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Application of the cybernetic approach to price-dependent demand response for underground mining enterprise electricity consumption

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Abstract. The article considers a cybernetic model for the price-dependent demand response (DR) consumed by an underground mining enterprise (UGME), in particular, the main fan unit (MFU). A scheme of the model for managing the energy consumption of a MFU in the DR mode and the implementation of the cybernetic approach to the DR based on the IoT platform are proposed. The main functional requirements and the algorithm of the platform operation are described, the interaction of the platform with the UGME digital model simulator, on which the processes associated with the implementation of the technological process of ventilation and electricity demand response will be simulated in advance, is shown. The results of modeling the reduction in the load on the MFU of a mining enterprise for the day ahead are given. The presented solution makes it possible to determine in advance the necessary power consumption for the operation of the main power supply unit, manage its operation in an energy-saving mode and take into account the predicted changes in the planned one (e.g., when men hoisting along an air shaft) and unscheduled (e.g., when changing outdoor air parameters) modes. The results of the study can be used to reduce the cost of UGME without compromising the safety of technological processes, both through the implementation of energy-saving technical, technological or other measures, and with the participation of enterprises in the DR market. The proposed model ensures a guaranteed receipt of financial compensation for the UGME due to a reasonable change in the power consumption profile of the MFU during the hours of high demand for electricity, set by the system operator of the Unified Energy System.

Keywords: demand response; cybernetic approach; system architecture; Internet of Things platform; underground mining enterprise; short-term load forecasting; digital twin

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Introduction. Underground mining is associated with a significant energy costs for production, almost half of which (according to some sources, up to 70 %) is spent on ventilation of an underground mining enterprise [1-3]. The main fan unit (MFU) has the highest energy consumption in the ventilation system. In this regard, underground mining enterprises, in order to reduce the cost of mined and processed products, actively introduce various technical and technological solutions into production, which make it possible to reduce the cost of electricity for the operation of the MFU and the ventilation system in total. These solutions include: struggling with the external air leaks [4, 5], air recirculation usage [6, 7], application of energy efficient air conditioning technologies [8-10], etc.

However, in the field of electric power industry, in addition to the cost of electricity, there is a problem of power balance in the form of generated and consumed electricity comparison, since most of the power plants in industrial areas continuously produce it during the day, while energy consumption is of the cyclical nature, tied to a 24-hour time interval. This leads to the fact that the electrical power produced during low demand hours is not demanded, while there is a shortage during peak demand hours. [11]. The inability to automatically respond to demand dynamics leads to a decrease in the flexibility of the power system and, as a result, high operating costs [12-14].

The world practice of creating flexible energy systems shows the high efficiency of price-dependent electricity demand response methods in the day-ahead load planning mode. The method provides for the analysis of historical data on energy consumption, the identification of the most repeated (predicted with high accuracy) energy consumers, the assessment of the expected demand for the day ahead and, the formation of a plan for the generation of electric power on their basis [15-17].

Russian demand response technologies are theoretically well developed and presented by a number of publications by Russian scientists; the papers present algorithms for regulating the load schedule of educational institutions based on the forecast of energy consumption [18-20]; the papers [21, 22] describe the proposed ways to accumulate electricity during hours of low demand (flexible systems). Despite this, the scientific and practical experience of their use in the real market has not been fully formed. This is largely due to the fact that the demand response market is new for Russia, regulated by regulatory documentation approved by Decree of the Government of the Russian Federation dated March 20, 2019 N 287. To implement these measures, the Electricity Response Management Aggregator was introduced – an electric power industry entity that combines the resources of retail consumers to provide services for managing the demand for electricity consumers to provide electricity demand response services. The aggregator is a participant in the wholesale electricity market that manages the change in the load of a group of consumers (for example, at mine or a shaft), in order to sell the set of regulation capabilities as a single object as a product/service on the wholesale market and/or on the system services market.

Despite the opening of the market, the processes associated with the automation of the participation of an underground mining enterprise have not been fully explored and are promising for reducing the cost of mining raw materials.

Formulation of problem. The cybernetic approach to price-dependent demand response for mines and shafts involves the use of a calculation model for the analysis of energy consumption and automatic reduction during the hours set by the system operator (SO) of the Unified Energy System (UES) of Russia. The reduction is achieved by reducing the productivity of the MFU, which, in turn, can be planned and unplanned. Thus, the performance of the MFU can be reduced when workers descend or ascend the ventilation shaft. These actions are known in advance, and the results of a decrease in productivity at such moments can be used in energy planning in day-ahead mode [23].

It is more difficult to reduce the productivity, and hence the energy consumption of the MFU outside of the planned technological processes. This is due to the fact that a large number of random factors affect the ventilation process [24]. For example, in the process of ventilation between mine shafts, the so-called “general mine natural draft” acts – the phenomenon of convective heat transfer, when warm air tends up and cold air goes down [25]. In this regard, the value and the direction of the general mine natural draft will depend on the parameters of the outside air. In this case, the resulting thrust can be directed in the direction of air movement, i.e. will contribute to ventilation (the so-called positive natural draft), or, vice-versa, may act in the opposite direction – interfere with the operation of the MFU (“negative” natural draft). Consequently, the ventilation mode will depend on the parameters of the air entering the mine shafts.

In [26] a method for calculating the predicted general mine natural draft with possible changes in the parameters of the outside air is presented. Since the meteorological forecast in the short term has an accuracy of 85-90 % [25, 27], then it is possible to determine the value of the general mine natural draft a day ahead and set the required MFU operation mode. During the air preparation period, in addition to the MFU, it is necessary to control the mine air heaters (MAH) modes, which complicates the process. But, taking into account the dependence of the operation of the MAH on the parameters of the outside air, and taking into account the heat output of the heaters, it is possible to determine the parameters of the air in mine shafts and predict the magnitude and direction of the general mine natural draft. The MFU operation mode depends on the magnitude and direction of the general mine natural draft. Under the action of positive general mine natural draft, it is possible to reduce the productivity of the MFU by reducing the cost of electricity for ventilation.

The potential possibility of unloading the power supply system of an underground mining enterprise as a result of reducing electricity consumption during the general natural draft operation can be used in practice after the implementation of an electricity demand response cybernetic model as part of the Internet of things platform. There are limitations to the use of such a platform at facilities, since it is impossible to control the operation of the MFU in automatic mode according to security rules. In this case, a necessary condition for ensuring the operability of the proposed solution is the use of a digital twin of the shaft (mine) ventilation process, in which measurement information will be accumulated, simulation modeling of technological processes will be carried out, and forecasts of the MFU productivity will be made when external factors change [28]. The architecture of the Internet of Things (IoT) platform and its interaction with the digital twin of the ventilation process are given in [26].

Methodology. The research methodology is based on the structural-algorithmic organization of the process of demand response for electricity for underground mining enterprises.

In general terms, electricity demand response (DR) is understood as the process of reducing the energy consumption of an object relative to a certain base level at time points set by the energy system operator, followed by receiving a monetary reward for successfully implemented unloading events.

From the point of view of the technical effect, the energy system of the region where underground mining enterprises operate receives a balancing tool that replaces the commissioning of expensive sources of electricity with an equivalent unloading in terms of volume, i.e. if an underground mining enterprise participates in DR activities, the load profile in this industrial area and partially beyond it will be smoother. The effect of the participation of the enterprise in the process of managing the demand for electricity is shown in Fig.1 [29].

Electricity supply curve S in the region increases sharply on the right side (Fig.1), which is due to the connection of backup energy sources, additional costs for planning, maintenance, etc. Reducing consumption during peak hours from the value P_1 to P_2 leads to a shift in the demand curve D_1 into a curve D_2 and a decrease in electricity prices by the amount ΔC_{12}. Similarly, the decrease in consumption during peak hours from the value P_2 to P_3 leads to a shift in the demand curve D_2 into curve D_3 and a decrease in electricity prices by the amount ΔC_{23}.

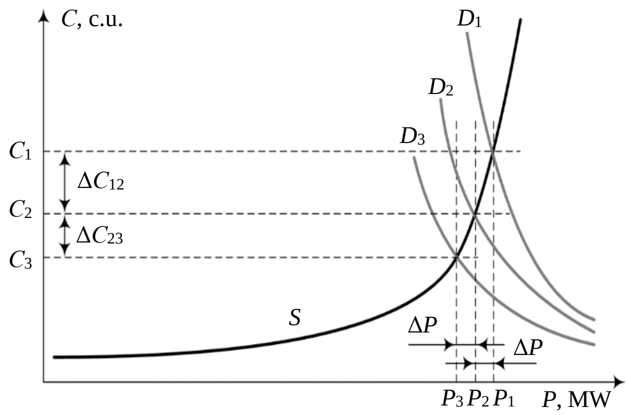

Fig.1. The dependence of the price on the electricity demand

It is important to note that with an equivalent decrease in the load of an underground mining enterprise $D_1 \rightarrow D_2$ and $D_2 \rightarrow D_3$ cost effect will vary. This indicates the expediency of strict observance of the unloading time. In order to ensure the timeliness of unloading within the framework of DR events, it is necessary to draw up an energy consumption plan in advance, in a day-ahead mode, coordinate this plan with the DR service operator, and on the day of the unloading event, implement a reduction in energy consumption in accordance with the previously adopted plan just in time (Fig.2).

In the presented model of process response for electricity of an underground mining enterprise, which is adapted for the Russian market, the following elements are distinguished:

• The system operator – body of operational and dispatching control, which, within the framework of the proposed DR model, forms a command for unloading for pre-selected aggregators and controls the fulfillment of obligations and pays for unloading.

• The aggregator – a power industry entity that acts as an intermediary between the system operator and the UGME, issues commands to reduce the energy consumption of the UGME after receiving unloading commands from the SO when the MFU is ready for unloading.

• The Internet of Things platform – an information product [30, 31], that monitors and manages the energy consumption of technological machines and equipment, in particular the MFU, generates notifications about the readiness to unload the UGME.

• Consumer – a UGME site that takes part in DR activities, for which it reduces energy consumption at certain hours of the day using manual, automated or automatic switching of the MFU operation modes.

• Controller – a device for measuring energy consumption at the input of the power receiving device of the ventilation system, in particular the MFU, as well as the implementation of control actions (in the event of receiving a control command from the Internet of Things platform), if necessary, automatic switching of the MFU operating modes.

• Load – a power receiving device that is involved in the technological processes of ventilation of the UGME, controlled by a controller.

Figure 2 shows several loads, since the demand response system itself involves other consumers in addition to the MFU. If there are several MFUs in the shaft (mine), then their work will be coordinated. The mechanism for managing the power consumption of the MFU in DR mode using the IoT platform is shown in detail in Fig.2.

An underground mining enterprise enters into a contract with a demand aggregator for the DR service. The contract is concluded for a fixed period of time, for example, one quarter. The aggregator

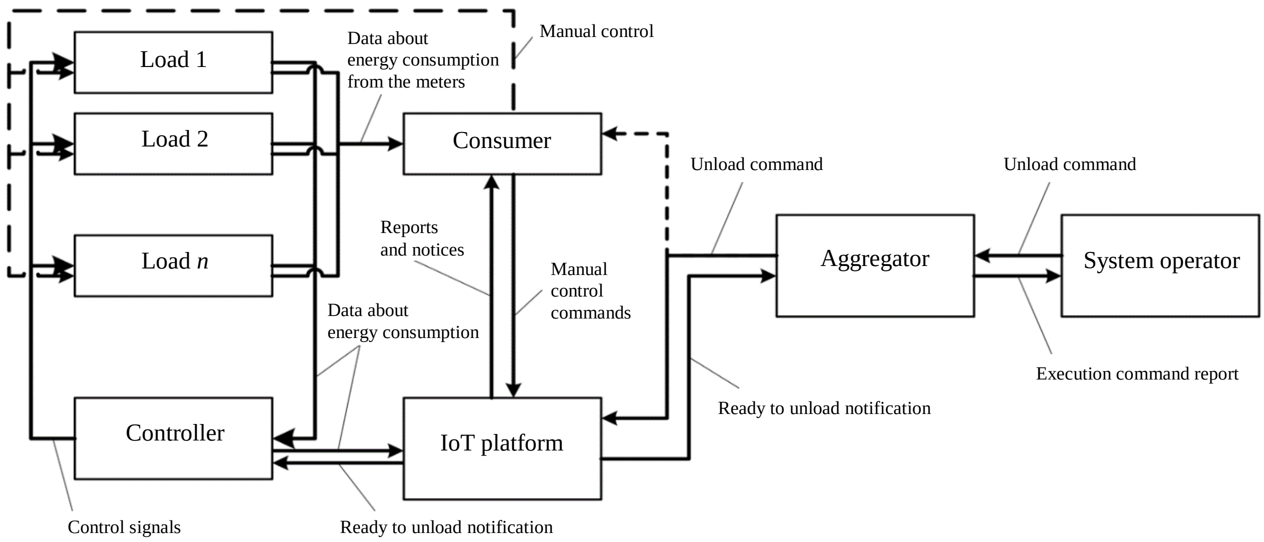

Fig.2. Power management model for MSU in DR mode using IoT platform

calculates the volume of unloading for each consumer within the organizational structure of the enterprise. Within the framework of the contract, the total volume of unloading, which the consumer must realize, is indicated. Every day, the consumer of an underground mining enterprise notifies the aggregator or system operator with whom he has concluded the contract for DR that unloading is ready for the next day.

As soon as the system operator identifies the possibility (forecast) of overloading the power system, he determines the need to reduce the load in the region. After that, the system operator sends this request to the aggregators with which there is an agreement. Aggregators must allocate the required amount of reduction in electricity consumption among the consumers of the UGME with whom they have an agreement, and notify them the day before reducing the load of the system. They can do it manually or with the help of an Internet of Things platform that connects through controllers to energy consumers [32, 33].

The aggregator, in turn, at the time of the load reduction event, undertakes to reduce energy consumption by the declared amount of electricity and, in case of successful fulfillment of the conditions, receive the remuneration established by the contract.

The consumer, receiving the appropriate signal, implements unloading, for example, by reducing the power consumption of the MFU. No more than five unloading signals per month are allowed. The signal contains information about the power unloading time and its value in kW (MW). The duration of the unloading period is two or four hours. At this time, the consumer must reduce his energy consumption (electrical power) by the specified amount. The consumer can implement this either manually or with the help of a controller and automation tools available at the enterprise.

Discussion. As part of the discussion, the following results of the authors' direct research were proposed:

1. Cybernetic scheme of price-dependent demand response at an underground mining enterprise with energy consumption forecasting.

2. Implementation results of a cybernetic approach to price-dependent demand response for an underground mining enterprise based on the Internet of Things platform.

When implementing a demand response strategy on the aggregator side, it becomes necessary to plan a reduction in energy consumption between UGME loads a day before the actual load reduction. At the same time, consumers also need to prepare in advance for unloading and know at what time it will be possible to reduce power. The magnitude and direction of the general mine natural draft depends on the parameters of the outside air, which may not change significantly in the required period. In this case, it will not be possible to achieve a reduction in the electricity consumed by the MFU, taking into account the general mine natural draft. The solution to the problem is short-term forecasting of energy consumption, which, in the absence of actual data, allows you to determine the load in terms of indicators based on past data that affect pricing and demand.

Figure 3 considers an algorithm for constructing a load reduction schedule in the process of managing demand for electricity for an underground mining enterprise based on the calculation of base load schedules offered by "System Operator of the Unified Energy System of Russia" JSC. The diagram illustrates the algorithm for determining the possible amount of load reduction during the hours indicated by the SO, and then plotting the load reduction schedule for one calculation day based on the actual energy consumption profiles of an underground mining enterprise for previous calculation periods.

The algorithm for scheduling unloading as part of the DR activities of an underground mining enterprise is as follows:

1. Construction of base load schedules for consumers, including MFU.

2. Construction of actual load curves for consumers.

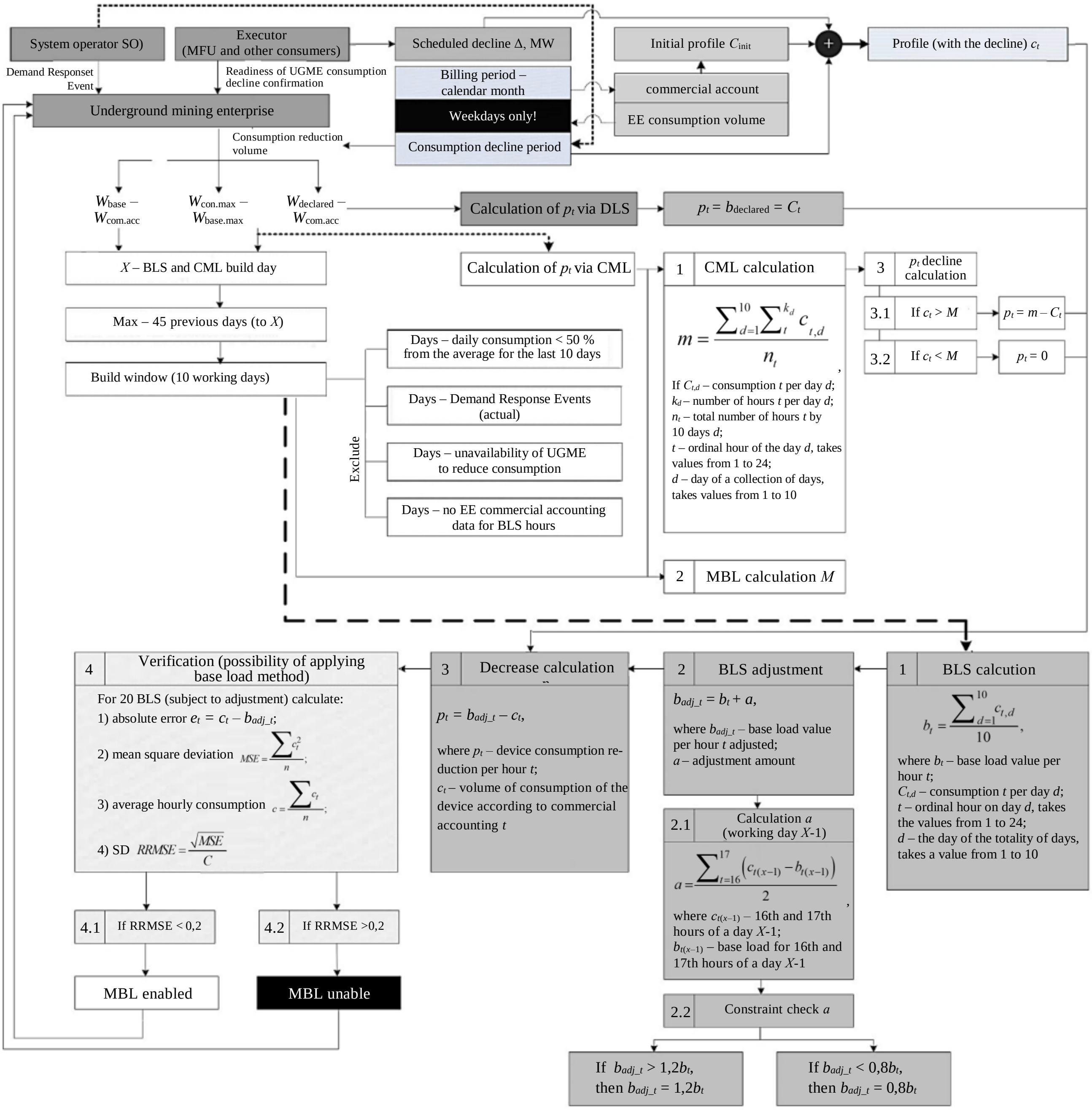

Fig.3. Scheme of price-dependent demand response for consumed electricity with UGME energy consumption forecasting

BLS – base load schedule; CML – conditional maximum load; MBL – maximum base load, DLS – declared load schedule, SO – system operator, P – performer, UGME – underground mining enterprise, SD – standard deviation, EE – electric energy

3. Calculation of the planned deviation of the actual from the base load with the determination of periods of excess / shortage of energy for each consumer (both planned and unplanned).

4. Distribution of consumers with excess productivity by hours of the settlement day.

5. Superposition (summation of values) of base load curves and actual load curves for consumers with excess power.

6. Calculation of excess productivity for a group of energy consumers of an enterprise by hours of the settlement day: calculation of the difference between the aggregated value of the basic load plan and the aggregated plan of the actual load (with a surplus);

• deviations sum calculation of the actual load from the base load with excess productivity for each hour of the settlement day (step 3-4).

7. Cases number estimation of load reduction N_d for each for the current month (current settlement day); must be $N_d \leq 5$ for the whole month.

8. The choice of a specific consumer within the power system of an underground mining enterprise to reduce the load in order to fulfill the unloading volume set by the aggregator during the specified hours is based on the calculation of excess productivity (step 6) with an emphasis on those technological objects that comply with the established reduction restrictions load (number of load reductions for the billing month $N_d \leq 5$).

Service-oriented implementation of the cybernetic approach to DR based on the Internet of Things platform requires compliance with a number of functional requirements:

• formation of a detailed consumption structure at a mining enterprise; classification of power receivers installed at the facilities of the enterprise by type of activity and modes of operation;

• monitoring the dynamics of energy consumption of an underground mining enterprise technological equipment, including MFU, with fixation of critical deviations and registration of electric power indicators in real time;

• description and preparation of initial data for energy consumption analysis with specification of features for power receiver classes;

• differentiated analysis with clustering of consumers in the energy system of a mining enterprise by the level and mode of energy consumption with the identification of typical regularities (patterns) taking into account the days of the week and seasonality;

• intelligent analysis of energy consumption data with the identification of peak load zones as potential time intervals from the DR point of view;

• ensuring the repeatability of load profiles and reducing excess (peak) energy flows, developing scenarios for typical control actions on switching (off-off) loads to smooth out the daily profile;

• statistics on operation and maintenance, including the withdrawal of mining enterprise power receivers for repair, reporting on energy consumption reduction at DR hours;

• forecasting of energy consumption for certain categories of power receivers of the power system of an underground mining enterprise;

• stabilization of the demand and consumption ratio, taking into account the predicted values (DR-modeling);

• development of alternative and integrated solutions for managing the energy consumption of technological units, including the MFU, with the determination of the duration of the decrease, the sequence of automatic shutdown/switching of power receivers.

The presented requirements are implemented programmatically through the development of a typical Internet of Things platform, for example, Tibbo Aggregate, InfluxData, Siemens MindSphere, GE Predix, etc. Such platforms are designed specifically for the implementation of various services basedon IoT technologies, with the connection of many data sources, using analytics, including machine learning, time series databases. The architecture is based on the IoT technology stack, which allows developing various applications using tools for collecting, storing, visualizing and analyzing data (Fig. 4). The platform provides integration of all elements of the demand management system at a mining enterprise into a single cyber-physical system [11, 34], which includes various types of controllers, web servers, and application servers that collect power consumption data and implement DR logic. All communications of the underground mining enterprise with SO can be processed by the data collection and transmission unit, which also allows you to receive data from the demand aggregator. This implementation is capable of handling up to 1,000,000 controller connections. Information about energy consumption and the DR platform is available to end users in the personal accounts of the platform website.

The platform works as follows. The source of data is the controllers C*, which record the energy consumption of the mining enterprise during several settlement periods (at least 45 days preceding

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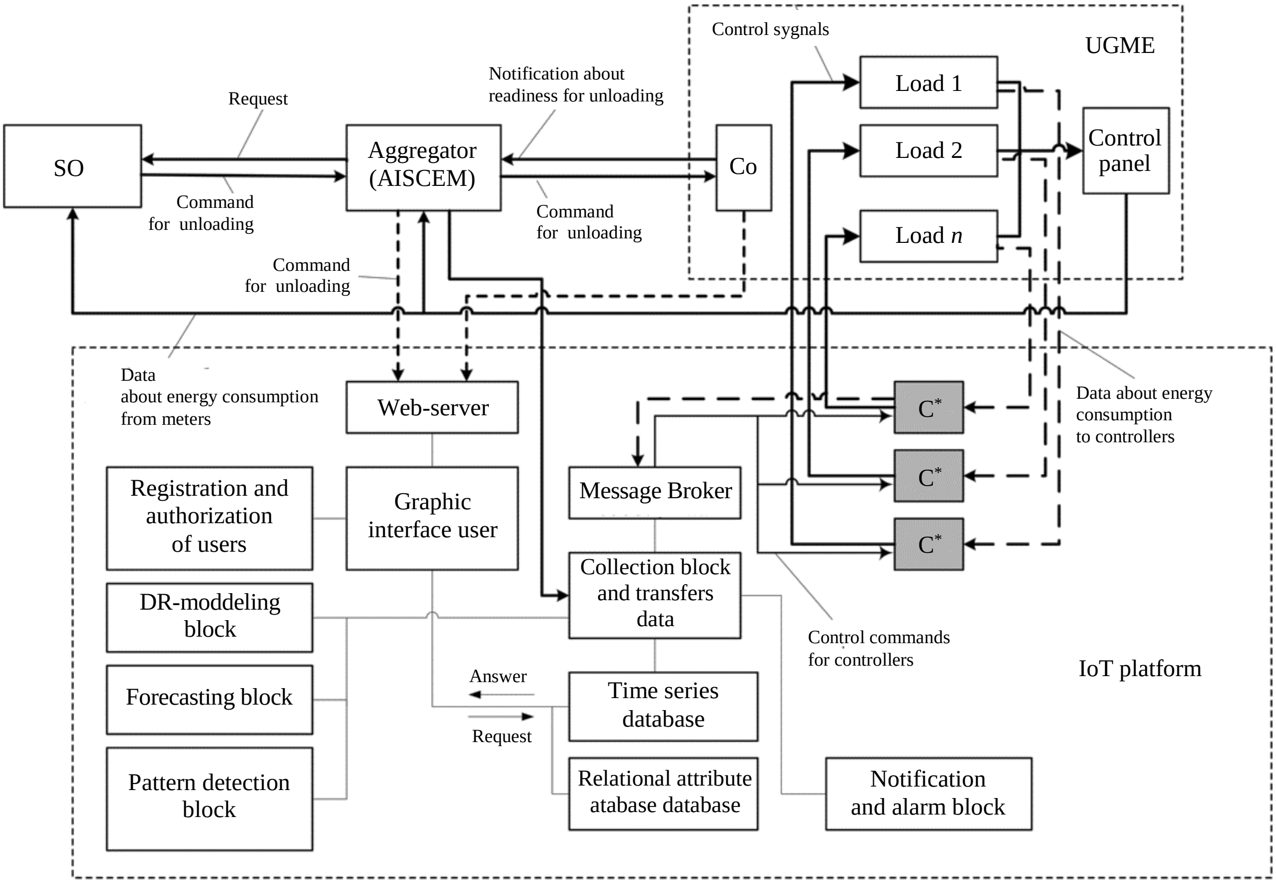

Fig.4. Scheme for the implementation of a cybernetic approach to DR of UGME based on the Internet of Things platform

the settlement day for which the analyzed load graph will be built). This implies that the enterprise includes one or more large loads in the form of local consumers (MFU in our case). The load profile is formed on the basis of electricity consumption indicators with a 30-minute interval and is stored in the energy monitoring process [35]. To simplify the demand response problem, the presented scheme does not take into account the reactive power flows when calculating the energy consumption indicators of the equipment of a mining enterprise.

For information interaction between the platform and real equipment, a message broker is used that supports the typical Internet of Things protocol, such as MQTT. Data from the broker, as well as from the automated information system for commercial electricity metering (AISCEM) of the demand aggregator, enters the data collection and transmission unit and then to the time series database. In online mode, these data are processed using the notification and alarm block, in case the parameters go beyond the required ranges, users are informed.

Calculation of energy consumption with the extraction of peak load zones is performed by typical days (working/weekend days of each month) in the pattern detection block. The DR-modeling block implements the calculation of hourly consumption statistics for the facilities of an underground mining enterprise; analysis of hourly statistics on the composition and modes of operation of the included equipment; calculation of the coefficients of the ratio of deficit and surplus of electricity (capacity) in the case of unloading; values of expected (preferred) restrictions on electricity consumption in case of participation in DR events.

The prediction block implements the construction of base load graphs for typical days. The predicted values of energy consumption for the objects of the mining enterprise are stored in the relational database of attributes for each calculation month (quarter). The results of unloadings are also stored there, deviations of the actual volumes of unloadings from the values specified in the framework of contractual obligations are additionally calculated.

Visualization of a summary graph of load reduction for a mining enterprise implemented using the graphical user interface of the IoT platform, available on the company's local network as a web server [36].

The presented cybernetic approach implies the possibility of introducing new analytical functions that improve the efficiency of estimating the total cost of electricity at a mining enterprise [37]. However, before using the above architecture scheme in practice, it is necessary to adapt the database and prediction blocks, taking into account the characteristics of specific enterprises. In particular, information security issues should be additionally considered, which are placed in the block of registration and authorization of users in the diagram.

Conclusion. The cybernetic approach to price-dependent demand response for electricity consumed by an underground mining enterprise involves providing the user with the following graphical screen forms:

• power consumption summary (including base load);

• report on the fulfillment of requests for unloading, logs of information exchange between the aggregator and consumers (statistics of requests, confirmation of readiness to fulfill requests);

• information on the calculation models for the distribution of SO commands by loads;

• base load forecasts, MFU unloading results, expected load energy profile calculations using Modelica Digital Twin [38, 39].

An example of a screen form showing the real power consumption of a MFU without unloading (*Active_power_Power_Station*) baseline plots (*demand response baseline*), base line with unloading (*demand response discharge*), predictive unloading profile (*demand response expected*) in the day ahead mode is shown in Fig.5.

It is proposed to build two types of reports for end users of the platform:

• PLAN report with predicted cumulative load reduction schedule according to the algorithm, which presents the baseline, predicted and expected load schedules, the RRMSE score as a metric for forecast accuracy, energy deficit and surplus. The following parameters are used: target day, time and duration of load shedding, total shedding volume (MW).

• FACT report that shows the actual graph of the cumulative load reduction. It shows base load curve, actual energy consumption, set load reduction commitments, RRMSE as a predictive accuracy metric, unload result (success/failure) by hour. The following parameters are used: target day, time

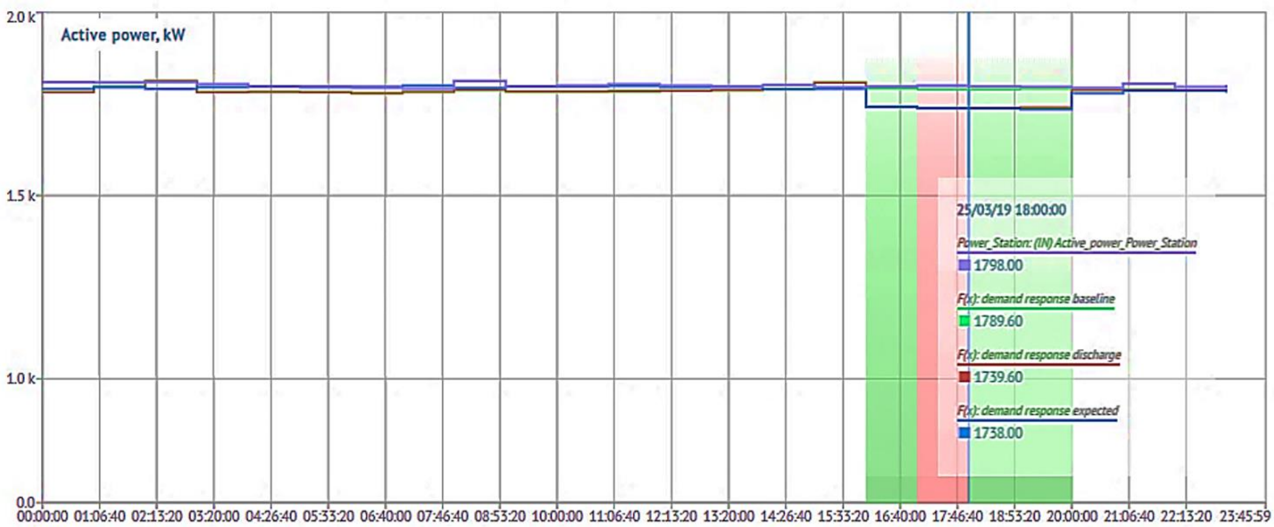

Fig.5. Modeling the load reduction on the MFU of a mining enterprise for the day ahead

and duration of unloading, total amount of load shedding (MW), load shedding readiness indicator, electricity demand response event presence indicator.

Consumers of a mining enterprise can be connected to the IoT platform with an implemented price-dependent demand response service in the following ways:

• By installing hardware (master controllers) in the infrastructure of a mining enterprise. Controllers will allow you to receive data on energy consumption, as well as automatically control the load of the consumer based on pre-installed scenarios or commands through a user application.

• It is assumed that the consumer has a high level of energy management automation (EMS). Then the integration of the platform can be implemented by software (without installing additional hardware) – connecting the IoT platform to the consumer's EMS and receiving data on energy consumption from it.

The presented cybernetic model of electricity demand response can be built into the cyber-physical ventilation system of an underground mining enterprise, in which all kinds of scenarios for changing technological processes and parameters of the involved electrical equipment will be implemented.

The analysis of the information received will be carried out by the Internet of Things platform, as a result of which at least two possible scenarios for reducing load consumption will be developed:

• based on the analysis of the operating modes of all energy consumers obtained from the readings of electricity meters;

• based on an analysis of external factors (reduction of unplanned load), for example, on the basis of a change in the parameters of the outside air that enters the mine shafts and affects the distribution of air between them (the volumetric flow rate of the incoming air changes due to a change in the value of the general mine natural draft), and therefore for the work of the MFU.

When analyzing external factors, as a result of modeling technological processes in a digital twin, it is possible to predict in advance (for example, within a day) options for a possible decrease in the performance of the MFU and, consequently, the consumed electricity.

The architecture considered in the paper will allow underground mining enterprises to occupy a niche in the DR price-dependent energy demand response market, thereby achieving sustainable development and adhering to energy saving policies. From the point of view of achieving a financial result, an enterprise can reduce the cost of the mining process to 700 thousand rubles. per 1 MW as a result of a decrease in electric power during the hours established by the SO.

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