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DEVELOPMENT OF CONTROL ALGORITHMS FOR MAGNETOELECTRIC GENERATOR WITH AXIAL MAGNETIC FLUX AND DOUBLE STATOR BASED ON MATHEMATICAL MODELING

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The object of this research is electromechanical processes in a generator with an axial magnetic flux and a double stator and an additional non-contact excitation winding operating as part of autonomous electric power systems. The power of the additional excitation system is about 2 % of the generator power.

The presence of an additional non-contact winding, which is powered by direct current, makes it possible to control the generator voltage by changing the excitation current. This resolves the task to stabilize the output voltage of the generator with permanent magnets when the load and shaft speed change.

This paper reports the construction of a three-dimensional field axisymmetric mathematical model of the generator under study, which has made it possible to calculate and investigate its characteristics and parameters, in particular the magnitude of magnetic induction in all structural elements. The model built takes into account the influence of finite effects, magnetic scattering fields, and the radial-axial nature of the closure of the main magnetic flux and the magnetic flux of the additional excitation winding. The use of a structure with a double stator makes it possible to more efficiently utilize the usable volume of the generator and to increase its power.

A mathematical model of the generator in the d-q coordinate system was built, which has made it possible to synthesize algorithms for controlling the automatic voltage stabilization system of the generator voltage under conditions of change in load and shaft speed. Control algorithms were developed on the basis of the concept of inverse dynamics problems in combination with minimizing local functionalities of instantaneous energy values, which ensures that the system is robust when changing generator parameters and that regulators are implemented in a simple way, due to the lack of differentiation operations.

Based on the models built and algorithms developed, the quality of control of the generator's output voltage when the load and frequency of the generator change was investigated by modeling in the MATLAB/Simulink environment. When setting a jump in the rated load and changing the rotational speed within ±15 % of the rated value, the automatic stabilization system provides astatic voltage control at a given level of 48 V.

The results can be practically used in the design of autonomous electric power systems with high energy conversion efficiency, in particular wind turbines and hydraulic units

Keywords: magnetoelectric generators with axial magnetic flux, double stator, mathematical modeling

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1. Introduction

Synchronous generators with permanent magnets, which possess high technical and economic indicators, are most common as electric generators of power plants for various purposes. The main disadvantage of these generators is the lack of effective methods for controlling the magnetic flux and, accordingly, the output voltage, which limits the optimization of the energy balance when the load and/or shaft speed change, in particular in modern conditions of rapid development of autonomous electric power systems.

One of the ways to solve this urgent problem is to use contactless magnetoelectric generators with axial magnetic flux (MGAMF), which have an additional fixed magnetization winding on the stator as a magnetic flux controller. The change in the amplitude of the main magnetic flux in the air gap occurs due to the use of a structural technique: part of the permanent magnets on the rotor is replaced by a magnetically soft material called a magnetic shunt. Magnetoelectric machines with axial magnetic flux are widely used in various industries: electric transport, renewable energy, for fans and pump drives, in aviation technology, robotics, as well as low-speed high-torque electric drives, since they have a compact structure that enables integration with a variety of devices.

2. Literature review and problem statement

Paper [1] proposes a method for improving the characteristics of generators with permanent magnets with a double stator with an axial magnetic flux. The performance improvement is achieved by incorporating a continuous and discrete stepped bevel along with a special winding connection. Due to the use of special design solutions, it was possible to reduce pulsations and torque fluctuations, simultaneously with an increase in the output torque. Torque pulsations create noise and vibrations that degrade the performance of the machine and shorten its service life. The specific volume and weight of the generator is kept constant along with the size of the magnet and the design parameters relative to known structures. Comparative analysis is performed using three-dimensional (3D) analysis by the method of finite elements. However, the cited work does not report the results of experimental research that could make it possible to assess the reliability of the findings.

Variants of structural execution of generators with axial magnetic flux, including non-magnetic designs of stators and with an iron core, are investigated in [2]. Based on analytical expressions, an algorithm for obtaining optimal characteristics of such generators is shown. A refining model has also been built that takes into account the higher harmonics of the magnetic field distribution. The paper presents a simplified mathematical model constructed for the cases of operation of an autonomous generator connected to a 3-phase power grid and loaded with a diode rectifier. To confirm the correctness of the reported calculations, analytical calculations, and calculations by the method of finite elements, as well as laboratory tests, were carried out. However, the analytical models are based on numerous assumptions and simplifications, which limits the use of the above expressions.

Comparison of methods for calculating generator parameters with axial magnetic flux and with permanent magnets is given in [3]. The generator under study is designed to work on a wind power plant. To calculate the parameters of a generator with an axial magnetic flux with permanent magnets without a magnetic core, an analytical method, and methods of two-dimensional and three-dimensional modeling by the finite-element method were used. The analytical method and the two-dimensional model were applied to individual cross sections through the air gap of the generator. Analytical methods and a two-dimensional model require the correct interpretation of the results when comparing them with the simulation results on a three-dimensional model. The work does not contain data on the error of the obtained results and information on the accuracy of measurements, which may cast doubt on the results.

Design, analysis, manufacture, and testing of two miniature generators with axial magnetic flux are given in [4]. To reduce the torque of magnetic resistance, the generator creates a static magnetic field consisting of a multilayer flat winding and two multipole rotors with permanent magnets on either side of the winding. To more significantly reduce the torque of resistance and save space, the second generator is made with a multilayer flat winding on the rotor and stator. This makes it possible to abandon the generator case. Experimental studies of prototypes were carried out on a low-speed wind turbine at a wind speed of 1–2 m/s. However, the work does not disclose the algorithm of the output voltage control system of this unit, which is especially important for autonomous wind power plants.

To ensure a stable output voltage of the generator with permanent magnets, paper [5] proposed a method to control the magnitude of the speed of rotation. A mathematical model of a generator with permanent magnets in the coordinate system of synchronous rotation is constructed in the work and a voltage stabilization scheme was developed. A generator voltage stabilization scheme was also built at different speeds and loads. By comparing the simulation results with experimental results, it is proved that the voltage stabilization circuit is suitable for the performance characteristics of a generator with permanent magnets. This provides a convenient and reliable method for designing and developing a voltage stabilization circuit and promotes the use of a generator with permanent magnets on agricultural vehicles. However, the cost of such a system significantly exceeds the cost of the generator and loses competition in the market. In addition, the use of a stabilization system based on a controlled rectifier increases the cost, weight, and volume of the generator with permanent magnets while reducing the efficiency of both the generator itself and the system as a whole.

In [6], the optimization of a fuzzy automatic voltage controller for the generation system using a real-time recurrent algorithm was carried out. Typically, this algorithm is used to train recurrent neural networks. The controller consists of a compact fuzzy system based on Boolean ratios, resembling controllers such as PI, PD, PID and second order. To implement the optimization of controllers, different values of error and output values are used. However, there are no results of experimental studies of such a system in the work, which may differ significantly from the simulation results.

Methods for improving the reliability and efficiency of axillary generators with hybrid excitation are presented in [7]. Since the magnetic flux of the proposed generator is three-dimensional, a three-dimensional mathematical model by a method based on an equivalent magnetic circuit has been built in the work. The model also takes into account the position of the rotor. The analysis of the efficiency of using an additional winding at different excitation currents and load currents was carried out. The simulation results coincide within satisfactory limits with the results of experimental studies. According to the authors of the work, this method of assessing the initial parameters of the generator has a significant amount of error and, to obtain accurate results, it is necessary to combine various modeling methods.

The method of controlling synchronous generators with permanent magnets due to the weakening of the magnetic flux is described in [8]. The paper proposes a new method for controlling the weakening of the flow with a quick response to the transition current. The change in dynamic voltage reserve and its reaction were analyzed in detail. Accordingly, it is proposed to control the weakening of the flow through joint control of dynamic current compensation and adjustment of the current error along the d axis. To assess the effectiveness of the proposed method, a traditional method of attenuation of the flow based on the PI-controller and a low-pass filter method have been developed. The results of the simulation and experiment show that the proposed method improves the transient. However, the high cost and complexity of such a system limits its use in energy-efficient systems.

In [9], the use of a six-phase synchronous generator with permanent magnets is considered. A simulation model in the MATLAB/Simulink environment has been developed to assess the effectiveness of the output voltage stabilization system. Using this approach makes it possible to reduce the amount of copper used while expanding the control range. No confirmation of the adequacy and reliability of the results obtained in the work is given.

Paper [10] reports a new wind power system using 2 five-phase synchronous generators with permanent magnets. It is controlled by a rectifier with fifteen switches for a system connected to the network. To improve the control efficiency of the proposed wind system, a sliding control mode was applied to control the converters both on the generator side and on the network side. The simulation results show that the controlled variables correspond to their standards regardless of wind speed fluctuations. The results of experimental studies are shown indistinctly, without a description of the necessary equipment and test program, which casts doubt on the adequacy of the results.

Thus, the results of our review revealed that the issue of increasing the efficiency of energy conversion in MGAMF requires further research, taking into account the effect on the output voltage of the generator of changes in the load and the speed of rotation of the shaft when working as part of autonomous electric power systems.

3. The aim and objectives of the study

The aim of this work is to increase the efficiency of energy conversion in MGAMF as part of autonomous electric power systems by designing and researching MGAMF with a double stator and an additional magnetization winding.

To accomplish the aim, the following tasks have been set:

– to build a three-dimensional field mathematical model of MGAMF with a double stator and an additional magnetization winding;

– to conduct research on the results of calculations and modeling of MGAMF using the constructed three-dimensional asymmetric field model;

– to build a mathematical model of MGAMF with an additional winding of magnetization in the coordinate system d–q;

– to develop algorithms for controlling the system of automatic stabilization of the generator voltage when the load and shaft speed change;

– to investigate the control quality of the designed system of automatic voltage stabilization of the generator.

4. The study materials and methods

The object of our research is electromechanical processes in a generator with an axial magnetic flux and a double stator operating as part of electric power systems.

The main hypothesis assumes that in order to regulate the output voltage of MGAMF, a change in the current of the additional winding is performed. This leads to a change in the magnetic flux in the air gap and, as a result, to an increase or decrease in the output voltage.

During MGAMF operation, it is assumed that the load is constant, and its values are not influenced by external factors and internal ones; the rotational speed is constant.

Fig. 1 shows the structure and cross-section of the studied MGAMF. The choice of the main dimensions for the generator is approximately based on calculations using classical procedures and employing the practical experience of research engineers [11]. To simplify the presentation of the material, the calculation procedure is not given in the current paper.

The magnetic shunt is made of a magnetic conductive material: a solid piece of steel, a composite ferromagnetic material, or a ferromagnetic powder material. The shunt forms a path for closing the main magnetic flux of permanent magnets on the one hand, and, on the other hand, forms a path for closing the magnetic flux of the additional winding.

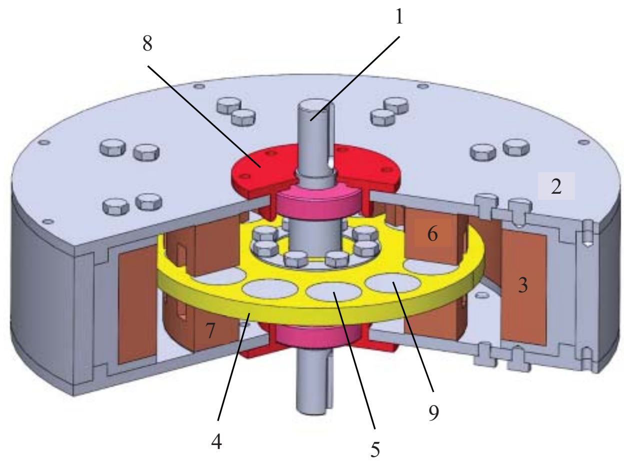

Fig. 1. Schematic showing the studied magnetoelectric generator with axial magnetic flux: 1 – generator rotor shaft; 2 – generator housing (capsule) made of magnetic conductive material; 3 – additional winding; 4 – generator rotor made of non-magnetic material; 5 – permanent magnets of type NdFeB N38H; 6, 7 – two stators of the investigated generator with an armature winding; 8 – flanges with bearings; 9 – magnetic shunt

Fig. 1, *b* shows the axial cross-section of the generator under study with the basic dimensions.

The main parameters of the electric generator under study are given in Table 1.

Table 1

The main parameters of the generator under study

No.	Parameter	Value	Measurement unit
1	Full rated power	700	V·A
2	Estimated voltage of the generator	48	V
3	Number of phases	3	–
4	Rotational frequency	1,000	rpm
5	Number of poles	6	–
6	Type of permanent magnets	NdFeB N38H	–
7	Diameter/axial length of permanent magnets	25/8	mm
8	Power factor	0.9	–
9	Diameters of the magnetic core of the stator	135/85	mm
10	The length of the stator core	23.0	mm
11	Axial length of the rotor	8.0	mm
12	The outer diameter of the generator	270.0	mm
13	The size of the air gap	0.5	mm
14	Estimated efficiency	92	%
15	The number of grooves on the stator	18	–
16	Steel brand	3416	–

The finite-element method used to solve the problem is implemented in the COMSOL Multiphysics 5.5 software package.

The study of control quality was carried out by modeling in a MATLAB/Simulink environment with generator parameters.

5. Results of investigating control algorithms for a magnetoelectric generator with an axial magnetic flux and a double stator

5. 1. Construction of a three-dimensional axisymmetric field mathematical model

To reduce the power of the computer, reduce the time spent on each iteration of numerical calculation, increase the efficiency of using numerical methods, an axisymmetric model has been built in the framework of this work. The model has 2 types of symmetry: geometric (sectoral) symmetry and mirror symmetry with respect to a plane perpendicular to the axis. This makes it possible to reduce the geometry of the total calculated area to such as shown in Fig. 2.

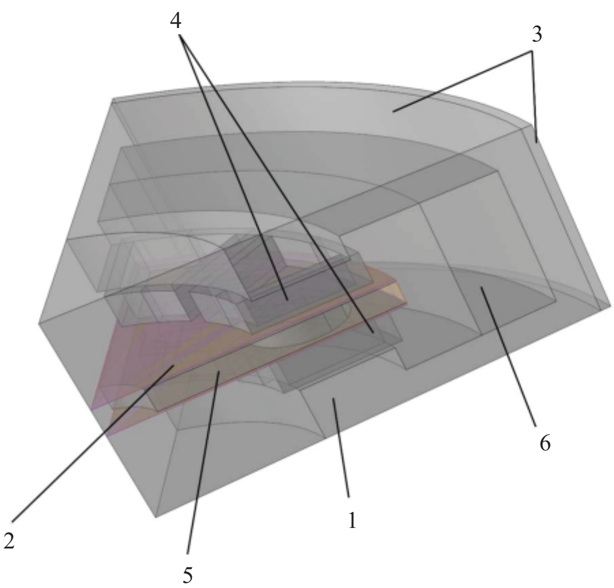

Fig. 2. Estimated area of the constructed model: 1 – periodic boundary conditions; 2 – boundary conditions between the stator and rotor; 3 – zero boundary conditions; 4 – armature winding; 5 – generator rotor with permanent magnets; 6 – additional winding

Periodic boundary conditions are set at the boundaries of symmetric sectors of the calculated area. For the model built, the condition of periodicity is given, since in neighboring sectors of the model the residual magnetization of permanent magnets changes its sign. Mathematically, the condition for the vector magnetic potential **A** is written as follows

$$\mathbf{A}_{12}=-\mathbf{A}_{21}. \tag{1}$$

Boundary conditions between the stator and rotor must coincide with the boundary conditions (1).

For this boundary of the calculated region, zero boundary conditions of the first kind are set for the tangent component of the magnetic potential

$$n\times\mathbf{A}=0. \tag{2}$$

To reduce the number of equations of the calculated region and the time spent on each iteration, a combined approach is used: for non-conductive regions, the solution is derived with respect to the scalar magnetic potential V_m. Classical equations for the electromagnetic field are used for the vector magnetic potential **A**. In addition, this solution makes it possible to improve the accuracy of calculating the magnetic flux at the boundaries (2, Fig. 2).

For all non-conductive parts (air, rotor, and some parts of the housing), a system of equations with respect to the scalar magnetic potential V_m is used

$$\begin{cases} -\nabla\cdot\left(\mu_0\nabla V_m-\mu_0\mathbf{M}\right)=0, \\ \nabla\cdot\mathbf{B}=0, \\ \mathbf{B}=\mu_0\cdot\mu_r\cdot\mathbf{H}, \\ \mathbf{H}=-\nabla V_m, \end{cases} \tag{3}$$

where μ_0, μ_r – magnetic vacuum permeability and relative magnetic permeability of the material of the region; V_m – scalar magnetic potential; **B** – vector of magnetic induction; **H** – magnetic field strength vector; **M** – magnetization vector.

The electromagnetic field formed by permanent magnets is also solved relative to the scalar magnetic potential, but the equation takes on a different form, given the properties of permanent magnets

$$\begin{cases} \mathbf{B}=\mu_0\cdot\mu_m\mathbf{H}+B_r, \\ B_r=\left\|B_r\right\|\dfrac{e}{\left\|e\right\|}, \end{cases} \tag{4}$$

where μ_m is the magnetic permeability of a permanent magnet; B_r – residual magnetization of a permanent magnet; e – the direction of the vector of residual magnetization of the magnet (x, y, or z axis).

The magnetic core of the stator, the generator housing, and the shaft are made of a magnetically soft material, which is characterized by a nonlinear relationship between magnetic induction **B** and the magnetic field strength **N**. Electromagnetic field equations for these regions and the nonlinearity of the ferromagnetic material are described by the following equations

$$\begin{cases} \nabla\times H=J, \\ B=\nabla\times A, \\ E=-\dfrac{\partial A}{\partial t}, \\ J=\sigma E, \\ B=f(H)\dfrac{H}{H}, \end{cases} \tag{5}$$

where **J** is the current density vector in the elements of the calculated region; E – vector of electric field strength; σ – electrical conductivity of the material.

For a three-phase winding of the armature of the generator under study, the first four equations of the system are valid (5). At the same time, the current density in the armature windings, induced by EMF and other winding parameters, are determined by the following system of equations

$$J_e=\frac{N\left(V_e+V_{ind}\right)}{S_c\cdot R_s},$$

$$R_s=\int_A\frac{N\cdot L}{\sigma_c\cdot a_c\cdot S_c}\mathrm{d}A, \tag{6}$$

$$V_{ind} = N \cdot \sum \frac{L}{S_c} \cdot \left(\int_{S_c} E_{zA} \mathrm{d}s - \int_{S_c} E_{zx} \mathrm{d}s \right),$$

where J_e is the magnitude of the current density in the armature winding, which depends on the magnitude of the load and the nature of the generator; N – the number of turns in the armature winding; S_c – cross-sectional area occupied by the winding of the conductor; R_c – active resistance of the stator winding phase; L – the average length of the turn of the stator winding phase; σ_c, a_c – the electrical conductivity of the stator winding material and the cross-sectional area of the elementary conductor; V_{ind} – the value of the induced EMF in the winding of the generator stator; V_e – voltage characterizing the generator load; E_{zA}, E_{zX} – electric field strength at the locations of the phase zones "A" and "x".

Another way to reduce the time of calculation of the generator according to the proposed mathematical model and reduce the power of the computer, in this model we use a direct method for solving nonlinear differential equations, rather than iterative [5]. To provide a single solution to the system of differential equations (3) to (6), an additional condition is set for all regions with vector magnetic potential **A** [5]

$$\nabla \cdot (\sigma \mathbf{A}) = 0. \tag{7}$$

In the equations of system (3), only the potential gradient is used, and not the potential value itself. To obtain a single solution to the problem, the Dirichlet condition is applied, given for one of the boundaries of the calculated region [6]

$$V_m = 0. \tag{8}$$

The model adopts the following assumptions: losses on hysteresis and eddy currents in the magnetic core are not taken into account; no calculation of electromagnetic moment and forces is carried out. The analysis of thermal conditions is not carried out since it requires the statement and solution of a separate problem.

The grid of finite elements (GFE) in the calculated area of the studied MGAMF is shown in Fig. 3.

The parameters of the selected GFE make it possible to obtain a minimum calculation time along with adequate results.

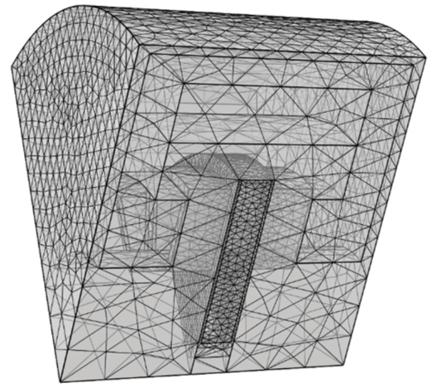

Fig. 3. Grid of finite elements of the generator under study

Table 2 shows a comparison of GFE parameters and the calculation time for the built axisymmetric (fragmental) model and the full-volume model of the generator.

Table 2

Comparison of GFE parameters

Parameter	MGAMF fragmental model	MGAMF full-volume model
The total number of tetrahedra covering the computational domain	586948	3716372
The number of boundary surface elements of GFE	196601	906164
The number of linear elements of GFE	16882	96727
The average time for calculating the given task, s	348	26604

Obviously, the use of an axisymmetric model can significantly save the resources of the computer.

5. 2. Simulation results of a magnetoelectric generator with an axial magnetic flux

In the simulation, the rated rotor speed of 500 rpm was adopted. Fig. 4 shows the distribution of magnetic induction (background coloring) and the closing lines of the main magnetic flux (arrow) for the initial moment and at time 0.02 s. The current in the excitation winding is I_e=0 A.

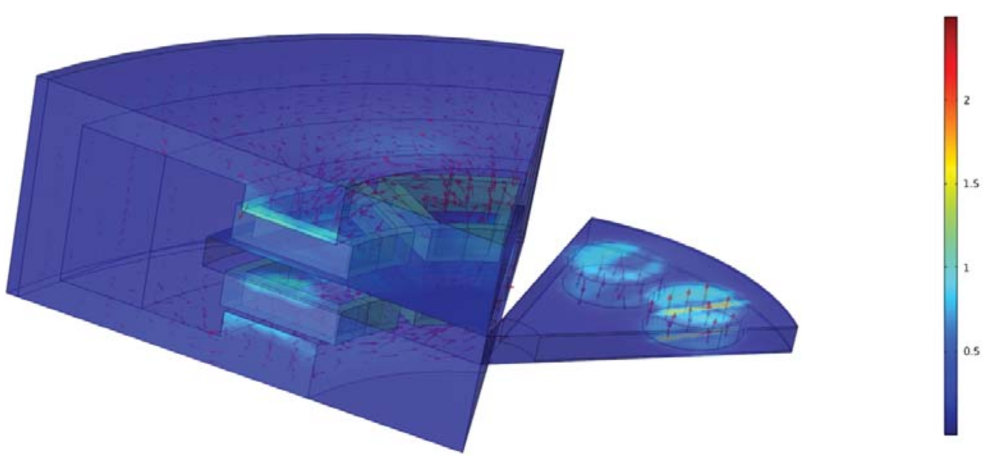

Fig. 4. Distribution of magnetic induction and magnetic flux in the calculated region of a magnetoelectric generator with an axial magnetic flux at I_e=0 A

Permanent magnets on the rotor and magnetic shunts are arranged in such an order and in such a way that a path is formed to close the main magnetic flux of permanent magnets (at I_e=0 A). Permanent magnet-air gap 1- stator tooth 1-stator yoke 1-generator body 1-backrest of housing-generator body 2-yoke of stator 2- stator tooth 2-air gap 2-permanent magnet. This nature of the closure of the main magnetic flux is due to the fact that that the structural elements of the generator (housing, back of the case) are unsaturated. Accordingly, at I_e=0 A, the magnetic resistance of this section is significantly less than expected due to the air gap and magnetic shunt. This is a feature of a magnetoelectric generator with an axial magnetic flux and a double stator.

Numerical calculations of the investigated generator were carried out for two modes of operation: with a current in the excitation winding I_e=0 A, and when supplying current to an additional winding I_e=1 A.

Fig. 5 shows the distribution of magnetic induction and the main magnetic flux when supplying current to an additional winding of the value I_e=1 A.

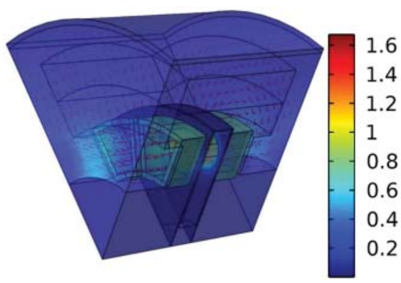

Fig. 5. Distribution of magnetic induction and magnetic flux in the calculated region of a magnetoelectric generator with an axial magnetic flux at I_e=1 A

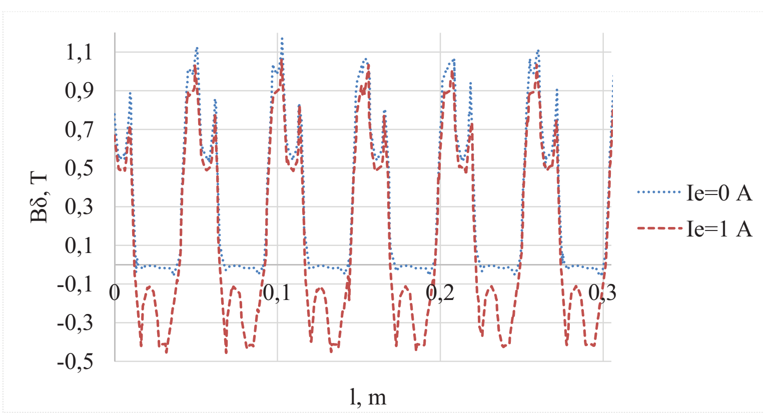

Fig. 6. Distribution of the normal component of magnetic induction in the air gap: 1 – with current in the magnetization winding I_e=0 A; 2 – when supplying current to the additional winding I_e=1 A

As part of the study, the external characteristics were calculated for a fully active load cosφ=1 when current is applied to an additional winding and at I_e=0 A. Change in the load of the generator under study is described by a system of equations (6).

Fig. 7 shows the external characteristics of the generator under study.

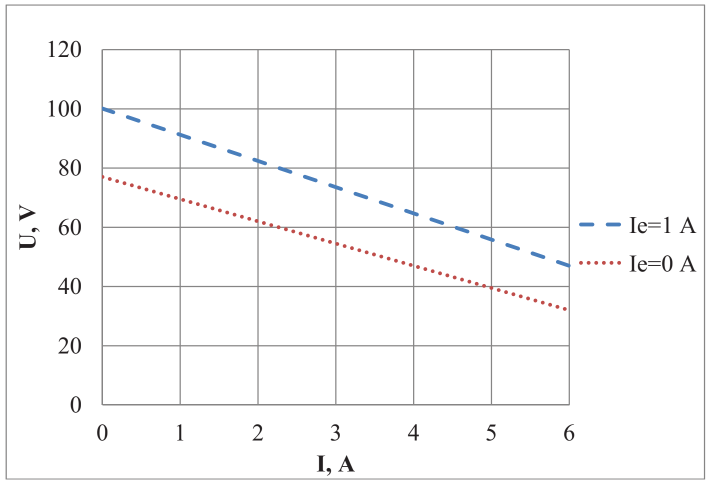

Fig. 7. External characteristics of the studied magnetoelectric generator with axial magnetic flux

Thus, the change in the parameters and characteristics of the generator under study when supplying current to an additional excitation winding corresponds to theoretical ideas about the operation of generators of this type. This indicates the correspondence of the mathematical model built with the physical processes in the generator and the feasibility of using the results obtained in further research.

5. 3. Mathematical model in the *d-q* coordinate system

Field methods make it possible to carry out calculations and studies of an electric machine at the design stage, but they are not suitable for the synthesis of coordinate control systems of electrical machines. To solve control problems, a mathematical model of MGAMF in the $d–q$ coordinate system based on its convolutional electrical circuit was compiled using a typical procedure. When constructing the mathematical model of MGAMF, the following assumptions were accepted: the air gap is uniform; the saturation of the magnetic system is neglected; the stator winding is evenly distributed. The nonlinear system of equations (9) describes the operation of a magnetoelectric generator in the $d–q$ coordinate system.

$$\begin{cases} L_s \dfrac{di_d}{dt} + R_s i_d = u_d + F_1, \\ L_s \dfrac{di_q}{dt} + R_s i_q = u_q + F_2, \\ L_f \dfrac{di_f}{dt} + R_f i_f = u_f + F_3, \\ J\dfrac{d\omega}{dt} = \left[-M + M_C\right], \\ M = \dfrac{3}{2} Z_p \left[\psi_0 i_q \pm L_m i_q i_f\right], \\ F_1 = \omega Z_p L_s i_q - L_m \dfrac{di_f}{dt}, \\ F_2 = -\omega Z_p L_s i_d - \omega Z_p L_m i_f - \omega Z_p \psi_0, \\ F_3 = -L_m \dfrac{di_d}{dt}, \end{cases} \qquad (9)$$

where L_f, R_f – inductance and active resistance of the additional magnetization winding; u_f, i_f – voltage and current of the additional winding; $L_s=L_q=L$ – stator inductance along the q and d axes; R_s – active resistance of the stator winding; L_m – interinductance of windings; i_q, i_d – stator currents along the axes q and d; u_q, u_d – stator voltages along the axes q and d; ω – angular velocity of the generator rotor; ψ_0 – flux coupling created by permanent magnets; Z_p – number of pairs of poles; M, M_c – electromagnetic moment of the generator and drive propulsion; J – total moment of inertia; F_1, F_2, F_3 – coordinate perturbations.

The functional diagram of the generator voltage control system when the rotor speed or load change is shown in Fig. 8.

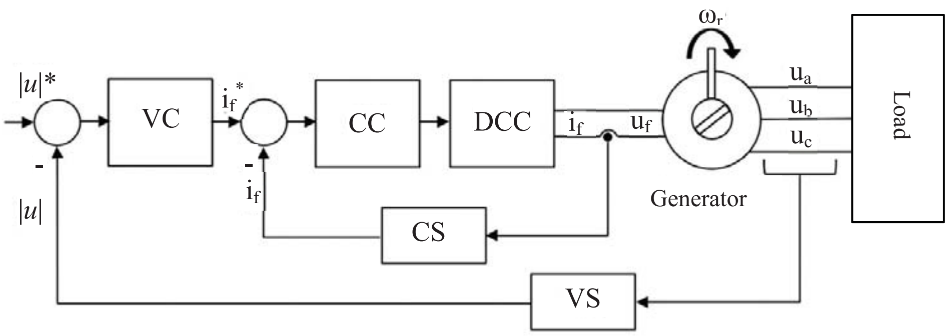

Fig. 8. Voltage control system of magnetoelectric generator: marked: VC – generator voltage controller; CC – generator excitation current controller; DCC – DC converter; CS – generator excitation current sensor; VS – generator voltage sensor; |u|*, |u| – specified and measured value of the operating voltage of the generator; i_f^*, if – set and measured value of the generator excitation current; ua, ub, uc – phase voltages of the generator

The task of the control system is to stabilize the voltage of the autonomous generator when the load and/or speed of the generator change. The system must ensure first-order astatism, which means the absence of static error. The dynamic error in setting and dropping the rated load should not exceed the standard values. The output signal of the voltage controller VC is the task signal for the excitation current controller CC.

5. 4. Development of generator voltage control algorithms

The development is carried out by the method of inverse dynamics problems in combination with minimization of local functionalities of instantaneous energy values, based on the idea of reversibility of the direct Lyapunov method for the study of stability. The method makes it possible to find the law of control in which the closed loop has a predetermined Lyapunov function. This gives the system the property of stability as a whole, which makes it possible to solve problems of controlling interdependent objects according to mathematical models of local contours. A characteristic feature of optimization is to find not an absolute minimum of quality functionality, as in classical systems, but a certain minimum value that provides a dynamic error of the system that is permissible under technical conditions. The obtained control algorithms provide dynamic decomposition of the interdependent object, weak sensitivity to parametric perturbations, and do not contain differential links, which enables their practical implementation.

Coordinate perturbations F_1, F_2, F_3 are interpreted as indefinite but limited in magnitude $F_1 \le F_1^0$, $F_2 \le F_2^0$, $F_3 \le F_3^0$. The level of control voltages is sufficient to compensate for them $u_d > F_1^0$, $u_q > F_2^0$, $u_f > F_3^0$. Thus, an interconnected nonlinear system of the 4th order turns into a system of 4 linear equations of the first order. As a result, the task of controlling an object (9) is reduced to solving local problems of controlling linear subsystems.

The desired quality of the closed control loop according to the concept of inverse problems of dynamics [12, 13] is given by the differential equation of the following type

$$\frac{d^n z}{dt^n}+..+\gamma_i\frac{d^i z}{dt^i}+..+\gamma_0 z= \\ =\beta_m\frac{d^m x^*}{dt^m}+..+\beta_j\frac{d^j x^*}{dt^j}+..+\beta_0 x^*. \quad (10)$$

Using the coefficients of equation γ_i and β_j, the desired nature and duration of the transition process of the original coordinate z is given when moving along a given trajectory x^*, where: x^* is a time-differentiated function in the required number of times; $m<n$.

The preferred closed-loop control transfer function derived from equation (10) for the case n=3 and m=1 is (where $s=d/dt$ is the Laplace operator)

$$W_s(s)=\frac{z(s)}{x^*(s)}= \\ =\frac{\beta_1 s+\beta_0}{s^3+\gamma_2 s^2+\gamma_1 s+\gamma_0}. \quad (11)$$

The corresponding transfer function of the open control loop is equal to

$$W_r(s)=\frac{W_s(s)}{1-W_s(s)}= \\ =\frac{\beta_1 s+\beta_0}{s^3+\gamma_2 s^2+(\gamma_1-\beta_1)s+(\gamma_0-\beta_0)}. \quad (12)$$

(12) demonstrates that in order to obtain a control system with first order astatism ν=1, it is necessary to set the values of the coefficients $\beta_0=\gamma^0$, then

$$W_r(s)=\frac{\beta_1 s+\gamma_0}{s\left[s^2+\gamma_2 s+(\gamma_1-\beta_1)\right]}, \quad (13)$$

and with second order astatism ν=2, one needs to set $\beta_0=\gamma_0$ and $\beta_1=\gamma_1$

$$W_r(s)=\frac{\gamma_1 s+\gamma_0}{s^2(s+\gamma_2)}. \quad (14)$$

The specified quality at the speed of the system (13) is determined by the expression $D_\omega^z=\gamma_0/(\gamma_1-\beta_1)$, and the quality with respect to the acceleration of the system (14) is equal to $D_\varepsilon^z=\gamma_0/\gamma_2$. The order n of equation (10) can be different for each closed control loop according to the requirements of the control quality and is usually equal to or one above the order of the control object.

The structure and parameters of the desired control quality equation (10) are set so that the perturbed motion is asymptotically stable. According to the Hurwitz stability criterion for the third-order equation, this condition is met with the ratios of parameters $\gamma_0>0$; $\gamma_1>0$; $\gamma_2>0$ and $\gamma_1\gamma_2>\gamma_0$, and for second- and first-order equations – at positive values of coefficients.

The relationship between the coefficients of equation (10) and the necessary indicators of control quality, such as the control time, the type of transient process, overshoots are established using well-known methods of automatic control theory, for example, root, frequency, or standard polynomials, followed by refinement by modeling.

The development of an algorithm for controlling the excitation current of MGAMF is carried out on the basis of the third equation of system (9). The local control object is described by the first-order equation, so the order of the desired closed-circuit equation of the current of the form (10) is also assumed to be equal to one (n=1, m=0)

$$\dot{z}+\gamma_{0f}z=\gamma_{0f}i_f^*, \tag{15}$$

with the provision of first order astatism ν=1 and the given quality at speed $D_\omega^z=\gamma_{0f}$. The duration of the monotonous current transient process is determined using the value of a single coefficient γ_{0f}.

It is necessary to find such a control function of the excitation current controller u_f so that the quality of current control approaches the desired one given by equation (15). The degree of approximation of the real process of controlling the current to the desired is estimated by the functionality, which characterizes the energy normalized by inductance of the first derivative of the magnetic field in the form $\dot{W}_m=L\frac{\dot{i}^2}{2}$.

$$G(u_f)=\frac{1}{2}\left[\dot{z}(t)-\dot{i}_f(t,u_f)\right]^2. \tag{16}$$

Finding the control function $u_f=u_f(i_f)$ by classical methods of the theory of automatic control, provided that the absolute minimum of the functional is achieved

$$\min_u G(u_f)=0, \tag{17}$$

leads to the traditional law of management of the compensation type, the implementation of which requires accurate information about the structure and parameters of the object. Deviation of parameters from the calculated values leads to a deterioration in the quality of control.

This disadvantage is eliminated if we abandon the exact fulfillment of condition (17) but only limited by the requirement that the value of functional (16) belongs to some vicinity of the extreme minimum, which provides a dynamic error permissible under technical conditions. To do this, the minimization of the functionality is carried out according to the gradient law of the first order

$$\frac{du_f(t)}{dt}=-\lambda_f\frac{dG(u_f)}{du_f}, \tag{18}$$

where $\lambda_f>0$ is a constant.

Taking into account (9) and (15), the derivative of the functional is equal to

$$\frac{dG(u_f)}{du_f}=-\frac{1}{L_f}(\dot{z}-\dot{i}_f). \tag{19}$$

After substitution (19) in (18), the excitation current control algorithm is found

$$\dot{u}_f(t)=k_f(\dot{z}-\dot{i}_f), \tag{20}$$

where k f=λ_f/L_f=const is the gain of the excitation current controller.

A necessary condition for the convergence of the process of minimizing functionality at $t\to\infty$

$$\frac{dG(u_f)}{dt}<0,$$

$$G(u_f)\to 0, \tag{21}$$

is met in accordance with the rule of signs

$$\text{sign}(k_f)=\text{sign}(1/L_f). \tag{22}$$

The variable $\dot{z}$ in the control algorithm (20) is a necessary (given) derivative of the excitation current, which is determined in real time from the desired quality equation (15) by closing the control system for feedback on the excitation current $z=i_f$

$$\dot{z}=\gamma_{0f}(i_f^*-i_f). \tag{23}$$

Finally, the excitation current control algorithm takes the form after integrating both parts of equation (20) taking into account (23)

$$u_f(t)=k_f(z-i_f),$$

$$z=\gamma_{0f}\int(i_f^*-i_f)\mathrm{d}t. \tag{24}$$

On the basis of (24), a block diagram of the excitation current controller (CC) of type 101 (n=1, m=0, ν=1) is constructed, which is shown in Fig. 9.

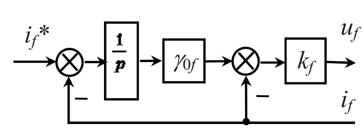

Fig. 9. Block diagram of the excitation current controller

As can be seen from Fig. 9, the controller has an atypical structure and does not contain the parameters of the control object (9), which is typical for classical controllers. The controller contains only a parameter γ_{0f} of the desired control algorithm (15), which sets the required time of the monotonous transient.

The generator voltage control algorithm is developed by analogy to procedure (15) to (24)

$$i_f^*(t)=k_u(z-|u|);$$

$$z = \gamma_{0u} \int_0^t \left(\left| u \right|^* - \left| u \right| \right) dt. \quad (25)$$

(25) demonstrates that the voltage control algorithm does not contain the parameters of the object (9). The block diagram of the generator voltage controller is similar to the current controller shown in Fig. 9.

5. 5. Investigating the control quality of the designed system

The study was carried out by modeling in the MATLAB/Simulink environment with the generator parameters given in Table 1. The controller of the excitation current and voltage of the generator have the following parameter values: γ_{0f}=1500; k_f=500; γ_{0u}=500; k_u=0.2.

Fig. 10 shows the plots of transients of the generator voltage when setting the nominal active load at 0.02 s and dropping it by 0.05 s.

Fig. 11 shows the plot of the transient process of the generator current. Under the action of the load, the current reaches a value of 7.3 A.

Fig. 12 shows plots of the transients of the generator voltage with a decrease and increase by 15 % of the generator speed.

During the operation of the automatic stabilization system, the established voltage remained unchanged at a given level of 48 V (red plot).

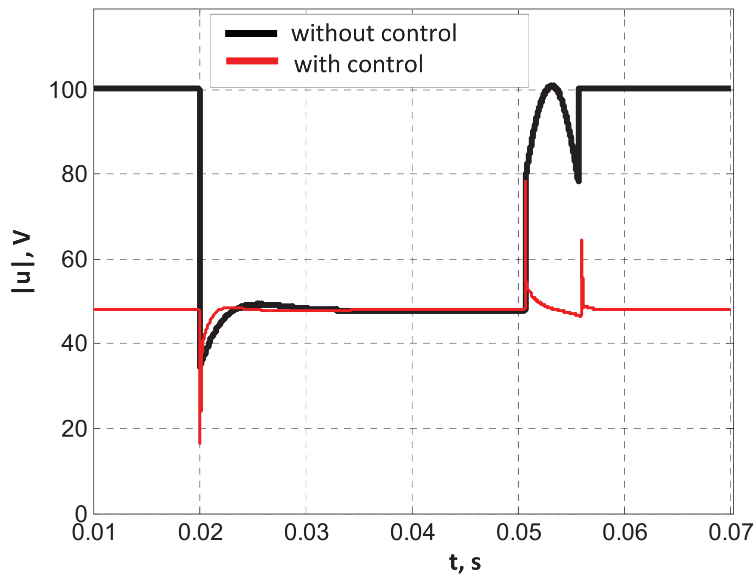

Fig. 10. Plots of transients of generator voltage when setting up and dropping the rated load

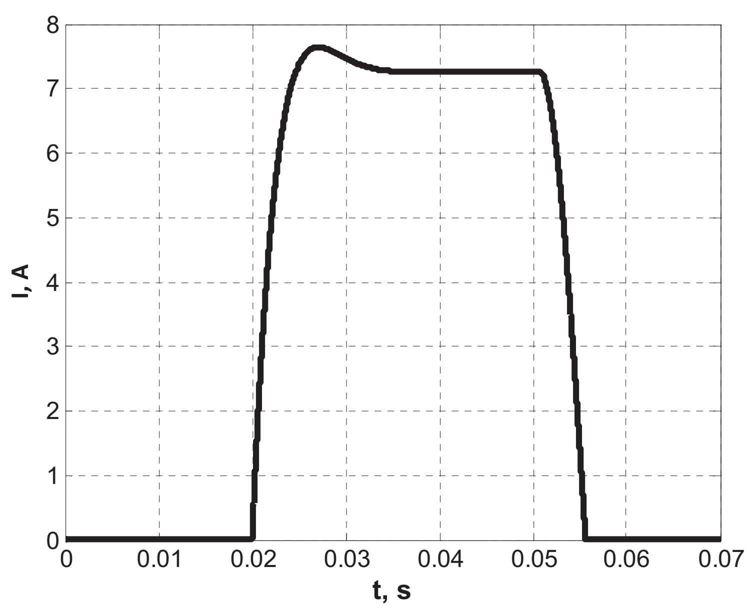

Fig. 11. Generator current transient process plot

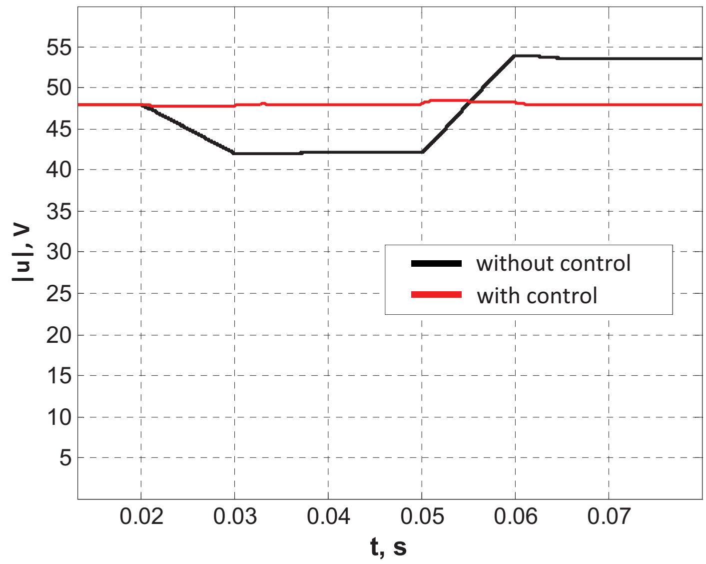

Fig. 12. Plots of transients of the generator voltage with a decrease and increase by 15 % of the generator speed

6. Discussion of results of investigating the voltage control system of a magnetoelectric generator with magnetic flux bypass surgery

The average value of magnetic induction in the stator teeth is 1.49 Tl, in the stator yoke – 1.04 Tl, in the air gap – 0.376 Tl (Fig. 4). The calculated values of magnetic induction in the structural elements of the generator under study are in the permissible range, which indicates the correct choice of basic geometric dimensions. For the selected steel grade, the permissible induction in the teeth can be 1.9 Tl. This makes it possible to use an additional winding to magnetize the magnetic core and provides an appropriate voltage adjustment range.

When a current is applied to an additional winding (Fig. 5), a significant magnetic induction of about 1.28 Tl appears in the housing (capsule) of the magnetic core of the generator under study. This increases the average value of induction in the stator teeth to 1.91 Tl, in the stator yoke –1.54 Tl, in the air gap – 0.477 Tl.

When a current is applied to the additional winding I_e=1 A (Fig. 6, curve 2), a path appears to close the magnetic flux of the additional winding through magnetic shunts: the back of the housing – the generator housing 1 – the stator yoke 1 – the stator tooth 1 – the air gap 1 – magnetic shunt – air gap 2 – stator tooth 2 – stator yoke 2 – generator body 2 – back of the housing.

The magnetic flux of the additional winding partially reduces the main magnetic flux under the poles with permanent magnets (Fig. 6, curve 1) and magnetizes the magnetic shunts of the rotor. Due to this, the average value of EMF in the air gap increases, and therefore the value of the EMF induced in the windings increases. Due to the design of the generator with a double stator and the connection scheme of the windings at the output, EMF of almost sinusoidal shape is obtained, which will be proved in our subsequent papers.

The normal component of magnetic induction B_n in the air gap is responsible for the amount of EMF induced in the winding of the armature of the generator under study. When I_e=1 A current is supplied to an additional winding, the value of the normal component of induction B_n in the air gap increases by about 27 %. This value is correlated with an increase in induction in the air gap and in the structural elements of the generator (Fig. 5).

When DC is supplied to an additional winding, the voltage at the generator output increases by 24 % (Fig. 7). This makes it possible to adjust the output voltage of the generator when the load or speed of rotation of the generator rotor change.

The designed functional diagram of the generator voltage control system when the rotor speed or load change is shown (Fig. 8). The control system consists of an internal excitation current control circuit i_f of an additional electrical winding and an external voltage control circuit of the generator $|u|$.

In the absence of control, the voltage during non-working stroke is 100 V (Fig. 10), and in the presence of a rated load is 48 V (black plot). During the operation of the automatic stabilization system, the established voltage during non-working stroke and in the presence of a rated load remains unchanged at a predetermined level of 48 V without static error (red plot). At the time of setting and resetting the load, a dynamic error of approximately 0.01 s is observed.

Fig. 12 shows plots of transients of the generator voltage with a smooth decrease by 0.02 s of the generator speed by 15 % of the rated value of 1000 rpm to 850 rpm. Then it smoothly increases by 0.05 s of rotational speed up to 1150 rpm (15 % more relative to the rated value). The generator load is rated. In the absence of control, the voltage decreased from 48 V to 42 V when the rotational speed decreased, and during the increase in the rotational speed increased to 53.5 V (black plot).

Existing methods of controlling the output parameters of generators with permanent magnets are mainly built on the use of external semiconductor converters. On the one hand, they are a reactive load for the generator, on the other hand, due to constant switching processes, they reduce the reliability of the generator, its utilization rate, and reliability. In addition, it complicates the structure as a whole and increases its cost, especially with an increase in the capacity of the autonomous energy complex. The proposed system is devoid of these shortcomings, it makes it possible to smoothly adjust the output voltage in a given load range and rotational speed.

The use of a magnetoelectric generator with an axial magnetic flux, in contrast to [2, 4], makes it possible to abandon the mechanical reducer. This will decrease the overall weight of the system and increase its reliability. This becomes possible due to the high rated torque of axial generators and the naturally low speed of their rotation.

Due to the developed methods of controlling a magnetoelectric generator with an axial magnetic flux, on the basis of the obtained simulation results, the reliability of autonomous electric power systems was increased. Due to voltage control without static error when changing the load and rotational speed.

The limitations of the proposed control method are associated with the saturation of the magnetic circuit of the generator when current is applied to the additional winding, in comparison with systems with electromagnetic excitation. The task of optimal design of such generators requires a balance between the specific power of the electric generator, its weight, and final cost.

The disadvantages of the proposed method of controlling the output voltage are associated with a higher cost, weight, and complexity of the structure and manufacturing technology compared to generators with permanent magnets. Also, with the need for an additional control system for additional winding.

This study will be advanced from the point of view of operation of electrical complexes consisting of magnetoelectric generators, which will increase the reliability of their operation. In addition, on the basis of our result, a number of further studies related to experimental studies of generators with axial magnetic flux for autonomous energy complexes emerge.

7. Conclusions

1. A three-dimensional field mathematical model of MGAMF with a double stator has been built, which makes it possible to obtain the distribution of the electromagnetic field of the generator and makes it possible to analyze its parameters and characteristics. The model fully takes into account the design features of the generator under study, namely the presence of an axial flow from the stator winding and the flow generated by the additional winding. With the help of the model, an external characteristic was calculated, indicating that the mathematical model built corresponds to physical processes.

2. The analysis of magnetic induction in the air gap and in other structural elements of the generator under study was carried out. Analysis of the obtained values showed that the geometric dimensions of the generator that were selected previously are correct and do not require significant adjustments. In the future, this makes it possible to use the results of this calculation for the preparation of documentation for the manufacture of the prototype.

3. On the basis of the alternate electrical circuit of MGAMF, its mathematical model in the coordinate system d–q was built. When constructing the generator model, assumptions were adopted about the uniformity of the air gap, the absence of saturation of the magnetic system, and the uniform distribution in the space of the stator winding. The mathematical model takes into account the relationship between the additional excitation winding and the stator current components along the axes d and q, as well as the dependence of the electromagnetic moment on the magnetic flux of permanent magnets and the additional excitation winding, which makes it possible to solve problems of controlling the coordinates of the generator and to study electromagnetic and electromechanical processes.

4. Algorithms for controlling the system of automatic stabilization of the generator voltage based on the concept of reverse dynamics problems in combination with minimization of local functionalities of instantaneous energy values have been developed. This provides voltage control without static error when changing the load and speed of rotation and dynamic decomposition of the interconnected system. A feature of control algorithms is their lack of generator parameters and differentiation operations, which ensures ease of implementation. The generator voltage is controlled by changing the excitation current of the additional fixed winding. The power of the additional excitation system is 2 % of the generator power. The automatic voltage control system consists of an internal excitation current control circuit and an external generator voltage control circuit.

5. The study of the generator voltage stabilization process using the proposed control system showed a high quality of regulation. When setting a jump in the rated load, the system provides astatic voltage control (without static error) at a given level of 48 V. In the absence of control, the voltage decreases from 100 V at a non-working stroke to 48 V in the presence of a load. When changing the generator speed within ±15 % of the rated value at rated load, the control system maintains the voltage at a predetermined level of 48 V. In the absence of control, the generator voltage decreases from 48 V to 42 V with a decrease in the rotational speed, and then rises from 48 V to 53.5 V with its increase.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The manuscript has no related data.

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