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V.A. Yarovenko, P.S. Chernikov

A CALCULATION METHOD OF TRANSIENT MODES OF ELECTRIC SHIPS' PROPELLING ELECTRIC PLANTS

The purpose of the work is to develop the method for calculating the transient modes of electric ships' propelling electric plants during maneuver. This will allow us to evaluate and improve the maneuverability of vessels with electric motion. Methodology. The solution to the problems is proposed to be carried out on the basis of mathematical modeling of maneuvering modes. The duration of transient modes in an electric power plant at electric ships' maneuvers is commensurable with the transient operation modes of the vessel itself. Therefore, the analysis of the electric power plants' maneuvering modes should be made in unity with all the components of the ship's propulsion complex. Results. A specified mathematical model of transient regimes of electric ship's propulsion complex, including thermal motors, synchronous generators, electric power converters, propulsion motors, propellers, rudder, ship's hull is developed. The model is universal. It covers the vast majority of modern and promising electric ships with a traditional type of propulsors. It allows calculating the current values of the basic mode indicators and assessing the quality indicators of maneuvering. The model is made in relative units. Dimensionless parameters of the complex are obtained. These parameters influence the main indicators of the quality of maneuvering. The adequacy of the suggested specified mathematical model and the developed computation method based on it were confirmed. To do this, the results of mathematical modeling for a real electric ship were compared with the data obtained in the course of field experiments conducted by other researchers. Originality. The mathematical description of a generator unit, as an integral part of an indivisible ship's propulsion complex, makes it possible to calculate the dynamic operation modes of electric power sources during electric vessels' maneuvering. There is an opportunity to design the electric ships' propulsion power plant according to the final result – according to the indicators characterizing the vessel and its maneuvering properties. The use of a system of dimensionless units provides a generality to the results obtained. Electric ships with equal values of dimensionless parameters will have correspondingly the same values (in relative units) of maneuvering quality indicators. Practical value. The developed mathematical model and the research method constructed on its basis allow calculating the current values of the basic regime parameters of all the components of the ship's propulsion complex. A mathematical apparatus for estimating the main indicators of the quality of electric ships' maneuvering is proposed. There is an opportunity to improve the electric ships' maneuvering characteristics by optimizing the operation of propulsion motors. References 21, tables 2, figures 3.

Key words: **electric ship's propelling electric plant, mathematical model of transient modes, calculation method.**

Целью работы является разработка метода расчета переходных режимов гребных электроэнергетических установок в составе судовых пропульсивных комплексов. Методика. На маневрах продолжительности переходных режимов в электроэнергетической установке соизмеримы с переходными режимами работы судна. Поэтому анализ маневренных режимов ее работы следует проводить в единстве со всеми составными частями судового пропульсивного комплекса. Результаты. Разработаны уточненная математическая модель и метод расчета переходных режимов всех составных частей пропульсивного комплекса электрохода на маневрах. Найдены безразмерные параметры комплекса. Они определяют основные показатели качества маневрирования. Адекватность модели и метода расчета подтверждены сравнением результатов математического моделирования с натурными экспериментами. Научная новизна. Метод расчета позволяет рассчитывать динамические режимы работы всех составных частей комплекса. Появляется возможность проектирования гребных электроэнергетических установок по конечному результату – по показателям качества маневрирования судна. Практическое значение. Метод расчета позволяет проводить исследования поведения пропульсивных комплексов на маневрах и отыскивать пути повышения маневренности электроходов. Библ. 21, табл. 2, рис. 3.

Ключевые слова: **электроэнергетическая установка электрохода, математическая модель переходных режимов, метод расчета.**

Actuality of the problem. In recent years, interest in the use of electromotion on ships of the merchant and navy has noticeably increased in the world shipbuilding industry. This is due to a number of undeniable advantages inherent in such a method of power transfer to propellers: the possibility of using high-speed thermal engines (TEs), using simplified design engines (non-reversible TEs are installed), splitting the total power into several parts and the ability of each heat engine to operate several screws which increases the vitality and flexibility of the power plant), the reduction of shaft length, the wide use of automation systems. The most important advantage of electromotion before the traditional drive of ship propulsors is the ability to provide high maneuverability of vessels equipped with this type of power plant. It is the maneuvering qualities of the propeller system that ensure, above all, the safety of maneuver operations by ships.

Modern rowing electrical installations (REIs) are built on the basis of induction frequency-controlled electric motors and based on valve propulsion motors. At the same time, a large number of vessels are in operation, the power plants of which are constructed using an alternating-direct current system. In this regard, both the design of modern electric trains with high maneuvering properties as well as the tasks of improving the management of rowing power plants of vessels in service are very relevant. Moreover, the need to assess the maneuverability of newly built electric boats is already at the initial stages of their design, and increasing the efficiency of performing maneuver operations of existing vessels is undoubtedly relevant at any stage of their life cycle.

State of the issue under consideration. A distinctive feature of the work of electric boats on maneuvers is that the duration of the transient processes in the ship electric power plant (SEPP) is commensurate with the duration of the transient processes of the ship's movement. Therefore, the traditional assumptions about the constancy of the speed of the propellers during the movement of the ship on maneuvers (as well as vice versa) are not acceptable. All the components of the electric motor complex are in close interconnection. Only when solving particular problems is it permissible to consider any element of a single propulsion complex in isolation from the others. (This, in particular, refers to the steady movement). When analyzing unsteady regimes, propulsion power plants should be considered in unity with all other elements of the propulsion complex, including SEPP, propellers and hull. Only in this setting can a thorough analysis of their maneuvering operating modes and assess the maneuverability of the electric ship.

An analysis of the state of the issue under consideration shows the following. Studies of transient modes of operation of propulsion power plants have a long history. Numerous research works deal with the problems of analytical and machine methods of calculating the basic maneuvering regimes – starting, stopping, reversing propellers. However, even today they all have a serious shortcoming. In practice, only the electric part of the propulsion system (generators, propulsion motors, converters, control panels, control stations) is meant and implied under the electromotive system without primary engines and propulsors. In particular, this is clearly presented in [1-4]. The main distinguishing feature of these and other thorough works is that the speed of the vessel's motion is considered constant throughout the considered maneuvers. Thus, the propulsion system is considered in isolation from a single ship propulsion complex. Of course, as a result of this simplification, it is much easier to analyze the maneuvering modes of the REI operation, but at the same time, the accuracy of the results obtained is reduced and, most importantly, the system principle of the approach to the analysis of operating modes of ship electric power plants is violated. There is no possibility to evaluate the efficiency of the electric power plant operation according to the «final result» – in terms of the quality of the maneuver performance of the electric boat as a whole.

The second distinctive feature of earlier studies is that the overwhelming majority of them have been performed with respect to specific electric trains (at best – to specific series of electric boats), to specific propulsion systems. The results of the calculations obtained with the help of these methods refer to specific SEPPs and can not be extended to other electric vessels. This does not allow us to carry out wide, valid scientific generalizations. This reduces the scientific value of the results of the investigations carried out.

An attempt to eliminate these shortcomings was undertaken by one of the authors of this paper in [5]. To analyze the maneuvering regimes of rowing electric power plants as part of propulsion complexes of electric ships, he developed a corresponding mathematical model. It describes the transient modes of operation of all components of the complex. The model is universal, covers the vast majority of modern and prospective electric boats with a traditional type of propulsors. At the same time, when describing the processes occurring in thermal engines, a number of assumptions were adopted that do not allow analyzing the dynamic modes of their operation. In addition, a mathematical description of the processes occurring in synchronous generators was built on the basis of a vector diagram of the generator, which also made it impossible to fully appreciate the dynamic modes of their operation. Thus, the mathematical description of the transient modes of operation of diesel generators is in need of improvement, which led to the need for this work.

The goal of the paper is development of an improved mathematical model of transitional modes of propulsion power plants of electric boats and a method of calculating on its basis maneuverable modes of operation of ships.

The solution of the problem was carried out with reference to the most common electric-motive system – on the basis of frequency-controlled induction propulsion motors.

A method for solving the problem. The structural diagram of the SEPP «thermal engine – synchronous generator – frequency converter – induction motor» of the propulsion complex of the electric ship is shown in Fig. 1. It corresponds to the generally accepted in the theory of electromotion the layout of the electric power plant [14, 16, 20]. At the same time, in accordance with the goal, namely, the need to improve the design and management of electric power plants in terms of the quality of maneuver operations performed by the ship, it additionally includes propellers, the steering wheel and the body of the electric ship.

The propulsion complex consists of two «power» circuits. Here: thermal motors – *D*, synchronous generators (SG) – *G*, frequency converters of electricity – *SE*, induction propulsion motors (IPM) – *M*, propellers – *P*, rudder – *H* and hull.

Elements of the automatic control system and the main parameters linking the power units and control signals: speed regulators of the primary engine – *DR*; automatic voltage regulators of the generator – *GR*; M_D and ω_D – the torque and angular speed of rotation of the heat engine; M_G – electromagnetic torque of the generator; U_d and U_q – the generator voltage along the longitudinal and transverse axes (internal coordinates); I_d and I_q – generator currents along the longitudinal and transverse axes (internal coordinates); U_G – voltage at the generator output; ω_{Set} – set the angular velocity of the speed controller; ξ_D – the course of the fuel pump rail; $\Delta\xi_D$ – the increment in the stroke of the fuel pump rail; $1/T_s p$ – the link of the servomotor; K_{Fb} and K_{is} – the gain factors for the links of rigid and flexible (isodromic) feedbacks; U_f and I_f – excitation voltage and current of the synchronous generator; I_G, I_M – currents of SG and IPM; α_{Set} and γ_{Set} – relative frequency and voltage of the converter (setting values); α and γ – the relative frequency and voltage at the output of the converter (taking into account the feedbacks); *FC* – the functional converter forming the law of frequency control $\gamma = f(\alpha)$; M_P and P_P – the torque and emphasis of propellers; M_M and ω_M – the torque and the angular velocity of the IPM rotation.

Isodromic all-regulators of indirect action are used as regulators of the rotation speed of the heat engine [8, 9]. As regulators of the voltage of synchronous generators [9, 10], combined (based on the control action and on the deviation of the regulated variable) regulators are used.

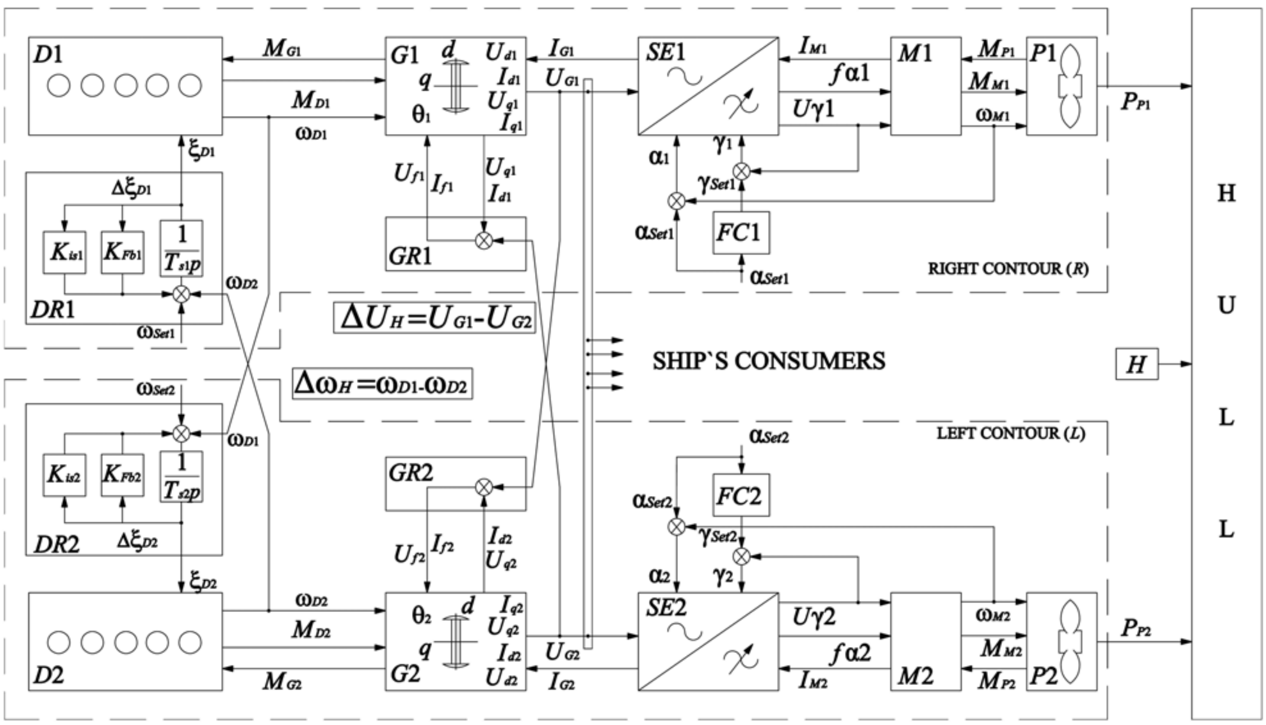

Fig. 1. Structural diagram of the propulsion complex of the electric ship

The system of equations describing the transient modes of operation of the electric power plant as part of the propulsion complex of the electric motor is presented below.

To make the results of the analysis more general, the model is reduced to relative units. As a result, the criteria for the dynamic similarity of propulsion complexes were revealed. These are the dimensionless parameters of the system «thermal engines – propulsion system – propulsors – hull». The ranges of the values of these parameters are found, covering the majority of series of electric boats with a traditional propeller drive. It is these parameters that determine the current values of the relative regime parameters of all components of the complex and determine the numerical values of the main quality indicators of maneuvering. This approach allows us to give a generality to the results obtained – electric vessels with equal values of dimensionless parameters will have the same values (in relative units) of the maneuvering quality parameters, respectively. There is an opportunity to generalize the results of research.

Relative values of performance indicators will be indicated by a symbol with a bar. (The index «0» corresponds to the values of the modes indicators when the electric motor operates in the nominal steady-state mode.)

For example, the relative electromagnetic torque of the generator:

$$\overline{M_G} = \frac{M_G}{M_{G0}}.$$

To simplify the perception of the material, the term «relative» is omitted from the text below.

The relative time is determined differently:

$$T = \frac{v_0}{L} t,$$

where v_0 is the vessel speed, L is the vessel length, t is the current time.

The final version of the generalized mathematical model of transient and steady-state operating modes of propulsion complexes of electric motors is presented below.

Heat engine and speed controller of its rotation.

Equation of motion of the heat engine [5]:

$$\frac{d\overline{\omega_D}}{dT} = N_D\left(\overline{M_D} - \overline{M_G}\right), \tag{1}$$

where

$$N_D = \frac{M_{D0}L}{J_D \omega_{D0} v_0} \tag{2}$$

is the criterion of dynamic similarity, J_D is the moment of inertia of the engine and the generator brought to the shaft of the heat engine.

The torque of the heat engine can be represented as the relative displacement of the fuel pump rail [8]:

$$\overline{M_D} = \overline{\xi_D}. \tag{3}$$

The heat engine power:

$$\overline{P_D} = \overline{M_D \omega_D} . \quad (4)$$

The equations of transient processes in the regulator of the speed of rotation of a thermal engine, taking into account rigid and flexible feedbacks and taking into account the operation of the active power distribution system (with parallel running generating sets (GS)), can be represented as [9, 10].

Increment of the stroke of the fuel pump rail:

$$\frac{d\overline{\xi_D}}{dT} = K_P\left(1 - \left(\overline{\omega_D} - \overline{\Delta\omega_H}\right)\right) - K_{Fb}\overline{\Delta\xi_D} - K_{is}\overline{\Delta\xi_D} , \quad (5)$$

where K_P, K_{Fb}, K_{is} are the gain factors for the regulated value (change in the speed of rotation of the heat engine), rigid feedback and flexible (isodromic) feedback, respectively;

$$\overline{\Delta\omega_{H1}} = \int_0^t \overline{U_{s1}} dt \quad (6)$$

is the difference in the angular frequencies of rotation of the generators;

$$\overline{U_{s1}} = \frac{\overline{I_{ae1}} - \overline{I_{ae2}}}{k_{ae1}} \quad (7)$$

is the voltage on the servomotor; k_{ae} is the gain factor of the automatic control loop of the active load distribution system;

$$\overline{I_{ae1}} = \overline{U_{d1} I_{d1}} + \overline{U_{q1} I_{q1}}, \quad (8)$$

is the active component of the SG current.

For the heat engine of the second generator set, the equations are written similarly.

A synchronous generator and an automatic voltage regulation system. In contrast to the «classical» [11] description of the SG, processes that are incommensurable with the time constants of the main components of the propulsion complex of the electric drive are not taken into account here, namely, the transformer EMF in the stator windings [12]. In view of the smallness, we neglect the active resistance of the armature [13], the mutual inductance, which is incommensurably small in comparison with the inductance of the excitation winding, as well as the flux linkages of the damper windings.

The combined system of automatic voltage regulation of synchronous generators includes a control loop for reactive power distribution (with parallel GSs).

Switching angle:

$$\gamma_G = \arccos\left(1 - K_{\gamma G}\frac{\left|\overline{I_G}\right|}{\left|\overline{U_G}\right|}\right), \quad (9)$$

where

$$K_{\gamma G} = \frac{0{,}5\left(3x_d'' + x_q''\right)}{\sqrt{6}}, \quad (10)$$

x_d'' and x_q'' are the supertransitive inductive resistance along the axes d and q.

Angle of phase shift between vectors $\overline{I_G}$ and $\overline{U_G}$:

$$\varphi_G = \frac{\gamma_G}{2}. \quad (11)$$

Angle of phase shift between vectors $\overline{E_G}$ и $\overline{I_G}$:

$$\psi_G = \operatorname{arctg}\left(\frac{\sin\varphi_G}{\cos\varphi_G} + \frac{x_q \overline{I_G}}{\overline{U_G}\cos\varphi_G}\right), \quad (12)$$

where x_q is the synchronous inductive resistance along the axis q.

Angle of phase shift (load angle) between vectors $\overline{E_G}$ and $\overline{U_G}$:

$$\theta_G = \psi_G - \varphi_G. \quad (13)$$

Generator currents (internal coordinates d-q):

$$\overline{I_d} = -\overline{I_G}\sin\psi_G, \quad (14)$$

$$\overline{I_q} = \overline{I_G}\cos\psi_G. \quad (15)$$

Generator voltages (internal coordinates d-q):

$$\overline{U_d} = -K_{d1}\overline{I_G}\cos\psi_G, \quad (16)$$

$$\overline{U_q} = -K_{q1}\overline{I_G}\sin\psi_G + K_{q2}\overline{I_f}, \quad (17)$$

where I_f is the current of the field winding of the generator.

Increment of the excitation current:

$$\frac{d\overline{I_f}}{dT} = N_f\left(\begin{array}{l} K_{f1}K_{Uq}\overline{U_q} + K_{f2}K_{Id}\overline{I_d} - \\ -K_{f3}K_U\left(\overline{U_G} - \left(1 - \overline{\Delta U_{H1}}\right)\right) - \overline{I_f} \end{array}\right), \quad (18)$$

where

$$\overline{\Delta U_{H1}} = \frac{\overline{I_{re1}} - \overline{I_{re2}}}{k_{re1}} \quad (19)$$

generators' voltages difference;

$$\overline{I_{re1}} = \overline{U_{q1} I_{d1}} - \overline{U_{d1} I_{q1}} \quad (20)$$

s the reactive component of the SG current;

$$K_{d1} = \frac{\sin\theta_0}{\cos\psi_0}, \quad (21)$$

$$K_{q1} = \frac{1 - \cos\theta_0}{\sin\psi_0}, \quad (22)$$

$$K_{q2} = 1 , \quad (23)$$

$$K_{Uq} = \frac{U_{G0}}{U_{f0}}, \quad (24)$$

$$K_{Id} = \frac{I_{G0}x_d}{U_{f0}}, \quad (25)$$

$$K_U = \frac{U_{G0}}{U_{f0}} \quad (26)$$

are the dimensionless parameters;

$$N_f = \frac{LU_{f0}}{L_f I_{f0} \nu_0} \quad (27)$$

is the criterion for dynamic similarity; L_f is the inductance of self-induction of the excitation winding; U_f and I_f are the voltage and current of the field winding; K_{f1}, K_{f2}, K_{f3} are the gain factors for the main signal, the disturbance and the deviation of the controlled variable, respectively; k_{re} is the gain factor of the automatic control loop of the reactive load distribution system.

Electromagnetic torque of the generator:

$$\overline{M_G} = -K_{G1}\overline{I_G^2}\sin\psi_G\cos\psi_G + K_{G2}\overline{I_f}\,\overline{I_G}\cos\psi_G\,, \quad (28)$$

where

$$K_{G1} = \frac{(L_d - L_q)I_{G0}^2}{M_{G0}}\,, \quad (29)$$

$$K_{G2} = \frac{M_{ad}I_{f0}I_{G0}}{M_{G0}} \quad (30)$$

are the dimensionless parameters; L_d and L_q are the inductances of self-induction of the armature winding along the d- and q- axes; M_{ad} is the inductance of mutual induction along the d-axis.

The relations (9) – (30) were obtained in [6, 7].

Voltage on the generator output:

$$\overline{U_G} = \sqrt{\left(\overline{U_d^2} + \overline{U_q^2}\right)}. \quad (31)$$

Active power of the generator:

$$\overline{P_G} = \overline{U_G}\,\overline{I_G}\cos\varphi_G. \quad (32)$$

A converter of the electric power. Considering the frequency converter as a non-inertial «quantizer» of electricity with ideal gates, we do not take into account the electromagnetic processes taking place in it, and we consider that the current at the output of the converter is continuous, and the converter itself does not go beyond the region of normal loads [14]. The converter type is a frequency converter with an autonomous voltage inverter (FC with AVI).

Output voltage versus input one:

$$\overline{U_M} = \gamma\overline{U_G}\,, \quad (33)$$

where U_M is the IPM voltage

Rowing electric motor. In the mathematical model [5], a mathematical description of the generalized propulsion motor is given. As a special case from it, a mathematical model of an induction electric motor (IM) follows with frequency control. It is based on the exact classical scheme for the replacement of blood pressure, which determines the necessary assumptions and simplifications. The voltage at the stator terminals is considered to be sinusoidal, the saturation of the steel of the machine is not taken into account, the distribution of the flow along the arc of the air gap is assumed to be sinusoidal, the steel losses in the stator are taken into account approximately, and in the rotor are not taken into account [15, 16].

Equation of motion of the IPM:

$$\frac{d\overline{\omega_M}}{dT} = N_M\left(\overline{M_M} - \overline{M_P}\right), \quad (34)$$

where

$$N_M = \frac{M_{M0}L}{J_M\omega_{M0}v_0} \quad (35)$$

is the criterion of dynamic similarity;

$$\overline{M_M} = K_M\overline{I_M}\,\overline{\Phi_M}\cos\varphi_M \quad (36)$$

is the IPM torque;

$$\overline{I_M} = C_{M24}\gamma\frac{1}{\sqrt{C_{M17} + C_{M18}\alpha^2 + \frac{C_{M21} + C_{M22}\alpha^2}{\left(C_{M19}\alpha - C_{M20}\overline{\omega_M}\right)^2} + \frac{C_{M23}\alpha}{C_{M19}\alpha - C_{M20}\overline{\omega_M}}}} \quad (37)$$

is the motor current;

$$\overline{\Phi_M} = C_{M25}\gamma\sqrt{\frac{x_{2M}'^2\left(C_{M19}\alpha - C_{M20}\overline{\omega_M}\right)^2 + r_{2M}'^2}{\left(b_M^2 + c_M^2\alpha^2\right)\left(C_{M19}\alpha - C_{M20}\overline{\omega_M}\right)^2 + \left(d_M^2 + e_M^2\alpha^2\right)r_{2M}'^2 + 2r_{1M}r_{2M}'\alpha\left(C_{M19}\alpha - C_{M20}\overline{\omega_M}\right)}} \quad (38)$$

is the IPM magnetic flux;

$$\cos\varphi_M = \frac{1}{\sqrt{1 + C_{M26}\left(C_{M19}\alpha - C_{M20}\overline{\omega_M}\right)^2}} \quad (39)$$

is the motor power factor;

$$C_{M17} = \frac{b_M^2}{r_{2M}'^2}\,, \quad (40)$$

$$C_{M18} = \frac{c_M^2}{r_{2M}'^2}\alpha_0^2\,, \quad (41)$$

$$C_{M19} = \alpha_0\,, \quad (42)$$

$$C_{M20} = \frac{\omega_{M0}}{\omega_{1Mn}}\,, \quad (43)$$

$$C_{M21} = d_M^2\,, \quad (44)$$

$$C_{M22} = e_M^2\alpha_0^2\,, \quad (45)$$

$$C_{M23} = 2\frac{r_{1M}}{r_{2M}'}\alpha_0\,, \quad (46)$$

$$C_{M24} = \sqrt{C_{M17} + C_{M18} + \frac{C_{M21}}{\beta_{M0}^2} + \frac{C_{M22}}{\beta_{M0}^2} + \frac{C_{M23}}{\beta_{M0}}}\,, \quad (47)$$

$$C_{M25} = \sqrt{\frac{\left(b_M^2 + c_M^2\alpha_0^2\right)\left(C_{M19}\alpha_0 - C_{M20}\omega_{M0}\right)^2 + \left(d_M^2 + e_M^2\alpha_0^2\right)r_{2M}'^2 + 2r_{1M}r_{2M}'\alpha_0\left(C_{M19}\alpha_0 - C_{M20}\omega_{M0}\right)}{x_{2M}'^2 + \frac{r_{2M}'^2}{\beta_{M0}^2}}}\,, \quad (48)$$

$$C_{M26} = \frac{x_{2M}'^2}{r_{2M}'^2} \quad (49)$$

are the dimensionless parameters;

$$b_M = r_{1M}\left(1 + \tau_{2M}\right), \quad (50)$$

$$c_M = x_{0M}\tau_M\,, \quad (51)$$

$$d_M = r_{1M}/x_{0M}\,, \quad (52)$$

$$e_M = 1 + \tau_{1M} \quad (53)$$

are the constant coefficients of asynchronous frequency-controlled IPM;

$$\tau_{1M} = \frac{x_{1M}}{x_{0M}}, \quad (54)$$

$$\tau_{2M} = \frac{x'_{2M}}{x_{0M}}, \quad (55)$$

$$\tau_M = \tau_{1M} + \tau_{2M} + \tau_{1M}\tau_{2M} \quad (56)$$

are the scattering coefficients; J_M is the moment of inertia of the motor; K_M is the constant constructive coefficient; ω_{1Mn} is the rotational frequency of the stator magnetic field; r_{1M} and r'_{2M} are the active resistances of stator and rotor (reduced); x_{1M} and x'_{2M} are the inductive resistance of the stator and rotor (reduced) of the IM; x_{0M} is the inductive magnetization resistance; β_{M0} is the absolute slip of the IM rotor. The relations (34) – (49) were obtained in [5].

Electric power plant control. Management is carried out from the control station (CS) on the bridge. The main task is to control the movement of the vessel in real time. The output signal of the CS forms two control actions on the frequency converter (with respect to the frequency α and the voltage γ).

Relative frequency of the output voltage of the frequency converter *SE* [5]:

$$\begin{aligned} \alpha = \alpha_{Set} - K_{\alpha P}\alpha_P - K_{\alpha\omega}\alpha_\omega - \\ - K_{\alpha f}(\alpha_f - \alpha_{f\max}) - K_{\alpha M}(\alpha_M - \alpha_{M\max}) - \\ - K_{\alpha I}(\alpha_I - \alpha_{I\max}) - K_{\alpha PD}(\alpha_{PD} - \alpha_{PD\max}) \end{aligned}, \quad (57)$$

where α_{Set} is the reference value of the relative frequency; α_P is the corrective communication for IPM power; α_ω is the corrective coupling for the angular velocity of rotation of the IPM; α_f is the cut-off according to the output frequency of the frequency converter; α_M is the cutoff on the torque of the IPM; α_I is the cutoff of the stator current of the IPM; α_{PD} is the cut-off according to the power consumed by the electromotive system; $K_{\alpha P}$, $K_{\alpha\omega}$, $K_{\alpha f}$, $K_{\alpha M}$, $K_{\alpha I}$, $K_{\alpha PD}$ are the gain factors that are determined by the particular control system.

Relative output voltage of the converter *SE* [5]:

$$\gamma = \gamma_{Set} - K_{\gamma I}(\gamma_I - \gamma_{I\max}) - K_{\gamma U}\gamma_U, \quad (58)$$

where γ_{Set} is the reference value of the relative voltage of the frequency converter – a signal that is a function of the relative frequency and the adopted voltage control law; γ_U is the corrective coupling for the IPM voltage; γ_I is the current stator cutoff of the IPM; $K_{\gamma I}$, $K_{\gamma U}$ are the gain factors. In each specific case, the automatic control system has its own «set» of control signals for each control channel. It is these control actions that directly affect the performance indicators of ship maneuver operations.

Propellers. The hydrodynamic reversal characteristic of the propeller, taking into account the ship's motion along a curvilinear trajectory, is represented in the form of a parabolic polynomial [17, 18].

Propeller torque:

$$\overline{M_P} = a_{21}\overline{\omega_P}^2 + b_{21}\overline{\omega_P \nu_e} + c_{21}\overline{\nu_e}^2 + a_M \overline{\nu}^2 tg^2\alpha_{Bev}, \quad (59)$$

where a_{21}, b_{21}, c_{21} are the coefficients of the universal characteristic of the screw (are constant in certain ranges of measurement of $\overline{\omega_P}$ and $\overline{\nu_e}$); $\overline{\omega_P}$ is the angular velocity of rotation of the propeller; $\overline{\nu_e}$ is the rate of water leakage onto the propeller; $\overline{\nu}$ is the speed of the vessel; a_M is the constant coefficient; α_{Bev} is the angle of the bevel of the water flow.

Propeller stop:

$$\overline{P_P} = a_{11}\overline{\omega_P}^2 + b_{11}\overline{\omega_P \nu_e} + c_{11}\overline{\nu_e}^2 + a_P \overline{\nu}^2 tg^2\alpha_{Bev}, \quad (60)$$

where a_{11}, b_{11}, c_{11} are the coefficients of the universal characteristic of the propeller; a_P is the constant coefficient.

The body of the electric boat. The movement of the vessel along the free water surface in the associated coordinate system *GXYZ* whose origin coincides with the center of gravity of the vessel *G* is considered. The *GXY* plane is parallel to the ship's main plane, the *GX* axis is located in the center plane and directed to the bow, the *ZY* axis to the starboard, *GZ* axis – vertically up. The associated moment λ_{26} is neglected [19].

The components of the ship's speed along the axes *X*, *Y* and the speed of rotation around the *Z* axis:

$$\begin{aligned} \frac{d\overline{\nu_X}}{dT} = C_{\lambda 2}\overline{\nu_Y \Omega_Z} + \\ + N_X \left\{ \sum_J K_{Pj}\overline{P_{ej}} - C_{RX}\beta_{RP}\overline{\nu^2} - \overline{R_X} \right\} \end{aligned}, \quad (61)$$

$$\begin{aligned} \frac{d\overline{\nu_Y}}{dT} = -\frac{1}{C_{\lambda 2}}\overline{\nu_X \Omega_Z} + \\ + \frac{N_X}{C_{\lambda 2}} \left\{ \sum_J K_{Pj}\alpha_{jz}\overline{P_{ej}} - C_{RY}\beta_{RP}\overline{\nu^2} - \overline{R_Y} \right\} \end{aligned}, \quad (62)$$

$$\begin{aligned} \frac{d\overline{\Omega_Z}}{dT} = -\frac{N_\Omega}{N_X}C_{\lambda 21}\overline{\nu_X \nu_Y} + \\ + N_\Omega \left\{ \begin{aligned} \sum_j K_{Pj}h_{Pj}\overline{P_{ej}} + \left(\overline{M_{PZ}} - \overline{M_{DZ}}\right) + \\ + C_{RY}\overline{X_R}\beta_{RP}\overline{\nu^2} \end{aligned} \right\} \end{aligned}, \quad (63)$$

where

$$\overline{R_X} = \left\{ \begin{aligned} C_{11}\cos 1{,}5\beta_{dr} - C_{12}\sin^4 1.5\beta_{dr} + \\ + C_{13}\left(\frac{2\beta_{dr}}{\pi}\right)^3 \end{aligned} \right\} \overline{\nu^2} \quad (64)$$

is the longitudinal force of the rudder;

$$\overline{R_Y} = \left\{ \begin{aligned} C_{21}\sin 2\beta_{dr}\cos\beta_{dr} + C_{22}\sin^2\beta_{dr} + \\ + C_{23}\sin^4 2\beta_{dr} \end{aligned} \right\} \overline{\nu^2} \quad (65)$$

is the transverse power of the rudder;

$$\begin{aligned} \overline{M_{PZ}} - \overline{M_{DZ}} = \left[\begin{aligned} C_{61}\sin 2\beta_{dr} + C_{62}\sin\beta_{dr} + \\ + C_{63}\sin^3 2\beta_{dr} + \\ + C_{64}\sin^4 2\beta_{dr} \end{aligned} \right] \overline{\nu^2} - \\ - C_{65}\overline{\Omega_Z}\overline{\nu^2} \end{aligned} \quad (66)$$

is the turning torque;

$$C_{\lambda 2} = \frac{m + \lambda_{22}}{m + \lambda_{11}}, \quad (67)$$

$$C_{\lambda 21} = \frac{2(\lambda_{22} - \lambda_{11})}{m + \lambda_{11}}, \quad (68)$$

$$C_{RX} = \frac{\mu_{rx} \frac{\rho}{2} v_0^2 S_C (1-\psi)^2}{\sum K_{Pj} P_{ej0}}, \quad (69)$$

$$C_{RY} = \frac{\mu_K \frac{\rho}{2} v_0^2 S_C (1-\psi)^2}{\sum K_{Pj} P_{ej0}}, \quad (70)$$

$$C_{11} = \frac{R_{X0}}{\sum K_{Pj} P_{ej0}}, \quad (71)$$

$$C_{12} = \frac{0.07 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (72)$$

$$C_{13} = \frac{c_4 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (73)$$

$$C_{21} = \frac{0.5 C_Y^{\beta} \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (74)$$

$$C_{22} = \frac{c_2 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (75)$$

$$C_{23} = \frac{c_3 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (76)$$

$$C_{61} = \frac{2 m_1 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (77)$$

$$C_{62} = \frac{2 m_2 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (78)$$

$$C_{63} = \frac{2 m_3 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (79)$$

$$C_{64} = \frac{2 m_4 \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}}, \quad (80)$$

$$C_{65} = \frac{2\left[0.739 + 8{,}7\frac{T}{L}\right] C_{m0}^{\omega} \frac{\rho}{2} v_0^2 F_D}{\sum K_{Pj} P_{ej0}} \quad (81)$$

are the dimensionless parameters;

$$N_X = \frac{L \sum K_{Pj} P_{ej0}}{(m + \lambda_{11}) v_0^2}, \quad (82)$$

$$N_{\Omega} = \frac{L^3 \sum K_{Pj} P_{ej0}}{2(J_Z + \lambda_{66}) v_0^2} \quad (83)$$

are the dynamic similarity criteria; X_R is the distance from the center of the coordinate system to the rudder; P_{ej} and K_{Pj} are the useful thrust of the propeller and its share in the total flow, respectively; L is the length of the vessel; m is the mass of the vessel; ρ is the specific density of water; λ_{11} и $\lambda_{22}$are the connected masses of water along the X and Y axes; λ_{66} is the connected moment of inertia of water; μ_{rx} is the drag coefficient of the rudder; μ_K is coefficient of lateral power of the rudder; ψ is the angle of the course; S_C is the reduced area of the rudder; c_4 is the coefficient of the longitudinal positional force of the water resistance; C_Y^{β}, c_2, c_3 are the coefficients of the body strength; m_1, m_2, m_3, m_4 are the coefficients of the positional moment of resistance; F_D is the reduced area of the submerged part of the ship's diametrical plane; M_{PZ} and M_{DZ} are the positional and damping moments of resistance; C_{m0}^{ω} is the coefficient of the damping moment of resistance; β_{dr} is the drift angle; J_Z is the moment of inertia of the vessel when it rotates about the Z axis.

Angle of attack of the helm:

$$\beta_{RP} = K_R \beta_R - \chi_C \left(\operatorname{arctg} \beta_{dr} - \varepsilon \frac{\overline{\Omega_Z}}{\overline{v}} \right), \quad (84)$$

where β_R is the angle of rotation of the helm; χ_C is the reduced coefficient of impact of the body and propellers on the rudder; ε is the value determined by the ratio l_R/L (l_R is the distance between the rudder and the midriangle frame). The relations (61) – (84) were obtained in [5].

The developed mathematical model allows to comprehensively analyze transients of propulsion complexes of electric boats on maneuvers.

To analyze the maneuvering modes of operation, a package of applied programs has been developed. The base program is a program that allows calculating the laws of time variation of relative regime indicators, when the electric power performs a variety of maneuvers. At the same time during the analysis of maneuvering regimes:

- dimensionless parameters of the component parts of the complex are calculated;
- for the maneuver under study, the control parameters are entered in accordance with the positions of the handles of the control posts and the shifting of the rudder;
- initial conditions are given;
- according to the selected maneuvers, the laws governing each power circuit are formed;
- current values of the main mode parameters of each power circuit are calculated in the course of the maneuver;
- the hydrodynamic forces and torques acting on the vessel are determined; the current values of the ship's motion parameters in the coordinate system associated with it are calculated, and then in the unrelated coordinate system.

The solutions of the system of equations (1) – (84) presented above is a solution of the Cauchy problem. The Runge-Kutta-Merson method was used as the solution method.

The final results of the calculations are presented in numerical form and in the form of ready-made graphs of the time variation of the mode indicators:

a) for each power circuit:

– angular speed of rotation – ω_D, torque – M_D and power of the heat engine – P_D;

– output voltage – U_G and current – I_G of the generator;

– excitation current of the generator – I_{fG};

– relative control voltage of the converter – γ;

– voltage – U_M and current – I_M of the propeller motor;

– torque – M_M and angular rotation speed – ω_M of the propulsion motor;

b) on the parameters of the vessel's movement:

– speed of movement – v;

– components of the speed v along the longitudinal axis X – v_X and along the transverse axis Y – v_Y;

– angular velocity of rotation about the axis Z – Ω_Z;

– angle of drift – β_{dr} and heading angle – ψ of the vessel.

If necessary, any other parameters, obtained during the calculation, can be recorded.

To confirm the adequacy of the developed mathematical model and the calculation method based on it, we compare the results of mathematical modeling with the data published in [20, 21] obtained in the course of field experiments by other researchers.

We use the oscillograms of acceleration and reversal of the propulsion power plant of the nuclear-powered ship «Arktika» presented in these publications.

Recalculated (for convenience of comparative analysis) into relative values, these oscillograms are shown, respectively, in Fig. 2, 3 by solid lines. Here, the dashed lines show the current values of the mode parameters obtained with the aid of the developed calculation method.

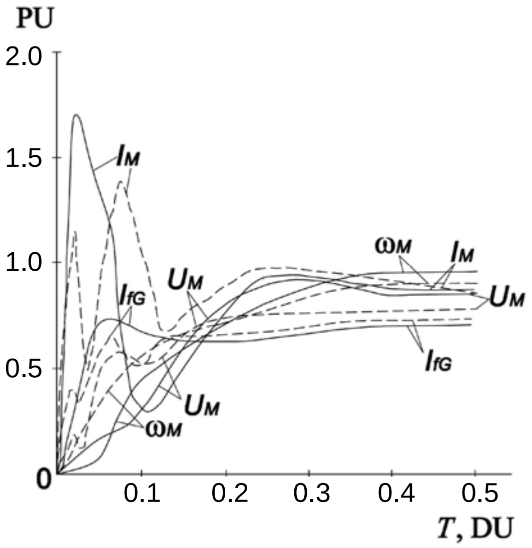

Fig. 2. Comparison of the theoretical calculation of the acceleration of the REI of the nuclear-powered electric ship «Arktika» with experimental data

The main parameters of the propulsion complex necessary for calculating the dimensionless parameters and the dynamic similarity criteria are presented in Table 1.

The generalized dimensionless parameters and the dynamic similarity criteria calculated from the above relationships are given in Table 2.

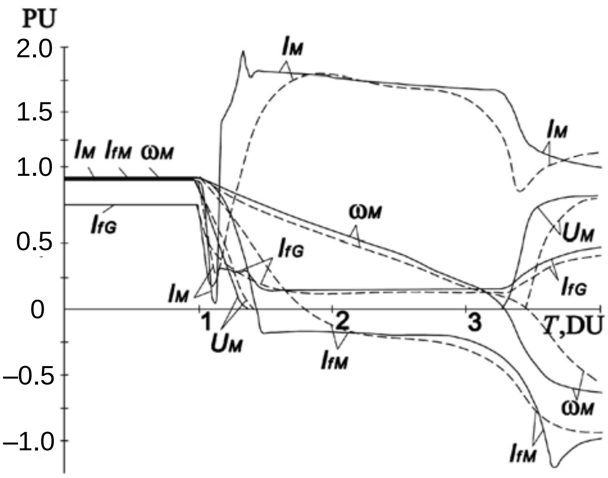

Fig. 3. Comparison of the theoretical calculation of the alternating reversals of the REI of the nuclear-powered electric ship «Arktika» with experimental data

Table 1

The main parameters of the propulsion complex

Length of the vessel by c.w.l.	136 m
Vessel speed	21 knots
Nominal parameters of thermal engines:	
power	27 600 kW
rotation speed	3500 RPM
Nominal parameters of synchronous generators:	
power	9000 kW
voltage	780 V
rotation speed	3500 RPM
power factor	0.88
winding data, p.u.:	
x_d	0.96
x_q	1.12
x''_d	0.14
x''_q	0.16
Nominal parameters of propulsion electric motors:	
power	17600 kW
Armature current	9200 A
rotation speed	130 RPM

Table 2

Dimensionless parameters and criteria for dynamic similarity of the nuclear-powered ship «Arktika»

K_M	K_{d1}	K_{q1}	K_{q2}	K_{G1}
1.071	1.12	0.294	1	–0.029
K_{G2}	N_D	N_{fG}	N_M	N_X
1.684	0.641	5.6	6.06	0.2
$K_{\gamma G}$	K_P	K_{Fb}	K_{is}	a_{21}
0.118	900	2	0.5	1.73
a_{11}	b_{21}	b_{11}	c_{21}	c_{11}
1.73	0.33	0.33	–1.06	–1.06

The control laws of each power circuit are given in the mathematical model in accordance with oscillograms of full-scale tests [16, 17]:

a) at acceleration $0 \le T \le T_1$:

$$\overline{U_{Gset}} = 0.8\left(1 - e^{-K_1 T}\right), \quad (85)$$

$$\overline{U_{Mset}} = 1; \quad (86)$$

b) at reversing from the forward to the rear $T_1 \leq T \leq T_2$:

$$\overline{U_{Gset}} = 0.8 - 1.5\left(1 - e^{-0.8K_2(T-T_1)}\right), \quad (87)$$

$$\overline{U_{Mset}} = 1 - 1.5\left(1 - e^{-K_2(T-T_1)}\right) - \quad (88)$$

for $\omega_M > 0$;

$$\overline{U_{Gset}} = 0.1 + 0.5\left(1 - e^{-1.5K_2(T-T_1)}\right), \quad (89)$$

$$\overline{U_{Mset}} = -0.5 - 0.5\left(1 - e^{-K_2(T-T_1)}\right) - \quad (90)$$

for $\omega_M \leq 0$;

c) at reversing from the rear to forward $T_2 \leq T \leq T_3$:

$$\overline{U_{Gset}} = 0.1 + 0.7\left(1 - e^{-1.5K_3(T-T_2)}\right), \quad (91)$$

$$\overline{U_{Mset}} = 0.5 + 0.5\left(1 - e^{-K_3(T-T_2)}\right) - \quad (92)$$

for $\omega_M < 0$;

$$\overline{U_{Gset}} = 0.6 - 1.5\left(1 - e^{-0.8K_3(T-T_2)}\right), \quad (93)$$

$$\overline{U_{Mset}} = -1 + 1.5\left(1 - e^{-K_3(T-T_2)}\right) - \quad (94)$$

for $\omega_M \geq 0$;

where U_{Gset}, U_{Mset} are the control signals in the excitation systems of the SG and IPM, respectively; K_1, K_2, K_3 are the time constants.

The results of calculating the mode indicators (I_{fG}, U_M, ω_M, I_M) carried out according to the developed method in accordance with the relations (18), (33), (34), (37) in the qb64 application package, matlab are shown by dashed lines in Fig. 2, 3.

Comparison of the calculated results with the developed method with the experimental data shows a fairly good convergence. Trends in the change of mode indicators coincide. Certain discrepancies in the initial stages of transient processes are expected, and are explained by the settings and gain factors of the automatic control system, which for each ship have their own values.

Thus, the conducted studies confirm the acceptability of the proposed mathematical model and the developed method for calculating the maneuvering operating modes of electric vessels.

Conclusions:

1. A refined mathematical model and a method for calculating on its basis the operating conditions of propulsion power plants in the composition of propulsion complexes of electric boats are proposed. The method makes it possible to calculate the current values of the basic mode indicators both in the steady-state and in the dynamic modes of electric power plants, and evaluate the performance indicators of electric boats on maneuvers.

2. The adequacy of the developed method of calculation is confirmed by the results of full-scale tests conducted by independent researchers.

3. The use of the developed method of calculation opens up wide possibilities in the study of transient and steady-state operating conditions for propulsion complexes of vessels with electric movement.

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V.A. Yarovenko[1]*, Doctor of Technical Science, Professor,*
P.S. Chernikov[1]*, Senior Instructor,*
[1] Odessa National Maritime University,
34, Mechnikova Str., Odessa, 65007, Ukraine,
phone +380 50 5980683,
e-mail: yarovenko@3g.ua; chernikov@onmu.odessa.ua

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