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PARAMETRIC SYNTHESIS OF CONTROL SYSTEMS FOR THE STEAM GENERATOR OF A NUCLEAR POWER PLANT

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This paper proposes models and methods of the parametric synthesis of automatic control systems for a steam generator at a nuclear power plant, based on the modification of unconditional optimization methods. A mathematical model of steam generator control systems designed for the synthesis of model parameters has been considered. Algorithms are given for calculating level objective functions that take into consideration the limitations of variable parameters and quality indicators of problems for identifying and optimizing model parameters. The methods of unconditional optimization have been modified by introducing the operation of comparing the values of the level objective functions. Using the information technology of optimization, computational experiments were carried out to synthesize the parameters of the steam generator control systems by optimizing the level objective functions. The values of 54 parameters for the model of the control system in the PGV-1000 steam generator were identified, the value of standard deviation in the processes of 1 % from the experimental processes was achieved in the model. The result of parametric synthesis of optimal control systems for a steam generator produced a minimum control time of 131 seconds while the time of computational experiments did not exceed 10 minutes. The peculiarity of the proposed approach to the parametric synthesis of control system models is that the level objective function as a single mathematical object includes all the information about the synthesis problem. Therefore, a given approach is promising for simplifying software for solving complex problems of parametric synthesis of control systems. The considered technology of parametric synthesis of control systems could increase the degree of scientific validity of technical projects to improve various applied and promising control systems

Keywords: nuclear power plant, steam generator, modeling, control system, synthesis, identification, optimization

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1. Introduction

Existing nuclear power plants (NPPs) require the modernization of automatic control systems (ACS) to improve their safety, based on modern mathematical methods and advanced information technologies [1]. NPP ACSs are safety-critical systems. At the same time, taking into consideration the rapid development of computer technology, it is possible to significantly improve the accuracy of ACS modeling. In addition, the use of optimization methods makes it possible to perform the synthesis of optimal systems based on quality criteria that take into consideration many modern technical requirements for the protection and safety of nuclear power plants [2]. Particularly complex and responsible is the synthesis of optimal control systems for NPP steam generators, which are sophisticated thermal objects consisting of many elements and functioning at high temperatures and pressure of water and steam.

Therefore, it is a relevant task to study the synthesis of NPP control systems, in particular control systems of steam generators, based on advanced information technologies.

2. Literature review and problem statement

In work [3], it is noted that the failure of systems critical for safety leads to significant financial losses, a threat to people's lives, and an adverse impact on the environment. Such a critical system for safety is the feed water management system of a nuclear power plant. A complete ACS for a steam generator (SACS) is double-circuit and includes an internal ACS of water level (LACS) in a steam generator and an external ACS of the water supply, which controls the performance of the steam generator by changing the flow rate of feed water. It is proposed to use models in the state space to quantify reliability at the design stage of the system. When modeling a complex system that is critical for safety, the problem of adequate modeling and optimization of system parameters arises. For SACS, this issue is still far from a practical solution, especially to ensure maximum performance. Paper [4] reports a mathematical model of SACS, which is used to study the dynamic processes in the steam generator when the load is discharged, although it is not clear how adequate it is to the real object.

In work [5], the Runge-Kutta method conducts simulation modeling of LACS to verify the dynamic characteristics of the model based on the solution to the system of differential equations (SDEs). This makes it possible to analyze the dynamic characteristics of LACS and design a controller but the problem of optimizing the parameters of the controller is not solved. It should be noted that the Runge-Kutta method does not make it possible to simulate ACS with rigid SDEs, which are currently used to describe the dynamics of the steam generator as an object of control. In work [6], to improve the quality of LACS, it is proposed to use a corrective controller with smoothing of the reference signal and compensation of the most dangerous perturbations but the choice of the optimal parameters for such a controller is not considered. For a cascade LACS, work [7] describes a method for configuring internal control with planned amplification but this method does not guarantee maximum system performance. Article [8] proposes an algorithm for stochastic approximation with simultaneous perturbation to optimize LACS parameters but the optimization of performance is not carried out. To adjust the parameters of ACS of water level controller, work [9] applies the Nelder-Mead method with the desired gain and phase margin, as well as with an integral indicator of the absolute error in time. Indirect quality indicators were applied there, which do not provide maximum performance.

It is obvious that the further development of SACS requires the use of modern information technologies. In work [10], for the design of critical safety control systems of nuclear power plants, the unified modeling language UML is used. The authors propose a method for comparing a UML model with a model in the state space for analyzing digital SACS. Article [11] develops a structure for the general information technology for optimizing complex dynamical systems. Elements of this technology have also been developed in the form of software for solving the problems of modeling, identification, and optimization of dynamic systems. It is proposed to apply this technology for the synthesis of information control systems of nuclear power units. However, the task of using such information technology for the synthesis of SACS, optimal in performance, remains unresolved.

Article [12] discusses the modern experience of modernization of the control and protection system of the NPP power unit. The analog-relay control equipment of the power unit was replaced by modern information control systems and software and hardware systems. An automated digital control system has been created, which has wide opportunities for further improvement but the tasks of synthesizing the optimal control of such a system are not considered.

Our review of the literature on the control of steam generators at NPP allows us to consider that the existing approaches to solving the problem of SACS synthesis are based on the modeling of LACS using indirect quality indicators. Obviously, such approaches produce solutions that are not optimal for the performance of ACS. The reason for this state is the difficulties of modeling SACS and calculating the indicator of its speed, as well as the use of numerical methods to optimize the performance indicator. All this justifies the feasibility of conducting a study into the information technology to address the synthesis of SACS, optimal in speed.

3. The aim and objectives of the study

The purpose of this work is to apply the information technology of the synthesis of optimal performance control systems for automatic performance control of the NPP steam generator in the presence of many limitations of the synthesis problem. This will make it possible to improve the quality of SACS in the modernization of existing NPPs and when designing new NPPs.

To accomplish the aim, the following tasks have been set:

– to conduct computational experiments to identify the parameters for the control systems of the steam generator;

– to conduct computational experiments on the synthesis of optimal performance control systems for the performance of the steam generator;

– to optimize the performance of the automatic control system of the steam generator.

4. The study materials and methods

To solve the tasks related to the parametric synthesis of SACS, information technology for optimization of complex dynamical systems was applied [11]. This information technology includes programs of models of dynamical systems, methods of integrating SDEs, calculation of system quality criteria, optimization methods, data structures, representation of textual and graphical information.

The mathematical model of the steam generator was built according to the formulas of thermodynamics, conservation of the mass of matter, circulation of the steam-water mixture [13]. In the differential equations of the dynamic processes occurring in the steam generator, a transition to relative variables was performed, the equations were linearized [14]. To these equations, we added the equations of auxiliary equipment and a controller [15]. To solve the problems of parametric synthesis, we derived models of a steam generator as a control object and SACS in the following form:

$$d\mathbf{X}/d\tau=\mathbf{A}(\mathbf{x})\mathbf{X}+\mathbf{B}_q(\mathbf{x})q+\mathbf{B}_u(\mathbf{x})u+\mathbf{B}_\phi(\mathbf{x})\phi,\ \mathbf{X}(0)=\mathbf{0}, \qquad (1)$$

where $\mathbf{X}=\mathbf{X}(\tau)$ is the vector of state variables; τ is the time variable; $\mathbf{x}$ is the vector of p variable parameters; $\mathbf{A}(\mathbf{x})$ is the state matrix; $\mathbf{B}_q(\mathbf{x})$, $\mathbf{B}_u(\mathbf{x})$, $\mathbf{B}_\phi(\mathbf{x})$ – input column vectors; q, u, ϕ – input effects: ϕ is the rotational speed of the rotor of the steam turbine, q is the thermal power of the heat carrier, u is the movement of the turbine valve. The rated mode of operation of the steam generator corresponds to the zero initial conditions of SDE (1), its order is indicated by n. For the steam generator as a control object, n=14, for SACS, $n\geq14$, and depends on the type of controller. The output variables of model (1) are determined by the vector $\mathbf{X}$: feed water flow $g=\mathbf{C}_g\mathbf{X}$, water level in the steam generator $\xi=\mathbf{C}_\xi\mathbf{X}$, steam pressure in the main steam collector $\pi=\mathbf{C}_\pi\mathbf{X}$, where $\mathbf{C}_g$, $\mathbf{C}_\xi$, $\mathbf{C}_\pi$ are the corresponding vectors of the output string.

The constraints of the variable parameter vector $\mathbf{a}\leq\mathbf{x}\leq\mathbf{b}$ were set, according to which the external penalty function (PF) of violation of the constraints $P(\mathbf{x})$ is formed.

To take into consideration the stability of SACS according to the state matrix of its model $\mathbf{A}(\mathbf{x})$, the Faddeev method was used to build a characteristic polynomial $\alpha(\mathbf{x},s)$ of the Laplace variable s with coefficients $\alpha_i(\mathbf{x})$, i=0, ..., n and calculate the coefficients of the first column of the Routh table $\rho_k(\mathbf{x})$, k=0, ..., n. To ensure the stability of SACS, all coefficients of the characteristic polynomial and the first column of the Routh table should be positive.

The degree of violation of the conditions of positivity of the coefficients of the characteristic polynomial is represented by the external penalty function $S(\mathbf{x})$.

To ensure meeting the variable parameter constraints, an algorithm for calculating the level objective function (LOF) has been constructed, which implements the function $\mathbf{F}$=Lofrest($\mathbf{x}$, $\mathbf{a}$, $\mathbf{b}$).

Algorithm 1. Calculation of LOF constraints.

Input parameters: $\mathbf{x}$ is a vector of variable parameters, $\mathbf{a}$ and $\mathbf{b}$ are the vectors of constraints.

The output parameter $\mathbf{F}$ is the value of LOF.

Step 1. Set $H=0$. Calculate PF $P=P(\mathbf{x})$. If $P>0$, then set $\mathbf{F}=(H; P)$ and exit.

Step 2. Set $H=H+1$. Calculate $\mathbf{A}=\mathbf{A}(\mathbf{x})$. Use matrix $\mathbf{A}$ to calculate the array of coefficients of its characteristic polynomial α. Calculate PF $S=S(\mathbf{x})$. If $S>0$, then set $\mathbf{F}=(H; S)$ and exit.

Step 3. Set $n=\dim(\alpha)-1$, $k=2$.

Step 4. Set $H=H+1$. Calculate $\rho=\rho_k(\mathbf{x})$. If $\rho\leq 0$, then set $\mathbf{F}=(H, -\rho)$ and exit.

Step 5. If $k<n-1$, then set $k=k+1$ and go to step 4.

In this algorithm, the variable H is used to determine the level of constraint that has been executed. When all constraints are met $H=n-1$, $\mathbf{F}=(n-1; 0)$. The dim operator in step 3 calculates the size of the array. As a result of the algorithm execution, the value of LOF $\mathbf{F}=(F_1; F_2)$ is defined by two numbers: F_1 is the constraint level, F_2 is the penalty for the violation of the constraint.

For the parametric synthesis of SACS models, an algorithm for calculating the LOF of identification [16] has been developed, which implements the function $\mathbf{F}$=Lofident($\mathbf{x}$, $\mathbf{a}$, $\mathbf{b}$, $\mathbf{Z}$).

Algorithm 2. Calculation of LOF of the identification.

Input parameters: $\mathbf{x}$ is the vector of variable parameters, $\mathbf{a}$ and $\mathbf{b}$ are the vectors of constraints, L is the number of integration steps, T_f is the integration time, Z is the vector of experimental values of the output variable of size L.

The output parameter $\mathbf{F}$ is the value of LOF.

Step 1. Calculate $\mathbf{F}$=Lofrest($\mathbf{x}$, $\mathbf{a}$, $\mathbf{b}$). If $F_2>0$, exit.

Step 2. Calculate the state matrix and input vectors of SDE (1).

Step 3. Solve the SDE with the parameters L and T_f.

Step 4. Determine the vector of values of the output variable $\mathbf{Y}$.

Step 5. Calculate $\Delta=\mathbf{Y}-\mathbf{Z}$, $D=\Delta^{\mathbf{T}}\Delta/L$, $s=\mathrm{sqrt}(D)$.

In this algorithm, in step 5, the sqrt square root extraction operator was applied, the variable s denoted standard deviation (RMS). When all constraints are met, $\mathbf{F}=(n; s)$.

Direct indicators of the quality (DIQ) of the control process are the overshoot $\sigma(\mathbf{x})$, the range of oscillations $\zeta(\mathbf{x})$, the control time $t_c(\mathbf{x})$ and its relative value $\tau_c(\mathbf{x})=t_c(\mathbf{x})/T_f$. For maximum speed of the control system, the control time should be minimal with the stability of the control process and the limitations of indicators $\sigma(\mathbf{x})\leq\sigma_m$, $\zeta(\mathbf{x})\leq\zeta_m$.

To synthesize the parameters of SACS controllers, an algorithm for calculating the LOF optimization has been developed, which implements the function $\mathbf{F}$=Lofopt($\mathbf{x}$, $\mathbf{a}$, $\mathbf{b}$, σ_m, ζ_m, δ_z).

Algorithm 3. Calculation of LOF of the optimization.

Input parameters: $\mathbf{x}$ is the vector of variable parameters, $\mathbf{a}$ and $\mathbf{b}$ are the vectors of constraints, L is the number of integration steps, T_f is the integration time, σ_m and ζ_m are the upper limits of DIQ, δ_z is the zone parameter of the steady value of the controlled variable.

The output parameter $\mathbf{F}$ is the value of LOF.

Step 1. Calculate $\mathbf{F}$=Lofrest($\mathbf{x}$, $\mathbf{a}$, $\mathbf{b}$). If $F_2>0$, exit.

Step 2. Calculate the state matrix and input vectors of SDE (1).

Step 3. Solve the SDE with the parameters L and T_f.

Step 4. Define a vector of values for the output variable $\mathbf{Y}$.

Step 5. Use vector $\mathbf{Y}$ to calculate DIQ σ, ζ, τ_c.

Step 6. Set $H= F_1+1$. Calculate $\Delta\sigma=\sigma-\sigma_m$.

Step 7. If $\Delta\sigma>0$, set $\mathbf{F}=(H; \Delta\zeta)$ and exit.

Step 8. Set $H=H+1$. Compute $\Delta\zeta=\zeta-\zeta_m$.

Step 9. If $\Delta\zeta>0$, then set $\mathbf{F}=(H; \Delta\zeta)$ and exit.

Step 10. Set $H=H+1$, $\mathbf{F}=(H; \tau_c)$.

In this algorithm, in step 5, the DIQ values are calculated by quadratic interpolation of the values of the output variable. When all constraints are met, $\mathbf{F}=(n+2; \tau_c)$.

In algorithms 2 and 3, in step 3, the matrix exponent method is applied to solve rigid SDEs [17]. Programs of algorithms 1–3 are included in the block of information technology criteria [11].

Level objective functions of the form $\mathbf{F}(\mathbf{x})=(F_1(\mathbf{x}); F_2(\mathbf{x}))$ take into consideration the bilateral constraints for variable parameters, the necessary and sufficient conditions for the stability of ACS and the requirements for the model quality indicators. Solving the problems of synthesizing SACS parameters is reduced to the optimization of LOF: $F_1(\mathbf{x}))$ is maximized, $F_2(\mathbf{x})$ is minimized, the maximization of $F_1(\mathbf{x})$ has a priority [17]. To optimize LOF, unconditional minimization methods were modified by introducing a "better" operation for two values of function (6) $\mathbf{U}=(U_1; U_2)$ and $\mathbf{V}=(V_1; V_2)$ [17]

$$U \prec V = \begin{cases} 1, U_1 > V_1 \vee U_1 = V_1 \wedge U_2 < V_2, \\ 0, U_1 < V_1 \vee U_1 = V_1 \wedge U_2 \geq V_2. \end{cases} \tag{2}$$

This operation is implemented according to the following algorithm.

Algorithm 4. Comparison of LOF values.

Input parameters: $\mathbf{U}=(U_1; U_2)$ and $\mathbf{V}=(V_1; V_2)$ are the LOF values.

The output parameter B is the binary result of the comparison.

Step 1. Set $B=0$.

Step 2. If $U_1<V_1$, exit.

Step 3. If $U_1>V_1$, set $B=1$ and exit.

Step 4. If $U_2<V_2$, set $B=1$.

With the use of this algorithm, unconditional optimization methods have been modified, in which, in order to solve the optimization problems of LOF, the scalar comparison < the values of the objective function is replaced by the "better" operation (2) for the LOF values. The Nelder-Mead, Hook-Jeeves methods, genetic algorithms, and other methods were modified. Programs of optimization methods and actions with the LOF have been developed, which are included in the block of information technology methods [11].

5. Results of parametric synthesis of steam generator control systems

5. 1. Computational experiments of the synthesis of models of control systems

Our computational experiments for the synthesis of control system models are performed for PGV-1000 steam generators, which are operated at 13 power units of Ukrainian NPPs. The values of the design and technological parameters of the steam generator PGV-1000, which were taken from various sources, contained errors. To build an adequate model, a parametric synthesis of the model according to the known experimental dynamic characteristics was carried out. In model (1), a vector **x** of 54 variable parameters is built. For the initial value of this vector $\mathbf{x}_0$, the values of 50 parameters are calculated from the design and technological parameters. In a real SACS of PGV-1000, proportional-integral level and performance controllers are used. The initial values for the parameters of the controllers are set to 1. A transition to the relative values of variable parameters is performed and the vectors of constraints **a** and **b** are determined for them. The vector of experimental values **Z** is taken, obtained by reducing the turbine load by 25 % of the rated value and consisting of 140 values of the water level in the steam generator and pressure in the main steam collector. The input parameters of algorithm 2 are set: T_f corresponded to 240 s, L is given to a multiple of the number of experimental data. With such values of input parameters, the optimization of LOF of the identification **F**=Lofident(**x**, **a**, **b**, **Z**) was performed by various methods. The best result was obtained by a cyclic application of a combination of genetic algorithms with Hook-Jeeves and Nelder-Meade methods [17].

Fig. 1 shows the processes of deviation of the level and pressure in SACS. Dots indicate experimental data, thin lines – processes at the initial values of the variable parameters of the SACS model, bold lines – processes obtained after the optimization of LOF. At the initial values of the variable parameters of the SACS model, the processes of level and pressure change are unstable oscillatory.

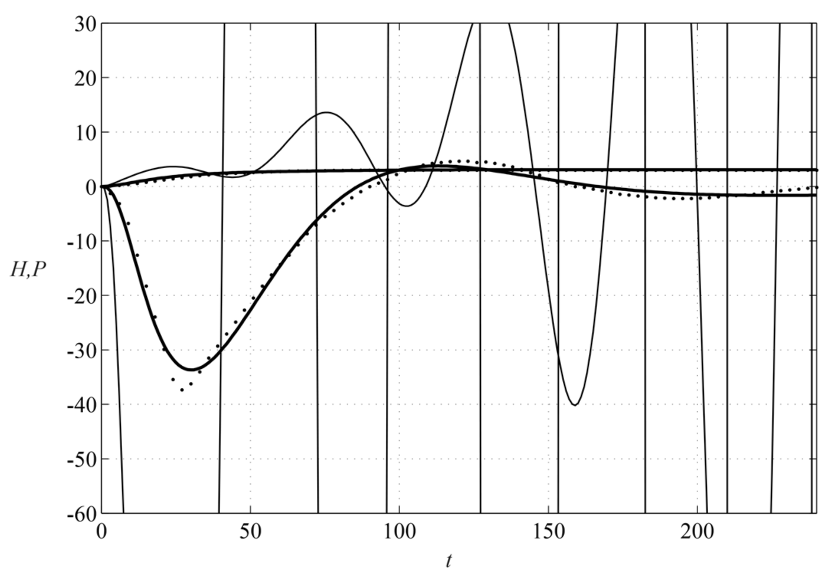

Fig. 1. Level and pressure deviation processes

After the optimization of LOF, the experimental and theoretical processes matched, the RMS was 1 mm with a range of changes in experimental data of the level of 101 mm, that is, a relative value of RMS of 1 % was obtained. The values of the SACS model parameters found as a result of identification were used to synthesize the optimal controller.

5. 2. Computational experiments on the synthesis of optimal control systems

To state the problem of optimizing the SACS parameters, the vector $\mathbf{x}\in R^p$ was built from the variable parameters of the controller K_p, λ_I and λ_D. For the proportional (P), integral (I), and differential (D) controllers, there was one variable parameter p=1, for PI, PD, and ID controllers p=2, for a PID controller p=3. For the parametric synthesis of the controller under the perturbation effect u and the output variable of the feed water flow rate g, the SACS model is represented in form (1), in which the values of the remaining parameters were obtained earlier by identification from experimental data.

The parametric synthesis of SACS with different types of performance controllers was performed according to model (1) with a perturbation effect u=1(τ). The constraints for the variable parameters are set a_i=0, b_i=100, i=1, ..., p. To obtain optimal processes with a minimum control time, the DIQ constraints are set: the value of the maximum deviation of the variable water flow rate σ_m=1, the permissible value of the oscillation index ζ_m=0.65. For the SDE integration method (1), the integration time is set to T_f=500 s, the number of integration steps L=200, the zone parameter of the set value for calculating the control time δ_z=0.05. To calculate the DIQ, SDE (1) was integrated by the matrix method [17]. With such values of the input parameters, the optimization of LOF **F**=Lofopt(**x**, **a**, **b**, σ_m, ζ_m, δ_z), which was calculated according to algorithm 3, was performed by various methods. The best result was obtained by the Nelder-Mead method.

The plots of LOF optimization for SACS with a PI controller modified by the Nelder-Meade method are shown in Fig. 2, 3. The variable parameters for the PI controller are the coefficients of its proportional and integral parts x_1=K_P and x_2=λ_I. The plots in Fig. 2, 3 show the search trajectory connecting the best search points, the starting point is marked with a circle, the final point with a diamond. Fig. 2 illustrates the process of maximizing a level function F_1(**x**) and makes it possible to conclude that all the constraints of the optimization task have been met at the endpoint. Fig. 3 shows the process of minimizing the penalty function F_2(**x**) and demonstrates that the minimum adjustment time point has been obtained.

Fig. 2, 3 clearly present information both about the optimization problem itself and about the method to solve it. A three-dimensional plot of the piecewise-constant function F_1(x) in Fig. 1 shows the division of the two-dimensional space of variable parameters into level areas with the execution of different groups of constraints of the optimization task. This plot demonstrates that most of the constraints at these values of the controller parameters are met. A generalized plot of the piecewise-continuous function F_2(**x**) in Fig. 2 is closely related to the plot in Fig. 1 and consists of the plots of penalty functions of violation of restrictions and a plot of the objective function as the time of regulation. Discontinuous functions F_1(**x**) and F_2(**x**) can be optimized only by direct lookup methods that are modified using operation (2) to compare the values of the level objective function. Among direct search methods, the modified Nelder-Meade method has made it possible to solve the problems of synthesis of optimal speed SACS with high accuracy and a minimum number of calculations of the level objective function. Qualitatively, this is confirmed by the search trajectory, connecting the best points of the Nelder-Mead method in Fig. 1, 2 when optimizing the parameters of the PI controller of SACS.

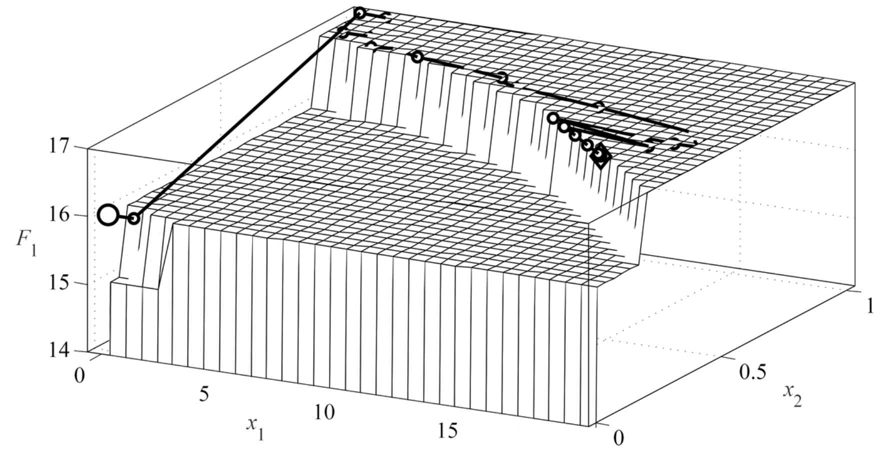

Fig. 2. Level function and optimization trajectory of proportional-integral controller parameters

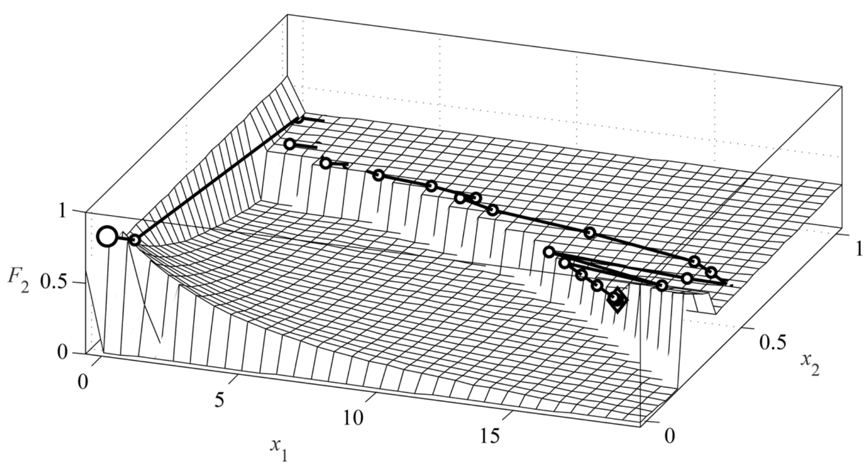

Fig. 3. Penalty function and optimization trajectory of proportional-integral controller parameters

5. 3. Optimization of the performance of the automatic control system of the steam generator

The modified methods for optimizing LOF have made it possible to solve all the tasks of synthesis of optimal SACS with various types of controllers. The duration of each of the computational experiments on average modern computers did not exceed 10 minutes. To optimize controllers with one variable parameter, the modified method of step adaptation turned out to be the most effective in terms of accuracy and speed, and to optimize controllers with several variable parameters, the modified Nelder-Mead method proved to be the most effective. The results of the synthesis of SACS by optimizing LOF with various variable parameters for P, I, D, PI, PD, ID, and PID controllers are given in Table 1 in ascending order of the optimal adjustment time. Here are the type of controller P, the optimal values of the control time t_c^* and the parameters of the controllers K_P^*, λ_I^*, λ_D^*. Also given are the optimal values of LOF F_1^* and F_2^*, the indicator of fluctuations ζ^*, the number of calculations of LOF N_f. The results given in Table 1 show that all constraints for the problems of optimization of the parameters of controllers and DIQ limitations at optimal points are met. At the same time, the minimum values of the control time t_c^*, are obtained, which make it possible to compare the effectiveness of the controllers.

Analysis of the results of the synthesis of optimal SACS given in Table 1 shows that the lowest equal value of the control time t_c^* is demonstrated for PI and PID controllers, and the highest value for a D controller.

The PI controller at optimal parameter values provides the highest possible speed of the control process, which corresponds to the minimum control time of 131 s (Table 1). The regulation time for other controllers is much longer: for the ID controller, it is more by 7 %, for the I controller – by 20 %, for the PD controller – by 41 %, for the D controller – by 398 %. Thus, the expediency of using the PI controller in SACS is theoretically substantiated since the PI controller is simpler than the PID controller. It is this controller that is used in the practice of the power supply section of the power unit. In comparison with the minimization of integral quadratic estimates, minimization of the control time allowed us to significantly increase the speed of SACS [18]. For the PI controller in Fig. 4, we show the plots of the processes of changing the variable flow rate of feed water y=g at the starting and ending points of the search. A thin line indicates a process at the starting point, and a bold line indicates a process at the end point. Near the steady value y_∞=1, the dashed lines highlight the zone of the steady value corresponding to δ_z=0.05.

Table 1

Results of optimization of control system performance

C	t_c^*, s	K_P^*	λ_I^*, s^{-1}	λ_D^*, s^{-1}	F_1^*	F_2^*	ζ^*	N_f
PI	131	16.02	0.3741	–	17	0.2635	0.65	377
PID	131	15.69	0.3886	0.2676	18	0.2625	0.65	606
ID	140	–	0.6714	0.0047	18	0.2788	0.65	308
I	157	–	0.8356	–	17	0.3151	0.65	62
P	185	61.14	–	–	16	0.3708	0.54	62
PD	185	63.62	–	22.004	17	0.3691	0.54	345
D	653	–	–	100	17	1.3071	0.26	76

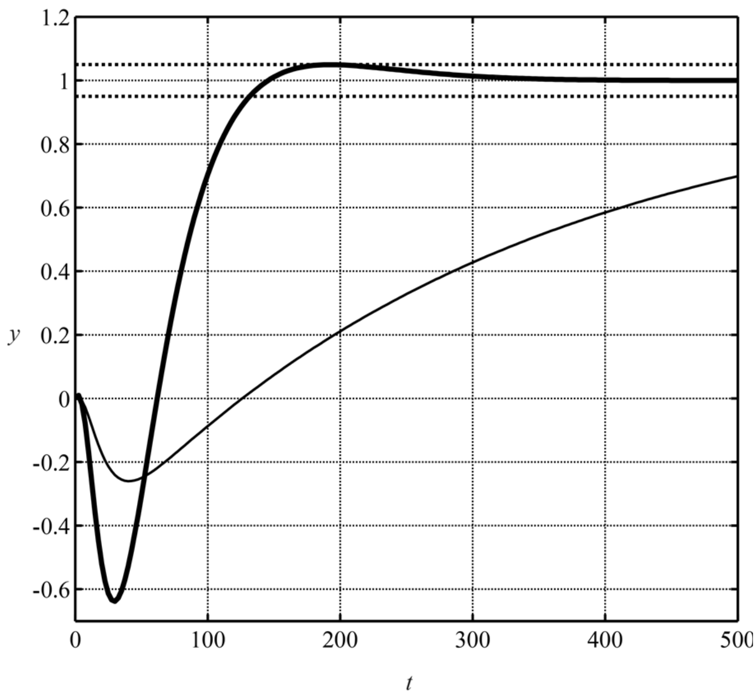

Fig. 4. Change in feed water flow rate

Plots in Fig. 4 show that with an increase in the load on the steam generator, the consumption of feed water first decreases. This is due to the known physical effect of the drop in the water level in the steam generator. After reaching the minimum, the flow rate of feed water increases and is set to a predetermined value.

Additional analysis of the change in state variables in SACS and a comparison of transient processes before and after optimization has made it possible to conclude that the maximum deviation of the variable water level in the steam generator decreased and its fluctuations disappeared. In addition, fluctuations in water flow, pressure in the feed turbopump and in high-pressure heaters disappeared, the maximum deviation and fluctuations in control errors were significantly reduced, fluctuations in the position of the regulating feed valve disappeared. Thus, the optimization of SACS quality indicators has made it possible to significantly improve the main control processes taking place in it.

6. Discussion of results of the synthesis of steam generator control systems

Our results of the numerical synthesis of SACS (Fig. 2–4, Table 1) indicate that the proposed approach to the synthesis of optimal ACS in terms of speed can significantly improve the quality of the control process. Indeed, Fig. 2, 3 show that when searching for an optimal solution, the number of fulfilled constraints for the conditional optimization problem increases and the adjustment time is minimized. Such a search process is based on the optimization of the level objective function using the comparison operation (2) in direct search methods and, therefore, does not present any particular difficulties. It should be noted that the effectiveness of solutions understood in the sense of the optimal value of the level objective function depends on the given constant parameters of this function. This, in particular, can be seen in Fig. 2, 3, wherein the break lines on the three-dimensional plots are determined by the boundary values of the criteria.

The peculiarity of the proposed approach to the synthesis of ACS is that the level objective function, as a single mathematical object, includes all the information about the problem of conditional optimization of the system's performance. Modified methods of optimization taking into consideration operation (2), in contrast to the known methods of conditional optimization, operate with one mathematical object. That is why a given approach should be recognized as promising in the direction of simplifying software to solve complex problems of ACS optimization. The proposed approach to optimization of process control systems has the advantage that, due to a simple modification of the numerical methods of unconditional optimization, it made it possible to optimize the speed of SACS. The reliability of the obtained results of the synthesis of optimal SACS is confirmed by the successful solution of many similar synthesis problems for other ACS of the NPP power unit by various optimization methods [11].

It should be noted that the task of synthesizing the optimal ACS of the NPP steam generator is not covered in the available literature. Most sources model the adjustment of a water level in the steam generator [5–9]. Mathematical models of the ACS of the steam generator are given in [4, 14]. The optimization of SACS, given the complexity of such a task, is even less often discussed. Thus, to adjust the parameters of the water level controller in the steam generator, the Nelder-Mead method was used only with an indirect integral quality indicator [9].

It should be noted that the current study is limited to the use of linear models of SACS, which makes it possible the application of the Routh stability criterion and the matrix method for solving linear SDEs. When modeling SACS, only different types of PID controllers were considered while the effect of random perturbations on the control process of the steam generator is not taken into consideration.

The disadvantage of this study is that the identification of the parameters of the mathematical model of the steam generator is performed on a limited set of experimental data due to the complexity of conducting experimental studies at nuclear power plants. The availability of data from full-scale tests of the NPP steam generator would increase the adequacy of the model.

The current study may be advanced by improving the accuracy of mathematical models, using new types of controllers, and expanding the set of requirements for the quality of the control process. This would require the application of high-order nonlinear mathematical models taking into consideration various uncertainties, new efficient numerical methods for solving high-order nonlinear rigid SDEs, as well as reliable optimization methods.

7. Conclusions

1. Using the information technology of optimization, computational experiments of parametric synthesis of control system models for PGV-1000 steam generators were

carried out by optimizing the level objective identification function. To conduct computational experiments, the methods of Nelder-Mead, Hook-Jeeves, genetic algorithms, and other methods using the operation of comparing the values of level objective functions have been modified. The algorithm for calculating the level objective function included checking the constraints of the parameters and calculating the standard deviation of the processes in the model from the experimental processes. The best result was obtained by cyclic application of a combination of genetic algorithms with Hook-Jeeves and Nelder-Mead methods. The values of 54 parameters of the model of the steam generator control system were identified. As a result of the identification of the model parameters, the relative value of the standard deviation of 1 % was obtained. The values of the model parameters of the steam generator control system found as a result of identification were used to synthesize the parameters of the optimal controller.

2. Computational experiments on the synthesis of optimal performance of steam generator control systems based on the level objective function and models of control systems in the form of systems of differential equations were carried out. The process of optimizing the parameters of the controller is clearly represented by three-dimensional plots of the level objective function. Plots of the level objective function display the division of the variable parameter space into level areas with the execution of different groups of restrictions of optimization tasks, as well as penalty functions of violation of restrictions and the objective function of performance as a time of regulation. The level objective function is not continuous, so its optimization is possible only by direct search methods modified using an operation to compare the values of this function. The Nelder-Mead method has made it possible to solve the problems of synthesis of optimal control systems with high accuracy with a minimum number of calculations of the objective function in comparison with other methods. This was qualitatively confirmed by the search trajectory when optimizing the parameters of the proportional-integral controller.

3. The modified methods to optimize the level objective function have made it possible to solve all the tasks of synthesis of optimal performance of steam generator control systems with various types of controllers. For different types of controllers, minimum values of the control time were obtained, which made it possible to compare the efficiency of controllers in terms of speed. The practical significance of these results is the fact that the expediency of using a proportional-integral controller in the control system of the steam generator has been theoretically substantiated. Such a controller, with minimal complexity and optimal parameter values, ensures the highest possible speed of the control process, which corresponds to a minimum control time of 131 seconds. The adjustment time for other controllers, with the exception of the proportional-integral-differential controller, is much longer: for the integral-differential controller, it is 7 % longer, for the integral controller – by 20 %, for the proportional-differential controller – by 41 %, for the differential controller – by 398 %. Optimization of the automatic control system of the steam generator has improved the main control processes occurring in it: the maximum deviation of the water level in the steam generator has decreased and its fluctuations have disappeared, fluctuations in water flow and pressure in the heaters have disappeared. The duration of computational experiments did not exceed 10 minutes. All this shows that the considered information technology for the synthesis of optimal performance of steam generator control systems can indeed be widely used in the practice of calculating optimal control systems.

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