Control systems design: the technology of simulation and optimization

L A Denisova$^1$ and V A Meshcheryakov$^2$

$^1$Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
$^2$Siberian State Automobile and Highway University, 5, Pr. Mira, Omsk, 644080, Russia

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

Abstract. The simulation and optimization technology is proposed for creating control systems that are designed for heat and power facilities. This paper presents an automatic feed control system of steam generators in the nuclear power plant unit on the basis of microprocessor controllers. The technology of simulation and optimization combines the methods of statistical modelling of disturbance signals, the control system simulation and the controller parameters optimization using genetic algorithm. As the initial data for the model design, we used archival information about processes on the existing unit equipment. The results of simulation studies and optimization of automatic control system’s parameters are derived in MATLAB.

1. Introduction
This paper discusses the approach to simulation and optimization of the automatic control system (ACS) for the steam generator (SG) feed system of the nuclear power plant (NPP) unit (as a typical automation object). For updating the ACS of SG feed used in the power units of Kol'skaya NPP, the specialists of Avtomatika-E (Omsk, Russia) and Omsk region scientists developed a software and hardware complex (SHC) on the basis of the microprocessor controllers VLR-2.1 [1]. The previous feed control system was updated due to its incompatibility with the modern safety and reliability requirements of an NPP. According to the requirements of Kol'skaya NPP, for each SG the technical specialists replaced the electronic control units and some components of the relay circuit responsible for technological blockings by the controllers VLR-2.1.

A SG feed system is one of the critical elements in the NPP with a water-water energetic reactor (VVER), therefore, the SHC for the ACS of SG feed with reliable and cost-saving operation of this system affects the performance of the whole power unit. In this paper, we present the simulation model of the SG feed ACS for the power unit of a NPP taking into account the actions of random disturbances on a controlled object. The autocovariance functions of random changes for technological parameters are estimated on the basis of archival data that characterize the industrial processes (IPs) in the power unit.

Simulation studies and optimization of the ACS of SG are carried out using the developed mathematical model and a genetic algorithm (GA).

2. Description of the SHC equipment
The SHC for the ACS of SG feed based on the controllers VLR-2.1 serves to keep feed water flows in SGs in all modes of power unit operation according to generated steam flows and to provide a water level setpoint in an SG. The software and hardware complex for the automatic control system of SG feed forms control actions to the electric drives of the main and start-stop feed control valves (FCVs). These valves perform water feed from a discharge header into a steam generator heated by a primary-circuit coolant. Strict requirements are imposed on water level stabilization in an SG. For the SG with VVER-440, the rated water level is $h_{gw}=1900$ mm. The precision of maintaining the specified level in
stationary modes makes up ±50 mm. The admissible dynamic overshoot is ±75 mm under load variation. Water level increase (decrease) with respect to the rated level is prohibited due to possible steam carryover into a turbine (heating surface exposure, respectively).

The SHC for the ACS of SG feed consists of six main controllers and six start-stop water level controllers used in SGs and realized via VLR-2.1 according to the number of SGs in a power unit. The main controller of each SG operates in the normal mode of the power unit, whereas the start-stop controller serves launching and terminating functioning of the unit.

Each of the main controllers of the SHC for the ACS of SG feed receives analog signals from three water flow sensors and three steam flow sensors, as well as from the actuating mechanism (AM) of the FCV position. According to the proportional-integral (PI) control law (formed jointly with the FCV AM), each of the main controllers in the SHC for the ACS of SG feed produces the control discrete signals for opening/closing of the main FCV, as well as the signal to the blocking circuit on exceeding the admissible value by water flow.

We will consider the issues of optimization for the ACS with the main controller. The main controllers of the SHC realize a three-pulse control system: the signals of measured water level (the basic controlled variable), feed water flow (the auxiliary variable) and superheated steam flow (the disturbance) are supplied to the controller’s input.

The ACS of SG forms control actions for the electric drive of the feed control valve which performs water feed from a discharge header into a steam generator heated by a primary-circuit coolant. Additionally supplied signals allow decreasing the influence of disturbances from the FCV and steam load variations on SG level.

The control action of the ACS of SG is feed water flow, and the disturbance is turbine steam flow which varies simultaneously with turbine power. Moreover, reactor power, heat supply from the primary circuit and other factors [2, 3] affect water level, too.

3. Estimation of disturbance statistical characteristics and synthesis of a shaping filter

The changes of SG water level, steam and feed water flows are processes that are affected by random disturbances. We plotted these technological parameters using archival data provided by the specialists of Kol’skaya NPP. We have presented the graph of one technological parameter, namely, the graph of the SG water level change (Figure 2a).

We evaluated the statistical characteristics of process parameters (such as random processes). So, we obtained estimates of the autocovariance functions of these processes. In Figure 2b, you can see the graph of the normalized autocovariance function for the SG level variations (sample size $n = 100$).

![Figure 1](image)

**Figure 1.** The measured and simulated SG water level signals and their autocovariance functions: a), b) - SG level variation; c), d) - SG modelled level variation with the shaping filter.
In the papers [9, 11], the authors previously proposed the technology of stochastic perturbations simulation for the study of production process control systems. The issues of the synthesis of a shaping filter that is designed to generate random signals with the required autocovariance function were considered. Spectral decomposition was used to obtain the transfer function of the shaping discrete filter.

Thus, we obtained that the discrete transfer function of the shaping filter and the recurrent algorithm for modeling the random process (with the autocovariance function $R(\tau) = \sigma^2 e^{-|\tau|} \cos \beta \tau$) have the following form, respectively:

$$K(z^{-1}) = \frac{a_0 + a_1 z^{-1}}{b_0 + b_1 z^{-1} + b_2 z^{-2}},$$

$$\bar{\xi}(n) = a_0 \xi(n) + a_1 \xi(n-1) - b_1 \bar{\xi}(n-1) - b_2 \bar{\xi}(n-2).$$

In these expressions, we denoted

$$a_0 = -\sigma \sqrt{\rho}; \quad a_1 = \sigma \sqrt{\rho}; \quad b_1 = -2 \gamma \cos \beta; \quad b_2 = \gamma^2; \quad \gamma = e^{-\alpha}; \quad v_1 = v_0 + \sqrt{v_0^2 - 1}; \quad v_0 = \frac{1 + \gamma}{2 \gamma \cos \beta};$$

$$\rho = \frac{(1 - \gamma^2) \gamma \cos \beta}{v_1}; \quad \xi, \quad \bar{\xi}$$

are the filter input signal (“white noise”) and the filter output signal (“color noise”), respectively. Parameters $\alpha$ and $\beta$ denote the decay and the periodic component frequency of the autocovariance function, respectively; $\sigma$ is the standard deviation of the signal; $\tau$ is a time lag; and finally, $z^{-1}$ is the inverse time shift operator.

The results of using the shaping filter to simulate a SG level signal are presented at Figure 1c. To control the results (correctness of the random process formation), we presented the autocovariance function graph for this process (Figure 1d).

4. The mathematical model of SG feed
In MATLAB/Simulink [5, 6] the model of the ACS of SG has been developed (see Figure 2). The system model consists of the following subsystems: the controller model, the subsystem for modeling the control valve (FCV) with AM, and the subsystem of control object (the steam generator model).

The digital impulse controller of the ACS of SG that have parameters are necessary to optimize implements the traditional control technique that is adopted in ACS with constant speed actuators. This technique is based on a proportional-plus-derivative (PD) relay-impulse converter. The converter is realized as two on-off relays (with dead zone and hysteresis) that are looped by common feedback.

In the feedback loop there is an inertial unit that has a transfer function $W_p(s) = \frac{1/k_p}{T_i s + 1}$, where $k_p$ is the controller’s gain; $T_i$ denotes the integration time constant. The controller receives a signal corresponding to the control error. It is formed as a weighted sum of the setpoint and current levels, as well as the steam flow and the feedwater flow.

The material balance signal between steam and feed water flows multiplied by a gain $k_g$ serves as local feedback in the system, guaranteeing high accuracy of required level maintenance. In the described relay-impulse controller, the pulse ratio of output impulses demonstrates the PD relationship with error signal variations. Such a relay-pulse controller together with AM approximately implements a proportional-and-integral control law. In addition, the system dam pens the input signals.
The controller’s tuning parameters are the gain $k_p$, the integration time constant $T_i$ and the feedback gain $k_g$. The sections with these parameters are shaded in Figure 2.

Being generated by the controller, the output pulse sequence comes to the AM of the FCV, which is represented by the amplifying and integrating sections. From the amplifying section output whose gain takes into account the FCV opening time $T_{am}$, the FCV travel speed signal comes to the integrator with restrictions (0 . . . 100%). The FCV position signal comes to the controlled object, where the feed water flow signal is formed as the product of the FCV position signal and the corresponding gain.

The subsystem steam generator is used for SG modeling (see Figure 3).

Figure 2. The model of the ACS of SG feed.

Figure 3. The SG model considering random disturbances.
This subsystem has two inputs, namely, the CV feed water flow and the parameter perturbation for forming deep disturbances of steam flow variations. The output variables are SG water level, steam and feed water flows with proper consideration of their mutual influence.

The parameters of the above linear SG model have been evaluated on the basis of design technological parameters of industrial equipment and also by approximation of SG dynamic characteristics computed using the nonlinear power unit model [3]. The control object parameters are given in Table 1. The parameter values are presented for the mode of disturbance of the steam flow.

### Table 1. The control object’s parameters.

| Parameter name                        | Designation (dimension) | Value    | Purpose of the transfer function                                                                 |
|---------------------------------------|-------------------------|----------|--------------------------------------------------------------------------------------------------|
| Transfer factor for the transfer function $W_3$ | $k_{w1}$                | -0.068   | The effect of feed water flow $G_w$ to steam flow $G_p$ ($W_3$)                                  |
| Time constant for the transfer function $W_3$ | $T_{w1}$ (sec)         | 2.5      |                                                                                                  |
| Transfer factor for the transfer function $W_2$ | $k_{w2}$                | 0.06     | The effect of feed water flow $G_w$ to SG level changes $h$ ($W_2$)                              |
| Time constant for the transfer function $W_2$ | $T_{w2}$ (sec)         | 13       |                                                                                                  |
| Transfer factor for the transfer function $W_1$ | $K_{p1}$                | -1.11    | The effect of steam flow $G_p$ to feed water flow $G_w$ ($W_1$)                                  |
| Time constant for the transfer function $W_1$ | $T_{p1}$ (sec)         | 40       |                                                                                                  |
| Transfer factor for the transfer function $W_4$ | $K_{p2}$                | 2.8      | The effect of reactor thermal power to steam flow $G_p$ ($W_4$)                                  |
| Time constant for the transfer function $W_4$ | $T_{p2}$ (sec)         | 10       |                                                                                                  |
| Transfer factor for the transfer function $W_5$ | $K_{p3}$                | 3.6      | The effect of steam flow $G_p$ to SG level changes $h$ ($W_5$)                                  |
| Time constant for the transfer function $W_5$ | $T_{p3}$ (sec)         | 5        |                                                                                                  |
| Object total transfer factor             | $K_{tot}$ (mm/ kg/ s)   | 0.18     | The transfer function of SG level changes                                                         |
| Decay of the autocovariance function     | $\alpha_{1}$           | 0.032    | The autocovariance function of SG level signal pulsations                                         |
| Periodic component frequency of the autocovariance function | $\beta_{1}$           | 0.01     |                                                                                                  |
| Parameter standard deviation             | $\sigma_{1}$ (mm)      | 1.8      |                                                                                                  |
| Decay of the autocovariance function     | $\alpha_{2}$           | 0.02     | The autocovariance function of steam flow signal pulsations                                       |
| Periodic component frequency of the autocovariance function | $\beta_{2}$           | 0.02     |                                                                                                  |
| Parameter standard deviation             | $\sigma_{2}$ (mm)      | 0.18     |                                                                                                  |
| Decay of the autocovariance function     | $\alpha_{3}$           | 0.03     | The autocovariance function of feedwater flow signal pulsations                                  |
| Periodic component frequency of the autocovariance function | $\beta_{3}$           | 0.01     |                                                                                                  |
| Parameter standard deviation             | $\sigma_{3}$ (mm)      | 0.4      |                                                                                                  |

SG water level is the integral from the material imbalance between steam and feed water flows. For modeling of SG dynamic properties by water level, each of influence channels is described by the sum of an integrator and an aperiodic section (note that the former is common for the both channels).
In addition, the SG model includes aperiodical sections necessary for describing the mutual influence of disturbances for steam and water flows. The fluctuations of random disturbances of the water level, steam and feed water flows are formed by a shaping filter and then added to the SG model outputs. At the same time, Band-Limited White Noise generates normally distributed white noise, which is fed to the shaping filter. For optimization, the model computes an integral control performance criterion (the performance criterion subsystem in Figure 3): \( J = \int_T^0 (\epsilon^2 + \lambda u)^2 \, dt \), where \( \epsilon \) is the controlled parameter deviation from the setpoint value; \( u \) denotes the controller’s output signal supplied to the AM; \( \lambda \) represents a weight coefficient; \( t \) indicates the current time; \( T \) means the upper limit of integration chosen not smaller than the response time. Minimization of the performance criterion \( J \) guarantees high response and the absence of overshoot, as well as decreases the number of AM runs. The developed mathematical model of the ACS of SG feed allows carrying out simulation studies in different operation modes and defining the parameters leading to minimization of the chosen performance criterion of ACS operation.

5. Experimental studies and parameter optimization of the ACS of SG
Experimental studies have been performed using m-files, i.e., MATLAB scenarios realizing multiple calls of the Simulink model of the ACS of SG. The following aspect has been taken into consideration. Computations with complete enumeration of adjustable parameters require a considerable time, whereas wider range of parameters or their smaller increments for higher solution accuracy actually further increases time costs and makes the task unfeasible. ACS optimization based on the genetic algorithm [7-11] from MatLAB/Global Optimization Toolbox eliminates this problem. Using the GA, we have found the optimal parameters of the ACS of SG and obtained the corresponding transient processes under for insignificant time costs.

The genetic algorithm represents an optimal solution search method based on genetic inheritance and natural selection [6]. In comparison with traditional optimization methods, the GA enjoys an advantage that solution search involves a set (population) of points. The algorithm considers only most promising search domains in the sense of optimal value approximation owing to the crossover of the most adapted individuals (application of the crossover operator). Next, the random mutation operator yields individuals with new properties. Figure 4 illustrates GA operation in one of the performed realizations during ACS optimization.

![Figure 4. ACS optimization using the genetic algorithm.](image)
Particularly, Figure 4a shows the dynamics of the performance criterion for the best individuals and its average value across the whole population. Merely 10 generations have been required for obtaining optimal parameters: clearly, the algorithm converges to the solution. And Figure 4b represents the elements of the optimal parameter vector $X_{opt} = (k_p; T_i; k_g)$ in the form of bar charts.

Since a random-number generator specifies the initial population in the GA, we have carried out several realizations of computations and selected the best ones among the obtained solutions. The optimization result for one of the realizations is demonstrated by Figure 5. Here SG runs in the disturbed mode: steam flow goes down by 15% from the nominal value at the 150th second.

The graphics show that the steam flow decrease is well processed by the SG water feed controller within one pulse only. Feed water flow is adjusted in accordance with steam flow, and the door position in operation range varies by less than 10%. SG level is maintained within the required accuracy ± 50 mm.

The controller’s parameters (obtained as a result of modeling and optimization) are presented Table 2. Note that the disturbance has been successfully processed by a small number of controller’s pulses in the majority of realizations. The conducted studies lead to a conclusion that the suggested optimization method based on the genetic algorithm is efficient for computer-aided design of ACS optimization with proper consideration of active random disturbances.

**Figure 5.** The transient characteristics for the ACS of SG under steam flow disturbance.

### Table 2. The controller’s parameters.

| Parameter name                          | Designation (dimension) | Value |
|-----------------------------------------|-------------------------|-------|
| Controller’s gain                       | $K_p$ (sec / mm)        | 0.1   |
| Time constant of the integration        | $T_i$ (sec)             | 5     |
| Feedback transfer factor                | $K_g$ (mm / (kg / s))   | 10    |
| Time constant of the level signal damping | $T_{f1}$ (sec)       | 1     |
| Time constant of the steam flow signal damping | $T_{f2}$ (sec)   | 1     |
| Time constant of the feed water flow signal damping | $T_{f3}$ (sec) | 2     |
| Controller dead zone                    | $\Delta_d$ (mm)        | 50    |
| Controller return zone                  | $\Delta_r$ (mm)        | 30    |

6. Conclusion
We have suggested the technology of system simulation and optimization that combines the methods of statistical modelling of disturbance signals, the control system simulation and the controller parameters optimization using genetic algorithm.

The developed mathematical model of SG feed allows performing control channels adjustment in the SHC for the ACS of SG feed and conducting simulation experiments for its dynamic characteristics in transient modes with different load variations under active random disturbances.

The dynamic tests of the developed model have proved that the SHC for the ACS of SG feed maintains the SG parameters in the normal operation ranges of the power unit.

Note that the obtained transfer function of the shaping filter that we have used for modelling of disturbance signals can be employed to model other IPs incorporating random disturbances under strict requirements imposed on control quality.

The mathematical model of SG feed with active random disturbances realized on the testing rig of Avtomatika-E makes it possible to carry out a prompt control system tests in different operation modes and to elaborate recommendations on parameter optimization of the SHC for the ACS of SG feed.

References

[1] 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

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

[3] 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

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

[5] 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

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

[7] 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)

[8] 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

[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] Denisova L and Meshcheryakov V 2016 Synthesis of a control system using the genetic algorithms IFAC-PapersOnLine vol 49 issue 12 pp 156-61

[11] 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