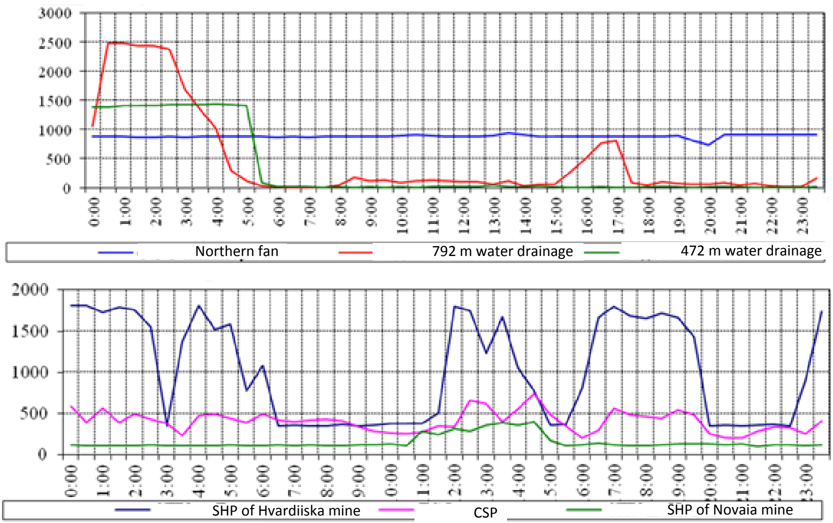


Fig. 3.4 – Daily load curves (January 31, 2014) of Hvardiiska mine, the PJSC "KZRK"

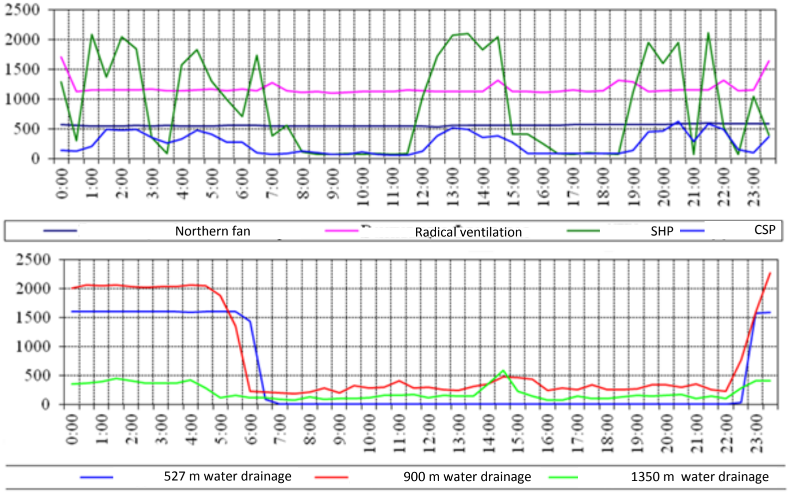


Fig. 3.5 – Daily load curves (January 2, 2014) of Ternivska mine, the PJSC "KZRK"

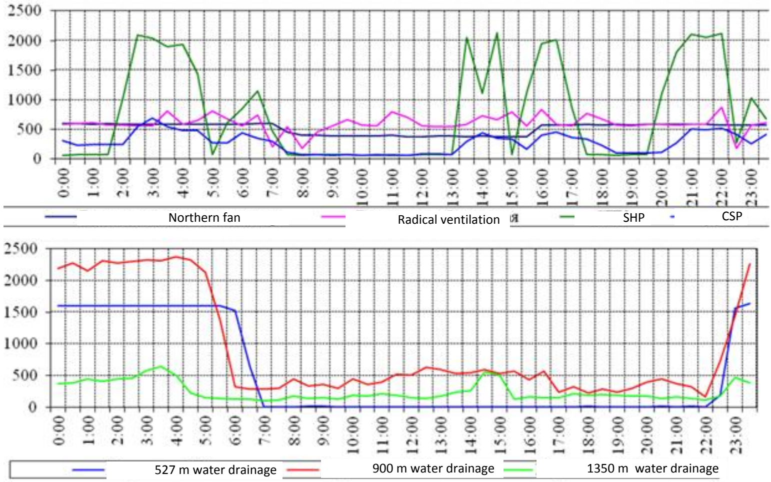


Fig. 3.6 – Daily load curves (January 31, 2014) of Ternivska mine, the PJSC "KZRK"

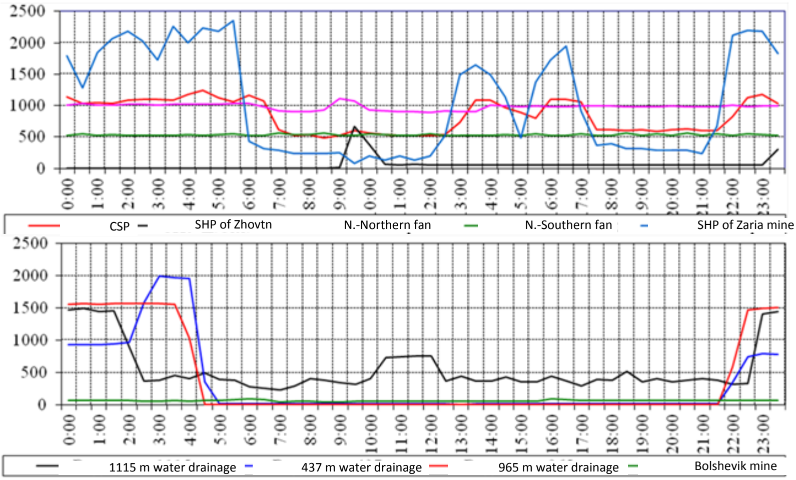


Fig. 3.7 – Daily load curves (January 2, 2014) of Oktiabrska mine, the PJSC "KZRK"

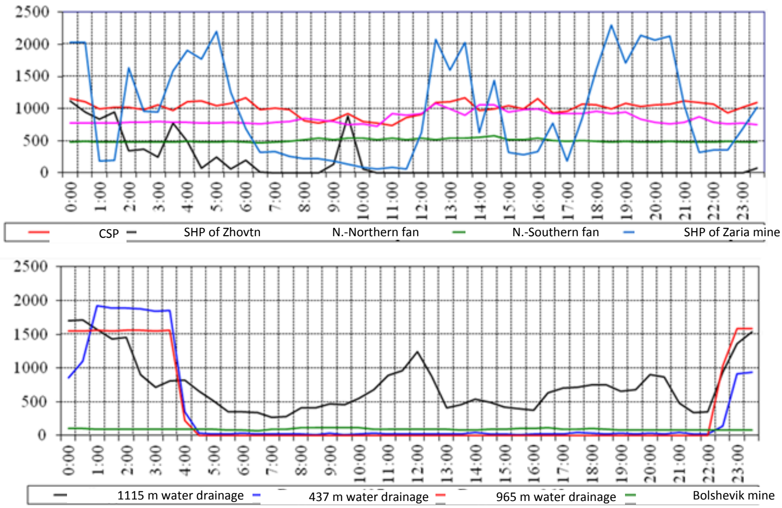


Fig. 3.8 – Daily load curves (January 31, 2014) of Oktiabrska mine, the PJSC "KZRK"

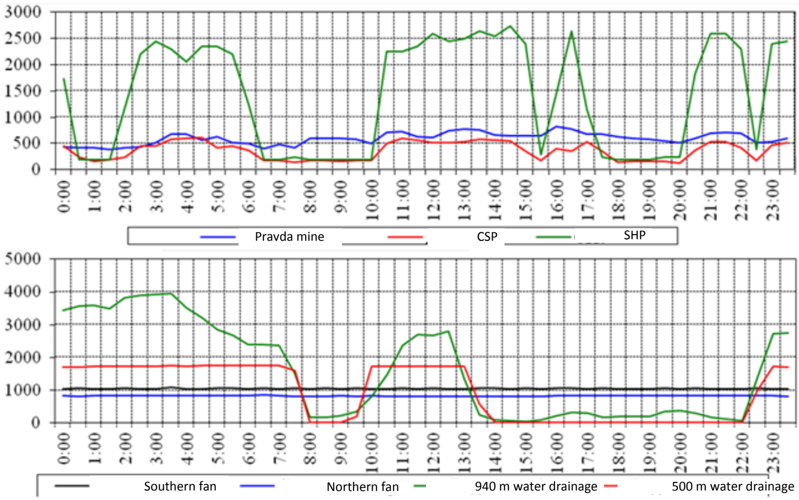


Fig. 3.9 – Daily load curves (January 2, 2014) of Rodina mine, the PJSC "KZRK"

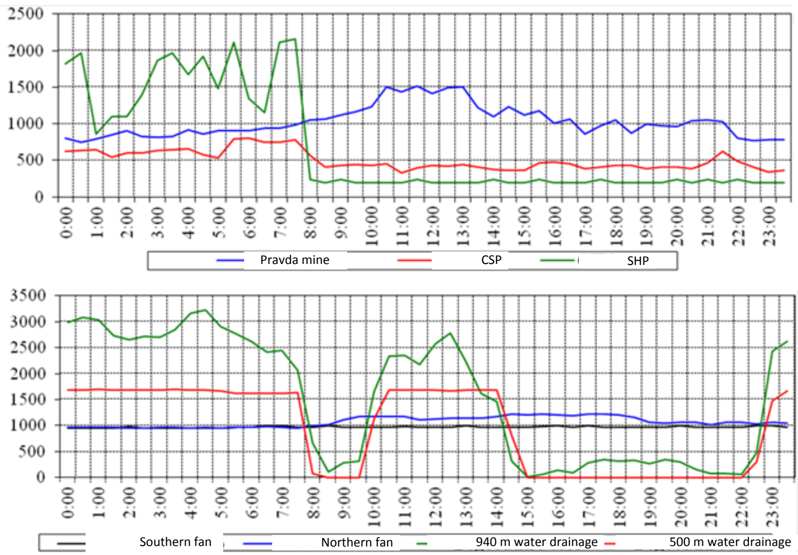


Fig. 3.10 – Daily load curves (January 31, 2014) of Rodina mine, the PJSC "KZRK"

While measuring, the following statistical characteristics of load curves of the site substations (substation inputs and feeders) are determined:

1. The mean power during measuring. In calculation, P_i power of 30-minute operation is used, splashes of less than 30 minutes are averaged with adjacent 30-minute power values:

$$P_{av} = \frac{\sum_1^n P_i}{n} \tag{3.28}$$

where n is the number of intervals of power values used to calculate.

2. Mean-square deviation of power values:

$$\sigma_{av} = \sqrt{\frac{1}{n-1}\sum_1^n \left(P_i - P_{av}\right)^2} \tag{3.29}$$

3. Under the confidential probability of power values Ф = 0.98 and the known number of degrees of freedom $k = n$-1 by means of Student's distribution, the guaranteed deviation factor t is determined.

4. The maximum confidential interval of power is determined by:

$$P_{max} = P_{av} + t \cdot \sigma_{av}\,. \tag{3.30}$$

5. The average consumption of active power per shift:

$$W_{a\,av} = \frac{\int_1^n W_{a\,i}}{n} \tag{3.31}$$

where $W_{a\,i}$ is consumption of active power per shift, $\mathrm{kW \cdot h}$;

n is the number of analyzed shifts.

Table 3.5 provides conducted calculations.

Table 3.5. Characteristics of load curves of Fig. 3.4-3.10

#	Name	P_{av}, kW	P_{max}, kW	$F_{reserve}$	$P_{in.}$, kW	F_{nom}
Artem mine						
1	Transformer SUS-3	27	37.1	1.37	68.3	0.4
2	Transformer 2 УПП-3	21.1	29.3	1.39	67.6	0.31
3	Load УПП-3	48.1	63	1.3	133	0.36
4	Transformer 1 SUS-5	26.4	32.4	1.23	70.3	0.37
5	Transformer 2 SUS -5	26.4	33.8	1.28	67.5	0.39
6	Load of SUS -5	52.8	70.1	1.33	97.5	0.54
Tsentralna mine						
7	Load of SUS	85.3	98.1	1.15	168	0.5
8	Ort 7	20.4	23.9	1.17	43.9	0.46

Saksahan mine						
9	Transformer 3 SUS - 10	32.8	36.9	1.12	58.8	0.56
10	Transformer 2 SUS - 10	7	10.7	1.5	26.2	1.27
11	Ort 209	14.9	19.4	1.3	44.1	0.34

Table 3.6. Peak-loads and demand factors

#	Mine, level, substation, site	$P_{av.}$, W	σ_{av}, W	N_{mot}	T, (p=0.98)	P_{max}, W	P_{in},W	F_{dem} actual	F_{dem} designed	ΔF_{dem} %
Artem mine, SUS-3										
1.	Section 1	47.5	14.8	67	2.4	83	273	0.3	0.321	+6.9
2.	Site 12	37.4	14.5	61	2.4	72	249	0.29	0.332	+14.5
3.	Section 2	41.6	15.1	57	2.4	78	215	0.36	0.354	-1.67
4.	Site 1	40.8	12.3	58	2.4	70	186	0.37	0.377	+0.5
Artem mine, SUS-5										
1.	Section 1	47.3	11.5	57	2.4	75	300	0.25	0.31	+24
2.	Site 4	34	9.9	49	2.4	57.8	273	0.16	0.321	+100
3.	Section 2	46	15.2	43	2.42	83	478	0.174	0.27	+55
4.	Site 5	12.2	4.6	33	2.45	23.5	386	0.061	0.285	+367
Oktiabrska mine, traction substation										
1.	Section 1	98	15.7	102	2.36	135	656	0.205	0.228	+11.2
2.	Access drive 4	13,4	3.2	27	2.48	21.4	18.5			
3.	Access drive 7	27,6	6.8	76	2.38	43.8	143	0.306	0.326	+6.54
4.	Access drive 10	16	5.1	68	2.4	28	91	0.108	0.398	+29.2
5.	Access drive 16	10.5	2.8	25	2.49	17.5	128	0.137	0.33	+140
6.	Access drive 22	11	3.75	19	2.55	20.6	131	0.157	0.337	+114
Yuvileina mine, SUS-10										
1.	Section 2	10.7	7.1	24	2.5	28.5	95.5	0.3	0.388	+29.3
2.	Section 3	44.2	9.63	32	2.45	67.8	630	0.108	0.228	+112
3.	Ort 205	19.3	5.9	38	2.43	33.5	341	0.1	0.253	+153
4.	Ort 209	26.3	7.2	43	2.42	43.7	280	0.156	0.264	+69.2

6. The mean-square deviation of power consumption per shift from the average one under the limited number of measurements (n< 30):

$$\sigma_{W_{a\ av}} = \sqrt{\frac{1}{n-1}\sum_{1}^{n}\left(W_{a\,i} - W_{a\ av}\right)^2} \qquad (3.32)$$

7. Under the confidential probability of measurements F = 0.95, the deviation factor of power consumption per shift was determined.

8. The maximum confidential interval of power consumption per shift was:

$$W_{a\,max} = W_{a\,av} + t \cdot \sigma_{Wa\,av}. \quad (3.33)$$

9. The confidential interval of the mean-square peak-load:

$$P'_{max} = \frac{W_{a\,max}}{7} \quad (3.34)$$

where 7 is duration of a shift, hours.

3.3 Determination of the real power factor

Conducted investigations result in the following conclusions:

1. The weighed tgφ for each analyzed input and site as well as for all inputs and sites is:

$$tg\varphi_{weighted} = \frac{\sum_1^n W_{ri}}{\sum_1^n W_{ai}}, \quad (3.35)$$

where $\sum_1^n W_{ri}$, $\sum_1^n W_{ai}$ is consumption of active and reactive power per input (site) during the time period analyzed.

According to the investigation programme, when measuring active and reactive power of each feeder, there were fixed values of changed efficiency of certain blocks and attachments as a whole and at places of unloading for tippers of certain levels. Parameters under study were registered during 143 shifts at 11 mining blocks and during 106 shifts at inputs of transformers of the site substations. Fig. 1.1-1.6 present measurement results of power consumption and energy-efficiency of the mines under analysis.

The power factor of the consumers is given in Table 3.8.

Table 3.8. Power factors

Mine, level, substation, site	$\sum_1^n W_{ai}$, kW·h	$\sum_1^n W_{ri}$, kVAR·h	$tg\varphi$	$\sum_1^n W_{ain\max}$, kW·h	$\sum_1^n W_{rin\max}$, kVAR·h	$tg\varphi_m$	P_{max}, kW	Q_{max}, kVAR·h	S_{max}, kVA
Section 1	2966	2590	0.91	511.3	375	0.73	83	60.6	103
Site #12	1947	1304	0.67	536	353.4	0.66	72	47.5	86.3
Section 2	1115	1030	0.92	377	377	0.846	78	66	102
Site #1	1548	1471	0.95	476	476	0.82	70	57.4	90.5
Section 1	2378	1859	0.78	546	386	0.706	75	53	92
Site #4	1237	939	0.76	188	137	0.73	57.8	42.2	71.6
Section 2	2109	1483	0.703	377.4	275.6	0.73	83	60.6	103
Site #5	432	871	2.02	128	216	1.69	23.5	39.7	46

Changes of efficiency as a technological factor depend on many factors, mining-technological conditions and operation procedure being the main ones. Efficiency has an indirect impact on power consumption resulting in the fact that connection of power consumption and efficiency is difficult to control as is shown in Fig. 3.11.

Similar studies conducted by V.F. Kalinichenko also indicate poor connection between power consumption and efficiency: the correlation for the most wide-spread system of sub-level caving makes r = 0.66. Considering the above, this method is unable to provide substantiated results and its application is possible in case of large-scale and constantly updated investigations.

For further study, one needs a complex approach considering basic factors influencing mining systems, the mechanization degree of operations, personnel's qualifications, etc.

Standardization and long-term planning of power consumption in ore mining are necessary to assess production efficiency and development of steps and means to control power consumption modes for technological operations.

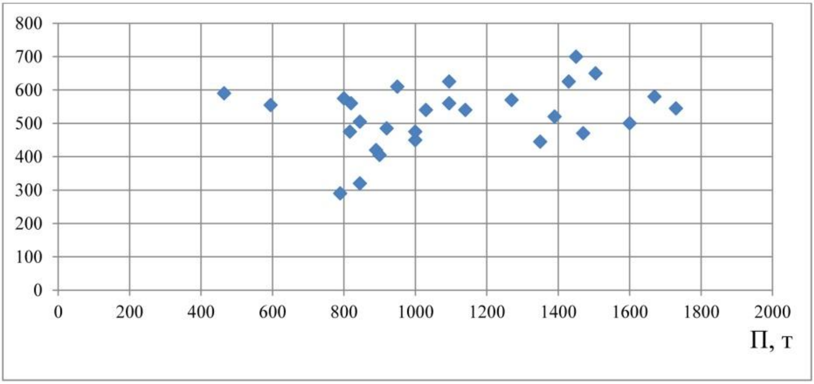


Fig. 3.11. Dependency of changed power consumption on efficiency

Table 3.9. Specific power consumption

Mine	Substation, input	Specific power consumption, $kW \cdot h/t$	Connection	Specific power consumption, $kW \cdot h/t$
Artem mine	SUS-3, input 1 SUS-3, input 2 SUS-5, input 1 SUS-5, input 2	0.904 0.33 0.615 0.778	Site 12 Site 1 Site 4 Site 5	0.593 0.307 0.32 0.159
Oktiabrska mine	"Tiahova", input	0.484	access drive 7 access drive10	0.203 0.385
Yuvileina mine	SUS-10, input 3	0.273	Ort 205 Ort 209	0.173 0.268

There are changes in power consumption, production of site or group of blocks, quantity and set capacity of power consumers. The reason for making measurements is that the norm of specific power consumption and the designed one are not constant and unchanged and they are related to a certain level of iron ore mining.

Obtained data enable determining power consumption per ton (Table 3.9). Analysis indicates that the range of changes at power transformer inputs including a group of sites makes 0.904 and for separate blocks it is 0.173-0.592.

The character of changes depends on values of specific consumption for certain operations. Total power consumption of a site (block) comprises two components:

– the component not depending directly on the site efficiency (power consumed by auxiliary fans, lighting devices, an electric boiler). This component ranges within some limits as the consumers do not operate during fixed hours during their shift;

– the component depending on the site efficiency (power consumed by scraper hoists, vibro-chutes). Increased site efficiency causes increased power consumption for scraper hoisting.

As a result, specific power consumption per 1 ton of ore (ratio of total power consumption per shift to changed site/block efficiency) reduces while efficiency increases.

3.4 Comparison of methods of calculating loads

Underground power receivers consume most power with voltage of up to 1 000 V as there are many transformer substations at mining sites.

To solve problems of power-supply, mines should observe economical efficiency and reliability terms depending on compliance of designs with certain conditions of operating electrical equipment. Fulfilled assessment of actual power-consumption modes and comparison of obtained results with the designed ones is of particular interest.

The primary stage of power-supply design is determination of expected loads resulting in choosing all elements of the power-supply system. This section contains analysis of applied methods of designing power supply of iron ore mine levels on the basis of experimental results. Calculation of loads at iron ore mines is based on "Standards of technological design of underground mining enterprises". They are based on applied factors of demand, capacity and coincidence of peak loads developed by the Institute "Lenhiproruda" for homogenous groups of electric receivers.

Proceeding from the demand factors, active load is calculated by summing up homogenous groups:

$$P_{cal} = \sum_{1}^{n} P_{set\sum} \cdot K_{dem}, \tag{3.36}$$

where K_{dem} is the demand factor for the homogenous group of electric receivers;

$P_{set\sum} = n \cdot P_{set}$ is total set power of all consumers of the homogenous group;

n is the number of electric receivers in the group;

P_{set} is set power of a single electric receiver.

The rated reactive power is calculated by the power factor:

$$Q_{cal} = P_{cal} \cdot tg\varphi \ , \qquad (3.37)$$

where $tg\varphi$ is determined by the value of the power factor *cosφ* for the group of homogenous receivers.

The rated power at underground substation bus bars is determined by the coincidence factor of peak loads ($F_{\text{max. coincidence}}$) presented in Table 3.10.

Table 3.10 – Values of the divergence factor of peak loads between homogenous groups

1	1	1
2	2–3	0.95
3	4–5	0.9
4	6–8	0.85
5	9–11	0.8
6	12–15	0.75
7	16–20	0.7
8	21–30	0.65
9	more than 30	0.6

The full rated power providing parameters for choosing transformers power for an underground substation is:

$$S_{cal} = F_{dem} \cdot \sqrt{P_{cal}^2 + Q_{cal}^2} \ . \qquad (3.38)$$

Tables 3.11-3.13 provide actual capacities of power consumers.

Table 3.11. Comparison of methods of calculating loads

Load centre	Rated power as to applied methods			Rated power as to suggested methods			Divergence, %
	Active power, kW	Reactive power, kVAR	Full power, kVA	Active power, kW	Reactive power, kVAR	Full power, kVA	
Section 1	87.5	82	120	87.4	87.4	123	+24
Section 2	75	75	106	76	76	107	
SUS 3	156	150	216	130	117	175	
Section 1	106	84	135	93	93	131	+33
Section 2	158	152	219	128	128	181	
SUS 5	252	224	337	188	169	254	
Block 0	57	52	77	47	47	66	
Block 4	8	6.6	10	14	14	20	
Block 7	73	59	94	46.5	46.5	66	

Block 10	34	30	45	36	36	51	+48
Block 16	43	41	60	44	44	62	
Block 22	44	42	61	44	44	62	
Section 1	212	205	295	149	134	200	
Section 2	43	38	57.4	37	37	52	
Section 3	191	179	262	144	144	204	+39
SUS 10	224	207	305	163	147	220	

While choosing transformer power for SUS substations, the closest great standard power, i.e. $S_{nom} > S_{cal}$ is taken, where S_{nom} is nominal transformer power, kVA.

Table 3.12. The rated calculation of 0.4 kV load of the take development stage at Artem mine under 75 % ore production plan

Power consumers	The number of installed consumers			Established capacity			Demand factor	Power factors	Consumed power at busbars of substations		
	Operational	Standby	Total	of a unit	Operational	Total			Active (kW)	Reactive (kVAR)	Full (kVA)
Scraper hoist											
17ЛС – 2СА	7	4	1	17	119	187	0.3	0.75	35.7	31.6	
30ЛС – 2СА	6	2	8	30	180	240	0.3	0.75	54	47.6	
55ЛС – 2СА	4	2	6	55	220	330	0.3	0.75	66	58	
Drag conveyor КС - 2	8	3	11	60	480	660	0.3	0.78	144	128	
Vibro-feeder ПВШ - 2	6	3	9	10	60	90	0.4	0.65	24	28	
Apron conveyor КПР – 1А	3	3	6	30	90	180	0.5	0.75	45	40	
Drilling machine НКР – 100м	8	2	10	2.8	22.4	28	0.3	0.7	8.4	8.6	
Loading machine ПНБ – 2к	9	2	11	30	270	330	0.3	0.65	81	94	
Fan ВСМ	5	2	7	14	70	98	0.6	0.8	42	32	
Fan ВМ-5	11	2	13	28	308	364	0.5	0.8	154	116	
Lighting									50		
Total					1949	2689			704	584	
Considering the maximum coincidence factor $F_{max.coincidence}$=0.85									598	554	805

One of the reasons of non-conformity of designed and actual loads is the fact that equipment assigned for the project differs from the installed one which is confirmed by studied loads of Artem-1 mine take at L 1045 m presented in Tables 3.12-3.13. Compared calculation results indicate the 1.6 increase of the designed values of the total installed power. The full designed power of equipment is 805 kVA instead of 507 kVA of the actual equipment.

According to the above, one can distinguish some main reasons for the increase of transformer power:

1) The current method of calculating loads provides the values overstated by 24-48 % compared to the recommended method.

2) While choosing a transformer, its overloaded capacity is neglected resulting in overstated designed power by 40-70 %.

3) Types, quantity and power of applied equipment differs from the designed ones. For example, total power of designed equipment at Artem-1 mine is by 1.6 times greater than that of the actual one.

4) The scale of nominal transformer powers has 1.6 ratio of adjacent powers. This fact and a designer’s desire to create similar transformers cause the increase of installed transformer power compared to the rated one.

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