The peculiarities of power conservation and energy efficiency in power supply systems of industrial enterprises

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Abstract. The paper deals with the peculiarities connected with energy efficiency and power conservation measures in power supply systems of industrial enterprises. The purposes and objectives of the research conventionally divided into several areas: electric networks, electric drive, control and monitoring of energy consumption. The current state of energy and resource efficiency at industrial enterprises is described. The scientific literature of Russian and foreign authors working in this field is analyzed. The objects of research which are a mine and a processing plant for the extraction and processing of diamondiferous raw material are identified. The methods of mathematical modeling and instrumental monitoring are applied to analyze energy efficiency and power conservation. The region power supply system, automated (frequency-controlled) electric drive of processing units of mining enterprises, automated systems for monitoring and management of enterprises’ production processes are considered in the paper in details. The methods with a significant contribution to power conservation and energy efficiency of mining enterprises developed by the authors are presented. The conclusions on the prospects of future research in the field of energy efficiency and power conservation at mining enterprises are made.

1. Introduction

In recent years, power conservation has become one of the focus areas of technological policy in all industrialized countries. Sustainable economic development requires increasing production and hence, the consumption of fuel and energy resources [1]. The effective use of energy is a significant internal reserve providing the enhancement of gross product competitiveness and the standard of living of the country’s population in the context of the established trend of rising energy prices and the increase of their share in the structure of production costs of commodity products and services [2]. Taking into account the fact that the share of costs related to power conservation in mining operations is 40-60%. It can be concluded that the implementation of organizational and technical measures for power conservation can lead to visible economy in fuel and energy resources [3].

Power conservation factors can be roughly divided into external and internal ones. The external factors include: global economic growth, the dynamics of prices at the world market of hydrocarbon resources, global demand and export volume of Russian hydrocarbons, and the environmental situation in the world. The internal factors of power conservation are divided into two groups: the
group of providing factors and the group of effective factors. They basically have two closely interrelated and interdependent aspects – the increase of resource stocks and the reduction of their consumption [4].

Power and resource conservation is one of the priority tasks [5] in the management of energy-intensive mining production. Energy efficiency and power conservation measures in power supply systems of mining enterprises can be conditionally separated into several areas: electric networks, electric drive, control and monitoring of energy consumption.

Thus, the purpose of the research is to formulate measures of energy efficiency and power conservation in the power supply systems of industrial enterprises. The following tasks are to be solved and the following issues have to be considered: the assessment of technical state of electric networks of the region; the prospects of the introduction of automated electric drive (AED) systems at the processing units of mining enterprises; the results of the introduction of the automated control system and power conservation management (ACSESM) at one of the sites of an industrial enterprise.

2. Methods of the research
The underground mine and the processing plant for the extraction and processing of diamondiferous raw materials located in Western Yakutia and related to the Mirny mining and processing division (MMPD) of the company PJSC ALROSA were chosen as the objects of the research. The selected mine and factory are located near Mirny in the Republic of Sakha (Yakutia) and get electricity from the supplier Western electric networks (WEN) of PJSC Yakutskenergo.

The mathematical modeling methods of automated electric drive and power supply systems [6]-[8] and instrumental monitoring of electric power quality [9]-[11] using up-to-date application programs and analyzers will be applied as the research methods, in addition to theoretical and experimental studies of current automated information and control systems of the enterprise.

3. Results and discussion
The current state of power and resource conservation at industrial enterprises will be briefly described further. The researches of domestic and foreign authors working in the field were analyzed.

Seemingly, the methods and means of the enhancement of power conservation and energy efficiency levels at mining enterprises [12] and [13] are described in details. But any specific proposals of the evaluation of technological feasibility and cost-effectiveness of the proposed methods were not provided.

In [14], technical solutions for reducing the level of higher harmonics, in particular, the use of semiconductor converters with an active rectifier are presented.

The promising method for improving energy efficiency in mining industry at the expense of using non-traditional renewable sources and combined energy storage is shown in [15].

In paper [16], the authors describe new switchgear devices reducing transition processes and improving electromagnetic compatibility in power supply systems of coal mines, but they are still being tested, and any information on their use in the Russian Federation is not available.

The author of paper [17] analyzes the prospects of the introduction of frequency-regulated electric drives into all possible spheres of the country’s economy. The importance of energy efficiency and conservation during the transition to innovative energy supply of production is indicated.

Papers [18] and [19] describe the excellent technique reducing the influence of higher current and voltage harmonics on the operation of electrical equipment developed and tested at a mining enterprise. However, it is only applicable to newly introduced sites, since otherwise the capital expenditures for the installation of active filters of higher harmonics will be too large.

The results of the analysis of scientific literature have shown that the methods proposed in the paper have novelty and practical significance for mining enterprises.
3.1. The power supply system of Western Yakutia

The first direction in the field of power conservation is related to the specific conditions of the Western region of Yakutia and the Western electric networks (WEN) which can be more than thousands kilometers long. It should be noted that WEN do not have an electrical connection with other power systems of the Republic, and operate in an autonomous mode. They practically do not have backup power plants, and power transmission lines (PTL) can be extremely long, have limited capacity and actually operate without a reserve capacity. The technical state of basic equipment of power plants and power lines has low reliability. Power plants and damage control teams are short-staffed. The details on the structure of WEN and the technical state of basic facilities are presented in [20], [21]. The fragment of the scheme of electrical connections (Fig. 1) of the studied objects of mining enterprises (mine and factory) can be seen in Figure 1.

![Figure 1. The scheme of electrical connections of the studied objects: 1-underground mine; 2-processing plant.](image)

Currently, electricity consumption in the region has stabilized at the level of 6.5 billion kWh per year, of which industrial consumption is more than 70 %. In recent years, the Vilyui hydro power station cascade exceeds the design capacity, due to the increased inflows to the reservoir, but probably they can be reduced in the future. To provide consumers of the first category with uninterrupted power, there are low-power backup gas distribution power plants and autonomous diesel generator power plants.

The analysis of the electricity demand of industrial enterprises in the region showed that the consumption can be increased by 10-15 % per year due to the introduction of new enterprises and the development of new fields by the companies of PJSC ALROSA, LLC TUNGD, LLC RNG and others.

The potential of a power system is determined by the necessity to increase the efficiency of backup and autonomous power plants, and to improve the reliability and throughput of power lines by upgrading existing and commissioning new power lines on metal supports. It is also important to reduce electricity consumption due to converting heating equipment to gas fuel.
It is evident that much depends on organizational measures, the environmental situation in a region, power industry itself (reliability and quality of power supply) and consumers (reactive power compensation, power savings, compliance with limits and schedules).

3.2. Automated (frequency-controlled) electric drive

The second direction in the field of energy saving is connected with the development and improvement of electric drives (ED) of technological installations of mining enterprises, which are the main consumers of electricity in industry. Currently, ED consumes about 65% of all generated electricity, and the consumption will be the same in the future (and may even be increased). ED accounts for the majority of total electricity losses in the power supply system of mining enterprises (ME). For today's large MEs, power losses in ED can reach 60-70% of the total losses in power supply system. It follows that the main effect of energy savings can be obtained in the case of rational use of ED.

The purposeful work is being carried out to introduce a frequency-controlled electric drive (FCED) at the enterprises of PJSC ALROSA. The authors describe these measures in details in [22]. However, the high cost of semiconductor frequency converters (FC) is the main obstacle of their use. For example, the cost of FC having a capacity of 200 kW can vary from 1 to 1.5 million rubles, while additional expenses are necessary. Therefore, the introduction of FCED should be preceded by the calculations showing the amount of energy savings with continuous speed control and the effectiveness of such method of regulation. Moreover, the feasibility study should take into account the increase of electricity prices. When making a final decision, it should be considered that the introduction of FCED is one of the best ways to reduce consumption bills.

The problem of FCED introduction is considered to be totally different when it comes to the so-called technical re-equipment of production. In the case, obsolete mechanisms and their accompanying systems reaching the end of life cycle are subjected to replacement.

So, the implementation of the FCED is inevitable (no matter how much it costs), and then one of the principle challenges remains – informed choice of the system to be introduced in terms of not only energy savings, but also electromagnetic compatibility.

A vivid example of such upgrade is the replacement of the fan unit for the main ventilation of underground mine “International” which was being carried out element-by-element from 2015 to 2017. In 2015, the FCED system was replaced: the obsolete frequency converter was substituted with Power Flex 7000. Then, in 2016, a new TLT Turbo TEC-36/21, 5-1 fan unit had been purchased and changed the old VOD-50 fan. In 2017, the old asynchronous SDSZ18-39-20RUHL4 engine was replaced by asynchronous motor A5L710P44-O8KBExpz. In [23], the authors made a detailed assessment of the effectiveness of modernization performed using mathematical modeling and instrumental control methods.

It is worth to note that before such a complete modernization (until 2015), the launch of the basic ventilation unit was accompanied by large voltage failures in the power supply system of the mine, which also affected household consumers of power supply system of Mirny (Substation “Mirny” 220/110/6 kV). So, one of these voltage dips when changing fan installations (they are changed once a month according to the regulations) is shown in Figure 2.

The electricity quality analyzer was installed at the substation of Mirny gas distribution power plant (Substation “MGRES”) in the period from March 26 to March 30, 2012. The failure was recorded in March 28 at 11:18 and lasted just under a second.

Another example of the analysis of the energy efficiency of the replacement of FCED to the pulp pump unit at the processing plant by mathematical modeling is given in [24]. The paper considers the reduction of costs only by reducing the energy intensity of the pulp pumping process.

So, the use of FCED leads to a significant reduction in operating costs. This is achieved mainly by increasing the service life of components and system elements by ensuring steady operation of the pumping unit in dynamic modes. To perform such complex calculations, it is necessary to have
appropriate mathematical models and methods based on them to study the economic efficiency of FCED. Currently, there are no such models and methods for the mining industry.

A significant part of potential consumers, having the lack of necessary information and unreasonably fearing the consequences of using complex up-to-date FCED systems, continue to suffer losses, resorting to extremely inefficient methods of regulation because of the absence of standardized research methodology and well-functioning data system on results achieved.

Currently, such work on the creation of models and methods based on them to study the cost-effectiveness of automated electric drives taking into account the specificity of mining enterprises is carried out by the specialized enterprise “Almazavtomatika” and the Institute “Yakutniproalmaz” of PJSC ALROSA. The main difficulty is the necessity to consider power supply system, frequency-controlled electric drive, operating machine, technological object as a united electromechanical system (UES), where the mutual effect of all elements on each other must be considered.

The result of one of such collaborative effort of the Department of Electricity and automation of industrial production of NEFU and “Almazavtomatika” of PJSC ALROSA was the development of the complex mathematical model taking into account all basic features of the specific elements of the EMS, energy losses in supply lines, electromagnetic processes in the motor, the presence of the nonlinear unit in the technological object, etc. Let’s take the example of a skip lifting installation of the blind skip shaft of the International underground mine, where multiple failures of frequency converter units and parts have been recorded since the beginning of its commercial operation (since 2017). In August 29, 2018, the first failure of the filter compensating device (FCD) was marked. This event led to long and complex scientific and technical researches of the team. It was assumed in the course of the research, as well as consultations with the manufacturer of the frequency converter that the main reason of the failure of the capacitor was a significant reduction in the service life of the capacitor under the influence of higher harmonic components in the supply network. In order to refute or confirm this assumption, the instrumental control of power energy quality indicators was performed, and the complex mathematical model including mathematical processing method and the analysis of measurement results of current and voltage higher harmonics in electric networks was developed.

Basic materials of the research have not been published yet, that’s why only the reference to the publication describing the modeling of the static and dynamic modes of DC motor operation of the elevator installation in the software package MatLab [25] and the graph of the variation of the phase currents at the moments of failures of elevator operation (Figure 3) is presented here. The failures took place at the end of acceleration under heavy load operation of skip hoist and were caused by the error of the frequency inverter “DC Link overvoltage”.

![Figure 2.](image) The voltage dip at the substation MGDPP when changing fan installations at International underground mine.
Thus, the calculations showed that the electricity consumption during the introduction of automated (frequency-controlled) electric drive systems is reduced by 1.5-2 times in all considered cases.

3.3. Automated system for monitoring and managing energy saving

The third direction in the field of power conservation is related to the introduction of automated systems for accounting power losses, power quality and distribution to enterprises in accordance with standards, limits and schedules. Information and control systems are made as hierarchical distributed complexes consisting of four main functional subsystems: one automatic emergency management system (AEMS) and three automated – dispatching control systems (ADCS), electric power control and accounting systems (EPCAC), production and technical activity systems (PTAS).

These subsystems can exist as separate products, so in the complex – in the form of automated energy saving management system of the enterprise (AESMS). Among them, there are only specialized hardware and software systems, but also general-purpose modular systems. The first ones take into account the specificity of the infrastructure where they are integrated into, and products based on a modular architecture require much greater investments and time for their introduction.

The cost of AESMS is determined by the scale of a mining enterprise and is calculated based on the required number of meters, hardware capacity, distances between automated workplaces and meters, as well as the type of communication channels. It should be noted that the introduction of AESMS at enterprises if properly operated is always economically justified. AESMS makes it possible to keep records and control not only power, but also the flows of almost all possible energy carriers: air, steam, water, fuel, etc., and also allows controlling security. Thus, in paper [26] the introduction of gas analysis systems of a new generation for mine protection is considered. They belong to the ADCS and are realized on the basis of the gas protection Protocol "MIKON III". In [27], [28] methods and automated systems for monitoring the distribution of dust sediment and dust suspension, and the devices for determining the mass of deposited and suspended dust in the air at the sites of a coal mine are described.

A significant contribution to the development and implementation of EPCAC at mining enterprises was made by the authors in paper [29]. One of the joint research projects of the MPTI (branch) NEFU, MPEI, MSMU, and PJSC ALROSA resulted in the development and implementation of an automated system for continuous monitoring power quality control in power supply system of the underground mine at the sections of elevator and the technological filling complex. The block diagram of automated system for continuous monitoring of power quality control is shown in Figure 4.

![Figure 3. The graph of changes in phase currents at the moment of failure of the elevator operation.](image-url)
Figure 4. Block diagram of an automated system for continuous monitoring of power quality control.

The analysis of the results of monitoring system measurements at the power consumption facilities (skip hoisting plant of the skip shaft and ball mill of the crushing section of the technological filling complex) of the mine for the first year of operation allowed us to identify one of the weak sites of the power system.

The calculation based on the data of the implemented monitoring system showed a low load factor of TM-1000 transformers, and, consequently, significant power losses at the idle speed of the transformer. In [30], the savings on electricity charges due to reducing idling losses of transformers through increasing their load factor were calculated. The savings amounted up to 1.8 million rubles for 5 years that is 4 times higher than the cost of the system.

4. Conclusion

As a result, it can be concluded that the basic directions in power conservation and energy efficiency at mining enterprises are the following: improving the reliability and quality of power supply; transition to a frequency-controlled electric drive; complex automation of all production systems. The directions are currently being intensively developed by PJSC «ALROSA» and other major mining enterprises. This is especially related to the increasing cost of energy and the desire of companies to save money in this area, as well as to the progress in the field of power conversion technology, microelectronics and automation tools.

It seems to the authors that future large-scale and detailed research in the field of energy efficiency and power conservation at mining enterprises should be developed namely by means of implementing the FCED. For this purpose, the research should be carried out on the following priorities: the formulation of technological requirements for the mechanisms of mining enterprises; the description
of the peculiarities of frequency converters operation at these enterprises; the determination of fundamental basics of the construction of frequency converters power circuits and the guidelines for controlling a frequency-controlled electric drive; conducting feasibility study of the market of modern frequency converters; the development of methods for data collection, processing and analyses of information on the operation of FCED systems; the development of diagnostic techniques of power semiconductor converter equipment; the creation of mathematical models for the EMC of mining enterprises.

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