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# POSSIBILITIES AND PERSPECTIVES OF THE CONSUMERS-REGULATORS APPLICATION IN SYSTEMS OF FREQUENCY AND POWER AUTOMATIC REGULATION

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*The Integrated Energy System (IES) of Ukraine functions as part of the European Union (EU) electric power system ENTSO-E. Each country whose IES operates in the ENTSO-E structure must ensure the presence of a full-fledged frequency and power automatic control system (AFPCS, AFPC system) in the national IES. The only exception is the IES of Ukraine, because its inclusion in the ENTSO-E happened during martial law and in the absence herewith of a full-fledged AFPC system. It violates the cornerstone requirements of the ENTSO-E structure formation. In the post-war period, the IES of Ukraine will be obliged to complete its own, full-fledged AFPCS as soon as possible. Three structures of the AFPC system development of the Ukrainian IES were studied: according to the traditional principle (on the basis of generators-regulators); on the basis of heat consumers-regulators with the involvement of heat pump installations and on the basis of heat consumers-regulators using electric heat generators that provide energy for the centralized heat supply system. Calculations and analysis of technical and economic indicators showed that the traditional structure of AFPCS extremely loses to both structures built on consumers-regulators. Significantly better of these two systems is the AFPCS, built on consumers-regulators in the form of electric heat generators. It provides an annual net profit of more than 1.8 billion USD, with a payback period of about 0.5 years, reduces by 2.7 billion m$^3$ of natural gas consumption, reduces by 13.9 billion USD needs capital investment, has short construction deadlines*. References 20, tables 5.
***Keywords*****:** automatic frequency and power control system, electric heat generator, heat pump installation, capital investment, profit, payback period.

**Introduction.** The reliable and efficient functioning of the integrated energy system is ensured by the simultaneous coordinated interaction in its structure of several complex and diverse technological systems. One of them is the automatic frequency and power control system.

In normal modes, the reliable operation of the IES is supported by the dispatching control. However, in emergency situations (unscheduled shutdown of a large power unit, a powerful power transmission line (PTL), or a large power consumer), the dispatching staff is not able to independently ensure the balance of production and consumption of electricity in the system, because under such conditions, transient electromechanical processes occur in it within parts of a second. Therefore, today, all over the world, the problem of the reliability and stability of the operation of IES in emergency modes is solved by building in their structure special AFPC systems [1]. The power deficit/surplus that appears is eliminated by increasing/reducing the power of generators covered by the AFPCS. In theory, generators of HPP, pulverized coal (PC) and gas-oil fuel (GOF) thermal power plant (TPP) can be used in the structure of AFPCS. One of the main requirements for such generators is to ensure the necessary velocity and have a sufficient range of regulation. In the conditions of the IES of Ukraine, as the analysis shows, the AFPCS, built on regulator-generators, can only use new or reconstructed PC units, since in Ukraine the regulation of NPP units is very limited, GOF units are unprofitable due to high fuel prices, and HPP are not can provide sufficient power.

In addition to this significant limitation concerning the choice of AFPCS regulating equipment there was a negative circumstance in the Ukrainian power system during the entire period of the country's independence up to and including 23.02.2022, namely, there were actually no self-sufficient reserves of automatic secondary regulation of frequency and power in its structure. During the specified period, the IES of


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Ukraine used the services of the AFPCS, which was general to the Russian, Ukrainian and Baltic energy systems. This AFPCS used Volga's HPP as regulating power plants on very favorable economic conditions for Ukraine. Starting from 23.02.2022, the Ukrainian AFPCS was disconnected from the specified general AFPCS and joined to the AFPCS of the European Union energy system ENTSO-E. At the same time, the IES of Ukraine was unable to provide regulatory sources for its AFPCS in the necessary volume. In the current state, their deficit is compensated by the capacities of the AFPCS of the ENTSO-E power system. Under such circumstances, the key technological parameters (frequency, power, etc.) in both energy systems will conform the current regulatory requirements. Thus, during almost the entire period of independence, the IES of Ukraine imported the necessary volumes of regulatory capacities to ensure the functioning of its own AFPCS. The exception was several months of 1997, when the IES of Ukraine operated in an autonomous mode, but then the system experienced large frequency deviations and so-called "rolling blackouts".

However, such a situation cannot be considered acceptable and cannot exist in modern conditions for a long time due to a number of factors, among which the following are the most important.

In accordance with the requirements of the ENTSO-E, only power systems, that are technologically capable of working in autonomous mode provided that the ENTSO-E requirements for the mode parameters of the connected power system for at least one year, can be connected to parallel operation with the ENTSO-E. This strict requirement was not applied to the energy system of Ukraine due the Russian invasion of Ukraine, but in the post-war period it will become relevant and will have to be fulfilled.

In the period until 2022, Ukraine received system (auxiliary) services from the Russian energy system in the form of regulating capacities almost free of charge for the reliable functioning of its own AFPCS. Settlements between these energy systems were based on the "zero balance" principle, when the parties agreed that during the day the volume of imported electricity of each party should be equal to the volume of electricity exported by it, without taking into account the cost of electricity. That is, the fact was not taken into account that in order to ensure the reliable AFPCS operation of the Ukrainian energy system, Russian power plants had to constantly keep a million kilowatts of additional highly maneuverable capacities in a state of circulating reserve. The Ukrainian party had the right to compensate for the volume of imported Russian energy at any time of the day. Such conditions were extremely beneficial for Ukraine, since it practically did not pay for the mentioned auxiliary services, as it paid for very expensive energy from hydroelectric power plants, in particular, energy from nuclear power plants.

An important factor that also needs to be taken into account is that in order to connect to parallel operation with ENTSO-E, the connecting power system must, when operating in the autonomous mode, ensure the mode parameters (frequency, power, voltage levels, stability reserves and etc.), which are maintained in the ENTSO-E power system. According to documents [1, 2], frequency and power regulation must be ensured for the following modes: the frequency must be within the normal limits of 50 ± 0.2 Hz without exceeding the maximum allowable 50 ± 0.4 Hz when the IES of Ukraine operates separately from the energy systems of other countries; parallel operation of the IES of Ukraine with the ENTSO-E power association with a standardized frequency within the regulation zone of 50 ± 0.02 Hz; parallel operation of the IES of Ukraine with the energy systems of other countries with provision of a standardized frequency within 50 ± 0.05 Hz (normal level) and within 50 ± 0.2 Hz (acceptable level). During the construction of the AFPC system on PC power units in the IES of Ukraine the normalized frequency values can be provided only in the isolated mode of its operation (the corresponding calculations are given below). To ensure a fourfold increase in frequency accuracy in normal mode during the parallel operation of the Ukrainian IES with the energy systems of other countries, and even more so to ensure a tenfold increase in its accuracy during parallel operation the Ukrainian IES with the ENTSO-E power association in the conditions of even reconstructed or new equipment of the Ukraine's IES will be not only technological difficult, but also extremely expensive. It will be not only technologically difficult, but also extremely expensive to provide such a large increase in frequency accuracy in the conditions of even the reconstructed equipment of the Ukrainian IES. The way out of the situation is the creation of a fundamentally new system of AFPC, built on the basis of innovative principles and the most effective newest technologies.

There is reason to believe that the current settlements between IES of Ukraine and ENTSO-E on the export/import of regulatory energy for their AFPC systems during the period of martial law in Ukraine are based and will be based until this state is removed, on the principle of "zero balance." After its cancellation, settlements will certainly be carried out on market principles based on the criteria of lost profit.

It should be noted that in the current state 6 hydro units of the Zaporizhia HPP and thermal power plants with a total installed capacity together of no more than 800 MW are included to the AFPC system of the Ukraine's IES , which is clearly insufficient for the construction of a full-fledged AFPC system in the IES of Ukraine (shown below).

The capacity currently available in the AFPC system of Ukrainian IES is about 11% of the required capacity. That is, the construction of the Ukrainian AFPC system will have to be carried out practically from scratch, which makes it possible to use new approaches and advanced technologies for automatic regulation of frequency and power in IES.

The purpose of this work is the construction and detailed study of a fundamentally new structure of the frequency and power automatic regulation system of the Ukraine's IES through its technological interaction with the systems of centralized heat supply (CHS) using heat consumers-regulators (HCR).

**Requirements for the functioning of the AFPC system.** Primary, secondary and tertiary regulation is used during the operation of the AFPC system. Each of them has its own reserves. Primary regulation [2] provides automatic stabilization of frequency in the range of 50Hz ± Δf in normal (quasi-stationary) modes, while secondary and tertiary regulation are almost not used. In the event of an emergency situation, for example, when a large power unit or a powerful transmission line is turned off, the primary regulation is activated at first in the system and its reserve is used for about 30 seconds. After about 20 sec. from the moment of the disturbance, the secondary regulation [3] is automatically activated, which, depending on the power of the disturbance, may exhaust its reserve after 15 min. after disturbance (Table 1). At this moment, the load of the primary regulation is completely transferred to the power of the secondary regulation.

**Table 1**

| Type of regulation | Beginning (from the moment of disturbance) | End |
|---|---|---|
| Primary | 1 – 2 sec | 30 sec |
| Secondary | ~ 20 sec | 15 min |
| Tertiary | 8 – 12 min | Not normalized. Depends on the conditions of the power system |
| The interval of displacement of the primary regulation by the secondary | 30 sec | 15 min |
| Interval of displacement of secondary regulation by tertiary | 8 – 12 min | 40 min |

Tertiary regulation [4] can be carried out by the dispatcher or automatically. With dispatch control, the tertiary regulation is activated after about 8 min. and with automatic control – after 12 min. after disturbance. After about 40 min. from the moment of disturbance, the entire load of the secondary regulation must be transferred to the power of the tertiary. At this time, secondary regulation reserves must be fully restored.

The received values of the primary reserve in the IES of Ukraine in the mode of its parallel operation with ENTSO-E are ±190 MW.

To compensate for the largest emergency loss of generation in the IES of Ukraine (according to the N-1 principle, it is 1000 MW), or loss of consumption, the estimated range of secondary regulation is determined for loading – 1000 MW and for unloading – 500 MW.

The estimated reserve of tertiary regulation should be: for loading - at least 1000 MW, for unloading – at least 500 MW.

For the implementation of primary and secondary regulation in the IES of Ukraine, separate methods have been developed, focused on TPP units [5], on HPP [6] and on NPP [7].

**Study of the AFPC system construction options.** All of the above-mentioned features of the current state and functioning of the AFPCS as part of the Ukraine's IES demonstrate its vulnerability to the action of (especially) external factors, in particular, the breaking of connections with the energy system of the European Union due to certain factors. Under such a scenario, the IES of Ukraine, as noted, will be practically inoperable. In such situation the country's energy security becomes the most important factor. In order to prevent an economic collapse, the energy industry must urgently develop and build, as part of the Ukrainian IES, its own full-fledged AFPC system, which is capable of meeting the requirements for the accuracy of frequency support and speed in emergency modes, which are developed and implemented for of the European energy system ENTSO-E.

In modern conditions, the construction of the AFPC system as part of the Ukraine's energy system can be carried out according to the following basic options. According to the first of them, it is implemented according to the traditional structure using generator-regulators as [1–4]. At the same time, it should be taken into account that in the current state until 2022 in the functioning AFPCS, the primary and tertiary regulation was built on Ukrainian equipment and can meet the requirements of the Guidelines [1] on speed and accuracy for these phases of regulation. That is, in the new Ukrainian AFPC system, it is necessary to complete its part, which must carry out secondary regulation. The function of secondary regulation according to [1, 3] can theoretically be organized using the capacities of hydroelectric power plants, pulverized coal and gas-oil fuel thermal power plants. However, as mentioned, the use of gas-oil fuel thermal power plants for this purpose is impractical, taking into account their economic indicators and the energy security factor (additional large volumes of natural gas are required for GOF thermal power plants). Ukrainian HPP are flat, low-water and low-power, their capabilities are not enough even to cover the variable part of the electric loads schedule (ELS) of the Ukrainian IES. Over time, this situation will only worsen, since the possibilities of the hydroelectric power stations capacity increasing are practically exhausted, and the amount of electricity consumption in the country will increase with the simultaneous decompression of ELS [8]. Thus, in the conditions of Ukraine, when trying to build a subsystem of secondary regulation in AFPCS according to the traditional scheme, the only possible option is the use of reconstructed pulverized coal power units in the role of generator-regulators.

Let's evaluate of the number of such power units necessary for the construction of a traditional subsystem for AFPCS secondary regulation according to the requirements of the Guidelines [5]. Wherein the change rate indicators in the power of power units turbines of 200 and 300 MW are decisive. Such power units in the conditions of IES of Ukraine can serve as the main equipment in the construction of the subsystem of secondary regulation of AFPCS on regulator-generators.

In the Table 2 shows the indicators of the initial change and the rate of further power change for the turbines of the specified power units [1, 3].

**Table 2**

| Type of turbine | Initial change $\Delta P$, MW/% | The rate of further change *dp/dt*, MW/min |
|---|---|---|
| К–210–130 | 20/10 | 1,0 |
| К–300–240 | 20/6,67 | 0,8 |

It is advisable to divide total regulation range $P_p = 1000$ MW into two: the range $P_{200}$=555,5 MW, which is provided by 200 MW units for 15 min., and the range $P_{300}$=444,5 MW for 300 MW power units during the same time. The values of these ranges are determined in proportion to the speed of power units *dP/dt* (Table 2). Then the number of installed power units $N_{200}$ with a power of 200 MW, which is required to cover the range $P_{200}$, can be determined from the dependence

$$P_{200} = N_{200} \cdot \alpha \cdot \left(\Delta P + dp/dt(200) \cdot T_p\right),$$

where α = 0,8 is the coefficient that relates installed power and operating power, $\Delta P$=20 MW is the power change (Table 2), $dP_{(200)}/dt$=1 MW/min is the turbine power change rate of the 200 MW power unit (Table 2), $T_p$ =15 min is the time allocated for secondary regulation in the AFPC system.

A similar equation is valid for establishing the required number of power units with a capacity of 300 MW.

The given dependence makes it possible to determine the installed power units number needed to ensure the necessary regulating power $P_p$ and regulation time $T_p$, namely, $N_{200} = 20$ and $N_{300} = 18$ with the total number of regulating generators in the AFPC system $N = N_{200} + N_{300} = 38$ (which meets the requirements of [3]) and with a total installed power of 7,400 MW. Such a large installed power (5.9 times more than required) is due to the insufficient speed of coal-fired power units. A rotating (hot) reserve of 1000 MW should provide the total number of units $N_p = \alpha N = 31$, of them $N_{200p}$=16 and $N_{300p}$=15. The average volumes of the secondary regulation reserve on each 200 MW block are 34.7 MW, and on the 300 MW block are 29.6 MW. The total power that Np power units can provide for output to the electric network is 6700 MW, i.e. about 15% of the operating capacity of 31 power units, which should operate as part of the AFPC system, is in the rotating reserve.

In the modern conditions of technological development in the energy sector, there is an opportunity to create AFPC systems on a fundamentally another basis, which is expedient to implement, first of all, in the energy system of Ukraine. Unlike the traditional approach, the construction of such a AFPCS is not based on the introduction of additional regulating capacities in the event of a deficit/surplus of active power in the IES, but strictly on the contrary, on the reduction/increase of energy consumption by a special structure of heat consumers-regulators (HCR). The technological processes of these consumers have such a feature that they allow a significant reduction (up to termination) of electricity supply for the necessary time (tens of minutes) at any time of the day and year.

The possibilities of using such consumers as part of the AFPC system were not sufficiently justified due to their power and speed limitations. Not so long ago, technologies appeared on the energy equipment market that can be successfully used in the role of HCR in the structure of the AFPCS. We are talking about compression heat pump units (CHP) and electric heat generators (EHG) of high power, which can work as part of CHS. Such thermal energy generators, being installed on the territory of powerful boiler plants, have the opportunity to use the special heat storage devices available on them. In addition, the system of centralized heat supply has significant opportunities for the accumulation of thermal energy in its own structures, in the soil, in buildings and constructions of consumers, as well as by regulating its temperature regime [9, 10]. The specified features of CHS make it possible to use CHP in modes of short-term (15–30 min.) termination of their operation without worsening of heat supply to consumers. Installations of the specified function are large consumers of electricity. The totality of the above features makes it possible to use CHP and EHG in the role of consumer-regulators in the construction of modern AFPCS.

In the publications [11, 12], a detailed analysis of the AFPCS technological indicators on generator-regulators and on consumer-regulators in the form of CHP was performed. A comparison of their main technical and economic characteristics demonstrates that the organization of AFPCS on the basis of CHP has a set of important advantages [13]:

– a large amount of TPP generating equipment (38 power units with a capacity of 200–300 MW) is freed from the need to operate in the rotating reserve mode, which significantly increases their efficiency and competitiveness;

– the amount of capital investments required for the construction of the AFPCS is decreasing;

– the AFPCS quickness and accuracy of frequency regulation are significantly improved;

– system reliability increases;

– the payback period of the necessary capital investments is reduced several times and the overall economic efficiency increases;

– the time required for the construction and commissioning of the AFPCS is significantly reduced.

The main reason for such advantages is obvious. The AFPCS according to the traditional structure is activated within 15 minutes several times a year, and at other times it works in idle mode, using additional equipment and fuel resources throughout the year. In contrast, AFPCS on the basis of CHP generates thermal energy throughout the year, except for a few stops per year during 15 minutes each giving it exceptional economic advantages.

Other important factors leading to the mentioned state are that the appropriate modernization of energy facilities and energy-intensive technologies, the introduction of new energy-efficient materials are based, first of all, on the measurement, control, diagnosis of physical characteristics and regulation of the physical processes parameters [14]. Monitoring and optimization of such processes ensure effective implementation of resource-saving and energy-saving measures, which, of course, has economic and social significance. The use of mathematical models of physical signals and fields of functioning of energy facilities, algorithms and programs for the determination and statistical evaluation of their characteristics is the basis of information support for the operation of monitoring and diagnostic systems [15]. Monitoring of real characteristics of energy facilities can be ensured taking into account the capabilities of measuring units [16, 17].

Qualitative analysis of the capabilities and indicators of the AFPCS, built on the basis of EHG, demonstrates that, compared to the traditional structure, it has almost all the advantages of the AFPCS structure developed using CHP. However, it is far from obvious which of the AFPCS structures built on HCR technology (CHP or EHG) will have better technical and economic indicators. CHP technology has, in particular, the specific costs of electricity during heat production several times lower than this indicator for EHG technology. On the other hand, specific capital investments for EHG are several times smaller than this indicator for CHP. In addition, some indicators of CHP (in particular, specific heat consumption for defrosting the soil and installations, etc.) have considerable uncertainty. Therefore, a comparison of the three AFPCS structures effectiveness is made as follows. The comparison of the effectiveness of the specified HCR technologies is made in this paper by means of calculations and a comparative analysis of the AFPCS technical and economic indicators of the Ukraine’s IES, calculated for the traditional structure in the prices of 2013 and for the EHG technology in the prices of 2021. The main indicators of the AFPCS according to the CHP technology, that are necessary for comparison, were taken from the publication [13], considering changes in exchange rates.

When calculating the indicators of AFHCS, built according to the traditional structure and based on EHG, the same initial data were used. The installed regulating capacity is assumed to be 1250 MW to ensure the operating regulating capacity of 1000 MW, which is determined by the requirements of the European power system ENTSO-E (N-1 reliability principle). The fee for auxiliary services is defined as the lost benefit when 1,000 MW of power is operated in the "hot reserve" mode during 1,500 hours/year at a tariff of 1.35 UAH /kW·h. At the same time, it is taken into account that the indicated power could be used in the peak mode [18]. The average exchange rate of the US dollar in 2013 was 8.02 UAH/$ and in 2021 was 28.8/ UAH $. Corporate income tax was equal to 21% in 2021.

The initial data and the results of the technical-economic indicators calculation of AFPCS secondary regulation subsystem based on generators-regulators are shown in the Table 3.

**Table 3**

| No | Indicator | | Unit measurement | Value |
|---|---|---|---|---|
| 1 | Installed power for the AFPC system | | MW | 7400 |
| 2 | Investment | 2.1 in total, incl. | $ USA | $13{,}95 \cdot 10^9$ |
| | | 2.2 on the equipment | $ USA | $10{,}73 \cdot 10^9$ |
| 3 | Annual capital investment (item 2.1/35) | | $ USA | $398{,}5 \cdot 10^6$ |
| 4 | Annual capital investments for the AFPCS (item.3x0,17) | | $ USA | $67{,}8 \cdot 10^6$ |
| 5 | Auxiliary services | | $ USA | $96{,}3 \cdot 10^6$ |
| 6 | Number of personnel | | person | 960 |
| 7 | Salary of staff with accruals | | $ USA | $8{,}57 \cdot 10^6$ |
| 8 | Other expenses (materials, etc.) - 2% of item 4 | | $ USA | $1{,}35 \cdot 10^6$ |
| 9 | Total annual costs for the construction and operation of the AFPCS (item 4 + item 7 + item 8) | | $ USA | $77{,}72 \cdot 10^6$ |
| 10 | Gross profit (item 5 – item 9) | | $ USA | $18{,}6 \cdot 10^6$ |
| 11 | Net profit (item 10x0,79) | | $ USA | $14{,}7 \cdot 10^6$ |
| 12 | Payback period of the project (item 9/ item 11) | | year | 5,3 |

When determining the necessary capital investments for equipment (item 2.2, Table 3), it is provided that 20 power units with a capacity of 200 MW and 18 power units with a capacity of 300 MW will be reconstructed with the installation of cleaning equipment with specific capital investments of 1,450 $ USA/kW, and total capital investments (item 2.1) exceed equipment costs by 30%. Annual capital investments (item 3) are determined based on the total service life of the subsystem of 35 years. Annual capital investments for AFHCS (item 4) are 17% of the indicator of item 3, since this system consumes such a part of the installed capacity (item 1). The number of service personnel is determined (item 6) by the relevant norms for TPP. The salary with accruals (item 7) corresponds to the average data of the Ministry of Energy for 2021. Other costs (item 8) are calculated according to methodical recommendations for the designing of energy facilities (2% of the equipment cost). Total annual costs (item 9) are obtained as the sum of costs for items 3, 7, 8, gross profit (item 10) – as the difference between the fee for auxiliary services (item 5) and total annual costs (item 9).

The technical-economic indicators of the AFHCS secondary regulation subsystem, built on electric heat generators, are given in the Table 4. The installed capacity of the EHG (item 1) is determined by the working capacity for electricity consumption by the AFHC system. The installed capacity of the EHG for heat production (item 2) is determined taking into account the EHG coefficient of efficiency (98%). Capital investment for equipment (item 4) considers that the specific capital investment for EHG is $35/kW, and the total capital investment (item 3) exceeds the costs of item 3 by 30%. Capital investments according to item 5 correspond to the period of EHG use namely 25 years. Item 13 takes into account the average salary for the industry and the 21% charge on it. The indicator of item 17 is determined by the Europe's market price of natural gas in the second half of 2021. The fee for auxiliary services (item 18) is taken from [18] with changes due to the exchange rate, since this indicator is more justified in compared with similar ones given, in particular, in [19] and other sources. The average market price of electricity (item 8) is determined by [20].

In the conditions of the full technological integration of the Ukrainian IES into the European Union energy system, which took place in February 2022, Ukraine, as noted, should have a full-fledged AFHC system in the structure of its own IES. However, this requirement was not fulfilled due to the introduction of martial law in Ukraine during this period. As a result, in the current situation, the AFHC system in the IES of Ukraine is provided with the necessary regulatory capacities by only 10 – 11%. It is clear that in the post-war period the AFHCS of the Ukraine's IES should be fully developed. But the question of what structure of the

AFHC system should be implemented remains relevant. In order to answer this question, it is necessary to make a comparative analysis of the technical and economic characteristics of AFHCS according to the following principles of organization: traditional structure based on generator-regulators; a system built on the interaction of IES of Ukraine and centralized heat supply systems using electric heat generators; a structure synthesized by organizing the connections of the power system and CHS on the basis of heat pump installations.

**Table 4**

| No | Indicator | Unit | Value |
|---|---|---|---|
| 1 | The EHG installed capacity for electricity consumption | MW | 1250 |
| 2 | The EHG installed capacity for the production of thermal energy | MW | 1225 |
| 3 | Capital investment for equipment | $ USA | $43{,}75 \cdot 10^6$ |
| 4 | Capital investment, all (item 3x1,3) | $ USA | $56{,}88 \cdot 10^6$ |
| 5 | Annual capital investment | $ USA | $2{,}275 \cdot 10^6$ |
| 6 | Working hours of the EHG complex | hours/year | 8760 |
| 7 | Electricity consumption by the EHG complex | kW·h | $8{,}939 \cdot 10^9$ |
| 8 | The market price for electricity by item 7 | ₴/ kW·h | 2,717 |
| 9 | The cost of electricity by item 7 (item 7x2,717/28,8) | $ USA | $843{,}3 \cdot 10^6$ |
| 10 | Heat produced at the EHG complex | Gcal | $7{,}39 \cdot 10^6$ |
| 11 | The tariff for produced heat by item 10 | ₴/Gcal | 2047 |
| 12 | The cost of heat by item 10 | $ USA | $525{,}6 \cdot 10^6$ |
| 13 | The number of personnel at the EHG complex | person | 1200 |
| 14 | Staff salary with accruals (item 13x608x12x1,21) | $ USA | $10{,}54 \cdot 10^6$ |
| 15 | Other expenses (2% від item 4) | $ USA | $1{,}1 \cdot 10^6$ |
| 16 | Natural gas replacement volumes (item 7x0,345·$10^{-6}$/1,15) | billion cubic m | 2,68 |
| 17 | The cost of replaced natural gas (item 16x0,95·$10^3$) | $ USA | $2{,}55 \cdot 10^9$ |
| 18 | Fee for auxiliary services | $ USA | $96{,}3 \cdot 10^6$ |
| 19 | Gross income (item 12 + item 17 + item 18) | $ USA | $3171{,}9 \cdot 10^6$ |
| 20 | Total annual costs for the EHG complex (item 5 + item 9 + item 14 + item 15) | $ USA | $857 \cdot 10^6$ |
| 21 | Gross profit (item 19 – item 20) | $ USA | $2314{,}9 \cdot 10^6$ |
| 22 | Net profit (item 21x0,79) | $ USA | $1828{,}8 \cdot 10^6$ |
| 23 | Payback period of the project (item 20/ item 22) | year | 0,47 |
| 24 | Economic effect (item 22– item 11 table 3) | $ USA | $1814{,}1 \cdot 10^6$ |

**Table 5**

| No | Indicator | Unit | Value |
|---|---|---|---|
| 1 | Installed capacity of CHP | MW | 1250 |
| 2 | Investment | $ USA | $469{,}6 \cdot 10^6$ |
| 3 | Gross income | $ USA | $1416{,}3 \cdot 10^6$ |
| 4 | Total annual expenses for the CHP complex | $ USA | $388{,}2 \cdot 10^6$ |
| 5 | Net profit | $ USA | $812{,}5 \cdot 10^6$ |
| 6 | Payback period of the project | year | 0,48 |
| 7 | Economic effect | $ USA | $798 \cdot 10^6$ |

The characteristics necessary for a comparative analysis of the first two variants of the AFHCS are given in the Tables 3 and 4 respectively. The same detailed indicators of the AFHC structure built on the basis of heat pump units are given in the publication [13]. The main ones, necessary for the specified comparative analysis, have been clarified according to the monetary and price indicators of 2021 and are listed in the Table 5.

**Conclusions.** 1. A number of important factors (energy security, economic efficiency, joining the European energy system ENTSO-E) make it necessary to develop a modern, full-fledged system of automatic frequency and power regulation in the structure of the Ukrainian IES .

2. A comparison of the technical and economic indicators of the considered variants for the construction of the AFHCS secondary regulation subsystem demonstrates the undoubted advantage of the structures used by heat consumers-regulators.

3. The construction of AFHCS based on electric heat generators requires 13.9 billion dollars USA less capital investment compared to the traditional option using regulator generators.

4. The AFHC system based on EHG provides a net annual profit of 1.83 billion dollars USA and the payback period of capital investments is 0.47 years, while these indicators for a system with a traditional structure amount to 14.7 million dollars USA and 5.3 years, respectively.

5. The AFHC system with EHG provides a reduction the natural gas using in boiler houses by 2.7 billion $m^3$ at a cost of 2.6 billion dollars USA, because EHG uses electricity produced without the use of natural gas. This factor ensures not only the high economic efficiency of the specified version of the AFHCS structure , but also a significant increase in the level of energy security of the state.

6. The economic effect of the EHG-based AFHC structure exceeds that of the traditional structure by 1.81 billion dollars USA annually.

7. The economic advantages of the structure of AFHC based on EHG in comparison with its structure based on CHP (as economic effect) amount to 1.02 billion dollars USA annually.


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**МОЖЛИВОСТІ ТА ПЕРСПЕКТИВИ ЗАСТОСУВАННЯ СПОЖИВАЧІВ-РЕГУЛЯТОРІВ У СИСТЕМАХ АВТОМАТИЧНОГО РЕГУЛЮВАННЯ ЧАСТОТИ І ПОТУЖНОСТІ**

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*Об'єднана енергетична система (ОЕС) України функціонує у складі електроенергетичної системи Європейського Союзу (ЄС) ENTSO-E. Кожна країна, ОЕС якої працює у структурі ENTSO-E, повинна забезпечити у складі національної ОЕС наявність повноцінної системи автоматичного регулювання частоти і потужності (система АРЧП, САРЧП). Винятком є лише ОЕС України, оскільки її входження до складу ENTSO-E відбулося під час воєнного стану та за відсутності у ній при цьому повноцінної системи АРЧП. Це порушує наріжні вимоги формування структури ENTSO-E. У повоєнний час ОЕС України зобов'язана буде добудувати власну, повноцінну САРЧП у найкоротші терміни. Досліджено три структури розбудови системи АРЧП ОЕС України: за традиційним принципом (на базі генераторів-регуляторів), на основі теплових споживачів-регуляторів із залученням теплонасосних установок та теплових споживачів-регуляторів з використанням електричних теплогенераторів, що забезпечують енергією системи централізованого теплопостачання. Розрахунки і аналіз техніко-економічних показників показали, що традиційна структура САРЧП безнадійно програє обом структурам, побудованим на споживачах-регуляторах. Помітно кращою із цих двох систем є САРЧП, побудована на споживачах-регуляторах у вигляді електричних теплогенераторів. Вона надає річний чистий прибуток більше 1,8 млрд дол. США, термін окупності біля 0,5 р., зменшує на 2,7 млрд куб. м споживання природного газу, зменшує на 13,9 млрд дол. США необхідні капіталовкладення, має малі терміни будівництва.* Бібл. 20, табл. 5.

***Ключові слова*:** система автоматичного регулювання частоти і потужності, електричний теплогенератор, теплонасосна установка, капіталовкладення, прибуток, термін окупності.

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