Improving the System Efficiency of CHP in the Context of Increasing Requirements for the Maneuverability and Environmental Friendliness of Power Plants

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Abstract. New trends in the fight against climate change on the planet, suggesting a reduction in greenhouse gas emissions, are influencing the formation of a new structure of the electric power system. As the experience of the European Union shows, the active development of renewable energy sources affects the electrical modes of operation of power plants and in the future can lead to a decrease in electricity production in a highly efficient combined generation mode at CHPs. Thus, there is an acute issue of finding a place for a CHP plant in the emerging power systems, in which generating equipment will be especially in demand, effectively operating in half-peak and peak modes to cover the daily load unevenness. The development and commissioning of a highly maneuverable GTU-CHPP, capable of operating in a combined generation mode with daily starts / stops, can significantly increase the efficiency of electricity generation in the peak part of the daily load schedule. The system effect of the commissioning of 10 GW of highly maneuverable GTU-CHPPs within the UES of Russia will reduce the consumption of fossil fuel by 19.6 million tce per year and CO₂ and NOₓ emissions by 55 million tons and 24.7 thousand tons per year, respectively.

1. Introduction

The Unified Energy System (UES) of Russia is characterized by a significant surplus of generating capacities. Thus, the installed capacity of power plants on January 1, 2020 was 246,342.45 MW at historical maximum power consumption of 157425 MW, observed December 21, 2012 [1, 2].

The excess of capacity supply over demand by more than 1.5 times leads to significant operating costs of the Unified Energy System and is associated, first of all, with daily and seasonal uneven consumption. To cover the daily load unevenness of at least 20,000 MW both in winter and summer, it is necessary to have generating equipment operating in half-peak and peak modes [3, 4]. The efficiency of operation of power plants, and, accordingly, the rational use of energy resources by a single power system depends on the correct choice of the structure of generating capacities.
In the 1960s, during the formation of the Unified Energy System of the country, the issues of the need to produce special generating equipment for operation in peak and semi-peak modes were already widely discussed [5, 6, 7, 8]. In the following decades, the development of a small-sized power unit MG-210 with a capacity of 210 MW with steam parameters of 13 MPa and 540 °C on solid fuel, intended for operation in a semi-peak mode with the possibility of daily shutdowns for the night. Also maneuverable steam turbines K-300 and K-500 were manufactured.

At present, the K-300 and K-500 power units, commissioned in the period from 1963 to 1980 and actively used to maintain the electrical modes of the UES of Russia, have basically exhausted their park resource [9, 10]. Therefore, the coverage of the unevenness of the daily consumption schedule is carried out mainly by the generating equipment of hydroelectric power plants, as well as by cogeneration turbines of CHPPs when operating in a condensing mode.

New trends in the fight against climate change on the planet, implying a reduction in greenhouse gas emissions, have a significant impact on the formation of a new structure of the Unified Energy System. Thus, the need for the active development of renewable energy sources and their integration into a single power system will greatly affect the electrical modes of operation of power plants and will lead to the need for daily start / stop of some of the generating equipment [3, 11].

When designing the development of a unified energy system in the face of stricter requirements for the maneuverability and environmental friendliness of power plants, special attention should be paid to increasing the system efficiency of CHP plants. This is due to the fact that the electric power and heat power systems are connected by common operating modes. Thus, it is necessary to consider the issues of simultaneous optimization of electricity and heat supply, the cost of electricity and heat for end users, the environmental effect, as well as the impact of the construction of a new generation on the operating modes of existing power plants. The minimum cost of energy resources is possible only for an efficient and balanced power system in terms of its structure.

2. Background

In Russia, along with the increase in the share of renewable energy sources, special attention is paid to the development of cogeneration at CHP plants, which is recognized as a priority area for increasing resource conservation and reducing greenhouse gas emissions [12, 13, 14]. This is due to the climatic and geographical features of the country, which determine the high demand for heat. Thus, in energy equivalent, district heating systems produce 1.5 times more heat than electricity. At the same time, district heating from a CHPP is the most environmentally friendly technology for heat production [15, 16].

At present, the CHPP in the mode of combined generation of electricity and heat operates in the basic part of the daily load schedule, providing high indicators of resource saving. When switching to condensation mode, the main generating equipment of the CHPP is used to back up the seasonal maximum load. In this case, the efficiency and environmental friendliness of production at the CHP plant is significantly reduced [17, 18].

An urgent task arises to ensure the use of combined generation of CHPP in the half-peak and peak parts of the daily load schedule, the solution of which will significantly expand the use of combined generation of thermal power plants in the power system.

Thus, the CHPP should contain highly maneuverable (peak) equipment that ensures efficient operation simultaneously in the peak (half-peak) mode according to the electrical schedule with daily starts / stops and the base mode according to the thermal load schedule.

The duration of the start, the number of start / stop cycles depends on the installed capacity of the gas and steam turbines. The lower the installed power, the higher the start / stop speed and the higher the factory-authorized number of cycles. Hence, generating equipment with a lower capacity is more maneuverable.

Reducing the electrical capacity of the generating equipment allows the power plant to operate in cogeneration mode with a fuel heat utilization rate of more than 80%. The most popular solutions due to their energy efficiency are the installation of combined cycle and gas turbine units at CHPPs.
Considering a CHPP as a peak thermal power plant, then the choice between CCGT-CHPP and GTU-CHPP is determined by the duration of start-up operations. The duration of start-up operations for low-power CCGT units from a hot state is at least 2.5 hours, while the duration of start-up of small GTUs does not exceed 15 minutes. A significant increase in the duration of the start-up of the CCGT unit, in contrast to the GTU, is determined by the high-pressure circuit of the steam waste heat boiler and the steam turbine [15, 17, 19].

A highly maneuverable GTU-CHPP should contain a gas turbine unit and an autonomous low-power steam turbine unit connected to a common automatic control system and capable of operating independently of each other. The gas turbine unit is designed to generate electricity and heat for external consumers in the daytime. The steam turbine unit is used to generate heat for external consumers and electricity for the power plant's own needs at night. A low-power steam turbine plant can additionally include hot water and steam boilers.

In order to reduce the duration of launch operations GTU-CHPP refuse the steam circuit when working in the basic mode from and simplify the structure of the recovery boiler is required.

3. Methods
To ensure the high maneuverability of the GTU-CHPP, it is necessary to determine the appropriate composition of the main power equipment, including a gas turbine unit, capable of operating independently low-power steam turbine unit and boiler equipment.

The analysis of gas turbines has shown that gas turbines with an electric power of up to 25 MW are commercially produced in Russia, corresponding to the declared maneuverability characteristics of a thermal power plant. Gas turbines manufactured by Perm Motors JSC with an installed capacity of 16 MW and 25 MW, Saturn JSC - 10 MW, and Turbomach 10 MW - 15 MW (in case of localization of production in the country) can be considered.

Russian-made gas turbines are characterized by a higher electrical efficiency in the entire load range compared to gas turbines manufactured by Turbomach. In turn, a decrease in the electrical efficiency of turbines "Turbomach" (Titan-130 and Mars-100) is a payment for better environmental performance in terms of NO, and CO emissions [20, 21].

The maneuverable characteristics of the GTU-CHPP are largely determined by the operating modes of the waste heat boiler, which should provide for the possibility of daily starts and stops. For these purposes, it is proposed to use a water-heating, water-tube, once-through, gas-tight waste heat boiler (HBWH) without using an afterburner system. The absence of an afterburner system removes the increased requirements for the heat resistance of the materials of the internal surfaces of the HBWH, as well as additional requirements for ventilation.

The design of the boiler allows the operation of the GTU through an empty boiler (dry). Carrying out the "dry" start-up of the HBWH can be ensured by using a bypass and / or heat-resistant steels for the manufacture of heat exchangers and the inner surface of the boiler. For a gas turbine exhaust gas temperature of about 500 °C, it is possible to use heat-resistant alloys with a relatively low cost. The use of elements with a minimum wall thickness allows to increase the start / stop speed and change in the load of the HBWH.

Generating equipment with a start-up time of no more than 300 seconds belongs to a rotating reservoir and can be used to quickly cover peak and semi-peak loads [22, 23]. At the same time, in accordance with the data of the manufacturers, the number of GTU starts / stops without changing the terms of service for the Titan 130 is 300-350 per year, for the Russian power unit GTD-10RME - 425-450 per year. In accordance with the requirements of the technical operation rules, the ventilation of the gas path is carried out before the start of the gas turbine, which automatically increases the duration of the start-up operations. The cold start time, including the venting time of the gas path, is 600 seconds (quick start less than 300 seconds).

Reducing the start-up time of the GTU-CHPP to 300 seconds can be achieved by changing the approaches to the ventilation of the gas path. The use of continuous ventilation of the gas path during the shutdown of the gas turbine unit will reduce the time of start-up operations to the required value.
In accordance with the characteristics of the generated composition of the generating equipment, a thermal scheme of the GTU-CHPP was developed, which is characterized by high maneuverability and environmental friendliness (Figure 1).

![Figure 1. Thermal diagram of a highly maneuverable GTU-CHPP.](image)

The proposed scheme includes a gas turbine (GTU), a gas network heater (GNH), a small-sized cylindrical steam generator (CSG), a screw steam engine (SSE), a heat exchanger (HE), hot water boilers (WB) and network pumps (P).

4. Results and discussion

The results of calculating the parameters of the developed thermal scheme of a highly maneuverable GTU-CHPP with a Titan-130 power unit manufactured by Solar Turbines, performed in the Thermoflow software environment, are presented in Table 1.

| №  | Parameter                                                                 | Outside air temperature, °C |
|----|---------------------------------------------------------------------------|------------------------------|
|    | Basic equipment mode                                                      | -30  | -3.6 | 15 | 30         |
| 1  | Total electric power, kW                                                 | 18 092 | 15 857 | 11 073 | 9 897 |
| 2  | Total thermal power, kW                                                  | 22 591 | 21 788 | 17 258 | 17 376 |
| 3  | Exhaust gas temperature, °C                                               | 482  | 492  | 503  | 587  |
| 4  | Water temperature at the entrance to the HBWH, °C                        | 70   | 48   | 40   | 40   |
| 5  | Water temperature at the outlet of the HBWH, °C                          | 150  | 94   | 74   | 74   |
| 6  | Fuel heat utilization factor during power unit operation in the main mode (day mode), % | 79.12 | 83.20 | 82.27 | 84.34 |
| 7  | Fuel heat utilization factor with disabled GTU (night mode), %           | 90.75 | 90.8  | 90.7  | 90.53 |
Comparative analysis of fuel efficiency and environmental friendliness indicators (in terms of CO$_2$ and NO$_x$ emissions) of the proposed scheme of a highly maneuverable GTU-CHPP, operating, inter alia, at peak loads in cogeneration mode, with schemes for the separate production of electrical and heat energy (GTU and hot water boiler (HWB); CCGT and HWB) is presented in Table 2. Calculations were made for the production of the same amounts of electricity and heat.

**Table 2. Comparative analysis of indicators of fuel efficiency and environmental friendliness of highly maneuverable GTU-CHPP.**

| Option                  | Equipment composition | Fuel consumption, % | Emissions of CO$_2$, % | Emissions of NO$_x$, % |
|-------------------------|-----------------------|---------------------|------------------------|------------------------|
| Separate production of electricity and heat | GTU and HWB           | 100,0%              | 100%                   | 100,0%                 |
|                         | CCGT and HWB          | 84,4%               | 84,4%                  | 91,0%                  |
| Cogeneration            | GTU-CHPP and HWB      | 74,6%               | 74,6%                  | 60,8%                  |

Thus, the proposed version of GTU-CHPP and HWB for the considered composition and operating modes of generating equipment is a priority from the point of view of fuel efficiency and CO$_2$ and NO$_x$ emissions.

The construction of highly maneuverable CHPPs will lead to an increase in the volume of peak generation in the power system, which will make it possible to additionally load the basic generation due to the removal of operating restrictions [3, 24].

Figure 2 shows a comparison of the electrical operating modes of the power system in the first price zone of the wholesale power market when 10 GW is put into operation (about 4% of the installed capacity of power plants in the UES of Russia) in the form of highly maneuverable GTU-CHPPs with the actual modes.

**Figure 2. Electrical modes in the first price zone of the wholesale market (summer day).**

The considered graphs show the following dependencies between the loading of various types of capacities and energy consumption: (1) - Loading of NPPs operating in the basic part of the electric load schedule; (2) - Loading of the NPPs taking into account the technological minimum of TPP; (3) - Loading of the NPPs taking into account the technological maximum of TPP; (4) - Electricity consumption within the energy system minus the generation of hydroelectric power plants; (5) - Loading highly maneuverable GTU-CHPPs.

The above dependences show that the use of highly maneuverable CHPPs will allow to remove operating restrictions and additionally load 6 GW of NPP electric power, as well as increase the volume of cogeneration output of CHPPs and reduce the use of ineffective condensation modes of operation of
turbines. In turn, this will lead to a decrease in the consumption of fossil fuel in the power system, which, according to the estimates obtained, will amount to 19.6 million tons of fuel equivalent per year.

The increase in the fuel efficiency of the GTU-CHPP and in the utilization of nuclear power plants in the power system will also reduce CO₂ and NOₓ emissions by 55 million tons and 24.7 thousand tons per year, respectively.

Another important effect will be a decrease in the marginal cost of electricity in the trading sector of the wholesale power market - the day ahead market. So, when using highly maneuverable GTU-CHPPs in the peak part of the daily load schedule instead of condensation generation of steam turbines with a steam pressure of 130 ata, it can be estimated at 188 billion rubles per year. At the same time, the decommissioning of 10 GW of ineffective TPP capacities will further reduce the financial burden on consumers by 16 billion rubles per year.

The direct costs of the program for the construction and commissioning of 10 GW of highly maneuverable GTU-CHPPs within the unified energy system of the country, depending on the serial production, will be from 600 to 1000 billion rubles. Due to the above-described system effect, the simple payback period of investments will be from 3 to 5 years, and the discounted one (with WACC = 12%) - from 5 to 8 years, which allows to conclude that the construction of highly maneuverable GTU-CHPPs is investment attractive.

5. Conclusion
Increasing the system efficiency of CHP plants in the context of stricter requirements for the maneuverability and environmental friendliness of power plants is one of the most important tasks in the formation of resource-saving energy systems both at the regional and national levels. Its solution requires the development of new thermal schemes and the determination of a suitable composition of the main power equipment, allowing CHPP to operate efficiently in peak and semi-peak modes.

A thermal diagram of the GTU-CHPP was proposed, including a gas turbine and a steam turbine unit connected to a common automatic control system and capable of operating independently of each other. The gas turbine unit is designed to generate electricity and heat for external consumers during the daytime. The steam turbine plant is used to generate heat for external consumers and electricity for the power plant's own needs at night. In order to reduce the duration of the start-up operations of the GTU-CHPP, the design of the waste heat boiler has been simplified.

Calculations carried out in the "Thermoflow" software environment have shown that the fuel heat utilization factor of a highly maneuverable GTU-CHPP during the heating period is 80-85%, and in the summer period in emergency mode it exceeds 53%. This achieves the following characteristics of maneuverability: the number of starts from 300 per year without changing the overhaul period; starting time up to 600 seconds (quick start up to 300 seconds); fuel consumption for start-up is less than 30 kg of fuel equivalent / MW; regulation range - 100% of available power.

The introduction of 10 GW of highly maneuverable GTU-CHPPs within the UES of Russia will remove systemic restrictions on the loading of NPP power units and ensure a decrease in fossil fuel consumption by 19.6 million tons of fuel equivalent per year and CO₂ and NOₓ emissions by 55 million tons and 24.7 thousand tons per year, respectively. It will also lead to decrease in the marginal cost of electricity in the wholesale power market, and thus in the electricity tariff for consumers.

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