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RESEARCH AND SYNTHESIS OF THE AUTOMATIC WATER LEVEL CONTROL SYSTEM OF THE MINE WATER TANK ACCORDING TO THE CRITERION OF MINIMIZING THE DISPERSION OF FLUCTUATIONS OF POWER CONSUMPTION

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ДОСЛІДЖЕННЯ ТА СИНТЕЗ СИСТЕМИ АВТОМАТИЧНОГО КЕРУВАННЯ РІВНЕМ ВОДИ У ШАХТНОМУ ВОДОЗБІРНИКУ ЗА КРИТЕРІЄМ МІНІМІЗАЦІЇ ДИСПЕРСІЇ КОЛИВАНЬ СПОЖИВАНОЇ ПОТУЖНОСТІ

The purpose. The purpose is to increase the efficiency of the process of automatic control of the water level in the mine reservoir due to the improvement of the automatic control algorithm. The main indicator of the quality of the system of automatic control of the water level in the mine reservoir is the minimization of the dispersion of fluctuations in the total power consumed by the pumps of the station.

Research methodology. The tasks are solved using the method of computational experiments with the use of specialized computer programs for modeling the process of controlling pumps in the reservoir. To study the automatic control system, theoretical research methods were used, namely, analysis and synthesis of the system based on the modern theory of automatic control, as well as systems analysis. Evaluation of the effectiveness of the automatic control process was carried out using the methods of mathematical statistics.

Research results. A simulation model of the system of automatic control of the water level in the mine reservoir was created. The method of synthesis of the system of automatic control of the water level in the mine reservoir was developed based on the introduction of expert rules in order to ensure the dispersion of fluctuations of the total power of the pump motors, close to the minimum value, with a special algorithm for switching on and off the pumps. There were obtained the results of the study of the effectiveness of the proposed expert algorithm for controlling pumps in the mine reservoir in comparison with the existing control algorithm.

Scientific novelty. A new approach to the synthesis of the system of automatic control of pumps of the water discharge station is proposed: the entire range of changes in the water volume in the reservoir is conditionally divided into average, elevated, high, ultrahigh, reduced, low, and ultralow levels. The task is to keep the water level between high and low levels by ensuring as long as possible a constant combination of active pumps 0/1, 1/2 or 2/3, and the ranges between elevated and high, as well as between reduced and low levels to move to another from the above-mentioned combinations according to the number of active pumps.

Thus, on a larger number of time intervals, the difference in the number of active pumps will not exceed one, which is a condition for reducing the dispersion of the total power consumed by the pumps.

Practical value. The synthesis method is proposed for the system of automatic control of the water level in the mine reservoir based on the introduction of expert rules, thanks to which the variance of fluctuations in the total power of the pump engines is minimized. Reducing the variance of the change in power over time increases the predictability of the amount of energy consumed for pumping water, and also reduces the amount of time when a significantly increased total power of the pump drives is observed. This makes it possible to reduce specific energy costs for water pumping using the differentiated approach when calculating the cost of electricity.

Keywords: *synthesis of the automatic control system, mine reservoir, water level*

Introduction. The technological process of mineral extraction under conditions of underground coal mining, considered in the article, is a component of the mining industry, which is one of the key industries of Ukraine.

As of 2021, coal was mined in Ukraine at 148 mines, including 102 state-owned mines [1]. The majority of coal-mining enterprises of the private sector are part of vertically integrated structures of metallurgy or power engineering. And the majority of state-owned coal mining enterprises, whose share in coal production is estimated at 28%, are low-capacity mines with difficult mining and geological conditions [2, 3].

According to the "World Coal Association" ("WCA"), about 30% of primary energy needs are covered by coal around the world. In general, about 41% of all electricity in the world is produced with coal. Coal is also used to produce 70% of the world's steel. About 7.8 billion tons of coal are mined annually in the world.

In 2019, according to the World Statistical Yearbook on Energy, 27 million tons of coal were mined in Ukrainian mines.

According to the concept of the development of the coal industry of Ukraine [4], coal is currently and in the distant future will be the only energy carrier whose volumes are potentially sufficient to almost fully meet the needs of the national economy. Therefore, taking into account the difficult economic situation of Ukraine, during the next several decades, coal mining, as a strategically important resource for the fuel, energy and metallurgical industries of Ukraine, is quite relevant for the economy of our state.

Formulation of the aims of the article. The aim of the work is to increase the efficiency of the process of automatic control of the water level in the mine reservoir through the improvement of the automatic control algorithm.

Main part.

As the main research tool, taking into account the technical characteristics of the pump drives and the known statistical characteristics of the water inflow, a simulation model of the system of automatic control of the water level in the reservoir was developed (Fig. 1).

The control object in Fig. 1 is represented by models of pumps and a model of a mine reservoir. The reservoir model is actually an adder that realizes the balance between the amount of water that arrived in the reservoir in 1 second and the amount of water pumped out by the pumps:

$$V_r = V_{beg} + V_{inf} - V_{pump1} - V_{pump2} - V_{pump3},\ \text{m}^3,$$

where V_r – is the current volume of water in the reservoir; V_{beg} – is the volume of water in the reservoir at the beginning of the simulation (set using the "Initial level" block in Fig. 2.1 equal to 900 m3); $V_{pump.1}$ – the volume of water pumped out by pump #1 from a certain point in time (in our case – from the moment the simulation started); $V_{pump.2}$ – is volume of water pumped out by pump #2 from a certain point in time; $V_{pump.3}$ – is the volume of water pumped out by pump #3 from a certain point in time.

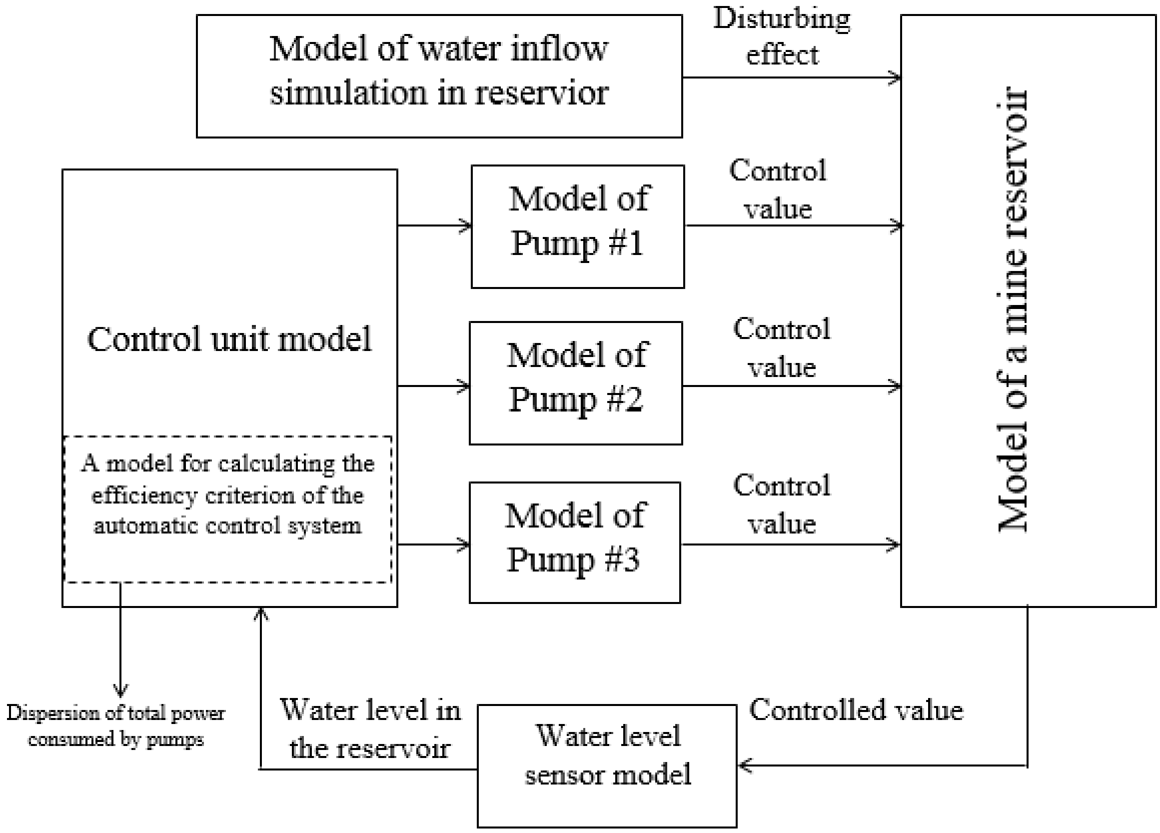

Fig. 1. Structural diagram of the simulation model of automatic control system of the water level in the reservoir

The simulation model of the pump is implemented on the basis of the integrator (Fig. 2), since the output value of the model is the amount of water (capacity) pumped out by the pump per unit of time.

The “Normalization” block in Fig. 2 takes into account the fact that the simulation in the Simulink application of the Matlab program is measured per second seconds, and in the technical characteristics of the pump, its performance is indicated per hour, therefore there is a conversion to the pump performance per second.

In addition, with the “Power” block, the control signal is multiplied by 350, which corresponds to the motor power condition of 350 kW with the pump on and 0 kW with the pump off.

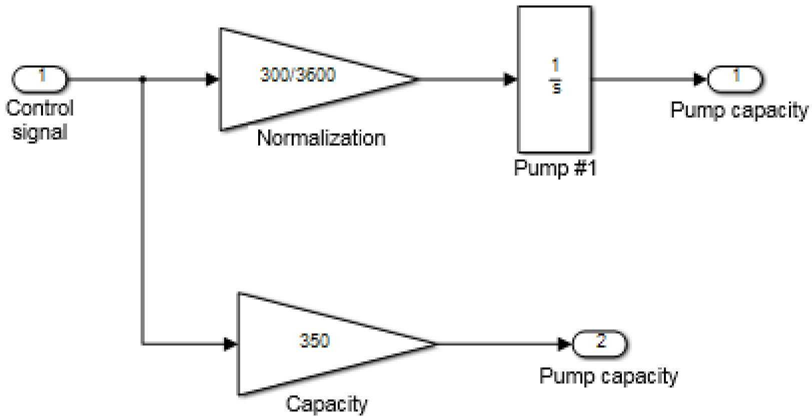

Fig. 2. Scheme of the simulation model of the pumping unit as an object of automatic control

In addition to the pump model, another main element of the control object model is the simulation model of the change in time of water inflow into the reservoir, which is the main disturbance for the automatic water level control system in the reservoir. In fact, this model is a generator of a random signal according to the normal distribution law, whose period of change in time is also a random variable described by the normal distribution law. The parameters of the generator correspond to the real mining and geological characteristics regarding the inflow of groundwater at mining enterprises of the Donetsk coal basin [5-8].

The model for calculating the quality criterion of the control system is an integral part of the model of the control unit, since it is actually a function of calculating the variance of the fluctuations of the total power consumed by the pumps and is performed programmatically on the basis of the controller. The control unit model itself is implemented on the basis of the pump control algorithm. The existing pump control algorithm is described by the block diagram in Fig. 3.

Under the condition of the first start of the system (block 1 in Fig. 3), in block 2, the condition for starting Pump #1 is checked, which is an excess of the actual volume of water in the upper level reservoir. If the condition is met, Pump #1 is turned on in block 3.

Next, in block 4, the condition for starting Pump #2 is checked, which is that the actual water volume in the reservoir exceeds upper level AND 90 seconds have passed since the start of Pump #1. If the condition is met, Pump No. 2 is turned on in block 5.

After that, in block 6, the condition for starting Pump #3 is checked, which is an excess of the actual volume of water in the upper level of the reservoir AND the 30 seconds time lapse since the start of Pump #2. If the condition is met, Pump #3 is turned on in block 7.

The condition for turning off all three pumps, which is checked in block 8, is that the water volume in reservoir has reached the lower level. When the condition in block 8 is met, all three pumps are turned off (block 9).

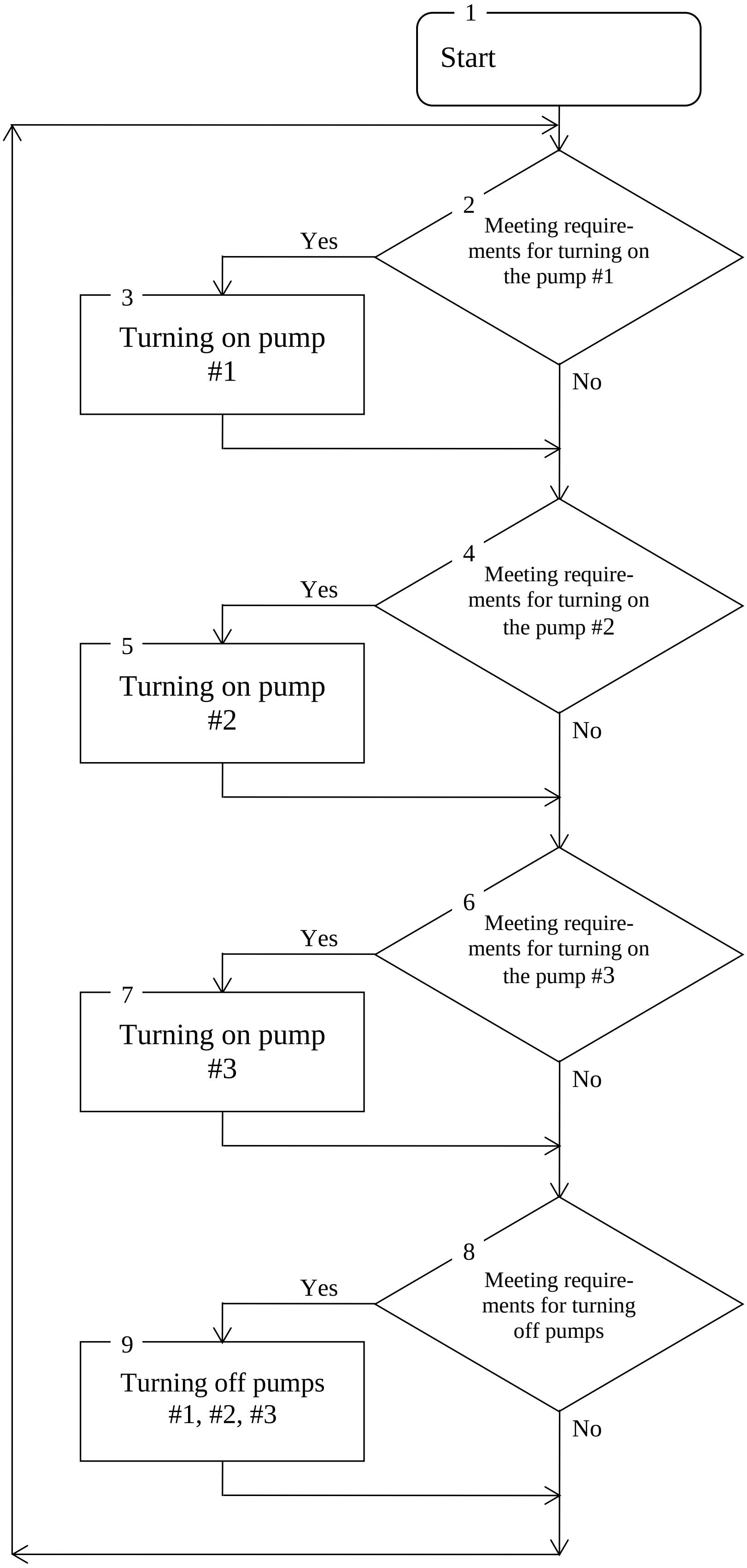

Fig. 3. Scheme of the existing algorithm for automatic control of the water level in the reservoir

Figures 4 and 5 show the results of the computational experiment under the condition of using the existing algorithm for automatic water level control.

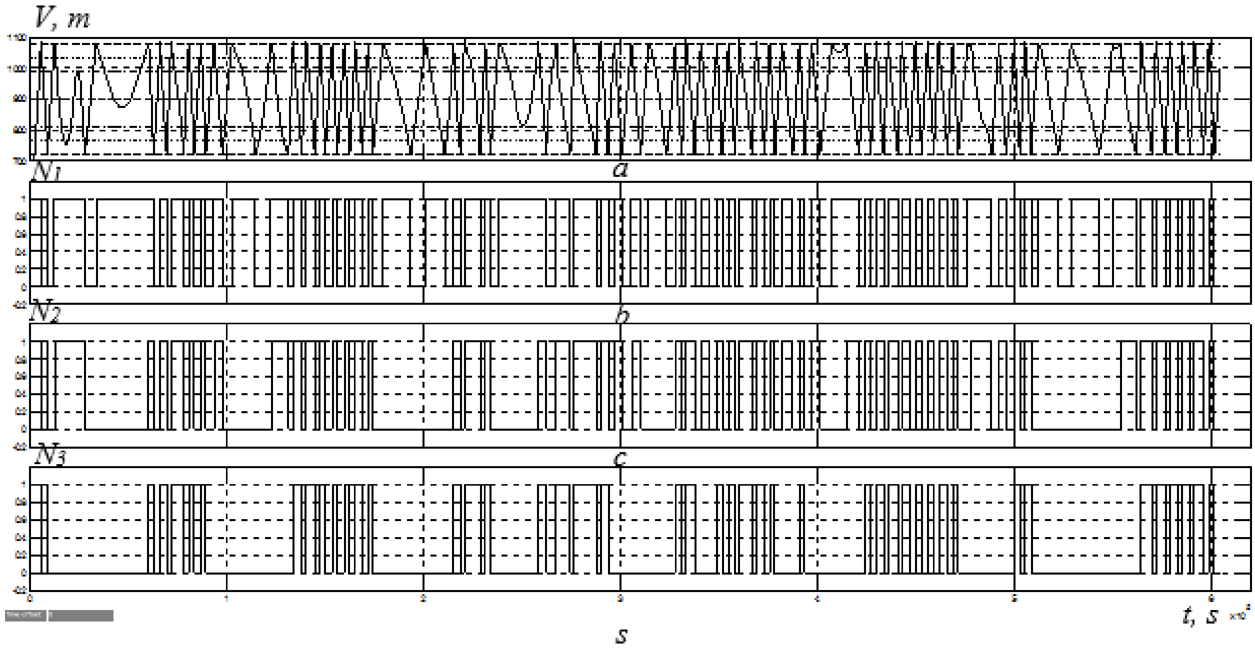

Fig. 4. Change over time: a – water level in the reservoir; b – state of pump #1; c – state of pump #2; d – state of pump #3 (existing automatic control algorithm)

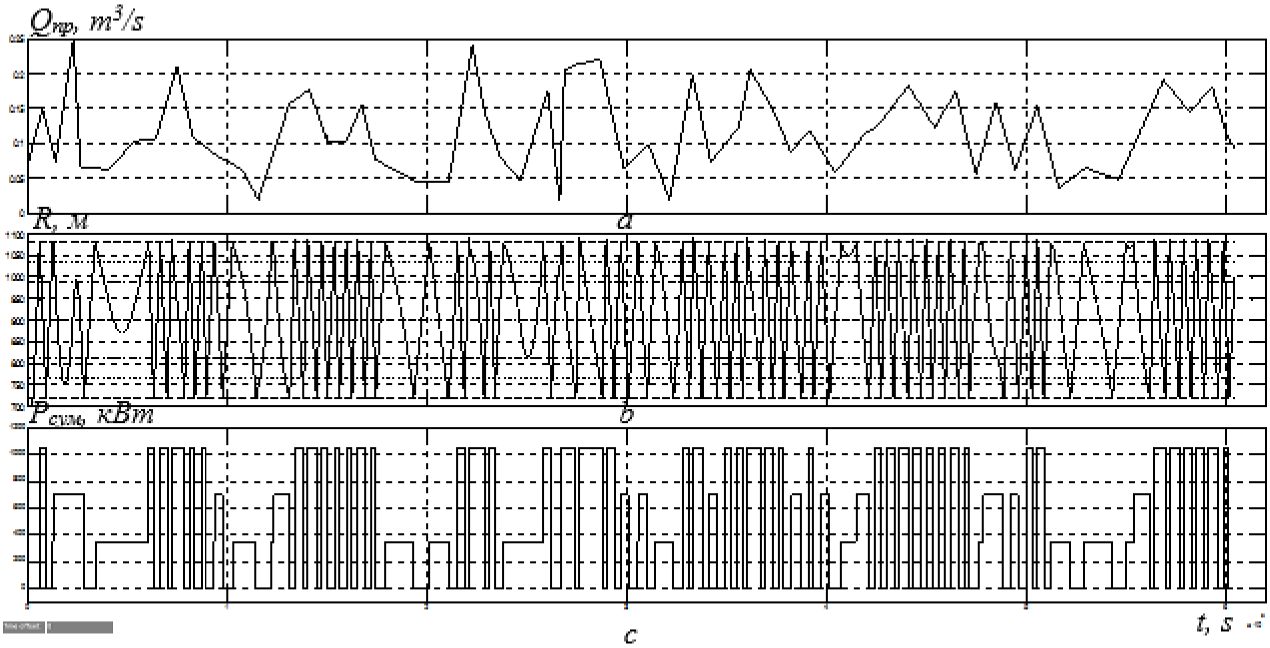

Fig. 5. Change over time: a – water inflow into the reservoir; b – water level in the reservoir; c – total power consumed by pumps (existing automatic control algorithm)

Fig. 4a confirms the correctness of the implementation of the existing control algorithm – we see that the controlled value changes between the upper (+20% of the set point) and the lower (–20% of the set point) levels with a different time differential, which is determined by the intensity of the water inflow in reservoir. At the same time, it can be seen from Fig. 4, b-d that, provided that the controlled value of the upper level is reached, depending on the intensity of the water inflow into the reservoir, at this moment one, or two or three pumps are turned on at the same time almost synchronously (taking into account a slight time shift 90 s according to the existing algorithm). This regularity of pump operation also corresponds to the existing control algorithm.

From the analysis of the results of the computational experiment in Fig. 5, we can see that the inflow of water into the reservoir is a complex disturbing effect (Fig. 5a) – its slow changes in time alternate unpredictably with rather sharp changes, and according to its level, it can be both less than the performance of one pump and more than the performance of two pumps. Because of this, we see that the total power consumed by the pumps also changes unpredictably, actually reflecting the change in the water inflow into the reservoir (Fig. 5c), – when the inflow is insignificant, we see periodic jumps in the total power only up to the level of 350 kW. When the inflow is between the performance of one and two pumps, the total power jumps up to 700 kW, and when the inflow is between the performance of two and three pumps, the jumps occur up to 1050 kW.

In order to evaluate the efficiency of the automatic control system according to the existing algorithm, the variance of the total power consumed by the pumps (Fig. 5c) averaged over the simulation interval was determined, which was $1.86 \cdot 10^5$ kW^2.

The idea of achieving the set goal of reducing the fluctuation variance of the total power consumed by the pumps is to use expert rules when making a decision to turn the pumps on or off. In these rules, there is implemented the idea of ensuring the change of the total power as long as possible in a constant range of values, provided that the inflow of water into the reservoir is within a certain range.

For this purpose, the entire range of changes in the water volume in the reservoir is conditionally divided into average, elevated, high, ultra-high, reduced, low, and ultra-low levels. The goal is to keep the water level between the high and low levels, and the ranges between elevated and high, and between reduced and low levels are needed to switch to different combinations of the number of active pumps (0/1, 1/2 or 2/3).

At the same time, in order to prevent frequent switching on of the pumps, when changing the combination of active pumps, the pump that has been working longer than all others is switched off, and vice versa – the pump that has been idle the longest is switched on. This will improve the secondary criterion of the effectiveness of the control system.

Taking into account the verbally described patterns of pump control, which will allow to improve the quality criteria of the control system, the following expert rules were formed:

1. If previously one pump was running AND the water reached a reduced level AND the gradient is less than zero, THEN all pumps are turned off.

2. If previously two pumps were running AND the water reached a reduced level AND the gradient is less than zero, then the pump that worked the longest is turned off.

3. If previously three pumps were running AND the water reached a reduced level AND the gradient is less than zero, then the pump that was running the longest is turned off.

4. If previously one pump was running AND the water reached a low level AND the gradient is less than zero THEN all pumps are turned off.

5. If previously two pumps were running AND the water reached a low level AND the gradient is less than zero, then the pump that was running the longest is turned off.

6. If previously one pump was running AND the water reached an ultralow level AND the gradient is less than zero, THEN all pumps are turned off.

7. If previously the pumps were not running AND the water reached an elevated level AND the gradient is greater than zero, THEN the pump that was idle the longest is turned on.

8. If previously one pump was running AND the water reached an elevated level AND the gradient is greater than zero, THEN the pump that was idle the longest is turned on.

9. If previously two pumps were running AND the water reached an elevated level AND the gradient is greater than zero, THEN the pump that was idle the longest is turned on.

10. If previously one pump was running AND the water reached a high level AND the gradient is greater than zero, THEN the pump that was idle the longest is turned on.

11. If previously two pumps were running AND the water reached a high level AND the gradient is greater than zero, THEN the pump that was idle the longest is turned on.

12. If the water reached an extremely high level, all pumps are turned on.

To investigate the effectiveness of the proposed algorithm, a computational experiment of the system of automatic control of the water level in the reservoir was conducted (see Figs. 6 and 7).

From Fig. 6, we can draw a conclusion about the correct operation of the control system according to the proposed algorithm – the controlled value in the absolute majority of cases changes only between reduced and elevated levels. And only four times there were cases when the system radically rearranged the combination of working pumps due to a sharp change in the time of water inflow into the reservoir, when the controlled value rose to the high or fell to the low levels.

From Fig. 6, b-d, we can see that the pumps work asynchronously in time as the proposed algorithm suggests – depending on the inflow level, an invariable combination of active pumps is observed for a certain time: with a low inflow 0-1, with an increased 1- 2, with a significant 2-3. This regularity is better traced in Fig. 7, c, from which it can be seen that combinations of active pumps 0-2, 0-3 or 1-3 never occur for a long time. This also confirms the correctness of the implementation of the proposed automatic control algorithm, and it is also the reason for reducing the variance of fluctuations in the total power consumed by the pumps.

It can also be seen from Fig. 6, b-d, that the pumps work alternately – the pump that has been idle the most is turned on, and the one that has been working the most is turned off, as the proposed algorithm suggests. Thanks to this, another criterion of the efficiency of the control system is improved – the frequency of turning on the pumps.

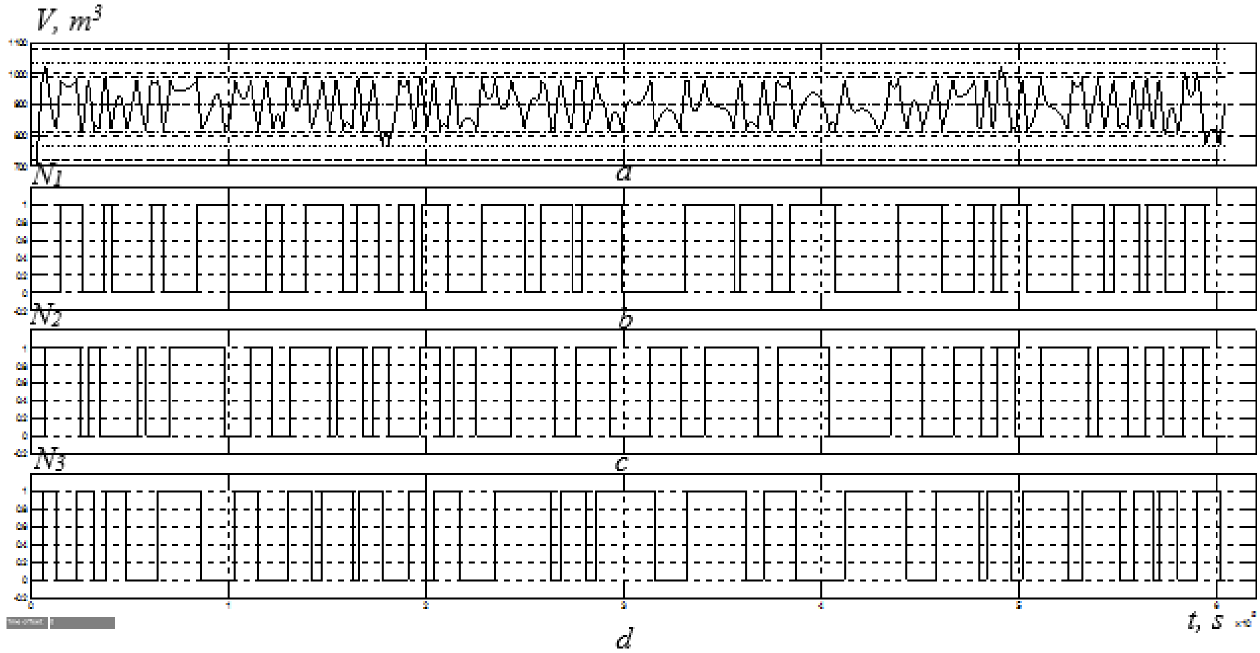

Fig. 6. Change over time: a – water level in the reservoir; b – state of pump #1; c – state of pump #2; d – state of pump #3 (proposed automatic control algorithm)

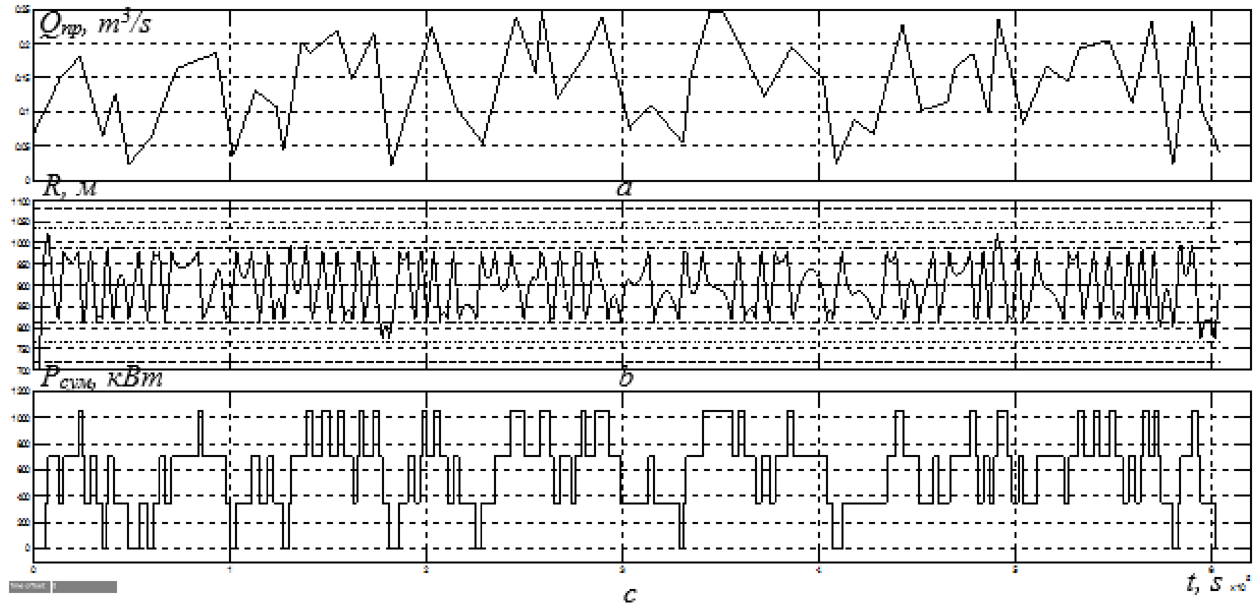

Fig. 7. Change over time: a – water inflow into the reservoir; b – water level in the reservoir; c – total power consumed by pumps (proposed automatic control algorithm)

In order to evaluate the efficiency of the automatic control system according to the proposed algorithm, the variance of the total power consumed by the pumps averaged over the simulation interval was determined (Fig. 7c), which was $8.19 \cdot 10^4$ kW^2.

Conclusion.

The analysis of the operation of the system of automatic control of the water level in the reservoir according to the existing algorithm showed that the control of only two levels leads to a significant number of time intervals in which the following combinations of switching pumps take place: 0/2, 0/3 and 1/3, which leads to an increase in the dispersion of the total power consumed by the pumps. In order to reduce this criterion of the efficiency of the control system, expert rules are proposed, which implement the idea of ensuring the change of the total power as long as possible in an unchanged and minimal range of values, provided that the inflow of water into the reservoir is in a certain range.

For this purpose, the entire range of changes in the water volume in the reservoir is conditionally divided into average, elevated, high, ultra-high, reduced, low, and ultra-low levels. The task is to keep the water level between elevated and reduced levels by ensuring as long as possible a constant combination of active pumps 0/1, 1/2 or 2/3, and use the ranges between elevated and high, as well as between reduced and low levels to move to another from the above-mentioned combinations according to the number of active pumps.

Thus, on a larger number of time intervals, the difference in the number of active pumps will not exceed one, which is a condition for reducing the variance of the total power consumed by the pumps.

Computational experiments based on the created simulation model of the automatic water level control system in the reservoir showed that the transition from the existing pump control algorithm to the proposed expert algorithm reduces the variance of the total power consumed by the pumps by 2.27 times.

References

1. *Вугільна галузь: скільки в Україні та світі працює шахт* (2021) https://www.slovoidilo.ua/2020/08/27/infografika/ekonomika/vuhilna-haluz-skilky-ukrayini-ta-sviti-pracyuye-shaxt
2. Немчинов М. (2018). *Що чекає на українські шахти* https://www.radiosvoboda.org/a/svoboda-v-detalyah/29458040.html
3. *Стан розвитку паливно-енергетичного комплексу України за 11 місяців 2017 року (за фактичними даними)* (2018). http://mpe.kmu.gov.ua/minugol/doccatalog/document?id=245265701
4. Концепція розвитку вугільної промисловості (2021). https://www.kmu.gov.ua/npas/18609693
5. Бубліков, А.В., Козарь, М.В., & Проценко, С.М. (2012). *Автоматизація технологічних процесів підземних гірничих робіт*.
6. Рухлова, Н.Ю. (n.d.) *Повышение энергоэффективности работы главного водоотлива угольной шахты в режиме потребителя-регулятора*. (Дис. канд. тех. наук).
7. Разумний, Ю.Т., & Рухлов, А.В. (2012). *Аспекти вирішення проблем нерівномірності споживання електричної енергії*.
8. Шаруда В.Г., Ткачов В.В., & Бубліков А.В. (2015). *Дослідницька частина в кваліфікаційній роботі магістра*.

АНОТАЦІЯ

Мета. Метою є підвищення ефективності процесу автоматичного керування рівнем води у шахтному водозбірнику за рахунок вдосконалення алгоритму автоматичного керування. Головним показником якості роботи системи автоматичного керування рівнем води у шахтному водозбірнику є мінімізація дисперсії коливань сумарної потужності, що споживають насоси станції.

Методика досліджень. За умови вирішення завдань дослідження за основу взятий метод обчислювальних експериментів з використанням спеціалізованих комп'ютерних програм для моделювання процесу керування насосами у водозбірнику. Для дослідження системи автоматичного керування використані теоретичні методи дослідження, а саме – аналіз й синтез системи на основі сучасної теорії автоматичного керування, а також системний аналіз. Оцінювання ефективності процесу автоматичного керування проведене з використанням методів математичної статистики.

Результати дослідження. Створена імітаційна модель системи автоматичного керування рівнем води у шахтному водозбірнику. Розроблений метод синтезу системи автоматичного керування рівнем води у шахтному водозбірнику на основі введення експертних правил з метою забезпечення дисперсії коливань сумарної потужності двигунів насосів, наближеної до мінімального значення, за рахунок спеціального алгоритму увімкнення та вимкнення насосів. Отримані результати дослідження ефективності запропонованого експертного алгоритму керування насосами у шахтному водозбірнику у порівнянні з існуючим алгоритмом керування.

Наукова новизна. Запропонований новий підхід щодо синтезу системи автоматичного керування насосами водовідливної станції, який полягає у наступному. Весь діапазон зміни об'єму води у водозбірнику розбивається умовно на середній, підвищений, високий, надвисокий, занижений, низький та наднизький рівні. Задачею є тримати рівень води між підвищеним та заниженим рівнями за рахунок забезпечення якомога довше незмінної комбінації активних насосів 0/1, 1/2 або 2/3, а діапазони між підвищеним й високим, а також між заниженим й низьким рівнями використати для переходу до іншої з означених вище комбінацій за кількістю активних насосів.
Таким чином, на більшій кількості часових інтервалів різність кількості активних насосів не буде перевищувати одного, що є умовою зменшення дисперсії сумарної потужності, що споживається насосами.

Практичне значення. Запропонований метод синтезу системи автоматичного керування рівнем води у шахтному водозбірнику на основі введення експертних правил, завдяки якому мінімізується дисперсія коливань сумарної потужності двигунів насосів. Зменшення дисперсії зміни у часі потужності підвищує прогнозованість кількості споживаної енергії на відкачування води, а також зменшує кількість часу, коли спостерігається суттєво підвищена сумарна потужність приводів насосів. Це дозволяє зменшити питомі енерговитрати на відкачування води за умови використання диференційованого підходу при розрахунку вартості електроенергії.

Ключові слова: *синтез системи автоматичного керування, шахтний водозбірник, рівень води.*