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SUBSTANTIATION OF ENERGY EFFICIENCY OF AUTOMATED HEATING TECHNOLOGY AT HPS

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Purpose. *Justification of rational control parameters of heat pumps to ensure energy-efficient operation of hydroelectric power plants in heating mode. Development of an automated methodology for calculating rational parameters for a complex system of hydroelectric power station (HPS) operating in heating mode.*

Methodology. *Mathematical analysis and modeling.*

Findings. *The application of the heat pump to ensure the heating mode at the hydroelectric power station for the needs of heating and hot water supply of buildings is analytically substantiated, as well as the rational parameters of the heat pump, which ensure the efficient heating mode at the hydroelectric power station, are determined. It is impractical and inefficient to pass the full flow of water passing through the hydraulic unit through the heat pump, because in this case the energy consumption in the heat pump compressor is several times higher than the consumption of the hydraulic unit in pumping mode, which devalues the proposed measure as an energy-saving measure. Therefore, the limiting and rational values of the design and operating parameters of the heat pump and heat accumulator, which ensure the heating mode of operation of the HPS to meet the needs of hot water supply, were substantiated. According to the proposed technology, the operation of a hydro unit with a typical capacity of 120 MW in the heating mode for various energy consumptions for the electric drive of the heat pump compressor was investigated. In accordance with these costs, the values and ratios of the electricity and heat generation shares of the modernized HPS changed.*

The proposed unconventional technology for converting hydroelectric power plants to the heat generation mode allows for wide effective maneuvering in different proportions of electric and thermal generation, unlike CHP and other power plants. The technology under consideration allows for virtually no consumption of non-renewable energy resources, providing consumers with both electric and thermal energy.

Originality. *The technology of using a heat pump to transfer the operation of the hydroelectric power station to the heating mode (heating and hot water of residential buildings) is substantiated. An automated technique for determining the rational parameters of heat pump (HP) for the implementation of HPS heating technology has been developed. The developed automated technique allows to calculate the values of operational parameters of HP for the balance and arbitrary modes, which ensure the heating operation of the HPS to meet the current needs of heating and hot water supply.*

Practical value. *The use of a heat pump at a hydroelectric power station for heating and hot water supply allows you to save a third of conventional fuel consumption compared to a boiler unit.*

Keywords: heat pump; heat accumulator; automation; energy saving; hydro storage power plant; thermal power; control.

I. INTRODUTION

In today's difficult conditions, the energy system of Ukraine has significant problems with the shortage of all types of energy, namely: not only electric but also thermal, especially in the cold season. Of course, to overcome this crisis, it is necessary to restore the destroyed generation and networks, but this requires huge capital expenditures, which are in short supply at this difficult time.

Therefore, it is necessary to use various technical improvements and non-traditional measures regarding the existing energy equipment in order to increase the variability of the use of the existing generating capacities and the possibilities of effective transformation of thermal energy into electrical energy and vice versa.

Currently, the production of electricity and thermal energy is mainly carried out separately, respectively, at thermal and nuclear plants and in boiler houses.

However, thermal power plants (TPPs) have a relatively small maximum efficiency (about 42%) and the majority of heat is wasted in the environment, which is shown in the diagram of fig. 1. Therefore, combined heat and power plant (CHPP) are used to increase the degree of use of thermal energy. Combined production of electricity and thermal energy is carried out at the TPP. At the same time, the coefficient of thermal energy utilization almost doubles - up to 80% in TPP plants with condensing turbines, which is shown in the diagram in fig. 2. But in turn, the share of electricity production in the total energy balance of the station is significantly reduced compared to the combined heat and power plant (on average twice). Also, the principle of mutual parallel production of thermal and electrical energy causes a strong interdependence of these generations and imposes significant restrictions on maneuvering modes of production of these energies. In addition, thermal power plants, like thermal power plants, operate mainly on coal fuel, which also has difficulties in terms of quality and availability.

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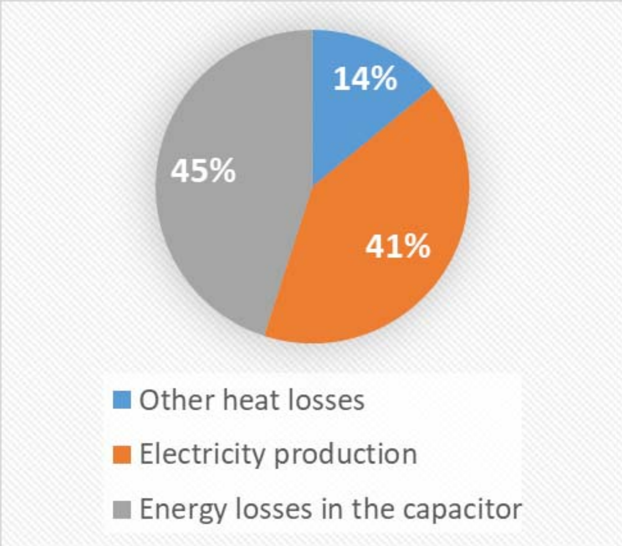

Figure 1. Components of the heat balance of the TPP

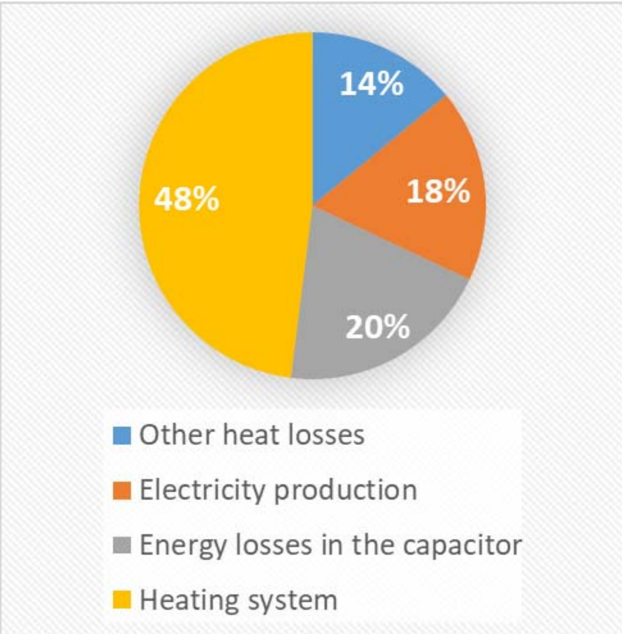

Figure 2. Components of the heat balance of the CHHP

Therefore, the idea of using a hydroelectric power station (HPS) in heating mode is relevant. To implement this unconventional technology, it was decided to use a heat pump. That is, during the operation of the hydroelectric power plant, the heat pump takes low-potential heat energy from the flow of water passing through the turbine and heats water for centralized heating and hot water supply systems.

II. ANALYSIS OF LAST RESEARCHES

In past studies, the author substantiated a number of innovative technologies for switching various power plants to heating mode. [1-5]. A heat pump was used in each variant. A universal automated method of calculating thermal processes was developed, with the use of heat pumps in the utilization of thermal emissions.

The main principle of the heat pump is that the device takes heat energy from various low-potential energy sources and transforms it into high-temperature heat energy, and only then transfers it to end users. Some energy is spent on the operation of the electric drive of the heat pump compressor.

Based on the results of research [1], conducted with the help of the calculation methodology developed by the authors, the possibility of using a heat pump in the thermal circuit of the TPP as a water heater in the hot water system is substantiated. It will allow the use of condensing power plants in the heating mode. The scheme is shown in fig.3.

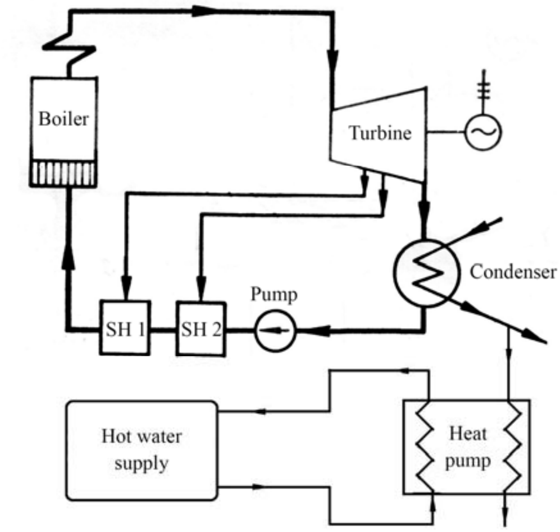

Figure 3. Scheme of application of the heating mode at the TPP (SH1, SH2 – steam heaters before the boiler)

The paper substantiates the rational mode of operation of the combined thermal power plant + heat pump system using the example of the power unit of the Kryvorizka thermal power plant with a condensing steam turbine of the K-300-240 KhTGZ type. According to the research results, the heat utilization factor for this system has acquired a rational value of 78%, and the energy conversion factor is 7.2, which corresponds to a high level of heat pump efficiency.

Heat pump and heat storage technology to transfer the functioning of the hydroaccumulating power plant (HSPP) to the heating mode of hot water supply of residential buildings was also substantiated. The scheme is shown in fig. 4. An automated method for determining the rational parameters of HP and HA for the implementation of HSPP heating technology was developed [2].

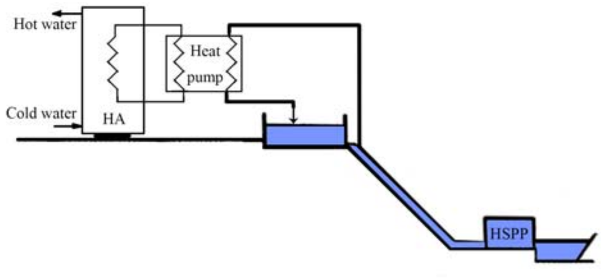

Figure 4. Scheme of application of the heating regime at the HAPP (HA – heat accumulator, HSPP - Hydro storage power plant)

It was determined that the use of a heat pump and a heat accumulator on the HSPP for the needs of hot water supply allows to save a third of conventional fuel consumption compared to a boiler unit.

However, passing the full flow of water passing through the hydraulic unit through the HP is impractical and inefficient, because then the energy consumption in the HP compressor is many times higher than the consumption of the hydro unit in pumping mode, which devalues the proposed measure as an energy-saving measure.

Therefore, the limiting and rational values of the design and mode parameters of HP and HA, which ensure the heating mode of operation of the HSPP to meet the needs of hot water supply, were substantiated.

That is, the use of HP requires conscientious research and justification in each case of the use of nontraditional technologies. In addition, such a scheme has significant limitations in maneuvering power ratios of electric and thermal generation.

Therefore, from the point of view of energy saving and providing consumers with electrical and thermal energy in a given ratio, an actual idea was proposed to substantiate the implementation of the heating mode of operation of the HPS for the needs of heating and hot water supply.

In works [3-5], the possibilities of using heat pump equipment for the use of heat from powerful units of industrial and domestic purposes for hot water supply and heating of premises were investigated. The use of heat accumulators showed a significant increase in efficiency from the use of the proposed technologies.

In works [6], are considered the main theoretical propositions on which the calculations in the study are based.

The work [7] substantiates the efficiency criteria by which the energy efficiency of heat pumps can be assessed. This is the energy conversion factor, which is equal to the ratio of the energy that reached the consumer to the energy that was used to implement the cycle. And the actual conversion factor, which takes into account the correction for the energy efficiency coefficient of the heat pump, which takes into account all energy consumption in the heat pump. The value of the energy efficiency of modern heat pumps is in the range of 0.65-0.7.

Sources [8, 20] reveal the issue of building a simulation model and methods of economic analysis of the obtained results.

Article [9] presents the results of experimental experiments on the implementation of a water heater with a heat pump, which uses low-pressure steam in a power plant condenser as a source of thermal energy. The influence of water flow, as well as the temperature of the water entering the condenser on the performance of the heat pump, has been experimentally proven. The data obtained are very important for the design of such systems, both in mathematical and simulation modeling. When conducting real experiments, a value of energy conversion coefficient of 4.5 was obtained, as well as other parameters, which makes it possible to check the adequacy of the constructed simulation and mathematical models.

The study [10] analyzed the use of heat pump equipment among the urban population. The results showed that more than 40% of surveyed households use heat pumps to heat water. The decisive factors have been identified when deciding to install heat pump equipment, the main one of which is price. The characteristics of the equipment used in the presented urban sample were analyzed. We used these data to forecast the prospects for the widespread introduction of improved heat pump technologies in Ukraine.

Article [11] discusses the results of experiments on an improved installation for heat pump water heaters. The improvement lies in the presence of a phase transition in the heat pump, which ultimately allowed the heater to operate stably and for a long time. At the same time, the capacity of the thermal accumulator, required to accumulate the same amount of energy, decreases. The thermal accumulator for a system built on the new technology is 57% of the volume of the thermal accumulator using the old technology, with all the same energy characteristics. This promotes the introduction of such technologies for household consumers.

The main goal of work [12] was to develop a model of a compact heat pump for hot water supply, as well as to conduct experimental tests. The peculiarity is that this is an intelligent model with low computational requirements. In addition, manufacturers can apply this model to existing pumps using simple experimental calculations. The reservoir model uses experimental correlations to account for the complex mechanism of mixing water flows during its intake. The results of these studies are taken into account when constructing our mathematical models of heat pump systems.

Article [13] describes the results of studies of an experimental installation of a water heating system with a heat pump, with a cyclic heating mode. The factors influencing the stability and efficiency of the heat pump are analyzed. The data obtained in the work was also used by us to assess the adequacy of the constructed models, and to carry out simulation and mathematical modeling.

In the article [14], the authors analyzed energy efficiency standards for heating, ventilation and air conditioning. The evolution of the development of these standards is considered, and recommendations are presented for further improvement of the criteria when introducing modern energy-saving heating, ventilation and air conditioning systems, even at the building design stage.

In works [17-18], we obtained basic methods for calculating the technological parameters of heat pumps and solar collectors, which can be used as modules in our technology.

In the study [19], using the example of the state of Korea, energy efficiency standards are analyzed. In the carbon-neutral era, energy efficiency goes beyond simply providing economic benefits through fuel savings, but is valued as the most effective means of responding to climate change.

Particularly important for our research was article [21], which proves the greatest energy efficiency of heat pumps with water as a source, compared to other heating equipment, including heat pumps with an air source of thermal energy. The relationship between the energy conversion coefficient and exergy efficiency with the temperature of water at the inlet and outlet of the evaporator and condenser is analyzed.

Based on the materials reviewed, we draw a conclusion about the feasibility of using turbocompressor heat pumps with a water source of thermal energy for use in technologies for extracting useful thermal energy for heating and hot water supply needs. Unlike the previously discussed technologies, our research will concern hydroelectric power as a source of thermal energy for the use of a heat pump.

III. FORMULATION OF THE WORK PURPOSE

Justification of rational parameters of HP to ensure efficient operation of HPS in heat-fixation mode. Development of an automated methodology for calculating rational parameters for a complex system of HPS operating in heating mode.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

The technology of applying the heating mode of operation of hydroelectric power plants for the needs of heating and hot water supply (HWS) was studied. To implement this idea, it was decided to apply HP. That is, during the operation of the hydroelectric power plant, the heat pump takes low-potential heat energy from the flow of water passing through the turbine and heats water for centralized heating and hot water supply systems. The scheme is shown in fig. 5.

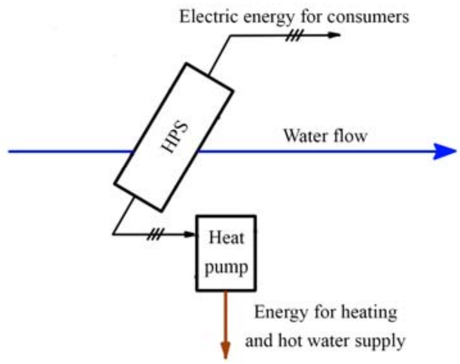

Figure 5. Scheme of application of the heating regime at the HPS

A steam compressor unit operating according to the main refrigeration cycle was presented as a HP. For this technology, on the basis of the p, i diagram of the selected refrigerant (Freon-11), the functions of changing the parameters of the refrigeration cycle from the heat capacity of the condenser and the condensation temperature of the refrigerant at the refrigerant evaporation temperature of 2 °C were determined. A hydro unit with a typical capacity of 120 MW for the Zaporizhzhya HPS was accepted as the research object.

The water in the HP will be heated from 5 to 85 °C (as for the cold period). Accordingly, the refrigerant condensation temperature is set at 90 °C.

The automated method of calculating the parameters of the integrated HPS system operating in the heating mode has the following action algorithm:

1. Setting the power of the hydraulic unit, the geometric head of the station, the initial and final temperatures of the water that gives heat to theHP and water in the heating and HWS systems, physical parameters of water and refrigerant, technical parameters of the heat pump.

2. Formation of functions for changing the parameters of the refrigeration cycle from the thermal power of the heat pump condenser, and the formation of the refrigerant condensation temperature at constant evaporation temperatures, which is necessary for mathematical modeling of the operation of heat pumps.

3. Formation of the function of the dependence of the thermal power of HP and the function of the dependence of the electric power going to the electricity supply of consumers from the electric power of the HP compressor for a given refrigerant condensation temperature.

4. Determination of the balance power of the HP compressor and its corresponding HP parameters and the power supply of electricity consumers.

5. Formation of the function of the dependence of the electric power of the HP compressor and the function of the dependence of the electric power going to the electricity supply of consumers on the thermal power of the HP for a given refrigerant condensation temperature.

6. Determination of HP parameters and HPS electricity supply capacity for arbitrary values of compressor power or HP thermal power.

7. Analysis and comparison of the received parameters of the HP and the power supply system of the HPS and the choice of a more profitable heating mode of operation of the HPS.

According to this technology, the operation of a hydro unit with a typical capacity of 120 MW in the heating mode for various energy consumptions for the electric drive of the HP compressor was investigated. In accordance with these costs, the values and ratio of the electric and thermal generation shares of the improved HPS changed. Figure 6 shows the dependences of the electric, thermal and total generation capacities of the HPS on the HP compressor capacity for the refrigerant condensation temperature of 90 °C, i.e. for the maximum load on the system during the heating period.

The heat generation power function is calculated as follows

$$Q_m(N_к, t_к) = f\left\{N_к = \frac{l_к(t_к)\cdot M(Q_m(N_к,t_к),t_к)}{\eta_a \cdot \eta_м \cdot \eta_e}\right\} \quad (1)$$

$N_к$ – electrical power of the HP drive, W; $t_к$ – refrigerant condensation temperature, °C; $l_к$ – theoretical specific work of the HP compressor, Дж/кг; M – mass flow of the refrigerant in the HP circuit, кг/с; η_a – adiabatic compressor efficiency; $\eta_м$ – mechanical efficiency of the compressor; η_e – compressor electric drive efficiency.

The function of power supply of electricity consumers

$$N_e(N_к) = N_{ген} - N_к \quad (2)$$

$N_{ген}$ – nominal capacity of the hydropower unit.

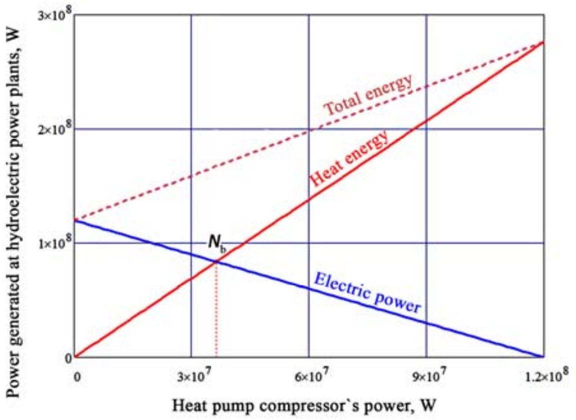

Figure 6. Determination of the balance power N_b of the heat pump compressor for a refrigerant condensation temperature of 90 °C

In turn, when the condensation temperature is reduced to 70 °C with average loads on the heating system, the efficiency of this system will essentially increase along with the conversion factor from 2.3 to 3.3.

Analyzing the graphs, it is possible to highlight such features of this technology as the ability to ensure the operation of the HPS in purely electric or purely thermal mode. Or it is enough to freely maneuver in different ratios of electricity and heat generation shares, which is impossible to achieve at a CHPP plant. At the same time, the mode of equal ratio of the shares of electric and thermal generation, which we called the balance regime, can cause significant interest. With the help of this technique, it is possible to determine the conditions for achieving this regime. Namely, it is about determining the appropriate value of the power of the HP compressor, which we also called the balance (N_b). It was noted that in this mode, about 30% of electricity is spent on heating needs, while ensuring an equal ratio of electric and thermal energy generation. In addition, the use of this technology allows you to save up to a third of conventional fuel for heating and hot water needs compared to a boiler with average loads on the heating system.

The balance value of the HP compressor power depending on the refrigerant condensation temperature

$$N_к^б(t_к) = f\{Q_m(N_к^б, t_к) = N_e(N_к^б)\} \quad (3)$$

Figure 7 presents the calculated dependences of the electric power of the HP compressor and the electric power supplied to consumers from the thermal power of the HP for a refrigerant condensation temperature of 90 °C. According to these functions, it is quite convenient to perform calculations on the redistribution of shares of electric and thermal generation of HPPs depending on the current needs of thermal energy consumers.

Thus, the dependence of the electric power of the TN compressor on the thermal power of the TN and the condensation temperature of the refrigerant

$$N_к(Q_m, t_к) = \frac{l_к(t_к)\cdot M(Q_m, t_к)}{\eta_a \cdot \eta_м \cdot \eta_e} \quad (4)$$

Q_m – thermal power of HP, W.

Then the dependence of the electric power that goes to the power supply of consumers on the thermal power of the HP and the condensation temperature of the refrigerant will be

$$N_e(Q_m, t_к) = N_{ген} - N_к(Q_m, t_к) \quad (5)$$

In turn, the mass flow rate of the refrigerant in the HP circuit, depending on the thermal power of the HP and the condensation temperature of the refrigerant, will be

$$M(Q_m, t_к) = \frac{Q_m}{q_к(t_к)} \quad (6)$$

$q_к$ – specific heat load of the condenser, J/kg.

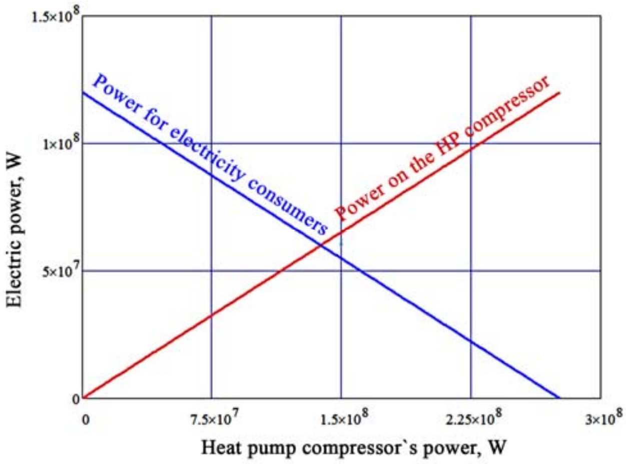

Figure 7. Dependence of the electric power generation capacity of the HPS on the thermal power of the HP for a refrigerant condensation temperature of 90 °C

The advantages include a sufficient number of low-potential energy sources, the close location of the hydroelectric power plant to large cities, relatively low costs for the operation of pumping equipment, and almost complete independence from fuel resources.

Difficulties in implementing this non-traditional technology include the need to design specialized high-power heat pump equipment.

V. CONCLUSION

The technology of using a heat pump to transfer the functioning of the hydroelectric power station to the heating mode (heating and hot water of residential buildings) is substantiated. An automated technique for determining the rational parameters of HP for the implementation of HPS heating technology has been developed. The following provisions were obtained.

1. The proposed non-traditional technology of switching the HPS to the heating mode allows for wide effective maneuvering in different ratios of electricity and heat generation shares, unlike CHPP and other power plants.

2. The use of a heat pump at a hydroelectric power station for heating and hot water supply allows you to save a third of conventional fuel consumption compared to a boiler unit.

3. The developed automated method allows to calculate the values of the operating parameters of HP for the balance and arbitrary modes, which ensure the heating operation of the HPS to meet the current needs of heating and hot water supply.

4. The considered technology allows not to waste non-renewable energy resources, providing consumers with electrical and thermal energy at the same time.

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ОБГРУНТУВАННЯ ЕНЕРГОЕФЕКТИВНОСТІ АВТОМАТИЗОВАНОЇ ТЕХНОЛОГІЇ ОПАЛЕННЯ НА ГЕС

ОЛІШЕВСЬКИЙ І.Г. аспірант та асистент кафедри безпеки інформації та телекомунікацій, НТУ «Дніпровська політехніка», Дніпро, Україна, e-mail: olishevskiyih@gmail.com; ORCID: 0000-0001-8573-3366

Мета роботи. *Обґрунтування раціональних параметрів керування тепловими насосами для забезпечення енергоефективної роботи гідроелектростанцій в режимі опалення. Розробка автоматизованої методики розрахунку раціональних параметрів комплексної системи гідроелектростанції (ГЕС), що працює в режимі опалення.*

Методи дослідження. *Математичний аналіз та моделювання.*

Отриманні результати. *Аналітично обґрунтовано застосування теплового насосу для забезпечення теплофікаційного режиму на гідроелектростанції для потреб опалення та гарячого водопостачання будівель, а також визначені раціональні параметри теплового насосу, що забезпечують ефективний теплофікаційний режим на гідроелектростанції. Пропускати через тепловий насос повний потік води, що проходить через гідроагрегат, є недоцільним і неефективним, тому що в цьому випадку споживання енергії в компресорі теплового насоса в рази перевищує споживання гідроагрегату в насосному режимі, що знецінює запропонований захід як енергозберігаючий.*

Тому обґрунтовано граничні та раціональні значення конструктивних та робочих параметрів теплового насосу та теплового аккумулятора, що забезпечують опалювальний режим роботи ГЕС для задоволення потреб гарячого водопостачання. За запропонованою технологією досліджено роботу гідроагрегату типовою потужністю 120 МВт в режимі опалення за різних енерговитрат на електропривод теплового насоса-

компресора. Відповідно до цих витрат змінилися величини та співвідношення часток виробництва електроенергії та тепла модернізованої ГЕС.

Запропонована нетрадиційна технологія переводу ГЕС у теплофікаційний режим дозволяє здійснювати широке ефективне маневрування у різних співвідношеннях часток електричної та теплової генерацій на відміну від ТЕЦ та інших енергетичних установок.Розглянута технологія дозволяє практично не витрачати невідновлювані енергетичні ресурси, забезпечуючи споживачів одночасно електричною та тепловою енергією.

***Наукова новизна.** Обґрунтовано технологію використання теплового насоса для переведення роботи гідроелектростанції в теплофікаційний режим (опалення та гаряче водопостачання житлових будинків). Розроблено автоматизовану методику визначення раціональних параметрів теплового насоса (ТН) для забезпечення теплофікаційного режиме ГЕС. Розроблена автоматизована методика дозволяє обчислювати значення експлуатаційних параметрів ТН для балансового та довільних режимів, що забезпечують теплофікаційне функціонування ГЕС для задоволення поточних потреб опалення та гарячого водопостачання.*

***Практична цінність.** Застосування теплового насосу на ГЕС для потреб опалення та гарячого водопостачання дозволяє на третину зекономити витрати умовного палива у порівнянні з котельним агрегатом.*

Ключові слова: тепловий насос; тепловий акумулятор; автоматизація; енергозбереження; гідроелектростанція; теплова енергія; керування.