OPTIMAL SYNTHESIS OF INTELLIGENT CONTROL SYSTEMS OF ATOMIC POWER STATION USING GENETIC ALGORITHMS

Seyed Mojtaba Jafari Henjani, Valery Severin

Abstract: *The paper is devoted to the development of a perspective concept of atomic station power block intelligent automatic control systems synthesis on the basis of mathematical models and numeric methods of vector optimization of systems quality indexes using genetic algorithms. The methods for calculation of direct quality indexes and improved integral quadratic estimates have been created. The step-by-step principle of transition to the domain of system stability has been based. There have also been suggested vector objective functions including stability conditions and taking into consideration quality indexes priorities. The reliable genetic algorithms for vector objective functions optimization have been suggested. Mathematical models in the state space for intelligent automatic control systems of nuclear reactor and steam generator have been worked out. The quality indexes optimization of power block intelligent control systems has been carried out, which allowed to estimate various controller types efficiency.*

Keywords*: automatic systems, intelligent control, optimal synthesis, nuclear reactor, steam generator, genetic algorithms.*

ACM Classification Keywords*: G.1.6 Optimization - Nonlinear programming*

Introduction

The experience of research of work of the power units of the atomic electric stations (AES) shows that priority is an increase of efficiency of methods of analysis and synthesis of the automatic control systems (ACS) — ACS of power (ACSP) of the nuclear reactor, ACS of level (ACSL) of water in steam generator and other systems [Ivanov, 1982], [Denisov, Dragunov, 2002], [Nikulina, Severin, 2009].

For the improvement of dynamic properties of ACS of power unit it is suggested to optimize the improved integral quadratic estimations and direct quality indexes (DQI) of the control systems — overshoot, index of vibrations and control time [Severin, Nikulina, 2004], [Severin, 2005], [Severin, 2008], [Jafari Henjani Seyed Mojtaba, Severin, 2009]. The models of reactor WWER-1000 are built on the basis of the systems of differential equations (SDE) of neutrons kinetics and heat sink. The models of steam generator PGV-1000 take into account SDE of material and thermal balances, differential equation (DE) of circulation. Adding to the control objects DE of actuating mechanism and controllers, get the models of ACSP and ACSL [Nikulina, Severin, 2009]. ACS models for optimization of DQI must be simple, as they are repeatedly used by the methods of optimization at the calculation of objective function. The algorithms of calculation of DQI of ACS are considered [Severin, Nikulina, 2004]. The algorithms of vector methods of ACS optimization taking into account the conditions of stability are suggested [Severin, 2008].

For ACS of AES power unit with such control objects as a nuclear reactor and steam generator, the parameters of which change random in the process of functioning, development of synthesis methods is needed. In such control systems in place of standard PID-controllers it is expedient to use intelligent controllers, built on the basis of fuzzy logic and artificial neural networks with the using of genetic algorithms [Goldberg, 1989], [Voronovskiy, Makhotilo, Petrashev, Sergeev, 1997], [Rotshtein, 1999], [Sabanin, Smirnov, Repin, 2003].

The purpose of the article consists of analysis of perspectives of application of genetic algorithms for the synthesis of the intelligent control systems of power unit of nuclear power plant. The general method of synthesis of parameters of controllers of ACS is examined. The parameters of controllers of reactor and steam generator are optimized. The analysis of possibilities of intelligent controllers, built on the basis of fuzzy logic, neural networks and genetic algorithms is investigated.

Methods of Optimization of Controllers Parameters

We will consider the general optimization method of controllers parameters on the example of linear PID controllers, forming the control action u on control object by mistake ε and consisting of proportional (P), integral (I) and differential (D) controllers: P controller is reflected by a proportional law

$$u_P = K_P \varepsilon \, , \tag{1}$$

I and D controllers are formed the integral and differential control laws:

$$u_I = \frac{1}{T_I} \int \varepsilon dt \, , \quad u_D = \tau_D \frac{d\varepsilon}{dt} \, ,$$

where K_p, T_I and τ_D are parameters of controllers. Proportional, integral and realizable differential control laws are answered the transfer functions (TF) of controllers:

$$W_P = K_P \, , \quad W_I(s) = \frac{1}{T_I s} \, , \quad W_D(s) = \frac{K_D T_D s}{T_D s + 1} \, .$$

Last TF at $K_D = 10$ approximately forms a differential control law with $\tau_D = K_D T_D$. With designations

$$\lambda_I = 1/T_I \, , \quad \lambda_D = 1/T_D \, , \tag{2}$$

we will write down differential equation of I controller and equation of the realizable D controller:

$$du_I/dt = \lambda_I \varepsilon \, , \quad dv_D/dt = -\lambda_D (v_D + K_D \varepsilon) \, , \quad u_D = v_D + K_D \varepsilon \, . \tag{3}$$

With P, I and D controllers we will build PI, PD, ID and PID controllers. For optimization of parameters of controllers K_P, λ_I and λ_D will form from them the vector of the variable parameters $x \in R^p$ of vector length $p \in \{1,2,3\}$. For P, I and D controllers $p = 1$, for PI, PD and ID controllers $p = 2$, for PID controller $p = 3$.

Let the linear or nonlinear models of the control systems be presented as systems of differential equations:

$$\frac{dX(x,t)}{dt} = A(x)X(x,t) + B(x)U(t) \, , \quad \frac{dX(x,t)}{dt} = f(x, X(x,t), U(t)) \, , \quad y(x,t) = C(x)X(x,t) \, , \tag{4}$$

where $U(t) = U_s 1(t)$ is input action, $y(x,t)$ is an output variable, $X(x,0) = 0$, $y(x,0) = 0$. A constant U_s sets the size of step input action: for a linear model $U_s = 1$, and for a nonlinear model $U_s \in [-1;1]$. If $y(x,\infty) \neq 0$, will define $C(x)$ so, that $y(x,\infty) = 1$.

We will impose the boundary conditions of the variable parameters

$$a_i \le x_i \le b_i \, , \quad i = \overline{1, p} \tag{5}$$

with the domain of constraint satisfaction

$$G_1 = \{ x \,|\, a_i \le x_i \le b_i \, , \; i = \overline{1, p} \} \tag{6}$$

and will form a penalty function:

$$S(x) = \sum_{i=1}^{p} \left[\max\{0,\, a_i - x_i\} + \max\{0,\, x_i - b_i\} \right]. \tag{7}$$

At linear ACS (4) for a matrix $A(x)$, and at nonlinear ACS for Jacobian of vector function of right part (4) by the method of D. K. Faddeev will define a characteristic polynomial

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

where n is an degree of ACS. For this polynomial on algorithms from [Jafari Henjani Seyed Mojtaba, Severin, 2009] we will calculate the coefficients of Routh-Hurwitz $\rho_k(x)$, $k = \overline{0,\, n}$, will form domains

$$G_2 = \{x \,|\, \alpha_i(x) > 0,\, i = \overline{0,n}\}, \quad G_k = \{x \,|\, \rho_{k-1}(x) > 0\}, \; k = \overline{3,n} \tag{8}$$

and will define a penalty function:

$$P(x) = \sum_{i=0}^{n} \max\{0, -\alpha_i(x)\}. \tag{9}$$

Integrating the systems of differential equations (4) on an interval $[0, T_f]$ with the number of steps L, will calculate the values of direct indexes of quality — overshoot $\sigma(x)$, scope of vibrations $\zeta(x)$ and time of control $t_c(x)$, proper the preset parameter δ_y of domain of the steady-state value of the output variable $y(x,t)$: at $t > t_c(x)$ $y(x,t) - y(x,\infty) \in [-\delta_y, \delta_y]$ [Severin, Nikulina, 2004]. We will set the upper bounds of overshoot σ_m, scope of vibrations ζ_m and will define domains

$$G_{n+1} = \{x \,|\, \sigma(x) \le \sigma_m\}, \quad G_{n+2} = \{x \,|\, \zeta(x) \le \zeta_m\}. \tag{10}$$

On the domains of constraints (6), (8), (10) we will form system of domains of simultaneous satisfaction of constraints $D_0 = R^p$, $D_k = D_{k-1} \cap G_k$, $k = \overline{1, n+2}$ and disjoint domains of levels of constraints: $H_k = D_k \setminus D_{k+1}$, $k = \overline{0, n+1}$, $H_{n+2} = D_{n+2}$. On these domains, functions (7), (9), $\rho_k(x)$, $\sigma(x)$, $\zeta(x)$ and the function of relative value of control time $\tau(x) = t_c(x)/T_f$, which is necessary minimize, will define a vector objective function:

$$F(x) = \begin{cases} (0;\, S(x)), & x \in H_0, \\ (1;\, P(x)), & x \in H_1, \\ (k;\, -\rho_k(x)), & x \in H_k,\, k = \overline{2, n-1}, \\ (n;\, \sigma(x) - \sigma_m), & x \in H_n, \\ (n+1;\, \zeta(x) - \zeta_m), & x \in H_{n+1}, \\ (n+2;\, \tau(x)), & x \in H_{n+2}. \end{cases} \tag{11}$$

This function, taking into account constraints of the variable parameters, necessary and sufficient conditions of stability of ACS and requirements to its DQI, will calculate by algorithms from [Severin, Nikulina, 2004], [Severin, 2008].

The first projection of function (11), representing the number of the satisfied constraints, it is necessary to increase, and the second projection — to diminish. The increasing of the first projection has priority, thus the values of this function $U = (U_1, U_2)$ and $V = (V_1, V_2)$ we will compare by a binary operation «better»:

$$U < V = \begin{cases} 1, & U_1 > V_1 \vee U_1 = V_1 \wedge U_2 < V_2, \\ 0, & U_1 < V_1 \vee U_1 = V_1 \wedge U_2 \geq V_2. \end{cases} \tag{12}$$

Optimization of vector objective function (11) will allow in a united computational process to satisfy constraints of the variable parameters (5), pass to the domain of stability of ACS and optimize DQI in this domain. For optimization of vector function (11) let's modify the methods of unconstrained minimization of scalar functions, replacing the operation of comparison of values of scalar objective functions by the operation of comparison of values of vector objective functions (12). For one-dimensional search we will use introduced by V. F. Korop the method, not requiring the calculation of scopes of interval of uncertainty and consisting in adaptation of step its multiplying by coefficient depending on the results of previous search. For optimization of function (11) of several variables the algorithms of vector methods of Hooke-Jeeves and Nelder-Mead are developed [Severin, 2005].

The Optimal Synthesis of Parameters of Controllers of Nuclear Reactor

We will consider the optimal synthesis of parameters of controllers of nuclear reactor WWER-1000. The ACS of reactor power includes an adder, the power controller (PC), actuating mechanism (AM), model of reactor and negative feedback (NFB) [Nikulina, Severin, 2009].

The input action of ACSP is setting of power U, an output is neutron power ν. A current value ν is measured by ionization chamber and with NFB given on adder, determining an error

$$\varepsilon = U - \nu . \tag{13}$$

An error acts on the input of PC, which forms control action u, given on AM. The AM shifts neutron-absorbing control rod and changes the component of reactivity ρ_d which is passed in linear or nonlinear models of reactor and changes the vector of its state X_R including ν:

$$\frac{dX_R}{dt} = A_R X_R + B_R \rho_d , \quad \frac{dX_R}{dt} = f(X_R, \rho_d), \quad \nu = C_R X_R . \tag{14}$$

Will present an actuating mechanism by DE

$$\frac{d\rho_d}{dt} = a_{dd}\rho_d + b_{du}u . \tag{15}$$

Values of parameters of model of reactor with six groups of delayed neutrons and AM given in [Nikulina, Severin, 2009].

On the models of nuclear reactor, actuating mechanism and controllers we will build the nonlinear and linear models of ACSP of reactor at the different laws of control in a kind (4). So, model of kind (4) with PI controller will build on (1), (3), (13), (15) at $x = (K_P, \lambda_I)$ and $u = u_P + u_I$:

$$X = \begin{pmatrix} X_R & \rho_d & u_I \end{pmatrix}^T, \quad C = \begin{pmatrix} C_R & 0 & 0 \end{pmatrix},$$

$$A(x) = \begin{pmatrix} A_R & B_R & 0 \\ -b_{du}K_P C_R & a_{dd} & b_{du} \\ -\lambda_I C_R & 0 & 0 \end{pmatrix}, \quad B(x) = \begin{pmatrix} 0 \\ b_{du}K_P \\ \lambda_I \end{pmatrix}, \quad f(x, X, U) = \begin{pmatrix} f_R(X_R, \rho_d) \\ a_{dd}\rho_d + b_{du}[K_P(U-\nu) + u_I] \\ \lambda_I(U-\nu) \end{pmatrix}.$$

We will get the models of ACSP with other PC similarly.

For optimization of DQI of ACSP of reactor will impose the values of boundary conditions of the variable parameters (5) with $a_i = 0$ and $b_i = 100$, $i = \overline{1, p}$. We will express through x the linear and nonlinear models of ACSP (4). The degree of model of ACSP with P controller is $n = 11$, with I, PI and PD controllers is $n = 12$, with ID and PID controllers is $n = 13$. For obtaining of the transient processes of power without overshoot and oscillation with the minimum time of control in the linear models of ACSP of reactor at input action $U = 1(t)$ we will set the values of parameters of task of optimization of direct indexes: acceptable values of overshoot and scope of vibrations $\sigma_m = 0$ and $\zeta_m = 0$, parameter of domain of the steady-state value $\delta_y = 0.05$. For I and ID controllers will set time of integration T_f 1000 s and for the other controllers — 100 s, number of steps of integration $L = 200$. We will form a vector objective function (11) and will optimize it in the case of one variable by the vector method of step adaptation, and in the case of several variables — by the vector method of Nelder-Mead [Severin, 2005].

In table 1 for different PC the optimal values of parameters of PC are presented K_P^*, λ_I^*, λ_D^*, and also the proper by it's the values of projections of function (11) F_1^*, F_2^* and value of control time t_c^*. Values F_1^* show that all constraints of the task of optimization of the direct indexes of quality are executed in optimal points. At the optimal values of parameters of P and PD controllers a static error excels 10 %. The systems with the I and ID controllers have large value of control time. Efficiency of PI and PID controllers is identical, they allow to provide the fast response of ACSP. From the optimal values λ_I^* and λ_D^* it is possible to pass to the values of time constants on formulas (2). Data of table 1 show that for PI controller an optimal process on a fast-acting is provided on the high bound of parameter K_P.

Table 1. Results of optimization of parameters of PC

PC	K_P^*	λ_I^*	λ_D^*	F_1^*	F_2^*	t_c^*, s
P	45.8	—	—	13	0.232	23.2
I	—	0.083	—	14	0.343	343.3
PI	100	2.59	—	14	0.138	13.8
PD	100	—	0,044	14	0.114	11.4
ID	—	0.083	100	15	0.343	343.3
PID	100	2.59	100	15	0.138	13.8

For optimization of nonlinear models of ACSP with PI controller at the different values of setting of power U_s will put $y(x,t) = \nu(x,t)/U_s$. In table 2 at $b_i = 25$, $T_f = 200$ s, $K_P^* = 25{,}0$ for different values U_s optimal values λ_I^* and control time t_c^* are given. With diminishing U_s λ_I^* diminishes and t_c^* increases.

Table 2. Results of optimization of nonlinear ACSP

U_s	λ_I^*	t_c^*, s	ν_s	λ_I^*	t_c^*, s
0.10	0.673	53.4	–0.20	0.659	54.7
0.05	0.671	53.6	–0.50	0.631	58.1
–0.05	0.667	53.9	–0.75	0.573	67.9
–0.10	0.664	54.2	–0.90	0.494	88.8

Thus, nonlinearity of mathematical model of nuclear reactor substantially influences on the optimal values of parameters of controller.

The Optimal Synthesis of Parameters of Controllers of Water Level in Steam Generator

The automatic control system of water level in steam generator (SG) PGW-1000 includes the level controller (LC), model of steam generator, NFB and adder [Nikulina, Severin, 2009]. On the input of the system control of level a setting of level $\xi_{cs}=0$ is given, an output is a coordinate of level ξ_c, which together with the increases of discharges of steam and water g_s and g_w form an error:

$$\varepsilon = \xi_{cs} - \xi_c + g_s - g_w \,.$$

We will express g_s and g_w through the vector of the state of SG X_G:

$$\varepsilon = -D_G X_G \,. \tag{16}$$

An error acts on the input of LC, forming control action u, given in the model of SG:

$$\frac{dX_G}{dt} = A_G X_G + B_{Gw} u + B_{Gs} U \,, \quad \xi_c = C_G X_G \,, \tag{17}$$

where U is disturbing influence of valve of control of turbine. We will build the models of the level control systems with different controllers in a kind (4). The model of ACSL with PI controller will get at $x=(K_P, \lambda_I)$ and $u=u_P+u_I$ on (1), (3), (16), (17):

$$X=\begin{pmatrix} X_G \\ u_I \end{pmatrix}, \quad A(x)=\begin{pmatrix} A_G - B_{Gw}K_P D_G & B_{Gw} \\ -\lambda_I D_G & 0 \end{pmatrix}, \quad B=\begin{pmatrix} B_{Gs} & 0 \end{pmatrix}^T, \quad C=\begin{pmatrix} C_G & 0 \end{pmatrix}.$$

We will impose on the values of the variable parameters constraints (5) with $a_i=0$, $b_i=100$, $i=\overline{1,p}$. We will express through x the linear models of the control systems of level of kind (4). The degree of model of the control system with P controller is $n=9$, with I, D, PI and PD controllers is $n=10$, with ID and PID controllers is $n=11$. For obtaining of optimal transient processes without vibrations with minimum time of control will set the values of parameters of task of optimization of DQI: proper the possible increase of level $h_c=15\,\mathrm{sm}$ value of maximal deviation of coordinate of level $\sigma_m=1$, proper processes without vibrations legitimate value of index of vibrations $\zeta_m=0$, time of integration $T_f=500\,\mathrm{s}$, number of steps of integration $L=200$, parameter of the domain of control time $\delta_y=0.05$ at steady-state value of process $y(\infty)=0$. We will form a vector function (11) which optimize by the vector method of step adaptation at $p=1$ or by method Nelder-Mead at $p>1$.

The results of optimal synthesis of parameters of controllers show that for ACSL with all considered types of controllers optimal processes are got without vibrations, inherent a process in real ACSL. The ASCL with P, D and PD controllers are static, and with the other ASCL — astatic. The best type of controller of level is PI controller with the optimal values of parameters, providing the most rapid transient process without vibrations.

Prospects of the Use of Fuzzy Controllers

Practical introduction of fuzzy controllers (FC) in the control systems of industrial sphere is intensively investigated. The investigated review on fuzzy controllers exposed the following:

— application of FC allows to use for control of technological processes information of qualitative type, which it is impossible to formalize during realization of traditional laws of control; an fuzzy controller is showed not sensitive to disturbances and demonstrates the best characteristics as compared to classic controllers;

— for composition of control rules of fuzzy controller intuition of developer and good knowledge of control object is required, methods for the direct synthesis of fuzzy controllers are practically absent;

— existent FR tune in to logic of user through the change of membership functions, thus a choice of membership functions is nontrivial procedure;

— there are not standardized recommendations on the choice of method of interpretation of fuzzy conclusion;

— possibility of application of fuzzy controllers is not certain for a multidimensional process.

Effective combination of methods of control theory and fuzzy logic theory allows to form the models of difficultly formalizable processes of control. The fuzzy systems are especially effective in the complex nonlinear processes of AES with parametric uncertainty.

Prospects of the Use of Neural Networks

The creation of artificial neural networks (NN) is based on development of principle new algorithms and methods of control for nonlinear dynamic objects. Most charts of neuron control are based on next approaches.

1. Successive chart of control. A neuron network will realize a reverse reflection in relation to a reflection «input-output» for the control object. Thus, if to set the supporting signal on NN, then the output signal of control object will be adopted by the same value. Teaching of neuron network is founded by back-propagation algorithm.

2. Parallel charts of control. NN of parallel type is used for tuning of input control signal which is the output signal of usual PID-controller. Tuning is executed so that an output signal of control object as possible more precisely corresponds the set supporting signal of ACS.

3. Control chart with self-tuning. A neural network is used for tuning the parameters of ordinary controller like tuning, to executable by a man-operator.

4. Control chart with an emulator and comptroller. Neural comptroller is taught on the inversion model of control object, and neural emulator on the ordinary model of object. Neural comptroller can be taught directly on the basis of back-propagation of error through neural emulator.

For the estimation of efficiency of neural comptrollers it is necessary to carry out computing experiments with the use of the developed models of objects of control of power unit and numerical methods of optimization.

Prospects of Application of Genetic Algorithms for the Systems Synthesis

For complex multiloop control systems and control systems with neural controllers it is characteristically large number of local extremes. At the synthesis of intelligent controller the surface of response is unknown, and the number of parameters which are necessary to be defined is large. According to ideology of work of genetic algorithm (GA) the form of surface of response does not matter for its successful work. The task of tuning of the parameters of intelligent controller, as a rule, is the multiextremal task of optimization. During optimization of the complex multiloop and multivariable control systems and intelligent systems with neural controllers genetic algorithms with high probability find global extreme. However the calculation of objective function on a time domain of transient process requires considerable computational resources that substantially influences on common work time of GA. It is expedient to develop the genetic algorithms in this direction.

Conclusion

The results of the investigated researches allow to present next conclusions.

1. The method of synthesis of parameters of controllers is considered on the base of optimization of vector objective function taking into account conditions of stability and direct indexes ACS.

2. The parameters of controllers of power of nuclear reactor WWER-1000 are optimized, that showed most efficiency of PI controller.

3. Optimization of parameters of controllers of water level of steam generator PGW-1000 showed most efficiency of PI controller with the optimal values of parameters.

4. The analysis of possibilities of intelligent controllers, built on the basis of fuzzy logic and neural networks, shows the wide prospects of their use in the automatic control systems of power units of nuclear power plants.

5. Application for the synthesis of the intelligent control systems of power unit AES the genetic algorithms will allow to raise quality of the systems.

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