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DESIGNING A VOLTAGE CONTROL SYSTEM OF THE MAGNETOELECTRIC GENERATOR WITH MAGNETIC FLUX SHUNTING FOR ELECTRIC POWER SYSTEMS

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The object of research in this work is a three-phase magnetoelectric generator with magnetic flux shunting based on industrial induction electric motors.

The presence of a magnetic shunt makes it possible to control the voltage of the generator by changing the excitation current in the non-contact electrical winding of the magnetic shunt, which is powered by direct current. Thus, the problem of stabilization of the output voltage of the generator with permanent magnets is solved when the speed of rotation and load change.

This paper reports the construction of a three-dimensional field mathematical model of the generator, which allows for electromagnetic calculations of the generator with specified parameters, taking into consideration the influence of final effects, magnetic scattering fields, as well as their radial-axial nature. The results of the calculation of the electromagnetic field are the initial parameters for building a simulation model in the MATLAB-Simulink environment. A simulation model of a magnetoelectric generator with magnetic flux shunting under conditions of changing rotational speed and load has been constructed in the MATLAB-Simulink environment.

On the basis of the built models, the performance characteristics of a magnetoelectric generator with magnetic flux shunting were established, which show the limits of control of the output voltage. Adjusting characteristics were determined at zero and rated shunt current for different types of load. The adjusting characteristics of the generator are presented at the rated voltage of the generator for different types of load and with an increase to 150 % of the rated value. The study's results show the high efficiency of the voltage control system of a magnetoelectric generator with a magnetic shunt at different speeds of rotation and load

Keywords: magnetoelectric generator, magnetic shunt, voltage control, load change, speed change

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1. Introduction

Dispersed sources of generation are widely used to supply power to local electric power systems of small generation of electricity. Most common electric generators for such sources are magnetoelectric generators, in particular permanent magnet synchronous generators (PMSG) based on industrial three-phase induction electric motors that have high technical and economic indicators. The main disadvantage of these generators is the lack of effective methods of direct voltage control, which limits the optimization of the energy balance of installations. One of the ways to solve the problem is to design and use magnetoelectric generators with magnetic flux shunting.

One of the factors determining the reliability and efficiency of operation of autonomous power plants is the control of the generator voltage under different operating and load modes. Controlling the output voltage of synchronous generators with excitation from permanent magnets is an urgent scientific and practical task.

2. Literature review and problem statement

In [1], a synchronous machine with hybrid excitation is considered. A three-dimensional mathematical model of the generator, implemented by the method of finite elements, has been built. A three-dimensional model of an equivalent magnetic system has also been constructed. The ability to control the magnetic flux and the simulation results are confirmed by comparison with experimental measurements. A feature of the approach is the combination of finite element methods and methods of the theory of equivalent substitution schemes. As an advantage of this approach, the authors declare a reduction in calculation time. That also makes it possible to take into consideration the nonlinear characteristics of ferromagnetic materials. The prototype machine is tested to confirm the predicted results. It is shown that the model of the magnetic equivalent circuit shows fairly accurate results compared to the three-dimensional method of finite elements with savings in computational time. However, this approach is based on numerous assumptions and simplifications that can be fully taken into consideration with the help of modern software.

A finite-element simulation model of a synchronous machine with hybrid excitation is described in [2]. The model built takes into consideration the effect of saturation, losses in iron, and harmonics of electromagnetic force of a higher order. Simulations and experimental studies show that this model more accurately reflects the processes in the generator compared to models constructed with the assumption of a sinusoidal form. 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 obtained.

A procedure for calculating the characteristics of a synchronous generator with hybrid excitation is proposed by the authors of [3]. The essence of the procedure is to compare the results of generator modeling using three-dimensional and two-dimensional mathematical models. The authors also claim that the results obtained using the three-dimensional model are more accurate. Although there are no grounds for such conclusions since there is no comprehensive comparison of the characteristics obtained. The main disadvantage of this approach is the lack of experimental research results of such a generator, which may differ significantly from the simulation results.

Paper [4] considered synchronous electric generator with hybrid excitation. As a source of additional magnetic flux, the excitation winding is used, which is powered by direct current, and the magnetic circle of the rotor. The results of modeling and experimental research are reported; however, the results of calculating the magnetic circuit of such a generator are offered as an experimental study, although photographs of the real structure are shown.

An unconventional approach to driving a hybrid synchronous generator that can be used for electric vehicles is shown in [5]. Hybrid excitation is implemented by an additional non-contact winding located on the rotor of the machine. The experimental results obtained on the prototype were compared with the results of three-dimensional mathematical modeling by the method of finite elements. This design, despite some additional difficulties in the machine's power supply system, simplifies the mechanical structure and reduces losses in the control winding compared to the design in which the coil is placed on the stator. Given the high cost and complexity of such a system, its use in energy-efficient systems is not advisable.

Work [6] describes a new methodology for developing a reliable synchronous generator with permanent magnets and with axial magnetic flux. The proposed methodology uses a modified version of the multipurpose evolutionary algorithm without the dominant sorting of the NSGA-III genetic algorithm. Since the design procedure correlates with dimensional and electromagnetic parameters, uncertainties may arise that reduce the efficiency of the generator due to inaccuracies in the structure and calculations of the field. In addition, the results of experimental studies are shown indistinctly, without describing the necessary equipment and test program, which casts doubt on the adequacy of the results.

Work [7] reports the study of a new synchronous machine with double excitation using three-dimensional finite-element analysis and experimental research. It is shown that the machine is really capable of regulating the magnetic flux. The work shows the principle of operation and structural features of this generator of the original design. The results of three-dimensional modeling are also compared with an experimental study conducted on a prototype having a different rotor design. Accordingly, the results of such studies are difficult to use and build a similar concept on their basis.

The task of regulating the output parameters is solved in [8] using a complex mathematical model of a synchronous magnetoelectric generator, a computer with subsequent control of the armature field of the sample under study. Comparison of the developed models (which are the software of the system) with the results of experiments show a fairly high convergence. However, the complexity of such a system and the high level of its individualization complicate the industrial practical use of the proposed approach.

In [1], a synchronous machine with parallel hybrid excitation is considered. The authors explore the structural topology and principles of operation of the hybrid excitation machine. The efficiency of magnetic flux control and the results of mathematical modeling are confirmed by comparison with experimental data. The paper compares different approaches to calculating the magnetic system of hybrid machines with experimental data. As a disadvantage, it is possible to note that the work does not contain conclusions on the efficiency of the generator under study and the error of the presented methods for calculating the magnetic system.

In [9], a two-winding magnetoelectric generator with permanent magnets for an autonomous wind turbine was investigated. Thanks to the special modular design of the generator, a compact layout has been developed, which significantly benefits in weight and size indicators compared to known analogs. Due to this, the proposed structure is much simpler compared to traditional double-winding generators with a double stator. Comparative studies show that the proposed design has a larger torque and a better flow control than existing single-winding counterparts. However, there is no comparison with traditional structures of magnetoelectric generators, in particular with the axial magnetic flux.

As a result, one can see that magnetoelectric systems used as synchronous generators have obvious advantages. These include the absence of losses on excitation, the absence of a contact system, in comparison with generators with electromagnetic excitation. This simplifies the design and increases its reliability. At the same time, the considered magnetoelectric generators have disadvantages associated with the impossibility of adjusting the magnetic flux without additional means. This makes it difficult to stabilize the external performance under loads, especially with a low power factor. Based on this, it is necessary to assess the limits of voltage regulation of a magnetoelectric permanent magnet synchronous generator with a magnetic shunt when changing the speed of rotation and load.

3. The aim and objectives of the study

The aim of this work is to design a voltage control system for magnetoelectric generators with magnetic flux shunting for electric power systems under conditions of changing rotational speed and load. This will make it possible to increase the reliability of autonomous electric power systems.

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

– to build a field mathematical model of a magnetoelectric generator with magnetic flux shunting;

– to construct a simulation model of a magnetoelectric generator with magnetic flux shunting under the conditions of changing rotational speed and load in the MATLAB-Simulink environment;

– to analyze the electromagnetic field, parameters, and characteristics of a magnetoelectric generator with magnetic flux shunting;

– to analyze the results of simulation of a magnetoelectric generator with magnetic flux shunting in the MATLAB-Simulink environment.

4. The study materials and methods

The object of our research is electromechanical processes in a magnetoelectric generator with magnetic flux shunting that works as part of electric power systems.

The main hypothesis assumes that in order to regulate the output voltage of a magnetoelectric generator with a magnetic shunt, a change in the current of the magnetic shunt is performed. This leads to a change in the degree of saturation of the magnetic core of the magnetic shunt and, as a result, to an increase or decrease in the main magnetic flux.

When operating a magnetoelectric generator with a magnetic shunt, it is assumed that the load is constant, and its values are not affected by external and internal factors.

The structure of the magnetoelectric generator with magnetic flux shunting is shown in Fig. 1.

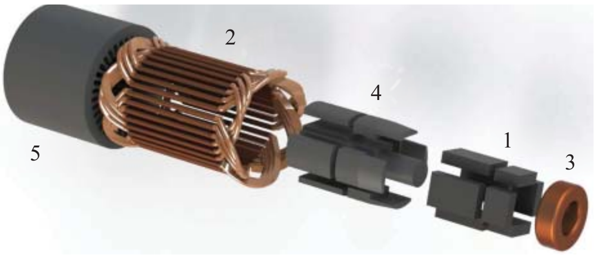

Fig. 1. Structure of magnetoelectric generator with magnetic flux shunting

Structurally, the generator rotor contains permanent magnets 1 and magnetic core 4. The stator winding 2 and the stator magnetic core 5 of the generator remain unchanged from the induction motor. The generator has a fixed electrical winding of the magnetic shunt 3, which is powered by direct current.

Electric generators with excitation from permanent magnets do not have natural means to regulate working magnetic flux. This leads to a change in the voltage at the generator output when the load changes.

The original solution is to design magnetoelectric generators with magnetic flux shunting based on industrial induction electric motors (IM). This is due to several reasons: first, industrial induction motors are already optimized; second, the use of stators of industrial induction motors for the manufacture of magnetoelectric generators with magnetic flux shunting enables the unification of generators. Third, the construction of magnetoelectric generators with magnetic flux shunting based on industrial induction motors is economical.

We studied a magnetoelectric generator based on the standard three-phase induction motor AIR100L4. The magnetic core of the motor stator remained unchanged, Fig. 2.

Fig. 2. Stator of magnetoelectric generator

The rotor of a magnetoelectric generator with permanent magnets is shown in Fig. 3.

Fig. 3. Rotor of a magnetoelectric generator with permanent magnets

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

Table 1

Parameters of the generator under study

No.	Parameter	Value
1	Full rated power, VA	1870
2	Nominal phase voltage, V	116
3	Nominal phase current, A	8.9
4	The number of pairs of poles	2
5	Nominal phase resistance of the stator winding, Ohm	1.43
6	The phase inductance of the stator winding along the *d* axis, H	0.089
7	Phase inductance of the stator winding along the *q* axis, H	0.048
8	Resistance of additional winding, Ohm	49
9	The inductance of the additional winding, N	0.2276
10	Nominal voltage of the additional winding, V	24
11	Nominal current of the additional winding, A	0.49
12	Magnetic flux of permanent magnets, Wb	0,372
13	Moment of inertia, kg*m^2	0.013

The data given in Table 1 are used to build mathematical models of the generator under study.

5. Results of investigating the magnetoelectric generator with magnetic flux shunting

5. 1. Construction of a field mathematical model of a magnetoelectric generator with magnetic flux shunting

The implementation of mathematical calculations of the electromagnetic field was carried out in the software package COMSOL Multiphysics by the method of finite elements [10].

The mathematical model of a magnetoelectric generator with magnetic flux shunting in the rotor coordinate system is represented by a system of equations (1):

$$\begin{cases} L_d \dfrac{di_d}{dt} + R_s i_d = u_d + F_1; \\ L_q \dfrac{di_q}{dt} + R_s i_q = u_q + F_2; \\ L_{sh} \dfrac{di_{sh}}{dt} + R_{sh} i_{sh} = u_{sh}; \\ J \dfrac{d\omega_r}{dt} = \left(-T + T_c\right); \\ T = \dfrac{3}{2} Z_p \left[\left(\psi_0 - \psi_{bypass} + L_{sh} i_{sh}\right) i_q + \left(L_d - L_q\right) i_d i_q\right]; \\ F_1 = \omega L_q i_q; \\ F_2 = -\omega L_d i_d - \omega L_{sh} i_{sh} + \omega \psi_{bypass} - \omega \psi_0 \\ \omega = Z_p \omega_r, \end{cases} \tag{1}$$

where i_d, i_q and u_d, u are the currents and voltages of the stator along the d and q axes, respectively; i_{sh} and u_{sh} are the current and voltage of the magnetic shunt winding; ω_r – the angular velocity of the rotor; Z_p is the number of pairs of poles; J – moment of inertia; T, T_c – electromagnetic moment and moment of load; ψ_0 – flux linkage; $\psi_{shunting}$ is the shunt flux linkage; L_d, L_q is the inductance of stator windings on d and q axes, respectively; L_{sh} is the inductance of the shunt winding; R_s, R_{sh} is the resistance of stator windings and magnetic shunt; F_1, F_2 – coordinate excitations.

To analyze the electromagnetic field, parameters, and characteristics of a magnetoelectric generator with magnetic flux shunting, a three-dimensional field mathematical model has been built that takes into consideration the influence of finite effects, magnetic scattering fields, as well as their radial-axial nature. The theoretical basis of mathematical modeling of electromagnetic fields is Maxwell's equation [11].

When calculating the magnetic field, a nonstationary nonlinear differential equation was used for the vector magnetic potential A in a moving electrically conductive medium.

$$\vec{\nabla} \times \frac{1}{\mu}\left(\vec{\nabla} \times \vec{A}\right) - \gamma \frac{\partial \vec{A}}{\partial t} + \gamma \vec{V} \times \left(\vec{\nabla} \times \vec{A}\right) = -\vec{J}_{st}, \tag{2}$$

where V is the vectors of the velocity of the medium; ∇ is a differential Nabla operator.

The estimated region of the magnetoelectric generator has different physical characteristics. For each region, a quasi-stationary field equation with respect to the vector magnetic potential is solved. For the region that includes the air gap, magnetic circuit, shaft, pole tips, and anchor winding, the equation takes the following form

$$\sigma \frac{\partial A}{\partial t} + \nabla \times \frac{\nabla \times A}{\mu_0 \cdot \mu_r} = J_e, \tag{3}$$

where J_e is the current density in the stator winding, which characterizes the mode of operation of the generator; σ – electrical conductivity of materials; μ_r – relative magnetic permeability of materials.

The magnetic field of permanent magnets is calculated using the following equation

$$\sigma \frac{\partial A}{\partial t} + \nabla \times \frac{\nabla \times A - B_r}{\mu_0 \cdot \mu_r} = J_e, \tag{4}$$

where B_r is the residual induction of permanent magnets.

The current density in the armature winding is set as a function of time and takes the following form

$$J_A = J_m \cos(\omega t);$$

$$J_B = J_m \cos(\omega t + 2\pi / 3);$$

$$J_C = J_m \cos(\omega t + 4\pi / 3), \tag{5}$$

where J_m is the amplitude value of the current density in the armature winding phase.

To calculate the induced EMF in the winding phase of the generator armature, the following integral expression is used.

$$E_A = \frac{L \cdot U_{\mathrm{p}}}{S_{\mathrm{p}} \cdot a} \left(\oint_{S_q} E_{zA} \cdot \mathrm{d}s - \oint_{S_q} E_{zX} \cdot \mathrm{d}s \right), \tag{6}$$

where L is the axial length of the generator; U_p – the number of turns in the groove; S_p – groove area for conductors; E_{zA}, E_{zX} – electric field strength at the location of the coils of the phase zones "A" and "x"; S_q – the area occupied by the conductors of one phase zone; a – the number of parallel branches of the armature winding.

Similarly, EMF is determined in the winding phases "B" and "C".

To obtain an unambiguous solution, the boundary conditions of the first kind are set on the boundaries of the estimated region

$$A(x,y,z,t)\big|_{G_1=0} = 0, \ \{x,y,z\} \in G_1. \tag{7}$$

Initial conditions are set when solving non-stationary problems. The value of field functions in the middle of the region at the initial point in time

$$A(x,y,z,t)\big|_{t=0} = A(x,y,z,0). \tag{8}$$

The results of the calculation of the generator under study in the COMSOL Multiphysics environment, namely the dependence of flux linkage on the current of the magnetic shunt winding $\Psi = f(i_f)$ are used as initial data for the construction of a simulation model in the MATLAB-Simulink environment.

5. 2. Construction of a simulation model under the conditions of changing rotational speed in the MATLAB-Simulink environment

The mathematical model of a magnetoelectric generator with magnetic flux shunting in a coordinate system (d–q), oriented along the magnetic axis of the rotor, is described by a nonlinear system of differential equations (9).

$$\begin{cases}\dfrac{di_d}{dt}=\dfrac{1}{L_d}\left[u_d-R_s i_d+\omega L_{sq} i_q\right];\\ \dfrac{di_q}{dt}=\dfrac{1}{L_q}\left[\begin{array}{l}u_q - R_s i_q-\omega L_d i_d - \\ -\omega L_{sh} i_{sh}-\omega\psi_0+\omega\psi_{bypass}\end{array}\right];\\ \dfrac{di_{sh}}{dt}=\dfrac{1}{L_{sh}}\left[u_{sh} - R_{sh} i_{sh}\right];\\ \dfrac{d\omega_r}{dt}=\dfrac{1}{J}\left[-T+T_c\right];\\ T=\dfrac{3}{2}Z_p\left[\left(\psi_0-\psi_{bypass}+L_{sh}i_{sh}\right)i_q+\left(L_d-L_q\right)i_d i_q\right];\\ \omega=Z_p\omega_r,\end{cases} \tag{9}$$

where i_d, i_q and u_d, u_q are the currents and voltages of the stator along the d and q axes, respectively; i_{sh} and u_{sh} – the current and voltage of the magnetic shunt winding; ω_r – the angular velocity of the rotor; Z_p is the number of pairs of poles; J – moment of inertia; T, T_c – electromagnetic moment and moment of load; ψ_0 – flux linkage; ψ_{shunting} is the shunt flux linkage; L_d, L_q is the inductance of stator windings along the d and q axes, respectively; L_{sh} – inductance of the shunt winding; R_s, R_{sh} is the resistance of stator windings and magnetic shunt.

According to (9), the mathematical model of a magnetoelectric generator with magnetic flux shunting is characterized by coordinate disturbances due to the mutual influence of the stator current components. When determining the parameters of the mathematical model of the generator from its specifications, errors arise due to the assumptions of the calculation methodology. During the operation of the generator, the electrical resistances of the windings change due to heating. Due to these parametric perturbations, the calculated values of parameters differ from real ones, which leads to a deterioration in the specified quality of control. It is possible to solve the problem of synthesis of the generator voltage control algorithm under conditions of parametric and coordinate disturbances by the method of inverse dynamics problems in combination with minimization of local functionalities of instantaneous energy values.

The method of inverse dynamics problems in combination with minimization of local functionalities of instantaneous energy values is based on the idea of the inverse of the direct Lyapunov method for the study of stability. The method makes it possible to find a control algorithm in which a closed loop has a predetermined Lyapunov function. This gives the system the property of stability as a whole, which makes it possible to solve the tasks 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 laws of control provide a weak sensitivity to parametric perturbations and carry out dynamic decomposition of the interconnected system. Control algorithms do not contain differentiation operations, which enables their practical implementation. These advantages of the method determine its use in this work.

The functional diagram of the automatic voltage stabilization system of the generator under conditions of changing the speed of rotation is shown in Fig. 4.

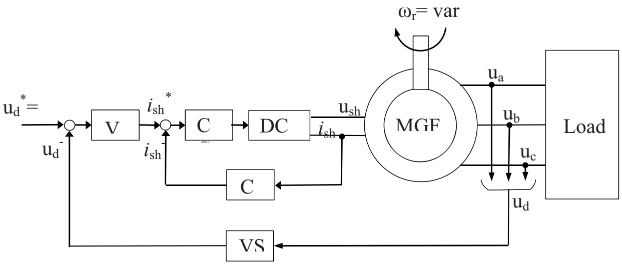

Fig. 4. Functional diagram of the automatic voltage stabilization system of a magnetoelectric generator with magnetic flux shunting

The control system has a cascading structure. The internal closed circuit for regulating the current of the magnetic shunt consists of a shunt CC current regulator, a CS shunt current sensor, and a DCC DC converter. The external closed circuit voltage regulation of the generator consists of a voltage regulator VC and a voltage sensor generator VS. In Fig. 4, the following is indicated: u_d^*, u_d are the set and measured operating value of the generator voltage; i_{sh}^*, i_{sh} – the specified and measured shunt current; u_{sh} – supply voltage of the shunt winding; u_a, u_b, u_c – phase voltages of the generator.

To solve the control problem, the original system of equations (9) is converted to form (1) according to the decomposition method proposed in [12]. Coordinate perturbations F1, F2 are interpreted as indefinite but limited in magnitude $F_1 \le F_1^0$, $F_2 \le F_2^0$. The level of control voltages is sufficient to compensate for them $u_d > F_1^0$, $u_q > F_2^0$. Thus, an interrelated nonlinear system of the 4th order is transformed 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 four local problems of managing linear subsystems (1).

The desired quality of the closed control loop according to the concept of the inverse dynamics problem is given by the differential equation of the following type

$$\begin{aligned}&\frac{d^n z}{dt^n}+..+\gamma_i\frac{d^i z}{dt^i}+..+\gamma_0 z=\\&=\beta_m\frac{d^m x^*}{dt^m}+..+\beta_j\frac{d^j x^*}{dt^j}+..+\beta_0 x^*.\end{aligned} \tag{10}$$

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, the required number of times, function; $m<n$. The desired closed-loop control transfer function derived from equation (10) for the case of n=3 and m=1 is (where $S=d/dt$ is the Laplace operator)

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

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

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

In accordance with (13), to obtain a control system with the first-order astatism ν=1, it is necessary to set the value of the coefficients $\beta_0=\gamma_0$, then

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

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

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

The specified quality in terms of the speed of the system (13) is determined by the expression $D_\omega^z=\gamma_0/(\gamma_1-\beta_1)$, and the quality related 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 in accordance with the requirements for the quality of control. By default, order n is equal to or one unity higher than the order of the control object. The relationship between the coefficients of equation (10) and the required indicators of control quality, such as the control time, the type of transient, the overshoot is easily established using the known methods from the theory of automatic control.

The development of an algorithm for controlling the current of a magnetic shunt i_{sh} is carried out based on the third equation of system (1). As can be seen, the local control object is described by the first-order equation, so the order of the desired closed-circuit equation of the current in the form of (10) is also assumed to be equal to one (n=1, m=0) with the provision of the first-order astatism ν=1 and a given quality in terms of speed $D_\omega^z=\gamma_{0f}$

$$\dot{z}+\gamma_{0f}z=\gamma_{0f}i_{sh}^*. \tag{15}$$

The duration of the monotonous transient process of the shunt current $t_r=3/g_{of}$ is given by the value of a single coefficient g_{of}.

It is necessary to find such a control function of the current regulator of the shunt u_{sh} so that the quality of current control approaches the desired quality (15). The degree of approximation of the real process of current control to the desired one is estimated by the functional, which characterizes the energy normalized by inductance of the first magnetic field derivative

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

The functional is minimized according to the gradient law of the first order

$$\frac{du_{sh}(t)}{dt}=-\lambda_f\frac{dG(u_{sh})}{du_{sh}}, \tag{17}$$

where $\lambda_f>0$ is a constant.

Taking into consideration (1) and (15), the derivative of the functional is equal to

$$\frac{dG(u_{sh})}{du_{sh}}=-\frac{1}{L_{sh}}(\dot{z}-\dot{i}_{sh}). \tag{18}$$

After substitution (18) in (17), the shunt current control algorithm is obtained

$$\dot{u}_{sh}(t)=k_{sh}(\dot{z}-\dot{i}_{sh}), \tag{19}$$

where $k_{sh}=\lambda_f/L_{sh}$=const is the gain of the shunt current regulator.

A necessary condition for the convergence of the process of minimizing the functional (16) at $t\to\infty$

$$\frac{dG(u_{sh})}{dt}<0;\ G(u_{sh})\to 0 \tag{20}$$

is met according to the rule of signs

$$\operatorname{sign}(k_{sh})=\operatorname{sign}(1/L_{sh}). \tag{21}$$

The variable $\dot{z}$ in the law of control (19) is a given derivative of the shunt current, which is determined in real time from the desired quality equation (15) by locking the shunt current feedback control system $z=i_{sh}$

$$\dot{z}=\gamma_{0f}(i_{sh}^*-i_{sh}). \tag{22}$$

Finally, the current regulator equation of the shunt CC in Fig. 4 takes the form after integrating both parts (19) taking into consideration (22)

$$u_{sh}(t)=k_{sh}(z-i_{sh});\ z=\gamma_{0f}\int(i_{sh}^*-i_{sh})\mathrm{d}t. \tag{23}$$

The development of an algorithm for controlling the output voltage of the generator is carried out based on the desired closed-loop equation of the first order

$$\dot{z}+\gamma_{0u}z=\gamma_{0u}u_d^*. \tag{24}$$

The duration of the monotonous transient process of the generator voltage $t_u=3/g_{ou}$ is given by the value of a single coefficient g_{of}. After the synthesis of the voltage control algorithm similar to (15) to (23), the following voltage regulator equation VC is derived in Fig. 4

$$i_{sh}^*(t)=k_u(z-u_d);\quad z=\gamma_{0u}\int(u_d^*-u_d)\mathrm{d}t. \tag{25}$$

where k_u=const is the gain of the voltage regulator.

5. 3. Analysis of the electromagnetic field, parameters, and characteristics of a magnetoelectric generator with magnetic flux shunting

The distribution of the electromagnetic field in the estimated region of a magnetoelectric generator with a magnetic shunt is shown in Fig. 5.

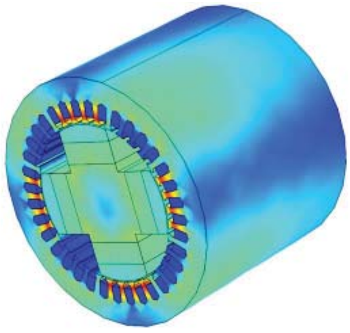

Fig. 5. Distribution of the electromagnetic field in the estimated area of the generator

The result of calculating the idling characteristics of a magnetoelectric generator with magnetic flux shunting is shown in Fig. 6.

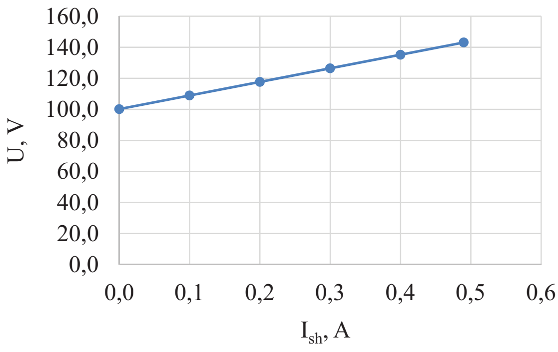

Fig. 6. Generator idling characteristics

Fig. 7 shows external characteristics of the generator at zero current of the shunt I_{sh}=0 for different types of load.

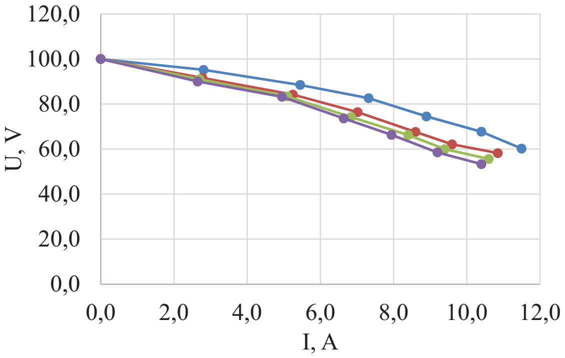

Fig. 7. External characteristics of the generator at I_{sh}=0: 1 – cosϕ=1; 2 – cosϕ =0.95; 3 – cosϕ=0.9; 4 – cosϕ=0.8

Fig. 8 shows external characteristics of the generator at the rated current of the shunt I_{sh}=0.49 A for different types of load.

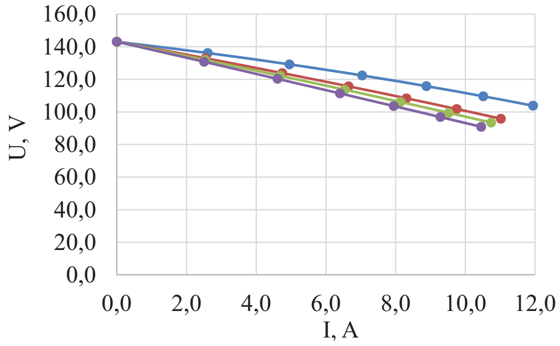

Fig. 8. External characteristic of the generator at I_{sh}=0,49 A: 1 – cosϕ=1; 2 – cosϕ=0.95; 3 – cosϕ=0.9; 4 – cosϕ=0.8

Fig. 9 shows the adjusting characteristics of the generator at the rated voltage of the generator U=116 V for different types of load and when it increases to 150 % of the rated value.

Fig. 10 shows the plots of transients when throwing a jump of 0.04 s and dropping the rated load at the rated current of the shunt I_{sh}=0.49 A.

The results (Fig. 10) allow us to conclude about the stability of the control system and the voltage stabilization system when perturbations appear as a whole.

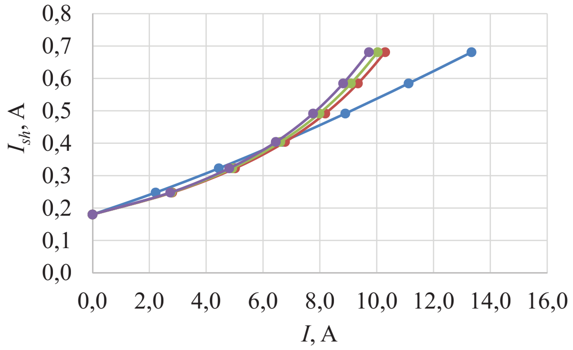

Fig. 9. Adjusting characteristics of the generator: 1 – cosϕ=1; 2 – cosϕ=0.95; 3 – cosϕ=0.9; 4 – cosϕ=0.8

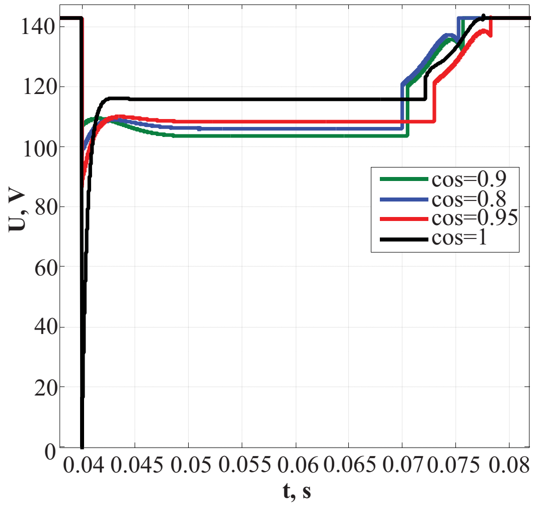

Fig. 10. Plot of the transient process

5. 4. Analysis of results of simulating a generator in the MATLAB-Simulink environment

We studied the effect exerted on the output voltage of the magnetoelectric generator by changes in the speed of rotation of the rotor based on the constructed simulation model in the MATLAB-Simulink environment. Fig. 11 shows the nature of the change in the speed of rotation of the rotor in relative units within ±15 % of the rated value.

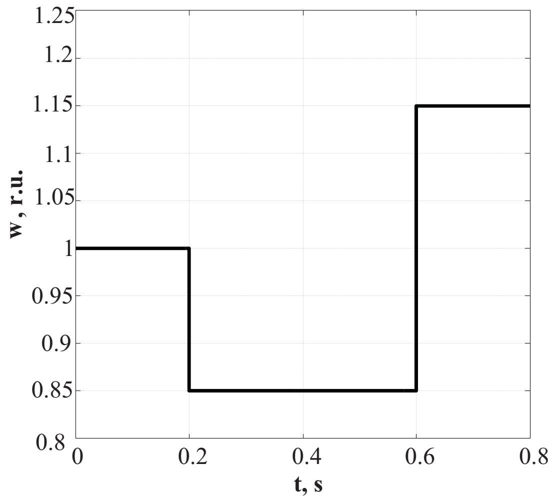

Fig. 11. The nature of change in the speed of rotation of the generator rotor

The change in the generator voltage in the absence of control and zero current of the magnetic shunt is shown in Fig. 12.

Fig. 13 shows the change in the output voltage of the generator in the absence of control and at the rated current of the shunt 0.49 A.

Fig. 14 shows the generator voltage during the operation of the automatic stabilization system in accordance with the functional scheme shown in Fig. 6.

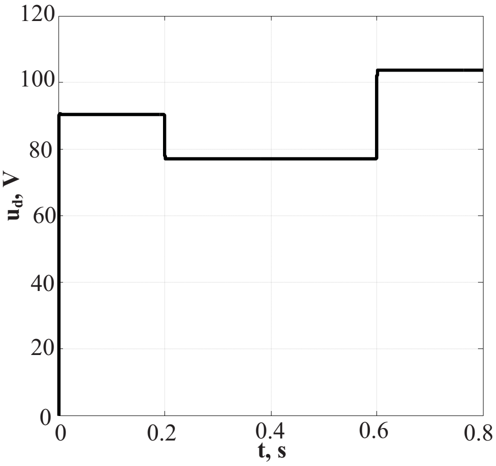

Fig. 12. Change in generator voltage in the absence of control and zero current of the magnetic shunt

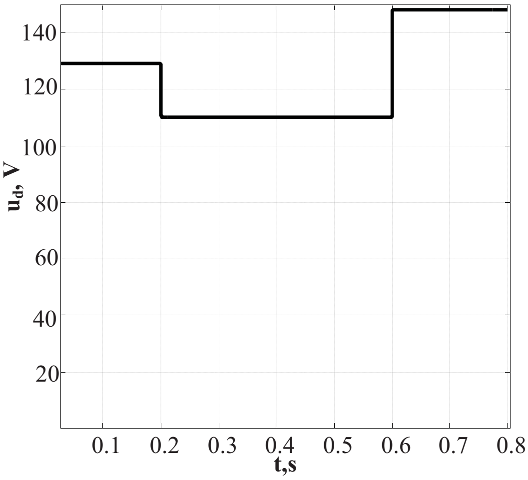

Fig. 13. Change in generator voltage in the absence of control and rated current of the magnetic shunt

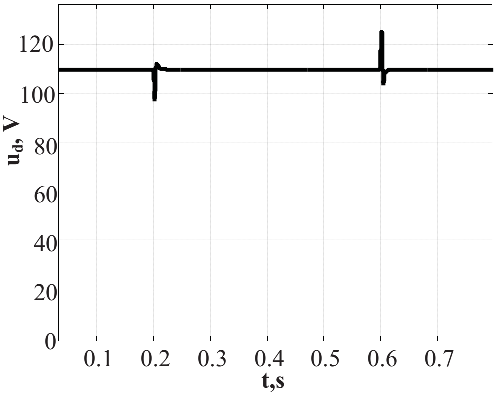

Fig. 14. Generator voltage plot during stabilization by the control system

Fig. 15 depicts a plot of the magnetic shunt current during the operation of the automatic voltage stabilization system of the generator.

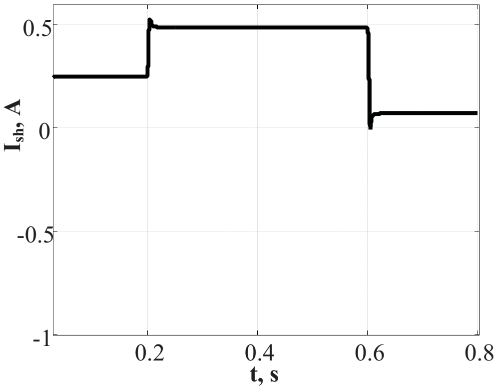

Fig. 15. Plot of the shunt current when stabilizing the generator voltage

After the transient process, the magnetic shunt current stabilizes and remains unchanged, which indicates the stability of the control system.

6. Discussion of results of the voltage control system of a magnetoelectric generator with magnetic flux shunting

A functional diagram of the automatic voltage stabilization system of a magnetoelectric generator with magnetic flux shunting has been designed (Fig. 4). The system changes the winding current of the magnetic shunt of the generator in such a way as to stabilize the voltage (Fig. 8, 9) when the rotational speed and load change.

The results of the calculation of the electromagnetic field in the estimated region of a magnetoelectric generator with a magnetic shunt (Fig. 5) are the initial data for the operation of the simulation model in MATLAB-Simulink.

According to the characteristic of non-working stroke (Fig. 6), when the current of the shunt I_{sh} changes from zero to the rated value of 0.49 A, the voltage of the generator U changes by 41 % from 101 V to 143 V. Thus, the change in the current of the shunt provides control over the output voltage of the generator. With an increase in the load to 150 % of the rated value, the generator voltage decreases by 41–49 % depending on the type of load. At rated load, the generator voltage decreases by 30–39 %, respectively (Fig. 7).

When the load increases to 150 % of the rated value, the generator voltage decreases by 29–36 % depending on the type of load. At rated load, the generator voltage decreases by 19–28 %, respectively (Fig. 8).

To study the effect exerted on the output voltage of the magnetoelectric generator by changes in the speed of rotation, the rotor rotation speed in relative units varied within ±15 % of the rated value (Fig. 9).

During the transient process, when the load is thrown, the generator voltage decreases by 99 % at active load and by 38 %, 31 %, 24 % at active-reactive load with $\cos\varphi=0.95$, $\cos\varphi=0.9$, and $\cos\varphi=0.8$, respectively. After the completion of the transient process when the load is thrown, the generator voltage decreases by 19 % at active load and by 24 %, 26 %, and 28 % at active-reactive load with $\cos\varphi=0.95$, $\cos\varphi=0.9$, $\cos\varphi=0.8$, respectively (Fig. 19).

Changing the speed of rotation in the absence of control leads to a change in the output voltage of the generator from 90 V to 77 V (Fig. 11). With a decrease in speed by 15 %, the voltage increases to 104 V with an increase in speed by 30 % (Fig. 12). In this case, the current of the magnetic shunt was zero. The generator load was 50 % of the rated value.

The generator voltage decreases from 129 V to 110 V with a decrease in speed by 15 %, and then increases to 148 V with an increase in speed by 30 % (Fig. 13).

The control system maintains the generator voltage at 110 V with zero static error. During the transient process, with a decrease in the speed of rotation of the rotor by 15 % (Fig. 14), the dynamic error is 9 %, and with an increase in speed by 30 %, the dynamic error is 13 %.

The shunt current increases from 0.24 A to 0.48 A with a decrease in speed by 15 %, and then decreases to 0.07 A with an increase in speed by 30 % (Fig. 15).

Existing methods of regulating the output voltage of generators with permanent magnets are based on the use of external stepwise capacitive regulators. They, on the one hand, load the generator with an additional reactive capacitive current, on the other hand, they require a switching system, which complicates the structure as a whole and reduces its reliability. The proposed system is devoid of these shortcomings, it makes it possible to smoothly adjust the output voltage in a given load range. It also does not cause additional electrical losses in the armature winding.

The limitations of the proposed method are associated with the saturation of the magnetic system of the generator when current is applied to the winding of the magnetic shunt, in comparison with systems with electromagnetic excitation. In addition, permanent magnets used in this generator have limitations on magnetic characteristics under non-stationary thermal conditions.

The disadvantages of the proposed method of controlling the output voltage are associated with a higher cost of the final product compared to generators with permanent magnets. And with power losses in the winding of the magnetic shunt, which can be up to 5–7 % of the generator power and the need for a magnetic shunt winding control system.

This study is to be advanced in the field of manufacturing electrical systems consisting of generators with a magnetic shunt, which will increase the reliability of their operation. In addition, based on the results obtained, several methods for correcting the output power of a synchronous generator follow, which can be described in the future.

7. Conclusions

1. A three-dimensional field mathematical model of a magnetoelectric generator with magnetic flux shunting has been built, taking into consideration the design features of the generator under study, including the presence of a radial-axial magnetic flux. This makes it possible to obtain initial data for the construction of a mathematical model of the electric generator in the MATLAB-Simulink environment.

2. The mathematical model of a magnetoelectric generator with magnetic flux shunting in the coordinate system (*d-q*) is oriented along the magnetic axis of the rotor in the MATLAB-Simulink environment. The obtained control laws provide weak sensitivity to parametric perturbations and carry out dynamic decomposition of the interconnected system. Control algorithms do not contain differentiation operations, which enables their practical implementation.

3. Analysis of the electromagnetic field, parameters, and characteristics has made it possible to calculate the total magnetic flux generated by the magnetic shunt winding and permanent magnets. The obtained characteristics of non-working stroke and external characteristics have made it possible to assess the potential limits of regulation of the output voltage when the speed of rotation and load change.

4. Our study of the voltage of a magnetoelectric generator with magnetic flux shunting for electric power systems confirmed the high quality of the output voltage regulation when the rotational speed changes within ±15 % and the load changes from 0 to 150 %.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

References

1. Asfirane, S., Hlioui, S., Amara, Y., Gabsi, M. (2019). Study of a Hybrid Excitation Synchronous Machine: Modeling and Experimental Validation. Mathematical and Computational Applications, 24 (2), 34. doi: https://doi.org/10.3390/mca24020034
2. Mbayed, R., Salloum, G., Monmasson, E., Gabsi, M. (2016). Hybrid excitation synchronous machine finite simulation model based on experimental measurements. IET Electric Power Applications, 10 (4), 304–310. doi: https://doi.org/10.1049/iet-epa.2015.0473
3. Bernatt, J., Gawron, S. A., Glinka, M. (2012). Experimental Validation of Hybrid Excited Permanent Magnet Synchronous Generator. Przegląd elektrotechniczny, 88 (12a), 66–70. Available at: http://pe.org.pl/articles/2012/12a/14.pdf
4. Xu, L., Liu, G., Zhao, W., Ji, J. (2016). Hybrid excited vernier machines with all excitation sources on the stator for electric vehicles. Progress In Electromagnetics Research M, 46, 113–123. doi: https://doi.org/10.2528/pierm15120305
5. Wardach, M., Bonislawski, M., Palka, R., Paplicki, P., Prajzendanc, P. (2019). Hybrid Excited Synchronous Machine with Wireless Supply Control System. Energies, 12 (16), 3153. doi: https://doi.org/10.3390/en12163153
6. Sabioni, C. L., Ribeiro, M. F. O., Vasconcelos, J. A. (2018). Robust Design of an Axial-Flux Permanent Magnet Synchronous Generator Based on Many-Objective Optimization Approach. IEEE Transactions on Magnetics, 54 (3), 1–4. doi: https://doi.org/10.1109/tmag.2017.2766229
7. Nedjar, B., Hlioui, S., Amara, Y., Vido, L., Gabsi, M., Lecrivain, M. (2011). A New Parallel Double Excitation Synchronous Machine. IEEE Transactions on Magnetics, 47 (9), 2252–2260. doi: https://doi.org/10.1109/tmag.2011.2134864
8. Wardach, M., Paplicki, P., Palka, R. (2018). A Hybrid Excited Machine with Flux Barriers and Magnetic Bridges. Energies, 11 (3), 676. https://doi.org/10.3390/en11030676

9. Jian, L., Liang, J., Shi, Y., Xu, G. (2013). A novel double-winding permanent magnet flux modulated machine for stand-alone wind power generation. Progress In Electromagnetics Research, 142, 275–289. doi: https://doi.org/10.2528/pier13072304
10. Chumack, V., Tsyvinskyi, S., Kovalenko, M., Ponomarev, A., Tkachuk, I. (2020). Mathemathical modeling of a synchronous generator with combined excitation. Eastern-European Journal of Enterprise Technologies, 1 (5 (103)), 30–36. doi: https://doi.org/10.15587/1729-4061.2020.193495
11. Chumack, V., Bazenov, V., Tymoshchuk, O., Kovalenko, M., Tsyvinskyi, S., Kovalenko, I., Tkachuk, I. (2021). Voltage stabilization of a controlled autonomous magnetoelectric generator with a magnetic shunt and permanent magnet excitation. Eastern-European Journal of Enterprise Technologies, 6 (5 (114)), 56–62. doi: https://doi.org/10.15587/1729-4061.2021.246601
12. Ostroverkhov, M., Chumack, V., Kovalenko, M., Kovalenko, I. (2022). Development of the control system for taking off the maximum power of an autonomous wind plant with a synchronous magnetoelectric generator. Eastern-European Journal of Enterprise Technologies, 4 (2 (118)), 67–78. doi: https://doi.org/10.15587/1729-4061.2022.263432

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IMPROVING TOOLS FOR DIAGNOSING TECHNICAL CONDITION OF SHIP ELECTRIC POWER INSTALLATIONS

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Existing information-measuring systems (IMS) do not fully correspond to the tasks of monitoring electric power installations (EPI) in terms of their characteristics. The capabilities of IMS have certain limitations regarding the probability of measurement results and the degree of invariance to the influence of operational factors. This proves that for modern failure-free EPI technical operation, new diagnostic tools are in demand. Such means should be seamlessly integrated in IMS to enable high operational efficiency and performance reliability. Therefore, it is of particular relevance to tackle the scientific and technical issue of rational combination of protection and preservation of the characteristics of fiber-optic sensors of relative humidity control systems in ship EPI. To solve the problem, the chosen object of this study is the processes of formation and transformation of the diagnostic signal in the means of humidity control. It has been established that the improvement of the characteristics of the control means can be achieved through the synthesis of known optical circuits and the latest materials. To register the parameters of relative humidity, a new circuitry solution was proposed for the sensor based on fiber-optic and elements made of nanomaterials. The main feature of the proposed monitoring tool is invariance to operational destabilizing factors. The scope of application of the obtained research results involves distributed fiber-optic systems for monitoring the technical condition of ship electric power systems. The introduction of a new means for measuring humidity will make it possible to achieve an increase in the efficiency of use and reliability of EPI by reducing the accident rate by 6...11 %, as well as a decrease in operating costs by USD 8...10 per 1 kWh of generated power per year of operation with an average load

Keywords: electric power installations, relative humidity, optical fiber, refractive index, layered structure

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1. Introduction

Innovative means of diagnosing and controlling the parameters of EPI, taking into account all modern challenges, are a prerequisite for reliable safety and stability. According to shipping safety and operational requirements, human errors result in 75...96 % of accidents. On the other hand, the paradigm of today's industry involves significant technological innovations that are expected to have a devastating impact on all shipbuilding industries in the near future. The new design criteria and operational requirements will lead to the replacement of traditional vessels with vessels with increased efficiency and sustainability. This approach will include real-time monitoring of EPI parameters and data mining in order to increase the overall level of efficiency in the updated management approach and introduce predictive models. Experimental studies have shown that optimizing ship control in general and EPI in particular can lead to significant resource savings, which in some cases can reach 15 % reduction in costs.

In the ship's electric power systems, one of the actual scientific and technical tasks is the implementation of maintenance and repair of EPI based on the analysis of data obtained from the results of preventive technical diagnostics. The greatest potential possibilities are inherent in the methods of technical diagnostics, which make it possible to identify defects at the stages of origin, and means that carry out continuous diagnosis and monitoring, over a long time, of partial discharges (PD) on high-voltage EPI. In many cases, PD are associated with the emergence and development