Comparative analysis of adaptive systems for automatic stabilization of the water level in the drum boiler

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Abstract. The comparative analysis of two kinds of adaptive systems for automatically maintaining the water level in the drum of large boilers of thermal power plants is carried out with the stabilization of their dynamic characteristics in the face of changing parameters of the control object. The analysis is carried out with the purpose of determining the most effective adaptation method and development on its basis, a typical local adaptive automatic control system for various paths of energy steam boilers. As a control object, for example, the drum boiler feed circuit is selected because the process of changing the water level in the drum due to a violation of the material balance between water supply and water consumption is the most responsible and complicated due to the astatic type of its transfer function. Both systems are unidentified and contain a reference model in the adaptation loop. The advantages and disadvantages of the analyzed systems and the prospects for the application of adaptation methods laid down based on their construction are established.

1. Introduction
The uninterrupted and efficient operation of large drum boiler units, which determine the operation of the thermal power station, largely depends on the system’s quality for automatically maintaining the water level in the boiler drum. The deviation of the water level in the drum from the index value is usually eliminated by automatically changing the feedwater flow by feedwater regulating valve using the appropriate automatic-control system - supply ACS [1-5]. However, a standard supply ACS has a significant drawback consisting in the deterioration of the quality rating of its operation due to departure during the long-term operation of the parameters of the control object (CO) from the calculated ones to disturbing internal influences while maintaining the controller’s parameters unchanged. The use of supply ACS with the calculated controller settings for the CO leads to unacceptable dynamic deviations up to the loss of stability in extreme situations [6].

There are two ways to solve this problem:
• Construction of a control system, insensitive to changes in the parameters of the CO (robust), [7-8];
• Development of adaptive ACS.

In the article, the authors conduct a comparative analysis of adaptive characteristics (AFC) and stabilization of the impulse response characteristic (IPC). [9-10].
2. Adaptive ACS with stabilization of AFC

The authors of the article developed an adaptive ACS with stabilization of the AFC [6], which has several advantages compared to well-known analogues [9-10].

In an adaptive supply ACS, the transfer function $W_{эм}(p)$ of the reference model is the transfer function of a closed-loop supply ACS: $W_{эм}(p) = K_{эм}(p)W_{ОУид}(p)/(1 + K_{эм}(p)W_{ОУид}(p))$ which provides the required quality indicators with the basic initial parameters of the transfer function of the CO $W_{ОУ}(p) = W_{ОУид}(p)$ and controller $K_{эм}(p)$ synthesized according to the known transition characteristic $H(t) = L^{-1}\left[\frac{W_{ОУид}(p)}{p}\right]$ of the CO from the condition of providing the required quality indicators in dynamics and statics (see figure 1).

![Figure 1. Transition process of the CO $W_{ОУ}(p)$](image)

In the developed adaptive ACS (see figure 2) parameters are automatically adjusted $\alpha_i, i = 1,2,...,n$ controller settings depending on the amount of error term $\varepsilon_i(j\omega) = u_i(j\omega) - v_i(j\omega)$ $i = \overline{1,n}$ between AFC of the reference model $W_{эм}(j\omega)$ and AFC of closed-loop supply ACS $W_{э}(j\omega) = K_{ро}W_{ОУ}(j\omega)\sum_{i=1}^{m} \alpha_i\phi_i(j\omega)/(1 + K_{ро}W_{ОУ}(j\omega)\sum_{i=1}^{m} \alpha_i\phi_i(j\omega))$ with fluctuations in the parameters of the transfer function of the CO $W_{ОУ}(p)$ [15].

The major loop of the adaptive supply ACS contains a control device (CD), including $n$ parallel-connected correction loop with variable parameters $\alpha_i(p), i = \overline{1,n}$, which used as the output signals of auxiliary astatic controllers $W_{арег}$, connected to the multiplier. Each of the coefficient $\alpha_i, i = \overline{1,n}$, being multiplied by transfer functions $W_{ОУ}(p)$ and transfer functions $W_i(p)$ narrowband frequency filters $\phi_i, i = \overline{1,n}$ with frequency response $W_i(j\omega)$, provides a dynamic dependency of the components of the transfer function of the controller $K_{п}(j\omega) = \sum_{i=1}^{m} \alpha_i(\omega_i)\phi_i(\omega_i)$ from frequency $\omega_i$, which reflects the dependence in the frequency domain $K_{п}(\alpha_i, \omega_i) = K_{ро}K_{п}(\alpha_i, \omega_i)$.

Astatic controllers $W_{арег}(j\omega_i)$, according to error term $\varepsilon_i(j\omega_i)$ in certain predetermined AFC areas allocated by narrowband frequency filters $\phi_i$, automatically adjust the parameters $\alpha_i$ adjusting the regulator to bring AFC of the closed-loop supply ACS $W_{э}(j\omega)$ and AFC of reference model $W_{эм}(j\omega)$ subject to time-varying parameters of the CO. Thus, based on a comparison of these AFC are changed parameters $\alpha_i, i = \overline{1,n}$ dynamic part (CD) in the direction of eliminating the error term between the reference model and the real supply ACS.
Figure 2. Block diagram of adaptive ACS with stabilization of AFC.

For the adaptation algorithm to work successfully, a harmonic signal must be supplied to the system input occasionally $x_{np}(\omega) = \sum_{i=1}^{n} \sin(\omega_i t)$, containing the selected frequency spectrum $\omega_i, i = 1, n$ (see figure 3).

Since in real boilers it is often challenging to implement such a test signal $x_{np}(\omega)$, instead of a harmonic signal, a test signal of another possible form is input $f(t)$, from which harmonics separated by Fourier series expansion [11-12]:

$$f(t) \approx A_0 + \sum_{\nu=1}^{n} c_{\nu} \sin(\omega t + \gamma_{\nu})$$  \hspace{1cm} (1)

Here $A_0 = \frac{1}{T} \int_{0}^{T} f(t) dt$ – constant component of the input signal $f(t)$; $\omega = \frac{2\pi}{T}$ – circular frequency; $T$ – input period $f(t)$; $c_{\nu} = \sqrt{a_{\nu}^2 + b_{\nu}^2}$; $\gamma_{\nu} = \frac{a_{\nu}}{b_{\nu}}$; $a_{\nu} = \frac{2}{T} \int_{0}^{T} f(t) \cos(\nu \omega t) dt$; $b_{\nu} = \frac{2}{T} \int_{0}^{T} f(t) \sin(\nu \omega t) dt$.

For example, for an input test signal $f(t)$, presented in the figure 3(a), the harmonic composition extracted using filters is partially shown the figure 3(b).
The developed adaptive supply ACS differ from the popular features:
• in order to eliminate “bounce” and to smooth the error term, anti-aliasing filter C, is used that implements the mathematical operation of calculating the moving average [13];
• to exclude self-oscillations in the adaptation loop, a nonlinear element H - Dead zone;
• as astatic regulators $W_{iper}$, in each $i$-th frequency range, proportional-integral controllers with optimally selected parameters are used [14].

3. Adaptive ACS with stabilization of IPC
The reference model in adaptive ACS of this type (see figure 5) is a set of values $k_m(\tau)$, $i = 0, m$ rated IPC closed-loop supply ACS (see figure 4), providing the required performance indicators of the system, subject to basic initial parameters of the CO [9-10].

A wideband test signal applied to the input of a closed system and impulse response estimator (IRE) $x_{ip}(\tau)$. In each $i$-th circuit of the IRE, the delay of the test signal by $\tau_i = 0, m$. Then the delayed signal values $x_{ip}(t-\tau_i)$ multiplied with system output $z(t)$ and integrate to calculate discrete values $k(\tau_i)$ closed-loop impulse response characteristic $k(\tau)$. A wideband test signal is applied to the input of a closed system and impulse response estimator (IRE) $x_{ip}(\tau)$ close in its characteristics to white noise. In this
case, the autocorrelation function of the test signal $R_{xx}(\tau) \approx \delta(\tau)$ is a $\delta$-function, and, therefore, from the Wiener-Hopf equation $R_{zz}(\tau) = \frac{1}{2T} \int_{-T}^{T} R_{xx}(\gamma - \tau)k(\gamma)d\gamma$ with a sufficiently long observation period $T$ should $R_{xx} = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t - \tau)z(t)dt = k(t)$. The values $k(\tau_i), i = 0, m$ in $m$ a sampling points system’s IPC hit the adder in the performance analyzer (PA), where do they compare with the calculated values of the impulse response characteristic of the model $k_m(\tau_i), i = 0, m$. Mismatch error signal $e(\tau_i) = k_M(\tau_i) - k(\tau_i)$ minimized by proportional-integral regulators $W_{\text{iper}}$, the outputs of which are variable (adaptable) parameters CD.

The structure CD in ACS with stabilization IPC similar to structure CD in the previously considered ACS with stabilization of AFS.

The change of controller’s parameters in CD (adaptation process) by performance analyzer (PA) occurs until, in predetermined time intervals. The values of the impulse response of the supply ACS $k(\tau_i)$ is reached preset value $k_M(\tau_i)$ calculated values of IPC reference model, with the error specified by the nonlinear element Dead zone.

![Figure 5. Impulse response of the control object $W_{\text{of}}(p)$.

4. Comparative analysis of the results
Consider the work of adaptive ACS when varying the gain of the CO $K_{ob}$. 


As can be seen from figure 6, both adaptive systems, with stabilization of the AFC and stabilization of the IPC, bring the transition characteristic of the ACS when the CO parameters change to the transition characteristic of the reference model with specified quality indicators.

To assess the quasistationarity, figure 7 presents a graph of the duration of the formation of one of the coefficients – $\alpha_i(p)$, adjusting the corresponding ACS parameter when changing $K_{ob}$ at 20% from the nominal value.

**Figure 6.** Transition processes
1 – typical ACS $K_{ob}=K_{paci}$; 2 – typical ACS $K_{ob}=125\% K_{paci}$; 3 – adaptive ACS with stabilization of AFC $K_{ob}=125\% K_{paci}$; 4 – adaptive ACS with stabilization of IPC $K_{ob}=125\% K_{paci}$.

**Figure 7.** Confirmation of the principle of quasistationarity
1 – dynamics of coefficient formation $\alpha_i^{\text{AFC}}$ in self-tuning system with stabilization of AFC; 2 – dynamics of coefficient formation $\alpha_i^{\text{IPC}}$ in self-tuning system with stabilization of IPC; 3 – gain variation $K_{ob}$ OY at 20% from nominal value.
As can be seen from figure 7, the adaptation time of the parameters $\alpha_1(p)$ of AFS approximately five times less than the typical time of gain’s fluctuation $K_{ob}$ of the CO, which confirms the fulfilment of the quasistationary condition.

To determine the most effective method for adaptive automatic power control of a boiler unit, we compare the performance indicators of ACS when using each of the types of adaptive systems discussed above (see figure 8). The quality indicators formulate, an artificial disturbance is introduced into the mathematical model of ACS, expressed as a change in one of the parameters of the transfer function $W_{OU}(p)$ of the CO ($K_{ob}$).

![Figure 8. Comparison of quality indicators of supply ACS. 1 – tipical supply ACS; 2 – adaptive ACS with stabilization of IPC; 3 – adaptive ACS with stabilization of AFC.](image)

5. Conclusion
When analyzing the results of the study, it can be argued that both types of adaptive ACS work out changes in the parameters of the CO quite well. As can be seen from figure 8, the difference in the performance indicators of the ACS is insignificant. Still it should be noted that the adaptation process in an adaptive ACS with stabilization of IPC proceeds somewhat faster than in an ACS with stabilization of AFC. It should emphasize that, despite the lower adaptation rate in ACS with stabilization of AFC, the principle of quasistationarity holds for both systems (see figure 7).

This allows us to conclude that it is advisable to choose ACS with stabilization of IPC, since an essential condition for the qualitative progress of the adaptation process is its speed relative to the rate of change in the fluctuation of the parameters of the CO.

However, it is worth noting that to finally resolve the issue of the appropriateness of using adaptive ACS, it is necessary to analyze the noise immunity in specific application conditions and the technological feasibility of applying trial effects. This work was supported by the Russian Foundation for Basic Research (project No. 20-08-00240)

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