The extension of the operational range of combined-cycle power plant with a triple-pressure heat recovery steam generator

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Abstract. In the article, the issues of operational flexibility improvement for CCGT with a triple-pressure heat recovery steam generator are described. The factors limiting the operational range of CCGT were identified and analyzed. Analytical dependences for the minimum and maximum load of the CCGT on the ambient air temperature were obtained. The ways of expanding an operational range due to water spray into air-intake path, supplementary firing before the heat recovery steam generator, intensifying regulation of compressor airflow using the IGV and its pre-heating are described.

1. Introduction
Currently, at the domestic thermal power plants powerful combined-cycle units with heat recovery steam generator (HRSG) of the three pressures and reheat are introduced, which are the most efficient type of generating plants on natural gas. Thus, they were designed as base load plants. However, in terms of Power Joint Market and the limited possibilities of load regulations of power systems, CCGT operating modes significantly differ from the basic adjustments. The reduction of electricity rate at night in Russia led to the necessity for deep discharges. There is also another problem. The dispatch schedule of power loads is made on the basis of certified value of electric power CCGT. High ambient temperatures at derated hours lead generating companies to losses because of reduced production of electricity and decrease of pay for capacity characteristics. Under such conditions, the extension of the adjusting range limit of loads of the CCGT would be relevant.

2. A short description of the object of study
In December 2014, the CCGT-420T power-generating unit was put into operation at the Combined Heat and Power Plant 16, an affiliated company of Mosenergo. The basic equipment of the power-generating unit comprises: an SGT5-4000F gas-turbine with an electric generator manufactured by Siemens AG; an SST5-5000 steam turbine with an electric generator manufactured by Siemens AG; and a horizontal triple-pressure drum waste heat boiler with a reheater manufactured by EMAl’yans. The electrical capacity of the power-generating unit is 421 MW and its thermal efficiency reaches 58.2% at the contract ambient conditions.

To investigate the characteristics of the CCGT, it was tested in 2014 – 2015, using a sufficiently complete, precise and automated authorized measuring system. In the course of the thermal tests, 92 modes were studied within the wide ranges of power outputs (from 5 to 302) MW and ambient temperatures from −12 to +24°C. The experimental data is made in accordance with [1]. Results of thermal tests and their analysis is given in [2]. On the basis of experimental characteristics was generated a calculation model of the generating unit CCGT-420 [3], which allowed to examine its modes,
parameters and indicators, and patterns of their changes in various loads and ambient temperatures. On the basis of computations and data, obtained during the experimental work, were identified and analyzed the factors limiting the adjustment range of power of the CCGT and of ways of its expansion.

3. CCGT adjustment range of load

Currently the most relevant operational flexibility characteristic for generating companies and system operator is the adjustment range of load, defined as the difference between the maximum and minimum electrical loads, achieved without changing the composition of the equipment units. In accordance with the requirements of the supplier, the gas turbine can be operated in the range of ambient temperatures from -45 to +40 °C. Figure 1 shows the dependences of the technological maximum load of CCGT-420 and the respective loads of the gas turbine (GT) and the steam turbine (ST). The maximum capacity of the GT is limited when reaching the maximum permissible level under the ambient conditions of the temperature of gases at the inlet to the gas turbine and the airflow through the compressor according to the strength conditions for rotor and row of blades. For the concerned GT the maximum electric capacity is obtained when the compressor inlet temperature is equal to -12 °C and is about 302 MW, the corresponding value of the CCGT electrical power is 436.8 MW. Thermal efficiency of GT in this case is 39.8%, and the thermal efficiency of the CCGT is 57.7%.

![Figure 1](image)

Figure 1. Change in maximum and minimum electrical output of the CCGT (\(N_{e\text{max}}^{\text{CCGT}}, N_{e\text{min}}^{\text{CCGT}}\)), the GT (\(N_{e\text{max}}^{\text{GT}}, N_{e\text{min}}^{\text{GT}}\)) and the ST (\(N_{e\text{max}}^{\text{ST}}, N_{e\text{min}}^{\text{ST}}\)), depending on the ambient air temperature (\(t_{\text{a,\,°C}}\)).

The maintenance of the GT capacity on the maximum permissible value at a further reduction of the ambient air temperature is achieved with the decrease of the airflow and fuel due to the simultaneous cover of the IGV compressor and a fuel valve of the fuel handling system. In accordance with the requirements of the supplier, the GT should not be operated when the compressor inlet temperature is below -20°. At lower temperatures in the preheat system it increases to the minimum permissible value according to operating conditions. In this region of ambient air temperatures, the rate of opening IGV and the fuel valve, and the GT exhaust temperature and flow as well as the steam properties in the steam turbine and its capacity remain constant. With increasing ambient air temperature the capacity of the GT
and CCGT are reduced to 266 and 400 MW at ambient air temperature of 25°C. In this connection, the thermal efficiency of the GT is reduced to 38.8%, and the thermal efficiency of the CCGT to 56.8%. Thus, unlike the conventional steam power units, the base load of combined cycle power plant is a variable value and its dependence on ambient air temperature should be considered when planning the unit commitment in the control of the power system. According to the data obtained in the current study of the operation modes of the CCGT-420, minimum permissible load of the GT and CCGT (solid lines in figure 1) in the range of ambient temperatures from -45°C to +40°C following analytical dependencies were obtained:

\[
N_{GT}^{max} = 0.0264 \cdot t_{aa}^2 - 0.5194 \cdot t_{aa} + 292.9 \text{ at } t_{aa} > -12°C
\]

\[
N_{CT}^{max} = 302 \text{ at } t_{aa} \leq -12°C
\]

\[
N_{CGGT}^{max} = -0.0359 \cdot t_{aa}^2 - 0.5917 \cdot t_{aa} + 425.5 \text{ at } t_{aa} > -12°C
\]

\[
N_{CGGT}^{max} = 436.8 \text{ at } t_{aa} \leq -12°C
\]

As the experience of using modern CCGT reveals, the lower limit of the adjustment range of CCGT loads is determined by the decrease in the reliability, the decline of the environmental performance and thermal efficiency of the unit when it is working at partial loads. Operation of the SGT5-4000F gas turbine with an annular combustion chamber and hybrid burners at low load after the full cover of compressor IGV increases concentration of NOx and CO in the exhaust gases. Adjustment of the airflow by using a compressor inlet guide vanes (IGV) allows to operate the combustion chamber with practically constant air-fuel ratio and to burn prepared homogeneous fuel-air mix with low NOx emissions (figure 2). At the load range from 50 to 100%. The combustion chamber operates almost without underburning and formation of carbon monoxide (figure 3). By decreasing the load of the GT after full cover of IGV, when the airflow remains constant, and fuel consumption continues to decline; what causes the increase of air-fuel ratio in the combustion chamber, burning of prepared fuel-air mix is stabilized by diffusion-flame burner, which is included in the two-stage hybrid burner, emissions of oxides of nitrogen begin to increase (figure 2). The minimum permissible load of the GT, corresponding to completely covered IGV, is ≈ 90-110 MW.

Figure 2. Change of the NOx concentration in the combustion products, depending on capacity of GT.

Figure 3. Change of the CO concentration in the combustion products, depending on capacity of GT.
Calculations carried out on the basis of the designed model of CCGT-420 show that, while declining power of GT after full cover of IGV, lowering the exhaust gases temperature in GT that leads to the temperature fall of the steam, generated in the HRSG, leads to an increase of the final moisture content, which creates the danger of erosion wear of ST last stage blades. This is connected with the reducing of the load of GT, which leads to a decrease of the steam temperature in the low-pressure steam turbine and increase of the vacuum in the condenser while the inlet steam pressure in low-pressure turbine remains almost unchanged. The steam expansion inside the ST in h,s-Diagram for Water-Steam shifts to the left and the final moisture content increases. The ambient air temperature decrease causes a decrease in the temperature of exhaust gases in GT and temperature of superheated steam at the steam turbine inlet, causing an exceeding of the minimum permissible load of GT, corresponding to rating value of final moisture content (≈12 %). While the ambient temperature is -20 °C, the minimum load of GT would be 100 MW.

Thus, the power range of GT, in which it is regulated using a compressor IGV, is acceptable. After the further decreasing of load after full cover of IGV it is necessary to control concentrations of NOx and CO in combustion products and final moisture content in the ST. On the basis of these prerequisites analytical dependences for determination of the minimum load of the CCGT-420 (dotted lines figure 1) in the range of ambient temperatures from -45 to +40 °C were obtained:

\[ N_{e, \text{min}}^{\text{GT}} = 0.0016 \cdot t_{\text{aa}}^2 - 0.4527 \cdot t_{\text{aa}} + 111,4 \text{ at } t_{\text{aa}} > -20 ^\circ \text{C} \]  
\[ N_{e, \text{min}}^{\text{GT}} = 110 \text{ at } t_{\text{aa}} \leq -20 ^\circ \text{C}. \]  
\[ N_{e, \text{min}}^{\text{CCGT}} = -0.003 \cdot t_{\text{aa}}^2 - 0.5386 \cdot t_{\text{aa}} + 196,1 \text{ at } t_{\text{aa}} > -20 ^\circ \text{C} \]  
\[ N_{e, \text{min}}^{\text{CCGT}} = 197,5 \text{ at } t_{\text{aa}} \leq -20 ^\circ \text{C}. \]

When ambient air temperature is < -20 °C minimum load of CCGT-420 is 197,5 MW (48% of rated power). In case of increasing the compressor inlet temperature up to 40 °C the minimum load decreases to 141 MW (34 % of nominal power).

4. Decreasing of the minimum load of the CCGT

Further decreasing of the load of CCGT can be accomplished by heating the air before the compressor and intensifying regulation of its airflow using the IGV (reclosing IGV) while maintaining the air-fuel ratio in the combustion chamber at a level corresponding to the completely covered IGV. The calculations showed that the decrease of the load of GT in this case is accompanied by an increase of exhaust gas temperature, the maximum value of which according to the GT manual is ≈ 600 °C. It limits the possibility of reducing the minimum load of the CCGT on the one hand, but on the other hand does not cause cooling of thick-walled elements of the HRSG and does not limit the ability of quick load increase.

For air heating before the compressor can be used anti-icing system of the GT. The calculations revealed that by the ambient air temperature < -15 °C possibilities of declining the minimum load due to preheating of air are limited by thermal power of the air heater, built in the complex air-cleaning installation, in which the maximum temperature increase is ≈ 50-55°C. At higher ambient air temperatures its heating before the compressor to 40 °C allows to reduce the minimum load up to 141 MW (34% of rated capacity) (figure 4), thermal efficiency of CCGT will amount to 48.6 %.

Intensifying regulation of airflow using the IGV leads to a significant decline of GT electric power, but to significant decline in ST electrical power caused by the reduction of the exhaust gases, incoming to the HRSG (figure 4). When ambient air temperature < -20 °C, reclosing IGV at a constant air-fuel ratio allows to reduce the CCGT minimum load to 105.4 MW (21 % of rated power), thermal efficiency of CCGT will amount to 45.5 %. At higher ambient temperatures reducing minimum load due to reclosing IGV is possible, but in less degree. However, it should be mentioned that the intensifying of airflow adjustment using IGV will reduce the efficiency of compressor and shift its characteristics to the surging boundary, therefore, the possibility of using such a way needs to be confirmed experimentally.
Figure 4. Change of the minimum electrical output of the CCGT ($N_{e\, min}^{CGT}$), the GT ($N_{e\, min}^{GT}$), the ST ($N_{e\, min}^{ST}$) when heating compressor inlet air and intensifying regulation of airflow using the IGV, depending on the ambient air temperature ($t_{aa}$).

5. The increase of available capacity of CCGT at high ambient temperatures.

The increase of ambient air temperatures leads to the decrease of available capacity of CCGT, and failure of the operations schedule. Stabilizing electrical power of GT by increasing the gas-inlet temperature is impractical because of the accelerated exhaustion of durability of expensive hot gas path’s parts. Without such aftereffects the capacity of GT during the peak hours can be boosted due to water injection in the inlet path of GT directly before the compressor. When using “wet compression” after inlet air filter, an spray nozzles system is installed. Part of the injected water supplied through the spray nozzles has time to evaporate before the compressor, lowering temperature and increasing airflow through it. Most of the water gets in the compressor. The maximum flow rate of the injected water is determined by the rate of evaporation of the drops on compressor.

According to the calculations, the water injection in the amount of ≈ 1.8% of the airflow when the ambient air temperature is 35 °C allows to stabilize the electric capacity of CCGT at rated level and increase its efficiency to 0.3 % (figure 5). This rate is close to the maximum possible by the terms of the evaporation of water during its being in the compressor. Possible increase as well as direct water injection after the compressor, can additionally increase the power but without reduction in the work of compressor and with some reduction in efficiency of GT.

Additional power production on CCGT to cover peak ratings is possible by using supplementary firing. The GT exhaust gases have a high temperature, and bulk concentration of oxygen is from 13 to 16%. They can be considered as quite an active oxidizer in the combustion process. The burning of fuel before the HRSG allows to increase the temperature of combustion products, to increase the quantity of
generated steam and ST power. By the ambient air temperature 35 °C, burning supplementary fuel before the HRSG in the amount of 1.7 kg/c also allows to stabilize the electric power of CCGT at rated level (figure 5). Power of CCGT in this case is increased by forcing steam circuit through a direct supply in the fuel heat. The temperature of the gases at the inlet to the HRSG is increased to ≈700 °C, and the efficiency of CCGT decreases to 1.14 %. Inasmuch as in this case the increase of CCGT power is done due to the expense of a corresponding increase in power of the steam turbine, produced with a lower thermodynamic efficiency, for CCGT of this type supplementary firing is always accompanied by a decrease in its efficiency.

Figure 5. Change in the electrical capacity of CCGT-420 \( N_e^{CCGT} \), GT \( N_e^{GT} \) ST \( N_e^{ST} \), depending on the ambient air temperature \( t_{a,a} \) with water injection at the compressor inlet and supplementary firing.

References
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