DOI: https://doi.org/10.15276/hait.04.2022.4
UDC 621.313-57

Modeling tools for improving energy efficiency of water drainage complexes at iron ore underground mines

Ihor O. Sinchuk[1)]
ORCID: https://orcid.org/0000-0002-7702-4030; olegovich.s@knu.edu.ua. Scopus Author ID: 55327932300
Albert B. Somochkyn[1)]
ORCID: https://orcid.org/0000-0002-3592-7899; a.syomochkyn@knu.edu.ua. Scopus Author ID: 57194694864
Kyrylo V. Budnikov[1)]
ORCID: https://orcid.org/55327932300; budnikov.kirill@icloud.com; Scopus Author ID: 57450131100
Svitlana V. Somochkyna[1)]
ORCID: https://orcid.org/ 0000-0001-9809-0048; somochkyna@knu.edu.ua
Vladyslav D. Baranovskyi[1)]
ORCID: https://orcid.org/0000-0002-0438-262X; vladislav.baranovskiy4@gmail.com
Oleksandr V. Danilin[2)]
ORCID: https://orcid.org/0000-0003-3207-1156; avdan@ukr.net. Scopus Author: ID 57202128990
[1)] Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine
[2)] National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, 37, Peremohy Ave. Kyiv, 03056, Ukraine

ABSTRACT

The natural presence of water in underground mining processes creates significant difficulties and requires constant water drainage, i.e. pumping water to the day surface into special reservoirs. The so-called main drainage complexes are used for performing these operations. Mine water drainage is an energy-consuming process. Therefore, the need to reduce energy intensity of water drainage complexes is a relevant task, which is so far unsolved to a level that is fully adequate. To solve the above-mentioned problem on a systemic basis, it is of primary importance to assess tools of improving energy efficiency of water drainage complexes according to their efficiency levels. It is vital for further formatting the scientific search for options that possess sufficient efficiency. For such technology-intensive types of consumers as underground mines, modeling of power consumption is an effective and affordable method of obtaining preventive results, which are close to real-life conditions. Of course, the level of adequacy of the modeling results obtained depends on compliance of input parameters of a model with real values. Such a model of the electric power system as a complex of groundwater drainage to the day surface can be used as a supporting option for modeling in order to get the required results for both developing energy-efficient control measures for drive electromechanical complexes and designing an effective structure of the entire drainage complex. It is in this perspective that the research methodology is built, the results of which are outlined in the article. Modeling the levels of efficiency in the use of some modern trends in improving the operation of drainage complexes of iron ore underground production made it possible to rank them according to the levels of implementation, starting with the use of controlled electric drives and ending with the optimization of their operating modes.

Keywords: Modeling; energy efficiency; iron ore underground mine; water drainage complexes

For citation*: Sinchuk I. O., Somochkyn A. B., Budnikov K.V., Somochkyna S. V., Baranovskyi V. D., Danilin O. V. Modeling tools of improving energy efficiency of water drainage complexes at iron ore underground mines.** ***Herald of Advanced Information Technology. **2022; Vol. 5 No.1: 40–51. DOI: https://doi.org/10.15276/hait.05.2022.4**

1. INTRODUCTION

Iron ore enterprises, with both underground (underground mines) and open pit (open pits, concentration plants) mining methods, belong to energy-intensive types of production [1, 2]. In this respect, energy intensity is associated with a limited type of power receivers, among which water drainage complexes are distinguished by their consumption volumes (Fig. 1).

Known and interesting scientific publications in the analyzed problem [3, 4], [5, 6], [7, 8], [9, 10], [11, 12] do not sufficiently highlight efficiency indices in general including those for water drainage complexes in particular resulted from introduction of various energy-saving measures. This constrains appropriate decisions on development of the expected engineering options aimed at improving efficiency of water drainage complexes.

In terms of energy consumption, engineering and economic indices of water drainage complexes provide for two ways to improve them:

– by either using more advanced equipment to reduce power consumption per unit of production (drainage of 1 m^3 of water);

– improving efficiency of available equipment.

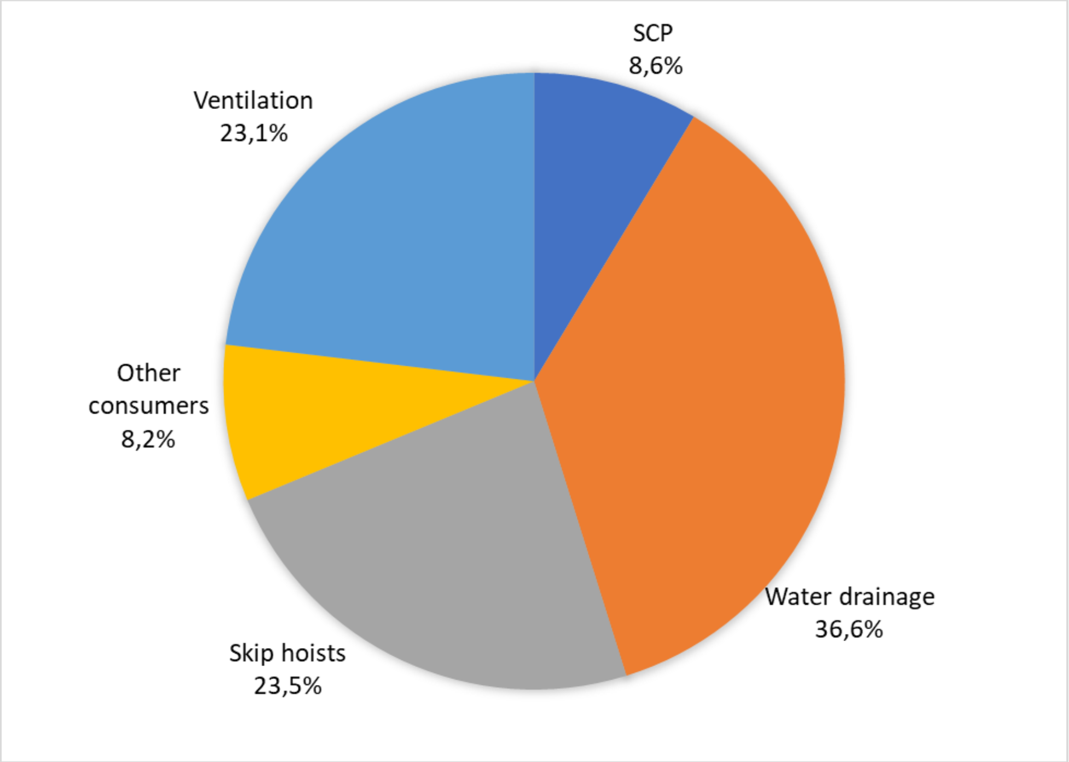


Fig. 1. **Averaged levels of power consumption by energy-intensive consumers of a typical iron ore underground mine**
Source: **compiled by the authors**

The research aims to analyze, assess and develop some basic recommendations for subsequent logistics solutions for designing relevant technical and technological solutions to improve efficiency of water drainage complexes at iron ore underground mines.

According to the given research aim, the following scientific tasks are formed:

– developing a research model to assess energy efficiency of electromechanical systems of main water drainage complexes by using frequency inverters of power supply for drive motors of pumps;

– developing methods and conducting a research into energy efficiency of mine water drainage complexes when using power storage units and optimizing operation modes of pumping facilities during the day, according to corresponding hourly tariffs for consumed power.

2. RESEARCH MATERIALS

Mine water drainage pumps have a low and, more importantly, non-linear efficiency. Induction drive motors of pumps also have a non-linear efficiency, depending on the load on their shafts. Technological parameters of the water drainage complex, which a hydraulic system, are also ambiguous. As a rule, six-seven pumps are installed at underground levels of national iron ore underground mines (segments of water drainage complexes). At least two-three pumps are in operation simultaneously. Besides, two or three parallel strings of pipelines (pump columns) connect sections of water drainage complexes on different levels. Application of different numbers of pumps for different numbers of parallel pipelines (which is a consequence of different values of hydraulic resistance) causes different operation modes of the hydraulic system, including energy inefficient ones. By controlling operating modes (i.e. switching the number of operating pumps in parallel to the parallel number of different pipelines) can provide energy savings.

This can mainly be achieved by bringing operating points of efficiency of drive motors and pumps to their nominal parameters as close as possible.

Computer modelling enables verification of this idea and possible ways of its implementation. Fig. 2 shows a functional diagram (known from previous articles by the author [4, 5]) of pumping stations of water drainage complexes at Rodina and Pravda underground mines (Kryvyi Rih), which is typical of iron-ore mining enterprises.

The diagram shows that the last stage of water drainage (from the 500 m level to the surface) can be carried out by three 325 mm pump columns (pipelines) from the level pumping station, which includes seven pumps: four pumps of the CPS (central pumping station) 300-600 type and three of the CPS 350-540 type. Specifications of these pumps are very close, so in order to simplify calculations without visible error, we will further apply characteristics of type 300-600 pumps (Fig. 3) [14]. The given station pumps water from three water reservoirs (tanks) with a total capacity of 9000 m^3.

According to Fig. 3, characteristics of the CPS pumps are approximated by the following expressions:

– for consumed active power:

$$N = 943.147 - 11075.4 \cdot Q + 97446.24 \cdot Q^2 ;$$

– for water performance:

$$H = 610.7143 + 2764.296 \cdot Q - 34719.84 \cdot Q^2 ;$$

– for efficiency:

$$\eta = -22.857 + 2142 \cdot Q - 12337 \cdot Q^2 .$$

where: Q is measured in m^3/s; η is measured in %.

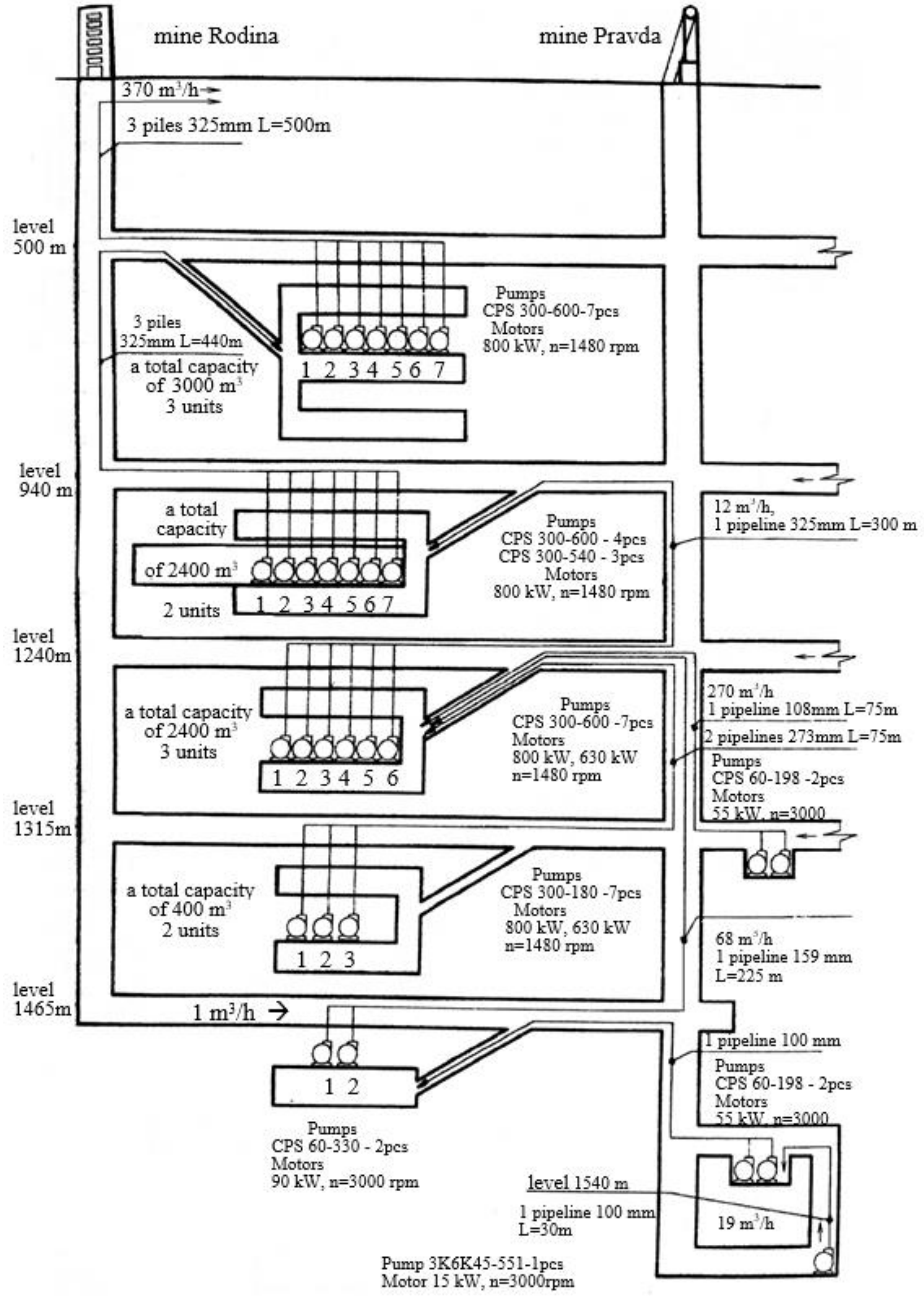


Fig. 2. **Pumping stations at Rodina and Pravda iron ore underground mines (Kryvyi Rih)**

Source: **compiled by [4, 5]**

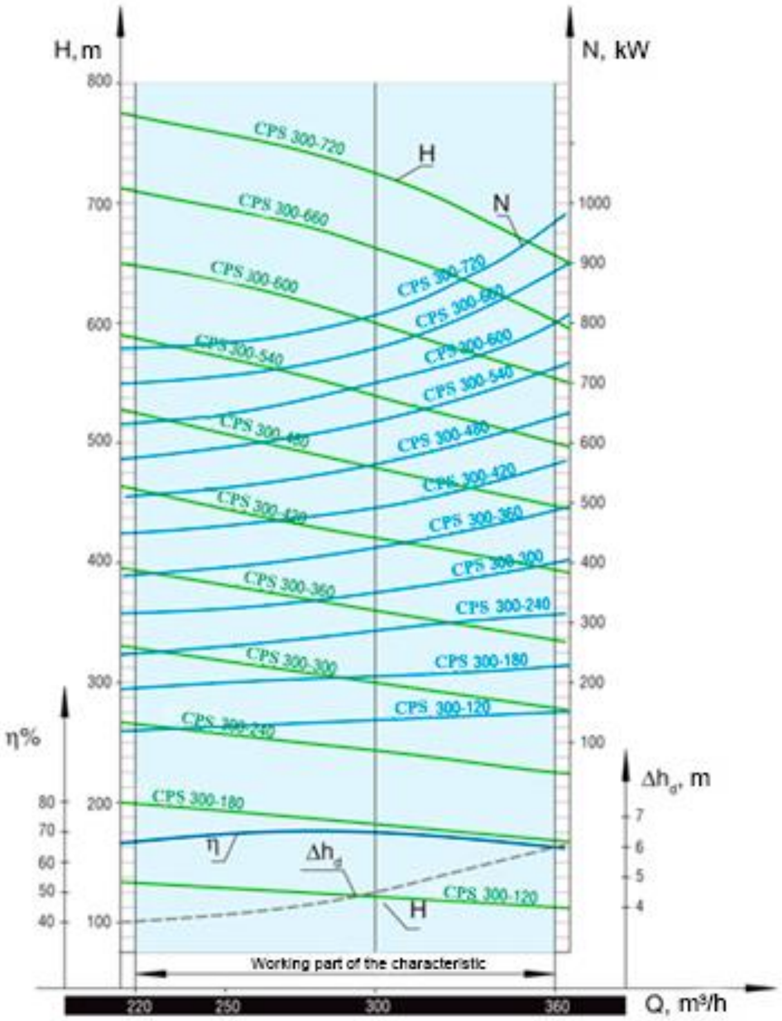


Fig. 3. **Characteristics of CPS pumps**

***Source:* [14]**

When controlling the speed of pump wheels, laws of similarity are in force:

$$\frac{Q_1}{Q_r}=\frac{\omega_1}{\omega_r},\ \frac{H_1}{H_r}=\left(\frac{\omega_1}{\omega_r}\right)^2,$$

$$\frac{N_1}{N_r}=\left(\frac{\omega_1}{\omega_r}\right)^3.$$

where ω_1 and ω_r are the optional and rated angular velocities of electric drive motor, respectively.

The MATLAB technical documentation states that the pump models reflect these laws of similarity.

The actual total volume of water drained to the surface from the 500 m level finally makes 476 m^3/h [4]. The theoretical value of 370 m^3/h consists of the natural water inflow of all levels below the 1240 m level (the total inflow is 358 m^3/h) and the natural inflow on the 940 m level, which is 12 m^3/h (Fig. 2). It is assumed that there is no natural inflow on the 500 m level, and its water reservoir is used in the same way as on other intermediate levels for water drainage. Since the maximum water is collected on the 1240 m level and then transported up in almost constant quantities, we accept that 476 m^3/h is the flow rate of water collected in the 1240 m level reservoir (tank).

3. ASSESSING EFFICIENCY IMPROVEMENTS WITH FREQUENCY INVERTERS

It is known that for any hydraulic system, adequate operation of pumps is important. Despite the fact that pumps can theoretically operate within a fairly wide range of capacity, the permissible level of their effective operation is significantly narrowed to certain limits specified by the manufacturer. For example, for CPS pumps, this range makes 220-360 m^3/h. To verify operation modes of pumps of the final 500 m level, a diagram is developed in MATLAB. Despite seven pumps available (Fig. 2), only three are in simultaneous operation. Fig. 4 presents a model developed by the authors to study operation modes of the 500 m level pumping station.

The hydraulic system of the 500 m level includes intermediate **Tank1** of the 500 m level, **Pump station 500 m**, **Pipes 1-3** (pipe columns), which are strictly vertical in the settings, with ports **A** located at 0 m and ports **B** - at 500 m; and the upper **Tank 2**. The pressure sensor **GP1** is connected in parallel to **Pipes 1-3**, and the flow sensor **QT4** is included in the split between the **Pump station 500 m** and **Pipes 1-3** columns. The water sensor (**Volume T1** and **Volume T2**) is connected to each of the reservoirs (tanks). The measurement ports of flow sensors **V_S1** and **V_S2** provide information about the water volume (**Volume m^3**) in **Tank1** and **Tank2**, which is visualized on the oscilloscope and digital meters. From the measurement ports of flow sensors **QT1-QT4** (where **QT4** designates the sensor itself and **QT4** is designates a measurement port of this sensor) comes the information on the flow rates of each of the three pumps individually and the total flow rate (**Flow m^3/s**) at the pumping station. Then, from left to right, **Pressure** (Pa) taken from the sensor **GP1** in the columns is visualized as well as the total effective **Power (W)** of the pumping station, which is proportional to the product of the pressure decrease in the columns and the total water flow rate of the pumping station. Blocks **Kpch1-Kpch3** (above the pumping station in Fig. 4) set output voltage frequencies of the conditional frequency inverters within the range 0-1 for each pump, which together with the motor is not really present in the model, their action is shown by the pump wheel rotation speed. The model calculates and visualizes the net power, efficiency and active power consumption for each pump separately. In the **Water Properties** Block, the properties of the pumped water are set (density, viscosity, temperature, etc. taken by default), and in Block **f(x)=0**, calculation parameters of the process are set (integration method, step, etc.).

The model (Fig. 4) presents the pump station in the option shown in Fig. 5.

This model features three separate pump lines that are identical to each other. Each of these lines contains a pump (**Pump 1 - Pump 3**), to which short 325 mm sections of pipelines (10.1 m on the left and 8 m on the right) are connected (all dimensions are arbitrary). The arrangement of pipelines is horizontal. In each line, one **Check Valve 1-3** and one **QT1-QT3** flow sensor are inserted into the interstices. **Tank1** and **Tank2** are connected by pipes into a communicating system and when the pumps stop, water flows down from the upper **Tank2** intake to the lower **Tank1**, that is not really happening in underground mine levels. Therefore, for the 500 m level pumping station model to operate properly, some check valves are introduced. To influence the rotation speed of pump wheels, **Speed Pump 1-3** blocks are formed and connected directly to the pump wheels through intermediate **Velocity Source Pump 1-3** blocks. The **Speed Pump** blocks generate the current pump speed by multiplying the relative frequency **Kpch** by the rated speed of the induction motor at the rated supply frequency of 50 Hz (1470 rpm). The settings window of the centrifugal CPS pump is given below (Fig. 6).

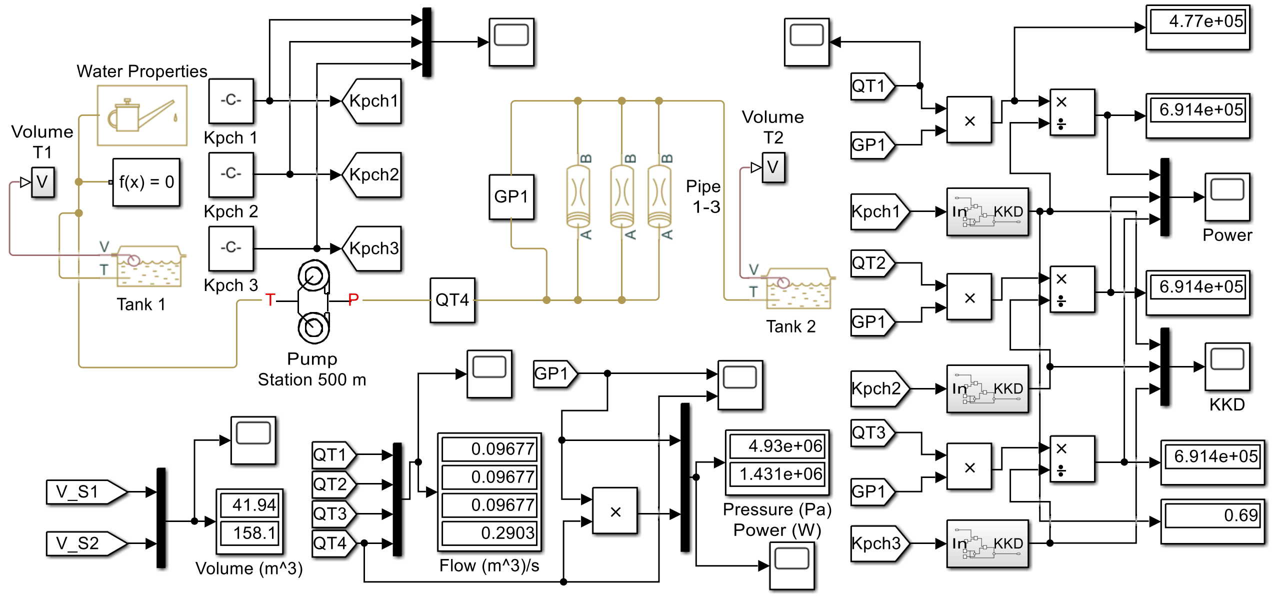


Fig. 4. **Model to study operation modes of the 500 m level pumping station**

Source: **compiled by the authors**

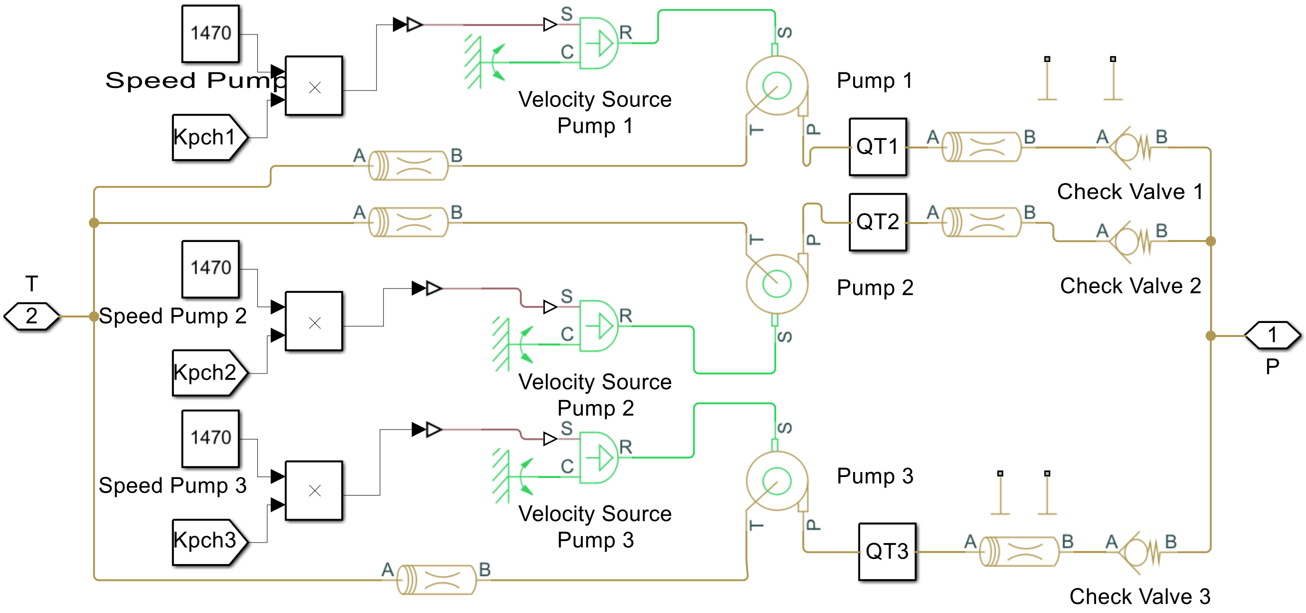
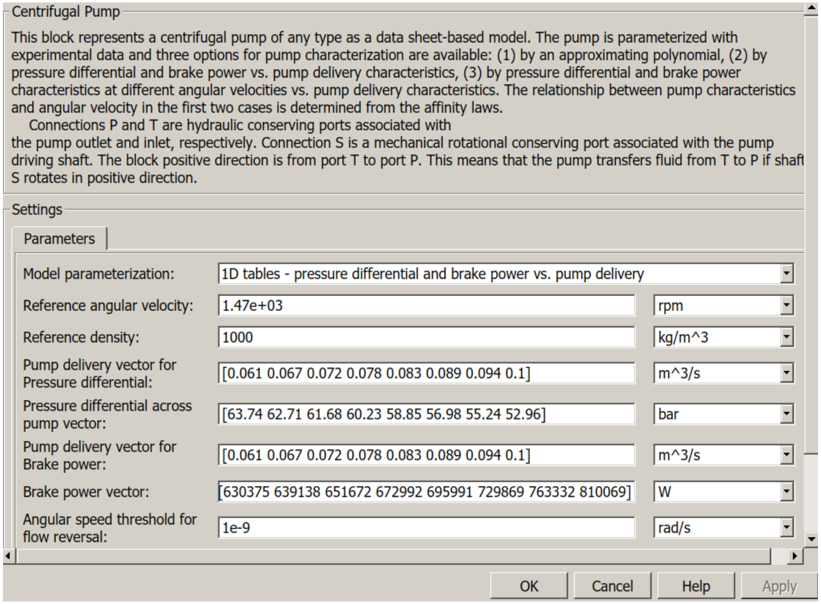


Fig. 5. **Model of the pump station of the 500 m level in MATLAB**
Source: **compiled by the authors**



Centrifugal Pump

This block represents a centrifugal pump of any type as a data sheet-based model. The pump is parameterized with experimental data and three options for pump characterization are available: (1) by an approximating polynomial, (2) by pressure differential and brake power vs. pump delivery characteristics, (3) by pressure differential and brake power characteristics at different angular velocities vs. pump delivery characteristics. The relationship between pump characteristics and angular velocity in the first two cases is determined from the affinity laws.

Connections P and T are hydraulic conserving ports associated with the pump outlet and inlet, respectively. Connection S is a mechanical rotational conserving port associated with the pump driving shaft. The block positive direction is from port T to port P. This means that the pump transfers fluid from T to P if shaft S rotates in positive direction.

Settings

Parameters

Model parameterization:	1D tables - pressure differential and brake power vs. pump delivery	
Reference angular velocity:	1.47e+03	rpm
Reference density:	1000	kg/m^3
Pump delivery vector for Pressure differential:	[0.061 0.067 0.072 0.078 0.083 0.089 0.094 0.1]	m^3/s
Pressure differential across pump vector:	[63.74 62.71 61.68 60.23 58.85 56.98 55.24 52.96]	bar
Pump delivery vector for Brake power:	[0.061 0.067 0.072 0.078 0.083 0.089 0.094 0.1]	m^3/s
Brake power vector:	[630375 639138 651672 672992 695991 729869 763332 810069]	W
Angular speed threshold for flow reversal:	1e-9	rad/s

Fig. 6. **Settings window for the centrifugal CPS pump**
Source: **compiled by the authors**

The initial speed of the loaded pump is set in **Reference angular velocity**, the density of the pumped water – in **Reference density**. The lines **Pump delivery vector for Pressure differential** and **Pressure differential across pump vector** represent the dependence of pump performance on the pressure developed by that pump, arranged as two vectors. The following two lines represent the dependence of the **Pump delivery vector for Brake Power** on the **Brake Power vector**. All of the above vectors are formed according to the specifications of CPS pumps in Fig. 3.

The modelling considers that the hydraulic system is completely balanced, all pumps operate within the permissible range of 0.061-0.1 m^3/s.

Let us check this assumption by modelling (Fig. 4) and studying modes of all three pumps operating in parallel on all three pump columns (500 m high and 325 mm wide). The modelling provides the following results: the total pump delivery flow of all three pumps makes 0.291 m^3/s, that of a single pump – 0.097 m^3/s [3]. This means that each pump of the pumping station operates in the permissible mode, power consumption of the pump making 691 kW.

Similar calculations are performed for the 940 m intermediate pumping station with three CPS-300/540 pumps for pumping water from this level into the 500 m reservoir through three parallel pump columns (325 mm wide and 440 m long). The model similar to that in Fig. 4 (but designated for parameters of other pumps and other water pumping heights) enables establishing that each pump's delivery flow is 0.088 m^3/s at power consumption of 550 kW. Similarly, for the 1240 m level pumping station with CPS pumps and 300 m long columns, by means of the model in Fig. 4, we obtain the delivery flow of 0.087 m^3/s with power consumption of 371 kW of the induction motor.

The information obtained is summarized in Table 1, which also includes the calculation results of 940 m and 1240 m level pumping stations.

Table 1. **Parameters of the current operation mode of single water drainage pumps for underground mine levels**

Level	500 m	940 m	1240 m
Maximum permissible rated capacity of pumps, m^3/s	0.1	0.1	0.1
Current capacity, m^3/s	0.097	0.088	0.087
Power consumption of the IM, kW	691	550	371

Source: **compiled by the authors**

To adjust the operation mode of the hydraulic system so that all pumps operate at maximum efficiency and the nominal flow rate of 0.083 m3/s, we use frequency control of the drive motors from frequency inverters. In practice, to bring the pump into nominal mode, the missing hydraulic resistance is adjusted by closing valves incompletely. This method is rather energy-consuming [14].

For 500 m level pumps, we set the IM rotation speed equal to 0.967 of the nominal (real operation mode) one, and obatain the nominal flow of each pump 0.083 m^3/s. At that, the power consumed by the IM is 598 kW, which is less than the initial one (691 kW).

If we reduce water delivery by using a frequency inverter to supply the drive motors to an extremely low level of 0.061 m^3/s, the power savings will increase significantly:

$$\Delta P = (691-442) = 249 \text{ kW}.$$

Thus, if one uses the frequency inverter to adjust the delivery flow so that all the pumps provide the minimum permissible rated capacity of 0.061 m^3/s, some other values of power consumption can be obtained using the Moody formula for assessing efficiency of pumps [4]:

$$\eta_1 = 1 - \frac{1-\eta_r}{\left(\dfrac{\omega_1}{\omega_r}\right)^{0.36}}.$$

To obtain power consumption of induction drive motors, the net H·Q capacity, which is automatically determined in the model (Fig. 4), is divided by the calculated efficiency value.

The parameters for the three levels are calculated more precisely. The model adequately calculates pump heads and capacities because, for the 500 m level example, the pump water height stops at ω_1/ω_2=0.86 because the pump head falls below the pressure of the still water in columns. Angular velocity ratio ω_1/ω_2 = 0.927 gives a minimum allowable flow rate of 0.061.

Thus, at the capacity of 0.061 m^3/s, we obtain the figures given in Table 2.

Table 2. **Operation parameters of the electromechanical complex of water drainage facilities for**

Level	500 m	940 m	1240 m
Maximum permissible rated capacity, m^3/s	0.061	0.061	0.061
Ratio of angular velocities ω_1/ω_r	0.927	0.921	0.945
Net capacity H·Q, kW	301	264	179
Efficiency, r.u.	0.6814	0.6807	0.945
Power consumption of IM with reduced angular velocity, kW	442	388	261
Difference in power consumption, kW	249	162	91

Source: **compiled by the authors**

The total expected savings in the level of power consumption is

$$249 + 162 + 91 = 502 \text{ kW}.$$

This rather noticeable economic effect can be achieved only by reducing the rotation speed of pumps by an average of 7 %.

4. EFFICIENCY ASSESSMENT CONSIDERING THE FLOATING POWER TARIFF

Let us consider a possibility of increasing economic efficiency of drainage pumps at iron ore underground mines through differentiating hourly power tariffs, grouping them with an acceptable error level on the “day-night” basis. As is known, in 2021, the night tariff (11pm-7am) averaged 1 ÷ 1.2 UAH/kWh, for the rest of the day making 1.9 ÷ 2.1 UAH/kWh. Since each of the levels has its own intermediate reservoirs of significant capacity (9000 m^3, 4800 m^3 and 4800 m^3 for 500 m, 940 m and 1240 m levels respectively), it is quite reasonable is to use these reservoirs for water storage and further pumping considering the difference in power costs during the relevant hours of the day. It is recommended to switch off as many water pumps as possible at daytime (in accordance with safety requirements) when power is expensive and use the maximum number of pumps at night-time, which is economical.

Let us assess pump storage potentials of level reservoirs. With the 4800 m^3 capacity and the water flow of 476 m^3/h, the first reservoir is filled during 4800/476 ≈ 10 hours without pumping. It follows that it is impossible to do without pumps when daytime power tariffs are in action. If one pump is switched on the 1240 m level with the minimum delivery flow (0.061 m^3/s), the water reservoir will theoretically be filled within

4800/(476-220) = 4800/256 = 18.75 (≈ 18 hours).

At this moment, according to the CPS 300-360 pump specification, the active power consumed by the motor at the 0.061 m^3/s capacity is 261 kW. When the daytime tariff (11pm) terminates, the 940 m reservoir will be filled within 16 hours · 256 m^3/h = 4096 m^3.

So, with the start of the night hourly tariff and until its termination (11pm-7am) 4096 m^3 of water should be pumped. To do this, you will have to switch on extra pumps on the 940 and 500 m levels to ensure full staged water drainage during the 8-hour night tariff. Let us calculate the number of pumps required for this purpose and the relevant delivery flow. The required total delivery flow is 4096 / 8 h = 512 m^3/h. It is evident that two pumps working in parallel are required with the capacity 512/2 = 256 m^3/h ≈ 260 m^3/h. The calculated power consumption of all the pumps at the 260 m^3/h pump capacity is given in Table 3.

Table 3. **Operation parameters of the level pumps at 260 m^3/h flow rated**

Level	500 m	940 m	1240 m
Ratio of flows ω_1/ω_r	0.948	0.938	0.974
Net capacity H·Q, kW	363	311	213
Efficiency, r.u.	0.684	0.6828	0.687
Power consumption of IMs with reduced flow, kW	533	455	310

Source: **compiled by the authors**

The total night-time power consumption per day is:

2 · (533 + 455+ 310) kW · 8 h = 20768 kW.

The power cost is the following:

$$C_1 = 261 \text{ kW} \cdot 16 \text{ h} \cdot 2 \text{ UAH/ kW} \cdot \text{h} + 20768 \cdot 1.1 \text{ UAH/kW} \cdot \text{h} = 31197 \text{ UAH/day}$$

or 11.38 mil UAH/year.

Thus, six pumps are supplied from the power grid for 8 night hours with the 260 m^3/h capacity, and one pump for 16 daytime hours with the 220 m^3/h capacities. Let us compare this option with the original one without frequency inverters applied. In that option, the maximum number of pumps is naturally applied at night, and during the day only if necessary and in accordance with safety requirements. For example, at 7pm the reservoirs of all the levels are empty. At the natural inflow of 476 m^3/h, the reservoir of the 1240 m level is filled in 4800/476 = 10.08 hours, i.e. at 5pm pumps should be switched on. On the 1240 m level, a single pump is similarly switched on, yet with the designed delivery flow of 0.1014 m^3/s and with the IM power consumption of 371 kW/h.

Let us solve the equation to define the pump operation duration and prevent the 1240 m level overflow before nightfall:

476 m^3/h · 16 h -365 · t = 4800 m^3, whence t = 7.7 ≈ 8 hours.

Thus, in the previous option, the 1240 m pump will have to run for 8 hours with motor power consumption of 371 kW. At night-time, all the water should be completely pumped to the surface.

Actual performance of the pumps calculated earlier should be considered as a fact: 1240 m level – 0.087 m^3/s at the capacity of 371 kW·h; 940 m level – 0.088 m^3/s at capacity of 550 kW·h; 500 m level – 0.097 m^3/s at capacity of 691 kW·h. As all the reservoirs should be emptied, as in the previous case, it is necessary to switch at least two pumps on each level. With that, only due to increased performance, they drain the reservoirs faster.

Thus, the lower reservoir of the 1240 m level is drained within:

$$t_1 = 4800 / (2 \cdot 0.087 \text{ m}^3/\text{s} \cdot 3600 \text{ s}) = 7.66 \text{ hours.}$$

The reservoir of the 940 m level is drained within:

$$t_2 = 4800 / (2 \cdot 0.088 \text{ m}^3/\text{s} \cdot 3600 \text{ s}) = 7.58 \text{ hours.}$$

The reservoir of the 500 m level is drained within:

$$t_3 = 4800 / (2 \cdot 0.097 \text{ m}^3/\text{s} \cdot 3600 \text{ s}) = 6.87 \text{ hours.}$$

As is seen all six pumps will have time to pump all the water during the night. Let us calculate power consumption in the original option:

$$C_2 = 371 \text{ kW} \cdot 8 \text{ h} \cdot 2 \text{ UAH/kW} \cdot \text{h} + (2 \cdot 371 \text{ kW} \cdot 7.66 \text{ h} + 2 \cdot 550 \text{ kW} \cdot 7.58 \text{ h} + 2 \cdot 691 \text{ kW} \cdot 6.87 \text{ h}) \cdot 1.1 \text{ UAH/kW} \cdot \text{h} = 31804 \text{ UAH/day}$$

or 11.6 mil UAH/year.

Both compared options - the original one and the delivery-control one are given in Table 4.

Table 4. **Comparative variability of efficiency of the analyzed tools**

Indicators	Delivery-control option	Original option
Number of operating pumps day-time, operation duration, capacity of the IM, kW	1 pump, 16 hours 1040 m level – 261 kW	1 pump, 8 hours 1040 m level – 261 kW
Number of operating pumps night-time, operation duration, capacity of the IM, kW	6 pumps, 8 hours 1040 m level – 310 940 m level – 455 500 m level – 533	6 pumps 1040 m level – 371 - 7.66 h 940 m level – 550 - 7.58 h 500 m level – 691 - 6.87 h
Yearly power cost	11.38 mil UAH	11.6 mil UAH

Source: **compiled by the authors**

Thus, the difference makes 11.6–11.38 = 0.22 mil UAH.

To install six frequency inverters for six pumps, one needs:

6·800 kW·250 USD·27 UAH/USD = 32.4 mil UAH.

The final expected economic effect looks not so optimistic, because the payback period is approaching the value of 32.4/0.22 = 147 years.

This is not a positive moment for investment. Thus, we state that the option of using the difference in day-night power costs at Rodina underground mine not effective enough.

5. ASSESSING EFFICIENCY BY POWER STORAGE DEVICES

Let us consider an option of accumulating power only at night-time by using pump storage facilities and then – at peak hours for normal operation of pumps. To do this, required power consumption is calculated. The daily natural inflow of mine water is 476 m^3/h · 24 hours = 11424 m^3.

To lift (pump) this volume to the 0 level, the following power should be consumed:

$$En_{(0\text{-}1240)} = m \cdot g \cdot h = 11424\ m^3 \cdot 1000\ kg \cdot 9.81\ m/s^2 \cdot 1240\ m = 138966105600\ J.$$

When converting the value in kWh it will be necessary to have capacities in the amount of:

$$P = E_{(0\text{-}1240)}/3600 = 138966105600/3600 = 38601696\ W.$$

We assume that at 7am, the reservoirs are completely drained, and the lower reservoir is filled with natural inflows. It is known that the reservoir of the 1240 m level is filled much earlier than the next night comes. With the inflow of 476 m^3/h, the reservoir of the 1240 m level is filled during 4800/476 = 10.08 hours. There are still six hours left until the next night. Let us calculate the operation mode of a single pump of the 1240 m level so that the reservoir is completely filled before the following night hours, i.e. in 16 hours considering that its nominal capacity is 300 m^3/h.

To do this, the following equation is solved:

$$476 \cdot 16 - 300 \cdot x = 4800\ m^3,$$

which results in: x = 9.38 hours.

Thus, to avoid the reservoir overflow on the 1240 m level, with the natural water inflow of 476 m^3/h, it is necessary to switch on one pump with the flow rate of 300 m^3/h for 9.38 hours. For simplicity in further calculations, but with an acceptable margin of error, we assume that the required operating time of one pump is 10 hours, which results in the pump capacity of 800 kW · 10 h = 8000 kW to ensure its power provision.

Thus, the following energy is required for energy storage devices:

$$En = 8000000 \cdot 3600 = 28800000000\ J.$$

According to the formula of potential energy of the capacitor, it is necessary to have the following total capacity of supercapacitors:

$$C = \frac{2E_p}{U^2} = \frac{2 \cdot 28800000000}{8100^2} = 878 \quad F,$$

where 8100 is the rated DC link voltage of the frequency inverter.

Let us take the averaged capacity value of 900 F. Then, power consumption at the night tariff instead of the daytime one will provide the following economic effect:

C1 = 800 kW · 10 h ·(2.0 UAH/kW·h – 1.1 UAH/kW·h) · 365 days = 2628000 UAH,

where: 800 kW is the drive capacity; 10 is the number of operation hours of the drive; 2.0 UAH/kW is the power cost during the day in 2019 prices; 1.1 is the power cost at night-time; 365 is the number of days in a year.

If we use Korean LSUC 2.8 V supercapacitors with the 3000 F capacity as an option, their number should be calculated. When the DC link voltage of the frequency inverter of 8100 V with a supercapacitor battery installed for convenience, 8100/2.8 = 2892 supercapacitors will be required in series connection. For simplicity, let us assume that we have

3000 super capacitors connected in series.

The total capacity in this case will drop to the value:

$$\text{Capacity} = 3000\ \text{F} / 3000\ \text{units} = 1\ \text{F}.$$

To increase the capacity to the required value of 900 F, we need to provide a series connection of 900 branches made of 3000 series-connected supercapacitors. Thus, in total 3000 · 900 = 2700000 supercapacitors should be used.

The current purchase cost is 1000 UAH/unit, so the direct costs for supercapacitors will be:

$$2700000 \cdot 1000 = 2700000000 = 2.7\ \text{bn UAH}.$$

Thus, with the economic effect of 2628000 UAH/year, the payback period will be unacceptable (2700000000 / 2628000 = 1027 years).

As an option, let us consider using storage batteries instead of ultra-expensive supercapacitors [19-23]. With the rated stator current of induction motors of 92 A, the current of the DC link in front of the inverter is 92 / 0.817 ≈ 113 A.

Using the obtained DC value of 113 A, we determine the value of the battery capacity:

$$113 \cdot 10\ \text{hours} = 1130\ \text{A·h}.$$

The number of consecutively in-series batteries will be:

$$8100\ \text{V} / 12\ \text{V} = 675\ \text{units}.$$

Thus, in order to create an electrochemical power storage device (storage battery), it is necessary to use 675 in-series connected batteries of 1130 A·h capacity each. The most common batteries are from 55 A·h to a little over 100 A·h. If 12 batteries of 100 A·h capacity are connected in parallel, then we can obtain the required total capacity of 100 · 12 = 1200 A·h.

Thus, the electrochemical cell battery will consist of 675 · 12 = 8100 batteries.

With their average cost of 3000 UAH per unit, the total cost will be:

$$\text{Total cost} = 8100 \cdot 3000\ \text{UAH} = 24300000\ \text{UAH}.$$

Provided that direct savings of 2628000 UAH are obtained, we will receive an unacceptably long payback period of 9.25 years.

6. CONCLUSIONS

1. Improvement of energy efficiency of main drainage complexes at underground mines is a multifactor problem.

2. Modeling of efficiency levels in using some modern trends of improving operation of water drainage complexes at iron ore underground enables ranging them by their implementation levels in the following order:

– application of adjustable types of electric drives to control capacity of pumping facilities and their operation modes by transferring “operating points” from the options of increased water supply to reduced ones results in a sufficient economic and technological effect and is recommended as the basic option for developing an automated control algorithm for electromechanical systems and water drainage complexes of underground mines;

– application of power storage devices, such as supercapacitors and batteries, which in the first approximation could accumulate power during night hours for its subsequent use in “peak hours” is not effective for the time being due to limited functionality of current types of storage units;

– optimization of operating modes of electromechanical systems of water drainage complexes in accordance with hourly tariffs for consumed power observing safety requirements to acceptable water levels in underground water reservoirs results in a small economic effect, although without attracting additional material costs, but this method should be accompanied by developing relevant energy-saving measures.

3. Further research should expand boundaries of the search for ways to improve energy efficiency of water drainage systems at underground mines, including unconventional areas for these types of power consumers.

REFERENCES

1. Vilkul, Yu., Azaryan, A., Rjkjsov, V., Karamanits, F. & Batareev, A. “Current state of the iron ore mining industry, developmet forecasting and prospects” (in Russian). *Collection of scientific papers “Quality of mineral materials*”. Kryvyi Rih: Ukraine. 2015. p. 9–24.

2. Prakhovnik, A. V., Rosen, V. P. & Degtyarev V. V. “Energy-saving modes of power supply of mining enterprises” (in Russian). Moscow: Russian Federation. *Publ. Nedra*. 1985. 232 p.

3. Tolmachov, S. T. & Ilchenko O. V. “Optimization of operating modes of pumping stations of the main drainage of mines according to the criterion of minimum power cost” (in Ukrainian). *Bulletin of KNU. Collection of scientific works*. Kryvyi Rih: Ukraine. 2017; Vol. 44: 137–142. – Available at: http://ds.knu.edu.ua/ispui/handle/123456789/1906. – [Accessed: 27 May 2017]

4. Korenkova, T. V. “Automated electric drive of pumping and fan installations solving problems of energy and resource saving” (in Russian). Kremenchuk: Ukraine. 2012. 198 p.

5. Sinchuk, O., Kupin, A., Sinchuk, I., Rohoza, M. & Plieshkov, P. “Certain aspects concerning the development of a functioning scheme of the auto-mated system to control energy flows of underground iron-ore enterprises”. *Mining of Mineral Deposits*, 2020; 14(3): 101–111. DOI: https://doi.org/10.3327/miningl4.03.101.

6. Sinchuk, O., Sinchuk, I., Beridze, T., Filipp, Yu., Budnikov, K., Dozorenko, O. & Strzelecki, R. “Assessment of the factors influencing on the formation of energy- oriented modes of electric power consumption by water-drainage installations of the mines”. *Mining of Mineral Deposits.* 2021; 15(4): 25–33. DOI: https://doi.org/10.33271/mining15.04.025 (Scopus).

7. Pujades, E., Orban, P., Bodeux, S., Archambeau, P., Erpicum, S. & Dassargues, A. “Underground pumped storage hydropower plants using open pit mines: How do groundwater exchanges influence the efficiency?” *Applied Energy.* March 2017; Vol. 190: 135–146. DOI: https://doi.org/10.1016/j.apenergy.2016.12.093.

8. Wu, T., Shieh, S., Jang, S. & Liu C. “Optimal energy management for a petrochemical plant under considerations of uncertain power supplies”. *JEEE Transactions on Power Systems*, 2005; Vol. 20 No. 3: 1431–1439. DOI: https://doi.org/10.1109/tpwrs.2005.852063. – [Accessed: 10 Aug. 2005].

9. Brand, E. L., Vosloo, J. & Mathews, E. “Automated energy efficien-cyproject identification in the gold minig industry”. *Proceeding of the 13th Conference on the Industrial and Commercial Use of Energy.* 2015. p. 17–22. DOI: https://doi.org/10.1109/ICUE.2015.7280241. – [Accessed: 25 Apr. 2015].

10. Rycroft, M. “Small pumped water storage systems: a new partner for renewable energy”. *Technology&business for development*. 2017. – Available from: https://www.ee.co.za/article/small-pumped-water-storage-systems-new-partner-renewable-energy.html. – [Accessed: 15 Nov. 2017].

11. Lohr McKinstry. Moriah hydro project proceeds. – Available from: http://www.processrepublican.com/news/localnews. – [Accessed: 17 Nov. 2018].

12. Agadzhanov, M. “In Germany, the coal mine will be converted in a pump storage power station” (in Russian). – Available at: https://geektimes.ru/post/287320/. – [Accessed: 15 Dec. 2020].

13. Leznov, B. S. “Energy saving and regulated drive in pumping and ventilation installations” (in Russian). Moscow: Russian Federation. *Publ. Energoatomizdat.* 2006. 360 p.

14. Kholomeniuk, M. V. “Pumping and fan installations” (in Ukrainian). Teaching guide. Dnipropetrovsk: Ukraine. National Mining University. 2004. 330 p.

Conflicts of Interest: the authors declare no conflict of interest

Received 22.12.2020
Received after revision 27.02.2021
Accepted 14.03.2021

DOI: https://doi.org/10.15276/hait.04.2021.4
УДК 621.313-57

Моделювання засобів підвищення енергоефективності водовідливних комплексів залізорудних шахт

Ігор Олегович Сінчук[1)]
ORCID: https://orcid.org/0000-0002-7702-4030; olegovich.s@knu.edu.ua. Scopus Author ID: 55327932300
Альберт Борисович Сьомочкин[1)]
ORCID: https://orcid.org/0000-0002-3592-7899; a.syomochkyn@knu.edu.ua. Scopus Author ID: 57194694864
Кирило Всеволодович Будніков[1)]
ORCID: https://orcid.org/55327932300; budnikov.kirill@icloud.com; Scopus Author ID: 57450131100
Світлана Володимирівна Сьомочкина[1)]
ORCID: 0000-0001-9809-0048; somochkyna@knu.edu.ua
Владислав Дмитрович Барановський[1)]
ORCID: https://orcid.org/0000-0002-0438-262X; vladislav.baranovskiy4@gmail.com
Олександр Валерійович Данілін[2)]
ORCID: https://orcid.org/0000-0003-3207-1156; avdan@ukr.net. Scopus Author: ID 57202128990
[1)] Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна
[2)] Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», просп. Перемоги, 37. Київ, 03056, Україна

АНОТАЦІЯ

Факт природної присутності вод в гірничих підземних виробках створює значні складнощі в процес видобутку корисних копалин шахтним способом і потребує постійного водовідведення – відкачування цих вод на денну поверхню в спеціальні водосховища. Для цього використовуються так звані головні водовідливні комплекси. Процес водовідведення шахтних вод є енергозатратним. Тому необхідність зменшення енергоємності головні водовідливні комплекси виглядає задачею актуальною и поки що невирішеною. Для системоутворюючого кінцевого рішення цієї задачі потрібно перш за все оцінити відомі, засоби підвищення енергоефективності комплексів відведення підземних вод згідно рівнів досяжності їх ефективності. Це необхідно для процесу подальшої форматизації наукового пошуку варіантів з достатнім рівнем ефективності. Ефективним і доступним заходом з отримання превентивних і близьких до реальних результатів, є моделювання процесів відкачування вод, включаючи електроенергетичні процеси в цих технологічно складних видах споживачів електричної енергії. Безумовно, що рівень адекватності отриманих результатів моделювання буде залежати від відповідності величин вхідних параметрів моделі ~~до~~ їх реальним значенням. Маючи таку модель електроенергетичної системи, як комплекс відведення підземних вод на денну поверхню, та використовуючи її як опорний варіант для моделювання, можливо отримати необхідні результати як для розробки заходів енергоефективного керування привідними електромеханічними комплексами, так і для розбудови ефективної структури усього водовідливного комплексу. Саме в такому ракурсі ~~і~~ побудована методологія досліджень, хід їх виконання і аналіз отриманих результатів. Моделювання рівнів ефективності використання деяких сучасних тенденцій удосконалення роботи водовідвідних комплексів залізорудного підземного виробництва дозволило ранжувати їх за рівнями реалізації, починаючи з застосування регульованих електроприводів та закінчуючи оптимізацією режимів їх роботи.

Ключові слова: моделювання; енергоефективність; залізорудна шахта; водовідливні комплекси

ABOUT THE AUTHORS

Ihor O. Sinchuk - Candidate of Engineering Sciences, Associate Professor of the Automated Electromechanical Systems in the Industry and Vehicles Department. Kryvyi Rih National University, 11, Vitalii Matusevich Str. Kryvyi Rih, 50027, Ukraine
ORCID: https://orcid.org/0000-0002-7702-4030; olegovich.s@knu.edu.ua. Scopus Author ID: 55327932300
Research field: Energy efficiency of iron ore mining; traction electromechanical systems

Сінчук Ігор Олегович - кандидат технічних наук, доцент кафедри Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна

Albert B. Somochkyn - Candidate of Engineering Sciences, Associate Professor of the Automated Electromechanical Systems in the Industry and Vehicles Department. Kryvyi Rih National University, 11, Vitalii Matusevich Str. Kryvyi Rih, 50027, Ukraine
ORCID: https://orcid.org/0000-0002-3592-7899; a.syomochkyn@knu.edu.ua. Scopus Author ID: 57194694864
Research field: Simulation of dynamics in electromechanical systems

Сьомочкин Альберт Борисович - кандидат технічних наук, доцент кафедри Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет. вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна

Kyrylo V. Budnikov - PhD student (Eng) of the Automated Electromechanical Systems in the Industry and Vehicles Department. Kryvyi Rih National University, 11, Vitalii Matusevich Str. Kryvyi Rih, 50027, Ukraine
ORCID: https://orcid.org/55327932300; budnikov.kirill@icloud.com. Scopus Author ID: 57450131100
Research field: Energy efficiency and power grids in iron ore mining

Будніков Кирило Всеволодович - аспірант кафедри Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна

Svitlana V. Somochkyna - Candidate of Engineering Sciences, Associate Professor of the Department of Computer Systems and Networks. Kryvyi Rih National University, 11, Vitalii Matusevich Str. Kryvyi Rih, 50027, Ukraine
ORCID: https://orcid.org/0000-0001-9809-0048; somochkyna@knu.edu.ua
Research field: Simulation of data transmission and processing systems

Світлана Володимирівна Сьомочкина, кандидат технічних наук, доцент кафедри Комп'ютерних систем та мереж. Криворізький національний університет. вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна

Vladyslav D. Baranovskyi - PhD student (Eng) of the Automated Electromechanical Systems in the Industry and Vehicles Department. Kryvyi Rih National University, 11, Vitalii Matusevich Str. Kryvyi Rih, 50027, Ukraine
ORCID: https://orcid.org/0000-0002-0438-262X; vladislav.baranovskiy4@gmail.com
Research field: energy efficiency and power grids in iron ore mining, power safety

Барановський Владислав Дмитрович - аспірант кафедри Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет. вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна

Oleksandr V. Danilin – Candidate of Engineering Sciences, Associate Professor of the Department of Automation of Electrical and Mechatronic Complexes. National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", 37, Peremohy Avenue. Kyiv, 03056, Ukraine
ORCID: https://orcid.org/0000-0003-3207-1156; avdan@ukr.net. Scopus Author: ID 57202128990
Research field: Modeling of electrical and mechatronic complexes

Олександр Валерійович Данілін - кандидат технічних наук, доцент кафедри Автоматизації електротехнічних та мехатронних комплексів. Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», просп. Перемоги, 37. Київ, 03056, Україна