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# PARAMETRIC OPTIMIZATION STRATEGY OF ELECTRIC SHIPS' POWER PLANTS

*A strategy of optimal design of electric ships' power plants was proposed. Algorithms and programs of search for the optimum multimodal multiobjective target function in parametric optimization were developed. Algorithms for calculating the criteria of objective functions were developed. The effectiveness of the elaborated strategies and algorithms was illustrated.*
***Keywords:*** *electric vessels' power systems, optimal design, parameter optimization techniques.*

*Предложена стратегия оптимального проектирования энергетических установок судов с электродвижением. Разработаны алгоритмы и программы поиска оптимума мультимодальных многокритериальных целевых функций при параметрической оптимизации. Разработаны алгоритмы расчета критериев целевых функций. Проиллюстрирована эффективность разработанной стратегии и алгоритмов.*
***Ключевые слова:*** *энергетические установки электроходов, оптимальное проектирование, методы параметрической оптимизации.*

*Запропоновано стратегію оптимального проектування енергетичних установок суден з електрорухом. Розроблені алгоритми й програми пошуку оптимуму мультимодальних багатокритеріальних цільових функцій при параметричної оптимізації. Розроблено алгоритми розрахунку критеріїв цільових функцій. Проілюстровано ефективність розробленої стратегії і алгоритмів.*
***Ключові слова:*** *енергетичні установки електроходів, оптимальне проектування, методи параметричної оптимізації.*

**The urgency of the problem.** Parametric optimization of electric ships' power plants (EPP) presents considerable difficulties due to the complexity of the power plants, a variety of options for their constructive solutions, a close relationship of the processes occurring in the EPP with the movement of the ship. Maneuverability characteristics have decisive influence on decision-making in the design of electric vessels, since it is maneuvering modes that are major operational modes for ships of this class. On this basis, close attention is paid to the issues of designing electric vessels with preset, or at least predictable, maneuverable properties.

In theory and practice of parametric optimization there are no universal algorithms suitable for optimal design of complex real multiple systems, which include modern electric vessels' power plants. In most cases, for solving such tasks it is necessary to use special optimization methods which take into account the nature of the problems to be solved and the peculiarities of systems under consideration. The construction of these search methods applied to electric ships' power plants is the aim of the present work.

**Basic material.** As noted, the electric ship's power plant is part of the unified ship's propulsion system, so the quality of its work can only be assessed in unity with all parts of the complex. Generalized block diagram of electric ship's propulsion system is shown in Fig. 1. Most often, it is a dual or three-loop system. The structure of each power circuit includes: prime movers *D*, power generator *G*, power converters *SE*, propulsion motors *PM* and propellers *P*. The power plant has a unified control system. In addition, the electric ship's propulsion system consists of a wheel *W* and ship's hull.

A mathematical model of transient and steady-state operation modes in a ship's propulsion system was developed to calculate the current values of the main regime indicators of electric ship's power plant [1].

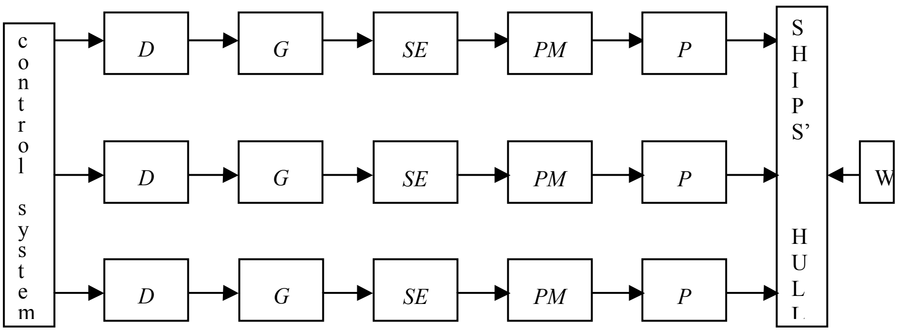


*Fig. 1. Block diagram of electric ship's propulsion system*

The model can not only calculate the current value of regime figures, but also assess quality indices of maneuvers. As such are proposed [2], the quality indicators of the following maneuvers: acceleration, braking, reverse, electric ship's output circulation:

- the maneuvering time *T*;
- fuel consumption to perform the maneuver *W*;
- deviation of prime movers' angular rotation velocity;
- maximum power of prime movers;
- bursts of generator's current during acceleration $(I_G)_{AM.}$ and reverse $(I_G)_{RM}$;
- set value of generator's current during acceleration $(I_G)_{AS}$ and reverse $(I_G)_{RS}$;
- voltage overfall at the generators' output $\Delta U_G$;
- the duration of the acceleration $(T_{PM})_A$ and reverse $(T_{PM})_R$ of propulsion motors and propellers;
- current spikes of propulsion motors during acceleration $(I_{PM})_{AM}$ and reverse $(I_{PM})_{RM}$;

- bursts of torque during acceleration $(M_{PM})_{AM}$ and reverse $(M_{PM})_{RM}$ of propulsion motors
- set values of torque of propulsion motors during acceleration $(M_{PM})_{AM}$ and reverse $(M_{PM})_{RM}$;
- set values of the angular rotation velocity of propulsion motors and propellers during acceleration $(\omega_M)_{AS}$ and reverse $(\omega_{PM})_{RS}$;
- the duration of the transient processes in power plants during acceleration $(T_{\text{EPP}})_{AS}$ and reverse $(T_{\text{EPP}})_{RS}$;
- shp's maximum speed by the end of the acceleration $v_{MAX}$;
- the duration of the propulsion system's acceleration to the target speed $(T)_{V=VT}$;
- path traversed by the ship at the end of the maneuver $(X1)_A$ or $(X1)_R$;
- changes in the power of prime movers of external $(\Delta P_D)_1$ and internal contours $(\Delta P_D)_2$ (with respect to the center of the circulation) of power circuits, when the electric vessel goes out to a steady circulation;
- changes in the stator current of propulsion motors of external $(\Delta I_{PM})_1$ and internal $(\Delta I_{PM})_2$ contours;
- changes in the torque of propulsion motors of external $(\Delta M_{PM})_1$ and internal $(\Delta M_{PM})_2$ contours;
- changes in the angular rotation velocity of propulsion motors and propellers of external $(\Delta\omega_{PM})_1$ and internal $(\Delta\omega_{PM})_2$ contours;
- reducing the vessel's speed, when it goes out to a steady circulation $(\Delta v)_{CIR} = v_{CIR}/v_{BEG.}$;
- vessel's angular velocity of rotation $\Omega_Z$ at the steady circulation $\Omega_{CIR}$;
- the diameter of the circulation $D_{CIR}$and its tactical diameter $D_{CIRT}$;
- vessel's pushing $L_1$ and its direct offset $L_2$;
- the angle of the ship's course after a defined period of time $\psi_{DEF}$;
- the duration of the complete revolution $T_{CIR}$;
- the duration of the evolutionary period of maneuver $T_{CIREV}$;
- the cost of fuel for the performance of the ship's complete revolution in circulation $W_{CIR}$.

Taken together, these indicators cover all major components of the electric ship's power plant and the whole electric ship in general, and are sufficient to assess the maneuvering performance of propulsion systems.

Integrated assessment of the quality of designing ships' power plants involves a multi-criteria optimization. In this case, the objective function of optimization processes $f(\mathbf{x}) = \sum m_j f_j(x)$ should include key quality indicators of maneuvers $f_j(x)$ with their weight contribution of $m_j$. Usually in such cases, there is a number of significant problems associated with the need to conduct a series of informal procedures. During the optimization we must take into account that:

- optimal solution is influenced by the ratio of weight coefficients $m_j$ of optimization criteria; these ratios are not known beforehand and in each case are selected depending on the intended purpose;
- there are difficulties related to expert estimates of weight contributions;
- there are frequent problems with scaling of quality indicators;
- optimization for individual maneuvers gives significantly different results.

As a result, when there is a large number of quality indicators, parametric optimization problems, in the general case, become insoluble. Therefore, in each specific case, depending on your goals, the number and importance of quality indicators, it is necessary to specify the type of the objective function and make trade-offs to a greater or lesser extent, satisfying the objectives.

Target functions constructed on complex criteria, appear (as shown by the study) multi-extremal with unknown number of local minima. They have a complex topography with many ridges and pronounced elongated ravines. The nature of the objective functions is such that the search for their derivatives is unpromising, and many protections and restrictions to ensure the normal operation of the power plant make finding the extremum even more difficult.

The objectivity of optimal decision making is in the first place, determined by the choice of minimization methods. Universal algorithms providing quick and proper motion to the optimum in the design of real-world complex multiple systems do not exist. There should be special procedures taking into account the nature of the objective functions to be optimized and specificity of problems to be solved. One of the possible methods of solving extremal problems is proposed below.

In its statement, the problems under consideration are in the area of nonlinear programming and consist in finding the extrema of multimodal objective functions $f(\boldsymbol{x})$ under given constraints $g_j(\boldsymbol{x})$ in the form of inequalities

$$\left.\begin{aligned} f(x), \quad x \in E^n; \\ g(x) \geq 0, \ j = 1, \ldots, p, \end{aligned}\right\}, \tag{1}$$

where $\boldsymbol{E^n}$ – admissible domain of $n$-dimensional space.

The optimal solution would be a pair of $\boldsymbol{x}_*$ and $f(\boldsymbol{x}_*)$, consisting of the optimal point $\boldsymbol{x}_*=[x_{1*}, x_{2*}, \ldots, x_{n*}]$ and the corresponding value of the objective function $f(\boldsymbol{x}_*)$

$$\left.\begin{aligned} x_* = [x_{1*}, x_{2*}, \ldots, x_{n*}]; \\ f_* = f(x_*). \end{aligned}\right\}. \tag{2}$$

The basis of the algorithm of global optimization is the method of global random search – random multistart. To prevent repeated descent to local minimum points in the global optimization algorithm we introduced a combination of a passive coating method – the method of random network – with a modified method of tunneling algorithm [3]. Information flowchart of the global optimum search is shown in Fig. 2.

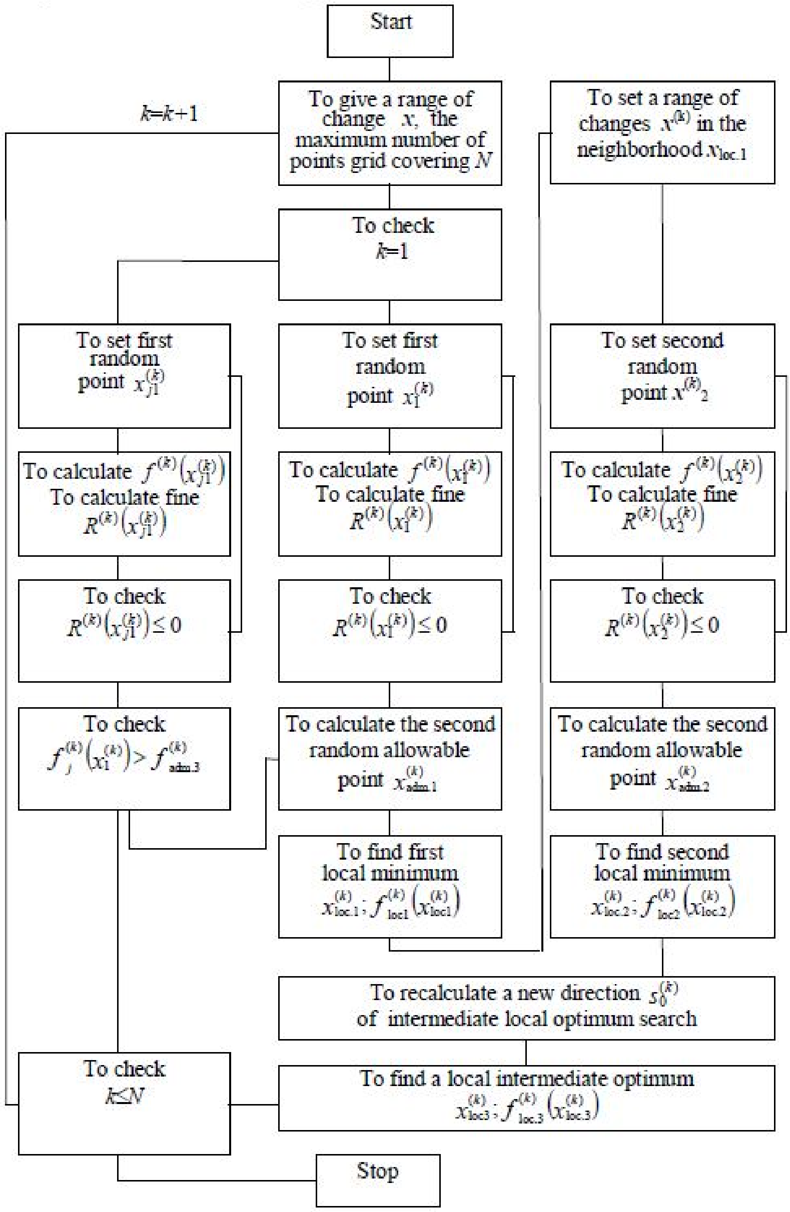


*Fig. 2. Information flow diagram of a global optimum search*

The essence of the developed procedures is as follows:

After finding points of intermediate local minima $\boldsymbol{x}^{(k)}_{loc.3}$, $f^{(k)}_{opt.loc.3}(\boldsymbol{x}^{(k)}_{loc.3})$ (the procedure of their search is outlined below), the allowable range of values of the optimized parameters $\boldsymbol{E}^n$ is covered by a grid of $N$ independent realizations of a uniformly distributed in $\boldsymbol{E}^n$ of random vector $\boldsymbol{x}$. The choice of the number of points $N$ is defined by the type of the objective function, obtained by the results and the required accuracy in the course of the optimization.

For each point, the objective function $f^{(k)}_j(\boldsymbol{x}_j)$, $k<j\leq N$ is calculated and the value $f^{(k)}_j(\boldsymbol{x}_j)$ is compared with $f^{(k)}_{opt.loc.3}(\boldsymbol{x}^{(k)}_{loc.3})$. If $f^{(k)}_j>f^{(k)}_{opt.loc.3}(\boldsymbol{x}^{(k)}_{loc.3})$, $j$-i point is discarded as the worst point. In the opposite case $f^{(k)}_j\leq f^{(k)}_{opt.loc.3}(\boldsymbol{x}^{(k)}_{loc.3})$ – a search of a new intermediate local minimum is performed, now based on $f^{(k)}_j(\boldsymbol{x}_j)$. The procedure for finding the optimal solution ends at the end of the sample $N$.

The search algorithm of intermediate local minima (global optimization internal procedures) was made on the basis of a combination of methods of local slopes and techniques of the ravine search. The essence of the algorithm is as follows.

After finding the first local minimum $\boldsymbol{x}^{(k)}_{loc.1}$, $f^{(k)}_{opt.loc.1}(\boldsymbol{x}^{(k)}_{loc.1})$ the second random riding point $\boldsymbol{x}^{(k)}_2$ near $\boldsymbol{x}^{(k)}_{loc.1}$ is found, so that $|\boldsymbol{x}^{(k)}_{loc.1}-\boldsymbol{x}^{(k)}_2|\leq D$ (where $D$ -variable parameter). The value $D$ depends on the nature of the objective functions and the admissible region $\boldsymbol{E}^n$. It must belong to points $\boldsymbol{x}^{(k)}_{лок.1}$ $\boldsymbol{x}^{(k)}_2$ to the region of one intermediate local minimum and is selected experimentally. From point $\boldsymbol{x}^{(k)}_2$ the second slope is made and the second local minimum $\boldsymbol{x}^{(k)}_{loc.2}$, $f^{k}_{opt.loc.2}(\boldsymbol{x}^{(k)}_{loc.2})$ is found.

Since the objective function has the form of an elongated ravine, we make a recalculation of a new direction of motion $\boldsymbol{s}^{(k)}_0$, built along the ravine from point $\boldsymbol{x}^{(k)}_{loc.1}$ to $\boldsymbol{x}^{(k)}_{loc.2}$ (or vice versa, depending on the relationship between $f^{(k)}_{opt.loc.1}(\boldsymbol{x}^{(k)}_{loc.1})$ and $f^{(k)}_{opt.\ loc.2}(\boldsymbol{x}^{(k)}_{loc.2})$. Along this direction is searched minimum of the objective function $f^{(k)}_{opt.loc.3}(\boldsymbol{x}^{(k)}_{loc.3})$, being an intermediate local optimum.

Methods that do not use derivatives should be applied to find local minima. Methods of Powell and Nelder-Mead turned out to be effective for solving this class of problems. When optimizing by Nelder-Mead method it is advisable to use one of its known modifications. According to it, the point of the compression step should be chosen not by a straight line connecting two worst points of the available ones (as in the original), but closer to the best vertex of the polyhedron. The calculations show that this change of compression procedure considerably reduces the number of calculations of the objective function.

Calculation of the current values of the propulsion system's regime indicators and evaluation of quality indicators of maneuvers is carried out using a mathematical model [1], of transient and steady modes of EPP in a ship's propulsion system. Calculation method of maneuvering is developed on the basis of a mathematical model. The enlarged version of the calculation algorithm is shown in Fig. 3.

In accordance with the algorithm, after setting the design parameters of the complex, control system parameters and initial conditions, the time variation laws of the control actions are formed. Thus, electric ship's maneuver is given. Then, the calculation of regime parameters of each circuit of the power plant is made. The end result of these calculations is the value of torque, of thrust and the angular velocity of propellers' rotation. Calculation of the parameters of ship's movement in the bouhd and then unbound with the vessel coordinate systems is made after determination of propeller's total thrust, hydrodynamic forces and moments acting on the ship and moments occurring at the wheel.

The current values of the basic regime parameters of each element of the complex are calculated during the computational procedures (in the course of the maneuver):

a) on the main circuit of power plant: the angular velocity of rotation – $\omega_D$, drive torque – $M_D$ and power – $P_D$ of heat engine; the relative costs of fuel to perform the maneuver – $W$; current – $I_G$ of the generator; generator's output voltage – $U_G$; the input voltage of the motor propeller – $U_{PM}$; current – $I_{PM}$ and torque – $M_{PM}$ propulsion motors; angular velocity of rotation of propulsion motors and propeller – $\omega_M$; propeller's thrust – $P_{PM}$;

b) the ship: her velocity – $v$; components of the velocity $v$ along the longitudinal – $v_X$ and transverse – $v_Y$ axes of the vessel; the angular velocity of rotation around the axis Z – $\Omega_Z$; drift angle – $\beta_{DR}$; the distance traveled (or longitudinal – $X$ and transverse – $Y$) along the axes unrelated to the vessel coordinate system; the angle of the course – $\psi_C$.

(If necessary, any other regime parameters obtained during computation can be registered).

The results of calculations allow to obtain the numerical values of quality indicators, which form the objective functions $f(\mathbf{x}) = \sum m_j f_j(x)$.

The considered model has certain features that led to the choice of the calculation method. The main ones are the following:

a) the time constants of differential equations differ greatly in size, value i.e., equations are classified as hard;

b) the intensity of change of regime parameters at different stages of transition processes vary within wide limits: they are maximal in the initial stages of power plants' acceleration and especially reverse propulsion and they are much lower when approaching a steady state operation.

Runge-Kutta-Merson method was the basis of the developed calculation algorithms of current values and regime indicators.

The results obtained on the basis of the maneuver "electric ship's acceleration to a speed $v$ = 0,7 $v_N$ – ship's reverse to $v$ = 0" illustrate the efficiency of the developed strategy of parametric optimization.

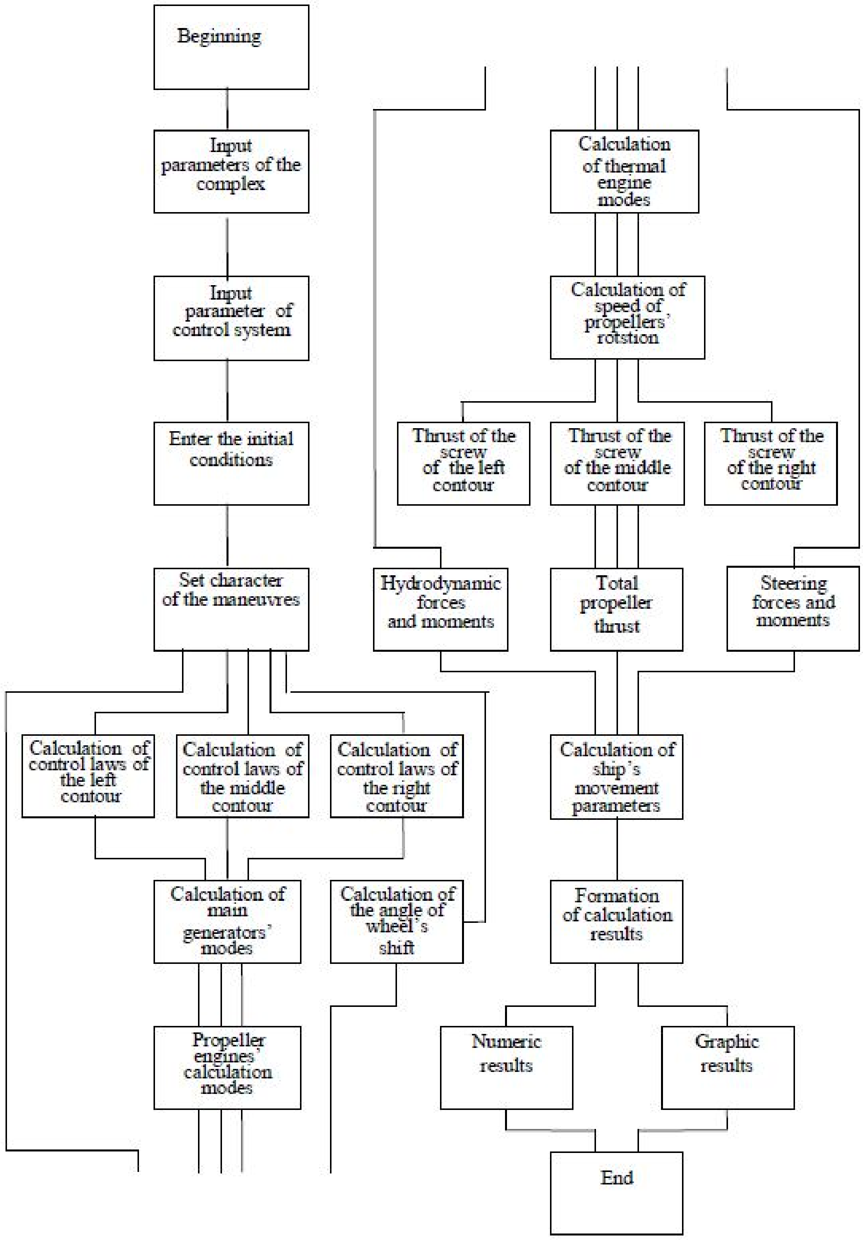


*Fig. 3. The enlarged version of the algorithm for calculating current values of regime parameters*

It was noted above that using the multiobjective parametric optimization in each specific case it is necessary (depending on the goals) to specify the type of the objective function and make trade-offs, to a greater or lesser extent, satisfying the objectives. The following will be chosen as quality indicators:

- the relative energy costs to perform the maneuver – $W$;
- the time required to perform the maneuver – $T$;
- the relative deviation from the steady operation regime of the prime movers' angular velocity of rotation – $\Delta\omega_D$ ;
- maximum power of prime movers – $P_{DM}$;
- the duration of the reverse of propulsion motors and propellers – $(T_{PM})_R$ .

In accordance with the principles of the systematic approach the selected quality indicators are divided into two groups:

a) first, which includes the indicators $W$ and $T$, characterizing not only ship's power plant, but also the whole electric ship;

b) second, which involves indicators $\Delta\omega_D$, $P_{DM}$ and $(T_{PM})_R$ characterizing engine performance of electric ship's propulsion plant.

Indicators of the first group have priority over the second. In accordance with the priorities exposed, the search for optimal parameters of propulsion systems should be carried out in terms of the criteria of the first group $W_{MIN}$ and $T_{MIN}$ multiple criteria quality indicator $J_{WT}$

$$J_{WT} = m_W W + m_T T,$$

with variable weight coefficients m $m_W$ and $m_T$.

It is necessary to clarify the optimized parameters in terms of the parameters of second group, following the principle of "non-worsening", and taking into account tolerance, of the first group indicators. As a multi-criteria quality index thus acts

$$J_{\omega PT} = m_\omega \Delta\omega_D + m_P P_{DM} + m_T (T_{PM})_R,$$

with variable weights coefficients $m_\omega$, $m_P$ and $m_T$.

The effectiveness of the above strategies of parametric optimization can be assessed by comparing the results of calculations performed for the propulsion system with the "averaged" dimensionless parameters (Fig. 4) with the calculation results for the complex with optimized parameters (Fig. 5). The results are obtained for the maneuver "electric ship's acceleration to a speed $v = 0{,}7\ v_N$ – ship's reverse to $v = 0$".

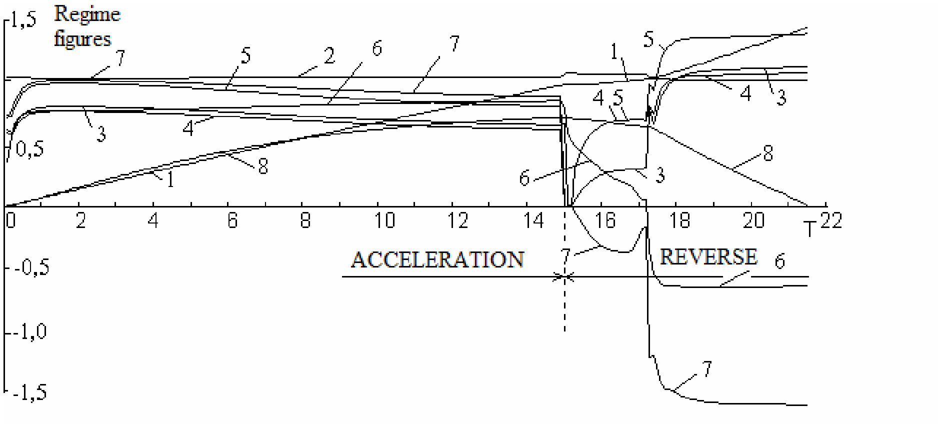


*Fig. 4. Regime figures at the average values of parameters*

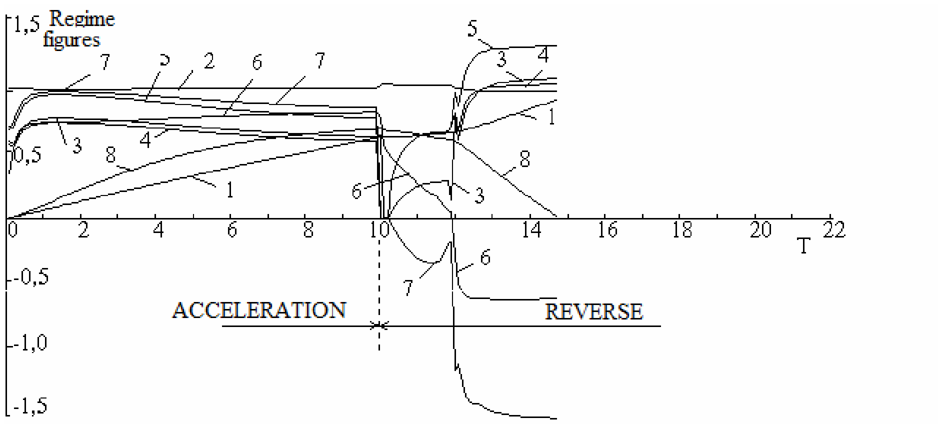


*Fig. 5. Regime figures with parameters*
*at the optimized values of the parameters*

The curves shown (in relative units) in figure correspond to:
*1 – the costs of energy in the course of the maneuver – W;*
*2 – prime movers' angular velocity of rotation* – $\omega_D$;
*3 – prime movers' power –* $P_D$;
*4 – main generators' current –* $I_G$;
*5 – propulsion motors' current –* $I_{PM}$;
*6 – angular rotation velocity of the propeller motors and propellers –* $\omega_{PM}$;
*7 – propulsion motors' torque –* $M_{PM}$;
*8 – electric ship's speed – v.*

The results of the comparison are the foillowing:
- a gain in energy costs is 34,3 %;
- a gain in time costs is 31,6 %;
- a gain in the deviation of the prime movers'angular velocity of rotation is 32,5 %;
- a gain in the value of the prime movers' maximum power is 12 %;
- a gain in length of propellers' reverse is 12,5 %.

The comparison results clearly confirm the effectiveness of the conducted optimization calculations.

**Conclusions**. The developed strategy of parameter optimization of electric ships' power plants, calculation and optimization methods of current values of propulsion system's regime indicators can significantly improve the efficiency of electric vessels' operation.

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