

Multicriterion Synthesis of Intelligent Control Systems of Generating Unit of Nuclear Power Station

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Quality indice

ABSTRACT

The paper is devoted to solution of some problems in nuclear power station generating unit intellectual control systems using genetic algorithms on the basis of control system model development, optimizations methods of their direct quality indices and improved integral quadratic estimates. Some mathematical vector models were obtained for control system multicriterion quality indices with due consideration of stability and quality indices criteria, this increasing the reliability of optimal control system synthesis. Optimal control systems with fuzzy controllers were synthesized for nuclear reactor, steam generator and steam turbine, thus allowing comparison between fuzzy controllers and traditional PID controllers. Mathematical models built for nuclear power station generating unit control systems, including nuclear reactor, steam generator, steam turbine and their control systems interacting under normal operational modes, which permitted to perform parametrical synthesis of system and to study various power unit control laws. On the basis of power unit control system models controllers were synthesized for normal operational modes.

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1. Introduction

The generating units of nuclear power plants (NPP) with reactors VVER-1000 are operated in Ukraine, Russia, Bulgaria and Czechia. Such generating units are planned for commissioning in Iran, India and China. Though the generating units VVER-1000 are operated during several decades, the practice requires improving of the control quality of generating

units what is stipulated by tasks of energy saving and energy efficiency, integration perspective of power systems of various countries into an integrated power system. In automatic control systems (ACS) of generating units VVER-1000 the conventional PID controls are mainly used. The improvement of the control quality of generating units can be achieved both by improving the existing controls and by using the brand new intelligent controllers including the fuzzy ones [1].

The synthesis of fuzzy controllers is connected with multiextremal objective functions for the optimization of which the global search methods – genetic

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algorithms – are used [2, 3]. In recent years the practical introduction of fuzzy controllers and fuzzy control systems have been intensively carried out in global power engineering for the improvement of control systems reliability, enhancement of their stability and quality criteria.

It is the problem of the quality improvement of NPP generating units' control systems by developing methods of multicriterion synthesis of intelligent control systems by genetic algorithms that determines the currency of the paper.

The research goal and tasks involve the development of multicriterion parametric synthesis of intelligent automatic control systems of NPP generating units on the basis of the optimization of quality indexes of control systems by genetic algorithms. To achieve the specified goal the following problems are formulated:

1. Analysis of problems of multicriterion parametric synthesis of automatic control systems of nuclear power plant generating units.
2. Development of models and methods of formation and calculation of automatic control systems multicriterion quality indexes.
3. Development of reliable methods of multicriterion parametric synthesis of automatic control systems by genetic algorithms.
4. Multi-criterion synthesis of local automatic control systems of nuclear power plant generating units.
5. Synthesis of intelligent control systems of a nuclear power plant generating unit in main normal operating modes.

The target of research involves control processes in generating units of nuclear power plants in normal operating modes. The subject of research includes methods of parametric synthesis of intelligent automatic control systems of NPP generating units.

2. Analysis of NPP Generating Units Control

The flow chart of power generation by the generating unit VVER-1000 is shown in Fig. 1.

In the nuclear reactor (NR) VVER-1000 the uranium nuclear disintegration energy is transferred to the coolant – water that is fed by the reactor coolant pump (RCP). The feed water is fed into the steam generator (SG) PGV-1000 through the high-pressure heater (HPH) by the turbine-driven feed pump (TDFP). In the SG the feed water is transformed into steam which is fed into the steam turbine (ST) K-1000-1500/60 through the reactor steam drum (RSD). The turbine rotates the rotor of the electric generator (EG) producing electric power.

The waste steam in the condenser (C) is cooled by water from the cooling reservoir (CR) fed by the circulating pump (CP), and by the condenser pump (CDP) through the low-pressure heater (LPH) it is fed into the deaerator (DA). From the DA the feed water comes to the TDFP. The generating unit is equipped

with an automated control system that combines local control systems of separate technological processes in components of the generating unit: power ACS of the nuclear reactor (PACS NR), water level ACS in the steam generator (WLACS SG), rotor speed ACS of ST (RSACS ST), et al.

The automatic control problems of the generating unit and its main assemblies have been analyzed. The engineering quality requirements of real systems are formulated in the form of direct quality indexes (DQI) such as overcorrection, correction time, indexes of process oscillation. The improved integral quadratic estimates (IQE) have been considered that determine the quality index describing direct quality indexes in the aggregate [4]. The approaches and methods of parametric synthesis of conventional and fuzzy control systems have been analyzed, and the advantages of use for the synthesis of genetic algorithms have been substantiated.

3. Formation of Vectorial Quality Criteria

Let's designate the set of variable parameters of the problem of parametric ACS synthesis with vector $x = (x_1, x_2, \dots, x_p) \in R^p$. We determine the ACS quality indexes by mathematical models of systems presented in the form of differential equation systems (DES) or in the form of a transfer function (TF):

$$dX/dt = f(x, X, u), dX/dt = A(x)X + B(x)u, y = C(x)X; \quad (1)$$

$$W(x, s) = \beta(x, s) / \alpha(x, s) \quad (2)$$

$$\beta(x, s) = \sum_{i=0}^m \beta_i(x) s^{m-i}, \quad \alpha(x, s) = \sum_{i=0}^n \alpha_i(x) s^{n-i},$$

where X is a state vector, u is an input action, y is a controlled variable; $f(x, X, u)$ is a vector function of model formation of nonlinear ACS; $A(x)$, $B(x)$, $C(x)$ are parameter matrices of linearized ACS. For the research of quality indexes the test TFs of the form (2) are selected:

$$W(x, s) = \frac{1}{s^2 + x_1 s + 1}, \quad W(x, s) = \frac{1}{s^3 + x_1 s^2 + x_2 s + 1} \quad (3)$$

The particular DQIs are overcorrection $\sigma(x)$, amplitude of oscillations $\zeta(x)$, decay of oscillations $\lambda(x)$, correction time $t_c(x)$ and its relative value $\tau(x) = t_c(x)/T_f$ we calculate by integrating DESs (1) by using matrix methods.

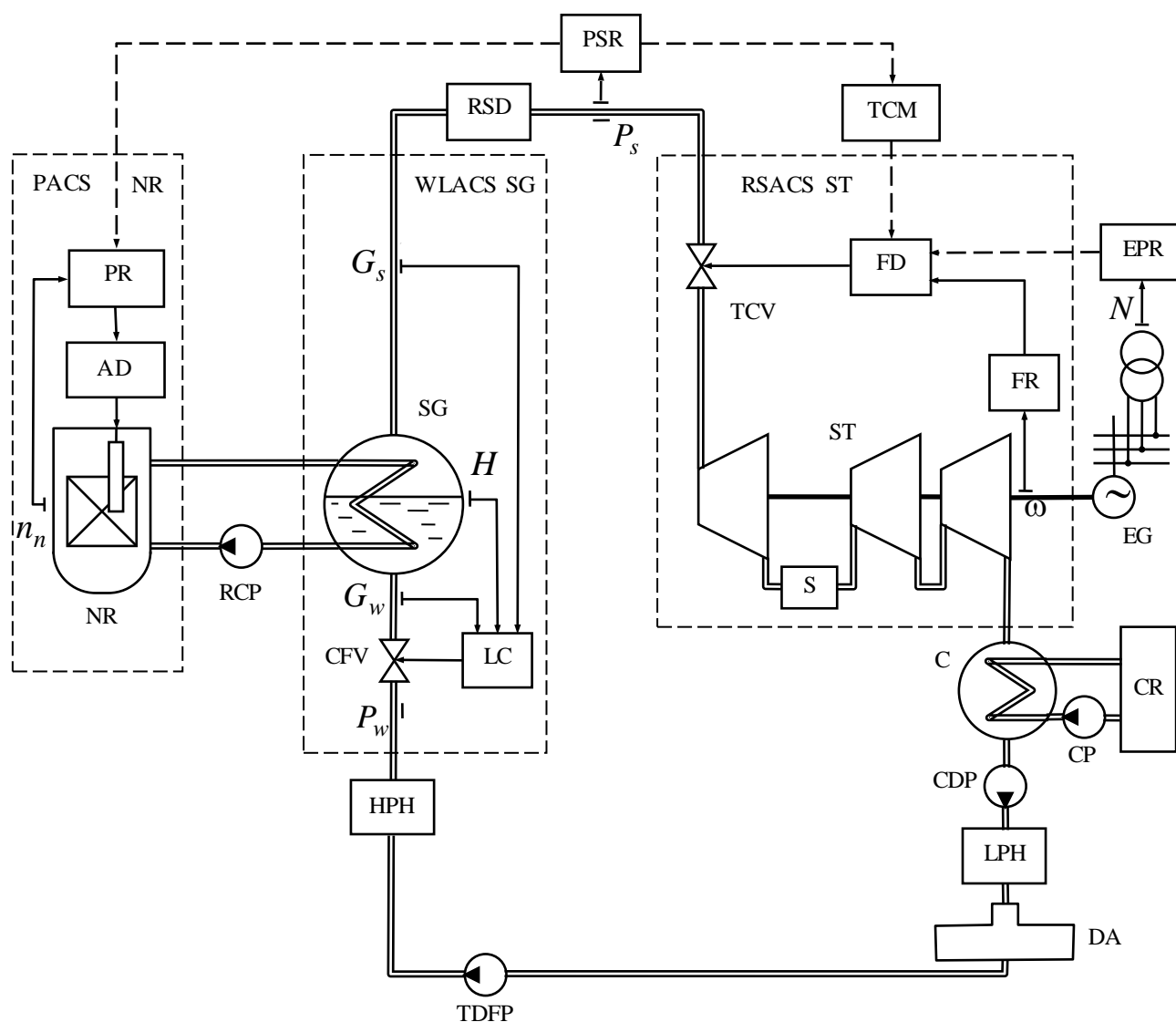


Fig. 1. Flow chart of the generating unit with reactor VVER-1000

Here $[0; T_f]$ is an interval of integration. When computing the default correction time the parameter of steady-state value zone is $\delta_z = 0,05$. The minimization of $\sigma(x)$ and $\tau(x)$ for systems (3) of orders $n = 2, 3$ given in Tab. 1.

Tab. 1. Results of particular DQIs minimization

| n | min | x_1^* | x_2^* | σ^* | τ^* | t_c^*, s |
|-----|-------------|---------|---------|------------|----------|------------|
| 2 | $\sigma(x)$ | 1,98 | — | 0,00 | 0,233 | 4,66 |
| | $\tau(x)$ | 1,38 | — | 0,05 | 0,143 | 2,86 |
| 3 | $\sigma(x)$ | 1,92 | 2,38 | 0,00 | 0,216 | 4,31 |
| | $\tau(x)$ | 1,45 | 2,02 | 0,05 | 0,161 | 3,22 |

Its results show: particular DQIs are contradicting.

The particular IQEs are determined as:

$$J_0(x) = \int_0^\infty [z(x, t)]^2 dt,$$

$$J_k(x) = \int_0^\infty [\partial^k z(x, t) / \partial t^k]^2 dt,$$

where $z(x, t) = y(x, \infty) - y(x, t)$ is deviation of controlled variable from its steady-state value. The results of minimization of these IQEs for systems (3) are given in Table 2 by $x_1, x_2 \in (0; 5]$. The particular IQEs are contradicting; the problem of their minimization is a multicriterion problem. For the solution of this problem the improved IQEs are applied [5]:

$$J(x) = \int_0^\infty \sum_{k=0}^l w_k [z_t^{(k)}(x, t)]^2 dt, \quad (4)$$

$$I(x) = \int_0^\infty \left[\sum_{k=0}^l \tau_k z_t^{(k)}(x, t) \right]^2 dt$$

The estimate $J(x)$ is a convolution of particular IQEs. When transforming it we can move to the estimate

$I(x)$ having the same minimum as shown in Fig. 2 for $n=2$, $l=1$, $w_1=1$, $\tau_1=1$. This estimate is preferred since it is connected with the extremal y_e for the optimum transient process y as shown in Fig. 3.

Tab. 2. Results of particular IQEs minimization

| n | k | x_1^* | x_2^* | J_k^* | σ^* | ζ^* | λ^* | t_c^*, s |
|-----|-----|---------|---------|---------|------------|-----------|-------------|------------|
| 2 | 0 | 1,98 | — | 1,0 | 0,16 | 0,19 | 0,16 | 5,29 |
| | 1 | 1,38 | — | 0,1 | 0,00 | 0,00 | 0,00 | 14,57 |
| 3 | 0 | 1,92 | 2,38 | 1,5 | 0,07 | 0,23 | 2,15 | 8,73 |
| | 1 | 1,45 | 2,02 | 0,1 | 0,00 | 0,00 | 0,00 | 12,62 |

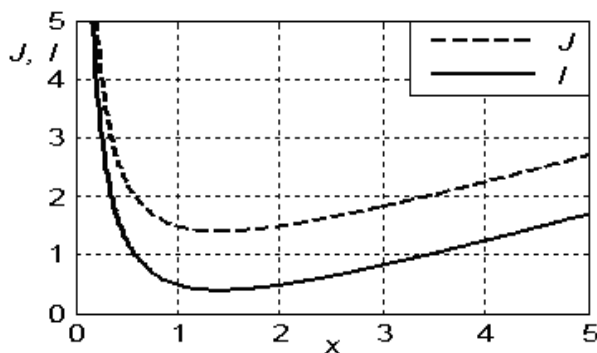


Fig. 2. Diagrams of improved IQEs

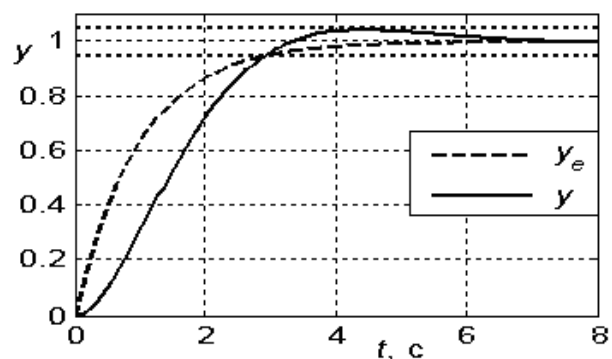


Fig. 3. Transient processes

For the multicriterion parametric synthesis of control systems the vectorial quality criteria suggested by V. P. Severin are developed on the base of step by step approach [6]. In the problem of ACS synthesis we take into account the conditions of technical realizability and stability, where $\rho_k(x)$ are elements of the first column of Routh table:

$$a_i \leq x_i \leq b_i, \quad i = \overline{1, p}; \quad \alpha_i(x) > 0, \quad i = \overline{0, n}; \quad (5)$$

$$\rho_k(x) > 0, \quad k = \overline{2, n-1}.$$

On the basis of these conditions the accessible region D is formed:

$$G_1 = \{x \mid a_i \leq x_i \leq b_i, i = \overline{1, p}\} \quad (6)$$

$$G_2 = \{x \mid \alpha_i(x) > 0, i = \overline{0, n}\}$$

$$G_k = \{x \mid \rho_{k-1}(x) > 0\}, \quad k = \overline{3, n}; \quad (7)$$

$$D_1 = G_1; \quad D_k = D_{k-1} \cap G_k, \quad k = \overline{2, n};$$

$$H_0 = R^p \setminus D_1; \quad H_k = D_k \setminus D_{k+1}, \quad k = \overline{1, n-1}; \quad (8)$$

$$D = D_n$$

To the conditions (5) the scalar penalty functions correspond:

$$P(x) = \sum_{i=1}^p [(a_i - x_i)_+ + (x_i - b_i)_+], \quad S(x) = \sum_{k=1}^n [-\alpha_k(x)]_+,$$

in which the cut-off operation $v_+ = \max\{v, 0\}$ is applied. To keep the synthesis process within the accessible region the vectorial penalty function is used:

$$F_S(x) = \begin{cases} (0; P(x)), & x \in H_0; \\ (1; S(x)), & x \in H_1; \\ (k; -\rho_k(x)), & x \in H_k, \quad k = \overline{2, n-1}. \end{cases} \quad (9)$$

Two of its values $U = (U_1; U_2)$ and $V = (V_1; V_2)$ are compared by the better operation:

$$U < V = \begin{cases} 1, & (U_1 > V_1) \vee [(U_1 = V_1) \wedge (U_2 < V_2)]; \\ 0, & (U_1 < V_1) \vee [(U_1 = V_1) \wedge (U_2 \geq V_2)]. \end{cases} \quad (10)$$

The problem of ACS synthesis by the DQI is formulated as a problem of conditional optimization:

$$x \in D, \quad \sigma(x) \leq \sigma_m, \quad \zeta(x) \leq \zeta_m; \quad \min \tau(x). \quad (11)$$

Such formulation does not take into account the priority of particular quality indexes. Let's expand regions (6) – (8) by regions for taking into account the inequalities (11):

$$G_{n+1} = \{x \mid \sigma(x) \leq \sigma_m\}, \quad G_{n+2} = \{x \mid \zeta(x) \leq \zeta_m\};$$

$$D_k = D_{k-1} \cap G_k, \quad k = \overline{n+1, n+2};$$

$$H_k = D_k \setminus D_{k+1}, \quad k = \overline{n, n+1}; \quad H_{n+2} = D_{n+2}.$$

For ACS synthesis by improved IQEs (4) and direct quality indexes on the basis of the function (9) the vector objective functions are formed:

$$F_I(x) = \begin{cases} F_S(x), & x \notin D; \\ (n; I(x)), & x \in D; \end{cases} \quad (12)$$

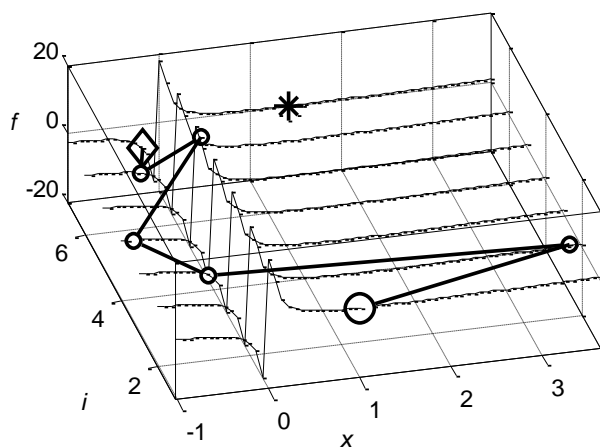


Fig. 4. IQE minimization for $n=2$

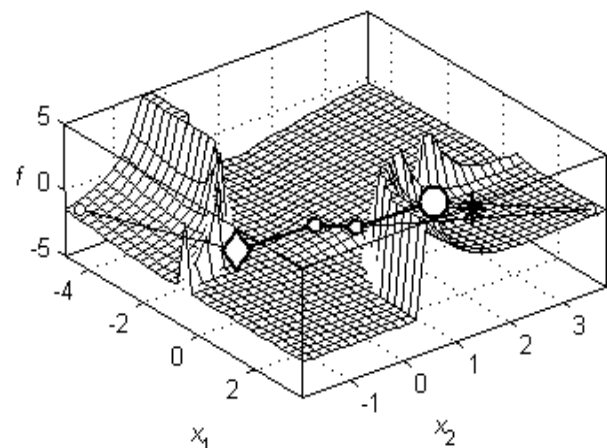


Fig. 5. IQE minimization for $n=3$

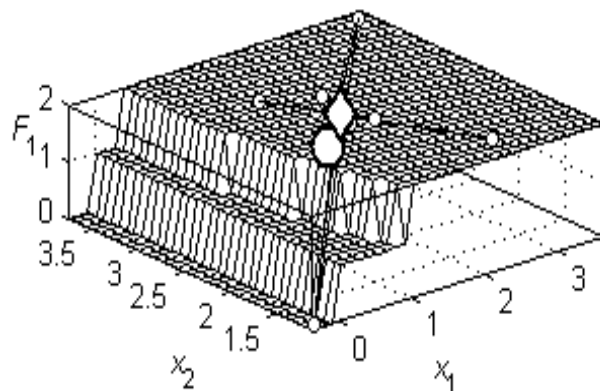


Fig. 6. IQE minimization by using the vector objective function

The vector functions (12), (13) are discontinuous and multiextremal, therefore to improve the reliability of ACS synthesis we apply genetic algorithms [2, 9]. Evolutionary algorithms are modified for solving

$$F(x) = \begin{cases} F_S(x), & x \notin D; \\ (n; \sigma(x) - \sigma_m), & x \in H_n; \\ (n+1; \zeta(x) - \zeta_m), & x \in H_{n+1}; \\ (n+2; \tau(x)), & x \in H_{n+2}. \end{cases} \quad (13)$$

4. Using of Genetic Algorithms

For IQEs computation the methods of A. M. Katz and K. Yu. Ostrem are used, but the minimization of function (4) $f(x) = I(x)$ can result in leaving the stability region [4]. Fig. 4 and 5 show several minimization steps of ACS (3) IQEs by methods of step adaptation and Broyden-Fletcher-Goldfarb-Shanno (BFGS) [7, 8]. The initial point is indicated by the circle, the end point is shown by the rhombus. The IQE minimum point indicated by the asterisk proved to be unachievable. On the projection diagrams of vector objective function (12) Fig. 6 shows the process of its optimization by the modified BFGS method for the test system (3) by $n=3$.

multi-objective optimization problems in various ways [10–12].

In the genetic algorithms (GA) the individual of the population we indicate with a chromosome

$\xi = (\xi_1, \xi_2, \dots, \xi_p)$ with length $M = mp$ composed of binary genes $\xi_i = (\xi_{i1}, \xi_{i2}, \dots, \xi_{im})$ with length $m = 32$, $i = \overline{1, p}$, $\xi_{ij} \in \{0; 1\}$ and determining the vector of variables $x = (x_1, x_2, \dots, x_p)$. Chromosomes $\Pi = (\xi^{(1)}, \xi^{(2)}, \dots, \xi^{(N)})$, points $P = (x^{(1)}, x^{(2)}, \dots, x^{(N)})$, values of vector objective function (12) or (13) $\Phi = (F^{(1)}, F^{(2)}, \dots, F^{(N)})$ form the population of the size N .

The initial population $\Pi^{(0)}$ is formed accidentally, for the next populations the following genetic operators are applied: selection, crossover, mutation. At the k -iterations the population is formed which the arrays of chromosomes $\Pi^{(k)}$, points $P^{(k)}$ and values of objective function $\Phi^{(k)}$ correspond to. The rank selection with the roulette principle (*Roulette*) is applied: the population is sorted by the comparison of vector function values by operation (10) (*Sort*); to the parental individual the roulette wheel sector is compared which is proportional to its rank; by the roulette principle the parents for crossing are chosen. By the single-point crossover (*Crossover*) with the subsequent mutation (*Mutate*) the new population is formed. Let's present the modified binary GA *GAB*.

Modified binary GA. Input parameters: a and b are constraint vectors of variables, N is a population size, m is a gene length, r_p is a share of parental pairs in the population, r_m is a share of mutation, N_k is a maximum number of iterations.

Output parameters: (x, F_x) is the best point.

1. Put $p = \dim(a)$, $l = b - a$, $M = m \cdot p$, $N_p = [r_p \cdot N]$, $n_p = [0.5 \cdot (N - N_p)]$, $n_m = [(N - 1) \cdot r_m \cdot M]$, $k = 1$.
2. Calculate $\Pi = \text{Round}(\text{Rand}(N, M))$.
3. Calculate $P = \text{Decod}(\Pi, a, l, m)$.
4. For $j = \overline{1, N}$ calculate $\Phi_j = F(P_j)$.
5. Put $(\Phi, J) = \text{Sort}(\Phi)$, $\Pi = \Pi(J)$, $P = P(J)$, $\Pi_p = \Pi(1 : N_p)$.
6. Calculate $(N_1, N_2) = \text{Roulette}(N_p, n_p)$, $(\pi_1, \pi_2) = \text{Crossover}(\Pi_p, N_1, N_2)$.
7. Put $\Pi = (\Pi_p, \pi_1, \pi_2)$.
8. Calculate $\Pi = \text{Mutate}(\Pi, n_m)$.
9. Calculate $P = \text{Decod}(\Pi, a, l, m)$.
10. For $j = \overline{1, N}$ calculate $\Phi_j = F(P_j)$.

11. Put $(\Phi, J) = \text{Sort}(\Phi)$, $\Pi = \Pi(J)$, $P = P(J)$, $\Pi_p = \Pi(1 : N_p)$.

12. Put $x = P_1$, $F_x = \Phi_1$.

13. If $k < N_k$, put $k = k + 1$ and move to item 6.

14. Exit.

The continuous GA (GAC) is also modified in which the population of points $P^{(k)}$ is initial.

To check the minimization of improved IQEs (4) the test TFs of orders from 3 to 105 with variable denominator coefficients have been used:

$$W(x, s) = 1/\alpha(x, s), \alpha(x, s) = s^n + \sum_{i=1}^{n-1} \alpha_i(x) s^{n-i} + 1 \quad (14)$$

Along with simple GAs *GAB* and *GAC* the combined binary and continuous GA with Hook-Jeeves and Nelder-Mead methods have been developed at the final search stage [6, 9].

By two variable coefficients of TF (14) denominators the minimum of estimates is found for all n only by the binary GA with the method of Nelder-Mead *GABNM*. By the variable coefficients $p = n - 1$ the minimum of estimates is found for all $p \leq 10$ by all methods.

By the number of calculations of the objective function the binary GA *GABNM* proved to be more efficient than the other methods. Fig. 7 shows projection diagrams of vector objective function (13) and the trajectory of the best points for the IQE minimization by the binary GA for test TF (14) with $n = 10$. The DQI optimization for orders of TF (14) from 3 to 7 confirmed the efficiency of *GABNM*. For problem (11) with additional constraint $\lambda(x) \leq \lambda_m$ and $\sigma_m = 0.05$, $\zeta_m = 0.065$, $\lambda_m = 0.3$ Fig. 8 shows the optimization of function (12).

The linear PID controls include proportional (P), integral (I), differential (D) controllers and by error $\varepsilon(t)$ the control $u = u(t)$ is formed by addition of u_P , u_I , u_D , determined by the equation [9]:

$$u_P(t) = K_P \varepsilon(t); \quad du_I/dt = \lambda_I \varepsilon;$$

$$dv_D/dt = -\lambda_D(v_D + K_D \varepsilon), \quad u_D = v_D + K_D \varepsilon;$$

where K_P , $\lambda_I = 1/T_I$, $\lambda_D = 1/T_D$, $K_D = 10$ are parameters of controllers, T_I and $\tau_D = K_D T_D$ are time constants of I and ideal D controllers. To the PI and PID controls the vectors of parameters $x = (K_P, \lambda_I)$ and $x = (K_P, \lambda_I, \lambda_D)$ correspond.

The fuzzy PI control is shown in Fig. 9 it uses the system of fuzzy inference (SFI) that includes a rule base and blocks of fuzzification, fuzzy inference and defuzzification [1].

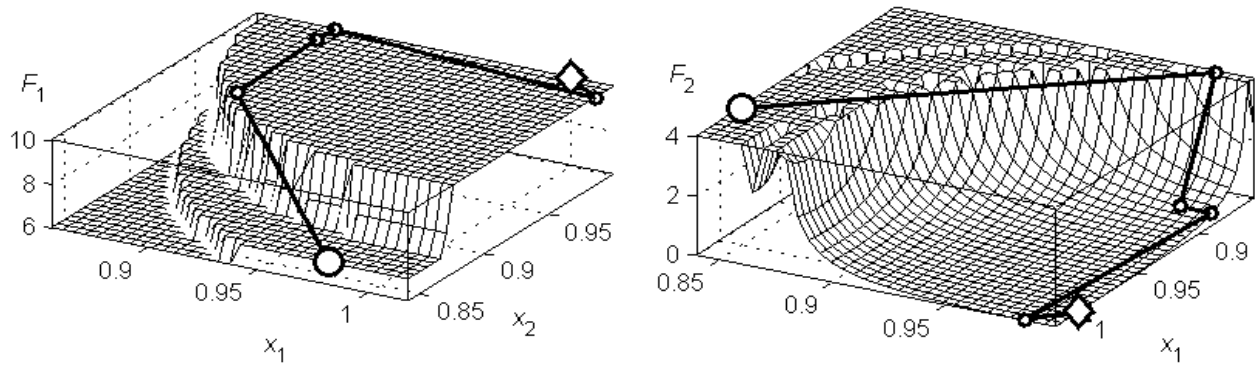
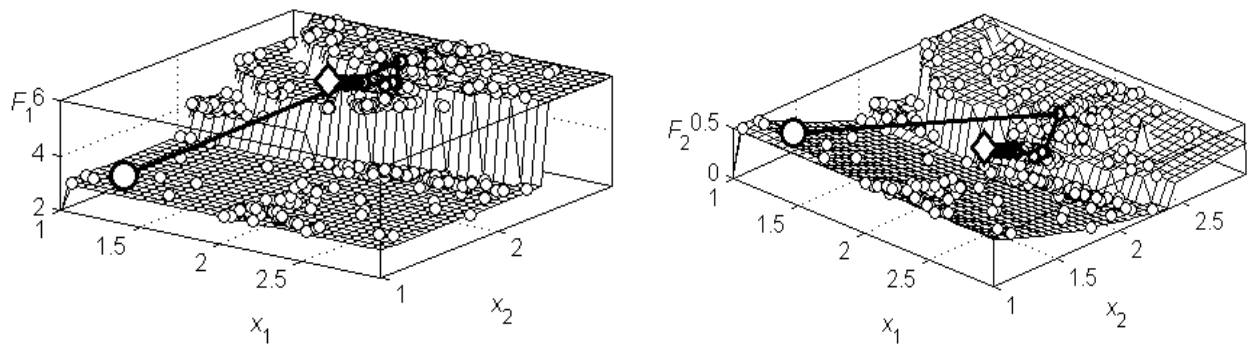
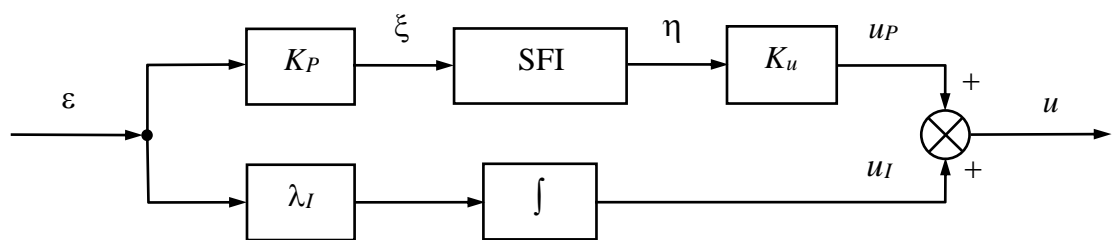
Fig. 7. IQE minimization for test TF with $n=10$, $p=2$ Fig. 8. DQI minimization for test TF with $n=3$, $p=2$ 

Fig. 9. Diagram of fuzzy PI control

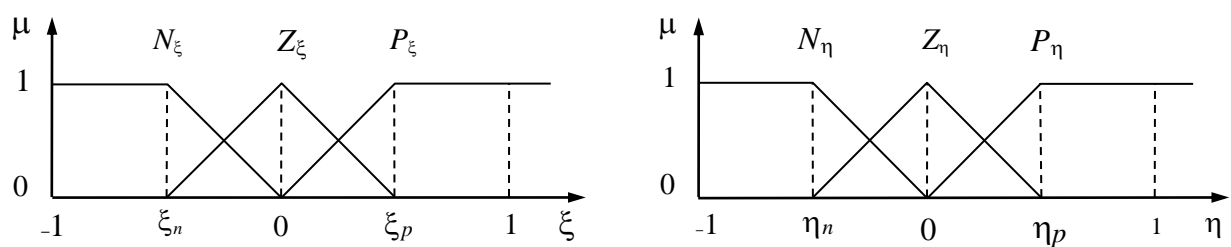


Fig. 10. Membership functions of input and output variables

The membership functions of input ξ and output η variables of SFI are presented in Fig. 10 where $\xi_n = -\xi_p$, $\eta_n = -\eta_p$, $\xi_p \in [0; 1]$, $\eta_p \in [0; 1]$. The

vector of variable parameter of fuzzy PI control is $x = (K_p, \lambda_I, K_u, \xi_p, \eta_p)$.

The elementary rule base is given by:

1) if $\xi = N_\xi$ then $\eta = N_\eta$;

2) if $\xi = Z_\xi$ then $\eta = Z_\eta$;

3) if $\xi = P_\xi$ then $\eta = P_\eta$.

We present the control action of the fuzzy PI control as:

$$u = u_p + u_I, \quad u_p = f_F(x, K_P \varepsilon) K_u, \quad du_I/dt = \lambda_I \varepsilon.$$

5. The Synthesis of Optimal Local Control Systems

The PACS NR VVER-1000 in Fig. 1 includes a nuclear reactor, a neutron-flux density sensor n_n , a power regulator (PR) and an absorber drive (AD). The models of reactor as a control object have been developed:

$$\begin{aligned} dX_R/dt &= f_R(X_R, u, \theta_{Ti}), \\ dX_R/dt &= A_R X_R + B_R u + B_{RT} \theta_{Ti}, \\ v &= C_R X_R, \quad \theta_r = C_{Rr} X_R, \end{aligned} \quad (15)$$

where X_R is a reactor state vector; A_R , B_R , B_{RT} , C_R and C_{Rr} are matrices with constant reactor parameters; u is a control signal of PR, θ_{Ti} is water temperature in the inlet pipeline; v is neutron power; θ_r is coolant temperature; the order of models is $n=7$. By models (15) the models of PACS with PI PR under the influence of power setting $v_s = l(t)$, $n=8$ are built:

$$\begin{aligned} dX_N/dt &= f_N(X_N, v_s), \\ dX_N/dt &= A_N X_N + B_N v_s, \quad v = C_N X_N \end{aligned} \quad (16)$$

To obtain monotonous transient processes with correction time $t_e = 100$ s in the function (13) the improved IQE (4) $I(x)$ with $l=1$ is set. In the function (12) $\sigma_m = 0$, $\zeta_m = 0$, τ are replaced by $(\tau - t_e/T_f)^2$. Results of the PR optimization are presented in Tab. 3 and Fig. 11.

Tab. 3. Results of the PR optimization

| M | QC | K_P^* | λ_I^* | K_u^* | ξ_p^* | η_p^* |
|---|-----|---------|---------------|---------|-----------|------------|
| L | IQE | 6,64 | 0,15 | — | — | — |
| L | DQI | 10,47 | 0,19 | — | — | — |
| N | DQI | 10,51 | 0,19 | — | — | — |
| F | DQI | 0,698 | 0,26 | 28 | 0,18 | 0,88 |

In Tab. 3 for different PI controls, linear L, nonlinear N and fuzzy F models (M) of systems (16) and quality criteria (QC) the optimum values of controller parameters are presented. For relevant PI controls in Fig. 11 the processes of power change in PACS which are optimum by IQE and DQI are shown.

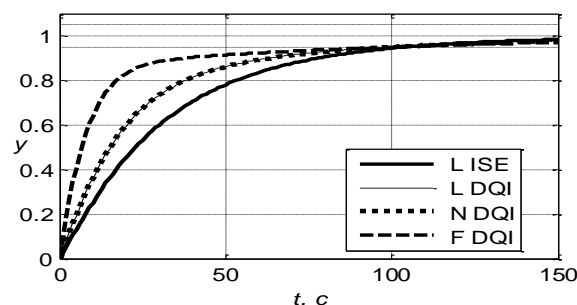


Fig. 11. Power change

For PACS with PI control in Fig. 12 the optimization process of the function (13) of variable parameters of the power regulator $x_1 = K_P$ and $x_2 = \lambda_I$ is shown.

The WLACS SG in Fig. 1 includes SG, level sensors H , feed water G_w and steam G_s flow-sensors, a level controller (LC) and a control feed valve (CFV). The SG model that includes models of RSD, drive of turbine control valve (TCV) and CFV actuator is given by:

$$\begin{aligned} dX_G/dt &= A_G X_G + B_{GT} \theta_T + B_{Gw} u + B_{Gs} u_s, \\ \xi_c &= C_G X_G, \quad \theta_t = C_{Gt} X_G, \quad \pi_k = C_{Gk} X_G. \end{aligned}$$

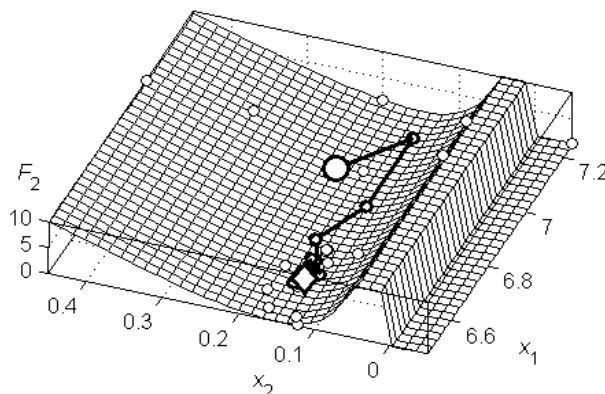
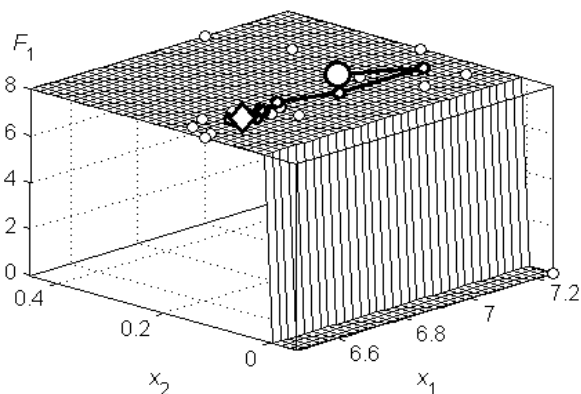


Fig. 12. Optimization of PACS PI power regulator

Here X_G is a state vector of SG; A_G , B_{Gq} , B_{Gw} , B_{Gs} , C_G are matrices of constant parameters of SG; q is coolant power; u and u_s are control actions on CFV and TCV; ξ_c is water level, θ_t is coolant temperature in SG, π_k is steam pressure in RSD; $n=9$. The perturbation actions of WLACS are coolant temperature θ_T and action on TCV u_s . By the SG model the WLACS models of the order $n=10$ with various LC types are built:

$$\begin{aligned} dX_L/dt &= A_L X_L + B_{LT} \theta_T + B_{Ls} u_s, \\ \xi_c &= C_L X_L, \quad \theta_t = C_{Lt} X_L, \quad \pi_k = C_{Lk} X_L \end{aligned} \quad (17)$$

By the modified GAS the parameters of models of SG and WLACS PGV-1000 are identified from experimental data of level deviation with disabled and enabled LC. The vectors of dimension variables $p=34$ and the vector function of the form (13) with the replacement of IQE by the residual function are formed. Fig. 13, 14 show processes of level deviation in SG by disabled and enabled LC: the points indicate experimental data, the dashed line indicates processes by initial values of model variable parameters, and the solid line indicates processes obtained by the optimization of vector function. The coincidence of theoretical and experimental processes is observed.

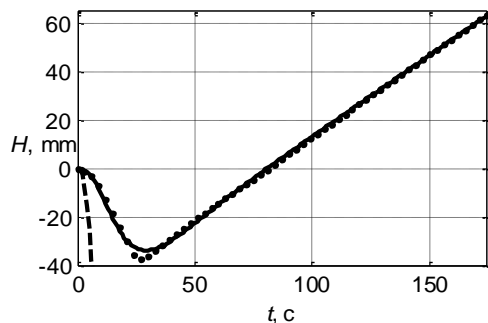


Fig. 14. Level deviation without LC

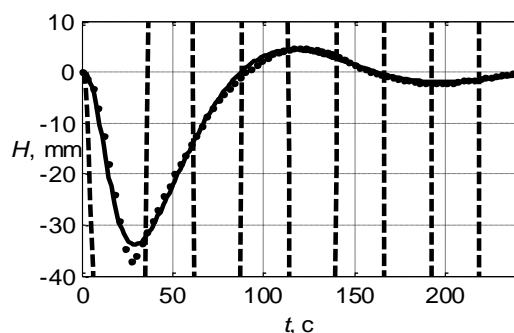


Fig. 13. Level deviation with LC

For DQI optimization of WLACS (17) at the perturbation $u_s = -1$, $\delta_z = 0.05$, $\sigma_m = 1$, $\zeta_m = 0$ are set, the vector x is formed from controller parameters. Results of the PR optimization are presented in Fig. 15 and Tab. 4. Fig. 16 shows processes of SG level change by different LC. The process PI0 corresponds to the PI control with identified values of parameters. The fuzzy controller has an incidental advantage. In Tab. 4 for PI control (PI) and fuzzy PI control (FPI) the optimum values of LC parameters, maximum deviation σ^* and correction time t_c^* are presented.

Fig. 16 displays points of the optimization process of level PI control with the vector of variable parameters $x = (K_P, \lambda_I)$.

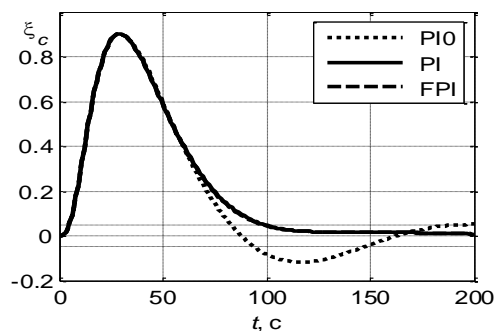


Fig. 15. Level change

Tab. 4. Results of the LC parameters optimization

| LC | K_P^* | λ_I^* | K_u^* | ξ_p^* | η_p^* | σ^* | t_c^*, s |
|-----|---------|---------------|---------|-----------|------------|------------|------------|
| PI | 2,5 | 0,15 | — | — | — | 0,90 | 98,4 |
| FPI | 0,4 | 0,14 | 1,9 | 0,3 | 0,4 | 0,91 | 97,6 |

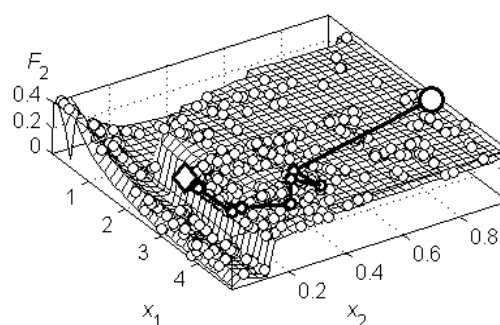
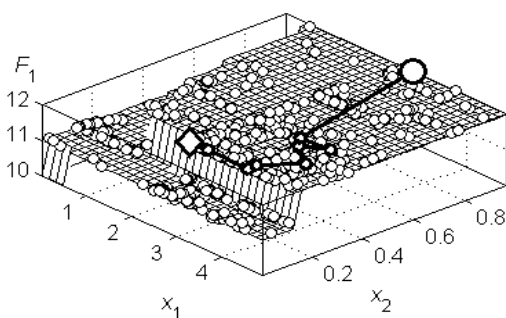


Fig. 16. Optimization of WLACS level PI control parameters

The RSACS ST in Fig.1 includes ST, frequency transducer ω , frequency regulator (FR), follower drive (FD) and TCV. By the turbine model of the order $n=19$ the RSACS model is determined by the perturbation action $v_{Es} = -1(t)$ that corresponds to the transition of the turbine from the rated power mode into the idle mode and by the output variable y of frequency deviation φ in per cent with PI FR:

$$\begin{aligned} dX_F/dt &= A_F X_F + B_F v_{Es} + B_{Fk} \pi_k, \\ \varphi &= C_F X_F \quad y = 100\varphi, \quad n = 20. \end{aligned} \quad (18)$$

The models of RSACS with PID control and fuzzy PI control are determined:

$$\frac{dX_F}{dt} = \begin{pmatrix} A_T X_T + B_{Tu}(f_F(\xi_p, \eta_p, (\varphi_s - \varphi))K_u + u_I) + B_{Tv}v_s \\ \lambda_I(\varphi_s - \varphi) \end{pmatrix}$$

The transient processes of frequency change are shown in Fig. 17. In Tab. 5 for PI, PID and fuzzy PI controls the optimum values of their parameters and DQI are given.

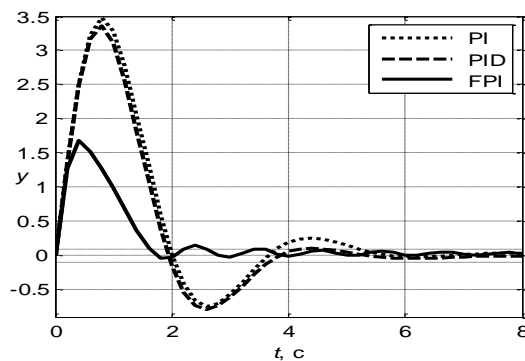


Fig. 17. Frequency change

For obtaining the optimum processes with minimum correction time the constraints of optimization problem of the function (12) are set: corresponding to the accessible frequency deviation 4% $\sigma_m = 4$, $\zeta_m = 1$, $\delta_z = 0,01$.

The optimization process of PI control with variable parameters $x_1 = K_p$ and $x_2 = \lambda_I$ is shown in Fig. 18. The most efficient one is the fuzzy PI control with optimum parameter values that provides the fastest transient process with the least frequency deviation.

Tab. 5. Results of the FR parameters optimization

| FR | K_p^* | λ_I^* | λ_D^* | K_u^* | ξ_p^* | η_p^* | σ^* | ζ^* | t_c^*, s |
|-----|---------|---------------|---------------|---------|-----------|------------|------------|-----------|------------|
| PI | 100 | 26 | — | — | — | — | 3,5 | 1,0 | 5,20 |
| PID | 98 | 34 | 1,7 | — | — | — | 3,4 | 0,9 | 4,20 |
| FPI | 7 | 48 | — | 8 | 0,9 | 0,1 | 1,7 | 0,2 | 2,21 |

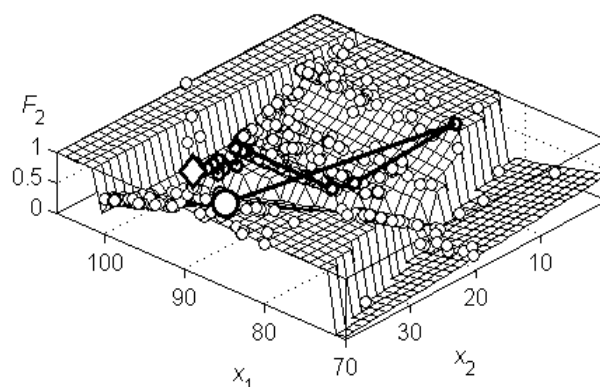
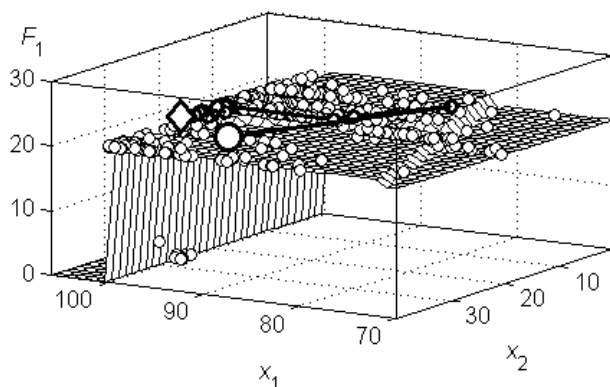


Fig. 18. Optimization of WLACS level PI control parameters

6. The Synthesis of Optimal ACS of NPP Generating unit in Normal Operating Modes

The basic diagram for the generating unit simulation is presented in Fig. 1. The models of the reactor outlet pipeline and joints of outlet pipeline of SG, RCP and reactor inlet pipeline are accepted as:

$$d\theta_T/dt = a_{TT}\theta_T + b_{Tr}\theta_r; \quad dX_c/dt = A_c X_c + B_c \theta_t,$$

$$\theta_{Ti} = C_c X_c, \quad n = 3. \quad (19)$$

The generating unit model is made up by the integration of DESs (15)-(19):

$$\begin{aligned} dX_U/dt &= A_U X_U + B_U u + B_{UE} v_{Es}, \\ v &= C_U X_U, \quad \pi_k = C_{Uk} X_U, \quad n = 40, \end{aligned} \quad (20)$$

$$X_U = \begin{pmatrix} X_R \\ \theta_T \\ X_L \\ X_c \\ X_F \end{pmatrix},$$

$$A_U = \begin{pmatrix} A_R & 0 & 0 & B_{RT}C_c & 0 \\ b_{Tr}C_{Rr} & a_{TT} & 0 & 0 & 0 \\ 0 & B_{LT} & A_L & 0 & B_{LD}C_{Fu} \\ 0 & 0 & B_cC_{Lt} & A_c & 0 \\ 0 & 0 & B_{Fk}C_{Lk} & 0 & A_F \end{pmatrix},$$

$$C_U = (C_R \ 0 \ 0 \ 0 \ 0),$$

$$C_{Uk} = (0 \ 0 \ C_{Lk} \ 0 \ 0),$$

$$B_U = \begin{pmatrix} B_R \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad B_{UE} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ B_F \end{pmatrix}.$$

The input actions are the control signal of neutron power regulator u and the signal of electric power change v_{Es} . The output variables are reactor neutron power v and steam pressure in RSD π_k .

The models of generating unit ACS in the N-mode which the systems of automated reactor neutron power maintenance correspond to are built by the generating unit model (20) with linear and fuzzy PI PR, $n = 41$:

$$dX_Q/dt = A_Q X_Q + B_Q v_s + B_{QE} v_{Es},$$

$$dX_Q/dt = f_Q(X_Q, v_s, v_{Es}),$$

$$v = C_Q X_Q, \quad \pi_k = C_{Qk} X_Q.$$

Similarly to PACS NR synthesis the optimization of power regulator parameters for preset correction time $t_e = 100$ s is made. In Tab. 6 the optimum values of PR parameters are presented. In Fig. 19 the transient processes of reactor power change in optimal systems are shown.

In T-mode of maintenance of constant steam pressure P_s in RSD (see Fig. 1) to NR PR the signal comes from the pressure regulator (PSR).

Tab. 6 Results of the PR parameters optimization

| PR | K_P^* | λ_I^* | K_u^* | ξ_p^* | η_p^* | t_c^*, s |
|-----|---------|---------------|---------|-----------|------------|------------|
| PI | 6,45 | 0,17 | — | — | — | 107,7 |
| FPI | 0,96 | 0,33 | 26,7 | 0,29 | 0,71 | 100,0 |

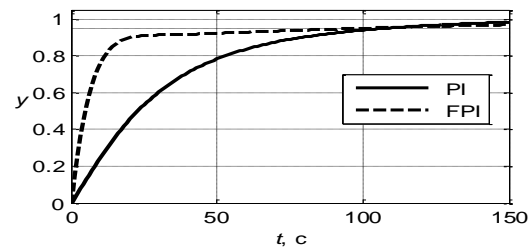


Fig. 19. Power change

The mathematical models of generating unit ACS for pressure control in T-mode with linear PI, PID and fuzzy pressure PI controls are developed:

$$dX_P/dt = A_P X_P + B_P v_{Es}, \quad dX_P/dt = f_P(X_P, v_{Es}),$$

$$\pi_k = C_P X_P, \quad n = 42, 43.$$

The PSR parameters by optimizing the function (12) by $\sigma_m = 1$, $\zeta_m = 0,2$ are synthesized. In Tab. 7 the optimum values of parameters and DQI $\sigma^* = 1$ are given. In Fig. 20 the relevant transient processes of steam pressure change in PSD are presented. These results allow concluding that the optimum conventional linear pressure PID control provides the fastest transient process with the least fluctuations.

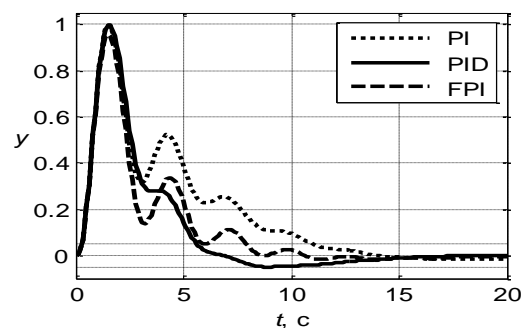


Fig. 20. Pressure change

Tab. 7. Results of PSR parameters optimization

| PSR | K_P^* | λ_I^* | λ_D^* | K_u^* | ξ_p^* | η_p^* | ζ^* | t_c^*, s |
|-----|---------|---------------|---------------|---------|-----------|------------|-----------|------------|
| PI | 13 | 5,7 | — | — | — | — | 0,21 | 11,0 |
| PID | 6,1 | 9,7 | 2,3 | — | — | — | 0,05 | 5,61 |
| FPI | 1,0 | 8,8 | — | 3 | 0,5 | 0,2 | 0,20 | 7,91 |

7. Conclusion

The paper is devoted to the solution of the theoretical and practical problem of multicriterion parametric synthesis of intelligent automatic control systems of NPP generating units on the basis of the optimization of vectorial quality indexes of systems by modified genetic algorithms. The main results of the work include the following.

The problems of multi-criterion parametric synthesis of automatic control systems of NPP generating units are analyzed and the wide opportunities of genetic algorithms use for the optimization of quality indexes are shown that allow improving considerably the reliability and the level of design automation and improvement of control systems.

The problems of multi-criterion parametric synthesis of control systems are brought to problems of vector optimization of quality indexes by forming the vector objective functions with account of stability criteria, direct quality indexes and improved integral quadratic estimates which allowed to develop models and methods of formation and calculation of vectorial quality indexes of control systems and to formalize the problem formulations of multicriterion synthesis of systems.

The methods of multi-criterion parametric synthesis of control systems by the construction of algorithms for the optimization of vectorial quality indexes are developed. The efficiency of vectorial genetic algorithms during the optimization of integral quadratic estimates and during the optimization of direct quality criteria for control systems of different order with various number of stability region constraints and variable parameters is investigated. The vectorial genetic algorithms allowed solving sequentially three main problems of automatic control systems design: to pass into the stability region, to keep the synthesis process in this region and to arrive at an optimal solution.

The mathematical models in state space in relative variables with various controllers for local automatic control systems of neutron reactor power VVER-1000, water level in steam generator PGV-1000 and steam turbine rotor speed K-1000-60/1500 are obtained. The model parameters of the water level control system in the steam generator are identified by experimental data by means of the optimization of vector functions by genetic algorithms that take into account the requirements of stability and minimum deviation from experimental data. For the rest of systems the values of constant model parameters are computed. The vectorial genetic algorithms perform the parametric synthesis of optimum local automatic control systems of the generating unit with conventional linear PID controls and fuzzy controllers what allows to compare the fuzzy controllers with the conventional controls.

The mathematical models of a nuclear power plant generating unit are built which include a reactor, a steam generator, a steam turbine interacting in normal

operating modes and their control systems what allows to perform the parametric synthesis of control systems and to research various control laws of the generating unit. On the basis of the model of generating unit automatic control systems the controllers for normal operating modes are synthesized.

For the improvement of the automation quality of the control processes in NPP generating units the methods of multicriterion parametric synthesis of genetic algorithm ACS have been developed which allow to formalize the problems of control systems synthesis more precisely and to enhance the scientific validity degree of engineering designs for the improvement of generating unit control systems. The mathematical models of intelligent ACSs of neutron reactor VVER-1000, water level in the steam generator PGV-1000 and rotor speed of steam turbine K-1000-60/1500 for the research of conventional and prospective control laws of generating units have been obtained. The intelligent ACSs of the generating unit VVER-1000 in main operating modes has been synthesized what allows comparing the intelligent ASCs with conventional systems.

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