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MODELING AND INVESTIGATION OF THE OPERATION OF THE TEMPERATURE DIFFERENCE CONTROLLER IN THE MODE OF SCHEDULED COOLING IN THE REACTOR CONTROL SYSTEM

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Annotation:
This research work is dedicated to modeling and investigating the operation of the temperature difference regulator during planned cooling in the control system of the VVER-1000 reactor based on the software and technical complex of technological software and technical means. The mathematical model and transfer function of the control object, as well as coding algorithms for the executive mechanism, control object, and regulator, were developed in the work. The influence of the regulator on the quality of regulation was investigated.

Keywords: VVER-1000, APCS, MWBRIDGE.

I. Introduction

"In the modern world, management of nuclear reactors is a complex and responsible process.

Automated control systems, such as the ones used in nuclear power plants (NPP), guarantee the safe operation of VVER power units. Nuclear power plants perform a socio-economic function by producing energy efficiently and safely, and by performing control and safety functions. The automated control system (ACS) of an NPP is divided into two main components: one for normal operation and the other for ensuring safety and protecting the reactor in the event of an accident [1].

For example, the normal operation monitoring and control system (NCS NE) in the reactor compartment provides control and management of 30 or more systems [2].

In nuclear power plants that generate electricity and/or heat from nuclear fission reactions, dynamic simulation is a prerequisite for control system design. This technique describes the dynamic characteristics of the facility by using a set of differential, difference, and algebraic equations that are derived from physical rules or operational data. The control system keeps deviations of process variables from their set values within satisfactory limits, while simultaneously reducing the risk of reactor shutdown [3].

II. Dynamic parameters of the control system (CS) and the actuator.

A characteristic feature of modeling the operation of a pressure compensator is that in various modes, both steam and water can be in either an equilibrium or non-equilibrium state. In the steady state, steam and water are in equilibrium; that is, the temperature and pressure in these media are the same and correspond to their values on the saturation line [4].

The heat balance equation for the Compensator of Pressure(CP):

$$Q_{tot} = Q_{heater} - Q_{injection} - \Delta Q_D \tag{1}$$

Where Q is the heat release rate, kJ/s (for heater and injection), ΔQ_D – change in the rate of heat release.

$$(V_W C_W \rho_W + V_s C_s \rho_s) \frac{dt_{CP}}{d\tau} = Q_{heater} - G_{inj}\rho_{ct}t_{ct} - G_t \rho_W C_W (t_{CP} - t_{ht}) \tag{2}$$

$$(V_W C_W \rho_W + V_s C_s \rho_s) \frac{d(t_{CP} - t_{ht})}{d\tau} = Q_{heater} - G_{inj}\rho_{ct}t_{ct} - G_t \rho_W C_W (t_{CP} - t_{ht}) \tag{3}$$

Flow rate of the heat transfer agent entering the Pressure Compensator from the first circuit or leaving the Pressure Compensator:

$$G_{TP} = k \cdot (V_W - V_{WCP}) \cdot \frac{dT_{average}}{dt} + k \cdot V_{WCP} \cdot \frac{dT_{CP}}{dt} \tag{4}$$

where k is the coefficient of thermal expansion of water, $T_{average}$– average temperature of the heat transfer fluid in the primary circuit, ˚C; – V_{WCP} – This is the volume of water in the pressure compensator, $м^3$.

$$\Delta Q_{heater} = 0 \;=>\; \frac{dQ_{heater}}{d\tau} = 0 \;=>\; Q_{heater} = \text{const.}$$

From equation (3) we find:

$$(V_W C_W \rho_W + V_s C_s \rho_s) \frac{d(t_{CP} - t_{ht})}{d\tau} = - G_{inj}\rho_{ct}t_{ct} - G_t \rho_W C_W (t_{CP} - t_{ht})$$

Then:

$$\frac{d}{d\tau} = s; \quad t_{CP} - t_{ht} = \Delta t; \quad V_W C_W \rho_W + V_s C_s \rho_s = A; \; \rho_{ct}t_{ct} = B; \qquad G_t \rho_W C_W = C \tag{5}$$

Substituting (5) into equation (4) we get:

$$A \cdot s\Delta t = B \cdot G_{inj} - C\Delta t \tag{6}$$

$$(A \cdot s + C)\, \Delta t = B \cdot G_{inj} \tag{7}$$

$$\frac{A}{C} = T; \quad \frac{B}{C} = K$$

we get:

$$(T s + 1)\, \Delta t = K\, G_{inj} \tag{8}$$

Thus, the transfer function of the control object:

$$W(s) = \frac{\Delta t}{G_{inj}} = \frac{K}{Ts+1} = \frac{0.5}{255.3s+1} \tag{9}$$

Transfer function of a control valve without inertia:

$$W(s) = К_{AM} \tag{10}$$

The input signals are the valve opening percentage (in %), and the output signals are represented by the flow rate of the working fluid (in $м^3/с$).

$$К_{AM} = \frac{\Delta Q}{100\%} \left[\frac{кг/s}{\%}\right] = К_V \sqrt{\Delta P \cdot \frac{1000}{\rho}} = 6.99 \, \frac{кг/s}{\%}. \tag{11}$$

Where ρ is the density of the liquid (for water 965.78 $\frac{кг}{м^3}$), ΔP – Pressure drop (7 MPa ≈ 70 bar), $К_V$ = 82.1 кг/s, ΔP =70 bar, P = 965.78 $\frac{кг}{м^3}$.

III. Real-time investigation of control system model

MWBridge provides the MikBasik programming language that enables easy access to real-time adjustable parameters and the previous value of the controlled parameter. This feature allows encoding a mathematical model of the controlled object with the transport equation (or differential equation) that represents the controlled object (CO) [5].

Transfer function $W(s) \frac{L[X_{out}(t)]}{L[X_{int}(t)]}$ with zero initial conditions

$$W(s) = \frac{K}{TS+1} = \frac{X_{out}(S)}{X_{int}(S)}; \qquad (12)$$

$$K \cdot X_{int}(S) = X_{out}(S) \cdot (TS + 1); \qquad (13)$$

$$T \cdot S \cdot X_{out}(S) + X_{out}(S) = K \cdot X_{int}(S); \qquad (14)$$

At: $S \to \frac{d}{dt}$;

$$T\frac{d}{dt}X_{out}(t) + X_{out}(t) = K \cdot X_{inp}(t); \; X^{I} = \lim_{\Delta t \to 0} \frac{X_{out}(t+\Delta t) - X_{out}(t)}{\Delta t};$$

$$T\left(\frac{X_{out}(t+\Delta t) - X_{out}(t)}{\Delta t}\right) + X_{out}(t) = K \cdot X_{int}(t); \qquad (15)$$

$$X_{out}(t + \Delta t) - X_{out}(t) = \frac{\Delta t}{T}(K \cdot X_{int}(t) - X_{out}) \qquad (16)$$

$$X_{out}(t + \Delta t) = \frac{\Delta t}{T}(K \cdot X_{int}(t) - X_{out}) + X_{out}(t). \qquad (17)$$

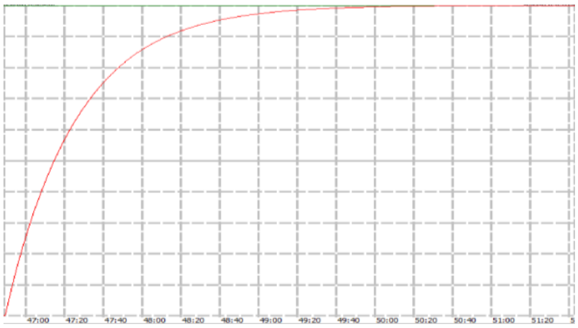

Figure 1. a) Step response with K_P =0.5

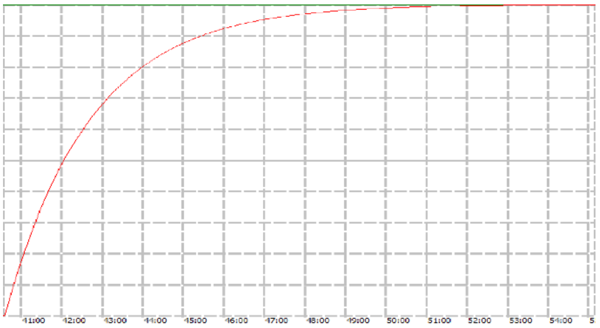

Figure 1. b) Step response with T_I = 0,001

The given figure shows the most optimal proportional and integral controller settings among the obtained results. The x-axis shows the time at which the system reaches stability. In figure 1a), the temperature difference smoothly approaches the steady-state value without any overshoots and oscillations in the step response. In figure 1b), the step response not only provides good speed of response but also high dynamic and static accuracy of regulation. The second figure shows the system's response to external noise.

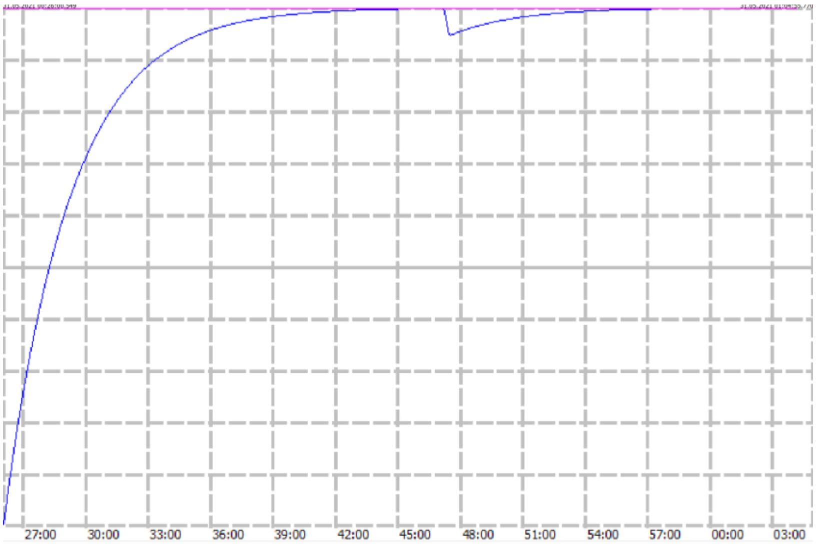

Figure 2. System response to external noise.

In control systems, an important function of feedback is partial compensation of disturbance effects. A disturbance is an unwanted signal that affects the quality of the system regulation. As seen in the figure, after some time the system recovers stability.

IV. Conclusions

This paper has addressed the issues of controlling a reactor in a planned cooling mode. Mathematical models and transfer functions of the control object, as well as coding algorithms for the executive mechanism, control object, and regulator, were developed. The influence of the regulator on the temperature regulation quality was investigated.

The results of the study have shown that the developed temperature difference controller effectively manages the temperature during planned reactor cooling and maintains it within the desired limits. This is an important step in ensuring the safety of the reactor operation. To improve the usability of the temperature difference controller model in the reactor control system, the development of a human-machine interface is planned. This interface will provide convenient and intuitive interaction between the operator and the model, allowing them to make decisions based on data analysis obtained from the simulation. Such an approach will simplify the decision-making process and increase the efficiency of the reactor control system.

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