# Innovative approaches and methods to the implementation of energy-saving measures and technologies at mining enterprises

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**Abstract.** The paper presents the evaluation of the implementation of innovative methods of energy savings in electric drive and power supply systems at mining enterprises. The evaluation involves mathematical simulation and instrumental monitoring of the defined indicators that allow obtaining a multiplier economic benefit through the appropriate approach to the implementation and subsequent exploitation of energy-saving technologies. For this purpose, the potential of energy savings in industry in general, and at mining enterprises in particular, is shown. Such indicators as power consumption in mining, the dynamics of power losses in public grids, specific power consumption for lighting and household needs, specific power consumption for lifting and supplying water, as well as for sewage treatment were evaluated. As an example, such measures as reactive power compensation, the introduction of frequency-controlled electric drive systems, the development and implementation of the systems for continuous monitoring of power quality indicators were considered pointwise (at some sites of enterprises). The mathematical simulation method was implemented using the MatLab software package. The instrumental monitoring was carried for 7 days with a ten-minute interval. As a result of the assessment of such measures, the total economic benefit approaching to 9.0 million rubles a year was obtained.

## 1 Introduction

In recent years, energy saving has become one of the main directions of technological policy in all industrialized countries. Sustainable economic development requires the increase in production and consumption of fuel and energy resources [1]. The effective use of power carriers is a significant internal reserve that allows increasing the competitiveness of the gross product and the standard of living of the country's population in the conditions of the established trend of rising power prices, the increase of their share in the structure of production costs of commercial products and services [2].

Energy- and resource- saving is one of the priority tasks [3] in the management of energy-intensive mining production. Taking into account the fact that the share of costs connected with energy saving amounts to 40-60 % during mining operations, it can be concluded that the implementation of organizational and technical measures of energy saving can save fuel and energy resources significantly [4, 5].

The effectiveness of the introduction of innovative energy saving methods was evaluated on the example of the North-East of Russia and international diamond mining company ALROSA. The paper [6] shows the experience in the extraction of diamondiferous raw materials by ALROSA enterprises, which can be of interest and value to other foreign companies. ALROSA's activity is focused on two regions of Russia: the Republic of Sakha (Yakutia) and the Arkhangelsk region. The largest deposits (pipes) of the company are «Mir», «Yubileinaya», «Udachnaya» and «Internatzional’naya». They are located in Western Yakutia where diamond-bearing rocks are currently being mined by the underground method. Such mining is a very energy-intensive process.

The assessment of technical condition of the region's electric grids and power supply systems of mining enterprises, the energy saving potential in industry in general, and in mining enterprises in particular, are shown in [7]. In [8], the evaluation of power savings potential is made. It is shown in [9] that the main share of power consumption is spent on the extraction of minerals and reaches 40 %.

Such indicators as power consumption in mining, the dynamics of power losses in public grids, specific power consumption for lighting and household needs, specific power consumption for lifting and supplying water, as well as for sewerage treatment were evaluated. The total potential of energy savings in the considered areas was estimated in 310-375 million kWh/year (Table 1).

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**Table 1.** Power Saving Potential: 1-Loses in public grids; 2-Lighting and household needs; 3-Lifting and supplying water; 4- Sewage treatment.

| No | Production volume, mln. kWh | Possible decrease, % | Economy, mln. kWh |
|---|---|---|---|
| 1 | 1284 | 2.5-3.0 | 240-291 |
| 2 | 1500 | 2.0-2.5 | 30-40 |
| 3 | 600 | 3.3-3.7 | 20-22 |
| 4 | 460 | 4.4-4.8 | 20-22 |
| Total power savings | | | 310-375 |

In [10-12], theoretical and experimental studies devoted to the measurements of power quality indicators at the underground mine extracting diamond-bearing rocks and at the processing plant were carried out. The following conclusions were made on the basis on the results of the instrumental examination of power supply systems of the mine and the factory:

- power quality at the processing plant meets the requirements of standards by any measure;
- power quality on the buses of 6.3 and 6.6 kV of the mine substation upon indications of the total harmonic distortion of voltage curve and the coefficients of the n-th harmonic component of voltage for a number of harmonics do not meet the regulatory requirements.

The reasons of the discrepancy are non-linear power consumers with different rectifying pulses and high rated power. Such installations have a capacity of more than 1 MW and make a great contribution to the power consumption of enterprises. They are driven mainly by means of a variable frequency drive (VFD). The mechanisms on which the VFD is used can be conditionally divided into two groups. The first group includes such installations as pumps and fans. Their automatic speed control allows saving energy depending on some technological parameter (fluid pressure in the pipeline, fluid level in the sump, air depression in the ventilation duct, etc.) [13]. The second group contains such mechanisms as mine hoisting machines and trip spotting hoists for dredges. Their speed control is necessary to ensure the required operating modes of a technological unit [14].

In [15], three most common electric drive systems of technological units of mining production were analyzed (on the example of ALROSA enterprises): a variable-frequency drive based on a synchronous motor of the fan installation of main ventilation of the mine; controlled rectifier - DC motor with separate excitation of the mine's skip hoist; variable-frequency drive based on the asynchronous motor of the slurry pumping station of the processing plant. The results of measurements of electromagnetic compatibility with the supply main of Power Flex 7000 and ACS5000 frequency converters were analyzed in [16]. The influence of variable-frequency drive systems on power quality was proved.

Considering all previous studies, including the researches of the authors of the paper, it can be concluded that the use of innovative methods of energy savings at mining enterprises implemented using mathematical simulation and instrumental monitoring is an urgent task. The methods can give a multiplier economic benefit in the case of correct approach to the implementation and subsequent operation in the technological processes of production enterprises.

The purpose of the research is to evaluate the potential for introducing innovative energy-saving technologies at mining facilities on the example of ALROSA company. To achieve the stated objective, measures of energy savings in power supply systems, power control and metering systems, electric drive systems of mining enterprises are considered.

## 2 Materials and Methods

The underground mine and the processing plant extracting and processing diamondiferous raw materials which is located in Western Yakutia were chosen as the subjects of the study. The purposeful work is being carried out at the chosen enterprises to improve power efficiency.

The main innovative research methods in the field of energy savings include mathematical simulation and instrumental monitoring of power supply and electric drive systems.

Currently, there are a lot of software products for mathematical simulation of technical systems. The MatLab software package holds a specific place among the classical mathematical packages such as MathCAD, Maple, Mathematica. This package is intended for simulating and research of static and dynamic systems broadly defined including discrete, continuous and hybrid models. The Simulink application being the part of the MatLab environment represents the library of blocks. It is currently one of the most popular numerical computation tools used in various fields of knowledge. In turn, the Simulink library includes SimPowerSystems subdirectory containing the necessary set of power blocks for developing power and electromechanical models.

The method of instrumental monitoring of power quality indicators was implemented in accordance for 7 days with a 10-minute interval. The following indicators were standardized: frequency deviation; slow voltage changes; voltage fluctuations and flicker; voltage nonsinusoidality ratio; voltage unbalance in three-phase systems; voltage of signals transmitted through electric grids; voltage interruptions; voltage dips and overvoltage; pulse voltages. The main indicator to be evaluated in the paper for the analysis of the compliance of the power quality with the standards during operation of high-tension frequency converters is the total harmonic distortion stipulating non-sinusoidality, i.e. distortion of the voltage waveform.

## 3 Results and Discussion

Energy efficiency and energy saving measures at mining enterprises can be conditionally divided into several directions: electrical grids (power supply systems), electric drive, monitoring and accounting of power consumption.

### 3.1 Power supply systems

In this part, attention is paid specifically to the power grids and the power supply system of the mining enterprise. Energy and resource savings is one of the priority tasks in the management of energy-intensive mining enterprise [17]. The evaluation of such virtual energy-saving measure as reactive power compensation was done using a universal mathematical model of the power supply system developed and described in [18].

Earlier, the universal mathematical model was developed taking into account the peculiarities of power supply of mining enterprises (Fig. 1). Functional blocks of the model were described, and their technical parameters were presented. The initial data for modeling were determined, the results of simulation were obtained during correct operation of the power supply system.

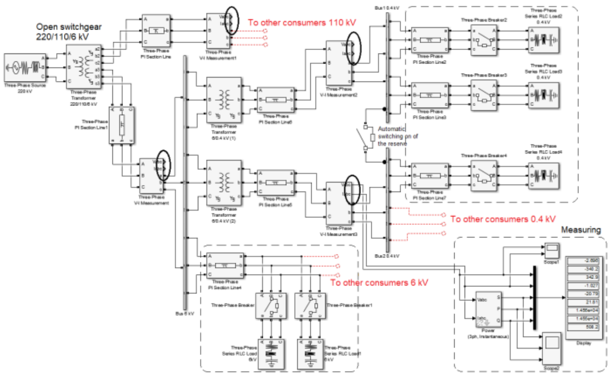


**Fig. 1.** Universal mathematical model of the power supply system.

For further research, the model was adopted to the power supply system of the specific site, namely the compressor station. The research on the implementation of virtual energy-saving measures by compensating the reactive power increasing the cost of no load operation does not operate effectively [19].

There are two main ways to compensate the reactive power: installing special compensating batteries, or using a synchronous motor as a compensator. In our case, the second option is more suitable, since synchronous motors are used to drive the compressors. Additional expenses are nearly not required.

The graphs of active and reactive power before (a) and after (b) compensation are shown in Fig. 2. It can be seen from the graphs that the reactive power decreases from 0.61 MVAr to the level of 0.38 MVAr.

The total capacity of the power supply system of the compressor station was determined and was equal to:

$$S = \sqrt{(P^2 + Q^2)}, \quad (1)$$

where P and Q are active and reactive powers, respectively.

The decrease in reactive power by 37% and thereby the decrease of the total power consumption from the grid by 3% (from 2.01 to 1.95 MVA) was obtained using the simulation.

The economic benefit from the use of reactive power compensation was calculated. As it was noted earlier, there were no any investments when using synchronous motor as a compensator. Only additional expenses for motor maintenance and repair were considered.

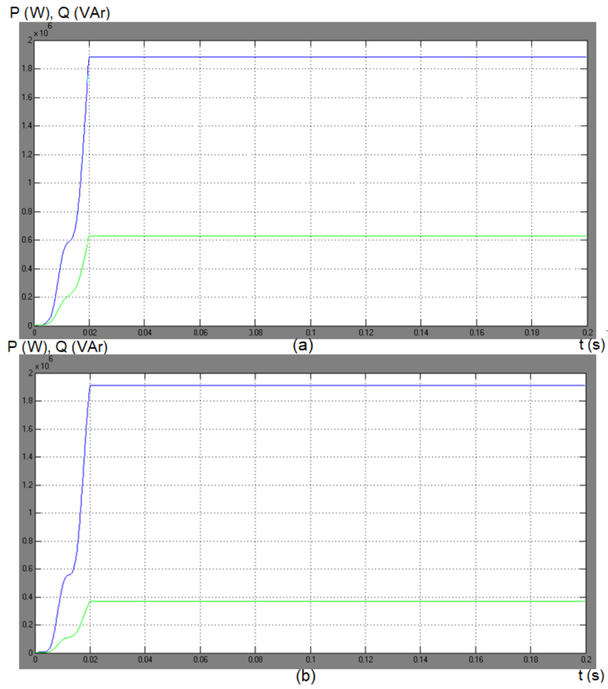


**Fig. 2.** Graph of active and reactive power before (a) and after (b) compensation.

The expenses of annual power consumption for the compressor station before and after reactive power compensation were determined according to the formula:

$$W_{Ci} = S \cdot (1 - \mathrm{Cos}\varphi)/\mathrm{Cos}\varphi \cdot k_{lf} \cdot T \cdot w, \quad (2)$$

where $S$ - total power, kVA; Cos$\varphi$ - power factor of the system, defined as the ratio of active power to total power; $k_{lf}$ - the load factor of the transformer, $T$ - operating time per year in hours; $w$ - the cost of one kWh of power.

The economic effect from the introduction of reactive power compensation taking into account the expenses of annual maintenance and repairs at the only one compressor station of the mining enterprise comprised thousand rubles:

$$W = W_{C1} - W_{C2} - W_r = 4908.8 - 4762.3 - 40.8 = 105.7.$$

Thus, the virtual implementation of energy-saving measures (reactive power compensation) was carried out using the method of mathematical simulation. The economic effect due to energy savings was calculated and amounted to more than 100 thousand rubles a year.

### 3.2 Power control and metering systems

In [20], the authors developed the experimental system for continuous monitoring of power quality indicators (PQI) at the underground mine (Fig. 3). The developed system was introduced into the operation of power supply systems of two mine sites: a mine hoist and a ball mill. The paper [21] presented the analysis of measured

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and processed power quality indicators. Further, only power quality indicators not corresponding to standards will be described.

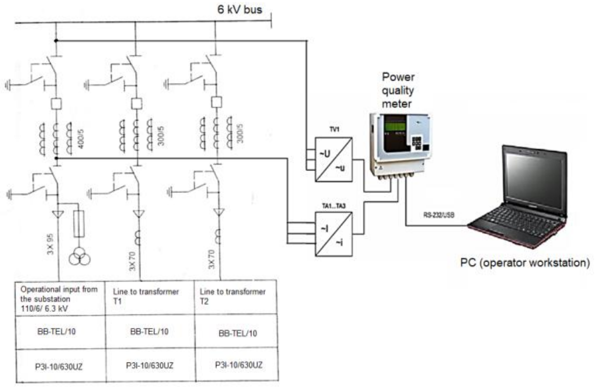

**Fig. 3.** Fragment of the structure of the system for continuous monitoring of power quality indicators.

Mine hoist site. The magnitude of phase deviation and voltage between phases exceeded the critical value of 5%, but did not exceed the critical value of 10% of the nominal; the coefficients of 23 and 25 harmonic components exceeded the maximum critical values and were 2.25% and 1.85%; the coefficients of 35 and 37 harmonic components exceeded the maximum critical values and were equal to 1.95% and 1.75% (Fig. 4 a, b).

Stowing complex site. The magnitude of the deviation of phase and phase-to-phase voltages exceeded the critical value of 5%, but did not exceed the critical value of 10% of the nominal; the coefficients of 35 and 37 harmonic components exceeded the maximum critical values and amounted to 1.25% (Fig. 4 c, d).

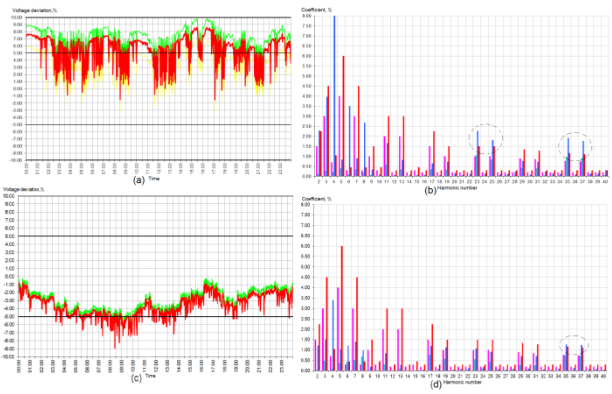

**Fig. 4.** Graphs of deviation and harmonic components of voltages.

The measurement analysis results for one year obtained at the power consumption facilities (skip hoisting unit of the skip shaft and a ball mill of the section of the technological filling complex) of the mine made it possible to identify one of the weak areas of the power system. The 350 kW synchronous ball mill motor is powered by a TM-1000 transformer. In accordance with norms, this power line is provided by two transformers. The calculation based on the data of the implemented monitoring system showed low load factor of the transformer, and, therefore, significant power losses during no-load running of the transformer, which were determined by the expression:

$$\Delta P_{id} = \Delta P_{nv} + \Delta P_{nl} \cdot k_{lf}^2, \quad (3)$$

where $\Delta P_{nv}$ - active no-load losses at rated voltage, kW; $\Delta P_{nl}$ - active load losses at rated load, kW; $k_{lf} = P_n/S_n$ - transformer load factor; $P_n$ - actual power of the load, kW; $S_n$ - the rated power of the transformer, kVA.

For two TM-1000 transformers, no-load losses were determined depending on the load factor of the transformer. The graph of the dependence of no-load losses on the load factor of transformers was plotted (Fig. 5).

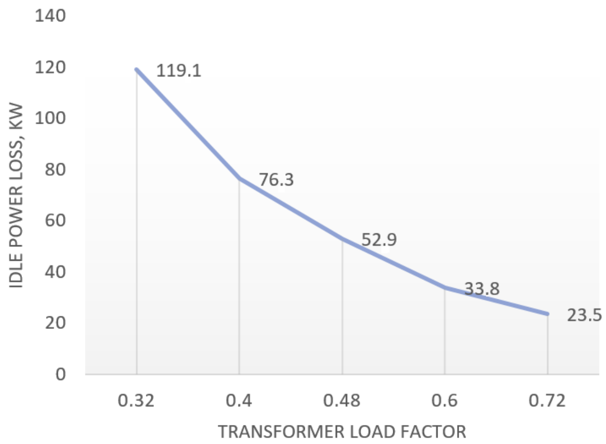


**Fig. 5.** Graph of the dependence of no-load losses on the load factor of the transformer.

To reduce no-load losses and increase the load factor at the mine sites, it was decided to increase the number and capacity of consumers connected to the transformer. The savings on power bills were calculated by reducing no-load losses in the transformer while increasing its load factor (Table 2).

**Table 2.** The calculation of annual energy savings.

| Parameter | 2020 | Planning time-frame, years | | | |
|---|---|---|---|---|---|
| | | 2021 | 2022 | 2023 | 2024 |
| $S_n$, kVA | 2000 | 2000 | 2000 | 2000 | 2000 |
| $P_n$, kW | 640 | 800 | 960 | 1200 | 1440 |
| $k_{lf}$ | 0.32 | 0.4 | 0.48 | 0.6 | 0.72 |
| $T$, hour | 5400 | 5400 | 5400 | 5400 | 5400 |
| $\Delta P_{id}$, kW | 119.1 | 76.3 | 52.9 | 33.8 | 23.5 |
| $w$, rub/kWh | 4.95 | 5.20 | 5.45 | 5.73 | 6.02 |
| $W$, kRUB | 3184 | 2143 | 1557 | 1046 | 764 |

The above-mentioned calculations show that operation optimization of the power supply system of the mine's technological stowing complex can save 2,419.6 thousand rubles for 5 years in future by reducing no-load losses and increasing the load factor of transformers.

Thus, the introduction of the experimental system for continuous monitoring of PQI at the site of the mining enterprise proved the necessity of optimizing power supply system operation. The implementation of such optimization gave an economic benefit of more than 1 million rubles for the first year, which is 3 times higher than the funds spent on introduction of continuous PQI monitoring system [22, 23].

### 3.3 Electric drive systems

The results of the simulation of electric drive system of the main fan unit were considered. The analysis of power savings by replacing the main fan unit of the mine extracting diamond-bearing rocks due to its unsatisfactory technical condition was made in [24]. A year earlier, the positive experience of practical operation of Power Flex 7000 frequency converters in mining industry was analyzed by the authors in [25]. The analysis showed that the converters proved their worth, despite the deterioration of electromagnetic compatibility of the supply main caused by them. The results were confirmed by the authors in [26-28].

The paper presents the evaluation of benefits from the introduction of a variable frequency drive (VFD) at the main fan unit (MFU) by the method of mathematical simulation [29]. The model shown in Fig. 6 allows obtaining the parameters of the fan at various motor speeds (impeller).

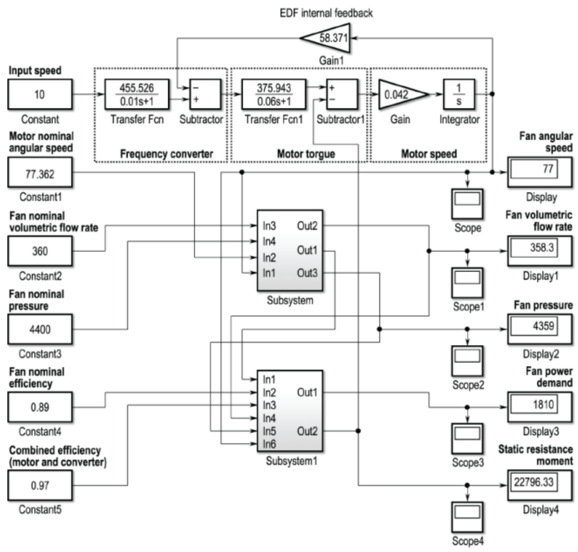


**Fig. 6.** Mathematical model of the main fan unit.

Graphical dependences of static pressure, feed and power on the angular velocity shown in Fig. 7 were made based on the data obtained as a result of simulation [30].

When evaluating, we considered the old MFU system with VOD-50 fan and a new one with TAF-36 /21.5-1 fan and Power Flex 7000 VFD. The reference values of power consumption for the fans under consideration were determined by the formula:

$$P_b = Q_n \cdot \rho_n / (1000 \cdot \eta_{fan} \cdot \eta_m \cdot \eta_{fc}), \quad (4)$$

where $Q_n$ and $P_n$ - the nominal flow and pressure of the fan, respectively, $\eta_{fan,\ m,\ fc}$ - the efficiency factor of the fan, motor and frequency converter, respectively.

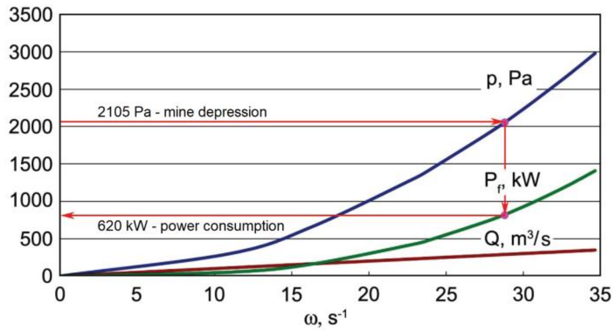


**Fig. 7.** Graphical dependencies of static pressure, flow and power on the angular velocity of the MFU.

Graphical dependences of the static pressure, supply and power on the angular velocity were constructed on the basis of data obtained as a result of simulation of two fan units. It can be seen from the graphs that the power consumption of VOD-50 fan is 800 kW, and TAF-36/21.5-1 - 620 kW to provide the required static pressure of 2105 Pa.

Taking into account that the operating time of MFU is 8760 hours/year, the approximate annual power consumption for both fans will be, kWh/year:

$$W_{vod} = P_{vod} \cdot T = 800 \cdot 8760 = 7008000,$$

$$W_{taf} = P_{taf} \cdot T = 620 \cdot 8760 = 5431200.$$

Then, power savings when using TAF-36/21.5-1 fan with VFD amount to 1576800 kWh/year. Thus, the savings from performed implementations are equal to rubles/year when converted into a monetary equivalent:

$$W = \Delta W \cdot w = 1576800 \cdot 4.95 = 7805160,$$

where $w = 4.95$ - cost of 1 kWh of power at the tariff of PJSC «Yakutskenergo», rubles.

Thus, obvious economic efficiency of the introduction of the system with frequency-controlled electric drive is observed as the result of the simulation of two systems. It reaches 7.8 million rubles a year in monetary equivalent.

## 4 Conclusion

It should be noted that the potential of energy savings amounting more than 300 million kWh/year was determined in order to introduce innovative energy-saving measures and technologies in electric grids of mining enterprises of North-Easten region of Russia.

As the result of evaluating the implementation of such measures, it was received the following:

1. Compensation of reactive power performed using mathematical simulation in MatLab software package at one site of the mining enterprise gave an economic benefit due to power savings which amounted to more than 100 thousand rubles a year.

2. Serious inconsistencies were revealed during instrumental monitoring of power quality indicators in the electric grids of the underground mine. The experimental system for continuous monitoring of power

quality indicators at an underground mine was developed. It yielded an economic benefit of more than 1 million rubles for the first year of operation that is 3 times more than the funds spent on its implementation.

3. The results of measurements of electromagnetic compatibility with the supply network of high-voltage frequency converters were analyzed. Their mathematical models were developed. The assessment was made; and the economic benefit of the introduction of frequency-controlled electric drive into the main fan unit of the underground mine was calculated. The economic benefit reached 7.8 million rubles a year in monetary equivalent.

Thus, the total multiplier economic benefit with the correct approach to the implementation and subsequent operation of innovative energy-saving measures in mining industry only at pointwise studies reached nearly 9.0 million rubles a year.

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