Assessment of the energy efficiency potential of mining enterprises

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Abstract. The paper studies the problematic issues of assessing the potential and improving the energy efficiency at mining enterprises. The necessity of developing a methodology for determining the unreasonable losses of energy resources and introducing the fast-payback options is substantiated. In order to solve this problem, a systematic approach has been used, which is based on experimental data and accounting the global economic situation. An experimental-mathematical approach is proposed for determining the main components of technologically unreasonable losses of electrical energy resources, such as the modes of transformers and pumps operation, an impact of electrical energy quality on energy consumption. The methodology was approbated at the “Mineral” mining enterprise. The proposed solutions are able to reduce energy consumption by 10% of the total with an average payback period of up to two years.

1 Introduction

The mining industry in Ukraine annually produces up to 10% of GNP (gross national product) [1]. In Ukraine, more than 70% of mining is performed in quarries [2]. The task of reducing the energy intensity of mining minerals is urgent, especially in the face of rising energy prices [3 – 5]. Further surface mining development is associated, first of all, with an increase in the depth and area of quarries, complexity of mining-geological and mining-engineering conditions, increase in the area of alienated lands [6]. At this, the energy costs share in the process of mining increases. All this comes against the background of rising prices for electrical energy in the world as a whole, and directly in Ukraine up to 40% [7, 8]. Thus, improving energy efficiency in the mining sector is an urgent task. By auditing data, the average share of costs for the energy resources at the mining enterprises of Ukraine is 40% for electrical energy, 60% for fuel. Since fuel is regulated by norms and its costs mainly depend on the characteristics of production machines and environmental conditions, the emphasis of this paper is on the reduction in electrical energy consumption.

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2 Problematic issues of implementing the energy efficiency strategy at mining enterprises

Today, the world is in the process of reducing global carbon emissions under the Paris Agreement of 2015. After signing this agreement, the companies' energy costs have increased from 10% to 20% of the total operating costs of mining enterprises [9]. According to the same source, by 2030 an increase in the costs for energy sources is expected to 40%. According to SchniderElectric data [10], when mining coal and metal ores, the potential for reducing energy use reaches 17% and 21%, respectively. According to the same data, with surface mining of iron ore, the potential is determined for reducing energy consumption in mining by 36 %. The potential for increasing energy efficiency in the mining industry as a whole is estimated at 10% of total consumption [11]. A number of countries have begun to centrally implement energy efficiency measures in the mining sector. For example, Canada [12] and Chile [13] are introducing renewable energy sources as their main power supply. However, the use of green energy sources leads to worsening the quality parameters of the electrical network, which in turn leads to a decrease in the service life of equipment and increase in electrical energy losses [14]. China [15, 16] and some African countries (for example, South Africa and Zambia) reduce electrical energy tariffs for mining companies, thereby increasing the tariffs on energy sources for other sectors of the economy, or for the population [17]. Other countries are introducing the latest technologies, characterized by unacceptable payback periods (more than 6 years) for developing economies. Thus, today there is no strategy to improve the energy efficiency of mining companies, which would not carry risks for the state or the economy. Therefore, this paper presents the approbation results of the methodology for determining the potential and improving the energy efficiency using only fast-payback options (up to three years) at the “Mineral” mining enterprise.

3 Assessment of the enterprise energy efficiency potential

For determining the potential of improving energy efficiency at the mining enterprise, the following methodology is proposed, which has successfully been approbated at the “Mineral” mining enterprise. Firstly, the analysis has been performed of the transformers’ loading for each feeder. According to data from the enterprise, maximum powers for transformer are determined from Table 1.

Based on the methodology [18], the annual active electrical energy losses from idle run and reactive electrical energy of magnetizing have been determined, which do not depend on the transformers loading (Table 2).

To reduce unreasonable technological electrical energy losses from idle run of unloaded transformers, it is proposed to optimize the circuit of power supply for consumers by reconnecting power supplies. It is proposed to transfer the equipment from the transformer to the nearest consumer. Thus, the active and reactive electrical energy losses from idle run will be reduced (the calculation was performed using the TM-25 transformer, Table 1), which is shown in Table 3.

Losses of other transformers are calculated in a similar way. It is proposed to group the least loaded of them. The expected savings are shown in Table 4.

After the transformer loading analysis, the operation mode of the most powerful consumers is analysed. Among the consumers of the studied mining enterprise, a motor 75 kW is noted, which, when washing the trains, supplies the power to the pump. With its frequency regulation, it becomes possible to control the flow not by changing the water flow, but by changing the velocity of the pump rotation. Thus, electrical energy consumption will decrease (Table 5).

Table 1. List of 0.4 kV transformers and maximum powers.

No.	Substation capacity, kVA	Equipment connected	Power, kW
1	25	Internet	0.05
2	25	Guard (post ESH No.3)	10
3	400	ERG-4, ST-2, ST-4	350
4	400	ERG-3, pump	185
5	160	pump	55
6	400	ST-3	135
7	40	Guard post C/K, lighting tower	10
8	400	Polish line	
9	400	E2503	
10	250	Central water pump station	55
11	100	Guard post	10
12	400	BR-100	
13	400	ERG-2	
14	400	ERG-2 (reserve)	
15	400	Pump, lighting tower	60
16	400	Pump	55
17	160	Pump	55
18	200	Pump, central water pump station	75
19	400	Grinding/fragmentation	–
20	400	Railroad cars washing	75
21	400	Pump	75
22	100	Winch (railroad cars movement)	22

Table 2. Annual losses of active and reactive electrical energy.

Parameter, units of measurement	Value
Total active power losses from idle run, kW	19.8
Total reactive power losses for magnetizing, kVAr	191.93
Total active electrical energy losses from idle run per year, kW·h/year	173 448
Total reactive electrical energy losses for magnetizing per year, kVAr·h/year	1 681 307

Table 3. Losses of active and reactive electrical energy using the TM-25 transformer.

Parameter, units of measurement	Value
Transformer	TM-25 (6/0.4)
Rated capacity, kVA	25
Idle run losses, W	120
Short-circuit losses, W	600
Short-circuit voltage,%	4.5
Idle run current,%	3.2
Loss of reactive power for magnetizing, kVAr	0.8
Loss of reactive power dissipation at normal transformer loading, kVAr	1.125
Transformer load factor, UOM	0
Number of transformers, pcs.	1
Reactive electrical energy losses of transformers, kVAr·h/year	7008
Active electrical energy losses of transformers, kW·h/year	1051.2
Tariff for reactive electrical energy, UAH/kVAr·h	0.0284
Tariff for active electrical energy, UAH/kW·h	2
Lost revenues caused by losses of active (idle run) and reactive (magnetizing and dissipation) electrical energy in transformers, UAH/year	2300

Table 4. Rationalization of the power-supply circuit.

Consumer group	Expected electrical energy savings, kW·h/year	Expected money savings, UAH/year
TP1 to TP2	up to 1 050	up to 2 100
TP to TP4, or TP5 or TP8	up to 1 400	up to 2 800
TP11 to TP12	up to 2 800	up to 5 600
TP19 to TP20	up to 7 000	up to 14 000
TP22 to TP21	up to 2 800	up to 5 600
TP24 to TP25	up to 7 000	up to 14 000
Total	up to 22 050	up to 44 100

Table 5. Simple payback period of frequency regulation.

Parameter, units of measurement	Value
Cost of the frequency converter, UAH [19]	148 000
Cost of electrical energy, UAH/kW·h	1.41
Average electrical energy savings,% [20]	20
Number of motor operation hours per year (at a rate of 4 hours/day), hours	1 040
Amount of saved electrical energy, kW·h/year	15 600
Motor capacity, kW	75
Cost of saved electrical energy, UAH/year	21 996
Simple payback period, years	6.7

In the works [21 – 24], it is analysed and determined that the parameters of electrical energy quality negatively influence on the energy efficiency. Therefore, to assess the level of energy efficiency at the mining enterprise, the quality parameters of electrical energy have been analysed. When measuring the parameters of the electric power line on October 17, 2016 using Metrel MI 2892, the voltage asymmetry has been recorded (measurement method is given in [14]), which is shown in Fig. 1.

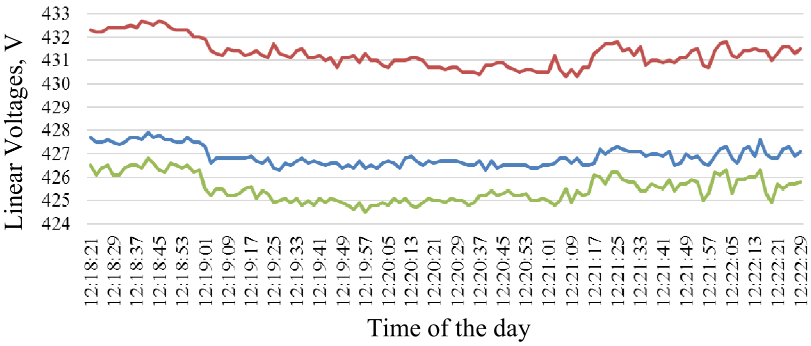

Fig. 1. Voltage asymmetry.

Based on the methodology [25], the voltage asymmetry coefficients for the zero and negative sequence have been determined. The value of the negative-sequence voltage of the fundamental frequency – $U_{2(1)i}$:

$$U_{2(1)i}=\sqrt{\frac{1}{12}\cdot\left[\left(\sqrt{3}\cdot U_{AB(1)i}-\sqrt{4\cdot U_{BC(1)i}^{2}-\left(\frac{U_{BC(1)i}^{2}-U_{CA(1)i}^{2}}{U_{AB(1)i}}+U_{AB(1)i}\right)^{2}}\right)^{2}+\left(\frac{U_{BC(1)i}^{2}-U_{CA(1)i}^{2}}{U_{AB(1)i}^{2}}\right)^{2}\right]},\quad(1)$$

where $U_{AB(1)i}$, $U_{BC(1)i}$, $U_{CA(1)i}$ are instantaneous values of the first harmonic linear voltages, V. The voltage asymmetry coefficient for the negative sequence K_{2Ui} is determined on a percentage basis as a result of the i-th observation [25]:

$$K_{2Ui}=\frac{U_{2(1)i}}{U_{1(1)i}}\cdot 100,\quad(2)$$

where $U_{2(1)i}$ is the effective value for the negative-sequence voltage of the fundamental frequency of a three-phase voltage system in the i-th observation, V; $U_{1(1)i}$ is the effective value for the positive-sequence phase voltage of the fundamental frequency in the i-th observation, V.

The average value of the voltage asymmetry coefficient for the zero sequence K_{2U} is calculated on a percentage basis as a result of averaging nine observations [25]:

$$K_{2U}=\sqrt{\frac{\sum_{i=1}^{n}K_{2Ui}^{2}}{N}},\quad(3)$$

where K_{2Ui} is voltage asymmetry coefficient for the zero sequence of the i-th observation, %; N is number of observations; i is number of the relevant observation.

The effective value for the zero-sequence voltage of the fundamental frequency U0(1)i in the i-th observation [25]:

$$U_{0(1)i}=\frac{1}{6}\sqrt{\left[\frac{U_{BC(1)i}^{2}-U_{CA(1)i}^{2}}{U_{AB(1)i}}-3\cdot\frac{U_{B(1)i}^{2}-U_{A(1)i}^{2}}{U_{AB(1)i}}\right]^{2}+\left(\sqrt{4\cdot U_{BC(1)i}^{2}-\left(U_{AB(1)i}-\frac{U_{BC(1)i}^{2}-U_{CA(1)i}^{2}}{U_{AB(1)i}}\right)^{2}}-\right.}$$
$$\overline{\left.-3\cdot\sqrt{4\cdot U_{B(1)i}^{2}-\left(U_{AB(1)i}-\frac{U_{B(1)i}^{2}-U_{A(1)i}^{2}}{U_{AB(1)i}}\right)^{2}}\right)^{2}},\quad(4)$$

where $U_{AB(1)i}$, $U_{BC(1)i}$, $U_{CA(1)i}$ are instantaneous values of the first harmonic linear voltages, V; U_A, U_B are values of instantaneous phase voltages, V.

The voltage asymmetry coefficient K_{0Ui} for the zero sequence is determined on a percentage basis as a result of the i-th observation [25]:

$$K_{0Ui}=\frac{\sqrt{3}\cdot U_{0(1)i}}{U_{1(1)i}}\cdot 100,\quad(5)$$

where $U_{0(1)i}$ is the effective value for the zero-sequence voltage of the fundamental frequency of the three-phase voltage system in the *i*-th observation, V; $U_{1(1)i}$ is the effective phase voltage value for the positive sequence of the fundamental frequency in the *i*-th observation, V.

The average value of the voltage asymmetry coefficient for the zero sequence K_{0U} is calculated on a percentage basis as a result of averaging nine observations K_{0Ui} [25]:

$$K_{0U} = \sqrt{\frac{\sum_{i=1}^{n} K_{0Ui}^2}{N}}, \tag{6}$$

where K_{0Ui} is voltage asymmetry coefficient for the zero sequence of the *i*-th observation, %; *N* – number of observations; *i* is the number of the relevant observation.

The effective voltage asymmetry coefficients for the negative and zero sequences are summarized in Table 6.

Table 6. Voltage asymmetry coefficients.

Parameter, units of measurement	Value
Voltage asymmetry coefficient for the negative sequence, %	2.9
Voltage asymmetry coefficient for the zero sequence, %	3.9

With a voltage asymmetry of 2%, the induction motors service life is reduced by 10.8%, synchronous – by 16.2% [26]. The equipment is heated as a result of additional electrical energy consumption, which reduces the efficiency factor of electrical installations. With a voltage asymmetry of 4%, the service life of induction motors is reduced by 50% [26]. According to the approved method [27], the electrical energy losses are determined, caused by asymmetry in transformers (Table 7) and in induction motors (Table 8).

Table 7. Electrical energy losses caused by asymmetry in transformers.

Parameter, units of measurement	Value				
Source data					
Transformer [28]	TM-400	TM-160	TM-250	TLC-200	TM-100
Rated capacity, kVA	400	160	250	200	100
Idle run losses, kW	0.83	0.46	0.65	0.59	0.32
Short-circuit losses, kW	5.5	2.65	3.1	3.6	1.97
Short-circuit voltage,%	4.5	4.7	4.5	6	4.5
Calculation					
Power of additional losses from asymmetry, kW [27]	2.26	0.99	1.27	0.83	0.80
Amount of transformer operation hours per year, h	8 760				
Transformer electrical energy losses caused by asymmetry per year, kW·h	19 797	8 727	11 137	7 276	7 076
Transformers electrical energy losses (20 TM-400, 2 TM-160, 1 TM-250, 1 TLC-200, 2 TM-100) caused by asymmetry per year, kW·h	395 952	17 454	11 137	7 276	14 154
The cost of electrical energy losses by 20 TM-400 transformers caused by asymmetry per year, UAH/year	791 904	34 908	22 247	14 552	28 308

Table 8. Transformer electrical energy losses caused by asymmetry in motors.

Parameter, units of measurement	Value
Source data	
Total motor capacity, kW	522
Induction motor coefficient, UOM [27]	2.91
Calculation	
Power of additional losses in motors caused by asymmetry, kW	3.039
Amount of motors operation hours per year, hours	8 760
Electrical energy losses in motors caused by asymmetry per year, kW·h/year	26 622
Cost of lost electrical energy in motors caused by asymmetry per year, UAH/year	53 244

To compensate for these losses caused by asymmetry, it is proposed to set phase-balancing installations (phase stabilizers). The simple payback period is summarized in Table 9.

Table 9. Simple payback period of phase stabilizers.

20 VPS-400-λ ± 2.5%-380, 2 VPS-160-λ ± 2.5%-380, 2 VPS-250-λ ± 2.5%-380, 2 VPS-100-λ ± 2.5%-380 [29]	
Idle run power (depending on configuration), kW	0.1
Electrical energy consumed by 26 stabilizers per year, kW·h/year	22 776
Cost of 26 stabilizers, UAH	2 551 642
Cost of losses caused by asymmetry per year, UAH/year	891 919
Cost of electrical energy, UAH/kW·h	2
Amount of saved electrical energy, kW·h/year	449 819
Cost of saved electrical energy, UAH/year	899 638
Payback period of 26 stabilizers, years	2.83
The service life of equipment will be further increased by 40%	

According to [30], energy resources losses during pump equipment operation can be reduced to technologically reasonable by determining the rational mode of the pump operation. When measuring on October 18, 2016, with the use of the ACTACOM AFM 3192 power analyser of the indicators of electrical energy consumed by drainage pumps, it has been determined that the pumps working capacity is about 29 kW. Due to the lack of passport data and labels, it has been determined through a visual inspection that the pump capacity should be about 55 kW, the pump type – cantilever. According to the working capacity and characteristics of the pump [31], the operating point of the drainage system has been determined (Fig. 2).

The operating point is determined: productivity Q – 52 m^3/h; pressure H – 98 m. According to the graph in Fig. 4, it has been found that the pump operates with reduced efficiency factor (46%). Therefore, according to the determined operating point, it is proposed to replace the pump with KSB Etanorm 060 – 050 – 250 [32] with motor working capacity of 20 kW and an operating point of Q – 52 m^3/h, H – 96 m (Fig. 3).

The simple payback period when replacing 2 pumps is calculated in Table 10.

Table 10. Simple payback period for pumps replacement.

Parameter, units of measurement	Value
The cost of KSB Etanorm 060 – 050 – 250 [33], thousand UAH	268
Amount of annually saved electrical energy of 2 pumps operation during 24 h/day; 5 days/week, 30 weeks/year, kW·h/year	64 800
Cost of saved electrical energy per year, UAH/year	129 600
Simple payback period for pump replacement, years	2

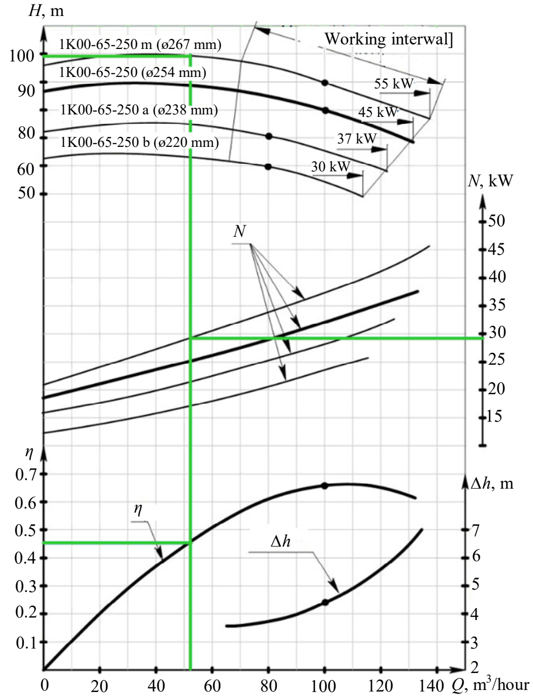

Fig. 2. Determining the operating point of the drainage pump.

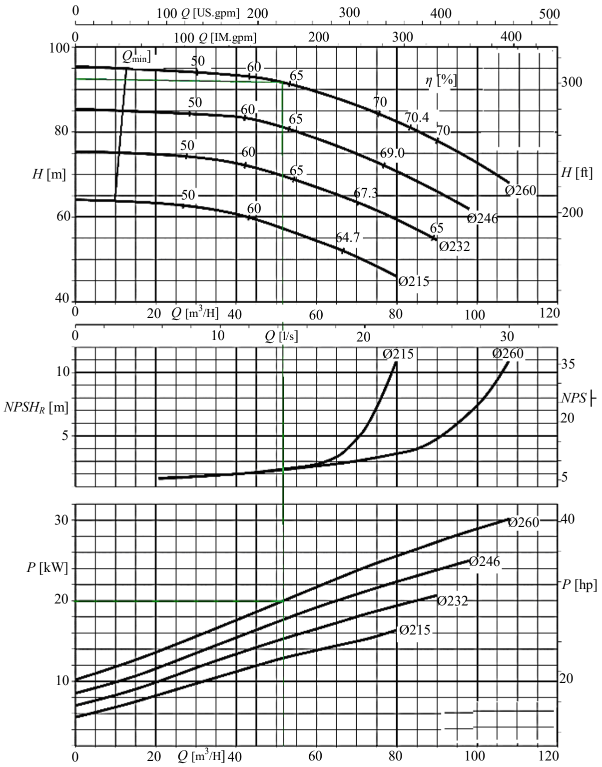

Fig. 3. Selecting the pump based on the operating point.

Thus, the saved electrical energy during pumps operation (24 hours/day; 5 days week, 30 weeks per year) will be 64 800 kW·h/year.

4 Conclusions

The methodology for determining the potential and improving the energy efficiency, using the example of the "Mineral" mining enterprise, is proposed and approbated in the study. The methodology includes analysis of loading the transformers, electrical energy quality parameters and pumps operation mode. This equipment is used in any processes of minerals mining, so the technique is repetitive. When performing the study, the following measuring equipment is used:

– Actacom AFM 3192 power analyser for determining the load of pump and transformer equipment;

– Metrel MI 2892, electrical energy quality analyser for measuring electrical energy quality parameters.

As a result, the potential has been determined for resource savings of up to 1031 MW·h/year, or up to UAH 2 million/year (at a tariff of UAH 2/kW·h), which is 10.1% of the total electrical energy consumed by the company. At the same time, the total cost of the proposed solutions does not exceed UAH 3.5 million, that is the average payback period for the company will not exceed 2 years.

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