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Development of a mathematical model of the control system for a 6 MW turbine-generator set

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Abstract. The stability of the rotation frequency of the synchronous electric generator as part of the turbine-generator set is one of the most important indicators determining the quality of the electric power and its suitability for various consumers. Maintaining the rated frequency of the generator rotor spinning and, as a consequence, the frequency of the generated current directly depends on the balance between the mechanical power developed by the steam turbine and the electric power consumed by the load. The automatic control system must constantly adjust the power generated by the steam turbine by changing the steam supply to its blade system in order to maintain the frequency at a specified level. The paper identifies the still ignored features of the control system of the turbine-generator set rotation frequency and power using a mathematical model to obtain the data needed to design of the turbine set. The development of the interconnected mathematical models of the turbine set elements is described, i.e. the synchronous generator, steam turbine, chambers in the turbine steam path and the implementation of the turbine-generator set as a whole. The results of the computational experiments simulating the disturbing impact on the turbine-generator set are presented.

Keywords: steam turbine, synchronous generator, turbine-generator set, controlling system, computer modelling, computational experiment.

Razvoj matematičnega modela krmilnega sistema za 6-MW turbinsko-generatorski sklop

Stabilnost frekvence vrtenja sinhronega električnega generatorja v turbinsko-generatorskem sklopu je ključni pokazatelj kakovosti električne energije in njene uporabnosti za različne porabnike. Ohranitev nazivnega vrtilnega momenta rotorja generatorja in s tem frekvence proizvedenega toka je odvisna od ravnovesja med mehansko močjo, ki jo razvije parna turbina, in električno močjo, ki jo porabi obremenitev. Avtomatski krmilni sistem nenehno prilagaja moč turbine z uravnavanjem dovoda pare, da ohrani frekvenco na želeni vrednosti. Članek s pomočjo matematičnega modela opiše še premalo raziskane značilnosti krmilnega sistema frekvence vrtenja in moči turbinsko-generatorskega sklopa ter opisuje razvoj povezanih modelov posameznih elementov sklopa (sinhroni generator, parna turbina, komore v parni poti) in simulacijo delovanja celotnega sistema. Predstavljeni so tudi rezultati simulacij, ki prikazujejo odziv sklopa na motnje.

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1 INTRODUCTION

At present, steam turbines are the main heat engines used in modern thermal power plants to drive electric generators. Compared with gas turbines and steam piston machines, steam turbines have the following advantages: they are relatively easy to maintain, they have the ability to change the operating power in a wide range of electric loads, they are economical to operate, and they have a high concentration of single capacities in one unit [1; 2]. The conversion of the mechanic energy from the rotation of the steam turbine shaft into the electric energy is carried out using synchronous machines - synchronous generators, where the frequency of the current generated by the generator is related to the rotor speed [3].

The presented work is based on a number of previous studies on the related issues. M. Dulaua and D. Bicab [4] develop of a mathematical model of a steam turbine with high, medium and low pressure sections based on the continuity equation. Using the model, the torque value depending of the control valves opening is obtained. It is shown that the dynamic response of the steam turbine can be associated with the change in the opening of the steam valves while the inputs to the generator are controlled (steam parameters), since the generator speed changes. In [5], a mathematical model of a 200 MW steam turbine and a generator is considered as a dynamic power system. A dynamic model of the controller, valve and turbine itself is given. The evaluation of the model response using the non-linear least-square method shows that the model is quite accurate. [6] proposes a method to minimize the electric grid frequency deviation and the power flow along the tie line. A method is described to estimate the dynamic parameters using the heat and mass balance data of a typical 660 MW steam turbine diagram and finding the frequency response depending on the load. Mathematical models of the generator and turbine shows that the dynamic parameters of the steam turbine models vary as a function of the load.

E. Alemay, M. Tadese and M. Jibril [7] model, design and analyse the steam turbine-generator. Their mathematical models of the DC generator, observer controller-based generator and generator with an LQR controller are presented. It is shown that the efficiency of the open-loop system is low. Author using their LQR controller, notably improved the efficiency. [8] models a T-63-13.0 / 0.2 turbine (PJSC Kaluga Turbine Works) directly, and the control of each of its control units. For control, the pulse-duration modulation is used (control of the shaft speed of the synchronous machine by changing the frequency of the supply voltage) due to the use of a frequency converter in the control system. The developed mathematical model of the automatic control system of the steam turbine takes into account the disturbing impact during the turbine testing and operation. [9] mathematically models several interconnected turbines of different types as part of an external and internal utility network (electricity generation, steam supply for technological processes and heating of boiler feedwater due to uncontrolled steam selection). A mixed integer nonlinear programming model is developed to model the turbine. The model is acceptable and its results are optimized.

A. Chaibakhsh and A. Ghaffari [10] develop a steam turbine model based on nonlinear mathematical models of the energy balance taking into account the thermodynamic principles. Nonlinear functions are developed to estimate the specific enthalpy and entropy at these stages of steam turbines. Their turbine-generator model can be used to synthesize the control system, ensure the safe operation of the turbine-generator under abnormal conditions (load rejection, excess turbine speed, etc.). [11] presents a mathematical model of a follower electromechanic drive (EMD), to control the position of the riding cutoff valve as part of the operating hydraulic mechanism (control unit) of a steam turbine with a given speed and accuracy. EMD functional and structural diagrams of the EMD of the riding cutoff valve are provided. To ensure a trouble-free operation of the turbine, it is shown that the most important are the ability to move EMD as quickly as possible to its complete working traverse with an apparent load and the smallest possible friction of the connected surfaces.

[12] develops a model of an automatic control system to supply on actuating medium to the flow path of a low-power steam turbine plant (a 6 MW condensing steam turbine) at the stage of a smooth warm-up. Structural diagrams of the warm-up system and a closed-loop control system are provided; the use of a reference model to ensure an non-periodic law of change in the output coordinate is substantiated. A conclusion is made about the optimality of using a discrete-continuous control system. S.V. Stelmashchuk and A.V. Serikov [13] describe the operating principle of a steam turbine with a linear actuator and develop a joint mathematical model of a steam turbine and an adjustable linear actuator. The mathematical model allows using the methodology of the linear theory of the automatic control to synthesize the controller.

The analysis of the above-mentioned works shows that in some of them, the modeling of the control systems of steam turbines, synchronous generators and elements of their control systems is made mostly separately, without being interconnected. However, the frequency deviation is one of the quality indicators of the electric energy [14] for the rotor speed to be at a given level, a balance between the turbine and generator powers (load) should be constantly maintained. As the system load constantly varies, to maintain a constant rotation frequency of the turbine-generator set, it is necessary to change the power developed by the turbine, while constantly maintaining a balance between the generated and consumed powers. Thus, an automatic frequency control (maintaining a constant value when the electric load varies) is continuously connected with the turbine power control, and, consequently, the active power of the synchronous generator (the term power hereinafter means the generator active electric power). To study the system for the rotation frequency and power control of a steam turbine at a variable load, and asymmetric operating modes, the generator dynamics should be taken into account.

Where the models of the turbine-generator set (TG) are understood as a combination of the turbine and its synchronous generator, there are unaccounted features of the control system, such as accurately defined coefficients in the mathematical model, accounting for extraction sections.

Following the above, developing of a mathematical model of a system to control the speed and power of a steam turbine taking into account the dynamics of a synchronous generator is a pressing task.

2 MATERIALS AND METHODS

The paper presents a mathematical model of a steam turbine of the P-6-3.4/0.5-1 type with the pertaining equipment, controlled steam extraction (industrial) and synchronous electric generator. In accordance with the performance specification, TG is equipped with an electrohydraulic automatic control system (EHACS).

The EHACS executive hydraulic-mechanical section (HMP) of the turbine consists of two independent steam distributions, each controlled by two hydraulic drives by means of a connecting linkage, namely:

1) The steam distribution of the high-pressure section (HPS) is of the nozzle-type installed at a live steam inlet to the high-pressure section of the turbine; it is organized by means of eight control valves located on a common traverse.

2) The steam distribution of the intermediate-pressure section (IMPS) is organized by means of a rotatable diaphragm installed in the wheelspace of the turbine on the steam supply to the low-pressure section from the turbine extraction section.

HMP of the EHACS in HPS and IMPS are identical hydraulic circuits. Their elements of which are located in one housing - the control unit.

The TPS-6-2EUZ generator is a synchronous, bipolar generator of a three-phase alternating current of a frequency of 50 Hz, power of 6000 kW, voltage of 10500 V and no damper winding. The connection of the stator frame phases is made according to the "Star" scheme.

Our study uncovers previously the unaccounted aspects of the speed and power control system of steam TG in its mathematical model to be taken into account when designing TG.

The objective of our work is to develop an adequate TG model in relative coordinates and to identify the dependencies of the change in the rotation frequency, power, torque, currents and voltages of TG with a change in the load on it, including the asymmetric operating states.

Using the developed mathematical model, the TG key parameters of transient processes are analyzed. Its tool is the Park-Gorev coordinate transformation for the conditions of the transient process ((*d,q,0*) rectangular coordinate system). The limitations of the used research method are the parametric uncertainty of a number of model coefficients and the ignorance of some nonlinear dependencies, for example, in the mathematical model, unlike in the original physical model, the induction coefficients no longer satisfy the reciprocity relation.

Generator model development. The centralized automatic frequency and power generator flow control system (AFPFC) need only the electric, and the actual power from the load.

We use mathematical model of the generator in the $(d, q, 0)$coordinates [15, 16]; as our work is not meant to be a detailed study of the generator, the damper circuits are neglected. In the calculation of the electric torque, the damper currents are not included.

The phase voltages on stator windings a, b, c and the voltage on drive winding $f$are determined by the equations:

$$u_a = R_a i_a + \frac{d\Psi_a}{dt},$$
$$u_b = R_b i_b + \frac{d\Psi_b}{dt},$$
$$u_c = R_c i_c + \frac{d\Psi_c}{dt},$$
$$u_f = R_f i_f + \frac{d\Psi_f}{dt}, \quad (1)$$

where R_a,R_b,R_c are the active resistance of the circuits of the corresponding windings, R_f is the active resistance of the exciting circuit, i_a, i_b, i_c is the phase current; i_f is the field coil current, Ψ_a,Ψ_b,Ψ_c are the resulting flux linkages of the corresponding windings, Ψ_f is the resulting flux linkages of drive winding and t is the time.

The drive winding and the three 'Star' connected stator windings contribute to a flux connecting each winding. The resulting flux linkages are given by the equations:

$$\Psi_a = L_a i_a + M_{ab} i_b + M_{ac} i_c + M_{af} i_f,$$
$$\Psi_b = M_{ba} i_a + L_b i_b + M_{bc} i_c + M_{bf} i_f,$$
$$\Psi_c = M_{ca} i_a + M_{cb} i_b + L_c i_c + M_{cf} i_f,$$
$$\Psi_f = L_f i_f M_{fa} i_a + M_{fb} i_b + M_{fc} i_c, \quad (2)$$

where L_a, L_b, $L_c$are the inductances of the corresponding windings, L_f is the drive winding inductance, M_{ab}, M_{ac}, M_{af},M_{ba}, M_{bc}, M_{bf}, M_{ca}, M_{cb}, M_{cf}, M_{fa}, M_{fb}, M_{fc} are the mutual inductances of the corresponding windings (indices a, b, c) and mutual inductances of the corresponding windings with the drive winding (index f).

The inductances in the corresponding stator windings and the mutual inductances depend on the electrical angle of the rotor and are determined by the equations:

$$L_a = L_{сф} + L_к cos(2\theta_{эл}),$$
$$L_b = L_{сф} + L_к cos\left(2\left(\theta_{эл} - \frac{2\pi}{3}\right)\right),$$
$$L_c = L_{сф} + L_к cos\left(2\left(\theta_{эл} + \frac{2\pi}{3}\right)\right),$$
$$M_{ab} = M_{ba} = -M - L_к cos\left(2\left(\theta_{эл} + \frac{\pi}{6}\right)\right),$$

$$M_{bc} = M_{cb} = -M - L_{\kappa}\cos\left(2\left(\theta_{эл} + \frac{\pi}{6}\right) - \frac{2\pi}{3}\right),$$
$$M_{ca} = M_{ac} = -M - L_{\kappa}\cos\left(2\left(\theta_{эл} + \frac{\pi}{6}\right) + \frac{2\pi}{3}\right),$$
$$\theta_{эл} = p\theta_p + \theta_{см}, \quad (3)$$

where$L_{сф}$is the stator self-inductance per phase (the average self-inductance of each of the stator winding), L_{κ} is the stator inductance fluctuation (representing the fluctuation of its own and mutual inductance when the rotor angle changes), $\theta_{эл}$ is the electrical angle of the rotor, M is the mutual inductance of the stator (the average mutual inductance between the stator windings), $p$is the number of the rotor pole pairs, θ_p is the mechanical rotor angle, $\theta_{см}$ is the rotor shifting (it is 0, when the electrical angle of the rotor is determined with respect to axis d; is $\frac{-\pi}{2}$, when the rotor angle is defined with respect to the q).

The TPS-6-2EUZ generator has one pair of the poles (two poles), so the electrical angle of rotor $\theta_{эл}$coincides with mechanical angle θ_p. The magnetization flux connecting winding $a - a'$is of its maximum at $\theta_{эл} = 0°$and is zero at $\theta_{эл} = 90°$. Thus:

$$M_{af} = M_f\cos(\theta_{эл}),$$
$$M_{bf} = M_f\cos\left(\theta_{эл} - \frac{2\pi}{3}\right),$$
$$M_{cf} = M_f\cos\left(\theta_{эл} + \frac{2\pi}{3}\right),$$
$$\Psi_f = L_f i_f + M_f\cos(\theta_{эл})\, i_a +$$
$$+M_f\cos\left(\theta_{эл} - \frac{2\pi}{3}\right) i_b + M_f\cos\left(\theta_{эл} + \frac{2\pi}{3}\right) i_c, \quad (4)$$

where M_f is the mutual field armature inductance.

The Park transformation for the transition from fixed coordinate system (a, b, c) to rotating one $(d, q, 0)$ for the case when the electrical angle of the rotor is determined with respect to axis d is:

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta_{эл}) & \cos\left(\theta_{эл} - \frac{2\pi}{3}\right) & \cos\left(\theta_{эл} + \frac{2\pi}{3}\right) \\ -\sin(\theta_{эл}) & -\sin\left(\theta_{эл} - \frac{2\pi}{3}\right) & -\sin\left(\theta_{эл} - \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (5)$$

Applying the Park transformation to (1), (2) leads to the equations describing the dynamics of the generator and the electromagnetic torque in coordinates $(d, q, 0)$:

$$u_d = \frac{d\Psi_d}{dt} - \Psi_q p\omega_p + R_a i_d,$$
$$u_q = \frac{d\Psi_q}{dt} + \Psi_d p\omega_p + R_a i_q,$$
$$u_f = \frac{d\Psi_f}{dt} + R_f i_f,$$
$$u_0 = \frac{d\Psi_0}{dt} + R_a i_0,$$
$$\Psi_d = L_d i_d + M_f i_f,$$
$$\Psi_q = L_q i_q,$$
$$\Psi_f = L_f i_f + 1.5 M_f i_d,$$
$$\Psi_0 = L_0 i_0,$$
$$M_{эл} = 1.5p\left(\left(L_d - L_q\right) i_d i_q + M_f i_f i_q\right), \quad (6)$$

where ω_p is the rotor angular rate (mechanical rotation speed), Ψ_d, Ψ_q, $\Psi_0$is the flux linkages with respect to axes d, q, 0, i_d, i_q, i_0 are the longitudinal cross flow and zero stator currents respectively, L_d is the inductance of the armature windings along direct axis d, L_q is the inductance of the armature windings along quadrature axis q, L_0 is the zero sequence inductance, and $M_{эл}$ is the generator electrical.

Equations (6) can be represented in the Cauchy form:

$$\frac{di_d}{dt} = a_{11} i_d + a_{12}\omega_p i_q + a_{13} i_f + b_{11} u_d + b_{13} u_f,$$
$$\frac{di_q}{dt} = a_{21}\omega_p i_d + a_{22} i_q + a_{23}\omega_p i_f + b_{22} u_q,$$
$$\frac{di_f}{dt} = a_{31} i_d + a_{32}\omega_p i_q + a_{33} i_f + b_{31} u_d + b_{33} u_f,$$
$$\frac{di_0}{dt} = a_0 i_0 + b_0 u_0,$$
$$M_{эл} = 1.5p\left(\left(L_d - L_q\right) i_d i_q + M_f i_f i_q\right), \quad (7)$$

where a_{11}, a_{12}, a_{13}, b_{11}, b_{13}, a_{21}, a_{22}, a_{23}, b_{22}, a_{31}, a_{32}, a_{33}, b_{31}, b_{33}, a_0, b_0 are the generator model coefficients.

The coefficients of the generator model are determined by the following equations:

$$a_{11} = \frac{-R_a L_f}{\left(L_d L_f - 1.5 M_f^2\right)}, a_{12} = \frac{p L_q L_f}{\left(L_d L_f - 1.5 M_f^2\right)}, a_{13} = \frac{M_f r_f}{\left(L_d L_f - 1.5 M_f^2\right)},$$
$$a_{21} = \frac{-p L_d}{L_q}, a_{22} = \frac{-R_a}{L_q}, a_{23} = \frac{-p M_f}{L_q}, a_{31} = \frac{1.5 R_a M_f}{\left(L_d L_f - 1.5 M_f^2\right)}, a_0 = -\frac{R_a}{L_0}$$

$$a_{32} = \frac{-1.5pM_fL_q}{\left(L_dL_f - 1.5M_f^2\right)}, a_{33} = \frac{-L_dR_f}{\left(L_dL_f - 1.5M_f^2\right)},$$
$$b_{11} = \frac{-L_f}{\left(L_dL_f - 1.5M_f^2\right)}, b_{13} = \frac{-M_f}{\left(L_dL_f - 1.5M_f^2\right)}, b_{22} = -\frac{1}{L_q},$$
$$b_{31} = \frac{1.5M_f}{\left(L_dL_f - 1.5M_f^2\right)}, b_{33} = \frac{L_d}{\left(L_dL_f - 1.5M_f^2\right)}, b_0 = -\frac{1}{L_0} \quad (8)$$

Development of the turbine model. The mathematical model of the turbine is made in relative coordinates, i.e. in relative deviations from the nominal value. The equation of the rotor rotation is:

$$T_\varphi \frac{d\varphi}{dt} = (1-\theta)(\alpha_в\xi_в + \alpha_н\xi_н - \lambda_{эл}) - \theta\varphi \quad (9)$$

where T_φ is the rotor time constant, θ is the equivalent self-control, $\alpha_в$, $\alpha_н$ are the shares of the rotor sections of HPS, IMPS in creating the turbine torque rating, $\xi_в$, $\xi_н$ are the relative deviations of the steam pressures (flow rates) in HPS, IMPS, respectively, $\lambda_{эл}$ is the relative deviation of the generator electric load, φ is the relative deviation of the angular frequency of the rotor rotation from the nominal value.

The rotor time constant is determined by the equation:

$$T_\varphi = \frac{(J\omega_{ном})}{M_{ном}}, \quad (10)$$

where J is the turbine-generator rotor moment of inertia, $\omega_{ном}$ is the rated rotor speed, and $M_{ном}$ is the torque rating of the turbine driving forces.

The relative deviation of the angular frequency of the rotor rotation ω_p from nominal value $\omega_{ном}$is determined as:

$$\frac{\varphi = (\omega_p - \omega_{ном})}{\omega_{ном}} \quad (11)$$

Development of a model of chambers in the turbine flow path. As a result of a compressible medium in the path, the changes in the flow rate across the flow section do not immediately follow the changes in the flow rate through the valves. Thus, to analyze this phenomenon, a system with distributed parameters continuously changing along the steam path should be considered. As this would significantly complicate the mathematical modeling, a certain degree of discretization of the continuous processes of the change in the flow rate and steam pressure in the flow section is usually used to identify the chambers where a certain amount of the steam is conventionally concentrated, and the compartments with the turbine stages located between these chambers, where the corresponding resistance to the steam flow is conventionally concentrated. The amount of the steam in the compartments themselves is negligibly small compared to the amount of the steam in the chambers.

In order not to excessively increase the order of the system of the model differential equations, the volumes of the chambers between the stages of HPS and IMPS are taken into account by an equivalent increase in the volumes, given the fact that the eigenvalues of the time constants of the intersection chambers between the stages are comparatively small. Then the corresponding equations of the steam volumes (the process of changing the parameters of the steam in the chambers is assumed polytropic) can be written in the following form:

$$T_{\xi в}\frac{d\xi_в}{dt} = \pi_{св.п}\mu_в + \pi_{св.п} + \mu_в - \xi_в,$$
$$T_{\xi н}\frac{d\xi_н}{dt} = \mu_н - \xi_н,$$
$$T_{\xi отб}\frac{d\xi_{отб}}{dt} = \xi_в - \xi_{отб} - (1-\beta_{отб})\mu_н - \lambda_{отб}, \quad (12)$$

where$T_{\xi в}$, $T_{\xi н}$ is the time constants of the volume chambers of HPS and IMPS (the time of a full filling of the chamber at a certain steam flow rate), $\pi_{св.п}$ is the relative deviation of the fresh steam pressure, $T_{\xi отб}$ is the time constant of the relative deviation of the steam pressure in the extraction section, $\mu_в$, $\mu_н$ are relative deviations of the pistons of the turbine servomotors of HPS and IMPSm respectively, $\xi_{отб}$ is a relative deviation of the steam pressure in the extraction section, $\beta_{отб}$ is the value characterizing the amount of the steam extraction for the production needs, and $\lambda_{отб}$ is the relative deviation of the steam flow in the extraction section.

The value characterizing the amount of the steam extraction for the production needs is determined by the equation:

$$\beta_{отб} = \frac{G_{отб}}{G_0} \quad (13)$$

where $G_{отб}$ is the real value of the steam flow through the extraction, and G_0 is the nominal value of the steam flow through the extraction.

Implementation of the TG model. Equations 7, 9-13 provide the basis for a structural TG diagram (the turbine and the synchronous generator) (Figure 1) and for the turbo-unit model in the Matlab (Simulink) software package [17].

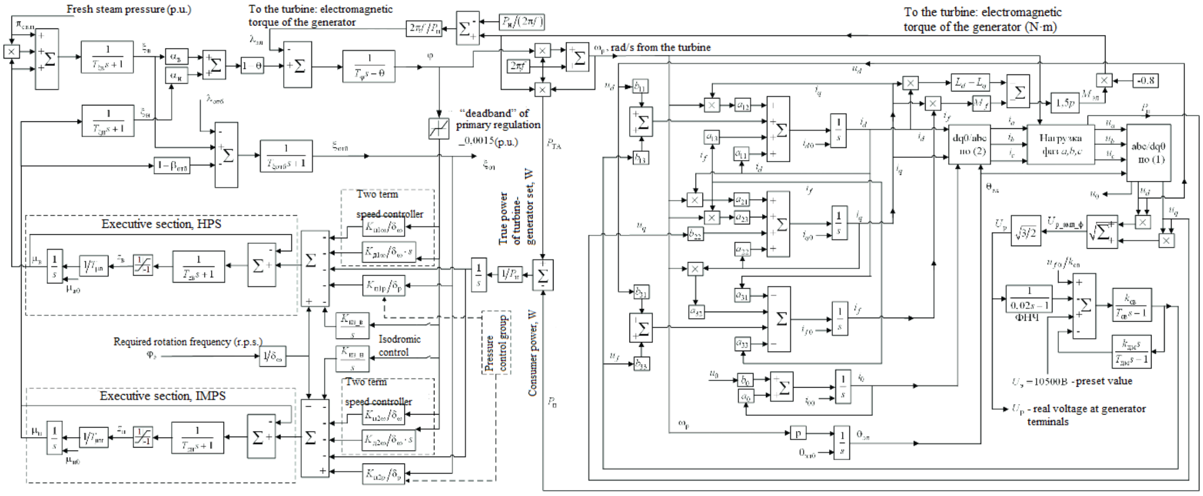

Figure 1. TG Structural diagram: turbine P-6-3.4/0.5-1, generator TPS-6-2EUZ.
Source: compiled by the authors

The generator parameters are:

$R_a = 0.037 \pm 4\%$ Ohm is the active resistance of each stator winding, $R_f = 0.46$ Ohm is the equivalent resistance of the drive winding, $L_d = 0.00572$ H is the inductance of the armature windings along direct axis d, and $L_q = 0.00547$ is the inductance of the armature windings along quadrature axis q.

$L_0 = 0.000532$ H is the zero-sequence inductance, $L_f = 3.3$ H is the drive winding inductance, $M_f = 0.11$ H is the mutual field armature inductance, $p = 1$ is the number of the pairs of the generator rotor poles, $S_н = 7500$ kVA is the total generator power, $P_н = 6000$ kW is the generator wattage rating, $f = 50$ Hz is the nominal speed, and $cos\,\varphi = 0.8$ is the generator power factor.

The coefficients of the generator model (8) are calculated using the provided parameters.

The power controller is presented as an integrating element. Desired active power P_n (determined by the consumer) and the real power calculated with generator electric torque $M_{эл}$are supplied to its input.

The speed controller is presented as an electronic and executive section separately for HPS and IMPS. The electronic part are the adder units. The executive section is a servomotor (an integrated element) and a riding cutoff valve with an electro-hydraulic converter (aperiodic link). The electronic part controls the speed according to the proportional and integral laws. The integral control is ensured by adjusting coefficients $K_{из\_в}$, $K_{из\_н}$, and the proportional control is ensured by adjusting coefficients $K_{п1\omega}$, $K_{\partial 1\omega}$, $K_{п1р}$, $K_{п2\omega}$, $K_{д2\omega}$, $K_{п2р}$.

The model contains "interface" blocks that converse the signals from one unit to another.

The generator excitation system controller is an aperiodic link:

$$\frac{k_{св}}{T_{св}s+1} \qquad (14)$$

where $k_{св} = 0.1902$, $T_{св} = 0.001$ s.

The generator damping filter is a differentiating link

$$\frac{k_{дм}s}{T_{дм}s+1} \qquad (15)$$

where $k_{дм} = 0.001$, $T_{дм} = 0.1$ s.

The turbine parameters are as follows:

$T_\varphi = 7.13$ s is the rotor time constant,

$\theta = 0 \div 0.05$ is the turbine self-control coefficient,

$\alpha_в = 0.42$, $\alpha_н = 1 + \theta - \alpha_в$ are the shares of the rotor sections of HPS and IMPS in creating the turbine torque rating,

$T_{\xi в} = 0.1 \div 0.12$ c, $T_{\xi н} = 0.1 \div 0.12$c, $T_{\xi отб} = 2$ s are the time constants of the volume chambers of HPS, IMPS and extraction section,

$\beta_{отб} = 0$ or $\beta_{отб} = 0.827$ is the value characterizing the amount of the steam extraction for the production needs in a condensing and extraction mode, respectively,

$T_{\mu в} = 0.267$ s, $T_{\mu н} = 0.53$ s are the time constants of servomotors HPS and IMPS, respectively,

$T_{zв} = 0.07$c, $T_{zн} = 0.07$s – time constants of the riding cutoff valves of the servomotors HPS and IMPS,

$\delta_\omega = 0.03 \div 0.08$ is the degree of the irregularity of the speed control when changing the electrical load,

$\delta_p = 0.1$ is the degree of the irregularity of the pressure control in the extraction section,

$K_{n1\omega}, K_{п2\omega}, K_{п1р}, K_{п2р}$ are the gear ratios, determined from the condition of the control independence by the frequency and pressure in the extraction section. Their values are the settings of the controllers by the frequency and pressure and are calculated as follows:

$$K_{n1\omega} = \frac{a}{(a+b)},\quad K_{п2\omega} = \frac{K_{n1\omega}}{a},\quad K_{п1р} = \frac{b}{(a+b)},\quad K_{п2р} = \frac{K_{п1р}}{\frac{\alpha_н}{\alpha_в}},\quad a = 1 - \beta_{отб};\ b = \frac{1-a}{\left(1+\frac{1}{\frac{\alpha_н}{\alpha_в}}\right)}. \tag{16}$$

where $K_{из\_в} = 7.5 \div 15$, $K_{из\_в} = 2.5 \div 10$ are the coefficients for the proportional speed control.

The model includes a block that simulates the generator three-phase load, which can be of an impulse reaction (inductance) nature.

3 Results

The generator initial conditions are obtained by converting the parameters of the three-phase nominal current into the $(d, q, 0)$coordinates: $i_{d0} = 0$ A, $i_{q0} = -582.7$ A, $i_{00} = 0$A; and from the generator datasheet specifications: $i_{f0} = 246$ A. The turbine initial conditions are taken as zero, since the turbine mathematical model is described in relative deviations from the nominal values.

Since our aim is to develop is a mathematical model of the EHACS turbine, and the turbine is the supplier of the active power to the network, in the computational experiments we use the most "unfavorable" excitations for the turbine. The change in its active component is used as the load.

The nominal active load is determined from the generator datasheet specifications. For the generator line voltage $U = 10500$ B and the generator current $I = 412$ A, the full phase resistance (Ohm) is:

$$Z = \frac{10500}{\sqrt{3} \cdot 412} = 14.7 \tag{17}$$

Full resistance Z, generally has an active and reactive component:

$$Z = \sqrt{R^2 + X^2} \tag{18}$$

where R is an active resistance component and X is a reactive resistance component.

Since the turbine is a source of the active energy, in the nominal conditions the maximum component of resistance is $R = 14.7$ Ohm.

Let's check the power loading:

$$S_н = 3RI = 14.7 \cdot 412 = 7500 \text{ kVA},$$
$$P_н = S_н \cdot \cos\varphi = 7500 \cdot 0.8 = 6000 \text{ kW} \tag{19}$$

where $S_н$ is the total power, and $P_н$ is the actual power.

Their values match the generators' datasheet specifications.

In the first two seconds of the simulation, the initial conditions of the TR model are determined. At time $t = 2$ s, the disturbing impact on the TR is simulated.

The total electric load rejection without production steam extraction. The load is symmetrical ($R_a = R_b = R_c = 417$ Ohm); at time $t = 2$ s, the electric load is rejected. In the $R_a = R_b = R_c = \infty$ Ohm theory, $R_a = R_b = R_c = 2000$ Ohm can be taken for modeling, so that computer calculations are not performed at the computer zero. The values are $\theta = 0.03$, $\pi_{св.п} = 0$, and$\delta_\omega = 0.04$, $\beta_{отб} = 0$. The results are shown in Figures 2–7.

The total electric load rejection with production extraction and change in the fresh steam pressure. The load is symmetrical ($R_a = R_b = R_c = 417$ Ohm); at time $t = 2$ s the electric load is rejected by 50% ($R_a = R_b = R_c = 2 \cdot 417$ Ohm), the steam consumption is shed by 100 ($\lambda_{отб} = -1$), fresh steam pressure increases by 10% ($\pi_{св.п} = +0.1$), $\beta_{отб} = 0.82$, $\delta_\omega = 0.04$, $\theta = 0.03$. The results are shown in Figures 8–13.

4 DISCUSSION

Figures 2-5 shows the following process characteristics of the turbine behavior with the extraction during a complete discharge of the electric load: the deviation of the rotation speed does not exceed the value of inequality (about 5%), the extraction pressure is less than 13%. The transition of the value of the electric torque occurs almost instantly, as in real conditions. Figures 6 and 7 show the changes in the generator currents and voltages. The current in each phase quickly decreases, while the voltage at the moment of load shedding increases sharply ("voltage jump") but quickly recovers, as in actually occurring processes.

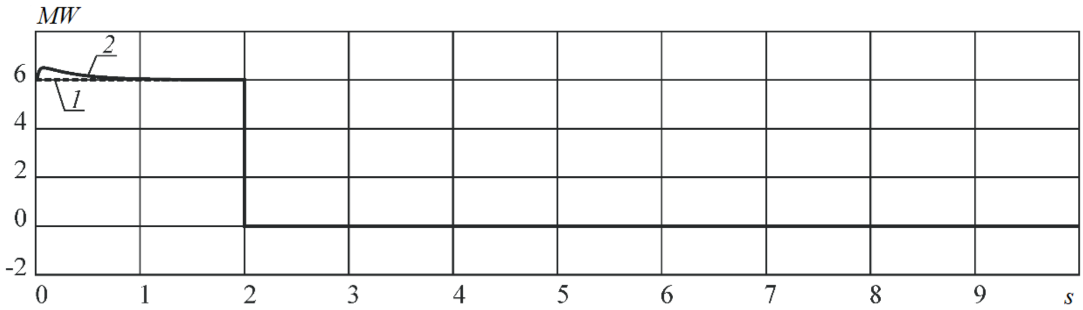

Figure 2. Load power P_n (1), turbo unit power P_{TA} (2). *Source:* compiled by the authors

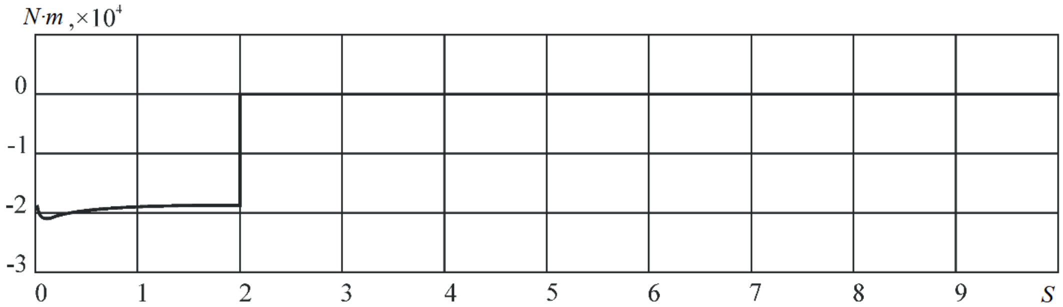

Figure 3. Electric torque of the generator $M_{эл}$. *Source:* compiled by the authors

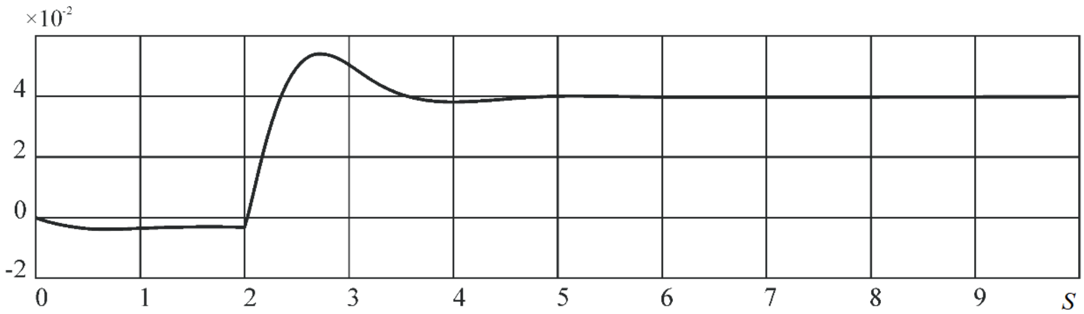

Figure 4. Relative deviation of rotor speed φ. *Source:* compiled by the authors

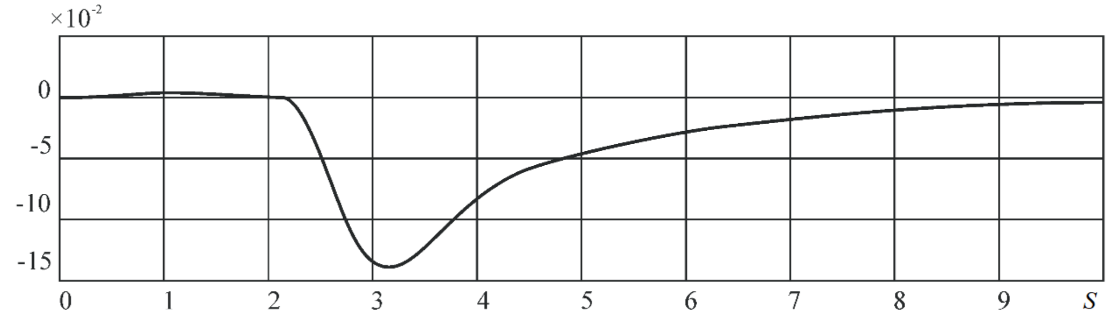

Figure 5. Relative deviation of the steam pressure in extraction section $\xi_{\text{отб}}$. *Source:* compiled by the authors

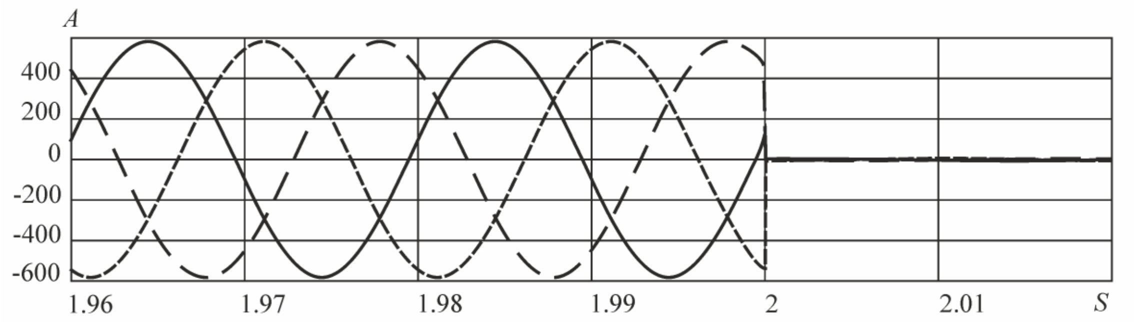

Figure 6. Generator currents i_a, i_b, i_c. *Source:* compiled by the authors

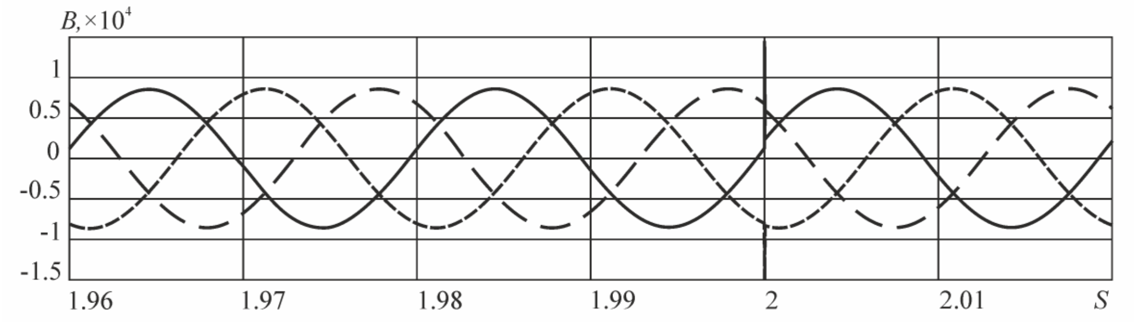

Figure 7. Generator phase voltages u_a, u_b, u_c. *Source:* compiled by the authors

The repetition of the computational experiment for the case with the production extraction and change in the fresh steam pressure has practically no effect on the transient processes for the generator electric torque. The transient processes for the rotor speed and extraction pressure acquire a more pronounced fluctuating character, consistent with the real behavior of the turbine under similar conditions (Figures 8-11). The generator currents decrease by half, which corresponds to a 50% load reduction (Figure 12), the generator voltage (Figure 13) remains the same in the steady conditions indicating an adequate excitation system model.

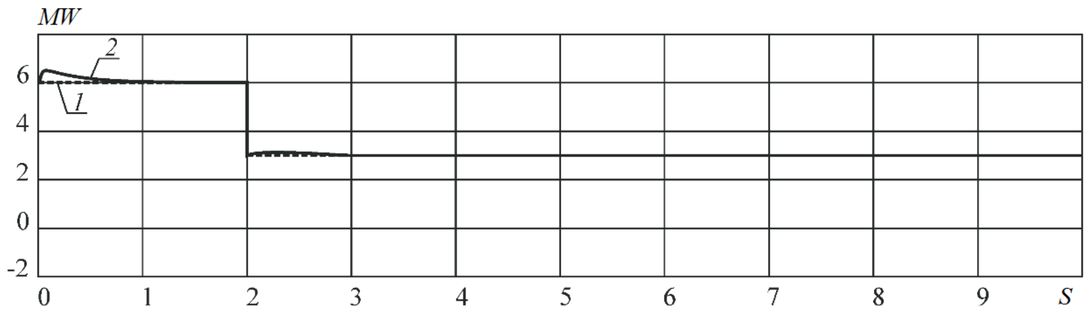

Figure 8. Load power P_n (1), TG power P_{TA} (2). *Source:* compiled by the authors

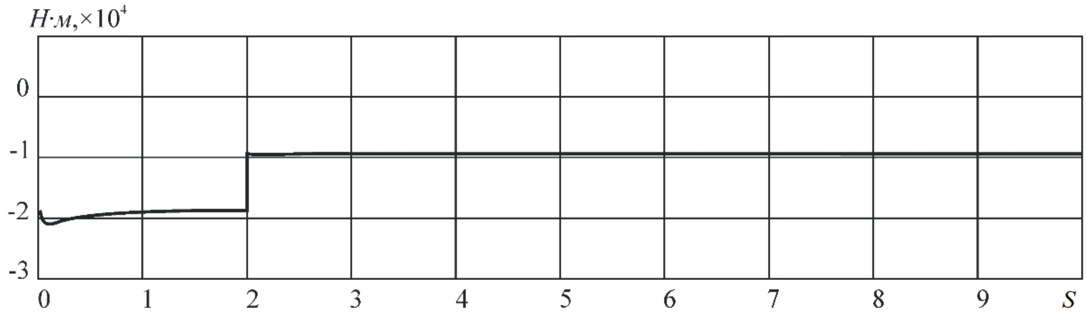

Figure 9. Generator electric torque $M_{эл}$. *Source:* compiled by the authors

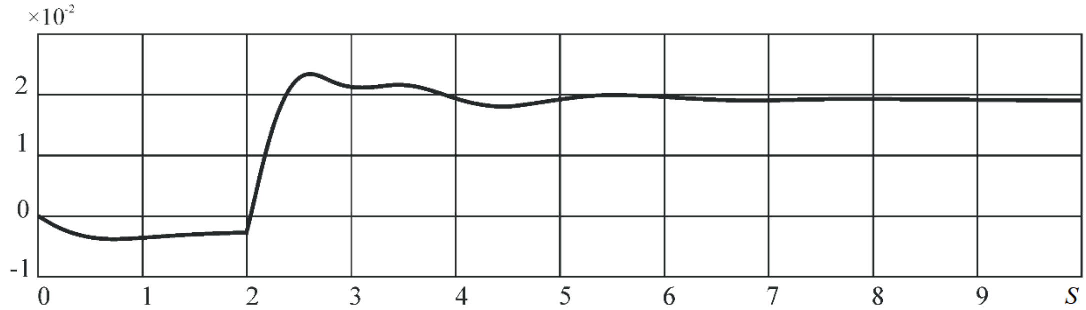

Figure 10. Rotor speed relative deviation φ. *Source:* compiled by the authors

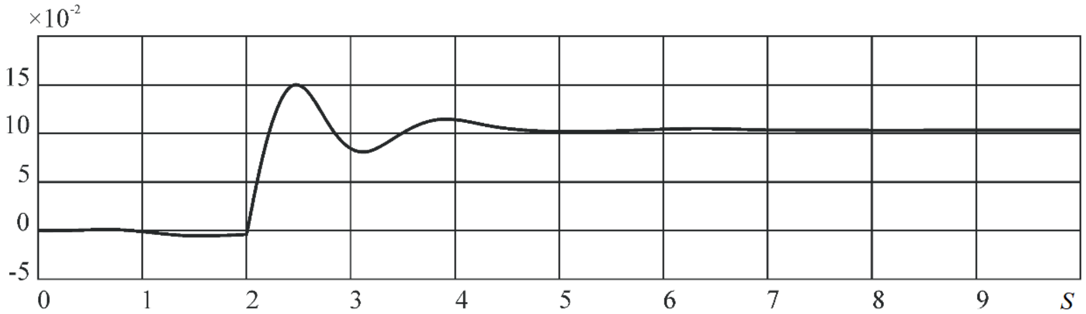

Figure 11. Relative deviation of the steam pressure in extraction section $\xi_{отб}$. *Source:* compiled by the authors

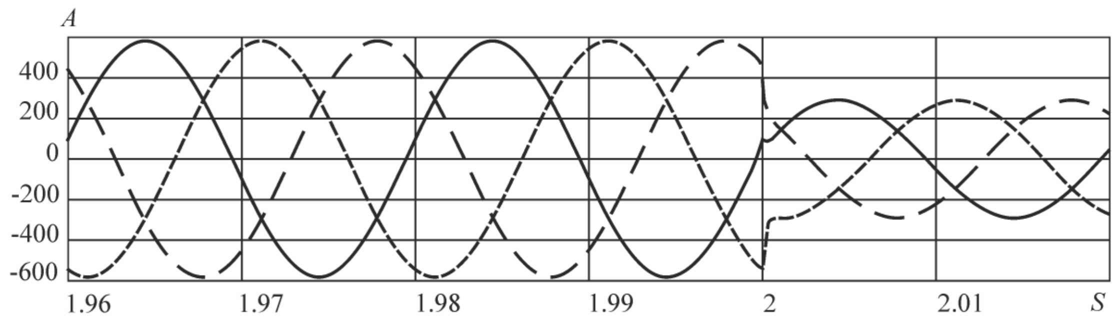

Figure 12. Generator currents i_a, i_b, i_c. *Source:* compiled by the authors

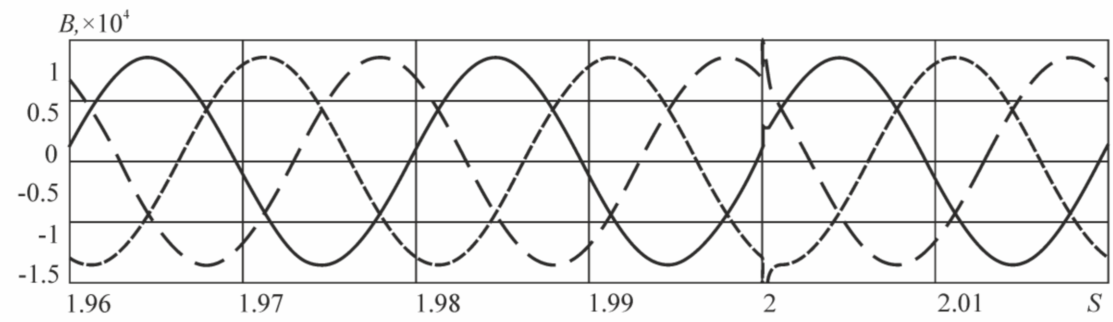

Figure 13. Generator phase voltages u_a, u_b, u_c. *Source:* compiled by the authors

5 Conclusion

Based on the described experiments, a mathematical model of a turbine-generator is developed and implemented in the Matlab package (a subsystem for block simulation of the Simulink dynamic systems).

The model provides the ability to analyze the dynamics of transient processes in the turbine rotation frequency and the electric power of the turbine-generator set when the load changes or when external excitations are applied: during the electric load discharge and rise, changes in the fresh steam pressure, and changes in the steam flow in the extraction section. The load can change asymmetrically in phases. The model also allows studying short-circuit states, including the asymmetric ones.

In the future, the presented model will be verified on a real turbine during mandatory tests when put into operation at a station (in accordance with the "Rules for the technical operation of power plants and networks of the Russian Federation"). A further research will be made to develop criteria for the optimal adjustment of the control loops, to take into account the research results when designing or upgrading the units of the turbine unit control system.

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