Synthesis of nonlinear multilinked control systems of thermal power plants

Oksana Porubay[1], Isamiddin Siddikov[2]
[1]Department of Software Engineering and Cybersecurity, Faculty of Information Technology and Telecommunications, Fergana State Technical University, Fergana, Uzbekistan
[2]Department of Information Processing and Management System, Faculty of Electronics and Automation, Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan

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ABSTRACT

The paper addresses the synthesis of nonlinear control laws for the technological parameters of drum boiler steam generators in thermal power plants, based on a synergetic control approach. The controlled system is considered to be multidimensional and highly interconnected. The inherent nonlinearity and interdependence of the technological parameters in thermal power plants necessitate the use of nonlinear control laws to achieve effective regulation. This approach enables the expansion of the range of permissible variations in regulator parameters, thereby ensuring the desired dynamic behavior of the controlled variables. An analytical method for synthesizing nonlinear vector control laws for steam generators is proposed. A methodology is developed for designing dynamic regulators capable of compensating for uncertain disturbances while accounting for control constraints. A Lyapunov function is constructed to describe the internal state dynamics of the control object. The proposed method for constructing the dynamic regulator ensures the asymptotic stability of the control system and stabilization of the controlled parameters over a wide range of load variations.

Corresponding Author:

Oksana Porubay
Department of Software Engineering and Cybersecurity, Faculty of Information Technology and Telecommunications, Fergana State Technical University
Mustakillik street 185, Fergana, 150100, Uzbekistan
Email: oksanaporubay@gmail.com

1. INTRODUCTION

At present, typical linear control laws synthesized based on linearized models of the object near the stationary mode are successfully used to control the technological parameters of a variety of systems, particularly in thermal power plants. However, the main disadvantage of such regulators is their inability to provide the desired quality of regulation over a wide range of load variations and operating modes of technological units. In such cases, the problem is usually addressed using adaptive or robust control methods [1]–[3]. The main drawbacks of adaptive control algorithms are their high complexity and labor intensity, which require significant computational resources. In works [4]–[7] the application of linear automatic control theory methods to solve the stated problem has been proposed. The known methods proposed by the authors in [8]–[10] are mainly intended for synthesizing adaptive control systems for linear dynamic objects. Linear control theory methods are primarily designed for the control of linear systems operating in steady-state conditions. The methods of classical control theory and automatic regulation are applied to idealized mathematical models that are only adequate to the real physical system in the vicinity of an asymptotically stable equilibrium point. At the same time, one approach to stabilizing control system modes under uncontrolled parameter changes and external disturbances is to introduce additional feedback on measured state variables into the control loop [11]–[13]. These feedbacks are designed for parametric compensation, which significantly complicates the system structure.

Despite this, most works aimed at solving the synthesis problem for control systems of dynamic objects using linear automatic control methods [14]–[16] are limited by the computational capacity of available technical means, which makes the implementation of nonlinear control laws difficult or impossible. The advent of new technical tools with enhanced computational capabilities enables the development of control systems based on nonlinear laws [17], [18].

In this regard, it becomes necessary to apply modern nonlinear control methods to dynamic systems with a multi-connected structure. An analysis of control system synthesis methods for drum-type steam boilers shows the following:

a. Currently, the synthesis of steam generator control systems primarily uses linear mathematical models, obtained by approximating the system along separate channels using typical first- and second-order elements, time-delay elements, etc.
b. The model parameters vary significantly depending on the boiler's operating mode, meaning that linear models adequately describe steam generation processes only within a narrow region near the operating point.
c. A controller designed for one specific mode based on a linear model often fails to ensure satisfactory regulation quality under different operating modes.

Based on the above, it can be concluded that effective steam generator control requires taking into account the nonlinearity and interconnectivity of the underlying processes. Thus, the synthesis should be based on nonlinear mathematical models that represent a wide range of boiler operating modes, using the methods of synergetic control theory [19]–[21]. This paper presents the results of a study on a control system with nonlinear, multidimensional, and multi-connected characteristics. On this basis, a synergetic control approach is proposed. A distinctive feature of the proposed method is the possibility of deriving an analytical form of the control algorithm, ensuring its universality in controlling nonlinear dynamic systems of varying complexity [22]. This approach reaffirms the relevance of the problem related to the design of nonlinear vector controllers, which account for critical properties of thermal power plants (TPPs), such as nonlinearity and interconnectivity, as well as the need to expand the control range. An example is provided of the implementation of a synthesized synergetic control system for the technological parameters of a boiler unit, specifically, the steam pressure at the generator outlet and the water level in the boiler drum.

2. METHOD

Currently, there are virtually no formalized procedures for synthesizing control systems for multi-connected nonlinear dynamic systems. A review of existing methods for solving this problem has shown that the most promising approach is the analytical design of aggregated controllers (ADAC), which forms the foundation of synergetic control theory [23]. An important aspect in designing effective control systems for the considered technological parameters is ensuring the stability of the closed-loop automatic control system. In this paper, to develop highly efficient control systems for nonlinear dynamic objects, we propose a synthesis procedure based on the synergetic approach. Synergetic control is a nonlinear control strategy that explicitly considers system nonlinearities during the design process and ensures asymptotic stability and high control performance. By using measurable state variables in the control law, the proposed method avoids the oscillations typically observed in sliding mode control systems [24]–[26]. In the following, we consider the synthesis procedure for a nonlinear control system of a drum boiler equipped with a superheater. The material and energy balance equations presented in [27]–[29] are employed to construct the mathematical model of the drum boiler.

The controlled and manipulated variables are first identified when formulating the process model:

$$Y = \{y_1, y_2, y_3, y_4, y_5\};$$
$$U = \{u_1, u_2\},$$

where, the controlled variables: $y_1 = l$ - drum boiler water level, $y_2 = p_b$ - steam pressure in drum boiler, $y_3 = x_{l.p.}$- mass fraction of vapor at the outlet of lifting pipes, $y_4 = V_e$- evaporation volume in drum boiler, $y_5 = p_{out}$- steam pressure at the superheater outlet; control variables: $u_1 = G_{f.w.}$- feed water flow rate, $u_2 = Q_L^T$- heat input.

The combined model of a drum boiler with a superheater is as follows:

$$\dot{y}_1(t) = \frac{1}{S_3}\Bigg(\frac{1}{\Delta_e}\Big((e'_{22} - \tilde{e}_1 e_{21})(u_1 - G_P(y_2, y_5)) - (e'_{12} - \tilde{e}_1 e_{11})\big(u_2 + u_1 i_{f.w.} - -G_P(y_2, y_5) i''(y_2)\big) + \frac{1}{e_{33}}\Big(\frac{\partial\bar{\alpha}_v(y_2,y_3)}{\partial y_3} V_{l.p.} - \frac{e_{43}}{e_{44}}\Big)\big(u_2 - y_3 r(y_2) G_{OP}(y_2, y_3)\big) + \frac{1}{e_{44}}\Big(\frac{\rho''(y_2)}{T_b}(V_e^0 - y_4) + + \frac{i_{f.w.} - i'(y_2)}{r(y_2)} u_1\Big)\Big)\Bigg);$$
$$\dot{y}_2(t) = \frac{1}{\Delta_e}\Big(e_{11}\big(u_2 + u_1 i_{f.w.} - G_P(y_2, y_5) i''(y_2) - e_{21}(u_1 - G_P(y_2, y_5))\big)\Big);$$
$$\dot{y}_3(t) = \frac{e_{32}}{\Delta_e e_{33}}\big(e_{21}(u_1 - G_P(y_2, y_5)) - u_2 + u_1 i_{f.w.} - G_P(y_2, y_5) i''(y_2)\big) + \frac{1}{e_{33}}(u_2 - -y_3 r(y_2) G_{OP}(y_2, y_3))$$
$$\dot{y}_4(t) = \frac{\tilde{e}_2}{\Delta_e}\Big(e_{11}\big(u_2 + u_1 i_{f.w.} - G_P(y_2, y_5) i''(y_2) - e_{21}(u_1 - G_P(y_2, y_5))\big)\Big) - \frac{e_{43}}{e_{33} e_{44}}(u_2 - -y_3 r(y_2) G_{OP}(y_2, y_3)) + \frac{1}{e_{44}}\Big(\frac{\rho''(y_2)}{T_b}(V_e^0 - y_4) + \frac{i_{f.w.} - i'(y_2)}{r(y_2)} u_1\Big);$$
$$\dot{y}_5(t) = \frac{1}{e_{55}}(K G_P(y_2, y_5) - G_{PG}), \quad (1)$$

where, V - volume, ρ - density, $r = i'' - i'$ - specific heat of vaporization, T_b and V_e^0 - steam residence time and steam volume in the drum boiler, respectively, $K = \frac{y_5}{y_n}$ - steam flow coefficient at the outlet and inlet of the drum boiler, $\Delta_e = e_{11} e'_{22} - e'_{21} e_{21}$. The expressions (1) include also: Functions for changing the steam pressure in the boiler unit y_2: $\rho', \rho'', i', i'', \frac{\partial\rho'}{\partial x_2}, \frac{\partial\rho''}{\partial x_2}, \frac{\partial i'}{\partial x_2}, \frac{\partial i''}{\partial x_2}, \frac{\partial\vartheta''}{\partial x_2}$;

The average volume of vapor content is defined as,

$$\bar{\alpha}_v = \frac{\rho'}{\rho' - \rho''}\left(1 - \frac{\rho''}{(\rho' - \rho'') y_3} ln\left(1 + \frac{\rho' - \rho''}{\rho''} y_3\right)\right);$$

water flow rate is calculated by the formula,

$$G_{OP} = \sqrt{\frac{2\rho' S_{OP}(\rho' - \rho'') g \bar{\alpha}_v V_{l.p.}}{k}},$$

where, S_{OP} - cross-sectional area of underwater pipes, g - free fall acceleration, k - coefficient of friction.

Steam flow rate from the drum boiler, is determined by the expression:

$$G_P = G_P^0 \sqrt{\frac{\rho''(p_b - p_{PG})}{\rho''_0(p_{b0} - p_{PG0})}},$$

here, p_0, p_b, p_{PG0} - parameter values in nominal mode.

The values of the e_{ij} function are determined from the state variables:

$$e_{11} = \rho' - \rho''; \; e'_{12} = V_{VO}\frac{\partial\rho'}{\partial y_2} + V_{PO}\frac{\partial\rho''}{\partial y_2}; \; e_{21} = \rho' i' - \rho'' i'';$$
$$e'_{22} = V_{VO}\left(i'\frac{\partial\rho'}{\partial y_2} + \rho'\frac{\partial i'}{\partial y_2}\right) + V_{PO}\left(i''\frac{\partial\rho''}{\partial y_2} + \rho''\frac{\partial i''}{\partial y_2}\right) + m_0 c_p\frac{\partial\vartheta''}{\partial y_2};$$
$$e_{32} = \left(\rho'\frac{\partial i'}{\partial y_2} - x_3 r\frac{\partial\rho'}{\partial y_2}\right)(1 - \bar{\alpha}_v)V_{l.p.} + \left((1 - y_3) r\frac{\partial\rho''}{\partial y_2} + \rho''\frac{\partial i''}{\partial y_2}\right)\bar{\alpha}_v V_{l.p.} + (\rho'' + +(\rho' - \rho'')y_3) r V_{l.p.}\frac{\partial\bar{\alpha}_v}{\partial y_2} + m_{l.p.} c_p\frac{\partial\vartheta''}{\partial y_2};$$
$$e_{33} = \big((1 - y_3)\rho'' + y_3\rho'\big) r V_{l.p.}\frac{\partial\bar{\alpha}_v}{\partial y_2};$$
$$e_{42} = y_4\frac{\partial\rho''}{\partial y_2} + \frac{1}{r}\left(\rho'' y_4\frac{\partial i''}{\partial y_2} + \rho'(1 - y_4)\frac{\partial i'}{\partial y_2} + m_b c_p\frac{\partial\vartheta''}{\partial y_2}\right) + y_3(1 + \beta)V_{l.p.}\left(\bar{\alpha}_v\frac{\partial\rho''}{\partial y_2} + +(1 - \bar{\alpha}_v)\frac{\partial\rho'}{\partial y_2} + (\rho'' - \rho')\frac{\partial\bar{\alpha}_v}{\partial y_2}\right);$$
$$e_{43} = y_3(1 + \beta)(\rho'' - \rho')V_{l.p.}\frac{\partial\bar{\alpha}_v}{\partial y_2}; e_{44} = \rho'';$$
$$\tilde{e}_1 = \left(\frac{\partial\bar{\alpha}_v}{\partial y_2} - \frac{e_{32}}{e_{33}}\frac{\partial\bar{\alpha}_v}{\partial y_3}\right)V_{l.p.} + \tilde{e}_2; \; \tilde{e}_2 = \frac{e_{43} e_{32} - e_{42} e_{33}}{e_{33} e_{44}}, \quad (2)$$

here $V_{VO} = y_1 S_3 + V_{PO} + \big(1 - \bar{\alpha}_v(y_2, y_3)\big)V_{l.p.} + y_4, V_{PO} = V_0 - V_{VO}, \beta$ - coefficient determining the steam flow rate from the steam volume.

To solve the synthesis problem, we will use the steam generator model in the form of (1) as the basic control laws. Under the ADAC method, the macro-variable relations are obtained:

$$\psi_1 = \beta_{11}(y_1 - y_1^0) + \beta_{12}(KG_P(y_2, y_5) - \varphi_1);$$
$$\psi_2 = \beta_{21}(y_1 - y_1^0) + \beta_{22}(KG_P(y_2, y_5) - \varphi_1). \quad (3)$$

This is the solution of the system of homogeneous differential equations:

$$\dot{\psi}_1(t) + \alpha_1\psi_1 = 0;\ \dot{\psi}_2(t) + \alpha_2\psi_2 = 0; \quad (4)$$

where, α_1, α_2 - coefficients. If condition $\alpha_1 > 0, \alpha_2 > 0$ is satisfied, we obtain a trivial solution of (4) $\psi_1 = 0, \psi_2 = 0$, which provides asymptotic stability of the process.

Solving (1), (3), (4) together, we find the general analytical expressions for the controls u_1 and u_2:

$$u_1 = \frac{1}{\Delta_F}\left(\frac{1}{K\frac{\partial G_P(y_2,y_5)}{\partial y_2}e_{55}}\left(K\frac{\partial G_P(y_2,y_5)}{\partial y_2} - \frac{\partial \varphi_1}{\partial y_5}\right)(KG_P(y_2, y_5) - G_{PG})f_3 - f_1f_6 + f_3f_4 + \right.$$
$$\left. + \frac{1}{\Delta_\beta K\frac{\partial G_P(y_2,y_5)}{\partial y_2}}\left(k_1f_3 + Kk_2f_6\frac{\partial G_P(y_2,y_5)}{\partial y_2}\right)\right), \quad (5)$$

$$u_2 = -\frac{1}{\Delta_F}\left(\frac{1}{K\frac{\partial G_P(y_2,y_5)}{\partial y_2}e_{55}}\left(K\frac{\partial G_P(y_2,y_5)}{\partial y_2} - \frac{\partial \varphi_1}{\partial y_5}\right)(KG_P(y_2, y_5) - G_{PG})f_2 - f_1f_5 + f_2f_4 + \right.$$
$$\left. + \frac{1}{\Delta_\beta K\frac{\partial G_P(y_2,y_5)}{\partial y_2}}\left(k_1f_2 + Kk_2f_5\frac{\partial G_P(y_2,y_5)}{\partial y_2}\right)\right), \quad (6)$$

where,

$$k_1 = \beta_{11}\alpha_2\psi_2, \qquad k_2 = \beta_{12}\alpha_2\psi_2 - \beta_{22}\alpha_1\psi_1,$$
$$\Delta_\beta = \beta_{11}\beta_{22} - \beta_{12}\beta_{21}, \qquad \Delta_F = f_2f_6 - f_3f_5,$$
$$f_1 = -\frac{1}{S_3}\left(\frac{e'_{22} - e'_{12}i''(y_2) - \tilde{e}_1\left(e_{21} - e_{11}i''(y_2)\right)}{\Delta_e}G_P(y_2, y_5) + \frac{1}{e_{33}}\left(\frac{\partial\bar{\alpha}_v(y_2,y_3)}{\partial y_3}V_{l.p.} - \frac{e_{43}}{e_{44}}\right) \times \right.$$
$$\left. y_3 r(y_2)G_{OP}(y_2, y_3) - \frac{1}{e_{44}}\frac{\rho''(y_2)}{T_b}(V_e^0 - y_4)\right),$$
$$f_2 = \frac{1}{S_3}\left(\frac{e'_{22} - e'_{12}i_{f.w.} - \tilde{e}_1(e_{21} - e_{11}i_{f.w.})}{\Delta_e} + \frac{1}{e_{44}}\frac{i_{f.w.} - i'(y_2)}{r(y_2)}\right),$$
$$f_3 = -\frac{1}{S_3}\left(\frac{e'_{12} - \tilde{e}_1e_{11}}{\Delta_e} - \frac{1}{e_{33}}\left(\frac{\partial\bar{\alpha}_v(y_2,y_3)}{\partial y_3}V_{l.p.} - \frac{e_{43}}{e_{44}}\right)\right),$$
$$f_4 = \frac{e_{21} - e_{11}i''(y_2)}{\Delta_e}G_P(y_2, y_5), f_5 = \frac{e_{11}i_{f.w.} - e_{21}}{\Delta_e}, f_5 = \frac{e_{11}}{\Delta_e}.$$

At the end of transients the following equality is satisfied $\psi_i = 0$.

When the representing point of the system falls [30] on the intersection of manifolds $\psi_i = 0$, $i = 1.2$, the dynamic decomposition of the phase space of the system (1), (5), (6) takes place. In this case, the change of vapor pressure at the steam generator outlet is described by the equation of the form:

$$\dot{y}_5(t) = \frac{1}{e_{55}}(\varphi_1 - G_{PG}). \quad (7)$$

Controls (5), and (6) allow the asymptotic stability of the motion of the closed-loop control system to the intersection of manifolds $\psi_1 = 0 \cap \psi_2 = 0 \cap \psi_3 = 0$, ensuring the fulfillment of the conditions of stabilization of steam pressure at the steam generator outlet $(y_5 = y_5^0)$ and water level in the drum boiler $(y_1 = y_1^0)$. This means that the motion of the closed-loop system along the intersection of manifolds is described by a reduced system of equations of the second order [31].

3. RESULTS AND DISCUSSION

As a result of the synthesis performed using the ADAC method, a control law in explicit analytical form was obtained. This ensures the broad applicability of the algorithm and facilitates its implementation in software for various types of microcontrollers. It has been established that, in the case of a piecewise constant external disturbance, its behavior can be effectively described using the corresponding mathematical model presented below:

$$\dot{z}(t) = 0, \\ G_{PG} = z. \tag{8}$$

Combining this model with the boiler model (1), we obtain an extended system of equations:

$$\dot{\tilde{y}}(t) = \mathrm{f}(\tilde{\mathrm{y}}, y_5, \mathrm{u}); \\ \dot{y_5}(t) = \frac{1}{e_{55}}(KG_P(y_2, y_5) - z); \\ \dot{z}(t) = 0, \tag{9}$$

where, $\tilde{\mathrm{y}} = [y_1 y_2 y_3 y_4]^{\mathrm{T}}$- incomplete state vector; f - vector containing the right parts of the first four equations of the system (1).

The dynamic controller in this case will be represented by the following system of equations:

$$\dot{w}(t) = R(\mathrm{y}, w, \mathrm{u}); \\ \tilde{z} = S(\mathrm{y}, w); \\ \mathrm{u} = \mathrm{u}(\mathrm{y}, \tilde{z}), \tag{10}$$

The procedure for synthesizing the static regulator $\mathrm{u} = \mathrm{u}(\mathrm{y}, z)$ by (9) is as follows:

$$\varphi_1(y_5, z) = z - \alpha_3 e_{55}(y_5 - y_5^0),$$

and in the regulator equations similar to (5), and (6), the variable z will appear instead of G_{PG}:

$$u_1 = \frac{1}{\Delta_F}\left(\frac{1}{K\frac{\partial G_P(y_2,y_5)}{\partial y_2}e_{55}}\left(K\frac{\partial G_P(y_2,y_5)}{\partial y_2} - \alpha_3 e_{55}\right)(KG_P(y_2,y_5) - z)f_3 - f_1 f_6 + f_3 f_4 + \right. \\ \left. + \frac{1}{\Delta_\beta K\frac{\partial G_P(y_2,y_5)}{\partial y_2}}\left(k_1 f_3 + K k_2 f_6 \frac{\partial G_P(y_2,y_5)}{\partial y_2}\right)\right), \tag{11}$$

$$u_2 = -\frac{1}{\Delta_F}\left(\frac{1}{K\frac{\partial G_P(y_2,y_5)}{\partial y_2}e_{55}}\left(K\frac{\partial G_P(y_2,y_5)}{\partial y_2} + \alpha_3 e_{55}\right)(KG_P(y_2,y_5) - z)f_2 - f_1 f_5 + f_2 f_4 + \right. \\ \left. + \frac{1}{\Delta_\beta K\frac{\partial G_P(y_2,y_5)}{\partial y_2}}\left(k_1 f_2 + K k_2 f_5 \frac{\partial G_P(y_2,y_5)}{\partial y_2}\right)\right), \tag{12}$$

Synergetic control theory methods were used in synthesizing the observer. The fact that the variable z enters (9) linearly allows us to simplify the observer synthesis procedure considerably.

The equations of the observer in this case will have the form:

$$\dot{w}(t) = -\tilde{\alpha}w - \tilde{\alpha}\big(\tilde{\alpha}e_{55}y_5 + KG_P(y_2, y_5)\big),\ \tilde{z} = -\tilde{\alpha}e_{55}y_5 - w. \tag{13}$$

Replacing in the found control law (11), (12) the variable z by its estimate $\hat{z}$ we obtain the final expressions for the controls u_1 and u_2. As a result of modeling a nonlinear multidimensional automatic control system based on synthesized control laws (11) and (12), time dependencies of the main technological parameters – the water level in the boiler drum and the steam pressure at its outlet—were obtained. The resulting graphs are shown in Figures 1 and 2.

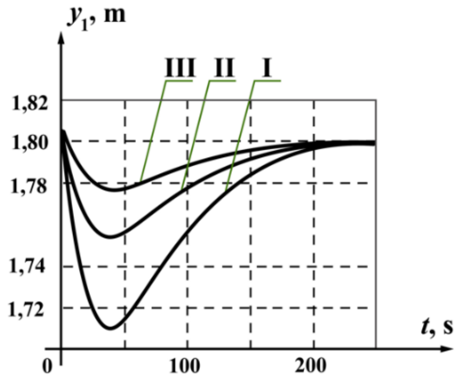

Figure 1. Change of water level in the drum boiler

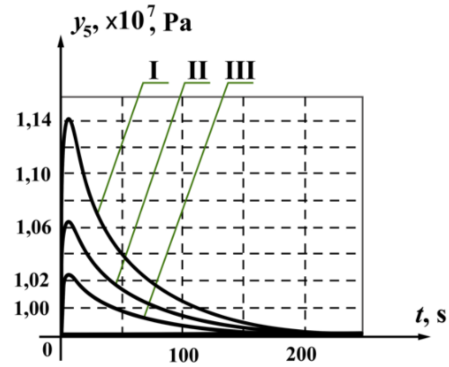

Figure 2. Variation of steam pressure at the boiler outlet

Plots of variation of steam pressure at the steam generator (G_{sg}) outlet and water level in the boiler drum at different loads: I–$G_{sg} = 0.6\ G_{sg}^0$, II–$G_{sg} = 0.8\ G_{sg}^0$, III–$G_{sg} = 0.9\ G_{sg}^0$, for system (1), with synthesized (5), (6). Equations (11) and (12) describe the dynamic controller equations responsible for maintaining the stability of steam pressure and water level in the drum boiler. Simulation results confirm that the proposed synthesis algorithm enables the closed-loop nonlinear multidimensional control system to maintain asymptotic stability across the entire admissible range of phase coordinate variations. The system effectively stabilizes both steam pressure at the generator outlet and the drum water level, even under significant load disturbances.

The novelty of the proposed approach lies in the development of a synthesis procedure for a nonlinear control law that guarantees the asymptotic stability of the closed-loop system over a wide range of parameter variations, while ensuring the stabilization of key technological parameters in the presence of uncertain disturbances. A distinctive feature of the proposed method is the derivation of the control law in an explicit analytical form, which simplifies its implementation and ensures its universality when applied to various classes of nonlinear dynamic systems. In addition, the developed control algorithm takes into account real technological limitations on control actions, such as valve throughput and fuel supply rate of change, which increases its practical applicability.

Compared to traditional control strategies – such as PID controllers, which often require frequent parameter adjustments and are prone to instability when operating conditions change – the proposed approach based on nonlinear control demonstrates higher efficiency. Quantitative comparisons show a 20%-30% improvement in transition time and overshoot, indicating better dynamics and faster attainment of a steady state. Overall, the proposed method of nonlinear control synthesis is an effective solution for stabilizing complex energy systems. It provides high dynamic accuracy, stability, and adaptability to external disturbances, making it promising for implementation in modern thermal power plants and smart energy systems (smart grid).

4. CONCLUSION

Based on the analysis of nonlinear models of steam generator units, a basic model was selected that best reflects the dynamic processes occurring inside the steam generator. A procedure was developed for the analytical synthesis of basic control laws for the interconnected regulation of steam generator units operating as part of a power plant. The proposed synthesis method ensures stabilization of the steam pressure at the steam generator outlet, as well as the water level in the drum boiler. The scientific novelty of the proposed approach lies in the development of a procedure for synthesizing a nonlinear control law that guarantees the asymptotic stability of a closed control system over a wide range of parameter variations and also ensures the stabilization of key technological parameters under conditions of uncertain external influences. A distinctive feature of the method is the possibility of obtaining a control algorithm in an explicit analytical form, which ensures its universality for regulating nonlinear dynamic systems of varying complexity. In addition, the developed control algorithm takes into account real technological constraints on control actions. The obtained control laws guarantee the asymptotic stability of the closed system over a wide range of thermal load changes. Given the increasingly widespread use of digital technologies for controlling structurally complex dynamic objects, further development of this area in terms of the synthesis of discrete nonlinear control systems for such classes of objects is of particular interest.

Given the results obtained, several promising areas for future research can be identified. First, a logical next step would be to implement the proposed control algorithms in real time on embedded digital platforms and industrial controllers. This would allow for the evaluation of computational efficiency, delays, and stability under real-world conditions. Second, the possibility of including fault-tolerant control mechanisms should be considered, which will increase the reliability of the system in the event of sensor failures, actuator failures, and other unforeseen disturbances characteristic of complex thermal processes. In addition, an urgent task is to adapt the developed continuous control to discrete time for practical application in digital control systems. This includes the development of equivalents of nonlinear controllers in discrete form based on the ADAC methodology while maintaining guaranteed stability and control quality properties. Such adaptation will ensure seamless integration into the existing digital infrastructure and open up new opportunities for application in networked and distributed control systems. Finally, further research may be directed toward extending the approach to multi-agent configurations and cyber-physical systems, where coordinated control of multiple interconnected steam generator units is required.

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BIOGRAPHIES OF AUTHORS

Isamiddin Siddikov received his degree in electrical engineering with a degree in automation and telemechanics in 1976 from the Tashkent Polytechnic Institute, Tashkent, Uzbekistan. In 1989 he defended his Ph.D. thesis in the specialty of Control in technical systems. In 2016 he defended his doctoral thesis in the specialty “Intellectualization of control processes for dynamic objects and technological processes.” He is currently a professor at the Tashkent State Technical University named after Islam Karimov. More than 20 PhDs were trained under his leadership. His research interests include the intellectualization of control processes for non-linear continuous-discrete dynamic objects, and the developed methods, and models used in the field of automation of electric power facilities, oil and gas, chemical-technological industries, and the light industry. In addition, he is a reviewer of leading scientific journals. He is the author or co-author of more than 150 peer-reviewed journal articles and conference papers, several monographs and textbooks, as well as 48 scientific articles indexed in the Scopus database (Elsevier). He can be contacted at email: isamiddin54@gmail.com.

Oksana Porubay Ph.D., associate professor, Department of Software Engineering and Cybersecurity, Faculty of Information Technology and Telecommunications, Fergana State Technical University. In 2007 received her Bachelor of Science in Information Technology from the Fergana Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Uzbekistan in 2009 - she Master of Science in Engineering, and in 2024 - she Doctor of Philosophy (Ph.D.) degree in technical sciences in the direction of “Automation and control of technological processes and production”. Her research interests are based on the main goal of scientific work - the development of models and algorithms for the intellectualization of solving control problems and optimizing the operating modes of electric power facilities. On this topic, she wrote and published many scientific papers in national and foreign scientific journals, including publications in journals indexed in the Scopus and Web of Science scientific databases. She can be contacted by email: oksanaporubay@gmail.com.