OPTIMAL DESIGN OF INTELLIGENT CONTROL SYSTEMS OF STEAM TURBINE USING GENETIC ALGORITHMS

Khrystyna Fedyanyna, Ievgeniia Kucher, Valery Severin

Abstract: One of the basic engineering problems of the automatic control systems synthesis for steam turbines is systems quality indices optimization task. The features of such task are defined by plenty of control systems structural parameters, complication of quality indices formalization and calculation, the systems models high order. The greatest difficulty of the control system synthesis is optimization models and methods design. The paper purpose is to develop models and methods for optimum design of the intelligent automatic control systems of atomic power station steam turbine using genetic algorithms. The steam turbine automatic control system is applied to stabilize turbine rotor frequency with high precision. The intelligent steam turbine control system includes a steam turbine, frequency sensor, intelligent frequency regulator, electro-hydraulic automatic drive and turbine adjusting valve. Input signals on an automatic drive can be given by the steam pressure regulator through the turbine management mechanism or by the electric power regulator. Assumptions substantiated to model the automatic control system and automatic drive as executive link of control system. The automatic drive diagram of principle includes electro-hydraulic transformer, sleeve valve, servomotor, position sensors and electronic part. In the paper were built the mathematical models of automatic drive and steam turbine, the models permanent parameters values were calculated, the mathematical models of the automatic control system were developed in state space with the intelligent frequency regulator, the regulator parameters were optimized with system quality indices using genetic algorithms.

Keywords: automatic control system, automatic drive, steam turbine, intelligent regulator, genetic algorithms.

ACM Classification Keywords: G.1.6 Optimization - Nonlinear programming

Introduction

One of the basic engineering problems of creation of the steam turbines automatic control systems is a problem of optimization of their quality indices [Fragin, 2005]. Used engineering methods of calculation of the control systems are usually based on models substantial simplification and application of close indirect scalar quality criteria. The greatest lack of calculations of the control systems of nuclear power station turbines is slight using of models with optimal intelligent regulators in this area. Intelligent regulators based on fuzzy logic and artificial neuron networks allow to solve more intricate problems of compound objects control than standard regulators.

During last years works on practical introduction of fuzzy regulators, fuzzy expert and control systems in industrial and nonproductive spheres are intensively conducted [Terano, Asai, Sugeno, 1993]. Moreover fuzzy regulators excel traditional PID-regulators in transitional processes quality and in achieving management aims.

The use of intelligent regulators results in the nonlinear non-obviously set models of the automatic control systems. For the optimal synthesis of such systems parameters taking into account multiextremeness of their quality indices it is expedient to use the global optimization methods, in particular, methods of direct search and genetic algorithms [Nelder, Mead, 1964], [Sabanin, Smirnov, Repin, 2003], [Goldberg, 1989], [Voronovskiy, Makhotilo, Petrashev, Sergeev, 1997]. It is necessary to modify these methods, usually used for optimization of scalar objective functions, for optimization of vector objective functions taking into account all requirements to automatic control system [Kirillov, 1988], [Troyanovskiy, 1983], [Severin, 2007].

The purpose of this article is to develop models of the rotation frequency stabilizing systems of steam turbine rotor and its watching drive in state space with the using of standard and fuzzy regulators, and also to analyses optimization possibilities by genetic algorithms of the frequency stabilizing systems quality indices.

This purpose achievement will allow to do the steam turbines automatic control systems more effective taking into account all structural and technological requirements produced to them.

Possibilities of Genetic Algorithms and their Modification to Optimal by Synthesize Control Systems

Previous research experience of the automatic control systems with linear regulators has showed that the criteria of optimization, as a rule, were the same one-extreme. However, for the complex multicontour control systems and control systems with intelligent regulators presence of the large number of local extremes along with global ones is significant. Local extremes appear also in imposing restrictions on the area of search. For the solution of the same one-extreme task of optimization, there is a sufficient number of algorithms of gradient methods and methods of direct search. One of the most effective methods of direct search is the Nelder-Mead's method of the deformed polyhedron [Nelder, Mead, 1964].

Application of Nelder-Mead's method for the optimization of the automatic control systems with the fuzzy regulators of different structure does not result in an optimum decision. In every case results depend on the chosen coordinates of initial point of search. A conclusion result from this that objective functions of similar tasks are multiextremeness, and for their solution the global optimization methods are required [Sabanin, Smirnov, Repin, 2003].

The present time the most preferable methods of multiextreme optimization are genetic algorithms realizing the postulates of evolutionism and experience of selection of plants and animals [Goldberg, 1989]. The purpose of optimization of the control systems by genetic algorithms consists in finding the best possible decision of optimization task by one or few criteria. To realize a genetic algorithm it is needed at first to choose a suitable structure for these decisions presentation. In the search problem statement copy of this data structure presents a point in space of search of all possible decisions. To optimize a structure using a genetic algorithm it is needed to set some measure of quality for every structure in search space. The function of fitness is used for this purpose. During maximization the objective function turns itself into a fitness function. For the tasks of minimization it is necessary to invert an objective function and displace it after that to the area of positive values. Strategy of search of optimum solution in genetic algorithms relies on the hypothesis of selection: the more fitness of an individual is higher the higher is the probability that descendants, got with its participation, will have determining fitness features stronger expressed [Voronovskiy, Makhotilo, Petrashev, Sergeev, 1997].

If to accept that every individual of population is a point in coordinate space of optimization task $X_i[x_{1i}, x_{2i}, \ldots, x_{li}]$ and fitness of an individual is the proper value of objective function $f(X_i)$ then individual populations can be examined as a great number of coordinate points in space, and process of evolution — as motion of these points toward the improvement of values of objective function. A feature of the genetic algorithm as a global search method is that none of genetic operators in the descendants generation process leans on knowledge of local relief response surface for the objective function. Forming of descendants by genetic operators occurs in a random manner, and that is why there is no guarantee that found solutions will be better than paternal. The enumerated features restrain wide application of genetic algorithms in engineering practice. However necessity in such algorithms for the solution of the applied tasks of comparatively small dimension constantly grows, especially in connection with the planned tendency of introduction of fuzzy and neural network technologies in the control systems. For the optimum synthesis of the automatic control systems it is expedient to use vector objective functions taking into account all complex of system requirements in order of their preference [Severin, 2007]. As genetic algorithms are mainly used for optimization of scalar objective functions for optimization of vector objective functions these algorithms are modified with the using of operations of vector function values comparison [Severin, 2007].

Design and Optimization of Watching Drive

An electro-hydraulic watching drive is the main executive link of the automatic control system of frequency of rotation of steam turbines rotor. We will develop the mathematical model of watching drive intended for optimization of its quality indices.

The chart diagram of principle of electro-hydraulic watching drive on a fig. 1 includes an electro-hydraulic transformer (EHT), chopping off slide-valve (CHV), servomotor (SM), sensors of position (SP), electronic part (EP).

On the models of transformer, chopping off slide-valve, servomotor and sensor of position models of charts of drive with the different number of sensors are got. The flow diagram of watching drive with three sensors is presented on a fig. 2. The diagram includes summators, proportional link with a coefficient K, model of successive connection of electro-hydraulic transformer, chopping off slide-valve and servomotor, sensor of position of slide-valve of electro-hydraulic transformer, sensor of position of chopping off slide-valve, sensor of position of servomotor, three negative feed-backs according to the position of slide-valve of electro-hydraulic transformer, chopping off slide-valve and servomotor with coefficients k_y, k_s and 1. Signal $\xi_u = K(\mu_s - k_y \xi_p - k_s \sigma_p - \mu_p)$ comes to the entrance of electro-hydraulic transformer.

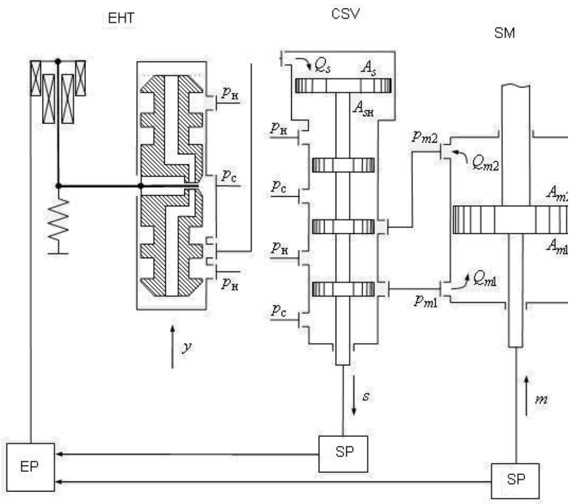

Figure 1. The chart of principle of watching drive

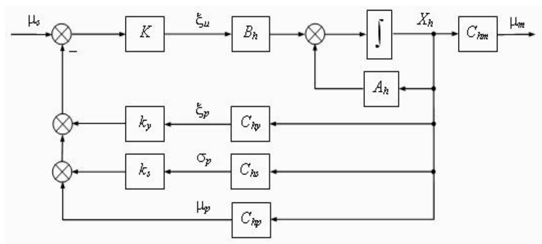

Figure 2. The flow diagram of watching drive

For the reliability of the automatic control system of rotation frequency of turbine rotor a watching drive must keep a considerable reserve of stability, be sensible to control signals and fast-acting. We will consider watching drive quality indices optimization by the modified genetic algorithms.

For optimization of drive we form a vector from its variable parameters $x = (K, k_y, k_s)$. We impose limitations $a_i \le x_i \le b_i$, $a_i = 0$, $b_i = 100$, $i = \overline{1,p}$ on the values of the varied parameters and form a penalty function for them: $S(x) = \sum_{i=1}^{p} \left[\max\{0, a_i - x_i\} + \max\{0, x_i - b_i\}\right]$. On the penalty function of limitations $S(x)$, penalty function of necessary condition of stability $P(x)$, coefficients of the first column of Routh table $\rho_k(x)$, $k = \overline{2, n-1}$, overshoot $\sigma(x)$, vibrations scope $\zeta(x)$, maximum values of overshoot and vibrations scope σ_m and ζ_m, control time $\tau(x)$ and domains of levels H_k, $k = \overline{0, n+2}$ we form the vector objective function:

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

This function takes into account all limitations of the system parameters. The first its projection — the function of level corresponds to the number of executed limitations, and the second projection the function of penalty determines the penalty of limitation violation [Severin, 2007].

The vector objective function in a priority order takes into account direct limitations on the system parameters, necessary and sufficient conditions of stability, limitations of direct quality indices, requirement of time minimum for the adjustment of the control system.

For its optimization the genetic algorithms were modified with the use of operations of the vector function values comparison [Severin, 2007].

The results of drive optimization with the applied quality criteria — improved integral quadratic estimation and direct quality indices – are presented in a table 1. For the number of calculating experiments N optimum values of the varied parameters K, k_y^*, k_s^* and adjustment time t^* founded by the modified genetic algorithm are presented. The graphs of the proper transitional processes are shown on a fig. 3.

Table 1. Results of optimization of watching drive

N	K	k_y^*	k_s^*	t^*, s
1	2.6	0.45	0.75	0.080
2	1.8	0.60	0.90	0.112
3	0.7	0.68	1.26	0.161
4	2.4	0.44	0.77	0.082
5	3.0	0.46	0.69	0.076
6	1.5	0.57	0.98	0.118
7	2.0	0.61	0.99	0.147
8	2.5	0.63	1.02	0.174

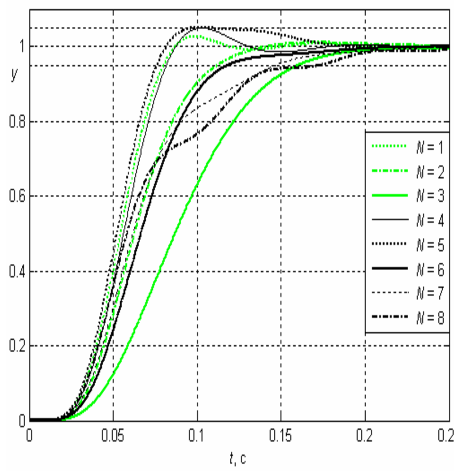

Figure 3. Optimum processes in a watching drive

These results, got by genetic algorithms, confirmed results that were got before by other optimization methods.

On a fig. 4 for $N=6$ the graphs of change of state variables of optimum watching drive are presented. Graphs turned out from the entrance step influence $\mu_s = 1(t)$.

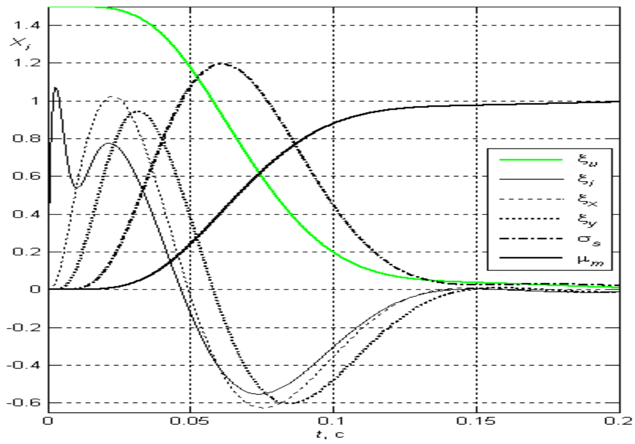

Figure 4. Change of state variables an optimal drive

All processes are smooth and quickly set without substantial vibrations. Coordinates of current ξ_i , displacement of managing spool ξ_x and slide-valve of electro-hydraulic transformer ξ_y from zero initial values increase at first, then diminished, reverse sign and aspire to zero eventual values. Coordinates of voltage ξ_u , chopping off slide-valve σ_S and servomotor μ_m are positive, ξ_u and σ_S aspire to zero eventual values, and μ_m aims at 1. Thus, watching drive quality indices optimization allowed to provide high quality of processes which flow in it.

Design and Optimization of the Control Systems of the Steam Turbine

We will consider the construction of mathematical models of the automatic control systems of the steam turbine K-1000-60/1500 in state space. The chart of principle of steam turbine is presented on a fig. 5 and includes the turbine adjusting valve (TAV), high pressure cylinder (HPC), volume before the high pressure cylinder, volume in a separator-superheater, separator-superheater valve (SSV), volume after the separator-superheater valve, middle pressure cylinder (MPC), low pressure cylinder (LPC), volume before the low pressure cylinder.

On the basis of the system of differential equations of watching drive, steam highway and rotor of steam turbine the mathematical model of turbine is got as a control object [Severin, 2007].

The automatic control system of frequency of steam turbine is intended for stabilization of the rotation frequency of steam turbine rotor. The heaviest test of the automatic control system of frequency of rotation is dropping of the nominal load of steam-turbine and passing to the no-load conditions. On developed model of the steam turbine K-1000-60/1500 we build models of the automatic control systems of rotation frequency of steam turbine rotor for the load dropping at the different laws of control with different regulators.

The flow diagram of the offered model of the real system of automatic control of steam-turbine rotation of frequency is presented on a fig. 6 and includes summarizing, regulator of frequency, steam turbine model and negative feed-back [Kirillov, 1988]. The signal of error is given on the entrance of standard regulator of frequency with a transmission function $W_C(t)$ and forms managing influence u . This influence and revolting signal ν_S come in model of steam turbine and change the vector of his state X_T . The coordinate of frequency φ is given by negative feedback on summarizing and with master influence φ_s forms the signal of error ε [Troyanovskiy, 1983]. The entrance perturbation action of the automatic control system of frequency is a signal of power change ν_S .

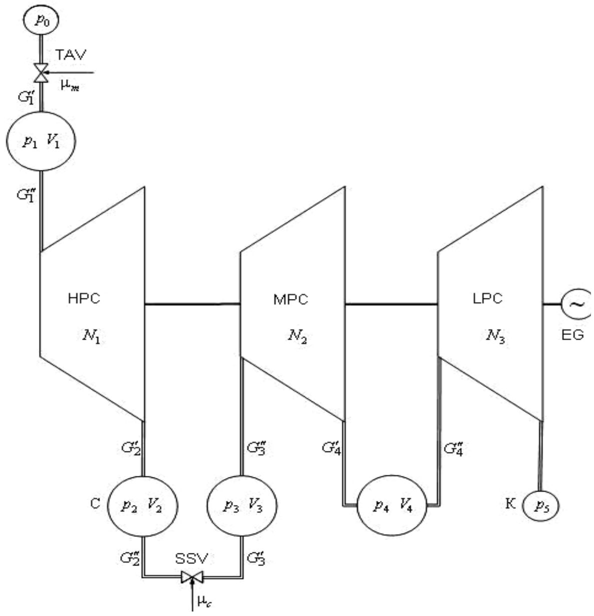

Figure 5. The chart of principle of steam turbine K-1000-60/1500

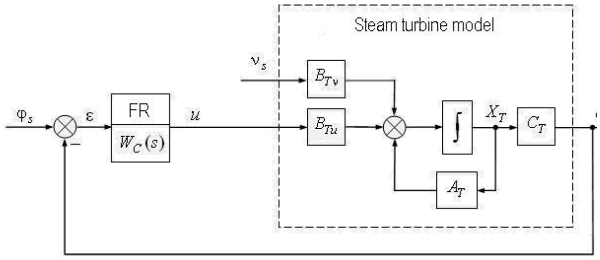

Figure 6. Flow diagram of the automatic control system of frequency of rotation

The output variable is frequency φ of steam turbine. On the basis of steam turbine model the mathematical models of its control systems are built with different regulators are built [Severin, 2007].

For optimization of parameters of the automatic control systems of rotation frequency we form a vector x from the varied parameters of PID-regulator of frequency K_P, λ_i and λ_D. We define the models of automatic control systems of rotation frequency at entrance perturbation action $\nu_s = -1(t)$ proper to the transition of steam turbine from the mode of nominal power $\nu = 0$ to the no-load conditions and to the output coordinate y of deviation of frequency in percents:

$$\frac{dX_C(x,t)}{dt} = f(x, X_C(x,t), \nu_S), \qquad y(x,t) = 100 \cdot C_C X_C(x,t),$$

where index C corresponds to the type of regulator P, I, D, PI, PD, ID or PID. Automatic control systems of rotation frequency with I, D and ID-regulators of frequency appeared uneffective as their optimum processes have frequency deviations which exceed 12 %. The results of optimization of vector objective function by the modified genetic algorithms are presented in table 2 and on fig. 7.

For the static automatic control systems of rotation frequency with P and PD-regulators $y(\infty) = 1.0$, and for the astatic automatic control systems of rotation frequency with PI and PID-regulators $y(\infty) = 0$. In the first four experiments the legitimate scope value of frequency vibrations is accepted $\zeta_m = 1$, and in the last two $\zeta_m = 0.5$. For $N = 5$ time of integration is set to $T_f = 50$, and in the other experiments to $T_f = 20$.

On fig. 8 the changes of some state variables of the optimum automatic control system of rotations frequency of steam turbine with a PID-regulator got at entrance step influence $\nu_S = -1(t)$ are presented. The coordinate of chopping off slide-valve $\sigma_S(t)$ changes in small limits and set in a zero value. The servomotor coordinate $\mu_m(t)$

diminishing takes on considerable negative values and passes to the value -1. The coordinate of power of turbine $\nu(t)$ from an initial zero value of nominal power after a few quickly attenuated oscillations aspires to the value -1 proper steam turbine idling. The frequency deviation coordinate $y(t)$ from an initial zero value after attenuated oscillations returns to zero nominal level. The signal of PID-regulator $u(t)$ diminishes and then after vibrations sets on a value -1. The electro-hydraulic watching drive output coordinate $\mu_m(t)$ repeats the signal change of frequency regulator $u(t)$ with a small delay.

Table 2. Results of optimization of the automatic control system of steam-turbine frequency

N	λ_I^*	λ_D^*	F_1^*	F_2^*	σ^*	ζ^*	t_c^*, s
1	—	—	20	2.0	3.6	3.0	3.56
2	27	—	22	0.3	3.5	1.0	5.19
3	—	1.1	21	1.7	3.5	2.7	3.16
4	31	1.1	23	0.2	3.4	0.8	3.50
5	10	—	22	0.4	3.6	0.5	19.42
6	23	1.1	23	0.3	3.4	0.5	5.04

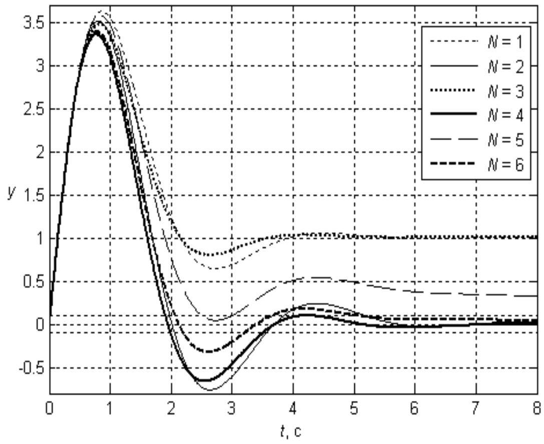

Figure 7 Change of frequency at different regulators

Thus, in this automatic control system of rotation frequency of steam turbine with a PID-regulator an electro-hydraulic watching drive and automatic control system of rotation frequency satisfy the requirements produced to them. Unlike the considered regulators a fuzzy PID-regulator allows to organize more flexible adjusting in PID control law with the automatic calculation of regulator adjustments for the objects with a proportional executive mechanism. Principle of action of fuzzy regulators differs from classic regulators by the fact that on the object entrance along with the regulator signal the additional trial sine wave signal of small amplitude is given. The calculation of regulator adjustments is carried out on amplitude and phase of harmonic constituent in the object output signal [Terano, Asai, Sugeno, 1993].

The fuzzy regulators use will allow to automatize better the process of contours adjusting and also to give up the use of object dynamics authentication ordinary methods and adjustment regulators optimum parameters calculation. As practice shows adaptive regulators allow to save up to 15% of raw material and energy resources as compared with a hand management or about 5% as compared with the not optimally adjusted classic PID-regulator. Moreover application of the adaptive adjustment leads to reduction of terms and costs of starting-ups and adjustment works.

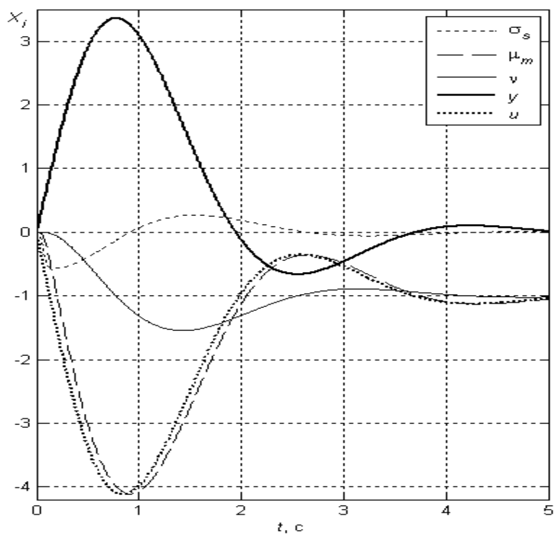

Figure 8. A state variables change in the optimal automatic control system of frequency

Conclusion

The results of the conducted researches allow to formulate following conclusions.

1. On the basis of models of electro-hydraulic transformer, chopping off slide-valve, servomotor and sensors of position a mathematical model in state space of steam turbine watching drive with three sensors is developed. Parameters optimization of this model provides high quality of monotonous process in a watching drive at the optimum value of amplification factor.

2. The mathematical models of the stabilizing systems of rotation frequency of steam turbine rotor are developed in state space with different standard and fuzzy regulators of frequency. The direct quality indices optimization tasks for the rotation frequency stabilizing systems are solved with the use of the modified genetic algorithms. The most effective standard type of frequency regulator at the turbine load dropping is a PID-regulator which provides the most rapid transitional process with the least deviation of frequency. Possibilities of fuzzy PID-regulators are analysed.

3. For optimization of vector objective functions of the automatic control systems the direct methods of unconstrained minimization and genetic algorithms which allowed to find the optimum values of indices are modified. Calculable experiments confirmed high efficiency of application of the modified methods.

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