Проведено аналіз критеріїв підвищення економічної ефективності при експлуатації електроенергетичного обладнання енергоблоків електростанцій. В існуючих методиках розрахунку економічного ефекту не враховуються чинники, які призводять до економічних витрат при остановах енергоблоку і зниженні навантаження електроспоживачів. Значним фактором у підвищенні економічної ефективності при експлуатації автоматизованих систем управління технологічними процесами на енергоблоці електростанції є оперативний контроль з виявлення низького рівня ступеня достовірності інформації. Показано, що надійність функціонування технологічного обладнання енергоблоку істотно залежить від ефективності автоматизованого управління у позаштатних ситуаціях, коли відбувається несанкціоноване зупинення енергоблоку, через помилкове спрацьовування. Виявлено, що причиною помилкових спрацьовувань є інформація про параметри технологічного процесу енергоблоку, яка характеризується низьким ступенем достовірності. Показано, що непередбачене несанкціоноване зупинення енергоблоку і зниження навантаження для електроспоживачів призводить до значних економічних і матеріальних втрат, а, отже, і до зниження економічної ефективності при автоматизованому управлінні енергоблоком. Показано, що у застосовуваних економічних моделях не враховуються фінансові та матеріальні витрати, які відбуваються через несанкціоноване зупинення енергоблоку і зниження навантаження для електроспоживачів при помилкових спрацьовуваннях в режимі реального часу. Розроблена єдина інтегрована економіко-математична модель, яка дозволяє розрахувати економічний ефект з урахуванням зміни надійності технологічного обладнання енергоблоку, за рахунок своєчасного оперативного виявлення помилкових спрацьовувань і інформації з низьким ступенем достовірності. Для розрахунку економічного ефекту на основі розробленої єдиної економіко-математичної моделі запропоновано модульний блок режиму нештатних ситуацій, зв'язаний з модулями помилкових спрацьовувань і аварійних ознак, який враховує статичні і оперативні економічні складові. Надано практичні рекомендації для застосування економічного модуля в програмно-технічному комплексі енергоблоку, що дозволяє проводити розрахунки економічного ефекту на основі статичних даних, що надходять з пам'яті даних і поточних даних з енергоблоку

Ключові слова: нештатний режим енергоблоку, критерії ефективності, методика розрахунку економічного ефекту

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COST-EFFECTIVENESS IN MATHEMATICAL MODELLING OF THE POWER UNIT CONTROL

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1. Introduction

The reliable and efficient operation of power units at thermal power plants (TPPs) and nuclear power plants (NPPs) in all operating modes is ensured by the use of I&C complexes of automated process control systems (APCSs) [1]. One of the most important requirements for I&C complexes of APCSs is reliable operation of a power unit with high economic parameters, based on a certain speed determined by the speed of the technological process when performing specified functions [2].

Due to the continuous increase in the automation of power units, the issues of economic efficiency of the operating and modernized I&C complexes of APCSs are becoming increasingly relevant. This is primarily due to the fact that significant costs are spent on hardware and software of I&C complexes of APCSs, and their maintenance and repairs claim heavy expenses by the operating personnel of TPPs and NPPs. The relevance of efficiency issues in the automation of the technological process control has especially increased at the present time since I&C complexes of APCSs use expensive electronic computer systems whose functioning requires qualified service [3].

By this time, there have been practically no studies of the dependence of economic efficiency on the increasing automation of the technological equipment control in abnormal modes of TPP and NPP power units.

The main reasons are that the existing methods accept only statistical data as the sources of economic efficiency of APCSs to calculate the annual economic effect and material costs. In the calculations of economic efficiency, this approach does not allow taking into account the dynamics of changing characteristics of the technological process parameters, especially when they deviate from the norm, in abnormal modes of TPP and NPP power units.

As is known [4], the sources of economic efficiency as well as the nature and degree of APCS impact on the economic parameters of electricity generation depend on the functional, algorithmic, software and technical solutions. However, due to the specific features of APCS functioning in abnormal modes of the power unit, it is necessary to take into account instead of specific economic efficiency its function depending on the time, nature and degree of data reliability [5]. This puts forward new additional requirements for comparability of economic efficiency calculations, taking into account the criteria for the reliability of information on technological parameters of a power unit in an abnormal mode.

According to many experts [6, 7], automation in the determining and analysis of economic factors exerts a significant economic effect due to the possibility of obtaining reliable and objective information about the parameters of the technological process of a power unit in real time.

Study [8] analyses the deviation of technological parameters from the norm, based on a change in the electrophysical parameters of intelligence signals that carry alarm signs. However, obtaining only a temporary criterion for assessing emergency signs of the technological parameters, with no regard for the impact of the degree of data reliability, does not give an objective assessment of the economic efficiency of the power unit control in real time.

Therefore, timely assessment of the information on technological parameters for the degree of its reliability, can significantly affect the operating modes of a power unit (for example, shutdown and reduction of a load of a power unit). In addition, low-reliability information can lead to distortion of control signals, generate false responses of actuators, process protections and interlocks and put the power unit into an abnormal mode [9].

Thus, the relevance of the research direction consists in studying the impact of low-reliability information about technological parameters on the economic efficiency of automated control of a power unit in abnormal modes.

2. Literature review and problem statement

One of the previous studies [10] analyses reliability criteria for the technological equipment of a power unit (TEPUs) at thermal and nuclear power plants (TPPs and NPPs). A quantitative assessment of reliability parameters of the power unit showed that the authors took into account only the total time of emergency operation of the technological equipment and the number of failures in a given time interval, i. e. the reasons for the shutdown of the power unit were not specified. In addition, when calculating reliability factors, the researchers overlooked the criteria and the degree of reliability of information on the characteristics of technological parameters in real time. Such an approach can lead to unpermitted shutdowns of the power unit, reduce the load for energy consumers, and, consequently, result in significant economic losses.

It was shown in [11, 12] that the economic effect of modernizing the systems of the power unit technological equipment control is determined, first of all, by a decreased damage from failures and accidents due to a higher reliability of the main equipment. In addition to failures of the technological equipment, there were also considered failures of APCS technological means, such as elements of a microprocessor system, the quality of which has the greatest impact on the reliability and efficiency of the technological equipment of a power unit [13].

In [14], there was proposed a methodology to assess the economic efficiency of an innovative system (IS). It allowed calculating the main components of the economic effect of new control elements for the power unit technological equipment. The devised methodology for calculating the economic efficiency of ISs is notable for taking into account both sudden and gradual failures. However, this technique considers only the average time between failures of technical equipment, without detecting random influences, which can lead to false alarms of automation, reducing the equipment reliability.

In [15], there were studied the sources of economic efficiency, the nature and degree of the APCS impact on the performance indicators (PI) and the dependence on functional, algorithmic, software and technical solutions. The study presented peculiarities of evaluating the economic automation of energy facilities. They consist in calculating the economic effect based on determining the technical effect by the control object, technical means of management, and maintenance staff.

Study [16] focused on the dependence of economic efficiency (EcEf) on the reliability of the power-generating equipment during shutdowns of a power unit and reduced energy consumer loads. It was shown that the economic effect is achieved mainly by saving fuel and material resources spent on repair and restoration of power units at TPPs and NPPs.

It was shown in [17] that the source of economic efficiency in the APCS operation is the high speed of transmission, processing of information about the state of the technological process parameters, and issuing control commands. However, this does not provide for operational monitoring of low-reliability information, which may lead to false control commands to actuators, process protections and interlocks of the power unit.

The authors of another study [18] proposed to increase the economic efficiency by integrating hardware and software on I&C complexes of APCSs of the power unit at the upper, middle and lower levels with certain economic models. However, the use of individual models does not allow processing information in real time, and, therefore, calculations of the economic effect are approximate.

A significant factor in improving the reliability and economic efficiency of APCSs at TPP and NPP power units is the operational monitoring and detection of random information signals that affect the information reliability.

Study [19] focused on the deviation of technological parameters from the norm, based on changes in the electrophysical parameters of information signals carrying alarm signs. However, there was obtained only a temporary criterion for assessing emergency signs of technological parameters, disregarding the influence of the information reliability degree, which affects assessment of the efficiency of a power unit control in abnormal modes.

Therefore, timely assessment of information on technological parameters for the degree of its reliability can significantly affect the functioning of technological equipment and lead to a change in the operating mode of a power unit (for example, shutdown of a power unit). In addition, low-reliability information can distort control signals, generate false responses of actuators, process protections and interlocks and put the power unit into an abnormal mode.

The above differences in the assessment of economic efficiency while introducing APCSs, are explained by the difference in calculation methods, a variety of premises from which the authors proceeded, as well as different operation conditions of power plants [19]. These include different fuel prices, unequal load schedules, different levels of staffing, different organizational structure, and other factors. It is important that the data on savings due to an increase in the reliability of the power-generating equipment differ most in these estimates, which indicates difficulties and low accuracy in assessing the corresponding sources of savings.

The analysis shows that reliability and efficiency of automated control of the power unit technological equipment in normal operation depends on the degree of reliability of the information on technological parameters. However, the influence of low-reliability information, especially for abnormal modes of a power unit, on the formation of control signals with signs of emergency had not been sufficiently studied.

Inaccurate information can generate false control signals to actuators, process protections and interlocks, which will lead to power unit shutdowns due to false alarms.

Reliability of information is one of the main criteria for the reliability of APCSs when generating control commands for actuators, process protections and interlocks to put the power unit into safe operation mode.

Unpermitted shutdown of a power unit and load reduction lead to significant economic losses (fuel, materials, repair and restoration work, etc.).

All the above mentioned confirms the feasibility of further studies of APCSs using advanced models and algorithms that take into account the degree of reliability of information in the methods for calculating the economic efficiency of automated control of power units in contingency.

3. The aim and objectives of the study

The aim of the study is to detect low-reliability information on the technological parameters in real time to increase the economic efficiency of automated control of a power unit in abnormal modes.

To achieve the aim, the following objectives were set:

– to improve the information-algorithmic scheme of I&C complexes of APCSs for power units at TPPs and NPPs during the equipment operation in abnormal modes;

– to improve the economic and mathematical model for calculating the economic effect, taking into account the flow of failures and the degree of reliability of information on technological parameters;

– to improve the methodology for calculating the economic effect for automated control of a power unit in abnormal modes;

– to design and introduce an emergency modular unit coupled with a false positive detection and alarm control module for the APCS of a power unit;

– to conduct experimental studies that would confirm the theoretical findings.

4. Validation of the APCS structure in regular and abnormal operation modes

Working out the structure of the APCS for a power unit is characterised by real-time monitoring of the process parameters and taking into account the criterion of control optimality.

To date, the most widely used are the structures of APCSs in the regular operation mode, where the main processing of information is carried out in the central control unit (CCU) (Fig. 1).

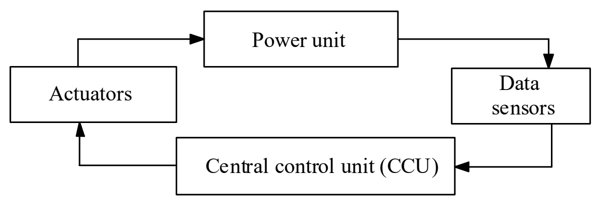

Fig. 1. A structure of the APCS with fully centralised information processing for the power unit in the regular operation mode

With this approach, the processing speed of data on changes in technological parameters is reduced, which affects the effectiveness of control signals on actuators, control and lock-up devices.

Therefore, we suggest the structure of the APCS where information is partially processed in the central control unit (CCU) and partially transmitted from control sensors directly to logic and analogue machines as well as technological protection devices (Fig. 2).

With such a control system, the central device is made in the form of a control computer, which allows you to change the task of local controllers, coordinate the work of logic machines, and monitor the progress of control operations.

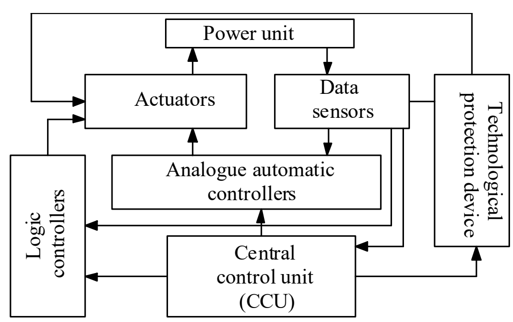

Fig. 2. A structure of the APCS with partially decentralised information processing for the power unit in the regular operation mode

It should be noted that the main problem of ensuring normal operation of the power unit is the control of information reliability when the unit goes into an emergency operation mode. Modern NPPs and TPPs are characterised by a large amount of discrete control, especially in non-stationary emergency modes (unpermitted shutdown and subsequent restart of the power unit).

Unpermitted shutdown and subsequent restart of the power unit may be due to false responses of the process protections and interlocks. Therefore, the structural schemes of the APCSs for regular operation modes should necessarily include auxiliary structural elements such as separate modules for checking the information reliability. Also, it is necessary to control the deviation of the technological process parameters from the norm in non-stationary abnormal operation conditions.

In this regard, it is proposed to perform the task of automated control of the power unit in abnormal operation conditions on the basis of the standard control system using an additional emergency modular unit (Fig. 3). This module will allow for efficient control of the power unit based on the improvement of software, hardware and mathematical models for random operational disturbances in real time.

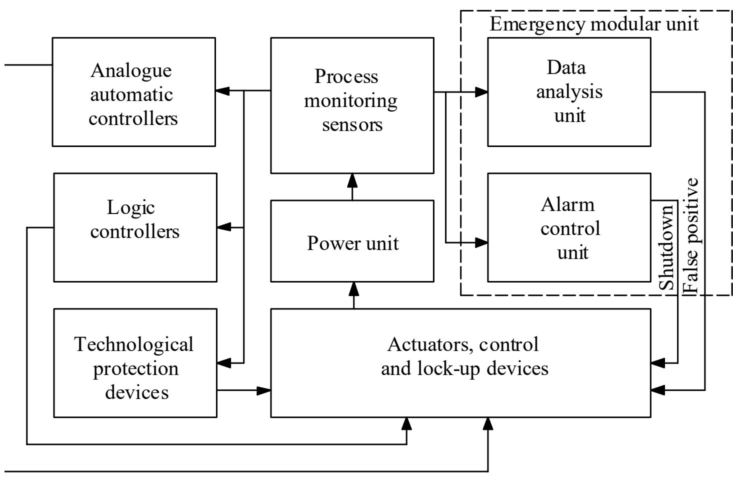

Fig. 3. A structure of the APCS for the power unit in abnormal operation conditions

Thus, the APCS of a power unit during its operation in abnormal operation conditions with the emergency modular unit, can take the form shown in Fig. 3.

In the proposed schematic version of the APCS structure, the validity and reliability of the received control signals must correspond to the real-time process control algorithm.

With the power unit equipment working in an abnormal mode, such structure of the APCS allows taking into account (at all levels of control) the following factors:

1. Stabilization of processes according to the set operation values of the technological parameters to ensure the safety of the technological equipment using automatic regulators, gauges, and automatic protection.

2. Carrying out operational correction of the control system (changing the settings of regulators, switching during non-stationary modes or when changing the type of fuel) in accordance with the parameter tables and operational technical manuals.

3. Adjustment of algorithms when changing the properties of an object (to optimize the parameters of correction algorithms) based on parameter tables and instructions.

4. Calculating the values of cost-effectiveness and quality of the process, their analysis, decision making, and reporting.

To implement the above factors and solve the control problems in emergency situations, we propose the following information-algorithmic scheme for the structure of the APCS of a power unit (Fig. 4).

It is necessary to consider the features of the information-algorithmic scheme of the APCS used when operating the power-generating equipment in abnormal modes of the power unit.

When collecting discrete information and primary processing of the measurement information, digital data are additionally sent to the data analysis unit to control the reliability of information on the process parameters (Fig. 3).

In the data analysis unit, the "False response" signal is generated to clarify the dynamic and probabilistic characteristics, whereas the "Stop the power unit" signal serves to detect suitable conditions for switching over at the start-up and for fallback to technical protection actuators of the power unit.

When an emergency is detected using emergency recorders, digital data are additionally sent to the alarm control module for their analysis and decision-making.

As a result of digital code processing in the alarm control module, a control signal is formed to change the operation mode of the power-generating equipment, i. e. transfer the power unit into the emergency mode.

Thus, the scientific validation of the structure of the power unit APCS in normal and emergency situations allows us to conclude that such structures are possible, to identify false alarms of equipment and inaccurate data on the technological parameters.

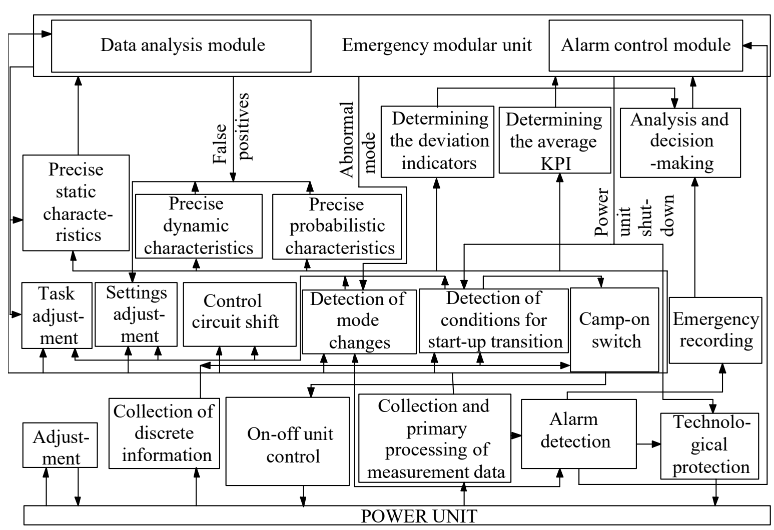

Fig. 4. The information-algorithmic diagram for the APCS of the power unit in abnormal operation conditions

5. Improving the methods for calculating the economic effect of automated control of the power unit

5. 1. Recommendations to improve reliability and economic efficiency of automated systems

The components to improve reliability and efficiency of the power unit are as follows:

– a more accurate control of normal technological parameters that determine the reliability of the power unit equipment;

– a lower thermal stress during start-ups;

– a developed diagnostic system for technological equipment;

– high reliability of the operator, which is determined by improving his interaction with the technology based on the person's psychophysical capabilities;

– fewer deviations in the technological parameters that determine the coefficient of performance (COP) of the power unit;

– higher average technological parameters that determine the COP of the power unit;

– optimized technological modes;

– a prompt personnel's response to deviations from the normal economic parameters;

– a lower heat loss during start-ups.

In this case, the economic requirements for technical means are the following:

– minimum capital investments in the complex of technical devices;

– minimum production space for the complex of technical devices;

– minimum costs for auxiliary equipment.

APCSs for power-generating objects are designed based on the economic principle that determines the choice of mathematical methods and models, the content of the used information, as well as necessary technical systems and software.

The CPM economic efficiency of the APCS I&C complexes is ensured by solving the following tasks:

1. Securing the cost-effectiveness of information due to the minimum cost of its processing, storage, transmission and reduction of the volume of data, as well as choosing the best forms to represent commands, operations and codes.

2. Providing operational control of the technological process due to the timely optimal solutions.

3. Reducing the number of failures and false positives with the timely detection of low-reliability information.

4. Reducing the cost of expensive computing equipment by introducing a modular principle to solve the tasks and functions of the APCS I&C complexes when the TPP and NPP power units are operating in real time.

5. Reducing the operations staff, with the control functions performed by modern highly effective technical means, which have a high speed of operations and management commands.

6. Reducing the number of pre-emergency and emergency situations due to operational control and impact on the deviation in the technological parameters of the power unit technological process.

5. 2. Assessment criteria for the economic effect in abnormal modes of the power unit

As is known [1–4], to date calculations and validation of the economic efficiency of automation systems for control of technological processes at power units are carried out based on the Typical Methodology for Determining the Economic Efficiency of Capital Investments.

This methodology [5] uses the current operational and one-time capital costs for the design and implementation of APCSs as the main indices of the automation system performance.

An analysis of the methods for calculating the economic effect of automated control, carried out on the basis of [1–4, 14], shows that most appropriate is calculation of the annual economic effect E_{aef} based on the annual savings. The operational and economic costs of hardware and software of APCSs are taken into account as additional conditions, as shown in the following equation (1):

$$E_{aef} = \Delta U - E_n \cdot \Delta Q, \text{ UAH,} \qquad (1)$$

where ΔU is the annual savings in operating costs of APCSs of TPPs and NPPs; E_n is a normative coefficient of economic efficiency (for the electric power industry, it is E_n=0.15); ΔQ is additional operational economic costs for hardware and software of APCSs of TPPs and NPPs.

Note that in the existing methods for calculating the economic effect, the components of the annual savings ΔU are based on statistical data for the year and do not take into account the current changes in abnormal modes of the power unit.

In addition, this technique does not allow taking into account the characteristics of parameters with a low degree of reliability, which significantly affects the number of failures of technological equipment in abnormal operation conditions. As a result, failure of the technological equipment of the power unit can lead to significant economic losses, for example, the daily idle time of a TPP power unit is estimated as the equivalent of 250,000–300,000 US dollars, and its restart – up to 150,000 US dollars [12].

Thus, to improve the methods for calculating the economic effect, it is necessary to select the assessment criteria that will take into account the degree of reliability of information in real time. At the same time, the economic efficiency of introducing microprocessor modules for evaluating low-reliability information should be based on comparison with the initial level of automation of the technological process.

Therefore, it is necessary to select and propose criteria for calculating the savings ΔU_{rtm}, in real time, for abnormal modes of a power unit, especially when a power unit is stopped and the load is reduced because of false alarms.

The authors of the study suggest calculating the benefits with regard to the following components of savings ΔU_{rtm} in real time:

– savings due to changes in the auxiliary power consumption of the power unit during its shutdowns and restarts;

– savings due to changes in the operational efficiency of the power unit when detecting alarm signs of deviations in technological parameters.

Let us consider what effect is exerted on savings ΔU_{rtm} in real time due to changes in the auxiliary power consumption of the power unit ΔU_{rtm} during its shutdowns and restarts.

As is known [4], the auxiliary power consumption of the power unit depends on the energy spent on power generation ΔW_{PG} and the power unit start-up W_{PUS}, as is shown in the following equation (2):

$$\Delta W_{ON} = W_{PG} + W_{PUS}, \tag{2}$$

where W_{PG} is energy spent on power generation; W_{PUS} is energy spent on the power unit start-up.

Power-plant consumption W_{PG} for power generation is calculated in thousands kWh by the following equation (3):

$$W_{PG} = \left(E_b^{ON} + E_{pg}^{ON}\right)\cdot K_{pg} + E_t^{ON}, \tag{3}$$

where E_b^{ON} is power consumption by the power-plant boiler, thousand kW h; E_{pg}^{ON} is power consumption by the power-plant unit when receiving heat transfer for power generation, thousand kW·h; K_{pg} is the share of the power-plant electric boiler; E_t^{ON} is power consumption by the power-plant turbine, thousand kW h.

After the power unit is shut down, it is restarted. The amount of consumed electricity to restart the power unit is found from following expressions (4), (5):

$$W_{PUS} = E_{PP}^{ON} + \begin{pmatrix} N_{wt} + N_{st} + N_{bi} - \\ -N_{pp} - N_{fg} - N_{tfg} \end{pmatrix}\cdot \tau \cdot 10^{-3}, \tag{4}$$

$$E_{PP}^{ON} = \begin{bmatrix} l_{wt}\cdot N_{twt} + l_f \cdot N_{tf} + \\ + l_{sf}\cdot\left(N_{ft} + N_{bp}\right)\cdot \tau_0 \end{bmatrix} + E_{him}\cdot \tau \cdot 10^{-3}, \tag{5}$$

where E_{PP}^{ON} is the plant-wide auxiliary power consumption related to the power unit operation;

N_{wt} is the capacity of the working transformer of the power unit, kW;

N_{st} is the capacity of the spare transformer of the power unit, kW;

N_{bi} is the capacity of each backup power input unit per each section of 6 kW, kW;

N_{pp} is the capacity of each transformer (mechanism) connected to the input sections of the power unit;

N_{fg} is the capacity of blowers and flue gas desulfurization pumps, kW;

N_{tfg} is the capacity of the electric motor of the smoke exhaust fan for flue gas denitrogenation, kW;

l_{wt} is the share of the plant-wide needs associated with water treatment related to the power unit operation;

N_{twt} is the capacity of chemical water treatment transformers, kW;

l_f is the share of the plant-wide needs associated with fuel oil facilities of the power unit;

N_{tf} is the capacity of the transformers of the fuel oil facilities, kW;

l_{sf} is the share of the plant-wide needs associated with solid fuel, related to the power unit operation;

N_{ft} is the capacity of the fuel supply transformers, kW;

N_{bp} is the capacity of each dredging pump;

E_{him} is power consumption for other mechanisms of the heating unit; it is obtained from the equation.

Therefore, based on the foregoing, the auxiliary power consumption of the power unit depends on the electrical energy spent on restarting the power unit after its shutdown, i. e. on the number of the power unit failures due to false responses.

In view of this, it is proposed to determine the savings due to changes in the auxiliary power consumption ΔU_{ON} of the power unit when it is stopped, which depends on the number of repeated starts in case of power unit failures due to false alarms, as follows (6):

$$\Delta U_{ON} = \Delta n \cdot \left(W_{PG} - W_{PUS}\right)\cdot S_{EL}, \tag{6}$$

where $\Delta n = n(t_2) - n(t_1)$ is the number of predicted failures of the power unit, recorded respectively when time t_1 and t_2 expired, which lead to the shutdown of the power unit;

$S_{EL} = b_{el}\cdot z_f$ is the average fuel component in the cost of net electricity supply by the power unit;

b_{el} is specific consumption of the fuel equivalent to produce electricity;

z_f is the price of fuel used to produce electricity.

As follows from [19], the number of power unit failures is determined by the failure flow parameter $\Delta n \cong P(t)$.

Study [19] focused on the dependence of the failure flow $P(t)$ on the number of false alarms N_{FA} and produced the following equation (7):

$$P(t) = \frac{N_{FA}\left(T_c + \Delta T\right) - N_{FA}\left[T_c - \left(\dfrac{\ln \Delta d_{fi}}{\left(\ln^2 2\right)\left|\Delta I_{\Sigma is}\right|} - \Delta T\right)\right]}{\left(T_c + \Delta T\right) - \left[T_c - \left(\dfrac{\ln \Delta d_{fi}}{\left(\ln^2 2\right)\left|\Delta I_{\Sigma is}\right|} - \Delta T\right)\right]}, \tag{7}$$

where N_{FA} is the number of false alarms; T_c is the cycle time; $\Delta T = t_2 - t_1$ is time increment, when false alarms are detected after t_1 and t_2; $\Delta I_{\Sigma is}$ is an increment in the amount of information characterising the degree of reliability; Δd_{fi} is a change in the fractal information dimension.

Then, substituting formula (7) into (6) and taking into account the average fuel component S_{EL}, we obtain the following equation (8):

$$\Delta U_{ON} = \left(W_{PG} - W_{PUS}\right)\cdot b_{el}\cdot z_f \times$$
$$\times\left(\frac{N_{FA}\left(T_c + \Delta T\right) - N_{FA}\left[T_c - \left(\dfrac{\ln \Delta d_{fi}}{\left(\ln^2 2\right)\left|\Delta I_{\Sigma is}\right|} - \Delta T\right)\right]}{\left(T_c + \Delta T\right) - \left[T_c - \left(\dfrac{\ln \Delta d_{fi}}{\left(\ln^2 2\right)\left|\Delta I_{\Sigma is}\right|} - \Delta T\right)\right]}\right). \tag{8}$$

The equation (8) shows that the savings due to changes in the auxiliary power consumption depend on the reduction in the consumption of power spent on restarting the power unit after its shutdown. This is achieved by reducing the number of unpermitted failures of the power unit when identifying and recording false alarms by actuators of the process protections and interlocks in the power unit technological equipment.

Consider the savings due to changes in the operational efficiency of the power unit, which according to [9] is obtained from the following equation (9):

$$\Delta U_\eta = S_{af}\cdot W_{ra}\cdot \eta_E, \tag{9}$$

where $S_{af} = b_e\cdot z_{fc}$ is the average fuel component of the cost of net electricity supply; b_e is specific consumption of fuel equivalent for electricity production; z_{fc} is the fuel component; $W_{ra} = h_y\cdot f\cdot N_{nom}$ is the amount of electricity supplied by the power unit annually; h_y is the time (hours) when the set capacity was used; f is the set power factor; N_{av}/N_{nom}; N_{nom} is the rated load of the power unit; η_E is the efficiency of the power unit during normal operation without deviation of the parameters from the norm.

As is known [1], in the regular operation mode, the efficiency of a power unit is described by equations (10), (11):

$$\eta_E = \frac{A}{\tau}\prod_{i=1}^{i=k}\left[\begin{array}{l} 1+\alpha_i\left(x_{i\,ad}-x_{ax}\right)\times \\ \times\left(\dfrac{1+sign\left(x_{i\max}-x_{i\,ad}\right)}{2}\right)\end{array}\right], \quad (10)$$

$$x_{ax} = \frac{\sum_{\gamma=1}^{r}\int_{t_{\gamma2}}^{t_{\gamma1}} x_i \mathrm{d}t}{\sum_{\gamma=1}^{r}\left(t_{\gamma2}-t_{\gamma1}\right)}, \quad (11)$$

where A is the coefficient of proportionality; τ is the start time; α_i is a coefficient that takes into account a decrease with an increase in the permissible boundary value of the i heating parameter; x_{iad} is a permissible deviation of the parameter; x_{imax} is the average value of the parameter excess during its deviation from x_{iad}; x_{imax} is maximum deviation of the parameter during the start-up period; t_{y1} and t_{y2} are the moments of the beginning and end of the parameter exceeding the permissible value x_{iad};; r is the number of excesses at the start-up.

It can be seen from expressions (10), (11), the deviation of the parameters from the norm Δx_i is determined only by the averaged values of the parameter excess x_{ax} relative to the permissible deviation x_{iad} for the time interval $\Delta t=t_{y2}-t_{y1}$. This is recorded only by the initial and final points in time, which generally leads to inaccuracies in calculations of the power unit efficiency.

Therefore, for x_{ax} in expression (11), it is necessary to regard the time of return τ_f of the technological parameter characteristics to normalized values, i.e. take into account the alarm signs (12):

$$x_{axf} = \frac{\sum_{\gamma=1}^{r}\int_{t_{\gamma2}}^{t_{\gamma1}} x_i \mathrm{d}t}{\sum_{\gamma=1}^{r}\left(t_{\gamma2}+\tau_f\right)-t_{\gamma1}}, \quad (12)$$

where τ_f is the time of returning the technological parameter characteristics to normalized ($\tau_f \leq t_{y1}$) or emergency values ($\tau_f > t_{y1}$). Therefore, taking into account the time of returning the parameters to normalized values from expression (12), we obtain the value of the the power unit efficiency taking into account alarm signs, i. e. deviation of the technological parameters from the norm (13).

$$\eta_{cr} = \frac{A}{\tau}\prod_{i=1}^{i=k}\left[\begin{array}{l} 1+\alpha_i\left(x_{i\,ad}-\dfrac{\sum_{\gamma=1}^{r}\int_{t_{\gamma2}}^{t_{\gamma1}} x_i \mathrm{d}t}{\sum_{\gamma=1}^{r}\left(t_{\gamma2}+\tau_f\right)-t_{\gamma1}}\right)\times \\ \times\left(\dfrac{1+sign\left(x_{i\max}-x_{i\,ad}\right)}{2}\right)\end{array}\right], \quad (13)$$

Thus, the relative change in the power unit efficiency, in view of alarm signs, i. e. deviations of the parameters from the norm, takes the following form (14):

$$\frac{\Delta\eta_E}{\eta_E} = \frac{\eta_E-\eta_{cr}}{\eta_E}. \quad (14)$$

Then, expression (9), taking into account (13) and (14), will take the form (15):

$$\Delta U_\eta = S_{af}\cdot W_{ra}\cdot\frac{\eta_E-\eta_{cr}}{\eta_E}. \quad (15)$$

Therefore, the savings due to changes in the operational efficiency of the power unit ΔU_η, depend on taking into account the duration of the restoration ($\tau_f \leq t_{y1}$) or non-restoration ($\tau_f > t_{y1}$) of the technological parameter characteristics when they deviate from the normalized values.

Thus, the real-time savings ΔU_{rtm} in abnormal modes of the power unit technological equipment are obtained from the following expression (16):

$$\Delta U_{rtm} = \Delta U_{ON} + \Delta U_\eta. \quad (16)$$

Then, the economic effect of E_{rtm} in real time, taking into account both false positives with a low degree of information reliability and alarm signs when the technological parameters deviate from the norm, are obtained from the expression (17):

$$E_{rtm} = \left(\Delta U_{ON} + \Delta U_\eta\right) - E_n\cdot\Delta Q_{\mathrm{mod}}, \quad (17)$$

where ΔU_{ON} is savings due to changes in the auxiliary power consumption of the power unit; ΔU_η is savings due to changes in the operational efficiency of the unit; E_n is the normative coefficient of cost-effectiveness (for the electric power industry); $\Delta Q_{mod}=Q_c+Q_i+Q_u+Q_l$ is pre-production costs of the development, installation of modules and modernisation of the APCSs; Q_c is the cost of computing operations; Q_i is the cost of installing modules; Q_u is the cost of modernisation of modules; Q_l is the cost of the module development and production.

It follows from expression (17) that the cost-effectiveness in abnormal modes of a power unit depends on the degree of the information reliability $\Delta I_{\sum is}$, and the presence of alarm signs η_{cr} concerning the technological parameters in real time. Substituting the parameter values in expressions (1) and (17), we obtain an expression for calculating the total economic effect (18):

$$\begin{aligned} \sum E_{aef} &= E_{aef} + E_{rtm} = \\ &= \left(\Delta U + \left[\begin{array}{l}\left(W_{PG}-W_{PUS}\right)\cdot b_{el}\cdot z_f\cdot P(t)+ \\ +S_{af}\cdot W_{ra}\cdot\left(1-\dfrac{\eta_{cr}}{\eta_E}\right)\end{array}\right]\right)- \\ &-E_n\cdot\left(\Delta Q+\Delta Q_{\mathrm{mod}}\right). \end{aligned} \quad (18)$$

Thus, we obtain a unified integrated economic and mathematical model for calculating the economic effect $\sum E_{aef}$, of the power unit APCS operation both per year and in real time.

5. 3. Practical recommendations for calculating the economic effect for abnormal modes of a power unit

To calculate the real-time economic effect for an abnormal mode of a power unit, it was proposed to introduce an emergency modular unit coupled with a false positive detection module (FPDM) and an alarm control module (ACM).

The study suggests practical recommendations on the application of the cost-effective module in the APCS I&C complexes of power unit No. 8 of the Zmiyiv TPP (Ukraine), as shown in Fig. 5.

Practical implementation of the methodology for calculating the economic effect when introducing the cost-effective module coupled with a FPDM and an ACM in the APCS I&C complexes of power unit No. 8 of the Zmiyiv TPP is possible due to the following flow chart (Fig. 5).

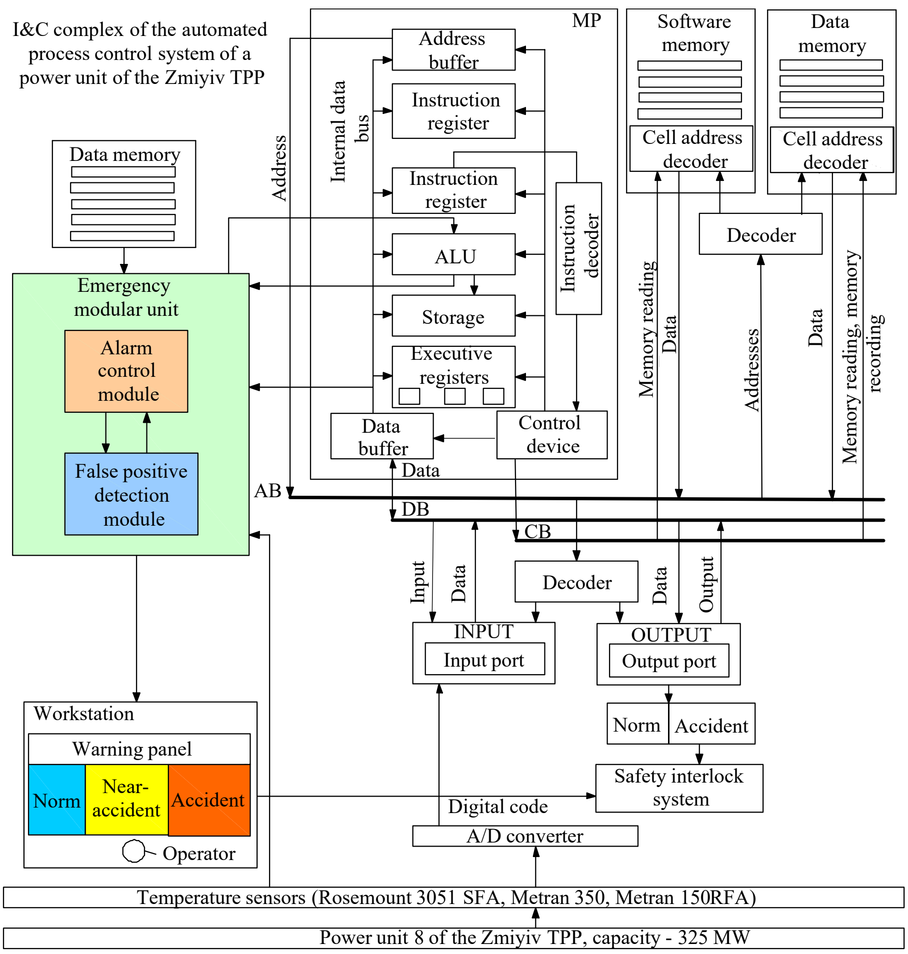

Fig. 5. A flow chart for the cost-effective module coupled with a FPDM and an ACM

It can be seen from the flow chart (Fig. 5) that the emergency modular unit uses for calculation both statistical data obtained from the data memory and current data on technological parameters obtained directly from the power unit. In addition, the current data are processed in an arithmetic and logic unit, then checked for the degree of reliability in the ACM and enter the emergency modular unit. Besides, when calculating the economic effect, one should take into account alarm signals detected in the ACM, in case of deviation of the technological parameter characteristics from the norm. The results of the calculation can be called up in real time by the operations staff on the warning panel of their automated workstation.

5. 4. Results of the numerical experiment on the improved methodology for calculating the economic effect

A numerical experiment of calculating the economic effect of introducing the cost-effective module coupled with the FPDM and the ACM used the Mathcad computer-aided design system.

Quantitative indices for parameters such as fuel consumption, power generation, auxiliary power consumption, power unit efficiency and auxiliary materials of power unit No. 8 of the Zmiyiv TPP served as initial data.

Calculations by formulae (2)–(18) have given the following main components of the economic effect:

– savings due to maintaining the reliability of the power-generating equipment of the power unit with a load decrease was 10÷17 %;

– savings due to maintaining the reliability of the power-generating equipment of the power unit at its shutdown amounted to 18÷25 %;

– savings by reducing emergency power shortages to consumers amounted to 7÷10 %;

– savings by reducing downtime amounted to 8 %.

A numerical experiment with the economic module coupled with the FPDM and ACM for the TPP power unit showed that the quality of identifying parameters with alarm signs improved on average by 24 %. With this in mind, the annual reference fuel (RF) savings at one power unit can reach 200 tonnes, which is equivalent to ≈800,000 c.u. per year with a total average annual economic effect of about 1 mln c.u.

Calculations show that it is advisable to introduce 240 sets of FPDMs and ACMs at power unit No. 8 of the Zmiyiv TPP.

The overall cost-effectiveness at all power units of the Zmiyiv TPP from the introduction of special software modules to the APCSs, taking into account the costs of research and implementation, amounted to 5.2. c.u. against 1.0 c.u. in the costs.

It should also be noted that the economic effect from introducing an alarm control module to the information and control system *Complex Titan-2* in the APCS of power unit No. 8 of the Zmiyiv TPP, with regard to additional costs, is ≈35.0 c.u.

Thus, the total cost of modules for detecting alarm signs for one power unit of a power plant is 8,500 c.u. To compare, failure of the power-generating equipment due to false alarms results in the power plant suffering losses of ≈30,000 c.u. per year (Table 1).

Table 1 shows that in case of false responses and failures of a power unit (once a month), with standard I&C complexes of APCSs, financial losses will amount to ≈30,000 c.u.

Table 1

Data on the dependence of economic effect (c.u.) on the number of false responses at the power unit

Month	The number of false responses	Losses due to false responses (k c.u.)	Economic effect (k c.u.)	RF (t of gas)
1	1	2.4	7.5	25.1
2	1	2.6	7.3	24.9
3	1	2.3	7.8	25.2
4	1	2.8	7.4	25.1
5	1	2.5	7.5	24.9
6	1	2.4	7.7	25.2
7	1	2.4	7.2	24.7
8	1	2.6	7.3	25.1
9	1	2.5	7.1	25.2
10	1	2.7	7.8	25.1
11	1	2.4	7.6	24.9
12	1	2.5	7.7	25.2
Σ per year	12	30.1 k c.u.	89.9 k c.u.	300.6 t of gas equivalent

When introducing an economic module to the information-algorithmic scheme of the I&C complexes of APCSs, with regard to false responses, the average annual economic effect will be ≈90,000 c.u., with savings amounting to ≈300 t of gas equivalent.

6. Discussion of the findings on the efficiency of automated control of the power unit operating modes

The present study shows that, when assessing the dependence of the failure flow on the number of false responses of the technological equipment and the power unit as a whole, it is necessary to take into account the following factors:

– the number of false responses of the technological equipment in case of real-time deviation of its technological parameters;

– life cycle of the technological parameters;

– time interval during which false alarms are recorded;

– change in the amount of information in the information space of the technological process characterising the degree of information reliability;

– change in the degree of filling the information space of the technological process with inaccurate data on technological parameters.

As was shown by the previous studies, to assess the data reliability with the characteristics of technological parameters changed, the "two of three" system is used: a digital code is compared on two channels and considered reliable. This approach does not take into account the information received on the third channel, which can lead to a false response of the technological equipment of the power unit. It is proposed to control the reliability of information on changes in the characteristics of technological parameters in the form of channel-by-channel comparison using the false positive detection module. In this case, the change in the capacity of the information space of the technological process is necessarily taken into account due to the formation of fractal-cluster structures during the time interval from 0 to 2 seconds when the area of abnormal values of the characteristics are formed. The length of the bit codogramme for each information channel is used as quantitative characteristics of the structure of filling the capacity of the information space of the technological process. Thus, the FPDM detects a digital code that deviates from the norm of the technological parameter in real time. This distinguishes the proposed complex from the system "two of three".

It is shown that the real-time economic effect, in contrast to the annual mean, depends on the number of false responses (with low degrees of information reliability) and false positives concerning the technological parameters. In this case, it is necessary to calculate the following:

– savings due to changes in the auxiliary power consumption and changes in the operational efficiency of the unit;

– normative coefficient of cost-effectiveness (for electric power industry);

– pre-production costs: for the development, installation and modernization of APCSs, for computational operations, as well as installation, modernisation, design and production of modules.

Thus, the economic effect in abnormal modes of the power unit is calculated with the use of the economic module based on the unified integrated economic and mathematical model, both per year and in real time.

The obtained results were used to improve the information and algorithmic scheme of the control system of the power unit during the power-generating equipment operation in abnormal modes: there have been introduced modules for monitoring the reliability of information and control of alarms.

In addition, the improved I&C complexes of APCSs of the power unit in an abnormal mode of operation, as exemplified by the Zmiyiv TPP, allows the operations staff to call up results of the economic effect calculation on the warning panel of their automated workstation in real time.

It is advisable to use the proposed emergency modular unit coupled with the FPDM and the ACM for modernising obsolete software and hardware systems of typical APCSs of the power unit at existing TPPs and NPPs in Ukraine.

We can note that the drawback of the study consists in the lack of information links between the proposed modules and the automated system of the enterprise control at TPPs and NPPs.

The usefulness of research on improving the reliability and efficiency of the automated control system of a power unit lies in further integration of control models and cost-effective models at the upper, middle and lower levels into a unified integrated economic and mathematical model for the entire power plant.

The research is a logical continuation of the theoretical studies made by the authors in [19–21], which outline the problems of detecting technological parameters with deviations from the norm, based on the identification of alarms due to the apparatus of the fractal-cluster theory.

7. Conclusions

1. The improved information and algorithmic scheme of the APCS allows controlling the power-generating equipment by introducing the emergency modular unit for abnormal modes to issue control signals for changing the operating mode of the power unit.

2. The devised unified integrated economic and mathematical model, unlike the known ones, allows calculating the economic effect with regard to the following factors:

– changes in the reliability of the technological equipment of the power unit, due to timely prompt detection of false positives using the false positive detection module with a probability of 0.986;

– changes in the reliability of technological equipment due to the detection of false information using the alarm control module with a probability of 0.974.

3. The economic effect of the APCS operation, based on the unified integrated economic and mathematical model, is calculated with the use of the proposed emergency modular unit coupled with the FPDM and ACM modules. It takes into account all static and operational economic components. The average annual economic effect from the economic module coupled with the FPDM and ACM at the power unit of the Zmiyiv TPP, as shown by a numerical experiment, is ≈90,000 c.u., with saving ≈300 t of gas equivalent.

4. Experimental studies have shown that with the introduction of the economic module coupled with the FPDM and ACM, the cost-effectiveness of the typical APCS operation has significantly increased. Taking into account the costs of research and implementation of these modules for the power unit 8 of the Zmiyiv TPP, the costs amounted to 3.1. c.u.

The total annual economic effect, at the stage of implementation of the economic module coupled with the FPDM and ACM, minus operating costs, increased by 17 % due to the following factors:

– savings due to changes in the reliability of technological equipment when the power unit is shut down (10 %);

– reduced losses from undersupply of electricity to consumers, i. e. load reduction (4 %);

– reduced repair downtime (3 %).

5. A numerical experiment with the FPDM and ACM for an 800 MW TPP power unit showed that the quality of identifying the alarm process parameters improved on average by 24 %.

With this in mind, the annual gas equivalent savings at one power unit can reach 200 tonnes, which is equivalent to ≈800,000 c.u. per year with a total average annual effect of ≈1 mln c.u.

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