



AN INCREASE IN EFFICIENCY AND OPERATING RELIABILITY OF THE SYSTEM FOR AUTOMATIC CONTROL OF STEAM TURBINES FOR NUCLEAR POWER PLANTS

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Abstract

First and foremost, operation of nuclear power facilities is inseparably linked with solving the problems of their safety. To enhance safety, assure high reliability and effectiveness of controlling power units, software and hardware (SH) for computer-assisted control over a power unit [VIII, IX, XIV, V] are introduced, with electronics of electro-hydraulic governing systems of turbines (EHGS). EHGS is the principal system, which ensures functioning of turbine in all stationary and intermittent operation modes.

Quality and reliability of supplying power to consumers directly depend on one function of the system for governing turbine, namely, on automatic frequency-capacity control. According to the existing standards of document [XVIII], regulation of frequency is specified by: the value of and time for mobilizing reserves, frequency droop, and dead-band of automatic control system (ACS). A response from power unit to changes in frequency shall be such that, when the value of drooping is fixed, a half of the required alteration in the power unit capacity is to be made within 10s, and 100% – within 30s. The standard specification prescribes the following recommended frequency droops for NPP turbines: 4...6%, recommended dead-band of the primary frequency regulation: a maximum of 0.02 Hz. Such requirements may be met rather well, when using turbines equipped with electronic speed controller (ESC), which eliminates frequency deviations with high accuracy and makes it possible to promptly adjust the degree of irregularity and dead zone of frequency controller. Hence, to introduce standard primary and automatic secondary control on the involved NPPs, pursuant to the modern requirements, a need has arisen to modernize their equipment. The design schemes of the systems for controlling steam turbines of NPPs had undergone changes, related to making

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electronics more sophisticated and simplifying hydraulics. However, in general, modernization has enhanced efficiency and reliability of the turbines' ACSs. The data of rough calculation of structural reliability of the designed and newly modernized hydraulic systems, presented in this article, prove the results of quantitative assessment of reliability. A comparative analysis is given of standby and design ACSs of turbine K-1000-60/1500-2 considering major technical parameters and functional capabilities.

Keywords: Automatic control system; power unit; modernization; turbine installation; frequency; turbine generator; electronic speed controller; efficiency; reliability; automation; safety.

I. Introduction

Nuclear power industry involves a variety of power plants, mostly specified by the type of nuclear reactors used [II].

A number of models of low-speed, condensing, steam turbines with 1500rpm rotation frequency designed by Turboatom PA are used at the NPPs with reactors of VVER-1000 type. There are several factors inherent in the process of operating steam turbine K-1000-60/1500 such as emergency shutdown and start-up of turbine, conversion of turbine to idling or BoP power supply load, operation with capacity limitations, which reduce its reliability and cost effectiveness. Hence, a constant work is underway to create new design alternatives with improved technical characteristics, therefore, turbine K-1000-60/1500 has two model types:

- K-1000-60/1500-1, a turbo generator 57.4m long (50.7m with no generator), with high-pressure cylinder (HPC), intermediate-pressure cylinder, and three low-pressure cylinders (LPC), with single-pass side condensers; 1030 MW rated and maximum capacity [XI];

- K-1000-60/1500-2, a single-shaft four-cylinder unit of up to 52.2m length, which consists of HPC, three LPCs; with under slung condensers; weight with condenser is 350 tons lower [IV, XV]; capable of generating capacity of up to 1114 MW, intended to be directly connected to 1000MW turbine generator actuator unit; slightly differs from the first model type.

A system of automatic control and protection (ACS&P) is an integral part of any turbo generator set. ACS of the designed turbine K-1000-60/1500 was made combined, and it involved EHGS, where control electronics and hydraulic actuation system were used together, as well as the hydraulic control system (HGS) with control hydraulics and the same hydraulic actuation system, as for EHGS [XIX, XX].

EHGSs of turbines of K-1000-60/1500 type were made according to the double-actuator scheme, where each hydraulic actuator of control valves was governed from electrohydraulic turbine control unit (EHTCU) of its own (Fig.1, [XVI]). The design alternative of the scheme has three lines of controlling servomotors, two of which are from EHTCU No.1 ($P_{1\text{contr}}$) and

Reliability and efficiency of operating turbine ACS may be enhanced through improving the quality of the turbine static and dynamic parameters, stability in maintaining them, and by modifying and improving the designed diagrams of governing system. Publications of the authors [XXII, XXIII] cover the main ways for modernization of the ACS hydraulics of turbine K-1000-60/1500-2, made stepwise based on the analysis of operation of the governing system hydraulic units, identification of problems of the designed hydraulic system, and search for alternative solutions to solve the problem of controlling. Introduction of ESC instead of hydraulic speed controller was the final stage of improving K-1000-60/1500-2 EHGS. It enabled to reduce the volume and functions of hydraulics, but, however, to extend the functions of governing turbine, when operated with no EHGS [XXIV], and automate the operations of switching over EHGS-ESC modes, when EHGS SHC fails to operate, and, thus, to enhance reliability and efficiency of turbine installation.

Modernization of Hydraulic Diagram of Electro-Hydraulic Governing System of Turbine K-1000-60/1500-2

The structural diagram of modernized ACS of turbine K-1000-60/1500-2 with ESC as its part is given in Fig.2 [VII].

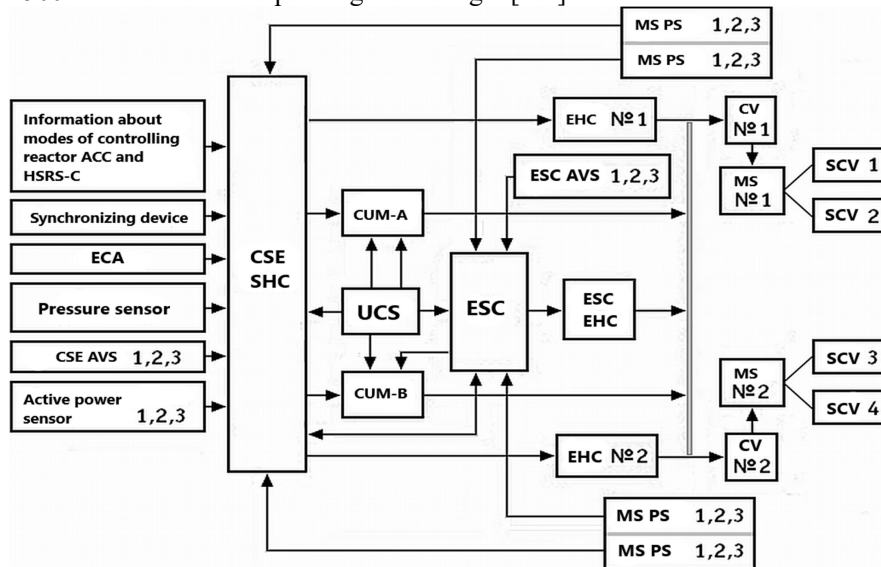


Fig. 2: Structural diagram of the system for governing turbine equipped with electronic regulator of speed: ECA - emergency control system, CSE AVS - angular velocity sensor of control system electronics; CSE SHC - software-hardware complex of control system electronics; UCS - unit control station; CUM-A, B – current unloader mechanism of sides A and B, respectively; ESC - electronic speed controller; ESC AVS 1, 2, 3 – angular velocity sensor of electronic speed controller 1, 2, 3; EHC 1,2 – electrohydraulic converter 1, 2; ESC EHC – electrohydraulic converter of electronic speed controller; CV 1, 2 – cutoff valve 1, 2; MS 1,2 – main servomotor 1,

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2; MS PS 1, 2, 3 - position sensor of main servomotor 1, 2, 3; SCV 1, 2, 3, 4 – stop and control valve 1, 2, 3, 4.

Technically, electronics of ESC (see Fig.2) is based on typical software-hardware tools (TSHT) [VII]. ESC receives and processes information, generates control signals, and passes commands to hydraulic actuation part of governing system according to the following operation modes [XXIV]: «Tracking» – mode without creating control commands to ESC EHC and CUM-A,B; «Initial ESC» – mode of off-state of control valves and control dampers; «PM» – mode of maintaining pressure in the main steam header (MSH); «ESC CVP» – mode of maintaining position of control valve of turbo generator set (TG); «PM-2» –standby mode of maintaining steam pressure in MSH with lowered setting.

Actuation mechanisms of ESC are: individual electro-hydraulic converter, which simultaneously governs servo motors of control valves on both turbine sides, and two mechanisms of current unloading: CUM-A, CUM-B– common with EHGS. Signal [XXIV] comes to ESC EHC

$$I_{\text{ESC EHC}} = \square + I_{\text{force}},$$

where \square – proportional signal; I_{force} – forcing signal.

Proportional signal \square in all the modes of ESC operation shall be as follows

$$\square = K \cdot (\square_{\text{ESC}} - (S_{\text{MS-A}} - S_{\text{MS-B}})/2) \square \cdot I_{\text{nom}},$$

Where K – proportion factor; \square_{ESC} – estimated discrete signal, which defines a specified position of servomotor of control valves for the current operation mode; $S_{\text{MS-A}}$, $S_{\text{MS-B}}$ – analog signals of feedback according to the position of control valves' servomotor; I_{nom} – nominal current, which ensures simultaneous closure of main servomotor (MS) and control dampers (CD); I_{force} – signal, which ensures forced closure of control valves.

ESC operates by the commands of electronics and governs control valves and control dampers. Electric control commands from ESC electronics are sent to ESC EHC and, at the same time, to CUM-A, B (see Fig.2). Simultaneous operation of ESC EHC and CUM-A, B changes pressure in two control lines, hence, cutoff valves shift, which causes changes in pressure drop on the main servomotors' piston due to changes in the supply and drain balance of actuation fluid. Due to this pressure drop, MSs, while moving, rearrange control valves in the specified direction.

When strong control signals are sent to close steam distribution elements, cutoff valves shift to the degree, which enables control dampers' CVs to be actuated due to changes in pressure in their control lines.

When ESC operates, hydraulic actuators of control valves are connected with hydraulic and electronic feedbacks from the set of position sensors. As main servomotors shift, signals from MS PSs to ESC electronics, considering which ESC electronics issues control commands to accurately position MSs.

CUM-A, B operate more slowly than ESC EHC. CUMs-A, B, while moving, compensate a need for maintaining high control currents for ESC EHC. Thus,

CUMs–A, B unload currents, and synchronize relative position of hydraulic actuators of control valves on the right and left turbine sides.

Since ESC is a standby system used in the case of EHGS electronics-related problems, its lifetime is limited to the time required to identify the reasons for failures and restoration of EHGS electronics. In case of simultaneous failure in EHGS and ESC, turbine shall be governed remotely. Then, an operator unloads turbo generator set according to schedule with further outage of turbine.

When comparing the main technical characteristics of K–1000–60/1500–2 turbine ACS in the designed and modified alternatives, it is obvious that efficiency and reliability of the modernized ACS operation are higher. Thus, the total degree of non-uniformity in static characteristic “active power – power-line frequency” amounts to $4.5 \pm 0.5\%$ of the rated rotation frequency (up to 10% for the designed alternative); rotation frequency insensitivity, while maintaining power line frequency, is not beyond 0.04% of the rated value (0.06% for the designed alternative).

If the functions of standby governing systems in the designed and modified alternatives are compared, the main HGS task is to maintain rotor rotation frequency with 4.0...5.0% non-uniformity and 0.2% non-sensitivity towards changes in rotation frequency. ACS of turbine with ESC functions as an independent digital PI-controller with a certain algorithm of operation. ESC is capable of maintaining turbine at the achieved level of capacity for a long time, defined according to regulations. “Flexibility” of governing system with ESC makes it possible to improve accuracy of synchronizing position and motion of control valve through the appropriate fine tuning of CV control circuits, which is not technically complex. Dynamic characteristics of ESC in operation, obtained during experimental tests on power unit No.2 of Rostov NPP [VII] are presented in Fig.3.

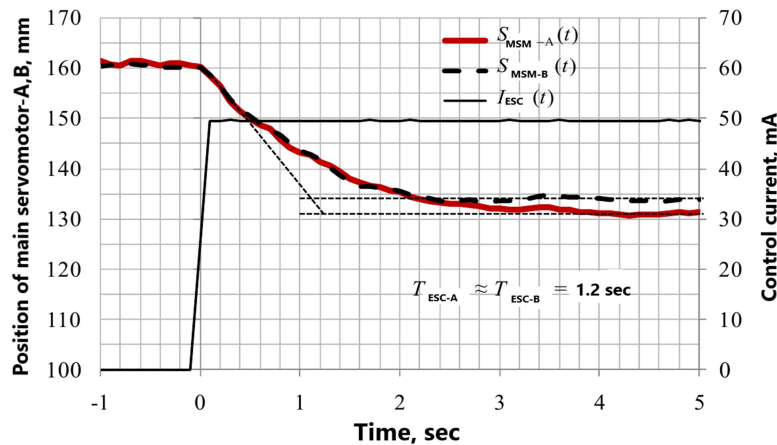


Fig. 3: Dynamic characteristics of servomotors when operated from ESC

Quantitative assessment of reliability of the two hydraulic systems of ACS of turbineK-1000-60/1500: alternative with ESC (see Fig.2) and designed option (Fig.4, [XXI]), is shown by the example of preliminary calculation of structural reliability. When assessing reliability, it has been taken into account that the turbine governing system is restorable, and ESC is on hot standby. Computation of reliability is based on the following assumptions: all elements are equally reliable; rates of failures in all the system elements do not depend on time, failure in any element results in failure of the whole system.

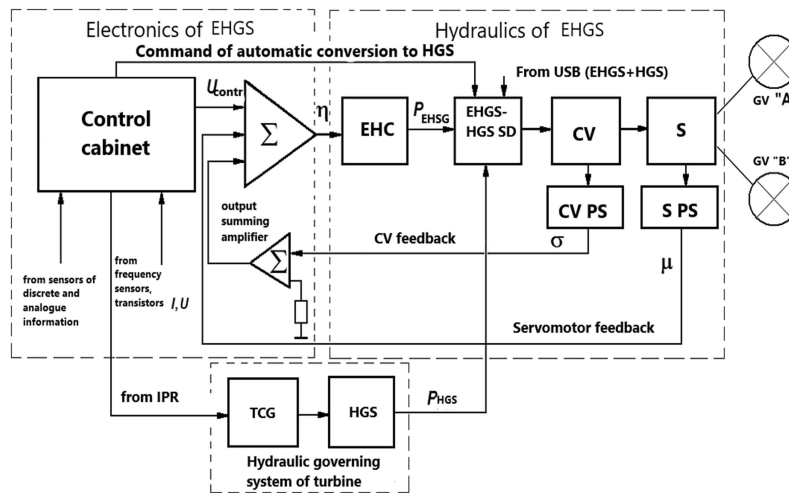


Fig. 4: Structural diagram of electro-hydraulic follower actuator of the designed ACS of turbineK-1000-60/1500

Failure in operation of each element of the designed models is both a breakdown, and a change in its parameters, which causes inadequate fulfillment of at least one function inherent in it within the specified requirements.

Statistics shows that most failures in the equipment of fuel and hydraulic systems are related to abnormal performance of precision pairs and sealing elements. Here, most failures, including breakdowns in hydroelectric units, occur due to improper operation of control and distribution devices, and plunger, piston, and laminated pairs, functioning like displacement or power elements of pumps and hydraulic motors [I].

Thus, for example, hydraulics of the designed ACS of turbine involves such elements as EHC, SD, SC, where spool functions as a sensitive element, which is constantly under pressure of hydraulic fluid and spring force. Minor changes in the power fluid pressure cause motion of a spool with respect to box and variation in hydraulic fluid consumption through the respective channels, connected to the spool and sleeve. As the friction forces between spool and box increase, the minimum value of pressure increment, to which the spool will respond, will increase, hence, operating parameters of sensitive element will worsen: sensitivity of controller will be lowered,

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static error in governing system will be greater, which, actually, constitutes an inadequate fulfillment of turbine ACS functions or failure.

Preliminary Computation of Structural Reliability of Hydraulics of the Turbine Governing System

4 years of the power unit lifetime shall be assumed to make a preliminary computation; the total operating hours of the system elements shall be $T_{\text{total}} = 4 \cdot 365 \cdot 24 = 35040$ h. This value shall be taken as the initial data on the basis of norms, according to data in [XII]: values of non-failure operating time shall be taken for control systems, used for automatic governing, as at least 20 thsd. hours.

The initial structural diagram, drawn based on the designed system hydraulics diagram (see Fig.4) for calculating reliability, is given in Fig.5.

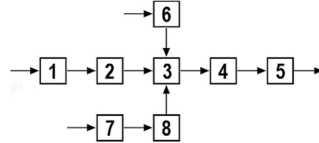


Fig. 5: Initial structural diagram of system: 1 – electro-hydraulic converter of electro-hydraulic governing system (EHGS EHC); 2 – switching device (SD); 3 – cutoff valve (CV); 4 – main servomotor (MS); 5 – high pressure control valve (HP CV); 6 – electro-hydraulic converter of hydraulic governing system (HGS EHC); 7 – pump-impeller (PI); 8 – speed controller (SC)

Elements 3, 6, 7, 8 in the diagram are connected in series; they shall be replaced with quasi-element A , failure-free operation probability of which shall be determined, pursuant to [X], by formula

$$P_A = P_6 \cdot P_3 \cdot P_7 \cdot P_8,$$

where P_6, P_3, P_7, P_8 – probabilities of failure-free operation of elements 6, 3, 7, 8 of structural diagram 5.

The diagram in Fig.5 shall be transformed, taking into account the replacement, into the diagram shown in Fig.6.

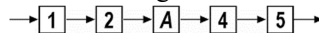


Fig. 6: Structural diagram after transformation

Elements 1, 2, A , 4, 5 in the modified diagram are also connected in series. Hence, the probability of failure-free operation of all the system

$$P = P_1 \cdot P_2 \cdot P_A \cdot P_4 \cdot P_5,$$

where $P_1 \cdot P_2 \cdot P_A \cdot P_4 \cdot P_5$ – probabilities of failure-free operation of elements of structural diagram 6.

Since, according to the condition, all the system elements function within the period of normal operation, during which gradual failures cannot yet be detected, however, sudden failures occur; to determine the probability of failure-free operation of elements 1-8, an exponential law of distribution shall be used [X].

$$P_i(t) = \exp(-\lambda_i t), \quad (1)$$

Where

λ_i – rate of the i^{th} element failure, 1/h; t – period of failure-free operation, h.

The results of calculating probabilities P of failure-free operation of quasi-element A and hydraulics of the designed system are given in Table 1.

Table 1: Calculation of probability of the designed system failure-free operation

Element	λ_i , 1/h	Running hours $t \cdot 10^3$, h						
		1	6	12	18	24	30	35
1	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
2	$1.000 \cdot 10^{-6}$	0.999	0.994	0.988	0.982	0.976	0.970	0.966
3	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
4	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
5	$30.000 \cdot 10^{-6}$	0.970	0.835	0.698	0.583	0.487	0.407	0.350
6	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
7	$13.500 \cdot 10^{-6}$	0.987	0.922	0.850	0.784	0.723	0.667	0.623
8	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
A	–	0.982	0.897	0.805	0.723	0.649	0.582	0.532
P	–	0.949	0.732	0.535	0.392	0.287	0.210	0.162

Rates of failures in the system elements and units, given in the table, are from sources [XVII, III].

Rate of failures in the main channel shall be defined by formula [X]

$$\lambda_o = \sum_{i=1}^n \lambda_i, \quad (2)$$

where λ_i – rate of failure of the i -thelement; n – number of elements.

The computed rate of failures in the main channel amounts to
 $\lambda_0 = 5.205 \cdot 10^{-5} \text{ 1/h.}$

An average time of failure-free system operation shall be computed using formula

$$T_{\text{syst}} = 1/\square_o .$$

(3)

Substitution of the values into expression (3) provides the average time of failure-free operation of the designed diagram of the system of
 $T_{\text{syst}} = 1.921 \cdot 10^4 \text{ h.}$

To compute reliability of standby diagram (see Fig.2), the structure of hydraulics of this ACS shall be transformed. Reliability of this diagram shall be computed with the same initial data, as for the designed one, i.e., the power unit lifetime amounts to four years, and the total period of the system elements operation is 35040 hours. The initial structural diagram of standby system hydraulics to compute reliability is given in Fig.7.

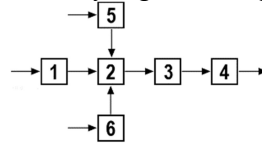


Fig. 7:Initial structural diagram of standby system: 1 – electro-hydraulic converter of electro-hydraulic governing system (EHGS EHC); 2 – cutoff valve (CV); 3 – main servomotor (MS); 4 – high pressure control valve (HP CV); 5 – electro-hydraulic converter of electronic speed controller (ESC EHC); 6 – current unloader mechanism (CUM)

Since elements 2, 5, 6 in the initial diagram are connected in series, quasi-element A shall be introduced for replacing these elements; then, the probability of its failure-free operation is as follows

$$P_A = P_5 \cdot P_2 \cdot P_6,$$

Where P_5, P_2, P_6 – probabilities of failure-free operation of elements 5, 2, 6 of diagram 7.

Considering the transformation made, the modified diagram shall take on the form, shown in Fig. 8.

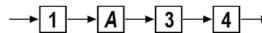


Fig. 8:Structural diagram after transformation

Elements 1, A , 3, 4 in the modified diagram are connected in series. Then, the probability of failure-free operation of the entire standby system

$$P = P_1 \cdot P_A \cdot P_3 \cdot P_4,$$

where P_1, P_A, P_3, P_4 – probabilities of failure-free operation of diagram 8 elements.

Table 2: Calculation of probability of standby system failure-free operation

Element	$\lambda_{ij}, 1/h$	Running hours $t \cdot 10^3, h$						
		1	6	12	18	24	30	35
1	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
2	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
3	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
4	$30.000 \cdot 10^{-6}$	0.970	0.835	0.698	0.583	0.487	0.407	0.350
5	$1.510 \cdot 10^{-6}$	0.998	0.991	0.992	0.973	0.964	0.956	0.949
6	$1.510 \cdot 10^{-6}$	0.998	0.991	0.982	0.973	0.964	0.956	0.949
<i>A</i>	—	0.995	0.973	0.947	0.947	0.897	0.873	0.854
<i>P</i>	—	0.961	0.798	0.650	0.522	0.405	0.325	0.269

Since, according to the condition, all the system elements function within the period of normal operation, the probability of failure-free operation of elements 1 – 6 shall be defined by formula (1). The results of computing probabilities P of failure-free operation of quasi-element A and hydraulics of standby system are given in Table 2.

The rate of failures in the main channel shall be defined by formula (2); estimated value will amount to $\lambda_o = 3.755 \cdot 10^{-5} 1/h$.

An average time of standby system failure-free operation is computed by formula (3), and will amount to $T_{\text{sys}} = 2.7 \cdot 10^4 h$.

Thus, quantitative assessment of enhancing reliability of ACS of the turbine with ESC has shown that the average time of the system non-failure operation has increased by 8000 hours due to minimizing the hydraulic component and improving quality of electronics and control algorithms. The completed modernization is in compliance with the requirements for safety of power units. No deviations of such main technological parameters, as steam pressure in MSH, electric capacity of power unit, and turbine rotation frequency from nominal rated parameters are allowed in the ACS of turbine K-1000-60/1500–2 with ESC. The technical basis, on which EHGS and ESC are made, allows performing further modernization with no need for changing the previously implemented technical solutions.

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