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Research Article

Mathematical simulation of an automatic steam turbine control system*

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Abstract

The paper considers the construction of a mathematical model for an electrohydraulic system to control automatically the T-63-13,0/0,25 product manufactured by JSC Kaluga Turbine Plant. Mathematical simulation of control systems makes it possible to improve considerably the quality of control, that is, the accuracy and reliability of such systems, as well as to accelerate greatly the development and calculation of the control system and the parameters of its individual components. The T-63-13,0/0,25 mathematical model of the ASTCS allows estimating the effects of design parameters during any load dropping (in a range of 0 to 100%) and the quality of control for the monitored parameters both in the process of operation as part of an isolated power system (generator output, frequency) and an integrated power system (generator output). A mathematical representation has been developed in the model for the control units, the T-63-13,0/0,25 product model, and the electronic controlling part of each of the control units. It has been proposed that pulse-width modulation be used to control the synchronous motors which makes it possible to control the synchronous machine shaft speed by changing the supply voltage frequency. To this end, the control system's model uses a frequency converter which is proposed to be used in the real control system. The developed control system with one adjustable steam extraction in the T-63-13,0/0,25 steam turbine is coupled and autonomous, that is, each of the two meters for the turbine's controlled parameters has effect on both steam distribution systems such that a deviation for one of the controlled parameters does not lead to excitations in the other.

Keywords

Power turbine, mathematical model, nonlinear automatic control system, stability of control process, control algorithm

Introduction

Mathematical methods are of special importance in investigating the dynamic performance of the power turbine automatic control systems (ACS). They not only form the basis fo analytical methods but also become an integral part of experimental studies. The key to success in this shall be mathematical models that reflect correctly the dynamic properties of components. A mathematical model makes it possible to determine the quantitative indicators of the quality of turbine control, this being a critical task since neither existing ACSs (and, accordingly, the turbines equipped with these) can be operated nor new ones developed without knowing

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these quality indicators. Mathematical simulation allows improving significantly the quality of control, that is, the accuracy and reliability of such systems, as well as speeding up greatly the development and analysis of the ACS and some of its components. The level of the model complexity shall not preferably exceed that required for the given type of studies. To build a model, the researcher always keeps in mind the objectives pursued, taking into account only those facts that are of most importance for achieving these objectives. Any model is not therefore identical to the original object and is, thus, incomplete since it is only the facts the researcher believes to be most important that are taken into account in the model construction process.

The mathematical model of the turbine control system is important for identifying at the design development stage the influence of such design parameters of the ACS actuators as the servomotor time constants, cutoff slide valve port areas and other components on the quality of transients, as well as for

- testing the stability of the turbine generator control process; and
- exploring the dynamic qualities of the control system during load sheddings (dynamic overshoots for the control system links, transient duration, etc.).

The objectives at hand allow estimating the ACS operation efficiency and the system reliability in conditions of long-term operation.

Construction of the mathematical model for the T-63-13,0/0,25 turbine control system

In the overwhelming majority of cases, steam turbines (ST) are used in power engineering as primary motors to drive synchronous generators. Since no generated electricity is accumulated anywhere in the grid, electricity generation shall at any time correspond to consumption. The criterion for this correspondence is the persistance of the grid frequency, a parameter the value of which in a steady-state mode is the same for any grid point. The rated power value of the grid frequency in Russia is equal to 50 Hz and shall be maintained with high accuracy (T-63-13.0/0.25, Technical Requirements, Vaynshteyn et al. 2010).

The key objective pursued in this paper is to build a model of an ACS with the facility being controlled to identify the influence of design parameters on the ST dynamics; this actually involves the problem of the closed ST ACS analysis.

The purpose of the closed nonlinear automatic control system analysis is to determine the output signal (transient) or error signal characteristic.

It should be noted that a number of assumptions shall be introduced both in analyzing and synthesizing the ST control systems, that is, the most important mode (100% electrical load shedding) is considered. This mode shall not lead to the operation of protection when shutoff valves stop to feed steam into the turbine. If the ST ACS develops this mode, the control system is assumed to operate normally (Vinogradov 2008).

A mathematical model has been built for the T-63-13,0/0,25 ST ACS, which makes it possible to assess the influence of design parameters at any load shedding (from 0 to 100%), as well as the quality of control for the monitored parameters in the process of operation both for an isolated grid (generator output power, frequency) and for an integrated grid (generator output power). The ACS mathematical model is presented in a functional form in Fig. 1.

The mathematical model comprises the following key nodes.

1. Control units (CU1 through CH4).
2. Operator control unit.
3. T-63-13,0/0,25 turbine model.
4. Electronic control part of each of the control units (CU1 ECP through CU4 ECP).
5. Electronic control part (ECP).

The units in items 4 and 5 form the general structure of the ECP for the electrohydraulic automatic control system (EHACS).

Control unit. Structurally, this comprises a hydraulic servomotor (SM) and a control device in the form of a cutoff slide valve tracking drive (CSVTD). The CU is designed to move the SM rod and the steam control valve (SCV) rigidly mounted to it in accordance with the law defined by the EHACS ECP. All four control units (CU1 through CU4) are identical.

Operator control unit. Acts as the setting adjuster. This unit sets the generator output power in the form of a setting or its variation law (T-63-13.0/0.25, Technical Requirements), and the operating mode: an isolated grid or an integrated grid.

T-63-13,0/0,25 turbine model. A mathematical model of the controlled facility: T-63-13,0/0,25 turbine (condensation mode of operation).

Electronic control part of control unit. Performs the following functions:

- the ECP control signal conversion to the CSVTD control signal (voltage- and current-sensitive control, signal amplitude matching, etc., as specified in the technical assignment (Technical Requirements));
- control of CU1 through CU4 during load shedding.

Electronic control part. This EHACS ECP unit implements the T-63-13,0/0,25 control algorithm. The ECP functions are to

- deliver the required electric power to the grid, with regard for the given setting;

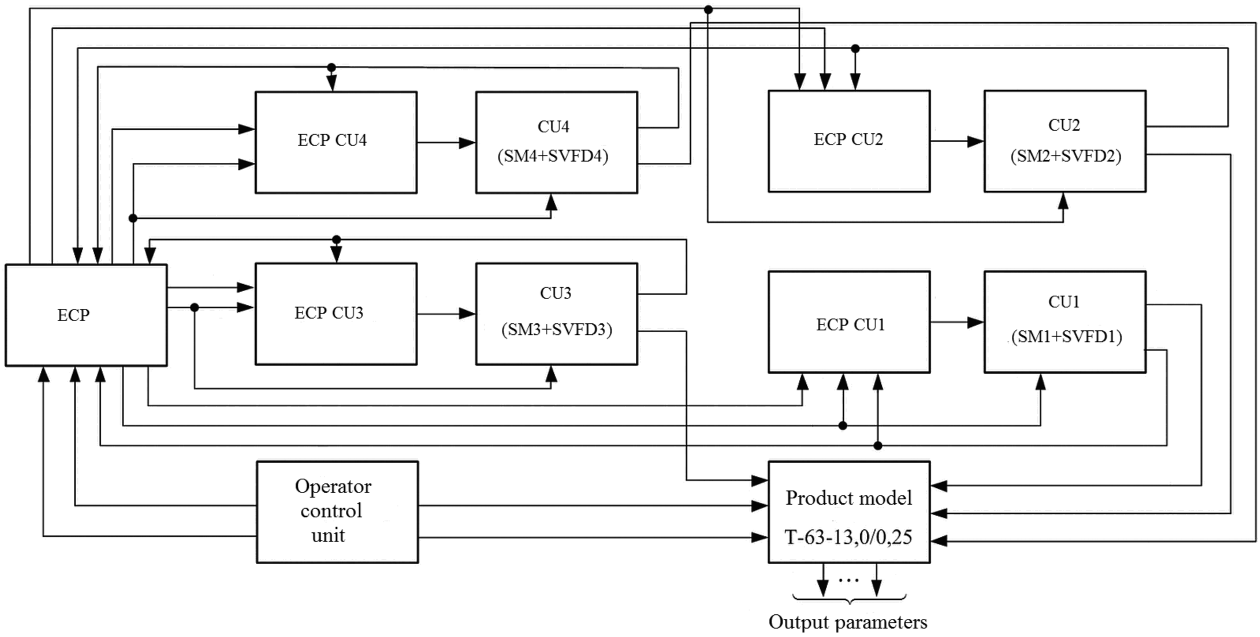

Figure 1. Functional diagram of the automatic control system for product T-63-13,0/0,25 (condensation mode).

- keep the given setting of the turbine generator electric power in the event of deviations from the rated steam parameters upstream of the turbine (integrated grid);
- keep the given setting of the turbine generator electric power in the event of deviations from the rated steam parameters upstream of the turbine (isolated grid);
- maintain the required T-63-13,0/0,25 ST speed during electrical load fluctuations at the consuming end (isolated grid);
- control the turbine generator during load shedding from 0 to 100%.

Cutoff slide valve drive control circuit. Pulse-width modulation (PWM) is used on an increasingly large scale in present-day electric drives to control synchronous motors, which makes it possible to use a microcontroller to feed the three-phase motor from dc sources (Vinogradov 2008). The shaft speed control for a synchronous machine is achieved by changing the feed voltage frequency. The feed voltage frequency needs to be increased to raise and reduced to lower the shaft speed. This can be achieved through a frequency converter (FC).

Structurally, an FC normally consists of the following key functional parts: a voltage rectifier (VR); power keys (PK), a PWM module.

Vector PWM is viewed as a special-purpose circuit including six high-power transistors of a three-phase converter operating in a key mode. Such converter circuit that feeds the synchronous motor has such form as shown in Fig. 2 where the following symbols are introduced: a, $\neg a$, b, $\neg b$, c, $\neg c$ (logic variables for the respective PK key closing); u_a, u_b, u_c (phase voltages).

T-63-13,0/0,25 mathematical model

The mathematical model of T-63-13,0/0,25 is shown in Fig. 3 as a block diagram. There is no condenser in the model and the spent steam fed from the ST exhaust line enters a conventional boundary node, this having no however effect on the adequacy of the simulation results in the framework of the problem under discussion (Trofimov et al. 2013, Yegupov et al. 2014). The paper does not consider the principle of the model's operation and does not describe the model. It should be noted that simulation of disturbing impacts leading to deviations from the ST rated electric power and, in the event of an isolated grid, to the ST speed, represents rather a challenge. Actually, it is required to simulate the load both from the electric power consuming end and deviations of the steam parameters from rated values (Rutily 2004, Amosov and Panasenko 2005, Nunes et al. 2013).

Signals from CU1 through CU4 corresponding to the movement of the SM rods (H_{SM1} through H_{SM4}) in mm, come to the inlets of four units, $G_i = f_i(H_{SMi})$ (i = 1, ..., 4). Signals (H_{SM1} through H_{SM4}) are converted in the above units to a value that characterizes the steam flow rate through each CU. Signals 4 through 7 serve to adjust the mathematical model and reflect the loss of the steam flow through the steam control valves, SCV1 through SCV4. Signal 3 is used to select the mode of operation.

- If there is a signal (equal to 1 in the model as set by the operator from the control desk), key K2 is closed, and key K1 changes to state 2, which matches the mode of operation for an isolated grid. The monitored parameters in this are N_{el} (output electric power of the turbine generator, MW), and n (ST speed, rpm).

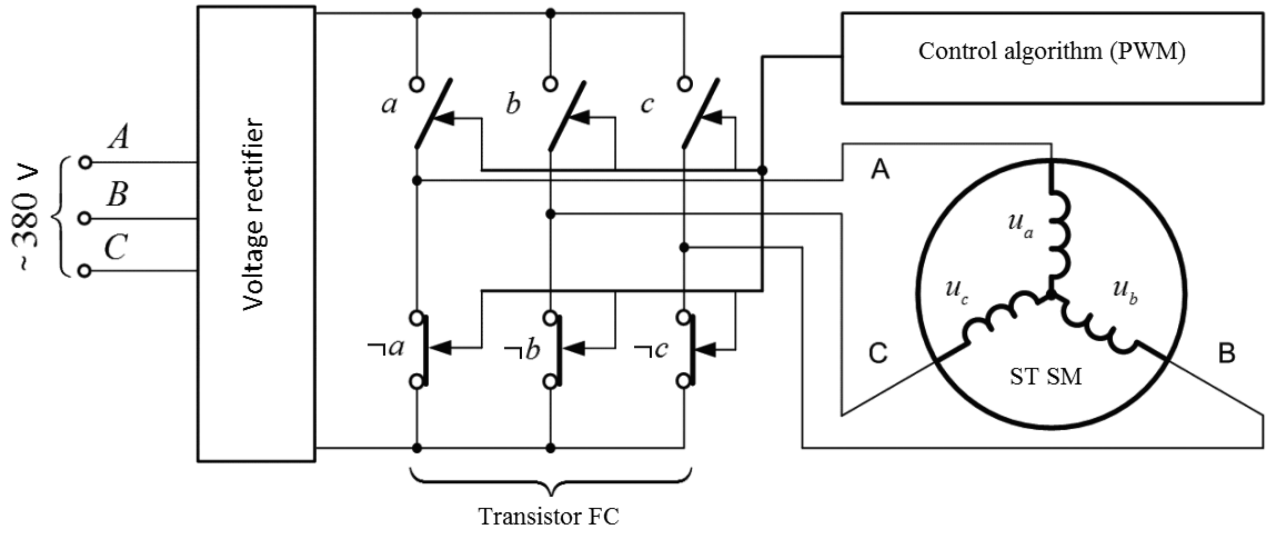

Figure 2. ST synchronous motor feed circuit.

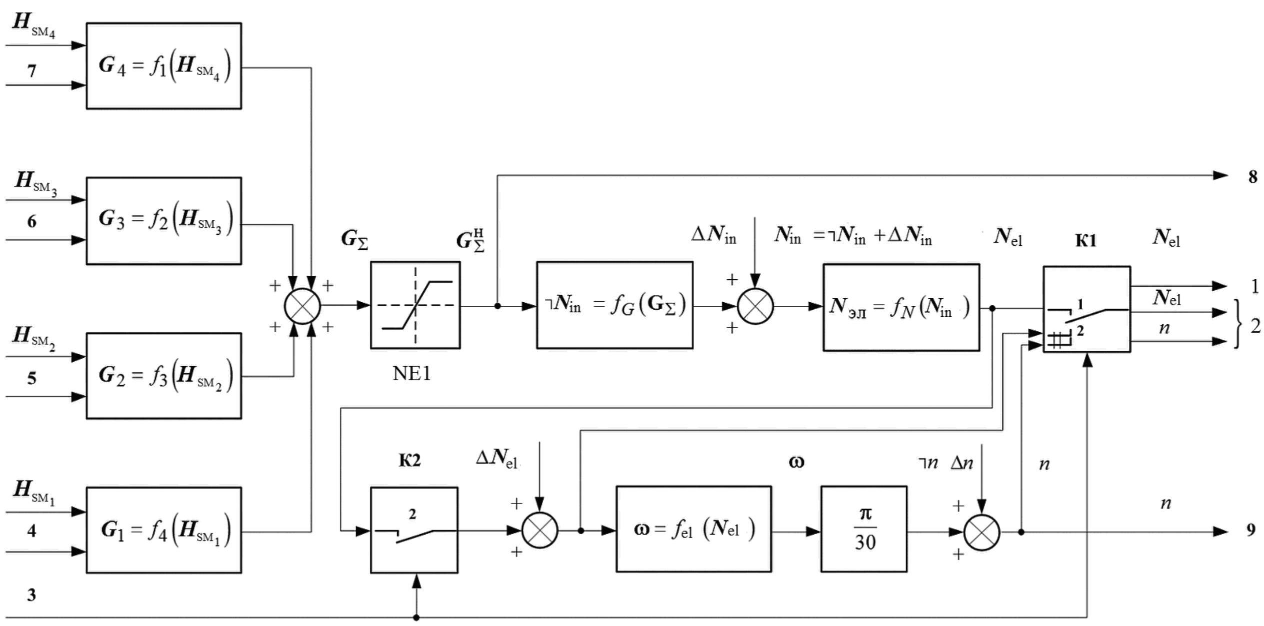

Figure 3. T-63-13,0/0,25 block diagram.

- If there is no signal (equal to 0), K2 is opened and K1 is in state 1, while the lower branch in the circuit is off (mode of operation for an integrated grid). The monitored parameter is N_{el} (output electric power of the turbine generator, MW).

The complexity of simulating the disturbing impacts arising during operation both for an isolated grid and an integrated grid is noted also in [14]. To solve the problem, the proposed block diagram (see Fig. 3) presents disturbing impacts as individual inputs: ΔN_{in} is the ST internal power disturbance (deviation of the steam parameters, etc.), and Δn is the ST speed disturbance (consuming-end load).

The monitored parameters are maintained through the ST steam feed control provided in the CU EHACS, the purpose of which is to control the ST steam supply during N_{in} and Δn fluctuations, and to provide the required steam flow to the grid with the given electric power.

Mathematical model of the CU electronic control part (CU ECP)

The functional diagram for CU1 ECP is presented in Fig. 4 (Amosov et al. 2003, Pupkov et al. 2003, Trofimov and Rogoza 2013). The mathematical model of the CU ECP consists of two components: a CU model and a CU control device (CU CD) model.

We shall discuss in brief the CU CD mathematical model and action using an example of the block diagram for the control device of control unit 1 (see Fig. 5).

The signal received at K1 indicates that this CU is on. Partial or complete load shedding leads to some of the CUs operating to close fully the steam control valves the number of which depends on the algorithm „weaved“ in the ECP. As soon as there is a signal to operate for the SCV full closure, K1 is opened; the output signal from the

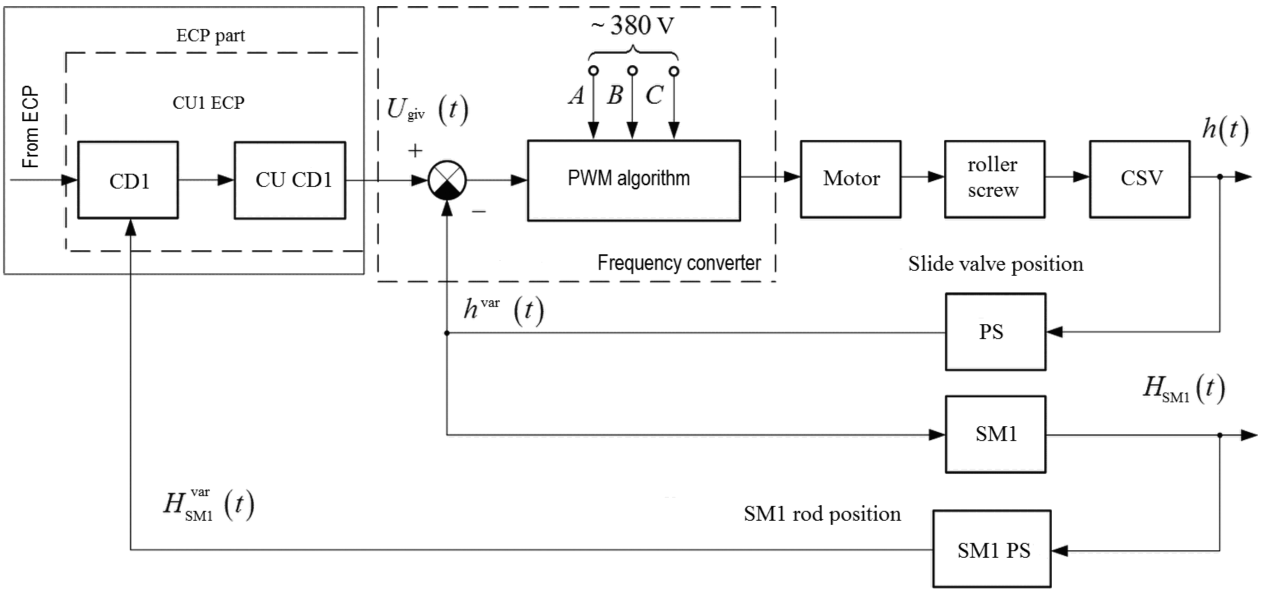

Figure 4. Functional diagram of the CU1 control unit with a control device (CU1 CD).

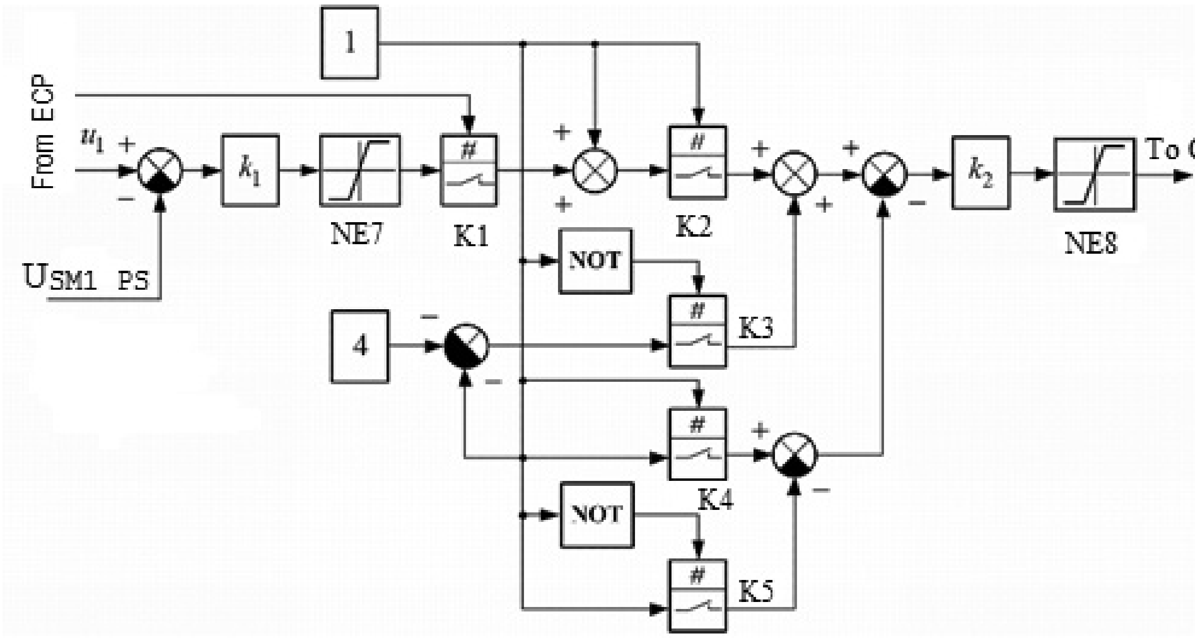

Figure 5. Block diagram of the control device for CU1 control unit.

CU CD in this case is defined by the setting value equal to 4 V. This setting is taken with a negative sign, which is explained by a conditional coordinate grid introduced for simplifying the CU model. The movement of the cutoff slide valve (CSV) to close is assumed to correspond to the negative input signal from the ECP and its movement to open is assumed to correspond to the positive sign. Accordingly, when the CSV moves to close, the servomotor rod protracts, this corresponding to the steam supply stoppage, and the SCV opens in the opposite case. Such assumption is connected with a peculiarity of the CU design which suggests that both SM cavities are filled and emptied in the course of control. The setting value has been determined based on the following considerations: in accordance with technical documentation (T-63-13.0/0.25), the control signal received at the CSVTD varies in terms of voltage in the limits of 1 to 5 V (the variation range is 4 V). Conversion uses the same pattern if control is based on a current signal (4 to 20 mA).

Coefficients k_1 and k_2 are scaling coefficients (they define the cordinate grid). Coefficient k_2 serves to restore the control signal received at the CSVTD in the voltage range of 1 to 5 V (multiplier).

CU switching algorithm. The sequence for opening the four control valves, SCV1 through SCV4, in the high-pressure section (cylinder) (HPS) is implemented by respective SMs in accordance with the flow characteristic presented in Fig. 6.

It is possible to adjust the valve opening sequence and extent in the process of design and commissioning, this

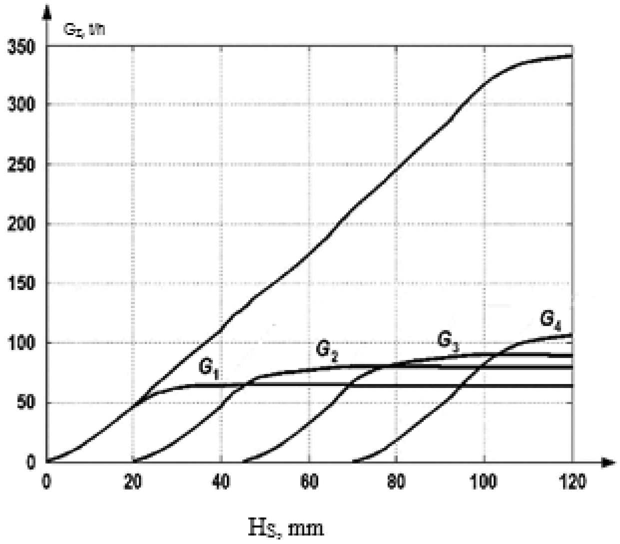

Figure 6. Diagrams of steam flows through the HPS control valves (SCV1 through SCV4) as a function of their strokes.

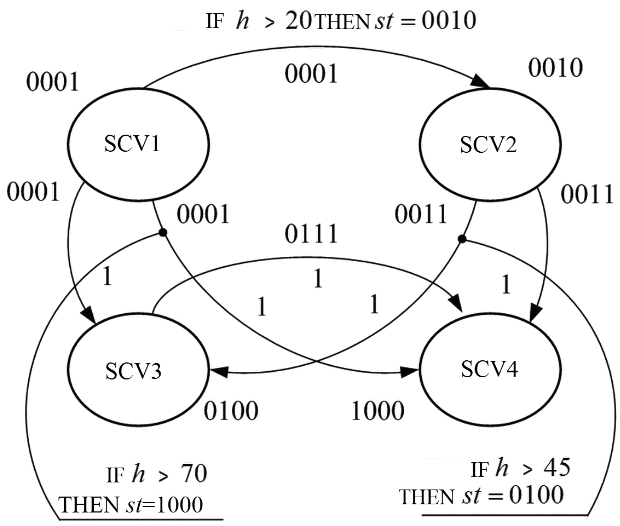

Figure 7. Constitutional diagram of control valves, SCV1 through SCV4, in control of steam supply to the T-63-13,0/0,25 ST.

being provided by the turbine set control algorithm. This algorithm includes a program segment which supports the CU switching depending on the total steam flow to the turbine and the operator-set output electric power.

The CU switching algorithm is implemented in the model in the form of a unit referred to conventionally as the decision making box (DMB). Its functions are to

- identify active CUs for the steam feed control;
- switch on in series the CUs during the ST speedup to the required output electric power in accordance with the setting;
- connect CU1 through CU4 to the turbine control algorithm.

A full disjunctive normal form (FDNF) of the finite state automaton, a logical sequence reflecting the DMB action, was prepared based on the tabular SCV status data. Fig. 7 presents a graphic interpretation of the FDNF.

Integration of models, construction of a generalized mathematical model of the EHACS with the controlled facility. Integration of models is the union of the above modules and nodes in the form of a single mathematical model. Such method of consideration was necessary to simplify the adjustment of computational patterns (Kantorovich 1948, Marchuk and Agoshkov 1981, Kazantsev 2009, D'Almeida et al. 2013).

The EHACS mathematical model (Kornyushin et al. 2015) comprises

- mathematical models of the ACS actuators (CU1 – CU4 models and the T-63-13,0/0,25 model);
- a mathematical model of the ECP (ECP CD, DMB and the turbine control algorithm);
- a model of disturbing impacts (Δn for the ST speed; ΔN_{in} for the ST internal power).

Conclusion

The developed mathematical model of the steam turbine automatic control system makes it possible to take into account different disturbing impacts in the process of the turbine testing and operation. The control system with single steam extraction in the T-63-13,0/0,25 ST has been designed as coupled and standalone, that is each of the two meters for the controlled turbine parameters acts for both steam distribution systems such that the deviation of one of the controlled parameters would not lead to disturbances in another.

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