IMITATIVE MODELING AUTOMATIC SYSTEM
CONTROL OF STEAM PRESSURE IN THE MAIN STEAM
COLLECTOR WITH THE INFLUENCE ON THE MAIN
SERVOMOTOR STEAM TURBINE

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Abstract. The research and setting results of steam pressure in the main steam collector "Do it-
sel" automatic control system (ACS) with high-speed feedback on steam pressure in the tur-
bine regulating stage are presented. The ACS setup is performed on the simulation model of
the controlled object developed for this purpose with load-dependent static and dynamic char-
acteristics and a non-linear control algorithm with pulse control of the turbine main servomo-
tor. A method for tuning nonlinear ACS with a numerical algorithm for multiparametric opti-
mization and a procedure for separate dynamic adjustment of control devices in a two-loop
ACS are proposed and implemented. It is shown that the nonlinear ACS adjusted with the pro-
posed method with the regulators constant parameters ensures reliable and high-quality oper a-
tion without the occurrence of oscillations in the transient processes the operating range of the
turbine loads.

1. Introduction.
The complex energy objects’ automatic control systems analysis operation in various modes of opera-
tion by the method of mathematical modeling is widely used in solving the optimizing the structure
problem and control systems parameters. However, when using this method, it is necessary to have
sufficiently accurate mathematical models of a controlled object and take into account the influence
of the automation tools nonlinearities used (regulators, measuring converters, actuators, etc.). The aim
of the work is to create and study a numerical simulation model of a vapor pressure in the main steam
collector (MSC) two-loop ASC with speed feedback on the vapor pressure in the regulating turbine
step.

2. The control object technological scheme.
The working steam from the steam generators of the power unit is supplied to the MSC. Then the
steam flows to the turbine through control valves, which are controlled by one main servomotor
(MSM) through the electrical part of the automatic regulation and turbines protection (EP SAR P) electro-hydraulic system.

To stabilize the mode of the steam generator are the regulators "Do itself" operation, which maintain the vapor pressure in the MSC by exposure to the MS. To improve the quality of vapor pressure stabilization in the MSC the regulating scheme, high-speed feedback is provided on the vapor pressure in the regulating turbine stage.

3. Mathematical model of changing the vapor pressure in front of the turbine.

The structure of the control object includes steam generators and steam pipelines with regulating and shut-off valves installed on them. The control area from the control action on the turbine (the change in the position of the MS output mechanism) to the place of pressure measurement the MSC in the information plan is a certain capacity, in which, under steady-state conditions, the pressure is the same at all points in the volume. However, in the process of steam transport from the MSC to the turbine, steam pressure gradients appear at the points of the steam pipeline. At the same time, capacitive and transport lags appear, which should be taken into account with the ACS settings.

A detailed study of the steam transport process requires the use of a partial differential equations system for the energy balance, mass and the vapor pressure momentum and the wave theory attraction for their solution [1]. This task is time-consuming. Therefore, in the work for the assigned task, an imitation model of minimal complexity was developed with the possibility of its operative refinement according to the test data during the commissioning process.

It is assumed that the transient graphs obtained during commissioning tests will be used to refine the ACS simulation model with the regulator parameters sets. In this case, the program of the numerical multiparametric optimization algorithm [3] will refine the parameters of the control object model, for which the transient processes coincide with the processes obtained during the tests. Then, for new values of the regulating object parameters, new values of the regulator parameters will be found that will meet the set quality requirements of the ACS.

The mathematical description is based on the model of the first order inertial link, which connects the vapor pressure in the MSC with the steam generator thermal state and the steam flow rate of taken out by the turbine [1]. For each specific evaporation intensity (heat load), this linear model allows to estimate the deviations of the vapor pressure before the turbine from the stationary state. On the calculations basis, the model coefficients dependences on the load were obtained [1]. For example, when the load varies from 30% to 100%, the value of the coefficient connecting the pressure deviations in the MSC and the steam flow varies from 0.11 to 0.25 %US/%US, and the calculated value of the basic time constant varies from 19.9 to 15.0 sec.

Taking into account the spatial distribution (the length of the steam pipelines to 80 m), a more complete dynamic mathematical model of the second-order control object with delay is adopted for the task of the steam pressure ASC investigating in the MSC. This model consists of two aperiodic links and a delay link chain with the time constants ratio 1/2 for all operating modes. The aperiodic links model the process of pressure deflection in the MSC and the pressure gradient along the pipelines without the formation of wave effects, and transport delay simulates the physical effects of signal transmission by means of measurement, etc.

The inertia on the leading channel (based on the steam pressure in the turbine regulating stage (RS)) depends on the steam pipelines volume between the valves and the turbine. The length of the steam pipes from the MSM to the regulating stage is small. Therefore, the time constant of this channel is assumed to be ten times smaller than for the main channel and does not depend on the load. Deviations of the transmission factor along the leading channel from load changes are also insignificant. Estimates are obtained from static calculations. Their values vary from 0.222 to 0.248 %US/%US. They are significantly smaller than for the main channel. For this section, a linear model is adopted in the form of an inertial link of the second order with the main time constant 2.5 sec and the ratio of the time constants 1/2 for all operating modes.
In models on the main and auxiliary channels, in order to take into account the phenomenon of spatial distribution in space, the time constants in the second aperiodic links are halved.

4. **Automatic control system.**

The ACS scheme is shown in figure 1.

![Figure 1. The ACS scheme pressure in the MSC "Do itself."](image)

Two information signals are used to form the control action: \( P_{\text{m}} \) is the pressure in the main steam collector; \( P_{\text{PC}} \) - pressure in regulating stages (RS) of turbo-aggregates.

The pulse regulating module unit (PRU) issues a pulses sequence "More" - 0 - "Less", by means of which, through the electrical part devices of the automatic regulation and protection of turbines (EP SARP) electrohydraulic system controls the operation of the MSM and turbine valves. The PRU module and MSM serial connection scheme forms a proportional-integral (PI) control law.

The main controllable value of the circuit is the vapor pressure in the MSC \( P_{\text{ГПК}} \), and the \( P_{\text{PC}} \) variable is used in the high-speed feedback circuit. The Diff module (differentiator) converts the \( P_{\text{PC}} \) signal according to the real differentiation algorithm. In this case, the oscillations of the \( P_{\text{PC}} \) signal are transferred to the input of the PRU module, and in the steady state the signal at the output of the Diff module is zero. The signal from the output of the Diff module is summed with the signal of the \( P_{\text{ГПК}} \) at the input to the PRU module. The PRU module with a pulse output together with the MS implements the PI control algorithm in a two-loop ACS with a differentiator.

In figure 2 the ACS pressure structural scheme in the MSC "Do itself" is shown. The diagram shows transfer functions: \( W_{\text{reg}}(s) \) - a steam pressure regulator in the MSC; \( W_{\text{d}}(s) \) - the differentiator; \( W_{\text{ГПК}}(s) \) - the object through the channel " MSM transfer - vapor pressure in the MSC"; \( W_{\text{PC}}(s) \) - the object through the channel " MSM transfer - vapor pressure in the regulating stage"; \( \lambda(t) \) - the disturbance due to the turbine load ( the steam flow to the turbine \( \text{Gn} \)).
5. **Simulation model.** In figure 3 shows the structural diagram of the ACS simulation model with PTC elements. It is implemented with the help of recurrent expressions, simulating the work of the control scheme functional modules. It consists of: the controller model, the actuator model, which performs the functions of the main servo motor of the turbine, the model of the object dynamics channels, represented by the transfer functions over the external $W_{ГПК}(s)$ and internal $W_{РС}(s)$ channels, and the disturbance input unit $\lambda(t)$ over the control channel.

The model on the channel "MSM rod displacement – the vapor pressure deflection in the MSC" has the form:

$$W_{ГПК}(s) = \frac{k}{(T \cdot s + 1) \cdot (0.5 \cdot T \cdot s + 1)} \cdot \exp(-\tau \cdot s),$$

and on the channel "MS rod displacement - the steam pressure deviation in the regulating stage":

$$W_{РС}(s) = \frac{k_1}{(T_1 \cdot s + 1) \cdot (0.5 \cdot T_1 \cdot s + 1)} \cdot \exp(-\tau_1 \cdot s),$$

The PRU module in the simulation model is implemented by a recurrent expression in the form of a parallel connection of the proportional and differential links and a non-linear element of insensitivity. The BRU module (regulating unit with pulse output) in the controller model realizes the conversion of the input signal according to the PD algorithm (derived from the PI algorithm). At the input of the BRU module there are non-linearities of the "insensitivity zone" type. Taking into account the integrating properties of the executive mechanism, the complex «BRU-SHIM-EM» implements the settlement PI-regulation law. Parameters of the BRU module configuration are: $Kp$ - coefficient of proportionality; $Ti$ is the integration time constant; $\Delta$ - insensitivity zone of the regulator.

The transfer function $W_d(s)$ in the simulation model in figure 3 is realized by the recurrent expression of the real differentiating element. Parameters of its setting are: $kd$ – coefficient of proportionality; $Td$- is the time constant of differentiation.

The SHIM module in the simulation model is implemented in the form of recurrent expressions of the sequential connection of the adder, integrator and relay element with negative feedback. It performs a proportional conversion of the analog signal into a reversed sequence of pulses. The parameter of its setting is the minimum pulse duration $t_{imp}$.

The EM (MSM) model is implemented by recurrent expressions of the integrator and non-linear elements modeling deviations from the linear integration law. In the simulation model of EM, the parameters of real MSM were installed and were not adjusted in the work.
6. Criterion of optimality.
A complex index of the quality of work was used for stepwise perturbation along the channel of the regulating organ when tuning the ACS, namely, the optimal parameters $kp^*$, $Ti^*$, $kd^*$ and $Td^*$ were determined from the condition of minimum sum of the module integral the error of regulation $\int_0^{\tau_{proc}} |y(t)\,dt$ and the number of inclusions of MS $N_{imp}$ (with a weight coefficient "a") in the time interval of the transient process $\tau_{proc}$.

$$F(kp,Ti,kd,Td) = \tau_{proc} \int_0^{\tau_{proc}} y(t)\,dt + a \cdot N_{imp} = \min$$

Time for calculating the indicator $\tau_{proc} = 180$ sec. The disturbance level is assumed equal to $\lambda = 10\%$.

When searching for $kp^*$, $Ti^*$, $kd^*$ and $Td^*$, the following restrictions were taken into account:
- the values of the coefficients should be positive;
- the degree of attenuation of oscillations: $|1-\psi| < 0.005$, that is, the degree of damping $\psi > 0.995$;
- the equality of the values of the linear integral $I_{lin}$ and the module integral $I_{mod}$, which ensures the absence of negative values in the transient processes: $|1-\frac{I_{lin}}{I_{mod}}| < 0.005$.

7. The ACS tuning.
The task of the ACS tuning is different in the following points.
1. The small inertia of the control system, especially the internal circuit, exacerbates the influence of non-linearities of technical means on the operation of the ACS and requires, in addition to the dynamic tuning parameters $kp$, $Ti$, $kd$ and $Td$, to adjust the parameters of the nonlinear elements, the insensitivity zone, and the minimum pulse width $t_{imp}$.
2. Vibrational processes in the ACS are not allowed. The task is complicated by the fact that it is required to find such parameters, in which in transients the oscillations should be absent in the operating range of the turbine load variation.
3. The main servomotor in the circuit is an actuator with a constant speed. It has a sufficiently long time for full running. For this reason, excitation of oscillations is possible in a closed ACS. To eliminate them, a matching of the insensitivity zone $\Delta$, the minimum duration of the impulses $t_{imp}$ and the time of the full course of the EM [2] is required.

The above factors limited the possibilities of classical frequency methods for tuning linear ACS [3] and required the use of advanced technologies and methods for analyzing and optimizing ACS by numerical algorithms.

The optimal values of the regulator and differentiator parameters were determined by the program of a numerical algorithm for multiparameter multiextremal optimization tasks [4]. The program re-
turns the vector of the values of the optimal parameters \( k_p^*, T_i^*, k_d^* \) and \( T_d^* \) and the values of the performance of ACS, integrals, linear \( I_{\text{lin}} \), quadratic \( I_{\text{kв}} \), module \( I_{\text{мод}} \) and the degree of attenuation \( \varphi \).

First fixed parameters of nonlinear elements \( \Delta \) and \( t_{\text{imp}} \) were set and at the same time optimal values of all four parameters for eight block loads from 30% to 100% in 10% steps were found. However, the averaged values of the parameters found did not ensure the elimination of oscillations at all loads of the block operation. Therefore, the task was divided into two stages.

At the first stage, the optimal parameters of the differentiator \( k_d^* \) and \( T_d^* \) were determined by the method of "compensated tuning" of a linear two-loop ACS with a regulator and a differentiator [5]. The technique of "compensated adjustment" of ACS is widely used by practitioners. It was required for us to set up an external ACS loop for two parameters of the PI regulator \( k_p \) and \( T_i \) using a two-dimensional response surface to display the quality index.

The essence of the "compensated tuning" method of ACS consists in converting a two-loop system with a differentiator to a single-loop ACS with an equivalent object that has favorable dynamic properties. In figure 4 shows the block diagram of the transformed system.

![Figure 4. Equivalent scheme of a two-loop ACS](image)

The parameters of the differentiator are found from the condition that the total (equivalent) signal \( y_e(t) \) in dynamics approaches the signal of the leading segment \( z(t) \), that is, it becomes less inertial, has no dips and humps, and in static it is in accordance with the basic inertial section \( y(t) \). In the time domain, this condition is expressed as follows:

\[
y_e(t) = y(t) + z(t) = z(t) \cdot K_y / K_z.
\]

Then the values of the settings of the differentiator \( k_d^* \) and \( T_d^* \) are determined from the solution of the problem of minimizing the integral:

\[
\int_0^\infty \left[ (z(t) \cdot K_y / K_z - (y(t) + z_\text{d}(t))) \right]^2 dt \Rightarrow \min.
\]

The parameters of the differentiator \( W_d(s) \) are found by the program of the numerical optimization algorithm from condition (5). In figure 5a shows the acceleration curves for 10% perturbations in the steam flow rate for a load of 30%; \( K_d* = 0.55, K_d* = 21.3 \text{ s} \); in figure 5 b for a load of 100%: \( K_d* = 1.11\% \), \( T_d* = 15.6 \text{ s} \). From the graphs, the effect of using a differentiator is seen to increase the speed of an equivalent object.

Further, for all eight loads, the optimization program obtained optimal values of the parameters of the PI controller \( K_p^i, T_i^i \), \( i = 1,2,...8 \) with the optimal values of the differentiator parameters found earlier \( K_d^i, T_d^i \), \( i = 1,2,...8 \).

For all loads, the quality of the ACS operation has been tested for compliance with the degree of attenuation \( \psi \). The testing was carried out based on the results of 400 calculations of the transient pro-
cesses in the ACS with the variation of the parameters of the PI controller for 20 points in the vicinity of their optimal values.

Figure 6 shows the three-dimensional images of the response surfaces in fractions of the optimal \( K_p^* \) and \( (K_p / Ti)^* \) values for the degree of attenuation \( \psi \): a) for a load of 30% and b) for a load of 100%. The points "O" on the projections show the coordinates of the optimal values \( K_p^* \) and \( (K_p / Ti)^* \).

From figure 7 it can be seen that at a load of 100% (figure 7, b) a zone with oscillatory processes appears, which violates a specified requirement for the type of control processes. On the simulation model, the problem of fine-tuning the parameters was solved manually by the form of the response surfaces.

It was necessary to weaken the action of the differentiator. This is shown in figure 5, b. Then, for fixed values of the parameters of nonlinear elements, the parameters of the regulator are shifted inside the zone of operation of the ACS without oscillations (\( \psi = 1 \)).

Table 1 shows the refined values of the ACS setup parameters, and figure 7 shows the transients of the variables \( y \) and \( z \) in the external and the internal control loops, as well as the control action \( \psi \), the number of pulses \( q \) in the time interval of the transient process.

![Image](image-url)

**Figure 5.** Transient processes along the main \( y \) and auxiliary \( z \) channels of the control object, the differentiator \( z_d \) and the equivalent object \( y_e \), with step perturbation \( \Delta \mu = 10\% \).

| \( K_p \) | \( Ti \) | \( K_d \) | \( T_d \) | \( \Delta \) | \( t_{imp} \) |
|---|---|---|---|---|---|
| 15.4 | 8.2 | 0.4 | 20 | 0.06 | 0.1 |
Figure 6. Surfaces of responses for the degree of attenuation $\psi$: a) load 30%; $K_d^* = 0.55$; $T_d^* = 21.3$ s; $K_p^* = 9.52$ and $T_i = 4.72$; B) the load is 100%, $K_d^* = 1.11$; $T_d^* = 15.6$ s; $K_p^* = 25.53$ and $T_i = 10.08$.

Figure 7. The processes in the ASC under the perturbation $\Delta \mu = 10\%$: a) and b) are the variables $y$ and $z$; в) and г) - the control action $\mu$ and impulses $q$; а) and в) - load 30%, b) and г) - load 100%.

8. Conclusions

1. An imitation model of the system for automatic control of vapor pressure in the MSC "Do it-self", containing non-linear elements inherent in the technical implementation of the PI control algorithm with a pulse output and a constant speed actuator is developed. The model makes it possible to simplify the adjustment of the current control system.

2. An optimality criterion is proposed that takes into account the specific requirements imposed on the system. As an error measure, the integral modulo the deviation of the controlled variable plus the number of fuel inclusions in the time interval of the transient process is adopted.
3. A two-stage procedure of multiparametric optimization for tuning the system taking into account the nonlinearities is presented.

References
1. Pliutinski V I, Pogorelov V I 1983 *Automatic control and protection of thermal power plants NPP. Textbook for technical schools* Moscow: Energoatomizdat, 296 p.
2. Bochkareva E Iu, Kuzishchin V F 2009 Adjustment of the pulse duration of the regulators with the constant speed actuator. *Electronic journal New in the Russian electric power industry, Inf. Agency «Energopress»*, 9, p 35-47.
3. Rotach V Ya 1985 *Theory of automatic control of heat-and-power processes: Textbook for high schools*. Moscow: Energ. 296 p.
4. Andriushin A V, Sabanin V R, Smirnov N I. 2011 *Management and Innovation in Heat Power Engineering: a tutorial* Publishing house of the MPEI, Moscow. 392 p.
5. Mironov V D 1948 Regulation with a leading impulse, *News of the All-Russia Thermal Engineering Institute*. 8.