Decision Support Methodology for Smart Regulation of Electric Power Consumption in Mine Drainage Systems

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Abstract

The paper presents a methodology for decision support aimed at regulating and optimizing electric power consumption in mine drainage systems, considering electricity tariff zones. The primary objective is to substantiate methods for regulating energy consumption from the perspective of achieving an optimal load mode within the power system. The proposed approach involves a stepwise ranking of pumping units (PUs) and their groups based on technical performance indicators, followed by an assessment of the required operating time and energy efficiency for each group. Based on these evaluations, the methodology provides justified recommendations for developing a daily schedule of equipment operation, taking into account the variable set of available units and their characteristics. This approach enables the use of drainage systems as flexible regulating consumers, helping to reduce peak and semi-peak loads and enhance the overall efficiency of energy use. Modeling based on field data confirms the effectiveness and practical value of the proposed methodology.

Keywords

Decision support, optimizing electricity consumption, pumping unit, phased ranking, mine drainage, tariff period.

1. Introduction

Energy independence is a crucial factor determining the level of national security. Amid wartime conditions, Ukrainian industry – including coal and mining enterprises – is actively pursuing measures to enhance energy efficiency. Frequent blackouts pose a serious challenge to the government's efforts to reduce energy consumption during peak load periods [1, 2]. Mining enterprises are among the major electricity consumers; however, the adoption of modern resource management strategies, particularly in mine water drainage systems, offers significant potential for energy savings [3, 4].

2. Statement of the problem

Managing electricity consumption efficiently in industrial facilities remains a complex task, particularly under fluctuating tariff conditions. Mine drainage systems, which operate continuously and consume significant amounts of energy, require careful optimization of load schedules to ensure both safety and operational effectiveness. However, traditional operation schemes often fail to exploit the potential of drainage equipment as a controllable or flexible load that could assist in balancing the power system during peak and semi-peak tariff periods. Therefore, developing a

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decision support methodology that allows for the dynamic adjustment of equipment operation based on technical efficiency and economic feasibility is essential.

3. Related works

Addressing energy conservation is a pressing research and engineering priority in the modernization of mine drainage electromechanical complexes, driven by the necessity to alleviate stress on power systems. Papers [5, 6] explore methods of energy-efficient management of mine dewatering systems, including optimizing pumping units and using pre-peak switching to reduce energy consumption. The relationship between energy consumption and GDP is analyzed. Papers [7-10] focus on state-of-the-art performance modeling methods and control approaches to improve the energy efficiency of a parallel pumping system. A comprehensive review of traditional scheduling methods and advanced computational intelligence-based control methods has been made to provide insight for future research. The papers [11-14] consider energy-saving approaches through frequency control of pumping unit drives using PI laws. Adaptive methods for adjusting the regulators are proposed. Paper [15] describes the experience of implementing centrifugal pump monitoring systems and big data research. Efforts have been made to schedule pump operations using universal algorithms to minimize the operating costs of water distribution system pumps and storage capacity. In [16, 17], the authors consider the issue of determining the optimal mode of operation of pumping stations. It is determined that combinations of switched-on pumping units can ensure the station's performance, while the combination with a certain liquid flow can include different PAs. When choosing the optimal number of operating units, it is also proposed to consider the duration of the service life and their operating mode. Issues [18-20] discuss the problems associated with energy analysis and improving the efficiency of fluid transportation systems. A method is presented to determine the specific energy consumption used to regulate the flow of pumping systems. Papers [21-24] present an algorithm for predicting the stable operation of a group of identical variable-speed pumps near the point of best efficiency determined by the manufacturer. It considers the prediction of starting and stopping pumps based on variable demand and required pressure. The algorithm activates additional pumps when the existing ones cannot provide the required parameters. The optimal pump operating areas (Q, H), effective combinations between Q, H, and the number of pumps, as well as the limits of their operating modes, are calculated and visualized. Paper [25] analyses the use of algorithms for automated drainage control considering peak power system loads. Various methods are considered, including forced switching on with regulation, three-point control, and time-based switching on. A comparative analysis shows that the three-point control method is the most efficient.

Coal mine drainage systems are significant consumers of electricity. According to various estimates, the share of electricity used to power mine drainage systems is 20-30% of a mining enterprise's total annual electricity consumption. On average, mines in eastern Ukraine must pump out up to 1 m^3 of water per 1 ton of coal produced [25]. Such enterprises should introduce off-peak management laws for their large electricity-consuming divisions, such as those in the mining industry. Reducing the load on energy systems during peak times is an important scientific and practical task. The urgency of the problem stems from the need to conserve energy during the operation of the drainage complex, as improving the energy efficiency of this link within the mining enterprise will have a significant economic impact. The rational use of the drainage complex involves monitoring the equipment's technical condition and applying classification methods with minimal negative mutual influence, as well as automated pre-peak switching. Based on this data, decisions can be made on the time, duration, and number of pumping units (PUs) to be switched on. Given the lack of decision-making systems in this area and the reduced requirements for the qualifications of operating personnel, there is a need to implement a decision support system for the mine drainage process.

This paper aims to substantiate the methods of regulating electricity consumption during mine drainage operations in terms of the optimal load regime of the power system, depending on the tariff zones.

4. Analytical description of the classification approach for pumping units and their groups

The operation of drainage systems in accordance with the power system load schedule can be organized using various control methods, the effectiveness of which is determined by specific operating conditions. The cost of electricity varies throughout the day in accordance with the regulatory documents of the National Energy and Utilities Regulatory Commission (NEURC's). Stashkov Mine's workings intersect aquifers, resulting in a significant water inflow (with an average hourly value of approximately 900 m^3/h). To ensure the economically rational operation of the dewatering plants (i.e., their shutdown during the power system's peak period), the catchment capacity must accommodate the entire water inflow of the mine during the peak, the magnitude and timing of which are set by the power system.

Given the energy intensity of coal mine drainage systems, any organizational or technical measures aimed at improving the energy efficiency of drainage systems lead to a significant economic effect. Every percentage point of efficiency improvement in these systems results in direct savings of hundreds of thousands of hryvnias in electricity costs.

The sources of additional costs arising from the operation of the drainage complex and energy-saving methods include:

- low efficiency of pumping units, where monitoring of the technical condition of pumping units and operation of pumps with the highest efficiency can be applied among possible technical solutions.
- negative mutual influence during the joint operation of pumping units, where among the possible technical solutions is the method of combining pumping units with the closest possible pressure characteristics.
- sub-optimal operation schedule of the drainage complex, where among the possible technical solutions is an algorithm for switching on pumping units in the optimal mode depending on the tariff zones [25].

To support decision-making on energy consumption regulation by influencing the operating modes of the mine drainage complex according to the energy efficiency criterion, a methodology consisting of three stages is proposed: determining the current state of the PUs, grouping the PUs by the minimum negative mutual influence, and recommending the PUs' operation schedule.

Stage 1. Determination of the current state of the PUs.

The key concept describing any pumping system is the QH-curve, which illustrates the relationship between the pump flow rate (supply) Q and the head H. The technical condition of pumping units significantly affects their efficiency, both when used in groups and individually. A shift in the pressure characteristic of a pump indicates that it is worn out and produces a lower flow rate. The pumping units with the highest efficiency should be operated from the available pumping units (Fig. 1).

Based on monitoring the condition of the pumping units, the current efficiency is determined for each switch-on of the PU using a well-known method [16].

The current efficiency data will prioritize switching groups that work on a common reservoir.

Mine drainage lines are characterized by high static pressure (the height water must be delivered) and a low dynamic pressure component (associated with friction between the fluid and the pipe and other hydraulic phenomena). Another important feature of mine systems is the parallel operation of pumps.

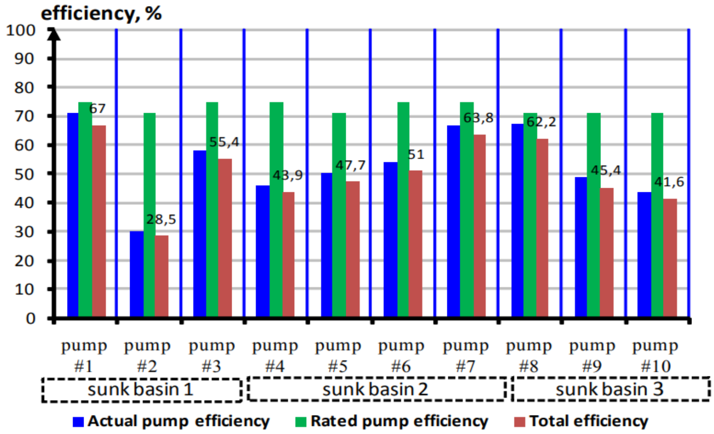

Figure 1: Summary histograms of the main energy parameters of pumping units [16].

The simultaneous operation of pumps with different QH curves results in a shift of the operating point of the 'weaker' pump to the low-flow area. In extreme cases, it can produce zero flow, consuming electricity. Thus, the specific energy consumption in the dewatering process depends not only on the general condition of the pumps, but also on their coordinated combination. Before grouping the pumps according to the minimum negative mutual influence, they are ranked by the decrease in their efficiency during individual operation. The efficiency values were obtained during the previous stage. The following factors are taken into account: pump numbers, efficiency and pump availability [26, 27].

As a result, we will get an array of records containing sorted data on PUs, starting with those with the highest efficiency (Table 1).

Given that the pumps used were of the same type with close flow rates, the efficiency in Table 1 can be considered an indicator of energy efficiency.

Stage 2. Grouping of PUs by the minimum of negative mutual influence.

According to the technical and operational regulations, not all the PUs are simultaneously involved in the pumping process. It is typical to switch on groups of two or three PUs simultaneously.

For the joint operation of pumps in groups of two and three, we determine the number of possible combinations of k pumping units out of their total number n using the combinatorial formula.

Stage 2, which includes the compilation of preliminary priority lists, it is calculated with the help of formula:

$$C_n^k = \frac{n!}{k!\,(n-k)!}. \quad (1)$$

Table 1

Classification of pumping units by efficiency during individual operation

№	PU	Efficiency during individual work	Adjusted efficiency during individual work	Readiness
1.	1	71%	71%	ready
2.	3	68%	68%	ready
3.	4	66%	66%	ready
4.	5	64%	64%	ready
5.	9	62%	62%	ready
6.	8	64%	61%	ready
7.	2	67%	0	not ready
8.	6	64%	0	not ready
9.	7	61%	0	not ready

Thus, there are 38 possible combinations for selecting two of the nine pumps and 84 combinations for selecting three of the nine pumps.

These combinations can be collected in appropriate tables ranked in descending order of the predicted efficiency value during the group operation of the PUs. Thus, the groups of PUs with the highest efficiencies will occupy the highest positions. Examples of such tables are shown below (Tables 2, 3). Considering that Tables 2 and 3 are based on the projected efficiency, the last step is to correct them based on the results of each start-up of the drainage equipment.

Table 2

Priorities for joint work of groups from two PUs

№	Combi-nation PUs	Predicted efficiency when working together	Total supply of PUs, m^3/h	Total electricity consumption, kWh
1.	1 – 3	61%	690	532761
2.	4 – 5	59%	660	945108
3.	8 – 9	56%	695	636075
4.	3 – 8	51%	642	640357
5.	…	…		

Table 3

Priorities for joint work of groups from three PUs

№	Combi-nation PUs	Predicted efficiency when working together	Total supply of PUs, m^3/h	Total electricity consumption, kWh
1.	1 – 3 – 9	52%	975	999938
2.	4 – 5 – 9	49%	940	1582158
3.	8 – 5 – 9	42%	940	1059571
4.	4 – 8 – 9	40%	937	1133662
5.	…	…		

Stage 3. Recommendations on the PUs operation schedule.

The input data for stage 3 are:

- priority tables for switching on the PUs for the case of joint operation of two and three pumping units, ranked by efficiency, containing the supply of pumping groups and electricity consumption per hour.
- tariff coefficients for calculating the cost of electricity by day zones and boundaries of day zones (information is updated as necessary).
- data on the catchment's water level is obtained by measuring or calculating the level from the daily water inflow.

We will combine the priority tables for switching on PUs into one and also calculate the operational cost of each pump group in the day's tariff zones (Table 4).

According to the NEURC's regulations, the cost of electricity varies throughout the day by tariff zone: 1,5 times the tariff during the hours of maximum load of the power system (from 8 a.m. to 11 a.m. and from 8 p.m. to 10 p.m.), full tariff during the semi-peak period (from 7 a.m. to 8 a.m., from 11 a.m. to 8 p.m., from 10 p.m. to 11 p.m., and from 11 p.m. to 11 p.m.) and 0.4 times the tariff during the hours of nighttime minimum load of the power system (from 11 p.m. to 7 a.m.). As of October 24, 2024, the electricity tariff is UAH 1,594 per kWh [27].

The pre-peak switching on of PUs ensures the full or partial release of the catchment from the water before the power system reaches its maximum load, creating conditions for off-peak electricity consumption [25]. The method requires that the reservoir volume be released so that it is guaranteed not to overflow, despite fluctuations in inflow within the range inherent in the mine workings' conditions, and in this case, the specific conditions of the M.I. Stashkov mine.

Table 4
Cost of IA groups in tariff zones

№	Combination PUs	Predicted efficiency when working together	Total supply of PUs, m^3/h	Total electricity consumption, kWh	Cost in the peak loading zone, UAH/hour	Cost in the semi-peak load zone, UAH/hour	Cost in the night load zone, UAH/hour
1.	1–3–9	52%	975	999938	2390851,76	1593901,17	637560,47
2.	4–5–9	49%	940	1582158	3782939,78	2521959,85	1008783,94
3.	8–5–9	42%	940	1059571	2533434,26	1688956,17	675582,47
4.	4–8–9	40%	937	1133662	2710585,84	1807057,23	722822,89
5	1–3	61%	690	532761	1273831,55	849221,03	339688,41
6.	4–5	59%	660	945108	2259753,23	1506502,15	602600,86
7.	8–9	56%	695	636075	1520855,33	1013903,55	405561,42
8.	3–8	51%	642	640357	1531093,59	1020729,06	408291,62

5. Results and discussion

If we consider the minimum cost of pumping a certain roughly constant daily water inflow as an objective function, the efficiency of PUs groups is irrelevant. The result is influenced by the cost of electricity consumed to power the PUs in the tariff zones. Let's assume that a small amount of water comes into the mine, 300 m^3/h, or 7200 m^3/day. Obviously, to obtain the minimum cost of pumping this volume of water, the pumps will primarily be operated at night (up to eight hours [27]) with the minimum tariff coefficient (Ktz=0.4). If this time is insufficient, then the pre-peak hours will be used with the appropriate tariff coefficient (Ktz=1). In this case, the time required for pumping and the cost of pumping the daily water inflow, with the assistance of PU groups (Table 4), will correspond to the data in Table 5.

Table 5
Time and cost for pumping out a daily inflow of 7200 m^3/day

№	Combination PUs	Total supply of HA, m^3/h	Total electricity consumption, kWh	Time for pumping out at high tide, h	Cost of work during peak hours, UAH, thousands	Cost of work during semi-peak hours, UAH, thousands	Cost of work at night, UAH, thousands	Total cost of pumping operations, UAH, thousands
1.	1–3–9	975	999938	7,385	–	–	4708	**4708**
2.	4–5–9	940	1582158	7,660	–	–	7727	7727
3.	8–5–9	940	1059571	7,660	–	–	5175	**5175**
4.	4–8–9	937	1133662	7,684	–	–	5554	**5554**
5.	1–3	690	532761	10,435	–	2068	3545	**5612**
6.	4–5	660	945108	10,909	–	4383	6574	10956
7.	8–9	695	636075	10,360	–	2393	4201	6594
8.	3–8	642	640357	11,215	–	3282	4579	7861

According to Table 5, group PUs 1-3-9 will perform the task during the night tariff zone at the lowest cost. Groups 8-5-9 and 4-8-9 will be the second and third in cost minimization. But then there is a group of two PUs, namely 1-3, which should operate in the night tariff zone and partially in the semi-peak zone. In other words, the use of groups 1-3 for pumping is cheaper than using a group of three PUs 4-5-9, although the latter will operate exclusively during the night tariff zone. This effect is achieved through lower power consumption.

Next, let's assume the mine receives 600 m^3/hour of water, or 14400 m^3/day. With such an inflow, the peak tariff zone (Ktz = 1,5) may also need to be used for water pumping. In this case, the time for pumping and the cost of pumping the daily water inflow with the help of PU groups (Table 4) will correspond to the data in Table 6.

According to Table 6, it is most expedient to operate group PUs 1-3-9 during the night tariff zone under the condition of a water inflow of 14400 m^3/day. However, the second most cost-effective group would be PUs 1-3, which should be operated during the night, pre-peak and partially peak tariff zones. The third group would be the 8-5-9 group, which covers the night and partially pre-peak tariff zones, utilizing three PUs. Close to the 8-5-9 group in terms of costs would be the 8-9 and 4-8-9 groups; however, operating two pumps is a better choice than three.

Finally, we assume a water inflow to the mine of 900 m^3/h, or 21600 m^3/day. The time for pumping and the cost of pumping the daily water inflow with the help of PU groups (Table 4) will correspond to the data in Table 7. Here, the calculations show that groups of two pumps will not have time to pump out the daily inflow. Only groups with a total flow of at least 900 m^3/h can be used. Of the groups considered, the best result in terms of minimum costs is given by groups 1-3-9. The second and third, respectively, are groups 8-5-9 and 4-8-9.

Thus, the preliminary rankings at Stage 1 and Stage 2 of pumps and their combinations, based solely on technical efficiency indicators, are insufficient to support the drainage operator's decision-making in regulating energy-efficient electricity consumption. An additional ranking of the table of time and energy costs by groups of drainage pumps under conditions of known daily water inflow is required.

According to the modelling of situations with different daily inflows of mine water, the cost of F pumping will be, UAH:

$$F = \begin{cases} \frac{Q_{day}}{Q} * K_{TZN} * T_b, & \text{if} \quad \frac{Q_{day}}{Q} \le 8 \\ T_b * \left(8 * K_{TZN} + \left(\frac{Q_{day}}{Q} - 8\right) * K_{TZH}\right), & \text{if} \quad 8 \le \frac{Q_{day}}{Q} \le 19 \\ T_b * \left(8 * K_{TZN} + \left(\frac{Q_{day}}{Q} - 8\right) * K_{TZH} + \left(\frac{Q_{day}}{Q} - 20\right) * K_{TZP}\right) & \text{if} \quad 19 \le \frac{Q_{day}}{Q} \le 24 \\ \text{no solution} \quad \text{if} \quad 24 < \frac{Q_{day}}{Q} \end{cases}, \quad (2)$$

where:

Q_{day} is daily water inflow, m^3/day;
Q is the total supply of the PUs group, m^3/h;
$\frac{Q_{day}}{Q}$ is the estimated time required for pumping the daily water inflow, h;
T_b is basic electricity tariff, UAH/(kWh);
T_b is basic electricity tariff, UAH/(kWh);
K_{TZN} is night tariff zone coefficient, 0.4;
K_{TZH} is coefficient of the semi-peak tariff zone, 1.0;
K_{TZP} is peak tariff zone coefficient, 1.5.

According to the calculated cost of pumping water, Tables 5-7 can be ranked again to provide the outfall operator with a recommended choice of options for using PUs groups. Once the choice has been made, the next task is to draw up a daily schedule for the operation of the PUs group.

Table 6

Time and cost for pumping out a daily water inflow of 14400 m³/day

№	Com-bina-tion PUs	Total supply of HA, m³/h	Total electricity consumption, kWh	Time for pumping out at high tide, h	Cost of work during peak hours, UAH	Cost of work during semi-peak hours, UAH, thousands	Cost of work at night, UAH, thousands	Total cost of pumping operations, UAH, thousands
1.	1–3–9	975	999938	14,769	–	10789	5100	**15890**
2.	4–5–9	940	1582158	15,319	–	18459	8070	26529
3.	8–5–9	940	1059571	15,319	–	12362	5405	**17766**
4.	4–8–9	937	1133662	15,368	–	13315	5783	**19097**
5.	1–3	690	532761	20,870	2382	10929	2718	**16028**
6.	4–5	660	945108	21,818	6368	20817	4821	32006
7.	8–9	695	636075	20,719	2615	12896	3244	**18756**
8.	3–8	642	640357	22,430	5252	14729	3266	23247

Table 7

Time and cost for pumping out a daily inflow of 21600 m³/day

№	Com-bina-tion PUs	Total supply of HA, m³/h	Total electricity consumption, kWh	Time for pumping out at high tide, h	Cost of work during peak hours, UAH	Cost of work during semi-peak hours, UAH, thousands	Cost of work at night, UAH, thousands	Total cost of pumping operations, UAH, thousands
1.	1–3–9	975	999938	22,154	7540	22560	5100	**35201**
2.	4–5–9	940	1582158	22,979	15051	37776	8070	60897
3.	8–5–9	940	1059571	22,979	10080	25298	5405	**40783**
4.	4–8–9	937	1133662	23,052	10984	27200	5783	**43967**
5.	1–3	690	532761	31,304	–	–	–	–
6.	4–5	660	945108	32,727	–	–	–	–
7.	8–9	695	636075	31,079	–	–	–	–
8.	3–8	642	640357	33,645	–	–	–	–

Considering that the night tariff starts at 23-00, recommendations for scheduling the operation of the selected PUs group are given in Table 8.

Table 8

Recommendations for drawing up a schedule for the operation of the vibration group of IA depending on the calculated pumping time

№	Required duration of the PUs group, hours	Recommendations for drawing up an operating schedule
1.	$\frac{Q_{day}}{Q} \leq 8$	1. You can plan to switch on the PUs groups from 23-00, but in such a way as to switch them off no later than 7-00 the next day
2.	$8 \leq \frac{Q_{day}}{Q} \leq 19$	1. Be sure to pump out water by the selected group of PUs from 23-00 to 7-00 the next day 2. For the period from 8:00 to 11:00 (morning peak) and from 20:00 to 22:00 (evening peak), the PUs group should be stopped 3. The daily operation schedule for the selected group PUs is from 7-00 to 8-00 (morning half-peak), from 11-00 to 20-00 (daytime half-peak) and from 22-00 to 23-00 (evening half-peak) is drawn up by the drainage operator based on the technical, technological and operational factors of the enterprise. The preference in choosing the time of operation should be given first to the morning half-peak, then to the evening half-peak, then to the daytime half-peak
3.	$19 \leq \frac{Q_{day}}{Q} \leq 24$	1. Be sure to pump out water by the selected group of PUs from 22-00 to 8-00 the next day and then from 11-00 to 20-00 2. The operator plans the mode of operation in the morning and evening peak tariff zone based on the technical, technological and operational factors of the enterprise

6. Conclusions

The proposed methodology for ranking pumping units (PUs) and PU groups based on technical factors, followed by an assessment of the required operating time and energy efficiency of industrial aggregates (IAs), enables the formulation of well-founded recommendations for drainage operators when developing daily equipment operation schedules. This approach is particularly effective under conditions where the list of available equipment and its technical parameters vary. Such optimization helps to reduce the load on the power system during peak and semi-peak tariff periods by allowing mine dewatering equipment to function as a controllable power consumer. Computational modeling based on field data confirms the efficiency and practical applicability of the proposed methodology.

Declaration on Generative AI

The authors used Grammarly to check the grammar.

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