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A MATHEMATICAL MODEL OF THE ELECTRICAL ENGINEERING COMPLEX FOR DRIVE OF MAIN CIRCULATION PUMPS OF NUCLEAR REACTOR VVER-1000 OF NUCLEAR POWER PLANTS

Tools for computer investigation of the modes of operation of induction motors of the main circulating pumps of the VVER-1000 NPP reactor have been created. The mathematical model of the electrical engineering complex "synchronous turbogenerator of NPP unit – electric grid of power system – two transformers of own needs – four induction motors" in phase coordinates, oriented on explicit methods of numerical integration of the system of differential equations is developed. On the basis of the mathematical model the software designed for the study of electromagnetic and electromechanical processes of the system of induction motors of the main circulating pumps of the VVER-1000 nuclear reactor in the modes of: operative switching including start and run, switching to standby power, self-start of the motors with turbogenerator's run-out and without it is developed. The investigations of the processes in the system of induction motors in the mode of operative switching during their power supply from the turbogenerator are carried out and the basic regularities of their course in qualitative and quantitative relations are established. References 10, figures 11.

Key words: **nuclear reactor, main circulation pumps, synchronous turbogenerator, transformer, induction motor, starting modes, self-starting, mathematical model, differential equations.**

Створено засоби комп'ютерного дослідження режимів роботи асинхронних двигунів головних циркуляційних помп ядерного реактора ВВЕР-1000 АЕС. Розроблено математичну модель електротехнічного комплексу: «Синхронний турбогенератор енергоблоку АЕС – електрична мережа енергосистеми – два трансформатори власних потреб – чотири асинхронні двигуни» у фазних координатах, орієнтовану на явні методи чисельного інтегрування системи диференціальних рівнянь. На базі математичної моделі розроблено програмне забезпечення, призначене для дослідження електромагнітних і електромеханічних процесів системи асинхронних двигунів головних циркуляційних помп ядерного реактора ВВЕР-1000 в режимах: оперативного перемикання включно з пуском і вибігом, переходу на резервне живлення, самозапуску двигунів з вибігом турбогенератора і без його вибігу. Виконано дослідження процесів системи асинхронних двигунів в режимі оперативного перемикання під час їх живлення від турбогенератора та встановлено основні закономірності їх перебігу в якісному та кількісному співвідношенні. Бібл. 10, рис. 11.

Ключові слова: **ядерний реактор, головні циркуляційні помпи, синхронний турбогенератор, трансформатор, асинхронний двигун, пускові режими, самозапуск, математична модель, диференціальні рівняння.**

Созданы средства компьютерного исследования режимов работы асинхронных двигателей главных циркуляционных насосов ядерного реактора ВВЭР-1000 АЭС. Разработана математическая модель электротехнического комплекса: «Синхронный турбогенератор энергоблока АЭС – электрическая сеть энергосистемы – два трансформатора собственных нужд – четыре асинхронных двигателя» в фазных координатах, ориентированная на явные методы численного интегрирования системы дифференциальных уравнений. На базе математической модели разработано программное обеспечение, предназначенное для исследования электромагнитных и электромеханических процессов системы асинхронных двигателей главных циркуляционных насосов ядерного реактора ВВЭР-1000 в режимах: оперативного переключения включительно с пуском и выбегом, перехода на резервное питание, самозапуска двигателей с выбегом турбогенератора и без его выбега. Выполнено исследование процессов системы асинхронных двигателей в режиме оперативного переключения при их питании от турбогенератора и установлены основные закономерности их протекания в качественном и количественном соотношении. Библ. 10, рис. 11.

Ключевые слова: **ядерный реактор, главные циркуляционные насосы, синхронный турбогенератор, трансформатор, асинхронный двигатель, пусковые режимы, самозапуск, математическая модель, дифференциальные уравнения.**

Definition of the problem and its relevance. Analysis of scientific publications. To date, 4 NPPs operate in the Ukrainian grid, with 13 VVER-1000 reactors and 2 VVER-440 reactors installed. Water-water nuclear power reactors of the VVER class are double-circuit [1-3]. The first circuit is intended for the removal of thermal energy from heat-emitting elements, which are installed in the core of the reactor and which contain nuclear fuel and the reaction of fission of nuclei under the influence of thermal neutrons takes place [1, 2]. Normal water serves as the coolant, which at the same time has the function of a neutron moderator, since the VVER reactors operate on thermal neutrons, that is, low-energy neutrons. The coolant circulates in the first circuit, the successive links of which are the following structural elements of the nuclear power plant: reactor core, main circulation pumps (MCPs), steam generators and water mains.

For extraction of heat from the reactor core, it is necessary to ensure the circulation of the coolant in the first circuit. This function is performed by the MCPs [2, 3]. At each of the VVER-1000 nuclear reactors, four main circulation pumps of the GCN-195M brand with power up to 6000 kW and coolant supply of 20,000 m^3/h were installed. Each of these MCPs pumps the coolant through the reactor and the steam generator, which together with the pump and piping system form a single loop [2].

Each of the four MCPs is driven by a separate short-circuited induction vertical motor VAZ 215/109-6AM05 with 8000 kW power and 6.3 kV supply voltage [2, 4]. The main circulation pumps belong to the responsible own need (ON) mechanisms. It is natural that the mechanisms of the NPP's own needs are subjected to high requirements for the reliability of the electric power supply of the motors, which propel these mechanisms and for the reliability of their operation. Failure of electric motors (EMs) of NPP's MCPs due to break of its power supply or their break may lead to a reactor emergency shutdown and a system failure – first circuit depressurization and, as a consequence, emission of radioactive elements into the atmosphere, which is dangerous for the life of the plant's personnel, damage to its basic equipment and the environmental impact. Therefore, for reliable electric supply of electric motors of the main circulating pumps of the VVER-1000 nuclear reactor, it is provided to use two power sources: working and standby [2, 4].

In order to comply with the rules specified in the instructions concerning the modes of operation of the EM of the MCP, it is necessary to have a clear and unambiguous understanding and reliable information about the course of electromagnetic and electromechanical processes that take place in these motors, in order to make timely correct decisions about their operative switching, conducting startup, switch to standby and emergency power, etc. The analysis of the literature indicates that the rules of operation of the EM of the MCP are stated only in job descriptions for NPP personnel [3], in which the algorithms of actions for the execution of these operations, including carrying out of profiles repairs and based solely on operating experience without a thorough analysis of the processes and problems of the motors operation modes.

The necessary information about the course of the processes can be obtained in two ways: 1) by conducting physical experiments directly on the electric motors of the MCP; 2) by conducting computer simulations using software developed on the basis of mathematical models of high-level adequacy. The first method is quite problematic due to the limitations of access to the systems of the EM of the MCP and the practical inability to carry out all the necessary experiments. The second one has no such restrictions, and therefore is considered promising.

The problem of the analysis of the modes of operation of electric motors of ON mechanisms of electric power plants is discussed in a rather large number of scientific works, and the material presented in these works is based on the classical theory of electric machines and presented in a general conceptual form, which makes it problematic to use it in a specific situation with motors of different types of different purposes and powers, as well as of the peculiarities of power supply curcuits. This means that in order to apply the provisions of these works in the practice of operating electric motors of specific ON units of power plants, significant refinements of these materials are required. In the light of the above, it is obvious that, to date, insufficient attention is being given to the development of information and technical means of analyzing the modes of operation of electric motors of the ON of power plants, which would be suitable for their immediate application in practice of operation of the power plants in general and NPPs in particular.

It is clear that more reliable information regarding the modes of operation of ON electric motors can be obtained on the basis of the solution of the system of differential equations, which describe the processes not only in steady but also in dynamic modes of operation of motors with the use of modern computer systems.

The above-mentioned suggests that the development of means of analysis of the modes of operation of electric motors of the own needs of NPPs, which are served by mathematical models and their corresponding software, is a relevant scientific and practical problem.

The goal of the paper is the development of a mathematical model and related software as a means of investigating the modes of operation of the induction motor (IM) system of the main circulating pumps of the VVER-1000 reactor of the NPP using modern computer technology.

Presentation of the main material. According to [2, 4], NPP's own-distribution switchgears are implemented with one assembled busbar system and one switch for connection. The number of sections of assembled busbars of the NPPs with voltage of 6.3 kV or 10.5 kV of normal operation is selected depending on: the number of MCPs, the allowed number of simultaneously connected MCPs without triggering the reactor emergency protection and the number and powers of installed ON operational transformers. On VVER-1000 reactors 4 MCPs are installed, drive induction motors of them motors are powered by the assembled busbars of 4 separate sections of normal operation (SNOs), the first two of which are powered by two secondary windings of the first working transformer of own needs (TON) of the first stage of transformation, and the primary winding of this transformer is connected to the first branch of the generating current lead. The other two SNOs are connected to the second branch of the generator current lead in the same way. Both working TONs are made with one primary and two secondary windings, which ensures the presence of four sections of normal operation per unit. Each of the two operational TONs of the unit on the base of the VVER-1000 nuclear reactor has power of 63 MVA.

Based on [2-4] and the above described, the system of electric motors of the MCP is referred to as an electrical engineering complex, the electrical circuit of which is shown in Fig. 1. The following system of designations is adopted in this Figure: the letter M denotes a three-phase electrical network that includes the power system together with the block transformer; TB, T1, T2, B1, B2, B3, B4 labels denote steam turbine, two operating TONs and four switches through which the stator windings of the induction motors are connected to the secondary windings of the TONs, and D1, D2, D3, D4 denote four asynchronous MCP's motors; letter G denotes synchronous turbogenerator (TG); letter F is the power source of the TG excitation winding; B5 is the generator switch for power unit; P1 – P4 are the main circulation pumps.

The other designations are: the letter φ denotes the potentials of the independent nodes of the circuit, the letter i denotes the currents of the phase branches of the structural elements, and the letter E denotes the electromotive force of the constant voltage source of the electrical circuit of the excitation of the turbogenerator. The lower indices indicate the numbers of independent nodes, the number of phase branches of the structural elements of the circuit and the numbers of the external branches of the structural elements. The letters M, T, G, D, F in the lower indices indicate the belonging of currents to the external branches: network, transformers, turbogenerator, induction motors, the power source of the excitation winding; M_e and T_P inscriptions indicate belonging to the internal currents of the network and transformers. The letter S in the lower indices indicates the identity of the phase currents to the stators of the induction motors and the turbohenegator, and the letter R – to the currents of the rotors of the induction motors. The numbers in parentheses in the upper index of the currents indicate the element number of the group of one type (transformers, switches and motors) to which this current belongs.

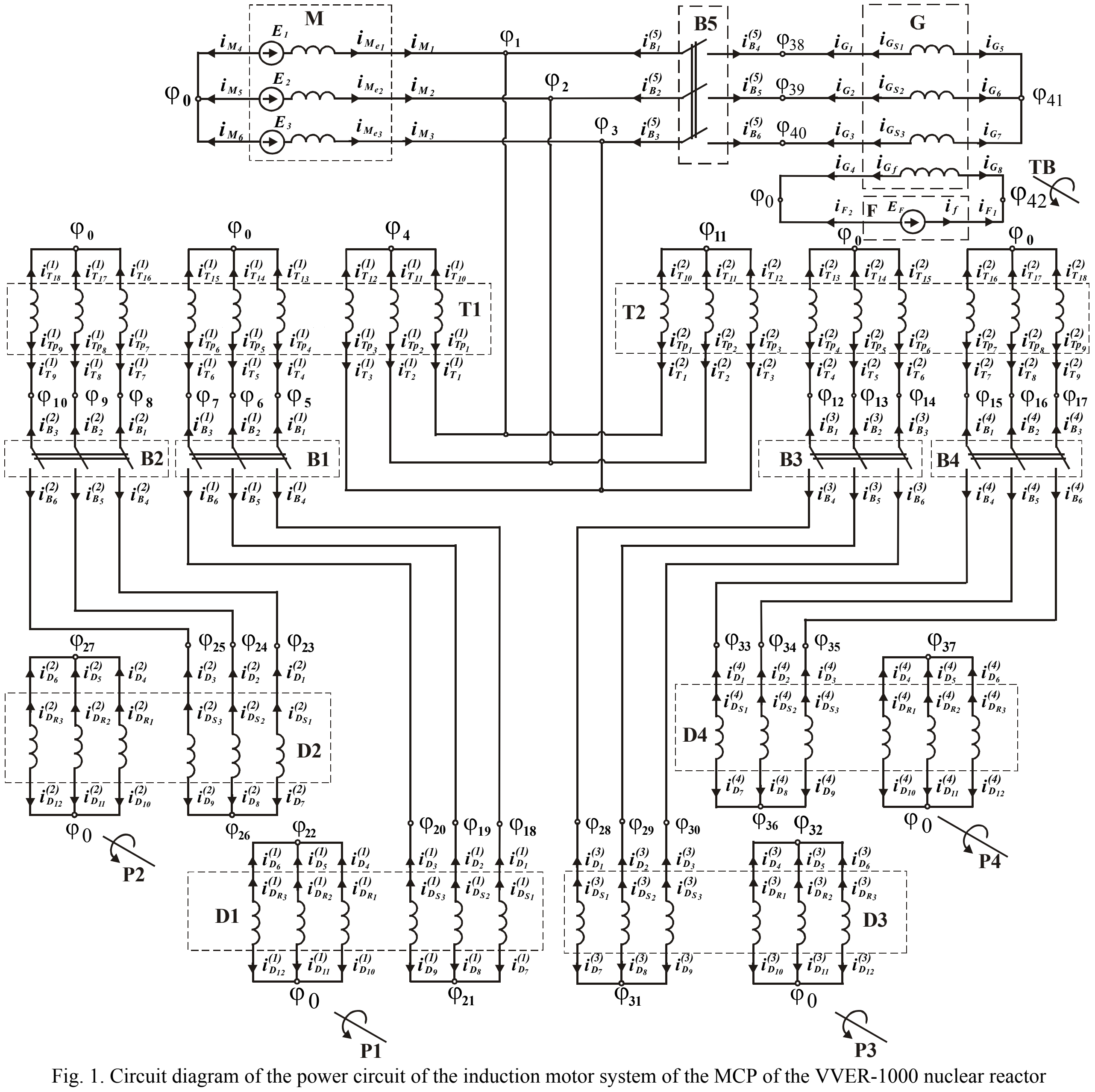

Fig. 1. Circuit diagram of the power circuit of the induction motor system of the MCP of the VVER-1000 nuclear reactor

For the practice of operation of the NPP unit on the basis of the VVER-1000 nuclear reactor, it is relevant to analyze the operation of the structural elements of the system of induction motors shown in the circuit of Fig. 1 in the following basic modes:

1) operation of the turbogenerator G in the normal mode on the power system M with the simultaneous electric power supply of the transformers of own needs T1, T2 and, accordingly, induction motors D1 – D4;

2) power supply of the TON from the power system through the block transformer when the turbogenerator is switched off;

3) operation of the MCP's induction motors in the situation of emergency shutdown with loss of connection with the power grid and shutdown of the turbogenerator due to the discontinuation of steam supply to the turbine, which translates TG into the run mode. Such a mode is indispensable for facilitating the transition to a natural coolant circulation in a nuclear reactor;

4) loss of power supply to the MCP's motors and the switch to the natural circulation of the coolant in the mode of the run of the units of the MCP (motors together with the pumps). To maximize run-time, which is critically important, induction motors are equipped with flywheels;

5) switching to the standby power supply of induction motors, followed by a short break in the supply of voltage to the TON for the duration of the automatic switching on of the reserve. Due to the re-supply of the voltage, the motors are restarted, that is, their further unwinding to the rated speed from the state in which there is less than the rated starting speed of the motors («self-start» in the literature);

6) mode of operative switching of MCP's induction motors.

The mathematical model of the electrical engineering complex (EEC) «TG-EM-T-IM» is developed on the basis of the theory of mathematical modeling of electromachine-valve systems (EMVS) [5] and a number of other developments presented in [6-10]. Thus, the mathematical model of the (EEC) «TG-EM-T-IM» is a system of differential equations of the electric state for the circuit of Fig. 1 and differential equations of mechanical state for induction motors together with MCP, turbogenerator with steam turbine, which serves as a source of primary mechanical torque of turbogenerator. The first system of equations describes the electromagnetic processes of the whole circuit of Fig. 1, and the second one – electromechanical processes occurring in induction motors and turbogenerators. The system of equations of electric state is written in phase coordinates and, together with equations of mechanical state, is oriented to explicit methods of numerical integration.

Each of the structural elements of the circuit (mains, transformers, switches, induction motors, turbogenerators, DC power source of the TG excitation winding) are represented by multipoles in the form of equations written by the second Kirchhoff law [5, 6].

Consider the mathematical models of structural elements of the electrical engineering complex on the example of a mathematical model of a turbogenerator.

System of equations of electrical and mechanical equilibrium of synchronous turbogenerator. According to [5, 8], a synchronous generator is represented by an eight-pole spanning three phases of the stator and the excitation winding, which is obtained by excluding the circuits of the damping winding represented by two circuits along the longitudinal *d* and the transverse *q* axis. The damping winding simulates the rotor array of the turbogenerator.

The electrical state of the synchronous generator is described by a vector equation of external branches that looks like this

$$p i_G + \mathit{\Gamma}_G \cdot \varphi_G + T_G = 0, \qquad (1)$$

where *p=d/dt* is the differentiation operator in time *t*; $i_G = (i_{G_1}, i_{G_2}, i_{G_3}, i_{G_4}, i_{G_5}, i_{G_6}, i_{G_7}, i_{G_8})$ is the vector of currents of external branches; $\varphi_G = (\varphi_{38}, \varphi_{39}, \varphi_{40}, \varphi_0, \varphi_{41}, \varphi_{41}, \varphi_{41}, \varphi_{42})$ is the vector of external potentials of the generator;

$$\mathit{\Gamma}_G = \begin{bmatrix} L_{\mathrm{G}}^{-1} & -L_{\mathrm{G}}^{-1} \\ -L_{\mathrm{G}}^{-1} & L_{\mathrm{G}}^{-1} \end{bmatrix}; \quad T_G = \begin{bmatrix} L_G^{-1} \\ -L_G^{-1} \end{bmatrix} \times E \qquad (2)$$

are the matrix of coefficients and the vector of free terms.

The components of the matrix of coefficient and the vector of free terms in (2) are determined by the following formulas:

$$L_G^{-1} = (L_{e,e} - L_{e,i} \cdot L_{i,i}^{-1} \cdot L_{i,e})^{-1};$$

$$E = p_0 \psi^{\gamma} \omega_G + R \cdot i - L_{e,i} \cdot L_{i,i}^{-1} \cdot (p_0 \psi_D^{\gamma} \omega_G + R_D i_D);(3)$$

$$L_{e,e} = \frac{L_d - L_q}{3} \begin{bmatrix} \cos(2\gamma) & \cos(2\gamma-\rho) & \cos(2\gamma+\rho) & 0 \\ \cos(2\gamma-\rho) & \cos(2\gamma+\rho) & \cos(2\gamma) & 0 \\ \cos(2\gamma+\rho) & \cos(2\gamma) & \cos(2\gamma-\rho) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} +$$

$$+ \begin{bmatrix} \frac{L_d+L_q}{3} + \frac{L_0}{3} & \frac{L_0}{3} - \frac{L_d+L_q}{6} & \frac{L_0}{3} - \frac{L_d+L_q}{6} & \frac{L_{ad}}{K_i}\cos(\gamma) \\ \frac{L_0}{3} - \frac{L_d+L_q}{6} & \frac{L_d+L_q}{3} + \frac{L_0}{3} & \frac{L_0}{3} - \frac{L_d+L_q}{6} & \frac{L_{ad}}{K_i}\cos(\gamma-\rho) \\ \frac{L_0}{3} - \frac{L_d+L_q}{6} & \frac{L_0}{3} - \frac{L_d+L_q}{6} & \frac{L_d+L_q}{3} + \frac{L_0}{3} & \frac{L_{ad}}{K_i}\cos(\gamma+\rho) \\ \frac{L_{ad}}{K_i}\cos(\gamma) & \frac{L_{ad}}{K_i}\cos(\gamma-\rho) & \frac{L_{ad}}{K_i}\cos(\gamma+\rho) & \frac{3}{2} \cdot \frac{(L_{ad} + L_{Gf})}{K_i^2} \end{bmatrix},$$

where $\rho = 2\pi/3$; K_i is the excitation current reduction coefficient of the stator current.

The matrix of mutual inductances between the stator and the excitation windings, on the one hand, and the circuits of the damping winding along the axes *d*, *q*, on the other hand, is as follows

$$L_{e,i} = \begin{bmatrix} L_{ad}\cos(\gamma) & L_{aq}\sin(\gamma) \\ L_{ad}\cos(\gamma-\rho) & L_{aq}\sin(\gamma-\rho) \\ L_{ad}\cos(\gamma+\rho) & L_{aq}\sin(\gamma+\rho) \\ \frac{3 \cdot L_{ad}}{2 \cdot K_i} & 0 \end{bmatrix}. \qquad (4)$$

The matrix of intrinsic inductances of the damper winding circuits is as follows

$$L_{i,i} = diag(L_{ad} + L_{\sigma dD},\ L_{aq} + L_{\sigma qD}). \qquad (5)$$

The matrix of mutual inductances between the damping winding circuits and the external circuits (stator and excitation winding) is as follows

$$L_{i,e} = \frac{2}{3} \begin{bmatrix} L_{ad}\cos(\gamma) & L_{ad}\cos(\gamma-\rho) & L_{ad}\cos(\gamma+\rho) & \frac{3 \cdot L_{ad}}{2 \cdot K_i} \\ L_{aq}\sin(\gamma) & L_{aq}\sin(\gamma-\rho) & L_{aq}\sin(\gamma+\rho) & 0 \end{bmatrix} \qquad (6)$$

Vectors ψ^{γ}, ψ_D^{γ} are determined by formulas

$$\psi^{\gamma} = L_{e,e}^{\gamma} i + L_{e,i}^{\gamma} i_D, \quad \psi_D^{\gamma} = L_{i,e}^{\gamma} i, \qquad (7)$$

where $L_{e,e}^{\gamma}, L_{e,i}^{\gamma}, L_{i,e}^{\gamma}$ are the derivatives of matrices $L_{e,e}, L_{e,i}, L_{i,e}$ by the angle of rotation *γ*; $i_D = (i_{D_d}, i_{D_q})$ is the vector of currents of the circuits of the damper winding; $i = (i_{G_{S_1}}, i_{G_{S_2}}, i_{G_{S_3}}, i_{G_f})$.

In (4)-(7) L_d, L_q, L_0 are the inductances along the longitudinal, transverse axes and inductance of the zero sequence; L_{ad}, L_{aq} are the inductances that correspond to the yoke response along the longitudinal and transverse axes of the yoke; $L_{\sigma dD}$, $L_{\sigma qD}$ are the inductances of the scattering of the damping coil along the axes *d*, *q*.

We describe mechanical processes occurring in a turbogenerator by differential equations of mechanical equilibrium, which has the following form:

$$(J_{TB} + J_G) \cdot p\omega_G - (M_{TB} - M_G) = 0, \qquad (8)$$

where J_{TB}, J_G are the moments of inertia of the turbine and generator rotor; $p\omega_G$ is the derivative of the mechanical angular rotational speed of the generator rotor in time t; M_{TB} is the mechanical torque of steam turbine; M_G is the electromagnetic torque of the generator.

Taking into account that the differential equations of the electric and mechanical states of the mathematical model are oriented towards explicit methods of numerical integration, an important point in the algorithm of integration of these equations is the definition of the integration vector, which all the coordinates are systemized that are included in the differential equations under the sign of the derivative and which are solved directly by integration.

The integration vector for a synchronous turbogenerator has the following structure:

$$pv_G = (pi_{G_{S1}}, pi_{G_{S2}}, pi_{G_{S3}}, pi_{G_f}, pi_{G_d}, pi_{G_q}, p\gamma_G, p\omega_G), \qquad (9)$$

where i_{G_d}, i_{G_q} are the currents of the damper winding along the axes d, q; γ_G, ω_G are the electric angle of rotation and the mechanical angular speed of the generator rotor.

The mathematical models of the switches were developed and described in [6] with the same approach (using the modular principle) as the mathematical model of the turbogenerator, and the mathematical models of the rest of the structural elements, including induction motors, were developed in a similar way based on [5, 8].

Direct integration of the system of differential equations of electrical and mechanical states is preceded by the formation and solution of a linear system of algebraic equations in the basis of the potentials of independent nodes in the electrical circuit of Fig. 1. For this purpose, derivatives of the currents of all electrical branches of the circuit are excluded from the system of differential equations of the electric state. Obtained in such a way system of linear algebraic equations of electric state has the following form [5, 6]:

$$A \cdot \varphi + B = 0, \qquad (10)$$

where A is the matrix of coefficients; B is the vector of free terms; $\varphi = (\varphi_1, \varphi_2, ..., \varphi_{42})$, is the vector of the potentials of the independent nodes of the circuit of Fig. 1.

The matrix of coefficients A and the vector of free terms B of the system of equations (10) are formed from the matrices of coefficients, vectors of free terms, and incident matrices of the structural elements of the circuit of Fig. 1.

To the mathematical model of the electrical engineering complex of the circuit of Fig. 1 (apart from the system of differential equations of electrical and mechanical states) an automatic control system (ACS) is also included designed to stabilize the voltage of the turbogenerator while increasing and reducing the load on it, as well as to stabilize the rotation speed of the generator rotor which is driven by a steam turbine. To stabilize the generator voltage, a proportional-integral controller is used, the operation of which is described by the following equation:

$$u_F = K_{uP}(u_z - u_{GS}^V) + K_{ui}\int(u_Z - u_G)dt + u_{F0}, \qquad (11)$$

where u_F, u_{F0} are the current and initial value of the excitation voltage; u_z, u_{GS}^V are the set value of voltage and module of imaging vector of phase voltages of the generator stator (their amplitude); K_{uP}, K_{ui} are the proportional and integral coefficients of the voltage regulator.

To stabilize the rotation speed of the generator rotor, a proportional-integral-differential controller is used, the operation of which is described by the following equation:

$$\begin{gathered} M_T = K_{\omega p}(\omega_z - \omega_G) + K_{\omega i}\int(\omega_z - \omega_G)dt + \\ + K_{\omega d}\, p(\omega_z - \omega_G) + M_{T0}, \end{gathered} \qquad (12)$$

where M_T, M_{T_0} are the current and initial value of the mechanical torque of the turbine; ω_z, ω_G are the set value and current value of generator rotor rotation speed; $K_{\omega_p}, K_{\omega_i}, K_{\omega_d}$ are the proportional, integral and differential coefficients of the generator rotor rotation speed controller.

The algorithm for the calculation of electromagnetic and electromechanical processes. The main input data are the catalog parameters of: electric network M; own need transformers T1, T2; induction motors D1, D2, D3, D4; turbogenerator G and DC voltage source F, as well as the initial conditions, which are systemized into a vector of integrated variables, having the following structure:

$$\begin{gathered} V = (V_M, V_T^{(1)}, V_T^{(2)}, V_B^{(1)}, V_B^{(2)}, V_B^{(3)}, V_B^{(4)}, \\ V_D^{(1)}, V_D^{(2)}, V_D^{(3)}, V_D^{(4)}, V_B^{(5)}, V_G, V_F, \\ \int(u_Z - u_{GS}^V)dt, \int(\omega_Z - \omega_G)dt, t) = \\ = (i_{Me1}, i_{Me2}, i_{Me3}, \\ i_{Tp1}^{(1)}, \dots, i_{Tp9}^{(1)}, i_{Tp1}^{(2)}, \dots, i_{Tp9}^{(2)}, \\ i_{B1}^{(1)}, i_{B2}^{(1)}, i_{B3}^{(1)}, i_{B1}^{(2)}, i_{B2}^{(2)}, i_{B3}^{(2)}, \\ i_{B1}^{(3)}, i_{B2}^{(3)}, i_{B3}^{(3)}, i_{B1}^{(4)}, i_{B2}^{(4)}, i_{B3}^{(4)}, \\ i_{DS_1}^{(1)}, i_{DS_2}^{(1)}, i_{DS_3}^{(1)}, i_{DR_1}^{(1)}, i_{DR_2}^{(1)}, i_{DR_3}^{(1)}, \gamma_D^{(1)}, \omega_D^{(1)}, \\ i_{DS_1}^{(2)}, i_{DS_2}^{(2)}, i_{DS_3}^{(2)}, i_{DR_1}^{(2)}, i_{DR_2}^{(2)}, i_{DR_3}^{(2)}, \gamma_D^{(2)}, \omega_D^{(2)}, \\ i_{DS_1}^{(3)}, i_{DS_2}^{(3)}, i_{DS_3}^{(3)}, i_{DR_1}^{(3)}, i_{DR_2}^{(3)}, i_{DR_3}^{(3)}, \gamma_D^{(3)}, \omega_D^{(3)}, \\ i_{DS_1}^{(4)}, i_{DS_2}^{(4)}, i_{DS_3}^{(4)}, i_{DR_1}^{(4)}, i_{DR_2}^{(4)}, i_{DR_3}^{(4)}, \gamma_D^{(4)}, \omega_D^{(4)}, \\ i_{B1}^{(5)}, i_{B2}^{(5)}, i_{B3}^{(5)}, \\ i_{G_{S1}}, i_{G_{S2}}, i_{G_{S3}}, i_{Gf}, i_{Gd}, i_{Gq}, \gamma_{Gd}, \omega_{Gq}, \\ \int(u_Z - u_{GS}^V)dt, \int(\omega_Z - \omega_G)dt, t). \end{gathered} \qquad (13)$$

The main points of the process calculation algorithm are the following actions:

- on the basis of the initial conditions of the vector V (13) and the catalog data, the matrixes of coefficient and vectors of free terms of structural elements (for the turbogenerator (2)) are formed and through them the matrix of coefficients A and the vector of free terms B of the system of equations of electric state (10), which is solved with respect to the vector φ;

- on the reverse course on the basis of the vector φ of the potentials of the independent nodes of the circuit of Fig. 1 the integration vector pV is defined equal to the derivative vector of integrated variables V (13) over time t ($pV=dV/dt$);
- one of the explicit methods of numerical integration, on the basis of the vector of integration pV and a given step of integration Δt, a new value of vector V is defined;
- the described procedure continues until the current time of integration t is exceeded beyond the specified final value.

According to the algorithm of the mathematical model, a software complex was developed. Below is a generalized analysis of electromagnetic and electromechanical processes occurring in the system of MCP's induction motors of a VVER-1000 nuclear reactor during the feed of transformers of own need (and thus of the induction motors) from a turbogenerator. In the actual operating conditions of the power unit, the rotational speed of the turbogenerator rotor is practically stable and corresponding to the frequency of the power grid voltage. In order to ensure such conditions, we use the possibility of a mathematical model and a software complex, which allows to provide a completely stable rotational speed of the generator rotor ω_G=const (although, as mentioned above, the mathematical model and the software package provide the possibility of calculation also the dynamic electromechanical process of the turbogenerator).

In this mathematical experiment, the corresponding ACS, described above (11), is used to stabilize the generator voltage during the operational switching of the MCP's induction motors.

The mathematical modeling results are the calculation dependencies of the basic coordinates, which include: the voltages and currents of all the electrical branches of the circuit of Fig. 1, the electromagnetic torques of IM and the moments of resistance of the MCP, as well as the rotational speed of the induction motors.

The input data are the catalog data of the turbogenerator, including the data of the power source of its excitation winding, induction motors, transformers of its own need and the electrical network. Here it is necessary to emphasize that the start-up AD of the MCP's IM of the VVER-1000 nuclear reactor is executed at total voltage of 6 kV (direct start), and the mechanical moment of inertia of the rotating mass of the rotor together with the flywheel is equal to 7250 kg·m^2. In addition, the input data includes information of an auxiliary character that determines the modes of operation of the software complex (integration step, end time of integration, etc.).

Simulation of electromagnetic and electromechanical processes is performed for the following mode of operation of MCP's induction motors: in the state of the moving with synchronous frequency rotor of the generator at the time taken by the initial (t = 0) the power source of the generator excitation winding is switched on. In the next stage, the first three IMs start in 5 s and at 5 s intervals (at times t_1 = 5 s, t_2 = 10 s, and t_3 = 15 s). At time t_4 = 30 s, the third motor is switched on, and at time t_5 = 40 s, the fourth motor is also switched on. At time t_6 = 70 s, all three induction motors that are currently running (the first, the second and the fourth ones) are switched off.

Below are graphs of the calculated dependencies of the basic coordinates on time and their analysis for the physics of the processes and operation of the electrical engineering complex of the drive of induction motors of the main circulating pumps of the VVER-1000 nuclear reactor while powering the motors from the turbogenerator of the nuclear power plant unit.

In Fig. 2 the calculated dependencies of the generator stator phase voltages are shown.

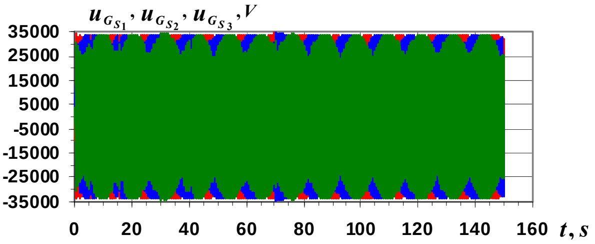

Fig. 2. $u_{GS_1}, u_{GS_2}, u_{GS_3}$ – generator phase voltages

Figure 3 shows the calculated dependencies of the phase currents of the generator. The nature of phase voltages and currents in Fig. 2, 3 reflects the processes of start and switching off of induction motors. The amplitude of phase voltages in Fig. 2 remains constant under the action of the ACS, and the amplitude of phase currents in Fig. 3 varies depending on the induction motors operation.

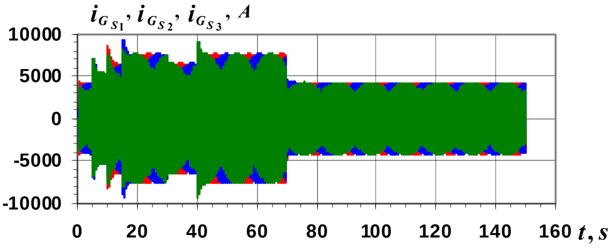

Fig. 3. $i_{GS_1}, i_{GS_2}, i_{GS_3}$ – generator phase currents

More clear and substantive information about the nature of phase voltages and currents in this mode of operation of the generator is given by the calculated dependences of the modules of the pictorial vectors of phase voltages and stator currents of the generator, which are shown in Fig. 4.

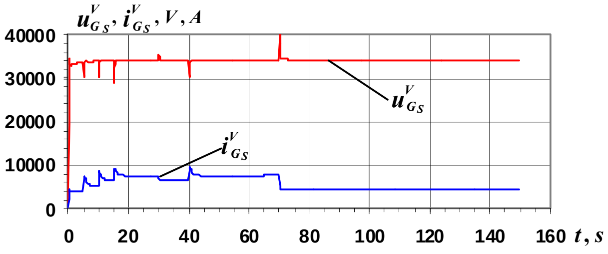

Fig. 4. u^V_{GS}, i^V_{GS} – modules of pictorial vectors of phase voltages and currents of the stator of the turbogenerator

The nature of the voltage and current curves in Fig. 4 clearly illustrates the patterns of change in the amplitude of the phase voltages and currents of the generator stator in the mode of operational switching of the IM, as well as the reaction and consequences of the action of the voltage ACS.

From Fig. 3, 4 it can be seen that during the period when the IMs are switched off ($t > 70$ s) the generator phase currents do not equal zero, although the voltage remains stable. This is due to the fact that at this interval both transformers of own need which are connected to the generator, operate in idle mode, and therefore in their primary windings the current does not equal zero in the situation with the motors switched off and has the value corresponding to this mode.

Functionally important information regarding the generator includes information about the nature of its voltage and excitation current. Therefore, in Fig. 5 the calculated dependencies of these coordinates are shown.

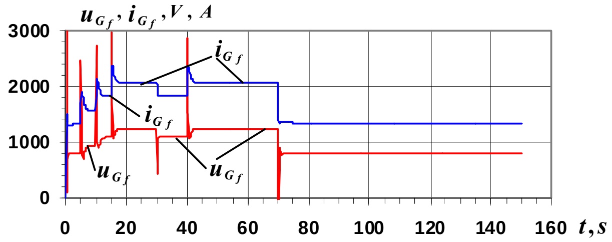

Fig. 5. u_{G_f}, i_{G_f} – voltage and current of the turbogenerator excitation

It is worth noting again that the ACS of the generator stator voltage operates precisely on the function of the module of the pictorial vector of phase voltages (11).

From the point of view of the operation of the MCP's induction motor system, it is important to have information about the main coordinates (voltages and currents) of the TON. In this context, let us consider and analyze the voltages and currents of the primary and two secondary windings of the first TON. In Fig. 6 the calculated dependencies of the modules of the pictorial vectors of the phase voltages of the primary and two secondary windings of the first TON are shown.

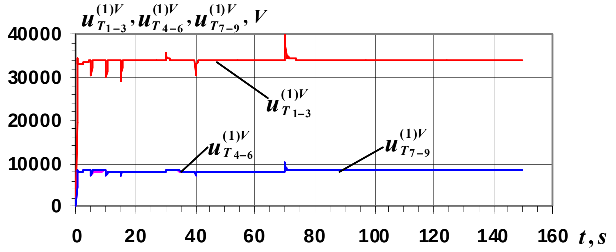

Fig. 6. $u_{T1-3}^{(1)V}, u_{T4-6}^{(1)V}, u_{T7-9}^{(1)V}$ – modules of the pictorial vectors of the voltages of the windings of the first transformer of own need

The Figure shows that the voltage of the primary winding is very close to the voltage of the generator in Fig. 4, and the voltage of the two secondary windings, the values of which coincide, corresponds to the current voltage value of 6.3 kV, which feeds the induction motors of the MCP. It is obvious that the voltages of the primary and two secondary windings of the second TON will be identical with the voltages of the first TON (Fig. 6).

Similarly to voltages, let us consider the winding currents of both transformers of own need. The modules of pictorial vectors of currents of the primary and two secondary windings of the first TON are shown in Fig. 7.

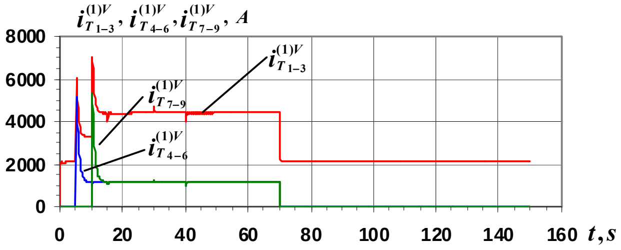

Fig. 7. $i_{T1-3}^{(1)V}, i_{T4-6}^{(1)V}, i_{T7-9}^{(1)V}$ – modules of the pictorial vectors of the currents of the primary and secondary windings of the first TON

As for the first one, the modules of the pictorial vectors of the currents of the primary and two secondary windings of the second TON are shown in Fig. 8.

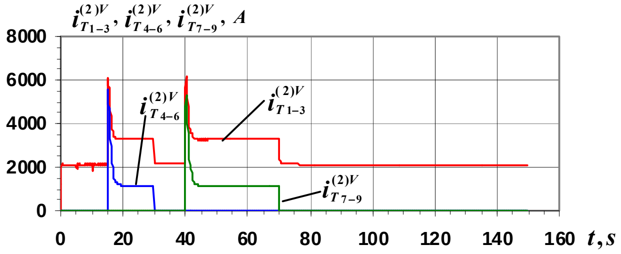

Fig. 8. $i_{T1-3}^{(2)V}, i_{T4-6}^{(2)V}, i_{T7-9}^{(2)V}$ – modules of the pictorial vectors of the currents of the primary and two secondary windings of the second TON

The calculated dependencies of the modules of the pictorial vectors of the secondary windings of the first and second TONs, which are shown in Fig. 7, 8 clearly illustrate the modes of operation of induction motors fed from the secondary windings of the TON. These Figures unambiguously and clearly show the moments of switching on and off of all four IMs, as well as the nature and frequency of the starting currents. The curves in Fig. 7, 8 also carry information on the nature and correlation of the primary and secondary windings of the TON, and together with Fig. 4 also about the ratio of the currents of the primary windings of the TON and the turbogenerator.

In the secondary windings of the transformers, the same currents flow as in the corresponding stator windings of the induction motors, which are connected by the switches. Therefore, the analysis of the currents of the secondary windings of the transformers serves at the same time for the currents of the IM stators. But to obtain more complete information about the IM stator windings currents, here we present only the instantaneous values of the phase currents of one of the randomly selected induction motors, which is the first. Therefore, the calculated dependencies of the instantaneous values of the phase currents of the first IM are shown in Fig. 9.

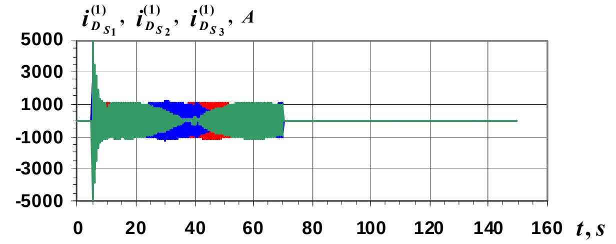

Fig. 9. $i_{DS1}^{(1)}$, $i_{DS2}^{(1)}$, $i_{DS3}^{(1)}$ – instantaneous phase currents of the stator winding of the first induction motor

It can be seen from the Figure that the curve of the module of the pictorial vector of the currents of the first secondary winding of the first transformer $i_{T4-6}^{(1)V}$ in Fig. 7 is such that goes around the current curves in Fig. 9, which uniquely responds to the physics of electromagnetic processes occurring in the system of the MCP's IM in accordance with the circuit in Fig. 1.

Above, we have considered and analyzed the electromagnetic processes described by the electrical coordinates to which the voltages and currents belong.

For the sake of completeness of information regarding the possibilities of the mathematical model and software complex in the analysis of modes of operation of induction motors of the MCPs of the VVER-1000 nuclear reactor, let us analyze the electromechanical processes, which are regarding IMs described by their rotational electromagnetic torques and mechanical moments of resistance of the MCP. Figure 10 shows the calculated dependencies of these coordinates.

It can be seen from the Figure that at the stage of acceleration of the first IM and, accordingly, the first MCP, the electromagnetic moment of the motor is substantially greater than the moment of resistance. In steady state, they are balanced, and at the run-out stage the electromagnetic torque of the motor is zero, and the mechanical torque decreases with the regularity of the decrease of the mechanical angular frequency of the motor with the pump according to the mechanical characteristics of the whole MCP unit. It is obvious that the regularities of the electromechanical processes of the other three motors are analogous, so there is no need to state them.

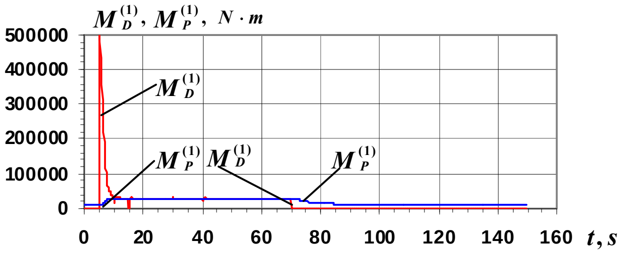

Fig. 10. $M_D^{(1)}$, $M_P^{(1)}$ – electromagnetic torque of the first induction motor and the moment of resistance of the first MCP

When it comes to the analysis of electromechanical processes of the MCP's IM of the VVER-1000 nuclear reactor, it is fundamentally important to have information about the nature and regularity of changes in the mechanical angular frequencies of rotation of the IM rotors, since these coordinates determine the productivity of the MCP operation and, respectively, the operation of both the nuclear reactor and the unit as a whole. Therefore, Fig. 11 shows the calculated dependencies of the mechanical angular rotation frequencies of the MCP's induction motors.

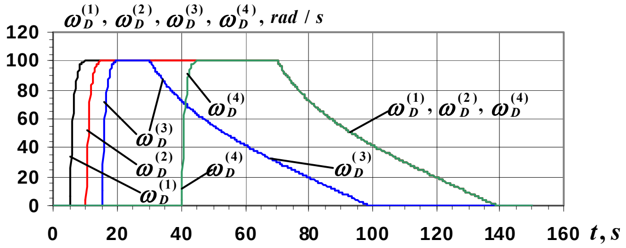

Fig. 11. $\omega_D^{(1)}$, $\omega_D^{(2)}$, $\omega_D^{(3)}$, $\omega_D^{(4)}$ – mechanical angular rotational speeds of MCP's induction motors

The Figure (as opposed to the Figures with curves of the currents) clearly shows not only the moments of switching on and off the IM, but also the time of their acceleration and running to a complete stop. Such information is critically important in ensuring the successful transition to the natural circulation of the coolant in a nuclear reactor in the event of an emergency shutdown of the power unit. To this end, the MCP's motors are further equipped with flywheels to increase the unit's run-time by the IM-MCP system.

Generalized analysis of curves in Fig. 11 and the curves of all other coordinates (the torques in Fig. 10, currents and voltages in all other Figures) shows that their character is fully consistent and fully interconnected in terms of the regularities of the electromagnetic and electromechanical processes, and at the same time it indicates a sufficiently high level of adequacy of both mathematical and numerical models. This result was achieved by describing electromagnetic and electromechanical processes by a single system of differential equations, including the ACS of the generator voltage and the rotor speed of the generator.

In the future, it is planned to carry out the research and to analyze the processes, including the transition to standup power, restart (self-start) of the IMs, as well as the analysis of the already mentioned modes of operation taking into account the dynamics of the generator rotor.

Important prospective studies (the necessity of which is especially emphasized in the scientific and technical literature [2, 4]) include the study of modes of operation of MCP's IMs during the transition to the natural circulation of the coolant of the nuclear reactor with the use of turbogenerator, which is obviously is of theoretical and practical interest in the operation of NPPs units based on the VVER-1000 nuclear reactor.

Conclusions.

1. Analysis of scientific literature indicates that the features of operation of electric motors of the MCP are stated only in the official instructions for NPP personnel, which stipulates the rules of operation: start-up, self-start, shutdown, switching to alternative power sources without a substantive scientific analysis of the regularities of the course of electromagnetic and electromechanical processes. There is clearly a lack of specific scientific research on this issue in scientific literature. The presence

of mathematical models and related software as a computer research tool would allow to investigate the modes of operation of the MCP's IMs system of the VVER-1000 nuclear reactor, necessary both in theoretical and practical aspects of exploitation of the NPP units.

2. A mathematical model of the system of MCP's induction motors has been developed, which takes into account the most important determinants that influence the course of electromagnetic and electromechanical processes, including: the mutual influence of the structural elements of the circuit of the IM system, the influence of the ACS on the operation of the TG excitation system, mutual influence of IMs and MCPs, which are driven by these motors, and also allows to study the operation of the MCPs during the self-start of the IMs and their operation during the run-out of the TG rotor.

3. A mathematical model has been developed that allows to study the most important modes of operation of the system of induction motors of MCPs with the help of modern computer technology.

4. In the first approximation, the study of electromagnetic and electromechanical processes of the system of induction motors of MCPs is carried out. In particular, the starting modes are investigated, the qualitative and quantitative parameters of the run-out of motors with large fly masses are obtained, which (according to the authors) is also the subject of a new scientific result.

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