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Integrated application of synergetic approach for enhancing intelligent steam generator control systems

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ABSTRACT

This article focuses on the integrated application of the synergetic approach to enhance the quality of intelligent steam generator control systems. By combining various techniques such as model-based control, adaptive control, and artificial intelligence, an efficient and flexible control system can be developed. Model-based control utilizes mathematical models of steam generators to formulate control algorithms and predict system behavior. Adaptive control enables the system to adapt to changing conditions by adjusting control parameters based on real-time measurements. Artificial intelligence techniques, including neural networks and genetic algorithms, facilitate learning, optimization, and data-driven decision-making processes. The objectives of this research are to investigate the benefits of the synergetic approach in steam generator control, including improved steam generation efficiency, optimized energy consumption, enhanced system stability and reliability, and adaptability to varying operating conditions and disturbances. The findings and conclusions of this study are expected to provide valuable insights for engineers, researchers, and professionals involved in the design and implementation of intelligent steam generator control systems. By integrating the synergetic approach, substantial enhancements in control quality can be achieved, leading to optimal operation and maximum efficiency of power plants.

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1. INTRODUCTION

Intelligent control systems play an increasingly important role in modern power plants, including steam generators. They provide the ability to automate and optimize control processes, resulting in improved efficiency, reliability and safety of system operation. However, the dynamic and non-linear nature of steam generators presents challenges for traditional control methods [1], [2]. In recent years, the synergetic approach has become increasingly recognized in the control of complex systems. Synergetics studies the interaction of components in a system and the creation of emergent properties that are manifested when components act together. The integrated application of the synergetic approach allows the combination of different methods and techniques to achieve a synergistic effect, where the interaction of components results in higher performance than when individual methods are used.

This paper discusses the integrated application of synergetic approach to improve the quality of intelligent steam generator control system. This approach combines various aspects and techniques including model-based control, adaptive control and artificial intelligence to create an efficient and flexible steam generator control system [3]–[5]. Model-based control provides a mathematical model of the steam generator, which is used to develop control algorithms and predict its behavior. Adaptive control allows the system to adapt to changing conditions and requirements by adjusting control parameters based on current measurements. Artificial intelligence includes techniques and algorithms such as neural networks and genetic algorithms that allow the system to learn, optimize its decisions and make decisions based on data analysis [6], [7].

The aim of this paper is to investigate and analyze the benefits of an integrated application of the synergistic approach in the context of steam generator control. Various aspects will be considered, including increasing steam generation efficiency, optimizing energy consumption, improving system stability and reliability, adapting to changing operating conditions and disturbances. The results and conclusions of this paper will be useful for engineers, researchers and professionals involved in the design and implementation of intelligent steam generator control systems. The integrated application of the synergetic approach can lead to a significant improvement in the quality of steam generator control, ensuring optimal operation and maximum efficiency of power plants [8]–[10].

The authors of the paper [11] investigate the application of synergetic synthesis method to achieve optimal control quality of steam generators. Synergetics is a science that studies complex systems and their interactions, and synergetic synthesis offers an approach based on combining different elements of a system to jointly achieve higher efficiency and synergy. The article [12] also draws attention to the importance of modelling and simulation of the steam generator control system. By creating a mathematical model of a steam generator and conducting simulation experiments, the effectiveness of proposed control methods and strategies can be evaluated. This allows scientists and engineers to conduct an iterative optimization process and improve the control system based on the results obtained.

Currently, in most cases, the steam generator control systems are a set of local subsystems for regulating boiler power, superheated steam temperature, and fuel consumption. At the same time, each of the subsystems is calculated as autonomous, and their mutual influences are considered as disturbing effects. The main disadvantages of this approach are the following:

a. Ensuring autonomy is an artificial technique. And although Kolesnikov [12], who owns the idea of the synthesis of autonomous control systems, considered autonomy as a way to improve the quality of regulation, it is obvious that this, at least, is not always the case. For example, in the conditions of actual restrictions on control actions, an autonomous system has degraded dynamic characteristics compared to a system of connected regulation.
b. The synthesis of the control system is based on linear boiler models obtained either by linearization of a nonlinear model, or, more often, by approximation of the model through separate channels by transfer functions. The parameters of the linear model, which adequately describe the processes occurring in the boiler in a narrow area near the selected mode, change significantly when the mode is changed. This, in particular, leads to the fact that the adjustment coefficients of local regulators, optimal in accordance with some quality criterion for one mode, for another mode will not only be not optimal, but may not even provide stable regulation. Recording the model in the form of transfer functions on separate channels, in addition to the above, has the following drawback: the structure of these transfer functions, as a rule, is such that it provides a fairly rough approximation. For example, the transfer function of a drum boiler through the channel "feed water consumption - water level in the boiler drum".

$$W(p) = \frac{k}{p} e^{-\tau p}$$

Describes the dynamics of the level in the drum, starting from point A in Figure 1. The phenomenon of "swelling" of the level that occurs at $t \in [0, \tau]$ is excluded from consideration in this case. At the same time, it is known that the main share of protection triggers excessive increase or decrease in the level is caused by this phenomenon.

The noted disadvantages are primarily due to the fact that the natural dynamics of a thermal power facility-the nonlinearity and interconnectedness of the processes occurring in it, is not taken into account when solving the problem of synthesis of the regulator. The desire to maximize the range of possible modes of operation of the boiler, to ensure its more effective participation in post-accident regulation, to increase its maneuverability makes it necessary to base the synthesis of the control system on a nonlinear, multidimensional and multi-connected model, using the methods of nonlinear control theory.

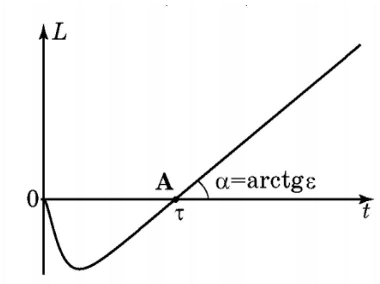

Figure 1. Changing the level

2. METHOD

To synthesize the control system, we will use a nonlinear mathematical model of a drum boiler described in [13]–[15]. Let‘s introduce the notation: x_1 is deviation of the water level in the boiler drum, x_2 is steam pressure in the drum, x_3 is mass vapor content at the outlet of the lifting pipe system, x_4 is steam pressure at the steam generator outlet, u_1 is feed water consumption, u_2 is heat flow to the heating screen surfaces; considering the fact that the steam flow rate from the circulation circuit (CC) $\widetilde{D''}$ and the steam flow rate entering the superheater (ES) differ by the amount of steam discharged into the condenser D_{con}.

$$D'' = \widetilde{D''} + D_{con},$$

Let‘s write it in the form:

$$\frac{dx_1}{dt} = \frac{1}{F_{e.m.}}\left(\frac{1}{\Delta_e}\left((e_{22} - \widetilde{e_1}e_{21})l_1 - (e_{12} - \widetilde{e_1}e_{11})l_2\right) + \frac{1}{e_{33}}\frac{\partial\overline{\varphi_{lif}}(x_2,x_3)}{\partial x_3}V_{lif}l_3\right);$$

$$\frac{dx_2}{dt} = \frac{1}{\Delta_e}(e_{11}l_2 - e_{21}l_1);$$

$$\frac{dx_3}{dt} = \frac{e_{32}}{\Delta_e e_{33}}(e_{21}l_1 - e_{11}l_2) + \frac{1}{e_{33}}l_3;$$

$$\frac{dx_4}{dt} = \frac{1}{e_{44}}\left(\widetilde{D''}(x_2,x_4) + D_{cool} - D_b\right); \qquad (1)$$

where the functions of the state variables included in the right-hand sides of (1) are defined by (2):

$$e_{11} = \rho' - \rho''; \; e_{12} = V_{s.o.}\frac{\partial\rho'}{\partial x_2} + (V_o - V_{s.o.})\frac{\partial\rho'}{\partial x_2}; \; e_{21} = \rho' i' - \rho'' i'';$$

$$e_{22} = V_{s.o.}\left(i'\frac{\partial\rho'}{\partial x_2} - p'\frac{\partial\rho'}{\partial x_2}\right) + \frac{\partial\rho'}{\partial x_2}(V_o - V_{s.o.})\left(i''\frac{\partial\rho\prime'}{\partial x_2} + p''\frac{\partial\rho\prime'}{\partial x_2}\right) + G_o c_p\frac{\partial\vartheta\prime'}{\partial x_2};$$

$$e_{32} = \left(p'\frac{\partial\rho'}{\partial x_2} - x_3 r\frac{\partial\rho'}{\partial x_2}\right)(1 - \overline{\varphi}_{lif})V_{lif} + \left((1 - x_3)r\frac{\partial\rho\prime'}{\partial x_2} + p''\frac{\partial\rho\prime'}{\partial x_2}\right)\cdot\overline{\varphi}_{lif}V_{lif} + (\rho'' + (\rho' - \rho'')x_3)rV_{lif}\frac{\partial\overline{\varphi}_{lif}}{\partial x_2} + G_{lif}c_p\frac{\partial\vartheta''}{\partial x_2};$$

$$e_{33} = \left((1 - x_3)\rho'' + x_3\rho'\right)rV_{lif}\frac{\partial\overline{\varphi}_{lif}}{\partial x_3}; \; e_{44} = V_p\frac{\partial\rho_4(x_4,\vartheta_\rho = \vartheta_\rho^0)}{\partial x_4};$$

$$\Delta e = e_{11}e_{22} - e_{12}e_{21}; \; \tilde{e}_1 = \left(\frac{\partial\overline{\varphi}_{lif}}{\partial x_2} - \frac{e_{32}}{e_{33}}\frac{\partial\overline{\varphi}_{lif}}{\partial x_3}\right)V_{lif}; r = i'' - i';$$

$$V_{s.o.} = V_{s.o.}^0 + V_{low} + (1 - \overline{\varphi}_{lif})V_{lif} + F_{e.m.}x_1; \; l_1 = u_1\widetilde{D}''(x_2,x_4) - D_{con} - D_{pur};$$

$$l_2 = u_2 + u_1 i_{f.w.} - \left(\widetilde{D}''(x_2,x_4) + D_{con}\right)i''(x_2) - D_{pur}i'(x_2);$$

$$l_3 = u_2 - x_3 r(x_2) D_{low}(x_2, x_3);\ \widetilde{D}''(x_2, x_4) = \widetilde{D}'' \sqrt{\frac{\rho_{\rho\left(x_4, \vartheta_b^0\right)(x_2 - x_4)}}{\rho_{\rho\left(x_4, \vartheta_\rho^0\right)(x_2^0 - x_4^0)}}}. \quad (2)$$

where ρ is density; i is enthalpy; V is volume; G is metal mass of heating surfaces; ϑ is temperature; functions i', i'' and ρ', ρ'' describe the state of water and steam on the saturation line (these are functions of the steam pressure in the boiler drum x_2); the indices "f.w.", "low", "lif", "o", "p" indicate that the parameter belongs to the feed water, the system of lowering or lifting pipes, the entire CC or the output package of ES; D_{pur}, D_{cool}, D_b - accordingly, the water consumption for purging and cooling, as well as steam from the boiler; $F_{e.m.}$ - evaporation mirror area; the index "0" indicates the value of the parameter in the nominal mode; function $\overline{\varphi_{lif}}$ is a well - known function describing the average volume vapor content in lifting pipes.

If we neglect the inertia of the steam lines connecting the boiler to the turbine or to the main steam main (MSM), then the steam flow D_b is equal to the steam flow through the valves regulating its flow to turbine $D_b = D_t$ or MSM $D_b = D_m$. The task assigned to these control valves is to maintain the required steam flow rate. For example, in the case of a steam generator operating as part of a power unit, this consumption depends on the number and power of consumers connected to the unit; when several steam generators are operating on an MSM, it is set by an upper-level control system that coordinates the control systems of individual steam generators. In any case, from the point of view of the control system of the steam generator, D_b is a piecewise constant disturbance, because in comparison with the time of regulation of steam pressure and water level in the boiler, flow control is carried out very quickly [16], [17].

The flow rates of steam taken into the condenser and water injected into the desuperheater and removed from the CC during continuous blowdown are regulated. At the same time, the time of their regulation is considered to be negligible compared to the time of the processes of interest to us. Thus, it is considered that at any moment of time these costs take on fixed values, and when constructing the control system for the steam-water path of the steam generator, they are considered as measurable piecewise constant perturbations [18].

In view of the foregoing, we formulate the control problem as follows: for a steam generator described by the system of (1), assuming that the measured disturbances D_b, D_{pur}, D_{con} and D_{cool}, act on the steam generator, find the control law u that ensures the translation of the representative point (RP) of the closed control system from an arbitrary initial state belonging to the area of permissible change of coordinates to a given state ($x_4 = x_4^0$ and $x_1 = 0$), in which stabilization of the steam pressure at the outlet of the steam generator ES ($x_4 = x_4^0$) and the water level in the boiler drum ($x_1 = 0$) is ensured. In accordance with the ADAR method [19]–[22], we introduce into consideration the following parallel set of macro-variables:

$$\psi_1 = \beta_{11} x_1 + \beta_{12}\left(\widetilde{D''}(x_2, x_4) + D_{cool} - D_b + e_{44}\alpha_3(x_4 - x_4^0)\right);$$

$$\psi_2 = \beta_{21} x_1 + \beta_{22}\left(\widetilde{D''}(x_2, x_4) + D_{cool} - D_b + e_{44}\alpha_3(x_4 - x_4^0)\right); \quad (3)$$

such that the relations $\psi_i = 0$ are the solution of the system of functional equations:

$$\psi_1(t) + \alpha_1 \psi_1 = 0,$$

$$\psi_2(t) + \alpha_2 \psi_2 = 0, \quad (4)$$

where α_1, α_2 - coefficients. Under the conditions $\alpha_1 > 0$, $\alpha_2 > 0$ the trivial solution of (4) $\psi_1 = 0$, $\psi_2 = 0$ will be asymptotically stable. By jointly solving (1), (3), (4), we find expressions for external controls u_1 and u_2:

$$u_1 = \frac{1}{\Delta F}\left(\frac{f_3(x_2,x_4) + D_{cool} - D_b}{\frac{\partial \widetilde{D''}}{\partial x_2} e_{44}}\left(\frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_4} + e_{44}\alpha_3\right) - f_1 f_6 + f_3 f_4 + \frac{1}{\Delta\beta \frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_2}}\left(k_1 f_3 + k_2 f_6 \frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_2}\right)\right); \quad (5)$$

$$u_2 = \frac{1}{\Delta F}\left(\frac{f_2\left(\widetilde{D''}(x_2,x_4)+D_{cool}-D_b\right)}{\frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_2}e_{44}}\left(\frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_4}+e_{44}\alpha_3\right)-f_1f_5+f_3f_4+\frac{1}{\Delta\beta\frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_2}}\left(k_1f_2+k_2f_5\frac{\partial \widetilde{D''}(x_2,x_4)}{\partial x_2}\right)\right); \quad (6)$$

where

$$f_1 = -\frac{1}{F_{e.m.}}\left(\frac{e_{22}-e_{12}i''(x_2)-\widetilde{e_1}\left(e_{21}-e_{11}i''(x_2)\right)}{\Delta e}\widetilde{D''}(x_2,x_4)+D_{con}\right)+\frac{e_{22}-e_{12}i''(x_2)-\widetilde{e_1}\left(e_{21}-e_{11}i''(x_2)\right)}{\Delta e}D_{pur}+\frac{x_3r(x_2)}{e_{33}}\frac{\partial\overline{\varphi_{lif}}(x_2,x_3)}{\partial x_3}V_{lif}D_{low}(x_2,x_3);$$

$$f_2 = \frac{1}{F_{e.m.}}\frac{e_{22}-e_{12}i_{f.w.}(x_2)-\widetilde{e_1}\left(e_{21}-e_{11}i_{f.w.}\right)}{\Delta e};$$

$$f_3 = \frac{1}{F_{e.m.}}\left(\frac{e_{12}-\widetilde{e_1}e_{11}}{\Delta e}-\frac{1}{e_{33}}\frac{\partial\overline{\varphi_{lif}}(x_2,x_3)}{\partial x_3}V_{lif}\right);$$

$$f_4 = \frac{e_{12}-e_{11}i''(x_2)}{\Delta e}\left(\widetilde{D''}(x_2,x_4)+D_{con}\right)+\frac{e_{21}-e_{11}i''(x_2)}{\Delta e}D_{pur};$$

$$f_5 = \frac{e_{11}i_{f.w.}-e_{21}}{\Delta e};\ f_6 = \frac{e_{11}}{\Delta e}. \quad (7)$$

$$k_1 = \beta_{11}\alpha_2\psi_2-\beta_{21}\alpha_1\psi_1;\ k_2 = \beta_{12}\alpha_2\psi_2-\beta_{22}\alpha_1\psi_1;$$

$$\Delta\beta = \beta_{11}\beta_{22}-\beta_{12}\beta_{21};\ \Delta F = f_2f_6-f_3f_5; \quad (8)$$

At the end of transient processes in system (4), the duration of which is determined by the coefficients α_i , $i = 1.2$ the equalities $\psi_i = 0$ will be fulfilled. If the matrix $B = \begin{bmatrix}\beta_{11} & \beta_{12}\\ \beta_{21} & \beta_{22}\end{bmatrix}$ is non-degenerate, this will mean that the following conditions are met [23]:

$$x_1 = 0, \widetilde{D''}(x_2,x_4)+D_{cool}-D_b = e_{44}\alpha_3(x_4-x_4^0), \quad (9)$$

The first of which corresponds to the stabilization of the water level in the boiler drum. When the RP system hits the intersection of the manifolds $\psi_i = 0$, $i = 1.2$ the dynamic decomposition of the phase space of the system (1) occurs. The further behavior of the closed system will be described by the first order equation:

$$\dot{x}(t) = -\alpha_3(x_4, x_4^0), \quad (10)$$

According to which, if the condition $\alpha_3 > 0$ is met, the variable x_4 after a time of the order of $3/\alpha_3$ will take on a well-defined value x_4^0 (the pressure at the outlet of the ES is equal to the specified one).

Controls (5), (6) ensure that the representative point of the closed control system is brought to the intersection of manifolds $\psi_1 = 0 \cap \psi_2 = 0$, where the condition for stabilization of the water level in the boiler drum ($x_1 = 0$) is ensured and its subsequent movement to the intersection with the manifold $\psi_3 = 0$: $\psi_3 = x_4 - x_4^0$, where the condition $x_4 = x_4^0$ - the steam pressure at the outlet of the steam generator is equal to the set value.

Controls (5), (6) guarantee for $\alpha_i > 0$, $i = 1,2,3$ the asymptotic stability of the motion of a closed control system to the intersection of manifolds $\psi_i > 0$, $i = 1,2,3$. The motion of a closed system along the intersection of manifolds is described by a first-order equation. In order to write the decomposed model, it is necessary to substitute in the equation describing the change in the mass vapor content x_3 of the closed control system (1), (5), (6), instead of the variables x_1, x_2, x_4 their values x_1^0, x_2^0, x_4^0, which they take at the intersection of the manifolds [24]. In this case, the value of x_2^0 is found by solving the equation.

$$\widetilde{D''}(x_2,x_4)+D_{cool}-D_b = 0.$$

The equation of the decomposed system will have the form:

$$\frac{dx_{3\psi}}{d\tau} = \frac{1}{e_{33}(x_2^0, x_{3\psi})}\left(\frac{1}{\Delta F}(f_1 f_5 - f_2 f_4) - x_{3\psi} r(x_2^0) D_{low}(x_2^0, x_{3\psi})\right); \quad (11)$$

where the functions ΔF and f_i are calculated by formulas (8), (7) provided that $x_1 = 0$; $x_4 = x_4^0$; $x_2 = x_2^0 = f(x_4^0, D_b - D_{cool})$. Thus, the right-hand side of (11) is a function of $x_{3\psi}$. The form of this function at different load values $\gamma: \gamma = (D_b - D_{cool})/\widetilde{D_0''}$ is shown in Figure 2.

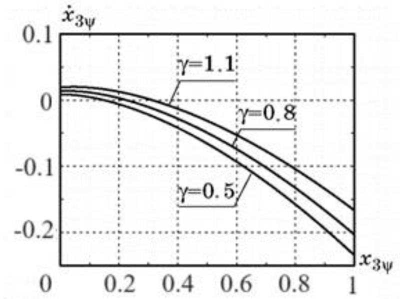

Figure 2. Graph of the behavior of the right side of (11)

As can be seen from this graph, the function on the right in (11), under any loads, is monotonically decreasing in almost the entire physically permissible range of the x_3 coordinate change and intersects the abscissa axis at a single point. The area of monotony lies in the interval: $0.01 \div 1$ at loads $\gamma = 0.5$; $0.02 \div 1$ at loads $\gamma = 0.8$; $0.045 \div 1$ at loads $\gamma = 1.1$. It should be noted that the lower limit of the range is approximately an order of magnitude less than the steady-state value of the vapor content corresponding to the same load value and is almost never reached in real operating conditions. Thus, there is a unique asymptotically stable equilibrium position, and the motion of a closed system along the intersection of manifolds is asymptotically stable.

On Figures 3 to 6 show the results of modeling the system (1) with control laws (5), (6) at various loads: I - $D_b = 0.7D_b^0$, II - $D_b = 0.8D_b^0$, III -$D_b = 0.95D_b^0$. The simulation was carried out for a steam generator with a steam capacity of 670 t/h, all the necessary parameters of which are given in the technical guidelines [25]–[28]. In this case, the regulator had the following adjustment factors:

$$\beta_{11} = 1, \beta_{12} = 1, \beta_{21} = 40, \beta_{22} = 1, \alpha_1 = 1/30, \alpha_2 = 1/32, \alpha_3 = 3/2.$$

The task for the steam pressure at the outlet of the steam generator, respectively, is equal to $x_4^0 = 13.73$ MPa. As can be seen from the graphs, the control laws (5), (6) ensure the stabilization of the steam pressure at the outlet of the steam generator in Figure 6 and the water level in the drum as shown in Figure 3 over a wide range of varying loads.

Control with an incompletely measurable state vector. Let us now discuss the following question. If the level deviation in the boiler drum x_1 and the steam pressure at the outlet of the steam generator x_4 are directly measurable, then it is difficult to directly measure the mass vapor content at the outlet of the lifting pipes. Although such techniques exist, their use requires additional funds. Below we will consider exactly how the control law (5), (6) should be modified so that it does not contain an immeasurable variable x_3.

In [25], it is noted that the linear model of the CC of the steam generator, written on the basis of the first three equations of the system (1), has the following poles:

$$p_1 = 0;$$

$$p_2 = -\beta_1/A;$$

$$p_3 = -\frac{r(x_2^0)}{e_{33}(x_2^0, x_3^0)}\left(D_{low}(x_2^0, x_3^0) + x_3^0 \frac{\partial D_{low}(x_2, x_3)}{\partial x_3} | x_2 = x_2^0, x_3 = x_3^0\right),$$

where $\beta_1 - D_0'' \frac{\partial i''}{\partial x_2}\Big| x_2 = x_2^0 + D_{pur}^0 \frac{\partial i'}{\partial x_2}\Big| x_2 = x_2^0$;

$$A = V_{b.o.}^0 \left(\rho' \frac{\partial i'}{\partial x_2} + \frac{\rho''}{\rho'-\rho''}\right|x_2 = x_2^0 + (V - V_{b.o.}^0)\left(\rho'' \frac{\partial i''}{\partial x_2} + \frac{\rho''}{\rho'-\rho''} r\right)\left|x_2 = x_2^0 + G_0 c_p \frac{\partial \vartheta''}{\partial x_2}\right|x_2 = x_2^0\Big).$$

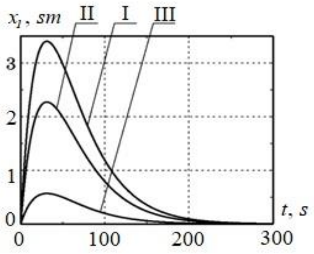

Figure 3. Changing the level

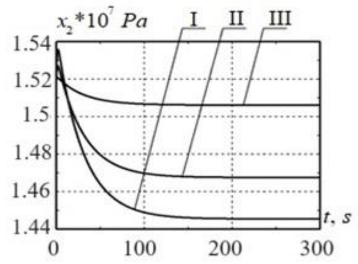

Figure 4. Changing the steam pressure in the drum

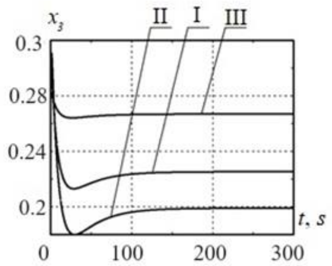

Figure 5. Change in vapor content

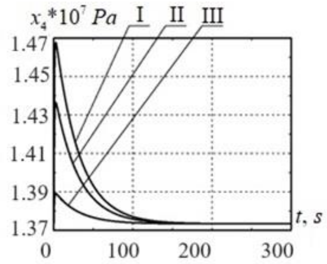

Figure 6. Change in steam pressure at the steam generator outlet

The value of parameter A is always positive, and parameter β_1 can be either positive or negative. If the purge value $p = D_{pur}^0 / D_0''$ satisfies the condition

$$p < -\frac{\partial i''}{\partial x_2} \Big/ \frac{\partial i'}{\partial x_2}, \tag{12}$$

pole $p_2 > 0$. In the absence of purging, condition (12) is fulfilled at pressures greater than 3 MPa. The value of the third pole is always negative and for the steam generator modeled above at the nominal operating mode is equal to $p_3 = -0.1205$. It characterizes the time of the transition process in the variable x_3. This time is small compared to the time of regulating the pressure and level in the boiler [26]. Therefore, we can use the function in the control laws (5), (6) instead of the value of x_3.

$$x_3 = F(x_2, x_4, D_{con}, D_{pur}), \tag{13}$$

Found on the basis of the steady state equations of the steam generator. Unfortunately, it is not possible to obtain an expression for x_3 explicitly, because the steady-state equations are nonlinear with respect to x_3, therefore it is also not possible to obtain an expression for the function $F(x_2, x_4, D_{con}, D_{pur})$ analytically. In this paper, the function $F(x_2, x_4, D_{con}, D_{pur})$ was approximated by a polynomial.

$$x_3(x_2, x_4, D_{con}, D_{pur}) = \beta_0 + \beta_1\left(\frac{x_2}{10^6}\right) + \beta_2\left(\frac{x_2}{10^6}\right)^2 + \beta_3\left(\frac{x_2}{10^6}\right)^3, \tag{14}$$

whose coefficients $\beta_i = \beta_i(x_2, x_4, D_{con}, D_{pur})$.

Let's write down the steady-state equations for the steam generator described by the model (1).

$$u_1 - \widetilde{D}''(x_2, x_4) - D_{con} - D_{pur} = 0;$$

$$u_2 + u_1 i_{f.w.} - (\widetilde{D}''(x_2, x_4) - D_{con} - D_{pur}) i''(x_2) - D_{pur} i'(x_2) = 0;$$

$$u_2 - x_3 r(x_2) D_{low}(x_2, x_3) = 0. \tag{15}$$

The third of (15) can be rewritten as (16).

$$x_3 r(x_2) D_{low}(x_2, x_3) = \left(\widetilde{D}''(x_2, x_3) + D_{con}\right)\left(i''(x_2) - i_{f.w.}\right) + D_{pur}\left(i'(x_2) - i_{f.w.}\right). \tag{16}$$

Substituting into (16) the expressions for the steam flow rate in the downcomers D_{low} and the average volumetric steam content $\bar{\varphi}_{lif}$.

$$D_{low} = \sqrt{\frac{2\rho'(x_2) f_{lif}\left(\rho'(x_2) - \rho''(x_2)\right) g \bar{\varphi}_{lif} V_{lif}}{k}};$$

$$\bar{\varphi}_{lif} = \frac{\rho'(x_2)}{\rho'(x_2) - \rho''(x_2)}\left[1 - \frac{\rho''(x_2)}{\left(\rho'(x_2) - \rho''(x_2)\right) x_3} ln\left(1 + \frac{\rho'(x_2) + \rho''(x_2)}{\rho''(x_2)} x_3\right)\right];$$

and introducing the notation

$$D\left(x_2, x_4, D_{con}, D_{pur}\right) = \widetilde{D}''(x_2, x_4) + D_{con} + \frac{i'(x_2) - i_{f.w.}}{i''(x_2) - i_{f.w.}} D_{pur},$$

We will get

$$x_3^2 - \frac{\rho'' x_3}{\rho' - \rho''} ln\left(1 + \frac{\rho' - \rho''}{\rho''} x_3\right) = \frac{k}{2g f_{lif} V_{lif}}\left(\frac{i'' - i_{f.w.}}{\rho' r} D\left(x_2, x_4, D_{con}, D_{pur}\right)\right). \tag{17}$$

The last equation can be rewritten as (18).

$$x_3^2\left[1 - \frac{1}{A x_3} ln(1 + A x_3)\right] = B \frac{k}{2g f_{lif} V_{lif}} D^2\left(x_2, x_4, D_{con}, D_{pur}\right), \tag{18}$$

where

$$A = \frac{\rho' - \rho''}{\rho''}, B = \left(\frac{i'' - i_{f.w.}}{\rho' r}\right)^2.$$

To approximate x_3 by the functional dependence

$$x_3 = \sum_{i=0}^{3} \beta_i\left(x_2, x_4, D_{con}, D_{pur}\right)\left(\frac{x_2}{10^6}\right)^i$$

The (18) was solved with respect to x_3 at a fixed value D from the range $(0.4 \div 1.4) D\left(x_2^0, x_4^0, D_{con}^0, D_{pur}^0\right)$ and changing x_2 from $0.3x_2^0$ to $1.3x_2^0$. Obtained in a table, the $x_3(x_2)$ function was then approximated by the least squares method. Repeated several times for different - $D\left(x_2, x_4, D_{con}, D_{pur}\right)$, this procedure gives tables of functions $\beta_i\left(D\left(x_2, x_4, D_{con}, D_{pur}\right)\right)$. Based on these tables, the functions $\beta_i\left(D\left(x_2, x_4, D_{con}, D_{pur}\right)\right)$ were then approximated by a 2nd order polynomial

$$\beta_i = \beta_{i0} + \beta_{i1} C + \beta_{i2} C^2,$$

where $C = \frac{k}{2g f_{lif} V_{lif}} D^2\left(x_2, x_4, D_{con}, D_{pur}\right)$.

The computational experiment diagram is shown in Figure 7. During the computational experiment, new control laws for drum steam boilers were developed and tested on the basis of their nonlinear mathematical model, adequately describing the processes in a wide range of operating modes. The obtained results allow us to conclude about the increase of efficiency and stability of steam boiler control when applying the developed control laws.

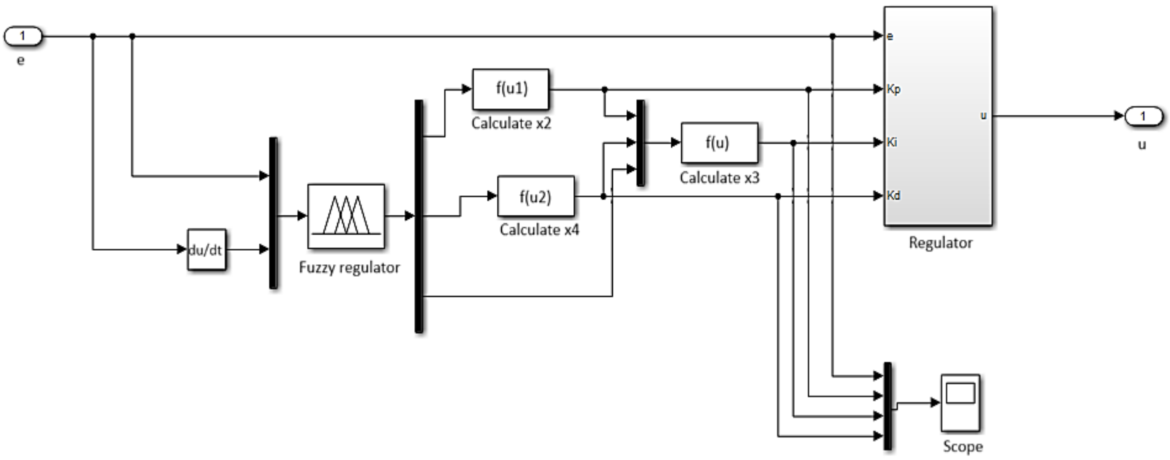

Figure 7. Block diagram of the experiment in MATLAB Simulink

3. RESULTS AND DISCUSSION

Figures 8 to 11 show the results of comparative modeling of the system (1) with the control laws (5), (6), for two cases: i) when a variable appears in the laws x_3 and ii) when it is replaced by an estimate obtained based on the calculation of the function (14). The simulation was carried out for a load of 80% of the nominal and the same parameters of the steam generator and regulator as in the previous case. As can be seen from the figures, the largest discrepancy is the graph of the level change. At the same time, the steady-state deviation of the level is different from zero, which is explained by inaccuracies in the approximation of the function (14). Figures 12 and 13 show graphs of changes in steam pressure at the outlet of the steam generator and the water level in its drum with varying load: I - $D_b = 0.7D_b^0$, II - $D_b = 0.8D_b^0$, III - $D_b = 0.95D_b^0$. For a regulator with an x_3 rating.

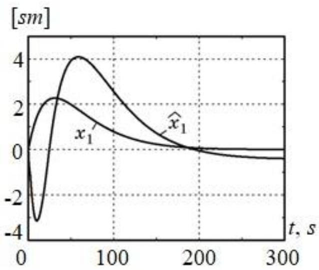

Figure 8. Changing the level

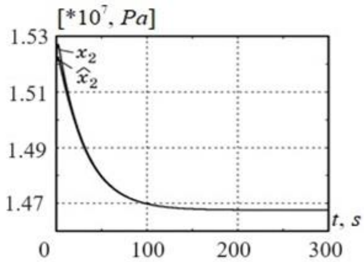

Figure 9. Changing the steam pressure in the drum

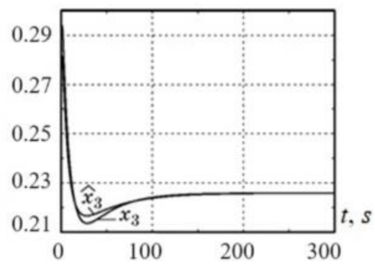

Figure 10. Change in vapor content

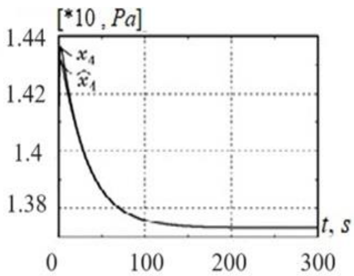

Figure 11. Change in steam pressure at the steam generator outlet

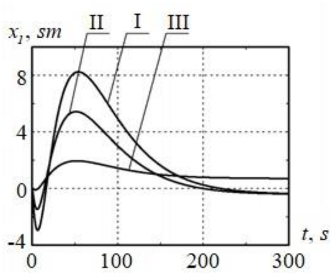

Figure 12. Level change

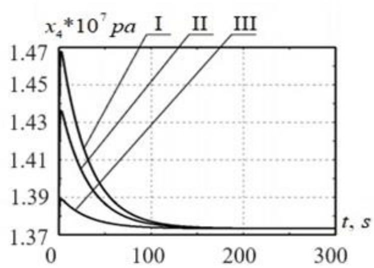

Figure 13. Steam pressure change at the steam generator outlet

4. CONCLUSION

In conclusion, this article highlights the significance of the integrated application of the synergetic approach in enhancing the quality of intelligent steam generator control systems. By combining model-based control, adaptive control, and artificial intelligence techniques, a more efficient and flexible control system can be developed. The synergetic approach, which focuses on the interaction and collaboration of system components, offers the potential for achieving higher performance compared to individual control methods. The use of mathematical models, adaptive control mechanisms, and artificial intelligence algorithms enables improved steam generation efficiency, optimized energy consumption, enhanced system stability and reliability, and adaptability to varying operating conditions and disturbances.

The findings of this research provide valuable insights for engineers, researchers, and professionals involved in the design and implementation of intelligent steam generator control systems. By embracing the synergetic approach, significant enhancements in control quality can be achieved, leading to optimal operation and maximum efficiency of power plants. Further research in this area could explore the application of synergetic synthesis methods for optimal control quality of steam generators. Additionally, the importance of modeling and simulation in evaluating control methods and strategies should be emphasized, allowing for iterative optimization and continuous improvement of the control system based on simulation experiments.

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