Adaptive automatic control system for air-cooled gas apparatus

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Abstract. The article deals with the synthesis of an energy-efficient automatic control system for gas air-cooling units. The need to use the adaptive control principle is caused by the large variability in the thermophysical parameters of such installations operated in far north and in regions with a continental climate. The adaptation technology is based on the use of a reference model with identifier. The energy efficiency of the proposed automatic control system has been experimentally confirmed. The article demonstrates that a continuous fan speed control in combination with an adaptive control makes it possible to obtain significant energy savings in gas cooling plants used in long-distance gas transportation techniques.

Compressor stations of gas mains use gas cooling devices to cool gas after compression. At most stations, cooling is performed by gas cooling units (GCU) equipped with several dozens of air-cooled gas apparatus (ACGA) with electric drives. The installed capacity electric drives of fans reach one or more MW. The power consumption for cooling reaches 60% of the electric power consumption for the compressor station's production needs. In the most of the currently operating GCUs uses a discrete mode for a fan’s air consumption control. Such method is not energy saving because of a fan’s drive energy consumption depends on the third power of its rotating velocity [1–6].

To drive fans induction motors are used, a speed of which can be continuously controlled by using frequency converters (FC). It is easy to show that in the case, when it is used a continuous mode of a fan rotary speed control instead of the discrete mode, an energy saving is proportional to the square of a ratio of a nominal and operating drive speed. In addition, using continuous feedback control systems provides an increasing not only in accuracy of a required gas temperature maintaining, but also improves reliability of the UOG [1–3, 10].

Here we consider a mathematical model of a generalized control object (GCO) that encompasses aerodynamic processes, heat exchange processes, and the dynamics of an electric drive. A specific feature of the GCO is a rather wide range of variations of its parameters. In particular, a value of a transmission coefficient of the GCO may vary up to 8 – 10 times [1, 2, 6, 7].

Results of experimental studies, which were accomplished at an operating GCU [9, 10], showed that mathematical model of the GCO can be specified as a dynamic object described by a first-order differential equation, and its transfer function can be represented in a form of an aperiodic link of the first order with variable parameters

\[ W_0(p) = \frac{\Delta \theta(p)}{\Delta f(p)} = \frac{k_o}{(T_o p + 1)}, \quad k_o \in [k_{o_{\min}}, k_{o_{\max}}]; T_o \in [T_{o_{\min}}, T_{o_{\max}}]. \]  

(1)
where \( \theta \) is gas at a heat exchanger outlet of the GCU, \( f \) is fan speed; \( k_{\text{omin}}, k_{\text{omax}}, T_{\text{omin}}, T_{\text{omax}} \) are lower and upper bounds of a transmission coefficient and time constant of GCO.

Taking into account nonstationarity of the GCO, it is expedient to use adaptive control systems to achieve the required quality of control, in particular, adaptive systems with a reference model [8].

The structural diagram of the adaptive control system of the ACGA with the reference model is shown in figure 1.

\[
\begin{align*}
W_{r2} & \rightarrow W_e \rightarrow W_o & \theta \\
& \downarrow W_m \downarrow \downarrow W_{r1} & f \\
& \downarrow \downarrow W_{r3} \rightarrow W_s
\end{align*}
\]

Figure 1. The structural diagram of the adaptive control system of the ACGA with the reference model.

In the structural diagram figure 1 separate elements dynamic properties (for increments of arguments) are reflected by corresponding transfer functions: \( W_e(p) \) is electric drive TF; \( W_o(p) \) is generalized control object; \( W_m(p) \) is temperature sensor of the ACGA; \( W_{r1}(p) \) is reference model; \( W_{r2}(p), W_{r3}(p) \) are regulators of the control system (on the structural scheme and further on the text operator \( p \) is omitted); reference signal at the input of the system is denoted by \( x \); \( \theta \) is output adjustable coordinate (gas temperature) at the outlet of the ACGA; \( f \) is fan speed.

To assess quality of dynamic characteristics of automatic control systems (ACS), the concept of roughness (robustness) with respect to some property inherited by an ACS model is widely used. This property is said to be robust, if it retains with variations of ACS model parameters. It was suggested in [8] to characterize the robustness as an ability of the system to maintain stability margins when variations of a controlling object parameters, takes place.

For the considered adaptive system, logarithmic amplitude (LACH) and phase (LFCH) characteristics of an open loop are shown in figure 2. The transducer gain of the controlled object varies by a factor of 10.

Figure 2 denotes: \( L_1(\omega), \varphi_1(\omega) \) is LACH and LFCH of the system with nominal parameters; \( L_2(\omega), \varphi_2(\omega) \) is LACH and LFCH of the system for the case when the object transmission coefficient is increased by factor 10; \( L_3(\omega), \varphi_3(\omega) \) is LACH and LFCH of the control object for the case when it's transmission coefficient was increased by factor 10.

As follows from the analysis of the characteristics given, the phase margin of the nominal and the variable system is; \( \Delta \varphi_1 \approx \Delta \varphi_2 \approx 90^\circ \) the amplitude margin is \( \Delta L_1 \approx \Delta L_2 \approx 23 \text{ dB} \). The result be confirm results testify to system roughness on the accepted indicator.
Figure 2. LACH and LFCH of the open loop system in a case when the transducer gain of the controlled object varies by a factor of 10; $L_1(\omega), \varphi_1(\omega)$ is LACH and LFCH of the control system with nominal parameters; $L_2(\omega), \varphi_2(\omega)$ is LACH and LFCH of the control system for the case of altered parameters; $L_0(\omega), \varphi_0(\omega)$ is LACH and LFCH of the controlled object for the case when it’s transmission coefficient was increased by factor 10.

The system under consideration should provide the required quality of control not only for the output variable gas temperature, but also for the control effect of the system that is a fan speed. The latter requirement is determined by the fact that the overshoot of the fan speed leads to unfavorable dynamic loads for the kinematic part of a drive. An effective way to eliminate overshoot is to introduce into a feedback loop a PD regulator with the TF

$$W_{R3} = (T_{R3}p + 1), \quad T_{R3} = T_{O,N}$$

(2)

where $T_{O,N}$ is time constant of the object with nominal parameters (nominal object) with TF

$$W_{O,N}(p) = -\frac{k_{O,N}}{(T_{O,N}p + 1)}.$$  

(3)

The TF of the reference model, taking into account relations (2), (3), is adopted in the form
\[ W_M = k_{O,N}W_EW_S. \tag{4} \]

For the synthesis controllers of the adaptive system with the model, the structural diagram of figure 1 is converted to a form of a two-loop system (figure 3). Further, the standard approach used in the synthesis of subordinate regulation systems can be used.

As the analysis showed, for approximate adjustment of the internal circuit to the modular optimum \cite{8}, it is expedient to use a proportional regulator with a PF

\[ W_{R_3} = k_3. \tag{5} \]

The value of the transmission factor \( k_3 \) is selected, so as to provide the required margin of stability of the internal circuit in conditions of variations of the transmission factor of the control object.

Analysis of the expression for the TF of the external circuit of the system showed that to adjust it to the modular optimum must be used an integral regulator

\[ W_{R_2} = \frac{1}{T_{R_2}P}. \tag{6} \]

It is possible to use a simplified reference model that does not take into account the inertia of the electric drive and the feedback sensor

\[ W_M' = k_{O,N}k_Ek_S. \tag{7} \]

The simulation of the system dynamic showed that the transition to the simplified reference model leads to insignificant losses of control quality.

The adaptive ACS regulators are implemented as a program in the programmable logic controller ABB AC500. The result of the algorithm execution by the controller is the signal value, which determines the frequency setting of all the frequency converters of the fan motors participating in the process. The signal from the controller is transmitted via the RS-485 bus by the Modbus RTU protocol, in addition, the controller sends commands to turn the drives on and off. The human-machine interface is realized with the help of a workstation with the installed SCADA-system MasterScada. Screens forms of the interface allow controlling the setting of the required gas temperature at the output of the ACGA, removing of service fans for repairing, manually putting in and out of action the separate fans at the required frequencies, and view the technological parameter trends, the system message log and much more.
Experimental studies of the gas temperature control system at the industrial gas cooling plant of the compressor station of OOO “Gazprom Transgaz Yugorsk” have been carried out. The energy savings after the introduction of the ACS were estimated: the specific electricity consumption decreased by 28% on average for a year, the decrease of the electricity consumption was 22%. The results of experimental studies indicate a high static and dynamic accuracy in controlling the temperature of natural gas at the output of the ACGA, as well as increasing the energy efficiency of the operating modes of the cooling unit after modernization. The use of the adaptive automatic control system ensures accurate maintenance of a technological mode of gas cooling in the conditions of a wide range of variations of the parameters of the external environment and operating conditions of the compressor station.

**Conclusion**

The developed adaptive automatic control system with a reference model for gas air cooling devices provides the required quality control parameters in the conditions of a wide range of parameters of the control object and provides a significant increase in the energy efficiency of gas cooling units.

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