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MATHEMATICAL MODEL OF STEADY OPERATION OF SHIP ELECTRICAL COMPLEXES

Currently, existing control systems for parallel operation of diesel-generator units do not control the presence of power exchange fluctuations and do not limit their level. Research conducted earlier led to the discovery of the negative impact of power exchange fluctuations between parallel-working diesel-generator units on the quality of the produced electrical energy and on the operation of electrical engineering complexes as a whole. In this regard, the development of methods for identifying the presence and level of power exchange fluctuations in electrical engineering complexes is relevant.

The article examines the issue of ensuring the stable operation of ship electrical engineering complexes. When conducting research, real oscillograms of exchange and in-phase power fluctuations are used, taken during joint-parallel operation of diesel-generator units, common bus bars of the main switchboard. One of the problems of electro technical ship complexes of marine vessels is considered appearance of alternating and in-phase power fluctuations when diesel-generator units are connected in parallel. To eliminate such fluctuations, it is necessary to influence the speed regulators and change their transmission coefficients so as not to disturb the stable operation of the entire electro technical complex of the ship. It is necessary to determine the permissible range of change of gain coefficients of frequency regulators of jointly parallel-connected generators to preserve the stable operation of shipboard power plants of marine vessels.

The results of mathematical modeling allow us to conclude that it is necessary to limit the change in the values of gain coefficients of frequency regulators. Based on the results of mathematical modeling, it is possible to recommend limiting the change in gain coefficients of frequency regulators during parallel operation. It is proposed to limit the change in gain coefficients of frequency regulators while eliminating power exchange fluctuations.

Key words: *power exchange fluctuations, parallel operation, autonomous electro technical complex, stability, generator set, the frequency regulator setting.*

Formulation of the problem. In the modern world, the maritime fleet includes hundreds of maritime vessels that perform various functions [1]. The main tasks of maritime floating objects include transportation of various types of goods, as well as cargo and personnel, extraction of fish resources and hydrocarbons, laying pipelines and communications, state defense, ensuring operation in Arctic conditions, and others [2, 3]. On board any maritime vessel, there is an autonomous electrical system consisting of generating energy objects and devices and mechanisms that consume electrical energy [4]. The conditions and peculiarities of operating electrical systems of maritime vessels are regulated by the requirements of the Maritime Register of Shipping and the International Convention for the Safety of Life at Sea (SOLAS) [5, 6]. Diesel generator sets connected in parallel are often used as sources of electrical energy, connected to the main distribution panel [7, 8]. The list of capacities and consumers is very wide and is determined by the type and purpose of the vessel [9]. Ensuring the stable operation of the power station of a maritime vessel with the production of quality electrical energy is a vital condition for the safety of the vessel and the fulfillment of its technological and production tasks [10].

The most rational scheme for the production of electrical energy on maritime vessels is the parallel operation of several diesel generator sets from a technical and economic perspective [11]. Each diesel generator has its own speed governor and voltage regulator [12]. The settings of the regulators determine the load distribution between the units in quasi-steady-state operating modes of the electrical power complexes of maritime vessels, leading to exchange and in-phase oscillations of power between the parallel-connected generators [11]. To eliminate such oscillations, it is necessary to influence the speed governor and change their gain coefficients in such a way that the stable operation of the entire electrical complex of the vessel is not disturbed. It is necessary to determine the permissible range of variation of the gain coefficients of frequency regulators for parallel-connected generators to maintain the stable operation of the power stations of maritime vessels.

Analysis of recent research and publications. One of the problems of electrical ship complexes of maritime vessels is the occurrence of exchange and in-phase power oscillations when diesel generator sets are connected in parallel [11]. Such oscillations lead to accelerated wear of diesel speed governors, the inability to use generating devices at full capacity, pulsating voltage in the vessel electrical network, a decrease in the performance of electrical drives and ship automation systems, as well as the need to use mathematical modeling to evaluate permissible limits and ratios when changing the gain coefficients of frequency regulators [12].

For synchronous machines with rotor excitation winding, a slow number of $0\ldots n_d$ equivalent short-circuited circuits in the d-axis and a slow number of $0\ldots n_q$ equivalent short-circuited circuits in the q-axis, the Park-Horjev equations in per-unit values can be written in the following form:

$$\frac{d\psi_d}{d\tau} + \omega\psi_q + ri_d = -u_d , \quad (1)$$

$$\omega\psi_d - \frac{d\psi_q}{d\tau} - ri_q = u_q , \quad (2)$$

$$\frac{d\psi_r}{d\tau} + r_r i_r = E_r , \quad (3)$$

Additionally, synchronous generators in stationary to d and q coordinates can be represented as a series of equations [11]:

$$\frac{d\psi_{sd}}{d\tau} = \psi_{sq}\omega_r - r_s i_{sd} - u_{sd} , \quad (4)$$

$$\frac{d\psi_{sq}}{d\tau} = -\psi_{sd}\omega_r - r_s i_{sq} - u_{sq} , \quad (5)$$

$$\frac{d\psi_f}{d\tau} = u_f - r_f i_f , \quad (6)$$

where $\psi_d, \psi_{sd}, u_d, u_{sd}, i_d, i_{sd}$ – The projections of the flux linkage vector, voltage vector, and stator current vector onto the d-axis can be represented as follows:

– Flux linkage vector projection on the d-axis: ψd = ψ · cos(θ)

– Voltage vector projection on the d-axis: Vd = V · cos(θv)

– Stator current vector projection on the d-axis: Id = I · cos(θi)

Here, ψd is the flux linkage vector projection on the d-axis, ψ is the flux linkage magnitude, θ is the angle between the flux linkage vector and the reference axis, Vd is the voltage vector projection on the d-axis, V is the voltage magnitude, θv is the angle between the voltage vector and the reference axis, Id is the stator current vector projection on the d-axis, I is the stator current magnitude, θi is the angle between the stator current vector and the reference axis.

These equations represent the components of the vectors in the d-axis direction, which is a coordinate axis commonly used in the analysis of synchronous machines;

$\psi_q, \psi_{sq}, u_q, u_{sq}, i_q, i_{sq}$ – The projections of the flux linkage vector, voltage vector, and stator current vector onto the q-axis ;

ψ_f, u_f, i_f, r_f – The projections of the flux linkage vector, voltage vector, current vector, and excitation winding resistance;

ψ_r, i_r, r_r – Projection of the flux linkage vector, voltage, current, and active resistance of the excitation winding;

E_r – Excitation voltage;

τ – Duration of the process.

The synchronous generator has a brushless exciter with a proportional voltage regulator:

$$\frac{du_f}{d\tau} = \left[-u_f + K_f\left(U_0 - u_m\right)\right] / T_в , \quad (7)$$

where K_f – Gain coefficient;

U_0 – Predetermined voltage value;

$$u_m = \sqrt{u_{sd}^2 + u_{sq}^2} .$$

Based on the above statement, an equation can be written for a diesel engine:

$$J_m \frac{d\omega_r}{d\tau} = M_d - M_g , \quad (8)$$

$$M_d = K_m h , \quad (9)$$

$$M_g = \psi_{sg} i_{sd} - \psi_{sd} i_{sg} , \quad (10)$$

where J_m – The referred moment of inertia of the diesel generator shaft;

M_d – Diesel engine torque;

M_g – Generator torque;

h – Fuel rail displacement;

K_m – Diesel speed gain coefficient.

Then the speed control regulator of the diesel engine installation will have the following form:

$$T_\omega \frac{dh}{d\tau} = K_\omega U_\varepsilon - h , \quad (11)$$

where T_ω – A constant time value;

K_ω – Gain coefficient;

U_ε – The difference between the set ω_{r0} andd actual ω_r rotational frequencies.

Presenting main material. In Fig. 1 you can see the results of the research using mathematical methods in the form of graphs of currents and rotational frequencies of two generators connected in parallel on the main distribution panel, at different values of proportional coefficients of their speed control regulators. $K_{\omega1} = 80$, $K_{\omega2} = 40$. The current graphs show synchronous power oscillations with a constant amplitude, while the generator rotational frequencies tend to reach the set value.

Figure 2 shows the results of mathematical control in the form of current and rotation frequency graphs of two generators operating in parallel on the main distribution panel busbars, with varying proportional coefficients (gain coefficients) of their rotation frequency regulators $K_{\omega1}$= 350, $K_{\omega2}$= 250.

The presence of in-phase current oscillations and increasing amplitudes, as well as the increasing instantaneous rotation frequencies of the generators, indicates instability in the operation of the vessel power plant. This suggests an approaching activation of protection measures with subsequent power outage of the vessel.

Discussion of experiments. Thus, changing the proportional coefficients (gain coefficients) of

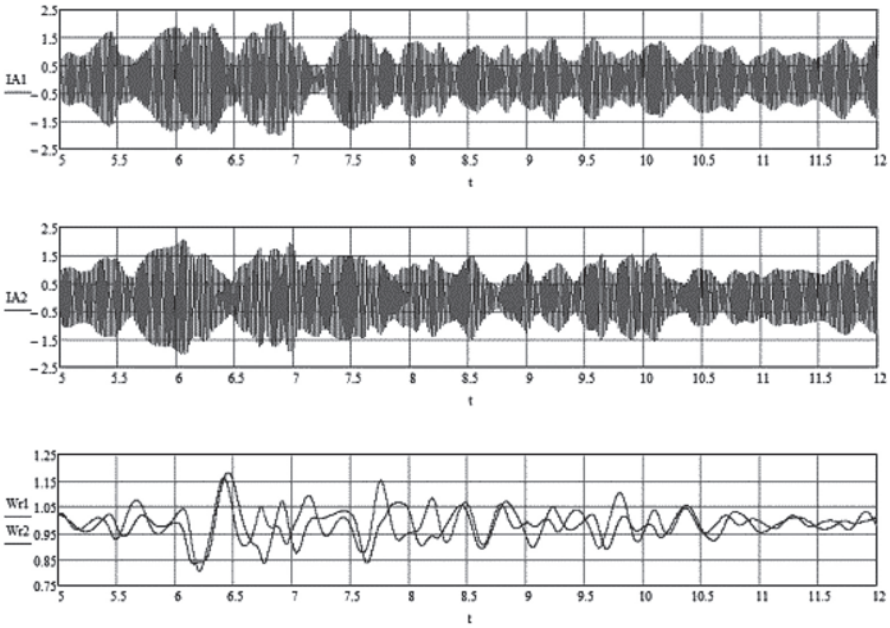

Fig. 1. Results of mathematical modeling of parallel operation of generators with $K_{\omega1}$ = 80, $K_{\omega2}$ = 40

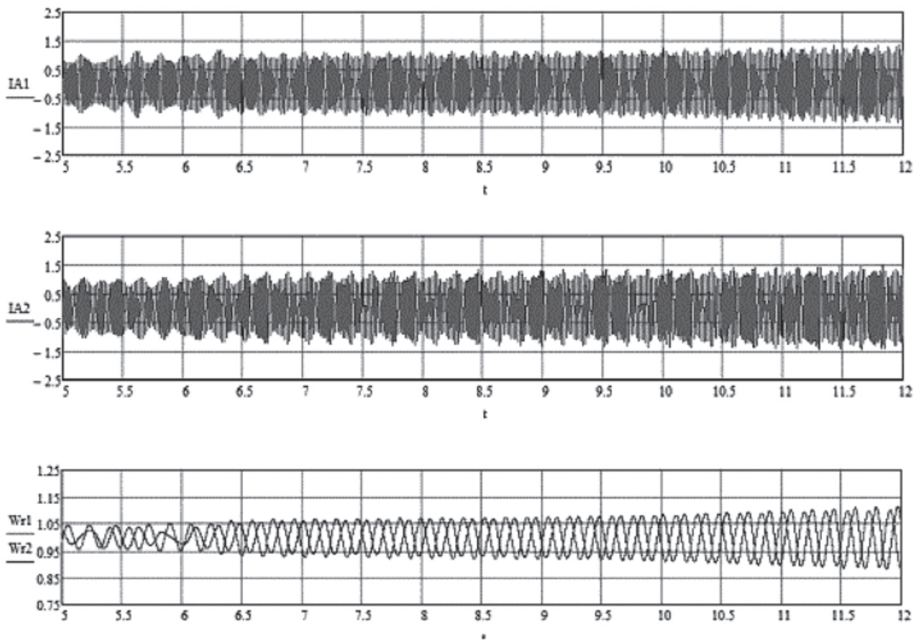

Fig. 2. Results of the investigation of parallel operation of generators with $K_{\omega1}$= 350, $K_{\omega2}$= 250

the frequency regulators when paralleling diesel generators on the main distribution panel can lead to uncontrolled growth of in-phase power oscillation amplitudes and rotational frequencies. In order to ensure stable operation of the vessel power plant during changes in the gain coefficients of the frequency regulators, mathematical modeling was conducted at various transmission coefficient ratios. The research results, where stable operation of the vessel power plant is maintained, are presented in Table 1, and the settings map is depicted in Figure 3.

It can be observed that when the gain coefficients of the frequency regulators in the diesel generators are equal, there are no power oscillations. The difference in gain coefficients leads to the appearance of power oscillations, and their amplitude increases with the increase in the difference between the gain coefficient values within the range of 0 to 200, as shown in Figure 1. Parallel-connected diesel generators operate stably under such conditions. However, when the gain coefficients exceed certain values, as shown in Figure 2, power oscillations occur, indicating unstable parallel operation of the generators.

The above-mentioned data was obtained for electrical complexes of maritime vessels. However, they can be applied to any autonomous electrical system that utilizes parallel operation of diesel generator units. While the operating conditions of a maritime vessel are entirely autonomous, making the operation of its electrical complex crucial, extreme situations can also arise in land-based systems where the viability of an entire operation depends on reliable power supply.

Table 1

Research the dependence of in-phase power oscillation amplitude of diesel generator on gain coefficient values of the frequency regulator in steady operation modes

$K_{\omega 1}$/ $K_{\omega 2}$	10	20	40	60	80	100	120	140	160	180	200
10	0,01	1,2	1	0,9	0,9	1,2	0,5	0,45	0,4	0,3	0,3
20	1	0,01	0,9	1	1	1	1,1	0,95	0,8	0,75	0,9
40	0,8	0,65	0,05	1	1,1	0,9	1,2	1,2	1,35	1	1,2
60	1,1	0,95	0,95	0,05	0,3	0,9	0,7	0,95	0,95	1,05	1,1
80	1	1	0,8	0,25	0,05	0,25	0,7	1,1	0,9	1	1,3
100	0,6	0,7	1,1	1,1	0,2	0,05	0,22	0,8	0,8	06	1,1
120	0,4	1	1,2	1	1,1	0,1	0,06	0,17	1,1	0,8	1,2
140	0,6	1,1	1,2	0,9	0,95	0,22	0,08	0,06	0,17	0,7	1,05
160	1,2	1	1,2	07	0,8	0,6	0,25	0,09	0,06	0,17	0,6
180	1,1	1,2	1,05	1,1	1,2	0,75	0,7	0,2	0,07	0,06	0,14
200	1	1,05	0,95	1,05	1,05	0,75	0,7	0,6	0,15	0,06	0,07

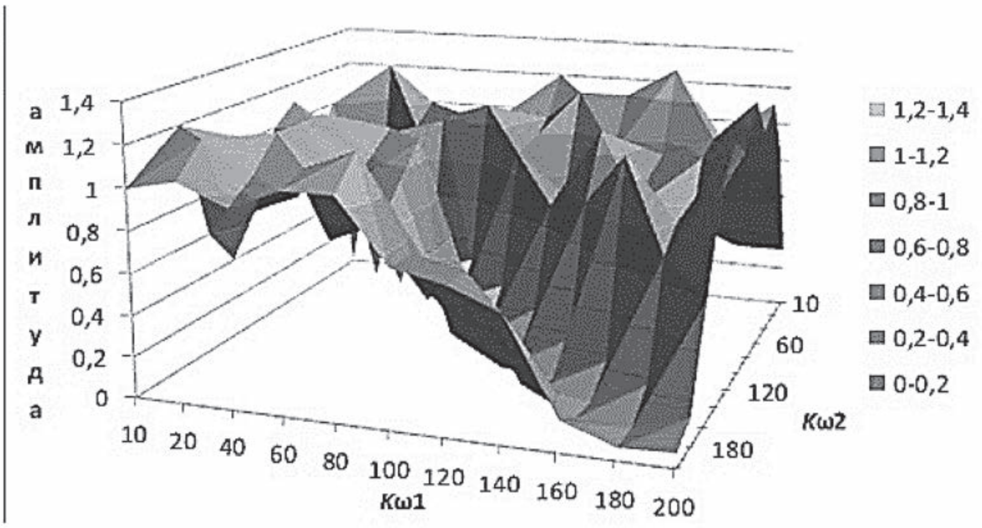

Fig. 3. Map of the dependency of power oscillation amplitude on gain coefficient values of frequency regulators in diesel generator

Conclusion. The conducted research has demonstrated the dependency of the stability of operation of a maritime vessel's electrical complex, with parallel connection to the main distribution panel of diesel generator units, on the values and ratios of gain coefficients of the frequency regulators. Based on the results of mathematical modeling, it is recommended to limit the variation of gain coefficients of the frequency regulators within the range of 0–200 during parallel operation. Such limitation should be taken into account when adjusting the gain coefficients of the frequency regulators to mitigate power oscillations.

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Дощенко Г.Г., Наговський Д.А. МАТЕМАТИЧНА МОДЕЛЬ СТАЛОЇ РОБОТИ СУДНОВИХ ЕЛЕКТРОТЕХНІЧНИХ КОМПЛЕКСІВ

У даний час існуючі системи керування паралельною роботою дизель-генераторних агрегатів не контролюють наявність обмінних коливань потужності та не обмежують їх рівень. Дослідження, що проводилися раніше, призвели до виявлення негативного впливу обмінних коливань потужності між паралельно працюючими дизель-генераторними агрегатами на якість вироблюваної електричної енергії і на роботу електротехнічних комплексів в цілому. У зв'язку з цим актуальним є розробка способів ідентифікації наявності та рівня обмінних коливань потужності в електротехнічних комплексах.

У статті розглядається питання забезпечення сталої роботи суднових електротехнічних комплексів при проведенні досліджень використовуються реальні осцилограми обмінних та синфазних коливань потужності, зняті при спільно-паралельній роботі дизель-генераторних агрегатів загальні шини головного розподільного щита. Однією з проблем електротехнічних суднових комплексів морських суден вважається поява обмінних та синфазних коливань потужності при спільно-паралельному включенні дизель-генераторних агрегатів. Для усунення таких коливань необхідно здійснювати вплив на регулятори частоти обертання та змінювати їх коефіцієнти передачі так, щоб не порушувалася стійка робота всього електротехнічного комплексу судна. Необхідно визначити допустимий діапазон зміни коефіцієнтів посилення частотних регуляторів спільно-паралельно включених генераторів для збереження сталої роботи суднових електростанцій морських суден.

Результати математичного моделювання дозволяють зробити висновок про необхідність обмеження зміни значень коефіцієнтів посилення частотних регуляторів. На основі результатів математичного моделювання можна рекомендувати обмежити зміну коефіцієнтів посилення частотних регуляторів при паралельній роботі. Запропоновано обмежити зміну коефіцієнтів посилення частотних регуляторів при усуненні обмінних коливань потужності.

Ключові слова: *обмінні коливання потужності, паралельна робота, автономний електротехнічний комплекс, стійкість, генераторний агрегат, налаштування регулятора частоти.*