Technical and economic feasibility of development innovative technological solutions for expansion the adjustment range of high-power CCP

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Abstract. The analysis of technical and parametric constraints on the adjustment range of high-power CCP and recommended technological solutions in the technical literature for their elimination. Established that in the conditions of toughening the requirements for economy, reliability and maneuverability on the part of the system operator with the participation of CCP in control the frequency and power in the power system, existing methods do not ensure the fulfillment of these requirements.

The current situation in the energy sector — the lack of highly manoeuvrable power equipment leads to the need participate in control of power consumption diagrams for all types of power plants, including CCP, although initially they were intended primarily for basic loads.

Large-scale research conducted at the department of Automated control systems of technological processes, showed the possibility of a significant expansion of the adjustment range of CCP when it operating in the condensing mode and in the heating mode. The report presents the main results of these research for example the CCP-450 and CCP-450T. Various technological solutions are considered: when CCP in the condensation mode — the use of bypass steam distribution schemes, the transfer of a part of the steam turbine into a low-steam mode; when CCP operation in the heating mode — bypass steam distribution and the transfer CCP to gas turbine unit — power heating plants mode with the transfer the steam turbine to the motor mode.

Data on the evaluation of the technical and economic feasibility of the proposed innovative technological solutions are presented in comparison with the methods used to solve this problem, which are used in practice, such as passing through the failures of the electric load graphs by transferring the CCP to the mode of operation with incomplete equipment. When comparing, both the economics, and the maneuverability and reliability of the equipment are considered.

1. Introduction
Currently, domestic steam power plants are actively introducing powerful combined-cycle plants (CCP) with waste heat recovery boilers of two pressures, which are one of the most common types of generating units on natural gas in domestic and world energy. Taking into account the high profitability of these CCP, especially the heating type, they were designed for operation mainly in the basic mode with a minimum number of starts and load changes. However, the limited possibilities of load regulation in power systems due to the absence of special maneuverable power plants led to the fact that in reality the CCP operation modes differ significantly from the base ones, and the low electricity tariffs at night led
to the need for their deep unloading. Simultaneously, the work of power plants in the electricity and capacity market led to an increase in the demands from the power system to maneuverability and reliability, especially during the hours of failure.

Recommendations for expanding the adjustment range and reserving the CCP power during the hours of load failure, indicated in a number of research relating to CCP-450 [1-3], are mainly suitable for the condensing mode of the CCP operation. At the same time, the district heating plants for a considerable part of the year work in the heating mode and the mentioned problem for such regimes is also obvious. The results of previous research, two characteristic features of CCP-450 were revealed when operating it in the power control mode in the power system:

- the presence of a gap 10% of the nominal power of the CCP between the powers of the lower limit of the adjustment range when the CCP operates with the full composition of the equipment (2GT + 2SB + PT) and the upper limit when operating it with an incomplete composition (1GT + 1SB + PT) The operation of the power unit is not allowed either by the reliability criterion or by environmental indicators.
- the dependence of the power upper and lower boundaries and the adjustment range of the CCP on the outside air temperature.

The first feature creates certain difficulties for both operational personnel and dispatch services, and therefore, research aimed at finding technological solutions that reduce or eliminate this gap is important.

The second feature requires considering this dependence when planning the participation of CCP in power regulation in both the daily and long-term (monthly, annual) time intervals.

The foregoing confirms the necessity and expediency of conducting further research with the aim of developing innovative solutions for expanding the adjustment range of a large-scale CCP unit when operating it in the heating mode with an assessment of their technical and economic feasibility, taking into account the characteristics of the heating mode — ensuring, first of all, the heat load required by the thermal schedule. The report presents the main results of these research using for example the CCP-450 and CCP-450T.

2. Analysis of factors affecting the CCP adjustment range in the heating mode

In accordance with generally accepted terminology, the range of electrical loads is understood as the adjustment range, which is provided without changing the number of operating equipment. For the combined-cycle power unit, both the upper and lower limits of the adjustment range are variable depending on the temperature of the outside air, which is related to the operation of the gas turbine plant.

The upper limit of the CCP adjustment range depends on the type of gas turbine plant and its characteristics and the actual operating conditions of the power unit.

The lower limit of the load range of the CCP is significantly influenced by the temperature of the gases behind the gas turbine, which determines the temperature of the steam produced and, accordingly, the operating mode of the steam turbine. The steam temperature at the entrance to the steam turbine in the condensing mode of the CCP, under the condition of reliable operation of the last stages of the LPC, should not fall below 475°C, which corresponds to a 285-290 MW CCP load with 2GT and 145 MW at 1GT operation.

When the CCP is operating in the heating mode, the steam turbine, as a rule, operates with a closed low-pressure control diaphragm, as a result of which this restriction does not apply. When the CCP is operating in transient modes with a partial flow of steam into the condenser due to a decrease in the efficiency of the last stages, the process of vapor expansion on the h-s diagram shifts to the right, which leads to a decrease in the humidity of the vapor, which ensures the allowable moisture of the steam under the conditions of reliable operation of the last stages of the LPC.

Environmental characteristics also have an effect on the lower limit of the load range of the CCP. With a decrease in the GT load below 85 MW, the combustion regime of the gas changes, characterized by large emissions of nitrogen oxides. Thus, to ensure the availability of this regime, the load of the power unit should not fall below 280 ... 290 MW (2GT) and 135 ... 145 MW (1GT).
The economical operation of the unit also changes with a reduction in the load of the unit, while below a certain load (after the closure of the Input guide) this fall becomes greater. According to [2], in order to maintain the efficiency within 95% of the nominal capacity of the unit, when operating CCP in condensing mode it should not fall below 315 ... 320 MW (2GT) and 140 ... 145 MW (1GT). This limitation in the operation of CCP in the heating mode, due to the high internal relative efficiency of the steam turbine, occurs at CCP loads when working with a full equipment of 260-270 MW.

When studying CCP modes at reduced loads, it is also necessary to bear in mind the fact that in the total power of the CCP the share of CCP power decreases with a corresponding increase in the fraction of the power of the steam turbine. Thus, at the maximum load of the CCP, the share of the CCP is 63.0-68.8% of the CCP power, and at minimal loads it decreases to the level of 57.6-61.1%. This is especially important when the CCP is operating in the heating mode, since when the CCP is unloaded by electric power the steam turbine can provide the heat load at a sufficiently high level.

Analyzing the results of the study, we can state:

1. The adjustment range of CCP-450 when operating it in the heating mode with the total composition of the equipment is within 35-41% of the nominal load, i.e. significantly inferior to the same indicator of condensing power units on gas-oil fuel (50-60% of nominal);

2. On the diagram of the operation modes of CCP-450 units when operating it in the heating mode under reduced loads, there is an undesirable zone from the point of view of the ecological and economic performance of the unit, which increases with the growth of the heat load (Figure 1), which creates certain difficulties for dispatching control and operational personal.

![Figure 1. Dependence of conventional fuel consumption on CCP 450 on thermal and electric loads](image)

In the operating conditions, in order to avoid block operation in this range of loads, the unit must be put into operation with the incomplete composition of the equipment, which leads to idle technological equipment, additional start-up of the stopped gas turbine and waste heat boiler with a subsequent increase in the load and, correspondingly, to additional fuel losses. In addition, frequent shutdowns of the gas turbine and waste heat boiler adversely affect the reliability and durability of their operation.

The results of the research presented above show the need to develop technological solutions that allow expanding the CCP adjustment range not only in the condensing mode but also in the heating mode of its operation.

In comparison with the condensing mode of operation of CCP in the heating system, additional restrictions and conditions arise that are associated with the need to provide a given volume of heat...
supply to thermal consumers, which significantly reduces the possibility of bypass steam distribution, especially in relation to CCP-450, in the scheme of which there are no peak system heaters for system water (PSH).

The main initial condition for the considered ways of expanding the CCP adjustment range is to ensure reliable operation of all its main components — gas turbines, waste heat boiler, steam turbine, network heaters, condenser, etc. as in the operational mode, and in terms of long-term prospects

To ensure this condition, the following technology of CCP-450 operation is proposed for the implementation of bypass steam distribution:

- unloading of the CCP in accordance with the operational instruction up to the permissible load of gas turbines, for example, for environmental restriction (let's call this load "basic");
- further unloading of the unit by electric load — at constant power of gas turbines by reducing the electric power of the steam turbine and increasing the generation of heat through the use of bypass steam distribution until the complete removal of the electric load from the steam turbine with the transfer of the CCP to the GTU-CHP (gas turbine unit - combined heat and power plants) mode.

The following options are proposed for the organization of bypass steam distribution (for example, CCP-450T, CCP-450)(Figure 2):

1. The discharge of a portion of the high-pressure steam into the low-pressure steam supply line into the steam turbine in an amount \( D_{\text{ limitless}} \), with a preliminary reduction of the vapor pressure to the low-pressure steam pressure and cooling it to a temperature different from the low-pressure steam temperature by no more than 50 °С ; high-pressure steam is cooled before it is discharged into the low-pressure steam line in a steam-water heater, while the main condensate is used as the coolant before it is fed to the gas condensate gas heater (the system water can be used before supplying it to PSH-1). The power of the CCP under this scheme is reduced by 2.5 MW, the increase in heat production by 7.6 Gcal/h.

2. Addition to process 1 of a high-pressure steam portion in an amount \( D_{\text{ limitless}}' \) is reset to the LPC with preliminary throttling in the throttle valve TV3 and cooling in MP4 to the pressure and temperature of the steam at the exit from the MPC. To reduce the temperature of the steam, condensate is used after the condensate pump. To maintain the balance of steam and condensate, the same amount of condensate is discharged to the condenser from the drain line at the outlet from the PSH-1. The amount of steam discharged into the LPC at the closed diaphragm and the power of the steam turbine depend on the ratio of steam costs to PSH-1 and PSH-2. The maximum power reduction of the steam turbine in this variant (36.5 MW) is due to the reduction of the HPC capacity, the heat production is increased by 36.4 Gcal/h.

3. The limiting mode of distribution of high-pressure steam in option 2 will correspond to the minimum allowable steam flow through the HPC (50 ton/h) and the discharge of the rest of the steam in the LPC — a reduction in power of about 60 MW, increase in heat supply-about 59 Gcal/h;

4. In the development of option 3 — the complete stopping of the high-pressure steam supply to the HPC with a partial transfer of the HPC section from the 1st to the 16th stage, i.e. To the place of supply of low-pressure steam in a steam-free (low-steam, motor) mode. The possibility of such a mode of operation of the HPC and the organization of the cooling scheme for the HPC blades in this mode has been proved in [5].

- discharge of a part of the high pressure steam into the low pressure steam supply line in the amount given above, with its preliminary throttling in the TV1 and cooling in cooler C1;
- discharge of a part of the high-pressure steam directly into the PSH-2 with its preliminary throttling in the TV2 up to the pressure determined by the temperature of the system water at the outlet from the CCP-2; If it is necessary to lower the temperature of the steam, it is cooled in cooler C3;
- the rest of the high-pressure steam is discharged into the LPC with its preliminary throttling in the TV3 and cooled to the permissible temperature for supply to the LPC in the mixer MP4;
- the steam supplied to the HPC via the low-pressure steam supply line after its expansion is throttled in the TV4 to the vapor pressure in the LPC sampling at PSH1, mixed with the steam flow from the LPC and enters the CPP-1.

This scheme of bypass steam distribution allows maximum unloading of the steam turbine by electric power (by 74.3 MW) with observance of all restrictions on steam pressure and temperature in steam samplings at CCP.

5. With respect to the CCP-450T with peak system heaters, the following scheme of operation is proposed: maximum discharge of high-pressure steam into one of the PSH through the reduction cooling unit (RCU) with a minimum use of the thermal power of the PSH. This mode corresponds to the minimum flow of high-pressure steam through the flowing part of the HPC set by the manufacturer — 50 ton/h; Supply of low-pressure steam according to the design scheme with further distribution of them between the PSH. Such a scheme will provide the electric power of the steam turbine is at the level of 21.0-22.0 MW with an increase in heat production by 68.8 Gcal/h.

Figure 2. Simplified design scheme for bypass steam distribution

6. Transfer of the CCP to the GTU-CHP regime with the complete removal of the load from the steam turbine by stopping it or transferring it to the motor mode (MM), i.e. without disconnecting the generator from the mains.

The operational disadvantage of the GTU-CHP regime with the stopping of the steam turbine is the need for its subsequent start-up, which is associated with fuel losses during the start-up period and the loading delay of the CCP as a whole. In the present paper, instead of stopping the steam turbine, it is proposed to put it into the MM. The technical feasibility and economic feasibility of the operation of the T-125/150 steam turbine in the MM during the operation of CCP-450 in the condensation mode is shown in [4, 5].

When the CCP steam turbine is operating in the MM during the CCP operation in the heating mode, the technology of transferring the steam turbine to the MM, the scheme for supplying steam to the seals and for cooling its flow section is the same as for the CCP operation in the condensation mode, but it also has some differences:
since gas turbines and heat boilers remain under the "basic" load, steam for cooling the flowing part of the steam turbine is taken from the corresponding steam supply lines (in addition to the steam turbine) to the system heaters (Figure 3), including: for the front seals HPC from the steam pipe of high-pressure steam through RCU1; To steam the HPC from the high-pressure steam pipe through the main steam valve (MSV) bypass line; On the LPC either from the high-pressure steam supply line to PSH-1 via RCU2, or from the low-pressure steam line at PSH-1, while cooling the steam in the mixer MP4 with condensate from the condenser, if necessary.

- the total flow of steam entering the condenser is the same as in the condensing mode, but the pressure in the condenser can be higher due to the fact that the temperature of the main condensate entering the gas condensate heater (GCH) at its flow rate equal to the sum Condensate flow from the condenser and condensate from the condenser cooler of the lower system heater must be at least 60 degrees.

Figure 3. Simplified scheme of operation of a steam turbine in the motor mode

The scheme for organizing the distribution of steam flows is as follows:
High-pressure steam is partially discharged into the low-pressure steam line as described above, mixed with low-pressure steam and supplied to PSH-2. The remaining high-pressure steam is supplied to PSH-1, while a steam-water cooler is installed in front of the PSH to reduce the vapor temperature. For cooling the steam, the system water is used after the condenser cooler PSH. To regulate the steam pressure on the steam supply lines in the PSH, pressure regulators after themselves (MM1) are installed.

An alternative scheme for the use of high and low pressure steam during the operation of a steam generator in an MM is to: completely discharge high pressure steam into a low pressure steam line with pre-cooling and reduce its pressure to the corresponding low pressure steam parameters, then distribute the entire vapor stream between PSH-1 and -2 (MM 2)
With regard to the CCP with peak system heaters, high-pressure steam is discarded in PSH-4, and low-pressure steam is partially supplied to PSH-3. This mode of operation of the unit ensures maximum heat production (MM 3).

The use of MR allows to maximally increase the generation of heat to the level of 316-323 Gcal/h, while the loss of efficiency of the CCP operation in relation to the "basic" regime is insignificant — the reduction of the overall efficiency of CCP-450 in the generation of electricity and heat does not exceed 0.3-0.93 %. Calculations carried out on the effectiveness of the application of the motor regime showed that with a duration of the CCP operation of 5.0-7.0 hours in the GTU-CHP regime it is more effective than stopping the steam turbine with subsequent start-up.

It should be noted that simultaneously with the increase in the maneuverability of the CCP, the conversion of the steam turbine to the MM also improves its reliability indicators by eliminating the cyclic temperature fluctuations of the vapor steamer bodies characteristic of its start-up during the set of revolutions and idling.

3. Conclusion

Thus, when the CCP 450 is used in the heating mode, the use of bypass steam distribution and the transfer of the CCP to the operation mode of the GTU-CHP with the transfer of the steam turbine to the MM allows to significantly expand the CCP adjusting range to 0.43 of the nominal capacity 450 MW, while the loss of economy is negligible — a decrease in the overall efficiency of the combined cycle plant for the generation of electricity and heat does not exceed 0.3-0.9%.

4. Reference

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