Developing the algorithm for the smart control system of distributed power generation of water drainage complexes at iron ore underground mines

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***Abstract* — The article highlights prospects for developing smart control systems of the power supply - power consumption process at underground iron ore mining enterprises. It is emphasized that it is possible to achieve the desired level of energy efficiency when transforming the power supply system from of the centralized power supply option into that with distributed generation sources as these very types of industrial enterprises are adaptable to such renovation. Creation of peak pumped storage power plants (PSPPs) based on water drainage complexes of underground mines is a priority among other effective solutions to the problem, thus providing autonomous power supply to industrial consumers. The authors suggest a new operation algorithm for the smart control system of the iron ore underground mine power supply involving distributed power generation facilities of this type. There is a comparative analysis of economic indices of the enterprise power system with two options of power supply of consumers – from the power grid and from the power grid with additional peak PSPPs. There are determined levels of power consumption by mine technological objects and operation parameters of hydrogenerators when application of the offered combined system of power supply with the smart control system is expedient.**

Keywords— iron ore underground mine, power grid, distributed generation, water drainage, pumped storage power plant, smart grid, peak power plant, net present value, levelized cost of energy

I. Introduction

Mining enterprises are energy-intensive industrial entities with a significant share of expenses for power consumption required for iron ore mining [1, 2].

This situation is associated not only with significant power consumption as one of the components of the iron ore cost, but also with the factor of its constant growth. As a result, in 2021, the power consumption component of iron ore underground mines reached almost 30% [3]. In its turn, electric engineering is the basic component affecting power consumption of these types of enterprises, which reaches over 85% of their total energy consumption [4].

Mining enterprises are forced to search for ways to change this situation. To do this, given that reduction of power consumption with the existing technology of iron ore production due to the natural increase in mining depths is almost impossible, energy services of mining enterprises are changing the format of time-of-day (hourly) power consumption.

Under this option, daily curves of power consumption at mining enterprises already characterized by significant ranges of consumption levels have become even larger. This complicates stability of Ukraine's power system and leads to significant fluctuations in power tariffs on the energy market. At the same time, the situation in the power industry of mining enterprises remains close to critical.

Autonomous generation sources based on using enterprises' own energy potential within their power supply systems are effective in increasing energy efficiency of iron ore underground mines and allow implementing the Smart Grids concept [5, 6].

Internal power supply systems of underground mines are transformed from the centralized power supply (the power grid) option to the synergetic one based on sources of distributed power generation, this making up an advantage for this type of the mine power grid [7]. Simultaneously, creating autonomous power sources as segments of power supply systems with distributed generation facilities based on water drainage systems from mine working areas is a positive trend [7–15]. In this case, water drainage complexes in cost-saving periods of the day operate in the mode of pumping water from underground levels to surface reservoirs, while during peak hours, it is discharged in the opposite direction to generate electricity. Thus, this very mode of operation classifies a pumped storage power plant (PSPP) as the peak type.

During operation of the distributed power generation system, it is necessary to provide high-quality control over power supply of an underground mine's technological objects. Application of the Smart Grids concept to monitoring and controlling allows ensuring reliable coordinated operation of centralized and autonomous generation, power transmission and distribution as well as its consumers. Development of this system and investigation into quality of its operation considering conditions of underground mining is an urgent research issue.

Both foreign and national scientists have been working at solving the problem of improving energy efficiency of mining enterprises [4–15]. This article continues the authors' scientific search in this direction, some research results being presented in a number of previous studies.

II. Materials and Methods

There are several naturally positive aspects of implementing synergetic power complexes with pumped storage distributed generation in the practice of mining enterprises which are related to the existing technologies of iron ore extraction.

However, a sufficient potential of energy efficiency of the complex power supply – power consumption of such energy-intensive and complex production as iron ore mining cannot be realized only via local solutions of creating power systems with individual autonomous power supply. The solution is to be comprehensive. In this case, the structure of such integrated automated control system (ACS) can be based on the corresponding local subsystems with their subsequent integration into a single management complex. This idea is confirmed by analyzing power consumption levels of individual consumers of iron ore underground mines (Fig. 1). The diagram shows that the overall level of power consumption of such enterprises is significantly affected by skip hoists, ventilation and water drainage systems. Therefore, in its preventive version, the ACS of electric power consumption should be of general character, while the process of power supply to consumers should be guided by a generalized algorithm for ACS control based on algorithms of relevant subsystems, components of the total structure of the ACS of electric power consumption of an iron ore underground mine.

According to the model of the IEC-1131 standard [16], a trivial hierarchy scheme establishes general subordination of lower-level subsystems to higher-level systems and determines priorities in information exchange. Namely, each subsequent level of the hierarchy is subordinated. At the same time, higher-level ACSs can set tasks and control operation of lower-level ACSs due to a higher priority.

Automated smart control of power supply of a typical underground mine belongs to the third hierarchy level according to the IEC-1131 standard. Therefore, according to such a hierarchy, its subsystems should subordinate local ACSs of lower levels 1 and 2, as well as form tasks (settings) and criteria for their operation. The feedback between the total ACS and the local ACS of levels 1 and 2 is carried out through control functions of the corresponding subsystems.

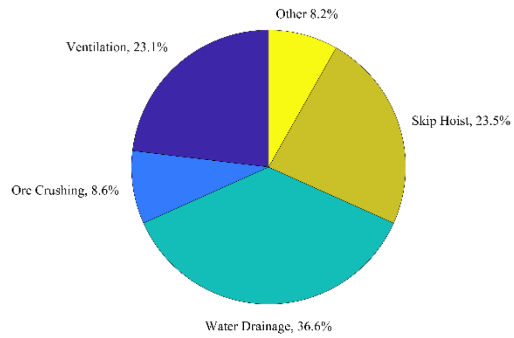

Fig. 1. Averaged distribution of power consumption by underground mines' technological objects in 2016-2021

In turn, the ACS is subordinated to the systems of a higher hierarchy level, namely levels 4 and 5. Information exchange in the forward and reverse directions between them is performed in the same way as above considering the relevant hierarchy.

Based on the above requirements, a functional diagram of implementing smart power supply control at an underground mine can be recommended (Fig. 2). The diagram shows structural and informational links throughout the ACS hierarchy.

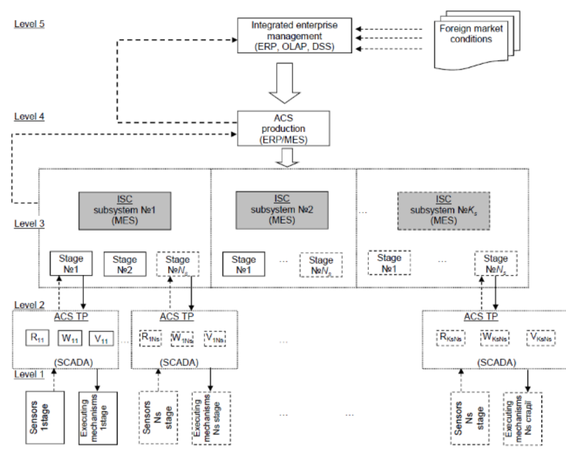

Fig. 2. Interaction of ACS subsystems with power supply of an iron ore underground mine in the general hierarchy according to the IEC-1131 standard: Ks – the number of subsystems at the mine; Ns - the number of stages of information collection

According to the structural technology of developing water drainage complexes, iron ore underground mines are divided into those with individual water drainage, when a mine independently pumps out the entire volume of water inflow to the surface and the group ones when water is accumulated from several mines in the reservoir of one of the mines.

In the latter case, the water from the satellites of the main water drainage mine can enter reservoirs both independently and by pumps. In both cases, a peak PSPP should be built at the main mine where the basic accumulative water reservoir is located.

Fig. 3 shows the option of developing a peak water drainage-based PSPP.

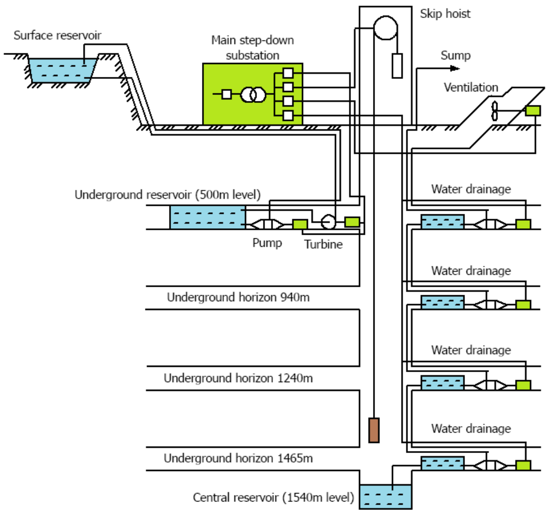

Fig. 3. Functioning of the water drainage complex in the peak pumped storage option

Fig. 4 shows a flow chart of the mine pumped storage plant with the total artesian condition.

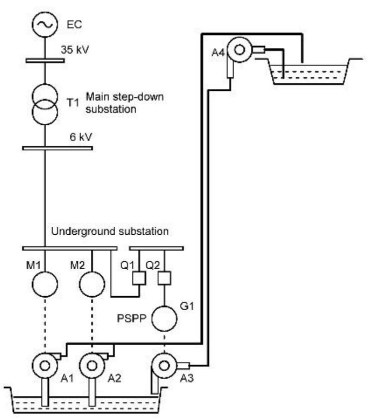

Fig. 4. Mine peak pumped storage power plant with the general artesian condition

The amount of power generated is also affected by pump flow rates at night-time drainage, the duration of the night period with the reduced power tariff and the flow rate of pump columns located in the shaft of the mine.

The presented diagram shows designs for the pumped storage complex used on the 500 m level with three 325 mm pump columns. Switching of surface pipes from the upper to the lower level and vice versa with varied water flows, as well as on the underground level from pumps to the Pelton turbine and vice versa is performed by electrical wedge valves. These valves can be controlled by the programmable logic controller considering night-time operation. The Pelton hydroturbine drives a synchronous generator G1 with the output voltage of 6000 V, which provides power to aligned pumps of the central pumping station with asynchronous motors M.

The power produced by the generator G is supplied to the 6 kV MSDS and covers the costs of internal consumers considering the total power balance when paying monthly to the power supplying company.

An option with laying two sets of pump columns in the shaft can be considered: one of the three pipes for pumping water from the underground level to the surface and the second of the three pipes for draining it from the surface to the underground level. In this case, the electrical valves and the programmable logic controller are switched off.

Using LabVIEW, a programme is developed (Fig. 5) to calculate power consumption by storage pumps at iron ore underground mines during the day.

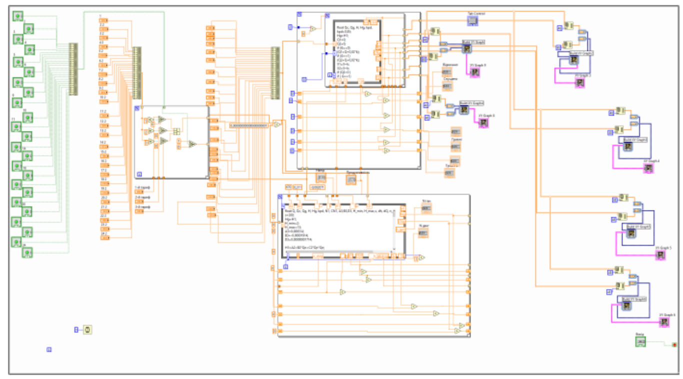

Fig. 5. Programme of power consumption and generation by peak PSPPs at iron ore underground mines

The structure of the programme algorithm presented below enables preventively investigate into and calculate basic parameters of a pump operating in the generator mode.

This programme enters data on the hourly drainage of a given volume of water in m3/h. The algorithm also provides for the use of time-differentiated zones to pay for power.

III. Results and Discussion

In the mathematical modelling of storage pumps of iron ore underground mines, the volume of water drainage (Fig. 6) to the surface is 370 m^3/h.

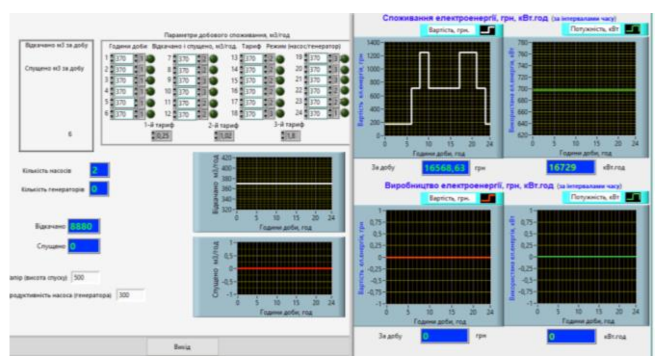

Fig. 6. Power consumption during the day at the iron ore underground mine

Tariff zones for the cost of water drainage are distributed as follows: Tariff 1 is 0.25 UAH/h, tariff 2 is 1.02 UAH/h, tariff 3 is 1.8 UAH/h.

After performing mathematical modelling, the following results are obtained. During the day (24 hours), the volume of mine water pumped makes 8880 m^3/h, while the value of power consumed by two storage pumps makes 16729 kWh, all this resulting in 16568 UAH in 2021 prices as payment for the power consumed.

The programme also enables calculating feasibility of using peak PSPPs as storage pumps of iron ore underground mines. Fig. 7 indicates the hours of the PSPP operation, and the following data can be seen: 6660 m^3/h is the volume of water pumped from the mine, 2220 m^3/h is the volume of water pumped back to the mine, while 2183 kWh is generated during the day, this resulting in savings for water drainage. 9.040 UAH/day is spent on water drainage and 6.550 UAH is the cost of power produced at the green tariff of 3 UAH/kWh per day.

Thus, the mathematical modelling of the algorithm of the smart control system reveals that there is a great potential of a PSPP introduced at iron ore underground mines.

If the systems are balanced according to the water drainage volume (8500 m^3/day), this volume should be raised to 615 m^3/h and generation hours should be redistributed by means of the peak PSPP during the day, namely from 9am to 6pm.

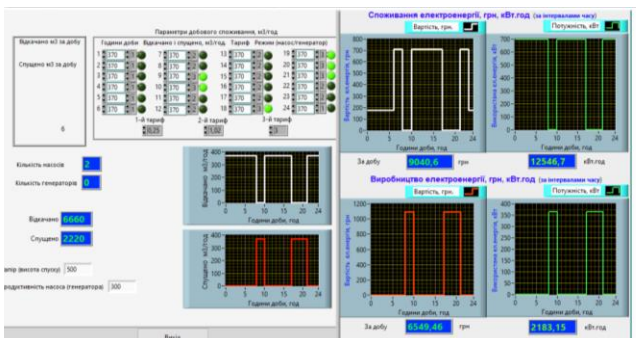

Fig. 7. Power consumption and generation during the day at the iron ore underground mine

When modelling (Fig. 8), it is established that during the day 8610 m^3 of water is pumped from the mine, 16220 kWh of power is consumed which corresponds to 16626 UAH. In the specified period, 3638 kWh is generated which results in 10915 UAH at the green tariff. The daily water drainage does not decrease, 3638kWh of power is generated by means of the peak PSPP.

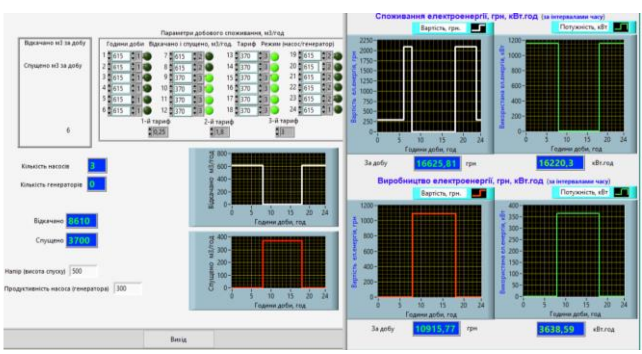

Fig. 8. Power consumption and generation during the day of the balanced system at the iron ore underground mine

At the next stage of the research, the option of installing peak PSPPs with two 1 MW hydraulic turbines on the 500m level is calculated (Fig. 3). This possibility is provided by increasing the pumped storage potential due to additional water from several neighbouring mines. There are determined the net present value (NPV), the Levelized Cost of Energy (LCOE) [17, 18] in systems with and without peak PSPPs (power supply only from the external grid).

The best system is the one with a lower NPV modular value. It is assumed that the cost of one hydroturbine of the peak PSPP is 16922.59 EUR, and its maintenance costs 3760.57 EUR/year. The corresponding dependence graphs are built. Cases of purchasing power from an external distribution operator at the basic (0.0029264 EUR/kWh) and peak (0.0043895 EUR/kWh) tariffs are considered. Areas of water consumption change in case of storage pumps and the level of power consumption at which it is advisable to implement one or another option of power supply are determined.

The results of the computational experiment for the basic tariff of 0.0029264 EUR/kWh are summarized in Table I. Their graphical representation is shown in Fig. 9 and Fig. 10.

TABLE I. ESTIMATED NPV AND LCOE FOR DIFFERENT OPTIONS OF THE POWER SUPPLY SYSTEM OF THE MINE WATER DRAINAGE OBJECTS AT THE POWER COST OF 0.0029264 EUR/KWH

Power, MWh/day	Flow rate via hydro-generator, m^3/sec	NPV, EUR		LCOE, EUR/kWh	
		Grid	Grid and peak PSPP	Grid	Grid and peak PSPP
10.8	0,07	123140.94	174205.4	0.0029264	0.0041399
	0,15		114131.81	0.0029264	0.0027123
	0,23		114131.81	0.0029264	0.0027123
21.6	0,07	246281.88	297346.34	0.0029264	0.0035331
	0,15		131330.81	0.0029264	0.0015605
	0,23		114131.81	0.0029264	0.0013561
43.2	0,07	492563.76	543628.22	0.0029264	0.0032297
	0,15		377612.69	0.0029264	0.0022434
	0,23		170935.15	0.0029264	0.0010155

The obtained data show an increase in the share of the NPV of the peak PSPP within the NPV of the system (Fig. 9). This is due to the increased power generation by storage pumps and reduced power shortages. As a result, the cost of purchasing power from an external distribution operator falls.

For the three most unfavourable conditions for the peak PSPP with Q=0.07 m^3/sec and 21.6 MWh/day, Q=0.07 m^3/sec and 43.2 MWh/day, Q=0.15 m^3/sec and 43.2 MWh/day, the share of the NPV is 29.34%, 15.04% and 22.41% respectively. That is, the share does not exceed the discounted cost of purchasing power from the external power grid during 25 years.

The NPV of the system with Q=0.07 m^3/sec and 10.8 MWh/day, Q=0.15 m^3/sec and 21.6 MWh/day and Q=0.23 m^3/sec and 43.2 MWh/day begins to depend mainly on the NPV of the peak PSPP (55.88%, 81.56% and 57.26% respectively). With Q=0.15 m^3/sec and 10.8 MWh/day, Q=0.23 m^3/sec and 10.8 MWh/day and Q=0.23 m^3/sec and 21.6 MWh/day, it is completely determined by the cost of hydroturbines, which is due to the increased generation to the level of autonomous power supply.

The NPV in the peak PSPP system with two hydroturbines is growing.

With an increase of water consumption via storage pumps to the nominal value Q=0.23 m^3/sec, the NPV of the combined power supply system with the peak PSPP becomes less than the NPV of the system, which is supplied only from the grid. For power consumption of 43.2 MWh/day, it is lower by 57.94%, for 21.6 MWh/day – by 64.52% and for 10.8 MWh/day – by 29.05%.

The power cost (Table I) exceeds the tariff set by the power supplying company for all power consumption options at Q=0.07 m^3/sec. In the case with Q=0.15 m^3/sec, Q=0.23 m^3/sec and 10.8 MWh/day, the LCOE is close to the basic tariff and lower by only 7.32%.

The growth rate of the NPV of the system decreases (Fig. 9) due to the higher initial value of the NPV in the area, which corresponds to higher values of water flow via the turbine and lower power consumption.

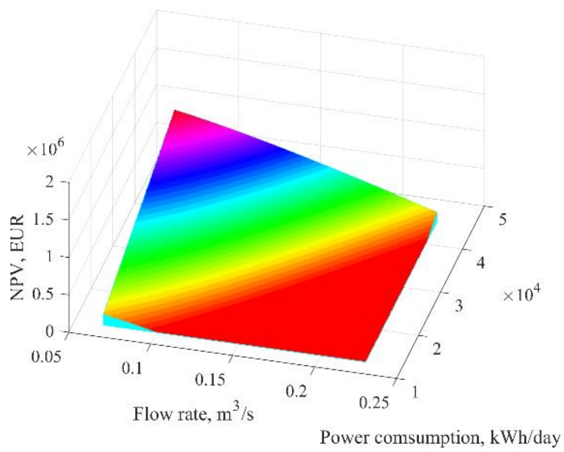

Fig. 9. Dependence of the NPV of the combined power supply system on water consumption via the hydroturbine and the level of power consumption with two hydroturbines introduced on the 500 m level (tariff 0.0029264 EUR/KWh)

Next, we determine the areas of optimal application of the considered designs of power supply systems. To do this, we build an Optimal System Plot [19], with blue denoting a distributed generation system with the peak PSPP, yellow – a system powered by an external grid.

Fig. 10 shows that the system without the peak PSPP should be used at water flow intensity below 0.1006 m^3/sec for 10.8 MWh/day, 0.1334 m^3/sec – for 21.6 MWh/day and 0.1906 m^3/sec – for 43.2 MWh/day.

When applying the peak tariff (Fig. 11, 12, Table II) with operating hydroturbines of the nominal water flow rate Q=0.23 m^3/sec the NPV for the system with the peak PSPP is less by 38.21%, 69.12% and 73.02% at power consumption levels of 43.2 MWh/day, 21.6 MWh/day and 10.8 MWh/day respectively than for the system without it. This is evidenced by the calculation results given in Table II. Compared to the option of the basic tariff (Table I), it is seen that the NPV criterion of efficiency of distributed generation systems increases, as the difference between NPVs becomes more significant.

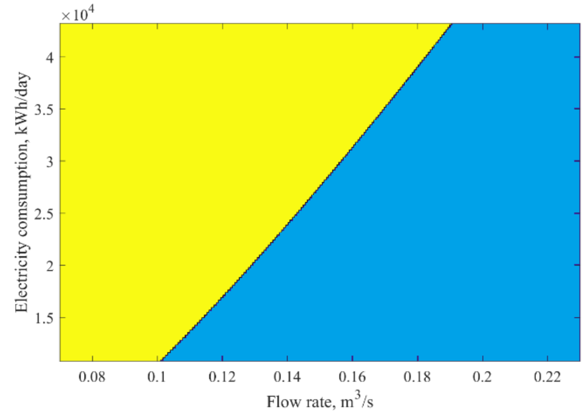

Fig. 10. Optimal in terms of the NPV criterion power supply system with two hydroturbines depending on changes in load and water consumption (tariff 0.0029264 EUR/KWh)

TABLE II. ESTIMATED NPV AND LCOE FOR DIFFERENT OPTIONS OF THE POWER SUPPLY SYSTEM OF MINE WATER DRAINAGE CONSUMERS AT THE POWER COST OF 0.0043895 EUR/KWH

Power, MWh/ day	Flow rate via hydro-generator, m^3/sec	NPV, EUR		LCOE, EUR/kWh	
		Grid	Grid and peak PSPP	Grid	Grid and peak PSPP
10.8	0.07	184711.41	204242.2	0.0043895	0.0048537
	0.15		114131.81	0.0043895	0.0027123
	0.23		114131.81	0.0043895	0.0027123
21.6	0.07	369422.82	388953.6	0.0043895	0.0046216
	0.15		139930.31	0.0043895	0.0016627
	0.23		114131.81	0.0043895	0.0013561
43.2	0.07	738845.64	758376.43	0.0043895	0.0045056
	0.15		509353.13	0.0043895	0.0030261
	0.23		199336.82	0.0043895	0.0011843

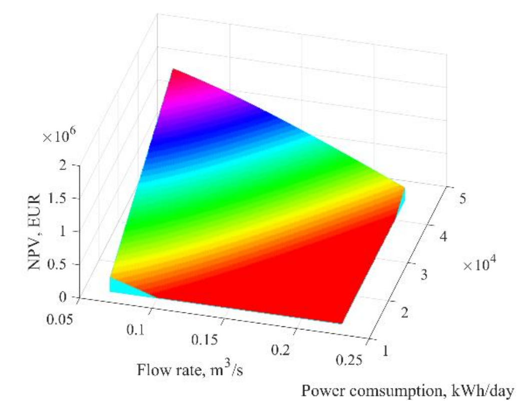

Fig. 11. Dependence of the NPV of the combined power supply system on water consumption via the hydroturbine and the level of power consumption with of two hydroturbines introduced on the 500 m level (tariff 0.0043895 EUR/kWh)

The system NPV at Q=0.07 m^3/sec and 10.8 MWh/day, Q=0.15 m^3/sec and 21.6 MWh/day and Q=0.23 m^3/sec and 43.2 MWh/day mainly depends on NPV of the peak PSPP, the share of which for the given parameters is 55.88%, 81.56% and 57.25% respectively. That is, in the first and the last case, NPVs are almost equal to the discounted cost of purchasing power from the external power grid. At Q=0.15 m^3/sec and 10.8 MWh/day, Q=0.23 m^3/sec and 10.8 MWh/day and

Q=0.23 m^3/sec and 21.6 MWh/day, autonomous power supply from the mine's own generation sources is performed.

The calculation data on the reduced power cost with two operating storage pumps (Table II) and the peak tariff indicate that compared to the option where the power shortage is covered by purchasing power at the basic tariff (Table I), its cost increases. However, except when Q = 0.07 m^3/sec, it remains below 0.0043895 EUR/kWh.

Fig. 12 shows that the system without the peak PSPP should be used at the water flow rate below 0.0926 m^3/sec for 10.8 MWh/day, 0.1261 m^3/sec – for 21.6 MWh/day and 0.1839 m^3/sec – for 43.2 MWh/day.

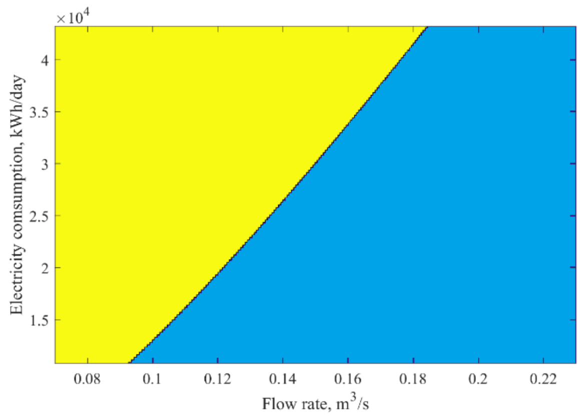

Fig. 12. Optimal in terms of the NPV criterion power supply system with two hydraulic turbines, depending on changes in load and water consumption (tariff 0.0043895 EUR/kWh)

That is, the area within which the use of the power supply system with the peak PSPP slightly expands by 4.34% to 55.91% compared to the option in Fig. 10 which corresponds to the basic tariff.

IV. Conclusions

The solution for the problem of improving energy efficiency of iron ore mining involves creating the generalized smart automated control system for the power supply – power consumption complex of an iron ore underground mine with its integration in subsystems controlling energy-intensive enterprises.

Analysis and assessment of power consumption levels of energy-intensive consumers of iron ore underground mines determines a priority area for building an automated control system for the power supply – power consumption complex which implies reasonable coordinated hourly control over centralized power supply, distributed generation and supply of water drainage facilities.

Given the specifics of the existing technology of iron ore underground mining, which includes unpredictability of changes in parameters of water inflow, water drainage control should be based on an algorithm with adaptability to forced changes in operation modes of receivers data based on acceptance and implementation of expert intelligence.

The use of peak PSPPs with several hydroturbines for distributed power generation in mine water drainage will increase efficiency of power supply to consumers by reducing the cost of purchasing power from the external power grid. This will reduce the cost of final products and increase their competitiveness. However, in order to maintain the proper level of power production, it is necessary to maintain intensity of the water flow passing through the turbine above a certain limit, especially during autonomous generation hours. Besides, with increased capacity of enterprise consumers, the efficiency of the combined power supply system decreases due to the shortage of power generated by the storage pump. Therefore, feasibility of using peak PSPPs should be investigated into individually.

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