DOI: https://doi.org/10.15407/pmach2023.04.006

UDC 621.165.5

WAYS OF TPP POWER UNITS MODERNIZATION DURING THEIR CONVERSION TO ULTRA-SUPERCRITICAL STEAM PARAMETERS

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The approach to solving the applied problem of modernization of the 300 MW series power units produced by JSC "Ukrainian Energy Machines" by converting them from supercritical to ultra-supercritical steam parameters, provided that regenerative feed water heating system is preserved as much as possible, which will lead to an increase in the energy efficiency of the TPP with minimal conversion, is analyzed in the paper. The conversion of the K-300-240-2 power unit to the parameters of fresh steam 650 °C/30 MPa and intermediate superheated steam 650 °C/7 MPa, determined as optimal as a result of previous studies, can be carried out by completely replacing the high-pressure cylinder of the existing unit for a new high-pressure cylinder with ultra-supercritical steam parameters and superstructure with an additional intermediate-pressure cylinder while fully preserving the parameters and designs of the intermediate- and low-pressure output parts. Two options for modernization of the 300 MW series power unit thermal circuit structure were considered, and the scale of conversion of the regenerative feed water heating system was evaluated. In the first option of the thermal scheme, the 1st steam selection is organized from the cold threads of the modernized high-pressure cylinder with ultra-supercritical steam parameters, and the 2nd one – from the cold threads of the additional intermediate-pressure cylinder. In this case, two high-pressure heaters and a turbo drive of the feed pump are subject to replacement. The disadvantage of this option is that due to a significant increase in steam parameters, it is impossible to choose high-pressure heaters from the existing model range, and a new design must be developed. The electrical efficiency for this modernization option increases from 36.5% (the initial thermal circuit of the K-300-240-2 turbine) to 42.5%. In the second option, it is proposed to install an additional turbine with a capacity of 3 MW, to the input of which a steam from cold threads of the high-pressure cylinder with ultra-supercritical steam parameters is supplied with a loss equal to the sum of the 1st and 2nd selections of the original version of the turbine, on the same shaft with a turbo drive of the feed pump for the sake of preserving the existing high-pressure heater. The steam from the additional turbine selections goes to high-pressure heaters HPH9 and HPH8 with parameters corresponding to the output data of the existing turbine. Taking this into account, high-pressure heaters will not be replaceable. In addition, the power of the additional turbine is sufficient to ensure the operation of the feed pump together with the turbo drive of the feed pump to obtain a water pressure of 34 MPa. In view of this, the turbo drive of the feed pump also remains unchanged, except for the additional turbine installation. The electrical efficiency for the second option of the modernization scheme of the K-300-240-2 power unit is 42.4%. It was determined that the payback period of the modernization according to the first option is 5 years, taking into account the modernization of the boiler unit, and according to the second one – 4.5 years. It is proposed to choose the option of the thermal scheme with an additional turbine, since in this case it is possible to modernize the K-300-240-2 power unit with the maximum possible preservation of the regenerative feed water heating system while increasing its energy efficiency by almost 14%.

Keywords: *ultra-supercritical steam parameters, thermal power plant, energy efficiency, regenerative feed water heating system.*

Introduction

One of the urgent problems of the modern energy industry, both in Ukraine and around the world, is the conversion of the current power generating capacities of TPPs to ultra-supercritical steam parameters. Modernization of thermal power plants can extend the service life of existing steam generators, improve environmental and economic indicators. Currently, the typical range of supercritical steam parameters is from 24 MPa to 28.5 MPa at a temperature from 540 °C to 596 °C [1–5]. The energy efficiency of such power units is about 37%. It is known that the higher the initial temperature and pressure of fresh steam at the input to the high-pressure turbine is, the greater is thermal efficiency of the power unit thermodynamic cycle. Over the last decade, studies on the justification of modernization of existing coal-fired power plants by using energy-preserving units with higher steam parameters have been conducted [6–9].

Such thermal power plants should be even more energy efficient and cause less pollution to the environment. According to experts [10], thermal power of power units when they are converted to work at the supercritical parameters of the cycle can increase by almost 6–7% (relative), which is very significant. In papers [1, 4], it is shown that at a pressure of fresh steam of 30 MPa and temperatures of fresh steam and intermediate superheat of 610/620 °C, the energy efficiency of power plants reaches 47%. Such parameters of the live steam are classified as ultra-supercritical.

However, the real technical capabilities of mechanical engineering impose restrictions on steam parameters. Thus, the temperature of fresh steam is limited by the capabilities of steel pipes (heating surfaces, steam pipes) and the metal of turbine rotors (primarily the rotor of an intermediate-pressure cylinder) [10]. Therefore, a crucial task for creating a power unit based on supercritical steam parameters is to develop a line of materials with the necessary characteristics of long-term strength and low-cycle fatigue [11]. An increase in the pressure of fresh steam is also associated with an increase in the walls thickness of the power equipment pipes. This leads to an increase in the boilers mass and a decrease in maneuverability (the ability to quickly perceive load changes). However, despite these shortcomings, supercritical boiler units have a relatively high efficiency (93.75%), a lower level of emissions into the environment and a smaller amount of ash [12]. Among the considered methods of modernization of thermal schemes, the introduction of flare boiler units and boiler units with a circulating fluidized bed designed for ultra-supercritical parameters of steam with two-stage overheating should be pointed out [13, 14].

Today, the global thermal power industry has already taken real steps towards a mass transition to power units that operate at supercritical steam parameters (30 MPa/600 °C, and even up to 35 MPa/650 °C). In literary sources, there are reports on works on the design of power units operating at an initial steam temperature of more than 700 °C [5, 10].

An analysis of the performance of the planned future advanced ultra-supercritical (A-USC) coal-fired power plant with a capacity of 700 MW, equipped with post-combustion carbon capture and storage (CCS) technology is shown in paper [15]. The A-USC reference plant without CCS achieves a net efficiency of 47.6% with CO_2 emissions of 700 kg CO_2/MWh. Compared to subcritical plants, the net efficiency of A-USC is 8% higher and CO_2 emissions are 16.5% lower.

Papers [16–18] provide data on the possible saving of the specific consumption of heat energy of a power unit at various parameters of its thermodynamic cycle. Thus, with fresh steam and intermediate superheat parameters of 600/620 °C and 28.5/6 MPa, the net energy efficiency is almost 45.5% [16], with steam parameters of 650/670 °C and 30/7 MPa – 47.58 % [17], and at 590/610 °C and 30/5.7 MPa – 43.84% [18]. The highest efficiency of the power plant in paper [17] is achieved due to the use of the Shevalsky cycle with a waste heat utilization system.

However, the increase in the ranges of operating modes requires a radical revision of approaches to the quality of thermal circuits designing due to the introduction of new technologies and types of power equipment. It is known that huge funds are spent on the development of thermal power plants, therefore, in modern economic conditions, it is necessary to develop and improve progressive methods of analysis and decision-making when designing thermal schemes of energy systems [17, 19–21]. At the same time, when analyzing the expediency of modernizing the TPP thermal scheme, it should be taken into account that the operation of the replacement equipment is determined by the efficiency of not only the main ones, but also the auxiliary elements of the power unit. Power units consist of a large number of elements, the dependencies between which are always complex. At the same time, not only the parameters inside the power unit are important, but also the analysis of all possible types of interaction of energy flows at the system boundaries.

A thermodynamic analysis of the supercritical Rankine cycle with single and double intermediate superheat for a modern steam power plant with a capacity of 1200 MW was carried out in [22]. With the help of variable calculations, it was determined that the increase in its electrical efficiency is more significantly affected by the increase in temperature than the increase in pressure. So, with fresh steam parameters of 32.5 MPa/700 °C, the efficiency of the single / double intermediate heating cycle is 46.45% / 49.4%, and at 35 MPa/650 °C, the efficiency of the cycle with one and two intermediate superheats is 45.40% and 47.92%, respectively. However, the authors did not consider the influence of the parameters of the intermediate superheated steam and did not define the limits to which it makes sense to increase the parameters of the fresh steam.

The research in [23] is devoted to the development of a computer model of an ultra-supercritical power plant. The authors performed a thermodynamic analysis, calculated losses of exergy flows in the main elements of the power plant. It was established that the maximum values of energy dissipation, almost 86% of the total exergy losses, take place in the boiler unit and amount to 615 MW for the considered station. At the same time, exergy losses in the condenser amount to only 15 MW. Based on this, the authors made an attempt to reduce exergy losses in the boiler, but at the same time they did not study the effect of the irreversibility of thermodynamic processes in other elements on the destruction of exergy in the boiler.

It should be noted that papers [4–23] are devoted to the creation of new power units, substantiation of research into new cycles and thermal schemes using modern methods of applied thermodynamics, and the design of new boiler equipment, etc. However, today in Ukraine there is an acute question regarding the conversion of existing power units to higher parameters of fresh steam, the determination of possible ways to modernize thermal plants with the lowest capital costs and time in the conditions of a difficult economic and military situation.

Study problem statement

This paper is a continuation of work on the conversion of power units of the 300 MW series produced by JSC "Ukrainian Energy Machines" from supercritical steam parameters (pressure 23.5 MPa; temperature 540 °C) to ultra-supercritical ones.

A design search for the optimal value of the ultra-supercritical parameters of fresh steam, as well as for the structure of the thermal circuit, which would meet energy and economic requirements, was carried out in paper [1, 2].

The paper [3] presents a thermodynamic and exergetic analysis of the operation of the TPP power unit when varying the parameters of fresh steam, which were chosen as follows: the temperature of fresh steam was successively taken to be equal to 540 °C, 650 °C and 700 °C, and its pressure was 24 MPa, 30 MPa and 35 MPa. As fixed parameters, the followings were taken: pressure and temperature of steam before the low-pressure part T_3=540 °C, P_3=3.6 MPa; pressure and temperature of the steam behind the low- pressure part T_4=26.68 °C, P_4=0.0035 MPa; boiler efficiency η_{boiler}=0.93; internal relative efficiency of the high-pressure part η_{hp}^{turb}=0.9; internal relative efficiency of the low-pressure part η_{lp}^{turb}=0.9; electrical efficiency of the generator η_{gen}^{el}=0.98; pumps efficiency – 0.85.

Regression equations of the relation between the exergetic efficiency of the entire system and the exergetic efficiency of elements of the TPP thermal circuit are obtained in paper [24]. The dependencies of exergetic efficiency on the controlled parameters of the equipment (for example, pressure, temperature), as well as indicators of thermal and isentropic efficiency of the equipment, were established. According to the exergetic indicators and capital costs for the implementation of the project, as well as taking into account the real technical capabilities of mechanical engineering, the parameters of fresh steam of 30 MPa and 650 °C were chosen as optimal ones, after intermediate overheating – 7 MPa and 650 °C (Fig. 1).

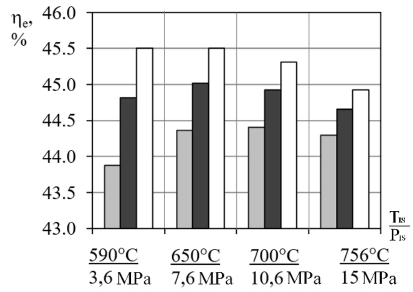

Fig. 1. Dependence of the internal efficiency of turbine unit from the steam parameters after intermediate superheat with different parameters of the live steam:
▨ – 590 °C/30 MPa; ■ – 650 °C/30 MPa;
□ – 700 °C/30 MPa

In paper [1], it is shown that the conversion of the K-300-240-2 turbine to such parameters of live steam and intermediate steam superheat can be carried out by completely replacing the high-pressure cylinder of the existing unit with the high-pressure cylinder with ultra-supercritical steam parameters (HPC USCP) and superstructure with an additional intermediate-pressure cylinder (AIPC) while fully preserving the parameters and structures of output parts of medium- and low-pressure.

Thus, taking into account the previous studies, it is possible to formulate the next goal of the paper, which consists in solving the applied problem of modernization of the 300 MW series power units produced by JSC "Ukrainian Energy Machines" by converting them from supercritical to ultra-supercritical steam parameters (650 °C/30 MPa and 650 °C/7 MPa) provided that the regenerative feed water heating system is preserved as much as possible, which will increase the energy efficiency of the thermal power plant with minimal conversion.

To achieve this goal, it is needed to:

1) develop options of the 300 MW series power unit thermal scheme structure when converting it to ultra-supercritical steam parameters (650 °C/30 MPa and 650 °C/7 MPa) and choose the most rational scheme in terms of energy indicators;

2) justify the choice of the scheme taking into account the minimum conversion of the power unit of the 300 MW series, subject to the reduction of emissions CO_2.

Development of the structure of the 300 MW series power unit thermal circuit when converting it to ultra-supercritical steam parameters

The condensing steam turbine without adjustable steam selections with one reheat and a nominal power of 300 MW at 3000 rpm is equipped with a regenerative feed water heating system, it provides selection for the turbo drive of the feed pump (TDFP).

Fig. 2 shows the initial thermal scheme of the K-300-240-2 turbine with the main parameters (pressure, temperature, enthalpy), and Fig. 3 – diagram of heat transfer in high-pressure heaters (HPH) *A*-scheme with a difference in the temperature of the feed water at the inlet and the saturation temperature of the heating steam condensate Δt=3 °C.

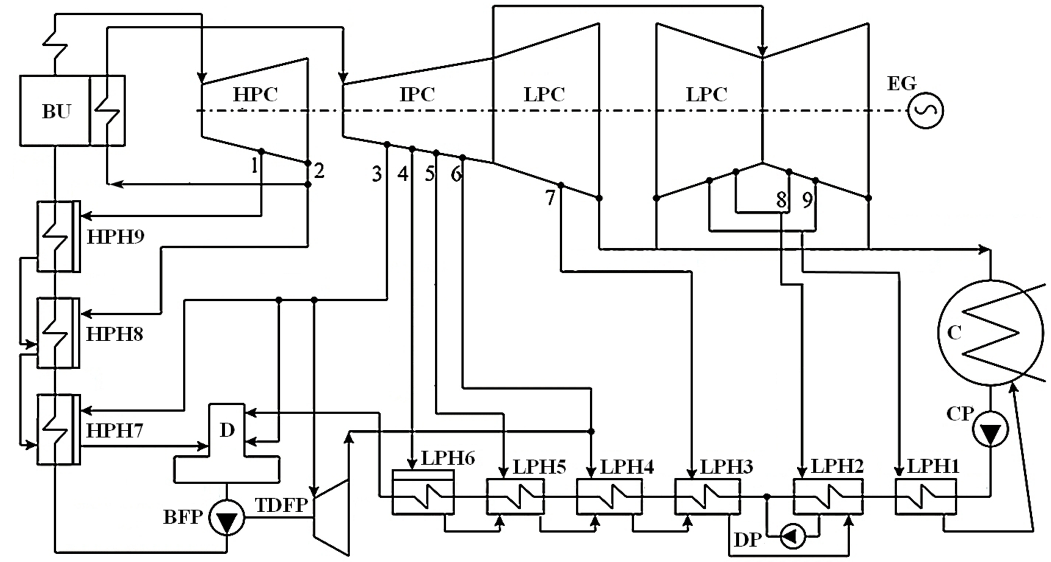

Fig. 2. The thermal scheme of the K-300-240-2 power unit (original A-scheme):
BU – boiler unit; D – deaerator; HPC, IPC, LPC – high-, intermediate- and low-pressure cylinders; 1 – 9 – steam extraction; CP – condensate pump; DP – drainage pump; C – condenser; HPH, LPH – high- and low-pressure heaters; EG – electric generator; BFP – boiler feed pump; TDFP - turbo drive of the feed pump

The regenerative system for steam heating of the feed water entering the boiler from the intermediate unregulated turbine intakes is designed for the K-300-240-2 turbine with a single thread in the low- and high-pressure parts [25].

Fig. 3 shows the diagram of heat transfer in the HPH of *A*-scheme, and the parameters of live steam and steam from regenerative selections for the original option of the scheme (Fig. 2) are given in Table 1.

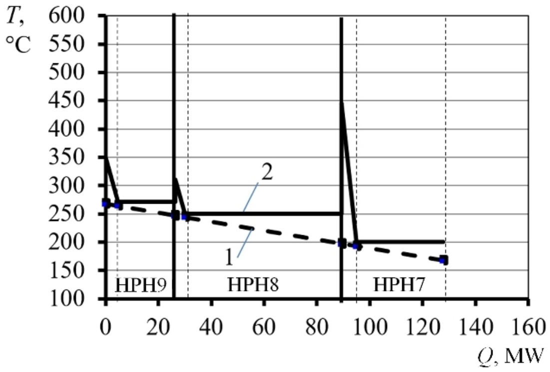

Fig. 3. Diagram of heat transfer in the HPH A-scheme ($\Delta t=3$ °C):
1 – nutrient water; 2 – a pair of selections

Table 1. Parameters of live steam and steam on regenerative selections (original A-scheme)

Process point	Pressure, *p*, MPa	Temperature, *t*, °C	Enthalpy, kJ/kg	Entropy, kJ/(kg·K)	Losses, kg/s	Selection on equipment
Before HPC	23.5000	540.00	3324.800	6.187900	266.70	
First steam selection	5.6000	350.00	3054.200	6.380500	17.50	HPH no. 9
Second selection	4.0000	310.00	2964.794	6.328100	23.30	HPH no. 8
Before IPC	3.7000	540.00	3540.400	7.246200	217.80	
Third selection	1.5600	445.00	3353.100	7.392200	10.00 30.47 5.14	HPH no. 7 Turbo drive Deaerator
Fourth selection	0.6100	323.00	3109.600	7.447900	7.50	HPH no. 6
Fifth selection	0.3600	262.00	2990.400	7.477300	5.40	HPH no. 5
Sixth selection	0.2100	205.00	2880.300	7.506000	7.50	HPH no. 4
Before LPC	0.2600	192.00	2851.500	7.347500		
Seventh selection	0.1180	150.00	2775.300	7.535900	6.10	HPH no. 3
Eighth selection	0.0540	90.00	2662.000	7.604600	2.80	HPH no. 2
Ninth selection	0.0226	62.72	2508.900	7.553285	5.30	HPH no. 1

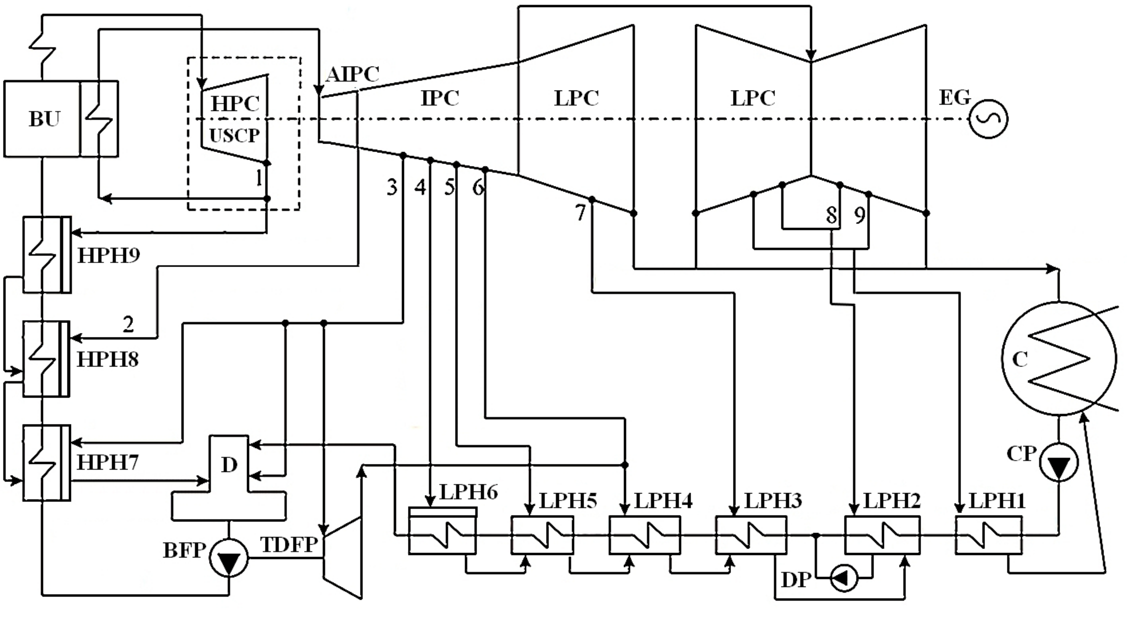

Fig. 4. The thermal scheme of modernization of the K-300-240-2 power unit (B-scheme)

Calculation studies were carried out with the help of a software package developed at the Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine [26]. Mathematical support of the complex allows to calculate stationary regimes of thermal power plants and is easily adapted for researching new structures of their thermal schemes. As a result of the calculations of the thermal circuit (Fig. 2), the electrical efficiency of the original power unit, which is 36.5%, was obtained.

Fig. 4 shows the first option of the circuit modernization, which was chosen as a result of thermodynamic analysis of circuit solutions when varying the parameters of live steam and intermediate overheating in previous studies [1], and is proposed as the most rational.

Modernization measures in this option consist in the organization of the 1st selection of steam from the modernized HPC USCP, and the 2nd - at the output from the AIPC.

Fig. 5 shows the diagram of heat transfer in the HPH *B*-scheme, which was obtained taking into account the new steam parameters in selections 1 and 2. Table 2 shows the calculated parameters of live steam and steam from regenerative selections in the high-pressure part.

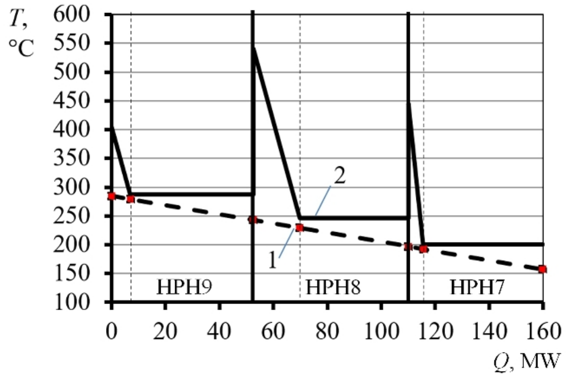

Fig. 5. Diagram of heat transfer in the HPH B-scheme (Δt=3 °C):
1 – nutrient water; 2 – a pair of selections

Table 2. Parameters of live steam and steam from regenerative selections in the high-pressure part (B-scheme)

Process point	*p*, MPa	*t*, °C	Enthalpy, kJ/kg	Entropy, kJ/(kg·K)	Losses, kg/s
Before HPC USCP	30.00	650.00	3599.4	6.4074	266.70
First steam selection	7.19	405.95	3171.4	6.4572	17.50
Before AIPC	6.79	650.00	3770.7	7.2384	249.20
Second selection (modernized)	3.70	540.00	3540.4	7.2462	23.30

It was determined that the electrical efficiency for the option of *B*-scheme of the modernization of the K-300-240-2 power unit increases from 36.5% (*A*-scheme) to 42.5%.

For this option of modernization (Fig. 4), two HPHs and a TDFP are subject to replacement. In addition, the 3rd selection from the medium pressure cylinder is subject to replacement due to an increase in the steam consumption going to the TDFP. The disadvantage of this option is that due to a significant increase in steam parameters, it is impossible to choose a HPH from the existing model range, it is necessary to develop a new design.

Based on the above, in order to preserve the existing HPH, as well as the TDFP, a second option of the scheme for the modernization of the power unit, which is based on a schematic solution known as the "Master Cycle" [21], is proposed. Thus, in *C*-scheme (Fig. 6), it is proposed to install an additional turbine with a capacity of 3 MW, at the input of which steam is supplied from the cold threads of the HPC USCP with a flow rate equal to the sum of the 1st and 2nd selections of the original version of the K-300-240-2 turbine, on the same shaft with a TDFP. From the selections of the additional turbine, steam enters the HPH with parameters corresponding to the output data of the existing turbine (Table 3). In view of this, HPHs are not replaceable. In addition, the power of the additional turbine is sufficient to ensure the operation of the feed pump together with the TDFP to obtain a water pressure of 34 MPa. Therefore, the TDFP also remains unchanged, except for the installation of the additional turbine.

The electrical efficiency of the modernized power unit (*C*-scheme) in this case is 42.4%.

Using the method given in [2], a technical and economic calculation was carried out and the payback period of the power unit modernization was determined according to two options: according to the first option, the payback period of the modernization is 5 years taking into account the modernization of the boiler unit, and according to the second one – 4.5 years at the approximate cost of coal as of September 2021 – 5.500 UAH/t and electricity – 3 UAH/(kW·h) also taking into account the modernization of the boiler unit.

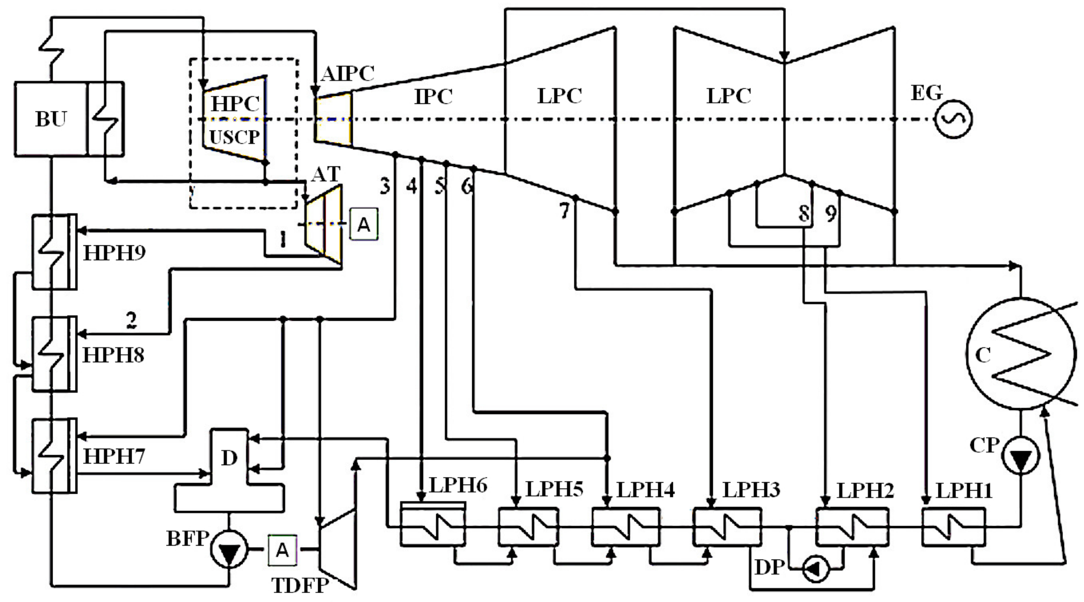

Fig. 6. The thermal scheme of modernization of the K-300-240-2 power unit with an additional turbine: (C-scheme):
AT – additional turbine; A – mechanical connection of the additional turbine shaft with the TDFP shaft

Table 3. Parameters of superheated steam and steam from regenerative selections in the high-pressure part (C-scheme)

Process point	*p*, MPa	*t*, °C	Enthalpy, kJ/kg	Entropy, kJ/(kg·K)	Losses, kg/s
Before HPC USCP	30.00	650.00	3599.4	6.4074	266.70
Before additional turbine	7.19	405.95	3171.4	6.4572	40.80
First steam selection	5.60	369.40	3106.7	6.4634	17.50
Before AIPC	6.79	650.00	3770.7	7.2384	241.10
Second selection (modernized)	4.00	324.70	3028.7	6.4784	23.30

Conclusions

1. Two options of the structure of the thermal circuit of the 300 MW series power unit were considered when converting it to ultra-supercritical steam parameters, and the scale of conversion of the regenerative feed water heating system was evaluated.

1.1. In the first option of the thermal scheme, the 1st steam selection is organized from the cold threads of the modernized HPC USCP, and the 2nd – from the cold threads of the AIPC. In this case, two HPHs and the TDFP are subject to replacement. In addition, the selection of steam from the IPC changes due to an increase in the flow of steam going to the TDFP. The disadvantage of this option is that due to a significant increase in steam parameters, it is impossible to get a HPH from the existing model range, it is necessary to develop a new design. It was established that the electrical efficiency for this option of the K-300-240-2 power unit modernization increases from 36.5% (output thermal circuit) to 42.5%.

1.2. In the second option, in order to preserve the existing high-pressure heaters, it is proposed to install an additional turbine with a capacity of 3 MW, at the input of which steam is supplied from the cold threads of the HPC USCP with a flow rate equal to the sum of the 1st and 2nd selections of the output option of the K-300-240-2 turbine, on the same shaft with the TDFP. The steam from the additional turbine selections goes to HPH9 and HPH8 with parameters corresponding to the output data of the existing turbine. With this in mind, HPHs will not be subject to replacement. In addition, the power of the additional turbine is sufficient to ensure the operation of the feed pump together with the TDFP to obtain a water pressure of 34 MPa. Therefore, the TDFP also remains unchanged, except for the additional turbine installation. The electrical efficiency for the second option of the modernization scheme of the K-300-240-2 power unit is 42.4%.

1.3. It was determined that the payback period of the modernization according to the first option is 5 years, taking into account the modernization of the boiler unit, and according to the second one – 4.5 years.

2. It is proposed to choose an option of the thermal circuit with an additional turbine, which allows to carry out the modernization of the K-300-240-2 power unit with the maximum possible preservation of the regenerative feed water heating system while increasing its energy efficiency by almost 14%.

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Received 19 June 2023

Шляхи модернізації енергоблоків ТЕС при переведенні їх на ультрасуперкритичні параметри пари

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У роботі проаналізовано підхід до вирішення прикладної проблеми модернізації енергоблоків серії 300 МВт виробництва АТ «Українські енергетичні машини» шляхом переведення їх з суперкритичних на ультрасуперкритичні параметри пари за умови максимально можливого збереження системи регенерації підігріву живильної води, що приведе до підвищення енергоефективності ТЕС при мінімальному переобладнанні. Переведення турбоустановки К-300-240-2 на параметри свіжої пари 650 °С/30 МПа й пари проміжного перегріву 650 °С/7 МПа, що визначено як оптимальні в результаті попередніх досліджень, може бути здійснено шляхом повної заміни циліндру високого тиску наявного блоку на новий циліндр високого тиску із ультрасуперкритичними параметрами і надбудови додатковим циліндром середнього тиску при повному збереженні параметрів і конструкцій вихідних частин середнього й низького тиску. Розглянуто два варіанти модернізації структури теплової схеми енергоблоку серії 300 МВт й оцінено масштаби переобладнання системи регенерації підігріву живильної води. У першому варіанті теплової схеми 1-й відбір пари організовано з холодних ниток модернізованого циліндра високого тиску із ультрасуперкритичними параметрами, а 2-й – з холодних ниток надбудови циліндру середнього тиску. При цьому заміні підлягають два підігрівачі високого тиску та турбопривід живильного насосу. Недоліком цього варіанта є те, що через суттєве підвищення параметрів пари неможливо підібрати підігрівачі високого тиску з існуючого модельного ряду, а необхідно розробляти нову конструкцію. Електричний ККД для цього варіанта модернізації підвищується з 36,5% (вихідна теплова схема турбіни К-300-240-2) до 42,5%. У другому варіанті пропонується для збереження наявних підігрівачів високого тиску на один вал із турбоприводом живильного насосу встановити додаткову турбіну потужністю 3 МВт, на вхід якої подається пара з холодних ниток циліндра високого тиску із ультрасуперкритичними параметрами з витратою, що дорівнює сумі 1-го та 2-го відборів вихідного варіанта турбіни. Пара з відборів додаткової турбіни надходить до підігрівачів високого тиску ПВТ9 та ПВТ8 з параметрами, що відповідають вихідним даним наявної турбіни. Беручи це до уваги, підігрівачі високого тиску не підлягатимуть заміні. Крім того, потужності додаткової турбіни достатньо, щоб разом із турбоприводом живильного насосу забезпечити роботу живильного насосу для отримання тиску води 34 МПа. З огляду на це турбопривід живильного насосу теж залишається без змін, крім монтажу додаткової турбіни. Електричний ККД для другого варіанта схеми модернізації турбоустановки К-300-240-2 дорівнює 42,4%. Визначено, що строк окупності модернізації за першим варіантом складає 5 років з врахуванням модернізації котлоагрегату, а за другим – 4,5 роки. Запропоновано обрати варіант теплової схеми з додатковою турбіною, оскільки у цьому випадку можна провести модерніза-

цію турбоустановки К-300-240-2 з максимально можливим збереженням системи регенерації підігріву живильної води при підвищенні її енергоефективності майже на 14%.

Ключові слова: *ультрасуперкритичні параметри пари, теплова електростанція, енергоефективність, система регенеративного підігріву живильної води.*

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