Development of automatic control system: simulation, optimization and analysis of stability

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Abstract. The issues of creating an automatic control system (ACS) as part of the software and hardware complex (SHC) designed to control the technological equipment of the turbine compartment of a nuclear power plant are considered. Multicriteria optimization was carried out using ACS simulation and an optimization method based on a genetic algorithm implemented by the MATLAB / Simulink / Global Optimization Toolbox. The approximation of SHC relay-pulse controllers, which are used in control loops, by linear regulators, is carried out. Based on this, an analysis of the system stability was performed. Resistance margins are determined taking into account the influence of signal discretization in control loops. The studies showed that the optimized ACS has sufficient stability margins and provides the accuracy of maintaining the object parameters in the normal operation of the power unit.

1. Introduction
The article presents the results of simulation, optimization of parameters and stability analysis of the automatic control system (ACS), which is part of the software and hardware complex (PTC) for controlling the equipment of the powerhouse of power units of Kola nuclear power plant (NPP). Currently, modernization and replacement of equipment used to control the technological processes of the turbine compartment of power units in order to increase the reliability of operation. During the upgrade, the existing electronic units were replaced with modern microprocessor controllers developed at Avtomatika-E LLC (Omsk, Russia) [1, 2]. Optimization and model studies were performed for the level controllers of industrial reheat units, a feed-deaerator unit, low and high pressure regeneration, and a condensate-vacuum system, taking into account the real characteristics of the equipment of the turbine unit [3].

It should be emphasized that when developing and optimizing the system, it is necessary to take into account the requirements due to the characteristics of the control objects. These requirements are associated with the static and dynamic properties of control systems [3–5]. Particularly important is the accuracy of control, which determines the errors that occur in various modes of the system. In addition, criteria are often applied based on minimizing the time of the transition process and energy consumption for control [1, 2, 6–9]. Also, during development, it is necessary to take into account the requirements associated with the stability of the system to the influence of external influences [4, 10, and 11]. As a result of the study, we received an optimally tuned system, which at the same time has sufficient stability margins and provides the required accuracy of object control in normal operation.

2. The problem statement. Initial data for development
The task of the controllers of the designed system is to automatically control the liquid level in the tanks, such control loops are typical control objects for thermal automation [1–5]. The level controllers
that are part of the PTC form the control actions on the electric actuating mechanisms (AMs) of the control valves (CVs). At the same time, the controllers implement:

- maintaining the water level setting with the required accuracy (see table 1);
- pulse control according to the proportional (P) control law together with the actuator and the position sensor of the actuator (with tight feedback on the position of the control valve).

The list of some of the main (typical) controllers and the characteristics of the level control loops for a turbine unit are given in table 1.

Table 1. List of level controllers.

| Controller name | Name of control valve | Setpoint and accuracy of maintenance |
|-----------------|-----------------------|---------------------------------------|
| Condenser level controller | Condenser level control valve | 750 ± 50 mm |
| Controller of the level in LPH-2 | Drain pump control valve for the low pressure heater LPH-2 | 900 ± 50 mm |
| Controller of the level in LPH-3 | Drain pump control valve for the low pressure heater LPH-3 | 900 ± 50 mm |
| Controller of the level in HPH-6 | Drain pump control valve for the high pressure heater HPH-6 | 400 ± 50 mm |
| Controller of the level in HPH-7 | Drain pump control valve for the high pressure heater HPH-7 | 350 ± 50 mm |
| Controller of the level in HPH-8 | Drain pump control valve for the high pressure heater HPH-8 | 350 ± 50 mm |
| Controller of the level in the condensate collector of the 1st stage of the separator with the steam superheater | Control valve on the condensate drain line from the superheater of the 1st stage of the separator with the steam superheater | 300 ± 50 mm |
| Controller of the level in the deaerator 1D-6 | Control valve on the supply line of chemically desalinated water to the turbine condenser | 2500 ± 100 mm |
| Controller of the level in the tank of technical water | Control valve on the inlet to the tank of technical water reserve | 1600 ± 100 mm |

Table 2 shows the control object parameters used in the calculation of the parameters of the level control loop. The level setpoint values for all controllers were set as a percentage of the maximum value of the variation range of the controlled parameter ($H_{\text{max}}$).

Table 2. Control object parameters (generalized).

| Parameter name | Designation and dimension | Value |
|----------------|--------------------------|-------|
| Level setpoint | $H_{\text{set}}$, % $H_{\text{max}}$ | from 30 to 50 |
| Control valve opening time | $T_{\text{am}}$, s | 25 |
| Object transfer coefficient | $K_{\alpha}$, % /% opening | 0.01 |
| Object time constant | $T_{o}$, s | from 30 to 40 |

Relatively high requirements are imposed on the accuracy of level control; in addition, it is desirable for us to have the lowest possible control costs and the least number of actuations of the control valve.
actuator. In this regard, we calculate the criteria \( F_1(X) = \int_0^T e^2(t)dt \) and \( F_2(X) = \int_0^T u^2(t)dt \). The first criterion characterizes the magnitude and duration of the existence of a control error \( e(t) \), and the second criterion characterizes the costs of control \( u(t) \). Time \( T \) is taken so that the transients in the system are completed. Also, during this time \( T \), the number of pulses \( n \) generated by the controller (which corresponds to the number of AM actuations) is considered: \( F_3(X) = n \).

As our previous experience in the design of control systems shows [4, 6], the minimum values of particular quality criteria \( F_i(X), i = 1, 3 \) are achieved with various parameters of the system. This fact indicates the need to achieve a compromise between the accepted criteria for optimization.

3. Theory.

Simultaneous minimization of the criteria \( F_i(X), i = 1, 3 \) corresponds to the construction of the Pareto-optimal solutions set \( P_\epsilon(X) \), that is, the sets of such feasible solutions that cannot be improved (i.e., reduced) by any of the available criteria without deterioration (increase) in some other criterion [4].

3.1. Optimization of level controller parameters

To solve the problem of multi-criteria optimization of the level ACS, an approach is used, which was proposed and tested by the authors for optimization of traditional relay-pulse control systems [4, 6]. This approach is implemented in three stages.

The first stage. From the adopted quality indicators \( F_i(X), i = 1, 3 \), the main particular criteria \( F_1(X) \) and \( F_3(X) \) are selected, which characterize the control accuracy and the costs of level control.

The second stage. The optimization problem is considered as two-criteria. For the main criteria \( F_1(X) \) and \( F_3(X) \), a set of Pareto-optimal solutions \( P_\epsilon(X) \) is constructed. Since the obtained set of solutions is not yet the final version of the parameters (it is necessary to obtain not several, but one preferred solution), it is necessary to use the additional criterion \( F_2(X) \).

The third stage. The minimum value of the criterion \( F_2(X) \) is found among the set of Pareto solutions obtained according to the criteria \( F_1(X) \) and \( F_3(X) \). Thus, the final solution was obtained - the vector of optimal parameters of the control system.

We have implemented the described approach using the Pareto approximation method based on the use of the genetic algorithm (GA). The genetic algorithm is a method for finding optimal solutions based on copying the mechanisms of biological natural selection and genetic inheritance [12, 13]. The advantage of GA over traditional optimization methods is that this algorithm searches for a solution based on many points (population). The main operations of genetic algorithms in constructing the Pareto set are the crossover operation of the fittest individuals, as well as the mutation operation (allowing individuals with new properties to be obtained). In addition, specific operations for the task of constructing a Pareto set are calculating the suitability of an individual, as well as selecting individuals for convergence to the Pareto front.

3.2. Simulation model of the control system

Using MATLAB / Simulink software tools [14], we developed the simulation model of the control system (Figure 1). This system model includes the controller model, the model of an actuator with a control valve and the technological control object model.

It should be noted that all of our controllers use the traditional control method used in level control systems when a constant speed AM is used. The controller implements a single-pulse control system: the signals of the measured water level (pulse by level) are fed to its input, as well as a signal by the position of the control valve, which forms local feedback. The error signal at the input to the level controller is calculated by weighted summation of the setpoint, the current level value, and also the feedback signal for the control valve position. In addition, due to the fact that the controller with feedback on the position of the RC has a static error, a special signal is input to its input, which
corrects the setting to eliminate this error. The output signals from the controller are pulses to the actuator to open or close the control valve. The duration of the generated pulses is associated with a proportional-differential (PD) dependence with a change in the controller input signal (the control error), and, together with a constant speed actuator, a proportional control law is implemented. In addition, the model has a damping unit for the signal of the measured level.

![Diagram of the level control system](image1)

**Figure 1.** The simulation model of the level control system.

The valve actuator is represented by amplifying and integrating units. The gain takes into account the valve opening time $T_{am} = 25$ s. The valve speed signal is sent to the integrator, limiting it in the range from 0 to 100% of valve opening. In the model of the control object, a water flow signal is generated: the valve position value is multiplied by the gain coefficient $k_w = 0.89 \text{ kg/s/\%}$. This coefficient value is taken to provide a material balance of water flow by inflow and outflow from the reservoir. In this case, the valve should move in the working range from 20% to 60% of the valve opening.

Let us consider separately the control object subsystem, which is designed to simulate the control channel "water flow from the control valve – changing the water level" (Figure 2).

![Diagram of the control channel](image2)

**Figure 2.** The model of the control channel "water flow from the CV – changing the water level".

This subsystem has two inputs: water flow from the control valve and perturbation parameter for generating disturbances (water flow at the inflow or drain, depending on the type of control object). The output of the subsystem is the water level, which is an integral of the material balance of water flow at the inflow and outflow from the tank. In addition, random level pulsations are taken into account in this model. These disturbances are realized by the Shaping Filter, the output of which is further summed with the output of the integrator. At the same time, an input normally distributed white noise is generated using the Band-Limited White Noise unit.

The parameters of the controller that need to be determined are: gain $k_p$, integration time constant $T_i$, and feedback coefficient $k_g$ (this is the main parameter that determines the quality of control). Units
that contain the specified parameters are highlighted in shadow in Figure 1. To determine the optimal values of these parameters, the model calculates the integral indicators of control quality.

We need to perform optimization of the level ACS, that is, find such values of the parameters $k_p$, $T_i$, $k_g$ that minimize the adopted indicators $F_i(X)$, $i = 1, 3$ to ensure speed, lack of overshoot and reduce the number of AM operations.

4. Model studies of the control system

To construct a set of Pareto solutions (for multiple simulations of the ACS level), we used the created m-files (MATLAB scripts) that make calls to the Simulink model (see Figure 1), set the necessary options and control the optimization. The search for the set of Pareto solutions was carried out by the `gamultiobj` procedure [15].

To obtain results, 5 to 20 generations of GA were required. Due to the fact that during the optimization of the system a search was carried out for parameters delivering a minimum of the accepted criteria, the parameter vector $X = (k_p, T_i, k_g)$ was adopted as an “individual”.

In the simulation, the number of individuals in the population of the genetic algorithm was set in the range from 50 to 80. Due to the fact that the initial population was formed randomly, several implementations of the calculations were performed and the best solutions were chosen.

As a result of the calculations (in most implementations), it was found that the minimum of criterion $F_3(X)$ is very close to the minimum point of criterion $F_1(X)$.

Figure 3 shows the graphs of transients occurring during level control (disturbance by setpoint). The processes while minimizing the criteria $F_1(X)$ and $F_3(X)$ are shown in Figures 3a – 3c, respectively.

![Figure 3. Transients during optimization of ACS.](image)

In the graphs, the dashed curve corresponds to the water level, the dash-dot curve corresponds to the position of the valve, and the continuous line corresponds to the pulse output of the controller.

The graphs of transient processes of the water level on an enlarged scale for all three cases are summarized in Figure 3d (curve 1 – at $F_1 = \text{min}$; 2 – at $F_2 = \text{min}$; 3 – at $F_3 = \text{min}$; 4 - set point).
As can be seen, transients in all cases under consideration are characterized by approximately the same number of controller operations caused by random pulsations of the controlled parameter. The transition process with a minimum criterion $F_2(X)$ is delayed in time (Figure 3b).

It should be noted that a system with parameters corresponding to the minimum of criterion $F_3(X)$ (the number of AM operations, Figure 3c) has dynamic characteristics approximately the same as when minimizing the criterion $F_1(X)$. It can be seen that in Figure 3d, curves 1 and 3 are close. For these cases, transients are characterized by good quality: high speed, no overshoot, and also a small number of controller operations.

Due to the fact that the feedback determines the overall gain of the system, the feedback coefficient $k_g$ is the most significant parameter for optimization. Therefore, its values varied in a narrower range than the values of the gain coefficient $k_p$ and the integration time constant $T_i$, which weaker affect the control accuracy. The values of the system parameters during optimization were selected from the accepted ranges: $k_p \in [0.1; 1]$, $T_i \in [10; 40]$, $k_g \in [0.1; 10]$. As a result of the study, it was found that minimizing the criterion $F_1(X) = \int_0^T \epsilon^2(t) dt$ allows you to get the required quality of the ACS.

Figure 4 shows the dependence of this functional on the main parameter of the ACS, which is the feedback coefficient $k_g$, and transients are given while minimizing this criterion.

![Figure 4](image-url)

**Figure 4.** The dependence of the criterion $F_1$ on $k_g$ and transients while minimizing $F_1$.

The parameters of the level controller obtained during optimization, taken as initial data for the analysis of the stability of the control loop, are also presented in the figure.

5. **Stability analysis of level controllers**

Based on the developed mathematical model of the level ACS and optimization results, an analysis of the stability of the control loop is performed. The following tasks were solved:
- approximation of the relay-pulse controller by a linear controller;
- transformations of the structural diagram of the system with an approximating linear controller have been performed in order to obtain equivalent transfer functions along the channel of the setting action;
- logarithmic frequency characteristics (Bode diagrams) with stability margins are constructed.
For stability analysis, we performed the approximation of a pulse-relay controller by a linear controller. Due to the fact that the relay-pulse controller in the main (sliding) mode of its operation obeys the linear control law, the functional relationship between the input signal of the controller and the actuator position is described by the transfer function in accordance with the following expression:

\[ W(s) = k_s \left( 1 + \frac{1}{T_s} \right) . \]

The gain \( k_s \) of the approximating linear PI-controller and the coefficient \( k_p \) of the equivalent initial pulse-relay controller are related by the dependence \( k_s = k_p T_1 100\% / T_{an} \).

We carried out the determination of the transfer function of the level controller along the channel of the setting action. To analyze the stability of the level control loop with a linear PI-controller, we used the model circuit (Figure 5), obtained from the initial system model circuit (Figure 1) taking into account the linear approximation of the controller.

![Figure 5](image)

**Figure 5.** Level control loop with equivalent linear controller.

To obtain the transfer function of the level controller, the circuit shown in Figure 5 was presented in the form shown in Figure 6a. The transfer functions that make up the system in Figure 6a are as follows:

\[ W_1(s) = k_s \left( \frac{T_1 s + 1}{T_1 s} \right), \quad W_2(s) = k_e, \quad W_3(s) = \frac{k_a k_0}{(T_1 s + 1)s} . \]  

(1)

Figures 6b and 6c show a sequence of equivalent transformations of the level controller circuit to its simplest form:

first, the transfer function \( W_4(s) \) is obtained, consisting of the block \( W_1(s) \) covered by negative feedback with the block \( W_2(s) \) (Figure 6b): \( W_4(s) = \frac{W_1(s)}{1 + W_1(s) W_2(s)} ; \)

then, finally, the transfer function of the controller via the setpoint channel is obtained

\[ W_5(s) = \frac{W_1(s) W_3(s)}{1 + W_1(s) W_4(s)} = \frac{W_1(s) W_3(s)}{1 + W_1(s) W_2(s) + W_1(s) W_3(s)} . \]  

(2)

![Figure 6](image)

**Figure 6.** Sequence of equivalent transformations of the level controller circuit.
After taking into account the transfer functions (1) in the obtained expression (2) and substituting the accepted numerical values \( k_s = 24\% \) opening \%/; \( T_i = 30 \text{ s} \); \( k_g = 1.2\% \) /%/ opening; \( T_f = 3 \text{ s} \), we got the closed loop transfer function for the level controller: 
\[
W_g(s) = \frac{120s^2 + 44s + 1.33}{289s^3 + 1060s^2 + 71.25s + 1.33}.
\]
Analysis of the influence of signal discretization on the stability of the control loop was carried out by converting the transfer function of a continuous control system into a discrete system. It was taken into account that the sampling period during the controller operation is, on average, \( t_0 = 0.2 \text{ s} \).

Using MATLAB, the logarithmic frequency characteristics (Bode diagrams) of an open-loop system are constructed. To analyze the relative stability of the system, we calculated the stability reserves of the system (amplitude margin \( G_m \) and phase margin \( P_m \)). It was taken into account that a system with an insufficient phase stability margin has significantly pronounced oscillatory transients, which is undesirable from the point of view of ensuring its technological operability.

Figure 7 shows the result of determining the stability margins for a system with the recommended parameters \( k_s=24\% \) opening \%/; \( T_i = 30 \text{ s} \); \( k_g = 1.2\% \) /%/ opening; \( T_f = 3 \text{ s} \) and with a 10-fold decrease in the feedback coefficient \( k_g = 0.12\% \) /% opening). In both cases, for the continuous system (continuous line), the phase-frequency characteristic, asymptotically tending to a value of minus 180°, does not reach it, therefore, the system margin of stability in amplitude is not limited \((G_m = \text{inf})\).

![Figure 7](image_url)

**Figure 7.** Determination of stability reserves of the level controller for a continuous (solid line) and discrete (dashed line) control system: at \( k_s = 1.2\% \) /%/ opening (a); at \( k_g = 0.12\% \) /%/ opening (b).

At the frequency at which the amplitude-frequency characteristic module has a value of 0 dB, the system phase stability margin is determined from the available phase shift. It amounted to \( P_m = 180° \) for the recommended value of the feedback coefficient \( k_g = 1.2\% \) /%/ opening) and \( P_m = 108.5° \) with a decrease in the feedback coefficient by 10 times, i.e. at \( k_g = 0.12\% \) /%/ opening. For a discrete system, in the case of a 10-fold decrease in the feedback coefficient \( k_g \), the system stability margins in amplitude and phase decreased \((G_m = 30.9; P_m = 105.9°)\), remaining in the range accepted in practice.

6. The discussion of the results
It should be noted that in all cases the phase stability margin of the system decreased if it was a weakening of feedback, but it remained sufficient. In practice, it is accepted that the phase margin should be in the range from 30° to 60° in order to ensure the technological operability of the system. However, it should be borne in mind that the calculations were performed for linearized systems; in real systems, due to the presence of nonlinearities with a significant decrease in the feedback coefficient, self-oscillating modes can occur. Therefore, the recommended values should be taken as the initial values of the tuning parameters.
7. Conclusion
The article discusses the control system for the equipment of the turbine compartment of power units of the Kola NPP. The results of optimization and stability analysis of control loops are presented.

- We developed the simulation model of the control loop, using which we optimized the parameters of the controllers and, in addition, received transient graphs.
- Multicriteria optimization of control loops was performed using simulation modeling and optimization software tools based on genetic algorithm.
- We approximated the relay-pulse controllers used in the control loops with linear controllers, and based on this we performed an analysis of the stability of the system. The stability margins were determined taking into account the influence of discretization in the control loops.

The performed studies allow us to conclude that the developed systems are stable when we accept the parameters of the controllers selected from the recommended areas. At the same time, the controlled parameters are maintained at the required level and there are sufficient stability margins in the normal operation of control loops.

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