This study's object is the process that controls water level in steam generator at a nuclear power plant. The task considered is to optimize the speed of operation and automatic control system of the steam generator.

Optimization information technology for water level control system in steam generator has been proposed, based on nonlinear mathematical models and level objective functions. Nonlinear mathematical model of control system has been considered, which is built to optimize quality indexes of the system.

Applying the developed algorithms, computational experiments were performed to identify and optimize parameters of control system by optimizing level objective functions. Values for 41 parameters in the model of a water level control system in PGV-1000 steam generator were determined. The resulting value for mean square deviation of the model's processes from experimental ones equals 0.43%, which is 54% less than when using linear model. As a result of optimizing water level control system when load is dropped by 20%, a minimum control time of 146 s was achieved. A change in the water level in a steam generator did not exceed 24% of maximum allowable value.

A special feature of the devised optimization information technology for control system is that the level objective function includes all information about optimization problem of a nonlinear control system. This simplifies algorithms and software for solving optimization problems in complex control systems. The technology for optimizing nonlinear control systems considered here could make it possible to increase degree of scientific validity of technical projects for improving various applied and promising control systems

Keywords: optimization information technology, steam generator control, nonlinear model, parameter identification

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DEVELOPMENT OF INFORMATION TECHNOLOGY TO OPTIMIZE THE SPEED OF A STEAM GENERATOR CONTROL SYSTEM WITH THE IDENTIFICATION OF NONLINEAR MODELS

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1. Introduction

Operating nuclear power plants (NPPs) in Ukraine require modernization of automatic control systems (ACSs) based on modern models, methods, and advanced information technology (IT) for their safe operation. Taking into account the rapid evolution of computing technology, it has become possible to significantly increase the accuracy of ACS modeling. The use of optimization methods allows for the synthesis of optimal systems based on quality criteria that take into account modern technical requirements for safety and protection of NPPs. Of particular importance is the design of optimal water level ACSs (WLACSs) in steam generators (SGs) at NPPs, which are complex heat engineering systems with many elements and operate at high temperatures and pressures of water and steam.

Therefore, research into the synthesis of optimal steam generator WLACSs based on advanced information technologies is relevant.

2. Literature review and problem statement

For the modernization of NPP power units, modeling and optimization of SG ACSs are widely used in solving many tasks. The experience of ACS modernization at NPP power units shows that for further improvement of ACSs and use of the wide capabilities of modern control systems, new problem-oriented IT is required [1]. This IT should combine models and methods of analysis, identification, and optimization of ACS. The issue of devising such unified IT for WLACS in GT based on nonlinear models remained unresolved, although various IT elements are successfully used.

The linear mathematical model of a typical ACS in GT is used to study dynamic processes in GT during load shedding [2]. However, its adequacy has not been substantiated. Based on the equations of conservation of mass, energy, and momentum, a nonlinear model of WLACS was built; its operation under typical disturbances was investigated in [3]. But for this model, the problem of parameter identification has not been solved, and the adequacy has not been substantiated. It is proposed to use models of SG ACS in the state space for quantitative assessment of reliability [4]. But the adequacy of these models has not been proven either.

Researchers' attention is paid to various issues of optimizing SG ACS. For a cascaded WLACS, a method of internal control tuning with planned amplification is provided [5]. However, such a method does not guarantee the maximum system speed. To improve the quality of WLACS, it is proposed to use a corrective controller with smoothing of the reference signal and compensation of the most dangerous disturbances [6]. But optimization of the parameters of such a controller is not considered.

Metaheuristic optimization of SG ACS with proportional-integral (PI) controllers was performed by minimizing the integral absolute error in the form of a cost function within the specified constraints [7]. However, such an approach does not guarantee the maximum speed of ACS. The steam generator WLACS was optimized by the modified simplex search method using the gradient using control performance measurements [8]. This approach also does not ensure the maximum speed of ACS. A particle swarm optimization method was proposed for the optimization of WLACS based on the reconstruction of the hybrid iterative model [9]. This also does not lead to maximum performance.

A model-free method based on GK-SPSA was used to optimize SG WLACS [10, 11]. But this does not provide maximum performance. Optimization was performed by the genetic algorithm of the controller for active disturbance elimination for WLACS using a nonlinear dynamic model of the steam generator and an extended state observer [12].

Control efficiency is checked by introducing stepwise perturbations of the set value of the water level and steam flow rate. In this case, the task of optimizing the performance of ACS was not set. An intelligent agent was designed that dynamically optimizes parameters for the digital PI controller of WLACS in real time based on the system state according to the observer information, which leads to improved control performance [13]. However, the task of optimizing the performance of ACS was not set either. A method of sequential optimization of parameters under offline mode for cascade proportional-integral-derivative (PID) controllers of WLACS has been proposed to improve control efficiency under significant changes in output power [14]. However, that also does not lead to maximum performance.

Thus, our review of all the above sources of information demonstrates that adequate nonlinear models are not used for WLACS optimization. Indirect quality indicators that do not provide maximum performance are used when optimizing WLACS. The likely reason is the following objective difficulties. First, these difficulties are associated with the complexity of obtaining experimental data for identifying model parameters and solving the identification problem. Second, there are difficulties in calculating the performance criterion of nonlinear ACS. Third, there are difficulties in optimizing the performance criterion.

Further development of WLACS requires the use of modern information technologies. To solve the problems of modeling, identification, and optimization of dynamic systems, a general IT structure has been designed; elements of this technology have been built in the form of methods, algorithms, and computer programs [15, 16]. Such IT has been successfully applied to the synthesis of optimal SG ACS based on linear models [17], as well as for modeling the dynamics of control over a nuclear reactor with division into zones along the vertical axis based on nonlinear models [18]. Optimization of WLACS speed with linear models and various controllers substantiated the advantage of the PI level controller [17], therefore it should be used in studies with nonlinear models. For IT optimization of control, a nonlinear model of a NPP steam generator was built [19, 20].

Thus, there is a task to design IT optimization for WLACS, optimal in terms of speed, based on the calculation of adequate nonlinear SG models with identification of parameters from experimental data.

3. The aim and objectives of the study

The purpose of our research is to design and experimentally substantiate the effectiveness of the information technology for optimizing the speed of operation for the water level control system in a steam generator based on the identification of the parameters of nonlinear models. This will make it possible to increase the degree of scientific validity of technical projects for improving the control systems for NPP steam generators.

To achieve this aim, the following objectives were accomplished:

– to develop an algorithm for optimizing the speed of operation for the water level control system in a steam generator with the identification of the parameters of nonlinear models;

– to conduct computational experiments to identify the parameters of the nonlinear mathematical model of a steam generator;

– to conduct computational experiments to optimize the water level control system in a steam generator based on the nonlinear model;

– to optimize the speed of the automatic water level control system in a steam generator using the nonlinear model.

4. The study materials and methods

The object of our study is the water level control processes in an NPP steam generator PGV-1000 (Ukraine). The principal hypothesis of the study assumes that the development of IT optimization using an adequate nonlinear SG model obtained by identifying parameters from experimental data could make it possible to significantly improve the performance of WLACS. When modeling SG, the physical equations of heat and material balance, conservation of momentum of the steam-water mixture, and the process of steam passage through the evaporation mirror (EM) were used [19, 20]. The interaction of SG with the regulating feed valve (RFV), the main steam collector (MSC), and the turbine control valve

(TCV) was also taken into account. After transformations and transition to relative variables, a nonlinear SG model was built as a control object in the state space in the form of a system of differential equations (SDEs) [20]:

$$\begin{cases} \theta_w = b_{wp}\pi_p - c_{wp},\ q_m = a_{qm}\left(\theta_m - \theta_w\right), \\ \dfrac{d\theta_t}{d\tau} = b_{tq}q - a_{tm}\left(\theta_t - \theta_m\right), \\ \dfrac{d\theta_m}{d\tau} = a_{mt}\left(\theta_t - \theta_m\right) - a_{mw}\left(\theta_m - \theta_w\right), \\ g_w = \alpha_{gw}\mu_w\sqrt{\pi_w - \pi_p},\ g_s = \alpha_{gs}\sqrt{\pi_p^2 - \pi_m^2}, \\ \pi_{pt} = \dfrac{b_{pw}g_w + b_{ps}g_s + q_m}{a_{pw}\xi_w + a_{ps}\xi_s},\ \dfrac{d\pi_p}{d\tau} = \pi_{pt}, \\ g_g = b_{gq}q_m - \left(a_{gw}\xi_w + a_{gs}\xi_s\right)\pi_{pt} - b_{gg}g_w, \\ \xi_{wt} = b_{wg}\left(g_w - g_g\right) - a_{wp}\xi_w\pi_{pt},\ \dfrac{d\xi_w}{d\tau} = \xi_{wt}, \\ \dfrac{d\xi_s}{d\tau} = b_{sg}\left(g_g - g_s\right) - a_{sp}\xi_s\pi_{pt}, \\ \xi_{ct} = \left(c_c - a_{cc}\xi_c\right)\pi_{pt} + b_{cg}\left(g_s - g_a\right),\ \dfrac{d\xi_c}{d\tau} = \xi_{ct}, \\ \varepsilon_m = \dfrac{\pi_t}{\pi_m},\ \beta_m = \sqrt{1 - \left[\dfrac{\varepsilon_m - \varepsilon_c}{1 - \varepsilon_c}\right]^2}, \\ g_m = \alpha_{gm}\mu_s\beta_m\sqrt{\pi_m},\ \dfrac{d\pi_m}{d\tau} = a_{mg}\left(g_s - g_m\right), \\ \dfrac{dg_a}{d\tau} = \dfrac{c_a + b_{ac}\xi_c - b_{aw}\xi_w - b_{aa}g_a^2 - g_a\begin{pmatrix} d_{ap}\xi_w\pi_{pt} + \\ + d_{aw}\xi_{wt} + d_{ac}\xi_{ct}\end{pmatrix}}{1 + a_{aw}\xi_w + a_{ac}\xi_c}, \\ \dfrac{d\mu_w}{d\tau} = a_{ww}\left(u_w + \mu_{0w} - \mu_w\right),\ \dfrac{d\mu_s}{d\tau} = a_{ss}\left(u_s + \mu_{0s} - \mu_s\right). \end{cases} \quad (1)$$

In this model, the relative time variable τ and the relative state variables are indicated as follows: θ_w, θ_t and θ_m are the average temperatures of water in SG, heat carrier, and metal of the heat exchange tubes; π_p and π_{pt} are the pressure in SG and the rate of its change; ξ_w and ξ_s are the volumes of water and steam in SG; ξ_c is the water level in SG; π_w is the water pressure before RFC; π_m is the steam pressure in MSC; q_m is the thermal power transferred from the heat exchange tubes to the feed water; g_w and g_s are the feed water and steam flows; g_g, ε_m, β_m are auxiliary variables; g_a is the steam flow through DH; ξ_{wt} and ξ_{ct} are the rates of change in the water volume and its level in SG; μ_w and μ_s are the positions of RFC and TCV valves; μ_{0w} and μ_{0s} are the initial positions of RFC and TCV valves. The input variables are the heat capacity of the heat carrier q, control effects on RFC and TCV u_w and u_s, the relative value of vapor pressure after TCV π_t. Based on the design and technological data on SG and related equipment [19, 20], 39 constant parameters of model (1) were calculated.

These are, firstly, the parameters of the heat transfer equations from the heat carrier to the feedwater b_{wp}, c_{wp}, a_{qm}, b_{tq}, a_{tm}, a_{mt}, a_{mw}, as well as the parameters of the vaporization equations b_{pw}, b_{ps}, a_{pw}, a_{ps}, b_{gq}, a_{gw}, a_{gs}, b_{gg}, b_{wg}, a_{wp}, b_{sg}, a_{sp}, c_c, a_{cc}, b_{cg}. Secondly, the parameters of the equation of the circulation of the steam-water mixture after SG ε_c, α_{gm}, a_{mg}, α_{gs}, a_{ss}. Thirdly, the parameters of the equations of steam equipment after SG ε_c, α_{gm}, a_{mg}, α_{gs}, a_{ss}, as well as the parameters for the equations of RFV and TCV α_{gw}, a_{ww}, a_{ss}. Based on the values of these parameters, a vector of 39 constant parameters of a SG model (1) $\mathbf{c}_g$ is formed.

The vector of state variables and its initial value are introduced [20]:

$$\mathbf{X}_g = (\theta_t, \theta_m, \pi_p, \xi_w, \xi_s, \xi_c, \pi_m, g_a, \mu_w, \mu_s)^{\mathrm{T}},$$

$$\mathbf{X}_{0g} = (\theta_{0t}, \theta_{0m}, 1, 1, 1, 0, \pi_{0m}, 1, 1, 1)^{\mathrm{T}}.$$

Model (1) is reduced to vector form [20]

$$d\mathbf{X}_g/d\tau = \mathbf{f_g}(\mathbf{X}_g, \mathbf{c}_g, q, u_w, u_s, \pi_t),\ \mathbf{X}_g(0) = \mathbf{X}_{0g}, \quad (2)$$

where $\mathbf{f_g}(\mathbf{X}_g, \mathbf{c}_g, q, u_w, u_s, \pi_t)$ is a vector function of the right-hand parts of SDE (1). Thus, the dynamic model of PGV-1000, as a control object, is a nonlinear SDE of order $n_g = 10$ in relative variables.

To control an actual PGV-1000 (Ukraine), a PI level controller (LC) is used as the most reliable and simplest. The WLACS model with PI LC is formed by combining the SG and LC models [17].

To assess the quality of control process, direct quality indicators (DQIs) were used: maximum deviation $\sigma(\mathbf{x})$, oscillation amplitude $\zeta(\mathbf{x})$, control time $t_c(\mathbf{x})$ and its relative value $\tau_c(\mathbf{x}) = t_c(\mathbf{x})/T_f$. The calculation of these QPIs is performed by integrating the SDE over the time interval $[0; T_f]$, at the end of which the transient process can be considered complete [16]. The maximum speed of control system can be ensured by the minimum value of control time at the stability of control process and the limitations of indicators: $\sigma(\mathbf{x}) \le \sigma_m$, $\zeta(\mathbf{x}) \le \zeta_m$.

5. Results of the design and justification of information technology for optimizing control system performance

5. 1. Development of an algorithm for optimizing control system performance

Information technology (IT) is a set of models, methods, processes, algorithms, software, and equipment used to generate, collect, process, store, transmit, and represent information. For IT identification and optimization of WLACS using a nonlinear model (4), algorithms and programs used with linear models were modified [15–17].

Based on the SG model (2), a WLACS model with a PI level controller was built:

$$\begin{cases} \varepsilon = \xi_{cs} - \xi_c + g_s - g_w,\ u_P = K_P\varepsilon, \\ du_I/d\tau = K_I\varepsilon,\ u_w = u_P + u_I, \\ d\mathbf{X}_g/d\tau = \mathbf{f}_g\left(\mathbf{X}_g, \mathbf{c}_g, q, u_w, u_s, \pi_t\right), \end{cases} \quad (3)$$

where ε is the control error; ξ_{cs} is the level setpoint; u_P and u_I are the proportional and integral components of control signal u_w; K_P and K_I are the coefficients of the proportional and integral components. We have built a vector of parameters for WLACS model (3) $\mathbf{c}_s = (\mathbf{c}_g, K_P, K_I)$ of size $p = 41$, the vector of WLACS state variables, and its initial value: $\mathbf{X}_s = (\mathbf{X}_g^T, u_I)^T$, $\mathbf{X}_{0s} = (\mathbf{X}_{0g}^T, 0)^T$. Model (3) is reduced to a vector form

$$d\mathbf{X}_s/d\tau = \mathbf{f}_s(\mathbf{X}_s, \mathbf{c}_s, q, u_s, \pi_t),\ \mathbf{X}_s(0) = \mathbf{X}_{0s}, \quad (4)$$

where $\mathbf{f}_s(\mathbf{X}_s, \mathbf{c}_s, q, u_s, \pi_t)$ is a vector function of the right-hand sides of SDE (3) of order $n = 11$.

Software has been developed for the use of nonlinear models (2) and (4) in the identification and optimization problems of WLACS.

To ensure that all the constraints of the variable parameters are fulfilled, the algorithm for calculating the level objective function (LOF) [15, 16] is modified. According to this algorithm, the LOF value of constraints $\mathbf{F} = (F_1; F_2)$ is calculated, where F_1 is the level that determines the number of sequentially fulfilled constraints, and F_2 is the penalty that determines the magnitude of the violation of the first of the violated constraints.

Using the algorithm for calculating the LOF of constraints, algorithms and programs for calculating the LOF for the identification and optimization of the parameters of nonlinear models have been developed [15, 16]. These algorithms and programs differ from the corresponding algorithms and programs for calculating the LOF of linear models by using the method of integrating nonlinear SDEs. For the integration of nonlinear SDEs, a first-power system method based on the calculation of the integral of the matrix exponent [16] was chosen. The program of this method is included in the module of IT integration methods. The system method of SDE integration allows for the integration of rigid SDEs.

In the LOF of form $\mathbf{F}(\mathbf{x}) = (F_1(\mathbf{x}); F_2(\mathbf{x}))$, two-sided restrictions on variable parameters, necessary and sufficient conditions for the stability of WLACS, as well as requirements for the value of quality indicators of nonlinear models, are taken into account. Solving the problems of identifying and optimizing the parameters of WLACS is reduced to optimizing the LOF: $F_1(\mathbf{x})$ is maximized, $F_2(\mathbf{x})$ is minimized, and maximizing $F_1(\mathbf{x})$ has priority [16]. For optimizing LOF, methods of unconditional minimization have been modified using the "better" operation for the LOF values according to the corresponding algorithm [15–17]. With the use of this algorithm, methods of unconditional optimization have been modified, in which for solving the LOF optimization problems, the scalar comparison of the objective function values is replaced by the "better" operation for LOF values. The Nelder-Mead, Hooke-Jeeves methods, genetic algorithms, and other methods of unconditional optimization have been modified. Programs of optimization methods and actions with LOF have been developed, which are included in the module of IT methods [15].

To identify the parameters of WLACS, a basic Algorithm 1 has been developed.

Algorithm 1. Identification of WLACS parameters.
Input parameters: initial values of structural and technological parameters of SG, experimental data on processes in SG and WLACS.
Output parameters: identified values of parameters of for SG and WLACS models, optimal value of identification LOF.
Step 1. Calculate values for SG model parameters.
Step 2. Form nonlinear SG and WLACS models in the form of SDE.
Step 3. Form a model of the identification problem in the form of LOF.
Step 4. Optimize the LOF of identification.

In Step 1 of this algorithm, the initial values of model parameters (2) were calculated based on the values of more than 300 design and technological parameters of SG. Also, a vector of variable parameters of the identification problem $\mathbf{x}$ was formed – 39 parameters for SG model (1) and 2 parameters for the PI controller. In step 2, nonlinear SG and WLACS models were built in the form of nonlinear SDEs (2) and (4). In Step 3, the identification problem model was built in the form of LOF. For vector $\mathbf{x}$, constraints $\mathbf{a} \le \mathbf{x} \le \mathbf{b}$ were set. The initial $\mathbf{x}_0$ value for vector $\mathbf{x}$ was calculated based on the known design and technological data on SG and related equipment. The values of the constraint parameter vectors $\mathbf{a}$ and $\mathbf{b}$ were chosen in such a way that the maximum relative deviations of vector $\mathbf{x}$ from $\mathbf{x}_0$ would be the same. To take into account the limitations of stability region for WLACS, linearization of the nonlinear model was performed by calculating the Jacobi matrix of the vector function of the right-hand sides of SDE (4) $\mathbf{A}(\mathbf{x}) = \partial \mathbf{f}_s / \partial \mathbf{x}$. In Step 4, methods for optimizing LOF were used [15, 16].

When identifying the parameters for SG, if all the limitations are met, the LOF value $\mathbf{F} = (n; s)$ is obtained, where s is the root mean square deviation (RMSD) of the values of the theoretical process from the experimental one.

To optimize the speed of WLACS, a principle Algorithm 2 was developed.

Algorithm 2. Optimization of the speed of WLACS.
Input parameters: values of the parameters for SG model, initial values of the variable parameters for WLACS.
Output parameters: optimal values of the variable parameters for WLACS, optimal value of the LOF of speed optimization.
Step 1. Build a nonlinear model of WLACS in the form of SDE.
Step 2. Build a model of the speed optimization problem in the form of LOF.
Step 3. Optimize the LOF of optimization.

According to the algorithm for calculating the LOF of optimizing the parameters of nonlinear models, the LOF value $\mathbf{F} = (F_1; F_2)$ is calculated. If all constraints are met, then $\mathbf{F} = (n + 2; \tau_c)$.

5. 2. Computational experiments for identification of model parameters

Computational experiments for identification of parameters for the nonlinear models of SG and WLACS were performed for steam generator PGV-1000 (Ukraine) in a power unit VVER-1000 (Ukraine) at an NPP with a capacity of 1000 MW. The values of parameters for a SG model contain errors of initial values of parameters and modeling errors, caused by the adopted assumptions, which leads to a significant cancellation of the theoretical process of change in the water level in SG from the experimental process. Therefore, identification of parameters for the nonlinear models of SG and WLACS was performed according to experimental dynamic characteristics [17].

To identify the WLACS parameters, a vector of variable parameters of the model (4) $\mathbf{x} = \mathbf{c}_s$ was formed. From the elements of vector $\mathbf{x}$ – variable parameters x_i, we proceeded to their relative increments $y_i = x_i/x_{0i} - 1$, $y_{0i} = 0$, $i = 1, 2, \ldots, p$. Here x_{0i} are the values of parameters for model (1), calculated from the known design and technological data on SG and related equipment. For variables y_i, restrictions are set from $-d$ to d, where d is the parameter of variable parameter restrictions. The state of SG under the nominal mode was disturbed by reducing the load by closing the main turbine control valve by 25%. The experimental process of changing the water level in SG with a step of the time variable $h = 3$ s when the level controller (LC) is turned off corresponds to 59 water level values. The experimental process of changing the level when the LC is turned on corresponds to 81 level values. The values of water level H, which depend on time variable t, are shown by points in Fig. 1, 2.

When calculating the LOF of identification by integrating SDEs (2) and (4) with a step h by the system method from the IT integration methods module, the corresponding theoretical values for the level were calculated. When fulfilling the restrictions on the experimental and theoretical values of the level, the RSMD was calculated as a function of variable parameters. The optimization of LOF of identification was performed by sequential application of modified genetic algorithms, modified Hooke-Jeeves and Nelder-Mead methods from the IT optimization methods module [11]. The optimal value of the vector of variable parameters of IUS $\mathbf{x}^* = \mathbf{c}_s$ was obtained, where $\mathbf{c}_s = (\mathbf{x}_g^*, K_P^*, K_I^*)$, $\mathbf{x}_g^*$ is the identified value of the vector of parameters for SG, K_P^* and K_I^* are the identified values for coefficients of the proportional and integral parts of LC. The final value for LOF $\mathbf{F}^* = (11;\ 0.435)$ shows that all the restrictions are fulfilled; the minimum value of RSMD was 0.435 mm.

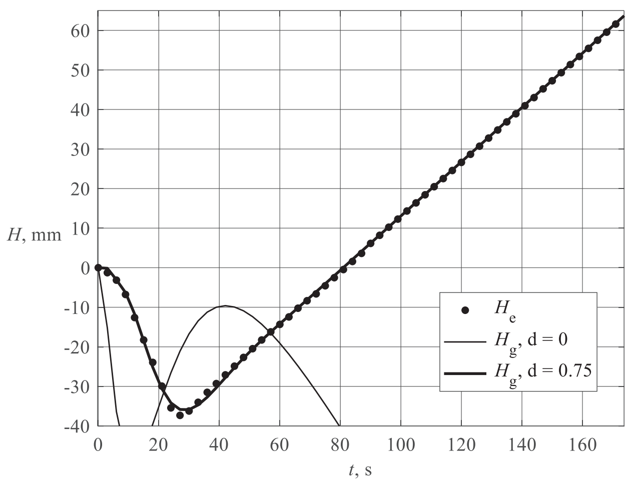

Fig. 1. Level deviation processes with the controller off

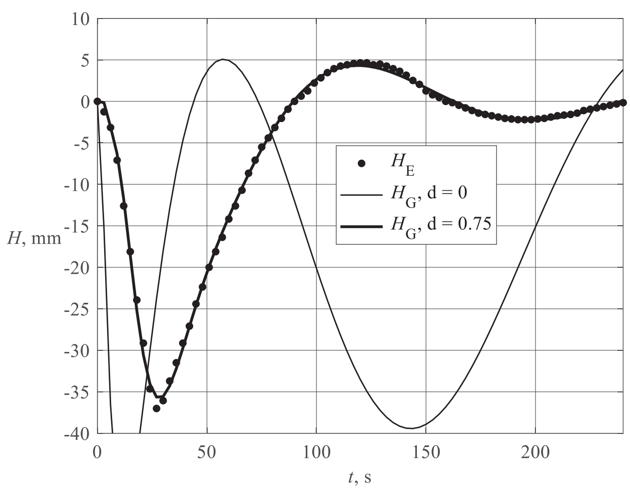

Fig. 2. Level deviation processes with the controller on

Earlier, using the linear model of SG, a minimum value for RSMD of 0.942 mm was obtained. For the nonlinear model of SG, the RSMD value decreased by 54%. With a range of experimental data changes within 101 mm, the relative RSMD value is 0.43%. For the linear model of SG, the relative RSMD value was 0.93%. These data indicate a significant increase in the accuracy of the nonlinear model of SG compared to the linear model.

Fig. 1, 2 show the processes of water level deviation in SG with the LC turned off and on. Dots indicate the experimental data; the thin line indicates the processes at the initial values of the variable parameters for SG models at the value of variable parameter constraints $d = 0$. The bold line indicates the processes after optimization of LOF at the value of constraint parameter $d = 0.75$. With the initial values of the variable parameters for SG models and the LC turned off, the level decreases rapidly with oscillations (Fig. 1), and with the LC turned on, the level change process is oscillatory (Fig. 2). After identification, there is a coincidence of processes in the model with experimental processes both with the LC turned off and on.

5. 3. Computational experiments with control system optimization

The values of parameters for the WLACS model found as a result of identification were used to optimize the parameters for the level controller. In the SG model (2) it is assumed $\mathbf{c}_g = \mathbf{x}_g^*$ for the vector of constant parameters. To state the problem of optimizing the parameters for WLACS, vector $\mathbf{x} \in R^p$ was formed from the variable coefficients of the proportional and integral parts of the PI controller K_p and K_I: $x_1 = K_P$, $x_2 = K_I$. For the PI controller, $p = 2$. Model (4) is reduced to the form

$$d\mathbf{X}_s/d\tau = \mathbf{f}_s(\mathbf{X}_s, \mathbf{x}, \mathbf{c}_s, q, u_s, \pi_t),\ \mathbf{X}_s(0) = \mathbf{X}_{0s}. \quad (5)$$

In this model, at the initial moment of time, the position of TCV changes abruptly from the initial value $u_s = 1.0$ to the value $u_s = 0.8$, which corresponds to a 20% reduction in the load on SG. Other input values of model (5) q and π_t corresponded to their nominal values.

The deviation in the relative controlled value of the level $y = \xi_{cs} - \xi_c$ is indicated. By integrating SDE (5) under the initial conditions of the nominal mode using the first-power system method program from the IT integration methods module, transient processes of SG state change depending on the values of the parameters of the PI level controller were obtained. The parameters for the PI controller were optimized using the Nelder-Mead vector method program from the optimization methods module by optimizing the LOF from the system quality criteria calculation module. The level objective function of form $\mathbf{F}(\mathbf{x}) = (F_1(\mathbf{x}); F_2(\mathbf{x}))$ took into account the two-sided constraints of variable parameters, the necessary and sufficient conditions for the stability of WLACS and the requirements for the value of the quality indicators of nonlinear models. For the integration of SDE by the first-power system method, the process observation time $T_f = 450$ s and the number of model integration steps (5) $L = 150$ were set. To calculate DQIs, the final constant value of the level $y_\infty = 0$, the parameter of the constant value zone $\delta_z = 0.01$, and the maximum permissible deviation value $z_m = 10$ were used. For the DQI optimization problem, the maximum permissible deviation value in the optimal process $\sigma_m = 1$ and the maximum permissible oscillation amplitude $\zeta_m = 0$ were set.

Thus, the optimal control process should be completely free of oscillations. Figures 3, 4 show the process of optimizing DQIs with an initial step $\delta = 1$ from initial point $\mathbf{x}_0 = (0.3719;\ 0.0872)^T$, obtained after the identification of WLACS, using the graphic module from the information representation module for solving IT problems.

In Fig. 3, 4, the plots of elements of the LOF – functions $F_1(\mathbf{x})$ and $F_2(\mathbf{x})$ from variable parameters $x_1 = K_P$ and $x_2 = K_I$ show the best search points. The starting point is marked with a circle; the final point is marked with a rhombus. The permissible error in the argument is 10^{-6}; 117 iterations and

230 calculations of the function were used. The starting point corresponds to the values of the vector function $\mathbf{F}_0 = (12; 0.044)$, the maximum level deviation $\sigma_0 = 0.238$ and the adjustment time is 233 s. The final optimal point $\mathbf{x}^* = (0.921; 0.370)^T$ corresponds to the values of LOF $\mathbf{F}^* = (13; 0.326)$, the maximum level deviation $\sigma^* = 0.234$ and the adjustment time is $t_c^* = 147$ s. Thus, the water level in SG changed by 24% of the maximum permissible value.

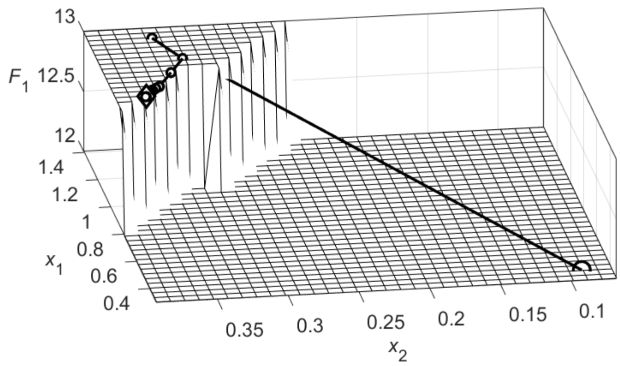

Fig. 3. Plot of function $F_1(\mathbf{x})$ and a trajectory of optimizing the controller parameters

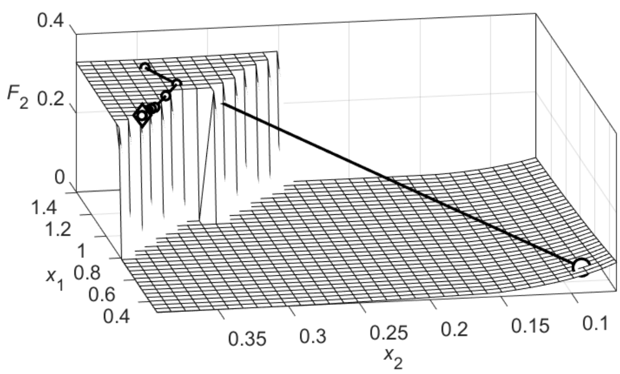

Fig. 4. Plot of function $F_2(\mathbf{x})$ and a trajectory of optimizing the controller parameters

The plot of the piecewise-constant function F_1(x) in Fig. 3 provides a division of the space of variable parameters into level regions. The upper part of this plot corresponds to the region where all 13 constraints are satisfied. The lower part, where 12 constraints are satisfied and the constraint on the oscillation exponent $\zeta(\mathbf{x})$ is violated, corresponds to oscillatory processes. The plot of function $F_2(\mathbf{x})$ in Fig. 4 shows the penalty functions. The upper part of this plot is the plot of objective function $\tau_c(\mathbf{x})$ as the control time. The lower part is the plot of the oscillation exponent $\zeta(\mathbf{x})$.

5. 4. Optimizing the speed of a water level control system

The modified Nelder-Mead method using LOF allowed us to solve the set problem of optimizing the speed of WLACS by changing the parameters of PI controller based on a nonlinear model obtained by identifying the parameters of SG from the experimental processes of changing the water level in SG. Fig. 5 shows the plots of the processes of changing the relative value of water level y at the initial and final points of optimization. The thin line indicates the process at the initial point, and the thick line indicates the process at the final point.

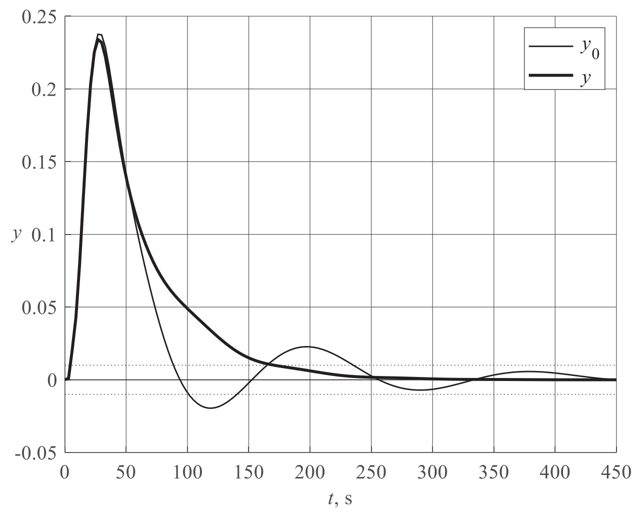

Fig. 5. Level deviation processes at the initial and final values of controller parameters

When the load on SG is reduced by 20% and the value of the constant value zone parameter $\delta_z = 0.01$, the process of changing the water level in SG without oscillations at a minimum control time of 147 s was obtained. Optimizing the speed of WLACS allowed us to significantly improve the control process.

6. Discussion of results related to designing and justifying the information technology for optimizing a steam generator control system

Using the nonlinear mathematical model (2) of the steam generator as a control object, a mathematical model of WLACS (4) has been built. Algorithms 1 and 2 were also developed for identifying and optimizing the WLACS parameters. The features of our algorithms are that they use modified LOFs, which contain all the information about the problems of identifying and optimizing the nonlinear WLACSs. This approach is promising in terms of simplifying the software for solving complex tasks to optimize ACSs.

The results of our computational experiments conducted to identify the parameters for the nonlinear WLACS models of the PGV-1000 steam generator at an Ukrainian NPP are shown in Fig. 1, 2. At the initial values of SG parameters, the processes of changing the water level in the SG, calculated from models (2) and (4), differ significantly from the experimental processes; the conditions for the stability of WLACS are not met. Optimizing the LOF allowed us to move into the stability region of WLACS and find the minimum RSMD of 0.435 mm. After identification in Fig. 1, 2, the coincidence of the processes in the model with the experimental processes is observed both with the LC turned off and with the LC turned on. To solve the identification problem, the most effective method was a combination of a binary genetic algorithm with the Hooke-Jeeves method. This problem was being solved over several days on a MacBook Pro computer. The identification process was accompanied by the output of a table of LOF values to the monitor. The developed software allows one to interrupt the optimization process and build its digital copy at the end of each day. Using a digital copy, we have the opportunity to continue this process the next day.

Based on the nonlinear model of WLACS (5) according to algorithm 2 computational experiments were performed to optimize the WLACS parameters. The optimization process is shown in Fig. 3, 4 on the plots of LOF elements. This process was accompanied by the display on the monitor of the table of values for the variable parameters and LOF. The results of WLACS optimization in Fig. 3, 4 confirm that at the final search point all the conditions of the optimization problem are met and the optimal LOF value is achieved.

The optimization of WLACS speed has been performed. The optimal process of changing the level without oscillations at a maximum level deviation of 3.51 cm and with a control time of 147 s is shown in Fig. 5. The water level in SG changed by 23.76% of the maximum permissible value, which satisfies the requirements for the operation of SG. These results of WLACS optimization show that the use of IT allows one to significantly increase the speed of the control process compared to the experimental process, also shown in Fig. 5.

The reliability of our results regarding the optimization of WLACS has been confirmed by successfully solved similar problems for other ACSs at the NPP power unit using various optimization methods [15, 17, 18].

It should be noted that the problem of optimizing the WLACS of an NPP steam generator based on a nonlinear model is not described in available sources of information. Most papers deal only with simulation modeling of the processes of regulating the water level in a steam generator [1–6]. Mathematical models of water level ACSs in a steam generator are given in [2, 3]. Optimization of WLACS performance is considered even less often because of the complexity of such a problem. Thus, for setting the parameters of a water level controller in a steam generator, the Nelder-Mead method was used only with an indirect integral quality indicator [8].

It should be noted that our research is limited to the use of a nonlinear WLACS model when the load is dropped from the nominal SG mode by 20%; other SG modes and the load drop values were not studied. When modeling WLACS, only the PI controller was considered, the influence of changes in SG parameters and random disturbances on the SG control process was not taken into account. The ACS for SG performance was also not studied.

To solve complex identification and optimization problems that require significant computing resources, the ability to memorize the results of the optimization process and then continue it was implemented. All this justifies the high reliability and accuracy of our IT, which determines its technical advantages over other known IT optimization of complex dynamic systems.

The devised IT for optimizing the speed of WLACS with the identification of SG parameters could be easily adapted to solve many other tasks. One may use other experimental processes in SG, other values of initial parameters, different sets and restrictions of variable parameters for identification and optimization problems.

The disadvantage of our study is that the identification of parameters in the mathematical model of a steam generator was performed on a limited set of experimental data because of the complexity of conducting experimental studies at an NPP. Availability of other full-scale studies on the NPP steam generator would make it possible to improve the adequacy of the model.

This study in the future aims to increase the accuracy of mathematical models by switching to nonlinear models with distributed parameters, using new types of controllers, and expanding the set of requirements for the quality of control process. This requires the use of high-order nonlinear mathematical models taking into account various uncertainties, new effective numerical methods for solving high-order nonlinear rigid SDEs, as well as reliable optimization methods.

7. Conclusions

1. An algorithm for optimizing the speed of operation for the water level control system in a steam generator based on the identification of parameters of nonlinear models has been developed. Our algorithm includes the formation of nonlinear models of SG and WLACS, models of identification and optimization problems, integration and optimization methods. The special feature of the developed algorithm for optimizing the automatic control system of a steam generator is that it uses a level objective function. This function, as a single mathematical object, includes all information about the conditional optimization problem. This simplifies algorithms and software for solving optimization problems related to complex control systems.

2. Computational experiments were conducted to identify 41 parameters for the nonlinear models of a water level control system in the PGV-1000 steam generator at an Ukrainian NPP. Optimization of the level objective function of identification was performed by sequential application of modified genetic algorithms, modified Hook-Jeeves and Nelder-Mead methods from the module of IT optimization methods. As a result of the identification of the nonlinear model parameters, the relative value of the mean square deviation in the model processes from the experimental processes was obtained as 0.43% instead of 0.93% when using the linear model. These data indicate a significant increase in the accuracy of the nonlinear model of SG compared to the linear model.

3. Computational experiments were performed to optimize the automatic water level control system in a steam generator based on the level objective function and the identified nonlinear model of the control system in the form of a system of differential equations. The process of optimizing the level controller parameters is clearly represented by three-dimensional plots of the level objective function. The plots of the level objective function reflect the division of space of variable parameters into two regions of levels with and without oscillations, as well as the penalty function of the oscillation range and the objective function of control time as an indicator of speed. The level objective function is not smooth; therefore, its optimization is possible only by direct search methods modified using the operation of comparing the values of this function. The modified Nelder-Mead method allowed us to solve the problem of optimizing the speed of the automatic water level control system in a steam generator with high accuracy, which was confirmed by the plot of the process that optimizes parameters for the proportional-integral controller.

4. The modified Nelder-Mead method for optimizing the level objective function allowed us to solve the problem of optimizing the speed of an automatic water level control system in a steam generator with a PI controller. The minimum value of control time was obtained, 147 s, when the load was unloaded by 20%. The practical significance of these results is that the feasibility of using information technology to optimize the automatic water level control system in the steam generator based on the identification of nonlinear models was experimentally substantiated. Optimization of the automatic control system in a steam generator improved the control process: the maximum deviation of the water level in the steam generator decreased and level fluctuations disappeared. The time of computational experiments to optimize the speed of the control system did not exceed one minute. All this shows that the considered information technology for optimizing the performance of a water level control system in a steam generator could indeed be widely used in the practice of calculating optimal control systems.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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