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 SchneiderElectric 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    |           |
| 16  | 400                      | Pump                    |           |
| 17  | 160                      | Pump                    |           |
| 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.

| Transformer, 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 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 2 800                                  | up to 5 600                     |
| TP19 to TP20 up to 7 000        | up to 7 000                                  | up to 14 000                    |
| TP22 to TP21 up to 2 800        | up to 2 800                                  | up to 5 600                     |
| TP24 to TP25 up to 7 000        | 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.](image)

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 – $U_{2(1)_k}$:
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]:

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

where $K_{2U_i}$ 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]:

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

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 $K_{0U_i}$ for the zero sequence is determined on a percentage basis as a result of the $i$-th observation [25]:

$$K_{0U_i} = \frac{\sqrt{3 \cdot U_{0(1)i}}}{U_{4i}} \cdot 100, \quad (5)$$
where $U_{0(i)}$ 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 $K_{0Ui}[25]$: 

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

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  | 3.039       |
| asymmetry, kW                                   |             |
| Amount of motors operation hours per year, hours| 8 760       |
| Electrical energy losses in motors caused by    | 26 622      |
| asymmetry per year, kW·h/year                   |             |
| Cost of lost electrical energy in motors caused | 53 244      |
| by asymmetry per year, UAH/year                 |             |

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.

| Parameter                                      | Value       |
|------------------------------------------------|-------------|
| 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 \( Q = 52 \, \text{m}^3/\text{h} \); pressure \( H = 98 \, \text{m} \). 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 \( Q = 52 \, \text{m}^3/\text{h} \), \( H = 96 \, \text{m} \) (Fig. 3).

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

Table 10. Simple payback period for pumps replacement.

| Parameter                                      | 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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