The control system simulation technology for optimization and determination of the feasible parameters domain

L A Denisova[1], V A Meshcheryakov[2], R D Karabtsov[1]

[1]Omsk State Technical University, 11, Pr. Mira, Omsk, 644050, Russia
[2]Siberian State Automobile and Highway University (SibADI), 5, Pr. Mira, Omsk, 644080, Russia

e-mail: denisova@asoiu.com, meshcheryakov_va@sibadi.org

Abstract. This paper focuses on the simulation technology for optimization of the automatic control system (ACS) parameters vector to be tuned and to provide a stable operating mode eliminating self-oscillations. A hybrid approach (synthesis of optimal control methods and simulation research) for designing ACS using genetic algorithms is presented, which allows taking into account constraints when searching for the optimal solution. Simulation of the ACS was performed using the software tools MATLAB / Simulink / Global Optimization Toolbox. It is shown that the proposed technology for determining the domain of recommended tuning parameters is effective for computer-aided design of ACS, it allows to significantly improve the quality of control and reduce the time spent on pre-setting developed controllers.

1. Introduction

Complexity of modern production technology processes requires the use of automatic process control systems. The problem of simplifying the controller parameters tuning on real equipment is urgent. Therefore automatic control systems (ACSs) should be designed with computer-aided tools that allow optimization of the control algorithms parameters at the design stage. Ensuring the sustainability of the control system should also be provided at the design procedure.

The article proposes the technology to optimize tuning parameters and determine the feasible parameters domain for the ACS using the example of a steam pressure control channel in a turbine section deaerator of a nuclear power plant unit. Because of the automation object complexity we suggest the technology of model-oriented design. The hybrid approach is based on synthesis of optimal control methods and simulation techniques. It is intended for design process formalization and allows to optimize the ACS and to provide the control efficiency. To solve the design problem, we developed the mathematical models of the control system using the MATLAB software.

2. The problem statement

The analytical methods of an ACS sustainability ensuring and optimal controllers design [1, 2] have theoretical foundation but require assumptions that simplify a model of control system. The typical control object we consider for example (the steam pressure control channel in the turbine section deaerator of a nuclear power plant unit [3, 4]) should be simulated for more control accuracy.

Let's consider the ACS designed to control the pressure and prevent the steam pressure in the deaerator from decreasing. The controller in the ACS generates the control signals for the actuating mechanism (AM) of the control valve (CV) and should provide stable operation and eliminate self-oscillations in the control loop. At the same time, the requirements for limiting the frequency of the mechanism actuation must be met, so that the frequency should not exceed six actuations per minute at a constant load of a power unit (general requirements for controllers of turbine units' technological parameters).

The features of the steam pressure control channel in the deaerator as a control object are as follows. On the one hand, random pulsations of the controlled parameter (steam pressure) are properties

actuating the AM. On the other hand, due to the low capacity of the control valve it is necessary to increase the system gain for effective process control. And this increase may cause the occurrence of self-oscillations, accompanied by frequent reversing actuations of the actuator [4].
Therefore, when setting up the controller (empirically), it is difficult to understand the reason for the frequent actuations of AM in order to eliminate them and to obtain the required quality of control. The proposed approach allows not only to solve this problem (taking into account the parameters constraints), but also to optimize the control process according to an accepted criterion increasing the efficiency of energy production in common.
We have determined the boundaries of the search area for the optimal solution based on the analysis of the system stability. We synthesized pulsed ACS and determined their parameters. At the same time, we took into account the constraints imposed on the search area for feasible parameters that exclude the operation of the system beyond the stability boundaries and the occurrence of self-oscillations. The use of software tools MATLAB / Simulink [5] and MATLAB / Global Optimization Toolbox [6] allowed us to perform simulation and optimization of ACS.

3. Mathematical model of pressure control system

Using MATLAB / Simulink tools, the mathematical model of the ACS for steam pressure in a deaerator was developed (figure 1). This model contains the following subsystems: controller, the control valve with the actuating mechanism and the control object. The error signal at the controller input is obtained as the difference between the setpoint and the object output (pressure value). The damping of the pressure input signal is carried out with the help of an inertial unit.

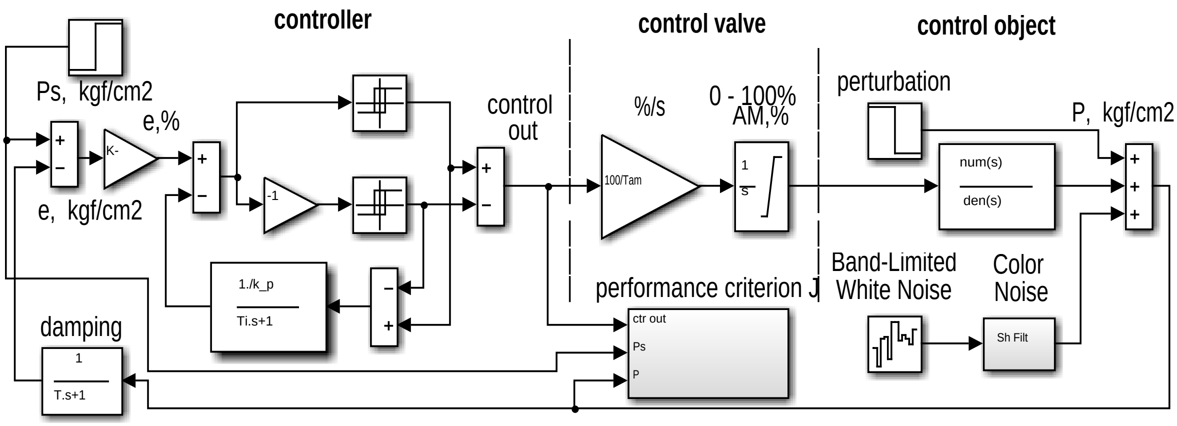

Figure 1. Simulation model of the automatic control system.

The controller uses the traditional method of control that is usually used in control systems where the actuators operate at a constant speed [4, 7, 8]. The basis of this control algorithm is a relay-pulse proportional and differential (PD) converter. It consists of two relays with a dead zone and hysteresis and looped by a common feedback in the form of the inertial unit. This unit has a transfer function $W_{oc}(s) = \dfrac{1/k_p}{T_и s + 1}$, where k_p is the controller gain; T_i is the integration time constant. The controller outputs are pulses to actuate AM to open/close CV. The controller and the actuating mechanism jointly implement approximately proportionally and integral (PI) control law.
CV with the actuator is represented by the gain (100% opening/T_{im}) taking into account the valve opening time and by the integrating unit with limitation of 0…100% opening (according to the position indicator of CV).
The control object (channel “CV position – pressure in the deaerator”) is modelled by the inertial unit. To form random signal (pressure changes in the deaerator), the shaping filter is implemented. The

filter output is a signal with the specified autocovariance function (the function parameters are experimentally obtained from the power unit) [9]. The shaping filter input is white noise with normal distribution (generated by the Band-Limited White Noise unit). Random pressure pulsations from the Shaping Filter are summed up with the output of the inertia unit.

The main parameters of the control system are: the controller gain k_p and the integration time constant T_i (the unit containing these parameters is highlighted with a shadow in figure 1). The choice of values of these parameters was carried out during optimization.

In the simulation, the performance criterion of the ACS is also calculated. For the period T (it must be not less than the duration of the transition process) a quadratic integral criterion is calculated

$$J(k_p, T_u) = \int_0^T [\varepsilon^2(t) + (\lambda u(t))^2]dt\,. \tag{1}$$

It characterizes the magnitude and duration of the control error ε (t) occurrence (pressure deviations from the setpoint). The criterion also takes into account control costs with a weighting factor λ (u is the controller output).

It should be noted that when developing ACS, the constraints imposed on the ratios of the parameters k_p and T_i are taken into account. The pulse controller contains the relay elements, and the non-linearities in the loop can cause self-oscillations. We should determine the constraints of the parameters k_p and T_i to eliminate self-oscillations.

Under some ratio Δ_r/Δ of the hysteresis value and the dead zone of the relay sections, each value of the integration constant T_i corresponds to the critical ratio $(k_pT_i/\Delta)_{crit}$ (determined experimentally). In order to have the self-oscillations absent, the condition $(k_\mathrm{p}T_\mathrm{i}/\Delta) < (k_\mathrm{p}T_\mathrm{i}/\Delta)_{crit}$ must be satisfied. So when we perform the optimization of the parameters, we must consider the constraint

$$G(X) = G(k_p, T_i) = k_pT_\mathrm{i}/\Delta - (k_pT_\mathrm{i}/\Delta)_{crit} < 0\,. \tag{2}$$

The purpose of the system optimization problem is to find the values of X=(k_p, T_i) that minimize the the objective function (1), i.e. accepted criterion for system performance, eliminate overshooting and make CV actuations infrequent. We must also determine the range of permissible ACS parameters, the boundaries of which, on the one hand, ensure stable operation of the ACS and, on the other hand, take into account the constraints G (X) <0 (in accordance with (2)).

4. Study of the self-oscillation in the optimization of ACS

When optimizing and determining the range of permissible ACS parameters, we took into account the possibility of self-oscillations in the control loop. Under normal operating conditions, self-oscillations are unacceptable, as they cause the danger of overheating of the actuator motor from frequent reversing actuations.

The study of the self-oscillation domain was carried out with optimization using the criterion (1). The parametric synthesis of the ACS includes searching for the parameters k_p and T_i minimizing the performance criterion $J = f(X)$. We apply the genetic algorithm (GA) [10, 11] of optimization that consider the vector of parameters $X = (k_p, T_i)$ as an "individual".

We preset the parameters of the GA as follows: the number of individuals in the population is m = 15; the number of generations is in range of [3; 5]; the initial values of the variables are chosen randomly from the ranges: $k_p \in [0{,}01; 0{,}2]$, $T_\mathrm{i} \in [5;\ 60]$.

The non-linear constraint in optimization problem is expressed by the inequality in accordance with expression (2). The self-oscillation boundary for the received ratio Δ_r/Δ=0.3 is a hyperbola determined by the expression $k_p = (1.03T_\mathrm{i})^{-1}$. In figure 2a–d, the boundary is shown by a solid curve: when selecting the parameters to the right of the boundary, self-oscillations are observed in the system.

Some selections of the ACS parameters are considered when minimizing the criterion $J(k_p, T_i) = \int_0^T [\varepsilon^2(t) + (\lambda u(t))^2]dt$, differing by the weight coefficient λ value. In addition, for the cases considered in figures 2a–c, there were no constraints on the domain of the search for the extremum (the inequality $G(k_p,T_i)<0$ was not taken into account in the search with the help of GA).

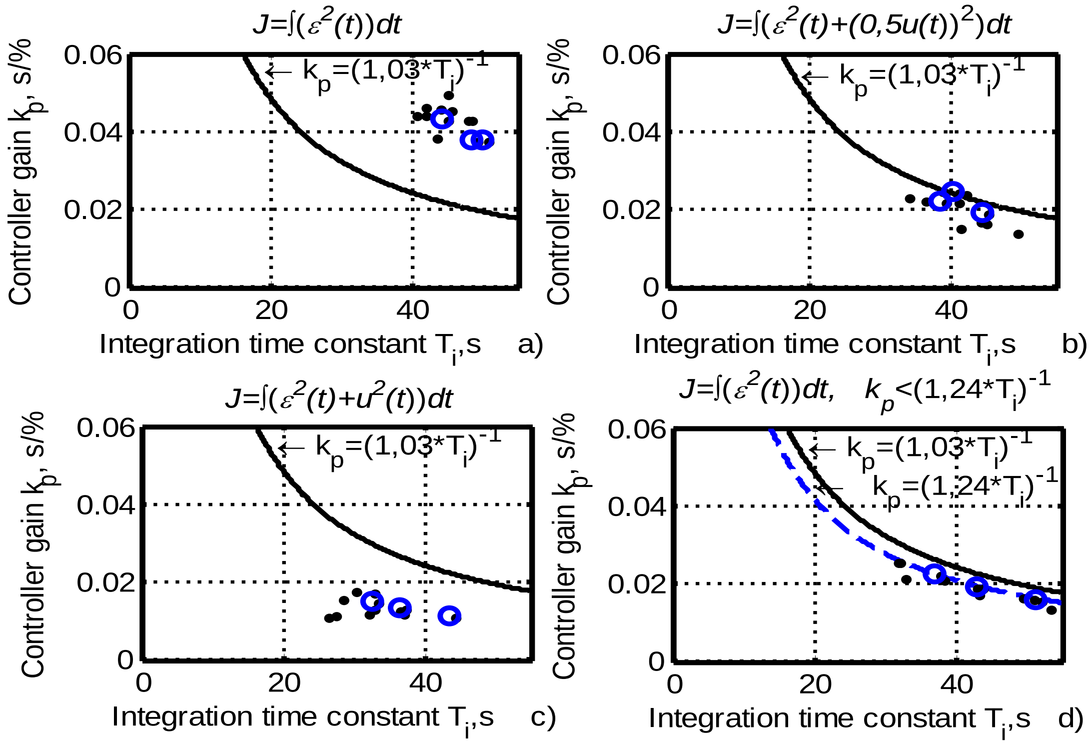

Figure 2. Investigation of the self-oscillation domain of the ACS with the minimization of the criterion $J(k_p,T_u)=\int_0^T[\varepsilon^2(t)+(\lambda u(t))^2]dt$: a) – for λ = 0, without taking constraints into account; b) – at λ = 0.5; c) – for λ = 1; d) - for λ = 0, taking into account the constraint $G(k_p,T_u)<0$.

The results are presented for 12 realizations of each case. Individuals of the GA (tuning parameters) are shown by dots, and for the three best solutions (each variant) are highlighted in circles.

Thus, in figure 2a we show the case of minimizing a criterion $J(k_p,T_i)=\int_0^T\varepsilon^2 dt$ that does not take into account control costs (λ = 0). It can be seen that the obtained values of the parameters are concentrated in the domain of self-oscillations.

In cases of accounting for control costs: at λ = 0.5 (figure 2b), the tuning parameters are moved to the self-oscillations boundary, and for $J(k_p,T_i)=\int_0^T(\varepsilon^2+u^2)dt$ (λ = 1, figure 2c), the optimal parameters for all implementations are in the domain in which there are no self-oscillations.

For comparison, figure 2d shows the result of minimizing the criterion $J(k_p,T_i)=\int_0^T\varepsilon^2 dt$ (without control costs, λ = 0), but taking into account the constraint $G(k_p,T_i)<0$ (compare with figure 2a). When searching for an extremum using GA, a dashed line $k_p=(1{,}24T_i)^{-1}$ was adopted as the boundary of self-oscillations (the coefficient in parentheses was increased by 20% of the initial value to provide some margin due to possible inaccuracies in the adopted model). Apparently, individuals of the GA (tuning parameters) are located along the boundary of self-oscillations.

Hence the conclusion follows that increase of the weight coefficient λ in the expression of criterion (1), i.e, accounting for control costs leads to the elimination of possible self-oscillations. But it should be borne in mind that the accuracy of control is thereby reduced.

Therefore, it is recommended to use the expression of the criterion for λ = 1. In this case, the technological operability of the automatic control system is ensured: the accuracy of regulation and the absence of self-oscillations.

Figures 3 and 4 show the results of minimizing the criterion $J(k_p, T_i) = \int_0^T \varepsilon^2 dt$ (without the cost of control, λ = 0), taking into account the constraints for the 15 implementations performed.

The dashed line $k_p = (1{,}24T_i)^{-1}$ was taken as the self-oscillation boundary, and the parameters (obtained by searching for an extremum using GA) are located along it (figure 3a). The optimal settings for each implementation are shown by dots, and for the two best implementations are marked with circles.

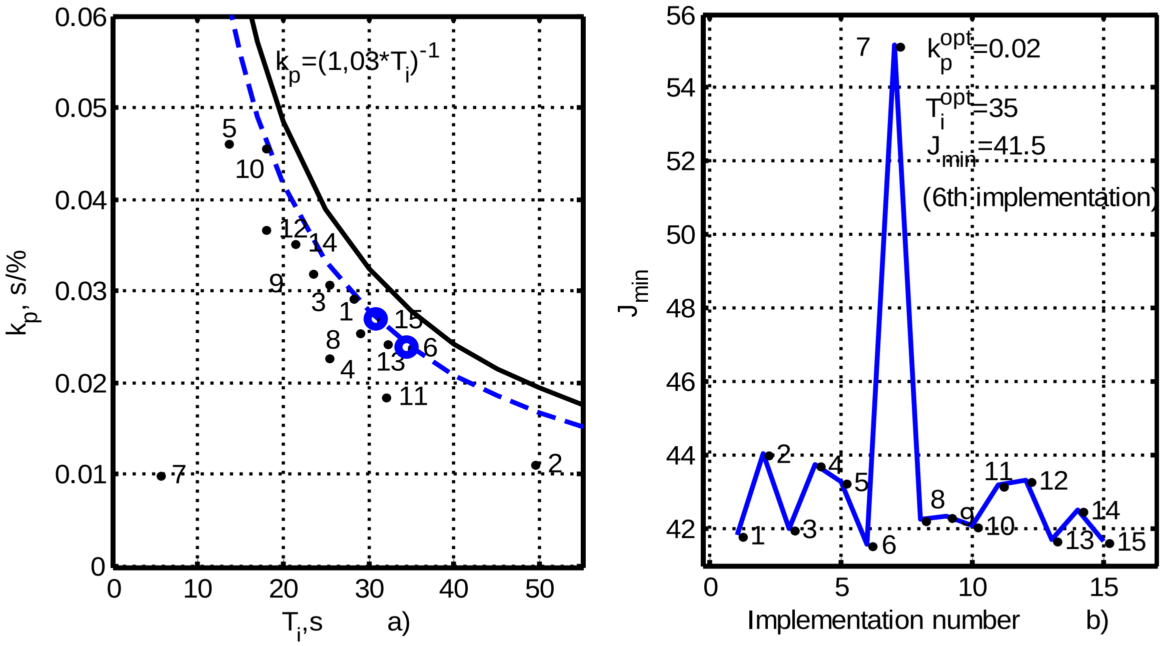

Figure 3. Results of the study of the self-oscillations field in the optimization of ACS: optimal parameters (a) and minimum criterion values (b) for each implementation.

Figure 3b shows the corresponding minimum values of the quality criterion for each implementation, as well as the values of the optimal parameters for the best implementation.

Figure 4 shows the of the genetic algorithm application. The results of the best implementations (6th out of 15 implementations) are shown when optimizing the ACS.

Figure 4a illustrates the quality criterion changes for the best solutions, as well as the average criterion value over the GA population. To obtain the optimal parameters, it took only three generations: the algorithm has good convergence to the solution.

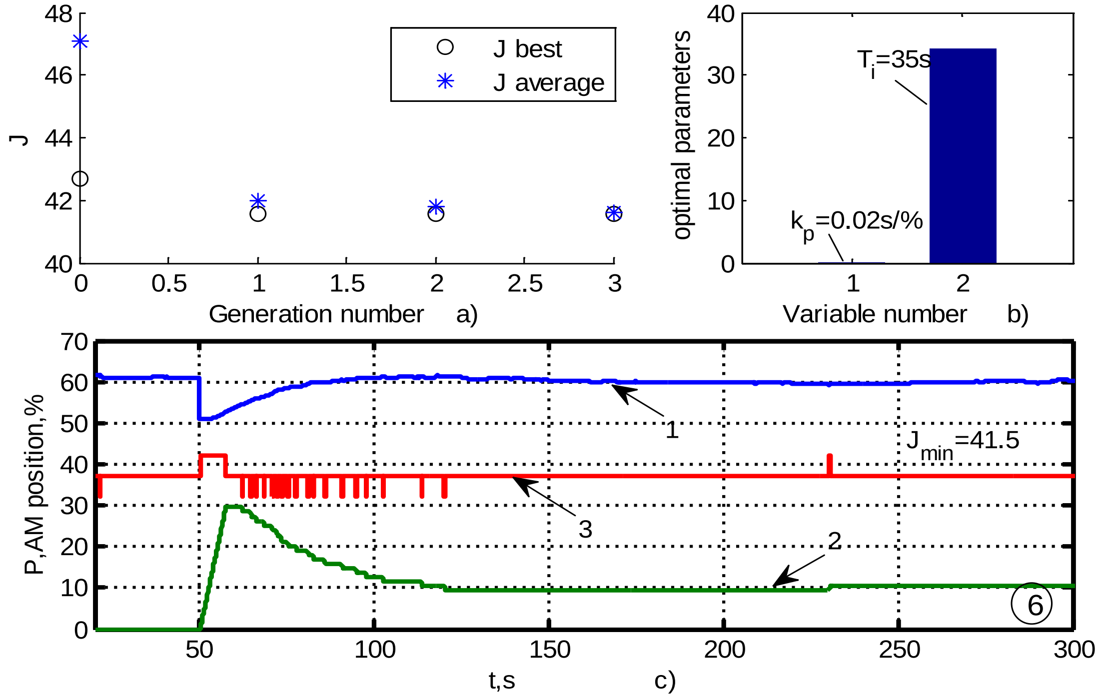

Figure 4. Optimization of ACS using GA (for one of the implementations):
a) dynamics of changes in the quality criterion; b) the vector of optimal parameters;
c) transients at optimal parameters of ACS.

Figure 4b shows bar plots of the components of the optimal parameters vector $X_{opt} = (k_p, T_i)$. Transients in ACS with optimal parameters obtained for this implementation are shown in figure 4c. The calculation for the perturbed ACS operation mode is presented: when the steam pressure decreases by 10% from the setpoint at the time t=50 s.

It can be seen from the graphs that the pressure reduction is worked off by the regulator, and the CV position changes by 30% according to the position indicator (2) for several actuators (3). The pressure in the deaerator (1) is maintained in the area of the required accuracy of 6 ± 0.1 kgf/cm^2 (60 ± 1.7%).

5. Determination of the stability boundary and the feasible parameters domain

In addition to the border of self-oscillations, we determined the boundary of the steady-state work of the ACS. Based on the developed model of ACS (figure 1) and optimization of parameters, the stability analysis of the pressure control loop is performed. In this case, for the application of analytical methods of stability analysis, the approximation of the relay-pulse controller by the linear PI- controller is performed [2, 13].

Figure 5 illustrates the definition of the ACS feasible parameters domains in the plot of the parameters T_i and k_p.

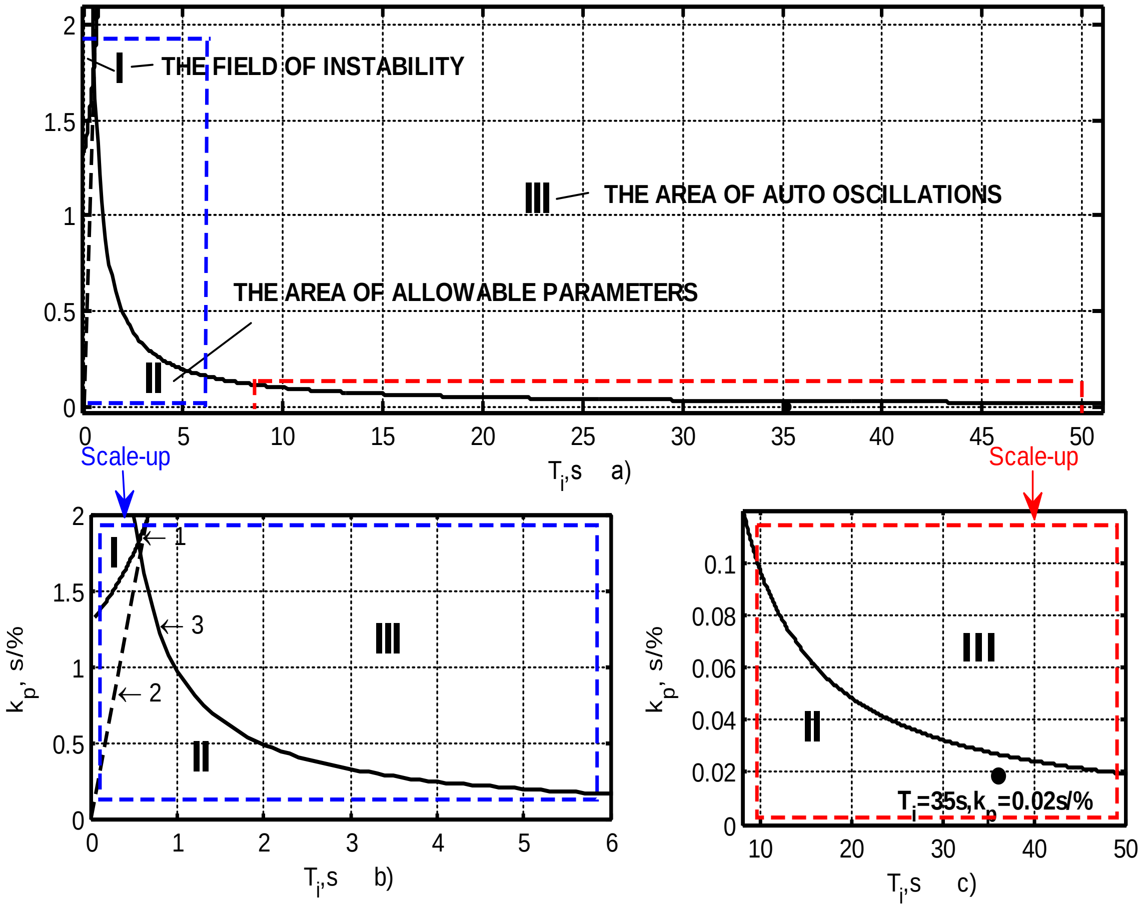

Figure 5. Determination of the allowable parameters domain: a) a general view of the parameters area; b) the region of the low time constant T_i; c) the region of low gain k_p.

Figure 5a shows the domain of unstable work, self-oscillations and feasible tuning parameters. For better visual representation of the results, the region of unstable work (figure 5b) and the domains of allowable / unallowable parameters (figure 5c) are scaled up. The boundary of the stability domain is constructed as a result of the calculations performed for the approximating linear controller (figure 5b, curve 1). To obtain an analytical expression, the boundary curve is approximated by a linear expression $k_p = 3.1T_\mathrm{i}$ (figure 5b, line 2).

Figure 5 also presents the self-oscillations domain boundary (see line 3) obtained by system simulation with ratio $\Delta_r/\Delta = 0{,}3$.

The boundaries of the region of feasible parameters of the pressure control system are obtained. At the same time, the recommended values of the parameters k_p, and T_i deliver the minimum accepted criterion of the quality of the system operation.

6. The discussion of the results

As a result of the research, we concluded that it is reasonable to choose the parameters values of relay-pulse pressure controllers from the feasible parameters domain. This will ensure stable operation of the control loop without self-oscillations. At the same time we do not recommend to choose the system parameters near the stability boundaries in order to ensure sufficient stability margin.

Automation of the synthesis of ACS implemented on the basis of the proposed method can significantly improve the quality of control and reduce the time spent on pre-setting the controllers.

7. Conclusion

The studies we have concluded that the proposed approach to the automatic control systems design allows us to get an informed solution with minor computational costs.

The results of the approbation and the experience of implementing the developed approach of control systems optimization have confirmed its effectiveness for creation of software and hardware complexes for energy objects [4, 8, 12, and 14].

The generality of the principles of the various technological processes control makes it possible to recommend the use of the proposed methods for development and optimization of control systems not only for heat and power facilities, but also for technological and production processes in other sectors of the national economy.

References

[1] Cava M L, Paletta G and Picardi C 1984 Stability analysis of PWM control systems with PID regulators *International Journal of Control* vol **5** No 39 (5) pp 987–1005

[2] Besekersky V A and Popov E P 2003 *Theory of Automatic Control Systems* (Saint Petersburg: Professiya Publ) 752 p

[3] Ivanov V A 1982 *Regulirovanie energoblokov* (*Power Unit Control*) (Leningrad: Mashinostroenie)

[4] Raskin E M, Denisova L A and Nadtochiy P N 2015 The software and hardware complex for automatic feed control of steam generators in the power unit of a nuclear power plant *Automation and Remote Control* vol **76** no 12 pp 2241-48

[5] Xue D and Chen Y Q 2013 *System simulation techniques with MATLAB and Simulink* (John Wiley & Sons)

[6] MATLAB Global Optimization Toolbox User's Guide R2018b Copyright 2004-2018 by The MathWorks Inc / www.mathworks.com/help/pdf_doc/gads/gads_tb.pdf

[7] Denisova L A and Meshcheryakov V A 2015 Automatic parametric synthesis of a control system using the genetic algorithm *Automation and Remote Control* vol **76** no 1 pp 149–156

[8] Denisova L A 2016 Automatic feed control of steam generator in the power unit of a nuclear power plant: modeling and optimization *Automation and Remote Control* vol **77** no 6 pp 1084–92

[9] Denisova L A and Meshcheryakov V A 2018 Control systems design: the technology of stochastic perturbations simulation *J. Phys.: Conf. Ser.* **1050** 012020

[10] Holland J H 1994 *Adaptation in natural and artificial systems. An introductory analysis with application to biology, control and artificial intelligence* (London: Bradford book edition)

[11] Purohit G N, Sherry A M and Saraswat M 2013 Optimization of function by using a new MATLAB based genetic algorithm procedure *International journal of computer applications* vol **61**(**15**) pp 1–5

[12] Denisova L and Meshcheryakov V 2016 Synthesis of a control system using the genetic algorithms *IFAC-PapersOnLine* vol **49** issue 12 pp 156-161

[13] Dorf R C and. Bishop R H 2011 *Modern control systems* (Prentice Hall)

[14] Raskin E M, Denisova L A, Sinitsyn V P and Nesterov Yu V 2011 A mathematical model of steam generator feed system at power unit of a nuclear plant *Automation and Remote Control* vol **72** no 5 pp 1118-26