Optimization of controlled processes in combined-cycle plant (new developments and researches)

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Abstract. All modern complex technical systems, including power units of TPP and nuclear power plants, work in the system-forming structure of multifunctional APCS. The development of the modern APCS mathematical support allows bringing the automation degree to the solution of complex optimization problems of equipment heat-mass-exchange processes in real time. The difficulty of efficient management of a binary power unit is related to the need to solve jointly at least three problems. The first problem is related to the physical issues of combined-cycle technologies. The second problem is determined by the criticality of the CCGT operation to changes in the regime and climatic factors. The third problem is related to a precise description of a vector of controlled coordinates of a complex technological object. To obtain a joint solution of this complex of interconnected problems, the methodology of generalized thermodynamic analysis, methods of the theory of automatic control and mathematical modeling are used. In the present report, results of new developments and studies are shown. These results allow improving the principles of process control and the automatic control systems structural synthesis of power units with combined-cycle plants that provide attainable technical and economic efficiency and operational reliability of equipment.

1. Introduction

All modern complex technical systems, including power units of thermal power plants and nuclear power plants, work in the system-forming structure of multifunctional process control systems (APCS). The development of the mathematical support of modern APCS allows to bring the level of automation to the solution of complex optimization tasks of equipment heat-mass-exchange processes in real time and has an interdisciplinary nature [1-3].

In the development of combined-cycle technologies, the problems of an interdisciplinary nature were manifested especially acute. The difficulty of efficient management of a binary power unit is related to the need to solve jointly at least three problems [2-4].

The first problem is determined by the physical features of steam and gas technologies: an active gas turbine part with an integrated automatic control system and a passive utilization part with almost absent necessary process control.

The second problem is determined by the criticality of the CCGT operation to changes in the regime (reduction of the thermal efficiency of the CCGT relative to the rated output) and climatic factors (fluctuations of temperature and pressure of an outdoor air).

The third problem is related to technological measurements and the need for rigorous justification of the vector of controllable coordinates of a complex control object operating in the system-forming...
structure of the process control system of the power unit with CCGT. At the same time, it should be noted that the information scale of modern automated control systems (more than 1-2 thousand control points) has an experimental and commercial origin and in general is not theoretically justified. For example, the temperature at the entrance to the GT is not controlled, and the measured temperature of the exhaust gases beyond the GT cannot be a representative signal due to the heterogeneity of the system and the dynamic features of the measurement channel.

To solve these complex interrelated physical problems of structural synthesis of control systems, the following approach was applied.

Firstly, to find the answer to the key question: "What parameters of CCGT should be controlled?" authors have used the methodology of generalized thermodynamic analysis of the efficiency of complex systems [1, 5]. As a result, for the first time for the power unit with a CCGT a strict theoretical justification of the vector of generalized thermodynamic coordinates of a complex technological object was obtained and technological management tasks were formulated.

Secondly, by taking into account the found vector of the parameters complex additional requirements were formulated, that allowed not only construct a mathematical model, but also significaantly improve it. An estimation of the mathematical model adequacy and the poly-model complex adequacy was performed with the use of the trends of the monitored parameters from the archive of the process control system of the power unit [4, 6].

Thirdly, on the basis of a poly-model complex studies were conducted on key factors, that exerted a significant influence on the violation of the design mode of operation of the equipment of the CCGT unit [4, 6, 7].

Fourthly, a generalization of the principles of the structural design of fuel and air supply systems was provided for efficient management of GTU and the operation of its utilization part in the technological structure of the power unit from CCGT. A method for solving the optimization task of heat-mass-exchange processes of equipment in real time was proposed.

2. Development of the method of generalized thermodynamic analysis of the efficiency of power units with CCGT

The essence of the methodology is to develop a generalized flow graph of works and transmitted energies made in the CCGT (Figure 1).

The flow graph illustrates the interconnections and continuity of the constituent parts of the CCGT as a complex control object [1, 5].

![Figure 1. Generalized flow graph of works and transmitted energies in CCGT.](image)
Indicated (Figure 1): $B_g$ – fuel consumption; $T_{o,a}$ – outside temperature; $G_{o,a}$ – outside air consumption; $G_{c}^{'}, G_{c}''$ – air flow at the compressor inlet and outlet, respectively; $G_c$ – air flow at the compressor intermediate point; $G_{cc}^{'}, G_{cc}''$ – air flow at the inlet and outlet of the combustion chamber, respectively; $G_{mc}$ – air flow to mixing chamber; $G_{gt}^{'}, G_{gt}''$ – the costs of flue gases at the inlet and outlet of the gas turbine, respectively; $G_{gen}$ – electric generator power.

The analysis of the physical work $A_i(t)$ and the transmitted energies $E_i(t)$ through the air and fuel supply channels reveals the internal relationships of the complex technological control object under study and allows us to give a rigorous theoretical justification for the overdetermined vector of generalized thermodynamic coordinates of the state of the object and its potentials, where $dA_i(t)=Y_i \cdot dy_i(t)$ changing the work performed on the arc of the graph.

In this case, the generalized physical quantity $Y_i$ (the generalized potential) is a quantitative measure of the intensity of the heat-mass transfer process, and the generalized physical quantity $y_i(t)$ is regarded as a controllable coordinate of the process state.

Among the components of the vector of generalized thermodynamic coordinates of the redefined object two important complexed indicators are identified: "mass air flow" fed to the compressor and, respectively, into the combustion chamber and "heat flow" into the waste heat boiler.

The parameter $G_m$ of the mass air flow characterizes the uncontrolled change in the density of the outside air, the randomness (so-called "floating" character) of which is determined by the daily and seasonal variations of the environmental parameters.

The first technological task of CCGT control follows from the requirement to stabilize the mass flow of air supplied to the compressor GTU in strict accordance with its GTU load. The second technological task of CCGT control realizes the requirement of the overall efficiency of the power unit with CCGT, which is determined by the efficiency of its utilization part.

Optimization of the operation of the utilization part of the CCGT requires the gas heat flow input into the waste heat boiler be at the highest possible level. Strictly speaking, this means that the problem of calculating a mixed extremum (minimax) must be posed. However, minimax as an optimality criterion can be interpreted as the smallest losses that cannot be prevented in the worst circumstances. Under the conditions of changing regime and climatic factors, since most of the parameters of GTU and CCGT are related in one way or another in the thermodynamic cycle and the change in one of them entails a change in the other parameters, the analytical solution of the minimax optimization problem for CCGTs seems to be a rather complex physical and mathematical problem.

In real time a joint solution of technological problems can be obtained by appropriate coordination of automatic systems for regulating air supply to the compressor and fuel into the combustor of the GTU of a multiply connected ACS [8].

3. Structural synthesis of multiply connected ACS

By structuring a complex technological control object in terms of the input-output model we get the traditional representation of the mathematical model (Figure 2).

Figure 2. The enlarged structure of the technological control object in terms of the input-output model.
Indicated (Figure 2): (a) – compressor; (b) – gas turbine; (c) – recovery boiler; (d) – steam turbine with condensing unit; \( G_{oa} \) – outside air consumption; \( G_m \) – air mass flow rate; \( \rho_{oa}, T_{oa}, P_{oa} \); \( \rho_{oa}, T_{oa}, P_{oa} \) – respectively, the density, temperature and pressure of the outside air; \( B_f \) – fuel consumption; \( Q'_{mh} \) – heat flow of flue gases at the inlet of the recovery boiler, \( Q'_{mh} = f_2(T_{fg}, G_{fg}, c_{fg}) \); \( T_{fg}, G_{fg}, c_{fg} \) – respectively, the temperature, flow rate and heat capacity of flue gases; \( Q_c \) – electric power of gas turbine generators, steam turbines and total combined-cycle power, respectively.

The analysis of the structures of the ACS for supplying fuel and air for effective control of the CCGT allows us to distinguish two principles of solving the problem in real time.

The well-known solutions for GTU implement the principle of "task-fuel-air" and provide for the structure of a control system in which the power regulator (RP) generates a task for the fuel flow regulator (RF) in the combustion chamber (the primary regulator) and the opening angle \( \alpha_{igv} \) of the compressor inlet guide vanes (IGV), that changed in proportion to the fuel consumption \( B_g \) (ancillary regulator). The influence factor of the external environment, as a rule, is not taken into account, or it is indirectly taken into account by discrete change of the RF setting as a function of the temperature \( T_{oa} \) outdoor air. According to the requirements for the safe operation of gas turbines (GTs) and the reliability of the operation of the power unit as a whole, the temperature of the gases in front of the GT must remain in the working (calculated) range. Therefore, in some advanced process control systems, there is a correcting regulator for the temperature of the gases behind the GT with the effect on the change in the position of the IGV. However, even in the absence of restrictions on IGV, the stabilization of temperature over GT does not solve the first technological problem. The second technological task related to the optimization of the operation mode of the utilization part of the combined cycle plant, in this case, also remains open.

A method for jointly solving the both technological problems of CCGT control can be realized by constructing the structure of the control scheme (Figure 3), in which the power regulator (RP) acts on the mass flow stabilizer (primary regulator), and the fuel is fed into the combustor of the GTU by the RF depending on necessary oxidizer (ancillary regulator).

Indicated (Figure 3): \( G_m \) – air mass flow rate; \( Q_g \) – heat flow beyond GTU; \( K_1, K_2 \) – coefficients that determine the “air-fuel ratio” and “air-heat per GT”; \( \lambda(t), T_{oa} \) – uncontrollable effects, respectively, fuel quality and outdoor temperature; RC – remote control; STEM – single-turn electric mechanism.

When the ACS is operating in a wide range of loads, the required value of the required mass air flow is determined by the setting from the regulator of a higher level - RP. At the same time, the stabilization of the "floating" mass flow of air supplied to the compressor GTU, removes uncontrollable disturbances along the oxidant supply channel (the first technological task). This is achieved by correcting the opening angle of the IGV compressor GTU [7], and with the full opening of the compressor IGV limits the automatic fuel supply to the compressor, respectively - the temperature.

\[ \text{Figure 3. Information structure of ACS for supplying fuel and air according to the scheme "target (power) - mass air flow - heat - fuel".} \]
before the GT and the possible overheating of the GT blades. The second technological task of maintaining the optimal heat flow before the recovery boiler is solved by correcting the fuel supply to the combustion chamber, which is achieved in real time by the appropriate system tuning along the channels $K_1$ and $K_2$ (compensation by $G_n$ ensures the invariance of the heat flux with a "floating" extremum to external disturbances). Thus, the proposed structure of ACS for supplying fuel and air according to the scheme "target (power) - mass air flow - heat - fuel" implements a joint solution of the first and second technological control tasks under the existing constraints.

4. Research results

Investigations of automatic control systems with the aim of their possible application in practice are performed by means of a multimodal complex of a power unit with a CCGT [4] with temperature changes $T_{o.a}$ от $+5^\circ C$ до $+25^\circ C$ and from $+5^\circ C$ до $-25^\circ C$ and at the limits of the load regulation range.

The air flow regulator (RA is a primary regulator), which changes the position of the compressor IGV in the conditions of changing the outside air temperature, and then the corresponding value of the required fuel consumption is formed according to the actual mass air flow (RF - ancillary regulator). The system automatically goes to the optimal value of electric power GTU in these conditions, while the heat flow in front of the waste heat boiler ensures the efficiency of the steam-power part (waste heat boiler and steam turbine) of the power unit and, accordingly, the efficiency of the CCGT achievable in these conditions.

The results of the study show that when the IGV range is exhausted in the proposed scheme (see Figure 3), the mass flow of air is limited by some optimal value (minimum losses) of the GTU load, at which the temperature of the flue gases beyond the GTU cannot exceed the established safe level.

In other words, the situation when in the process of regulation with changing parameters of outside air entering the compressor (i.e. changes in its mass flow) is eliminated, the limiting level of opening of the IGV, the value of which does not correspond to the required volume of air (oxidant) in the combustion chamber given load GTU.

The limiting level of opening of the IGV is determined by the constructive capabilities of the compressor, the limitations of which, as the results of investigations have shown, lead to significant violations of the conditions of normal operation. Therefore, it is advisable to carry out studies of the influence of the climatic conditions of the actual location of the power plant in a given range of regulated loads at earlier stages of designing and building power units by examining the compressor parameters of the purchased GTU and the integrated automatic control system that is integrated into the structure of the system-forming process control system of the power unit.

5. Conclusions

1. The main technological tasks of load management of the power unit with CCGT, which require a joint solution in real time, are formulated and justified.

2. A method for the joint solution of the optimization task of heat-mass-exchange processes of equipment in real time mode is proposed, which leads to a reduction in losses taking into account existing limitations in the operation of power units with CCGT.

3. It is shown the structural construction of a multiply connected ACS for supplying air to the compressor and fuel to the combustion chamber for efficient control of the GTU power and the utilization part (waste heat boiler and steam turbine) of the power unit with CCGT.

References

[1] Tverskoy Yu S 2013 Theory and technology of control systems. Multi-functional APCS for thermal power plants (Ivanovo: Ivanovo State Power Engineering University)

[2] Davydov A V and Radin Yu 2009 Experience in the development of combined-cycle power units CCGT-450T Electric stations vol 9 (Moscow: Energy progress) pp 22-26

[3] Budakov I and Budanov V 2015 Computational and analytical study of air intake duct of the GTE-110 gas turbine unit Vestnik of Ivanovo State Power Engineering University vol 3 (Ivanovo: Ivanovo State Power Engineering University) pp 12-19
[4] Tverskoy Yu and Muravev I 2016 Research on the mathematical model of the efficiency of joint operation of the gas and steam turbines of the power unit with CCGT Automation in the industry vol 1 (Moscow: Info Automation) pp 53-57

[5] Veinik A I 1966 Thermodynamics of irreversible processes (Minsk: Science and Technology)

[6] Tverskoy Yu and Muravev I 2011 CCGT power unit mathematical model and its application for calculation of plant efficiency Vestnik of Ivanovo State Power Engineering University vol 5 (Ivanovo: Ivanovo State Power Engineering University) pp 12-18

[7] Tverskoy Yu and Muravev I 2017 Airflow regulation in the gas turbines compressor on binary power plant under variable climatic conditions Energetik vol 2 (Moscow: Energoprogress) pp 49-51

[8] Silvestrov A and Chinayev P 1987 Identification and optimization of automatic systems (Moscow: Energoatomizdat)