ЕЛЕКТРОМЕХАНІЧНЕ ПЕРЕТВОРЕННЯ ЕНЕРГІЇ

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IMPROVING THE ENERGY EFFICIENCY OF SHIP ELECTRIC INSTALLATIONS BY USING ASYNCHRONOUS GENERATORS

L.V. Vishnevsky[*], M.Y. Mukha[**], A.O. Drankova[***]
National University Odesa Maritime Academy,
str. Didrikhsona, 8, Odesa, 65029, Ukraine
e-mail: leovikvish@gmail.com; n.mukha52@gmail.com; drankova64@gmail.com

The article considers one of the ways to increase the energy efficiency of marine autonomous power plants by using asynchronous generators with capacitor excitation instead of traditional generator sets with synchronous generators. A comparative analysis of transients of synchronous and asynchronous electrical installations for typical operating conditions, which showed the advantages of asynchronous generator sets (structural, energy, economic) and due to which they can be the main sources of electricity on board in the future. The graphs of the corresponding transients are given. References 10, figures 6.
Keywords: electric power generation, synchronous and asynchronous generators, comparative energy efficiency analysis.

Introduction. Reducing operating costs, reducing energy costs per unit of cargo transportation, and reducing the number of emissions into the atmosphere is one of the main concerns of the shipping industry today. The requirement that vessels must obtain an international certificate of energy efficiency establishes new rules for managing the vessel’s energy efficiency and ways to reduce energy consumption on water transport. Therefore, the development of an energy-efficient strategy for the operation of sea and river transport is a priority and relevant investigation, and the energy effectiveness of the vessel should be a part of the design and construction criteria for ships.

Problem analysis. At present in the shipboard energy flow "generation - consumption of electricity" the potential for improving energy efficiency is used only to a small extent. The specificity of improving energy efficiency in this complex is the significant saving of primary fuel resources by reducing power consumption.

In this regard, one of the ways to increase the energy efficiency of ships and reduce energy consumption is to develop methods for managing the flow of electric energy. Undesirable losses occur during the production, distribution, conversion, and use of electricity in the ship’s autonomous electrical system. Besides, ship electricity consumers mainly have an active inductive load, that is, the total current of generators, transformers, and cable lines should be increased relative to the required active load by a value that is inversely proportional to the value of the power factor, which is proportional to the increase in the number of electricity consumers. Therefore, generating plants must provide additional reactive power, which, in turn, reduces their efficiency due to the increased fuel consumption of primary engines (diesel engines).

Thus, as mentioned earlier, one of the ways to increase energy efficiency of the ship's operation and reduce a power consumption along with improving the operation modes of the ship's propulsion and optimizing the operation of auxiliary equipment and mechanisms is a develop of managing methods of the shipboard electrical energy flows.

ORCID ID: * https://orcid.org/0000-0003-1119-2602 , ** https://orcid.org/0000-0002-2923-6733,
***https://orcid.org/0000-0002-2072-1599

In our opinion, there are two ways to solve this problem. This determines two areas of research into this problem: 1) optimal control of the electrical energy flow at the stage of its generation and distribution; 2) optimization of energy flows at the consumption stage, i.e. at the stage of electromechanical electricity conversion.

A new solution to the scientific-applied problem [1] of increasing the energy efficiency of shipboard autonomous electric power systems using dynamically compensating reactive power in the load circuit as a function of changing the reactive conductivity of the loads made it possible to increase the speed, the accuracy of the process of reactive power compensation in transient operational modes of loads switching and voltage stability of an autonomous ship electrical system, and thereby reduce energy consumption and carbon dioxide emissions into the atmosphere by sea transport facilities.

The most significant energy-efficient solution in the design of new generation vessels is the ability to reduce the generated power (and, consequently, reduce the number of emissions into the atmosphere) of a ship power plant, which can operate with a power factor close to unity.

The use of condenser reactive power compensators as part of ship electric power systems facilitates the introduction of generator sets with asynchronous generators.

The purpose of the work is the scientific justification for the use of asynchronous generators in marine electrical installations to increase their energy efficiency instead of synchronous generators by comparing dynamic modes and energy indicators.

Materials and results of the study. Reliability and efficiency of energy sources in transport is a prerequisite. Traditionally, ship generators are used synchronous generators (SG), the production of which is well-established, and their design is optimized, [2-4]. An energy-efficient alternative to using SG in autonomous power plants is the widespread use of squirrel-cage asynchronous generators (AG) [5-7], which, for example, have practically replaced SG from wind power energy.

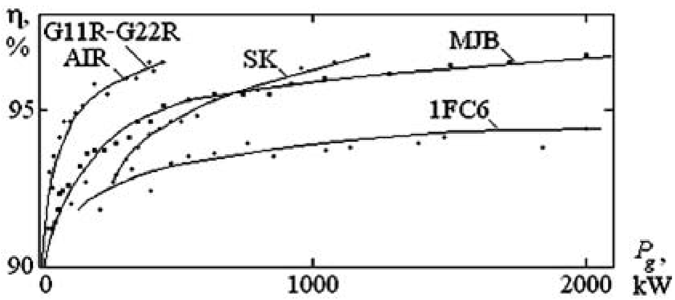


Fig. 1

Due to the simple design of the squirrel-cage rotor in the AG, the air gap and losses are significantly reduced, which made it possible to reduce the geometric dimensions of the rotor and the machine as a whole, to increase the working temperature of the rotor and increase its maximum rotation frequency, which extends the operational range of application of the asynchronous machines compared to synchronous.

With the same mechanical characteristics and degree of protection, the AG will have 1.4 times lower overall dimensions than SG with slip rings on the rotor, [8]. AG efficiency is about 2 % higher than SG of the same capacity, which makes its use more economical [1, 8]. For example, the annual savings from replacing a ship's synchronous generator with an asynchronous one with a capacity of 1 MW will be about 12 thousand dollars.

Fig. 1 shows the dependence of efficiency (η) synchronous (SK, MJB, 1FC6) and asynchronous (G11R-G22R) generators produced by different manufacturers on their active power P_g, as well as asynchronous machines of the AIR series, [2-4, 9].

The main reason why AGs are not widely used in autonomous power plants is the technical need for the excitation and voltage regulation of AGs to use an additional source of reactive power - power capacitors. The reduction in the cost of capacitors and thyristors has currently stimulated the production of controlled reactive power compensation units and their widespread use in enterprises and transport. Technologically, such plants differ from AG excitation systems only in controllers [9].

AG and SG also differ significantly in the way of excitation and control of the generated voltage. In the SG excitation is carried out forcefully from the side of the rotor chains. Due to this, the speed of the electromagnetic processes of the generator due to the large inductance and the time

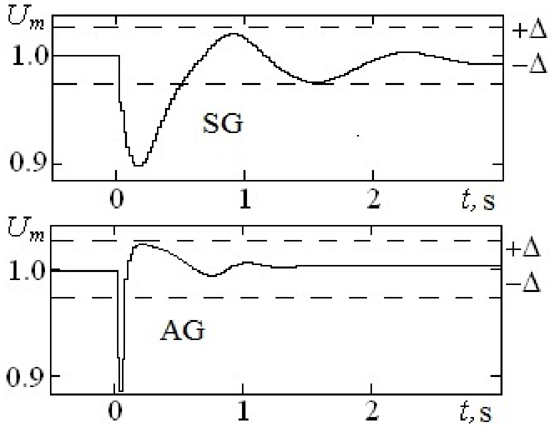


Fig. 2

constant of the field winding is significantly increased, and there is practically no fundamental possibility of increasing the speed of the SG. To increase the speed of the voltage regulation system, the SG regulator uses excitation force, the short-term value of the excitation voltage allows a value of 5...8 times the nominal value.

In AG, excitation is provided due to the oscillatory process of energy exchange between the inductance of the machine and the capacitance of excitation capacitors connected to the stator circuits of the AG. The AG voltage will depend on the magnetization curve of the machine, speed, load, and the value of the capacitive excitation current, [8, 9]. The AG excitation regulator changes the capacitive current of the capacitors depending on the voltage deviation from the nominal. The load current and the capacitive excitation current flow through one stator circuit of the generator, which allows almost instantly to compensate for the response of the generator to the load with a capacitive current. The problem remains only in the quick measurement and selection of the optimal control law. Regulation of AG excitation along the stator circuit allows one to create high-speed and invariant voltage stabilization systems [1, 8, 9].

In Fig. 2. shows the transition process of voltage recovery SG and AG after switching on 50% of the rated load with a power factor of 0.8, $\Delta = 0.02$. If the voltage measurement and switching of capacitors is carried out during one period of the generated current, then the transition process of restoration of the AG voltage after switching the load ends in 2...3 periods, i.e. for 0.04...0.06 s. At the same time, the minimum time of the transition process in the SG is 0.5 s, [9].

The difference in the excitation systems of the SG and AG is reflected in the overload capacity of the generators and their response to short circuits. With double (and more) overload and limited excitation capacitance, the AG sharply reduces the voltage to zero, which does not occur in the SG during overload, therefore it needs protection against such emergency conditions. In the event of a short circuit, the capacitance of excitation capacitors is shunted, and the AG is quickly excited due to the small-time constants of the generator scattering circuits. Thus, the short circuit mode for the AG is safe. Moreover, the selectivity of protection against short-circuit in a branched electric network, the AG should be provided for 2...3 periods of current, [9].

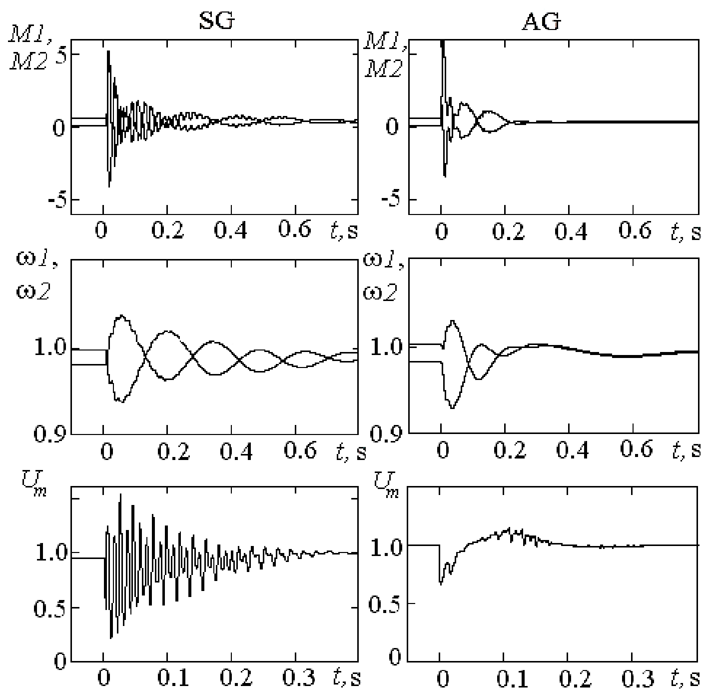
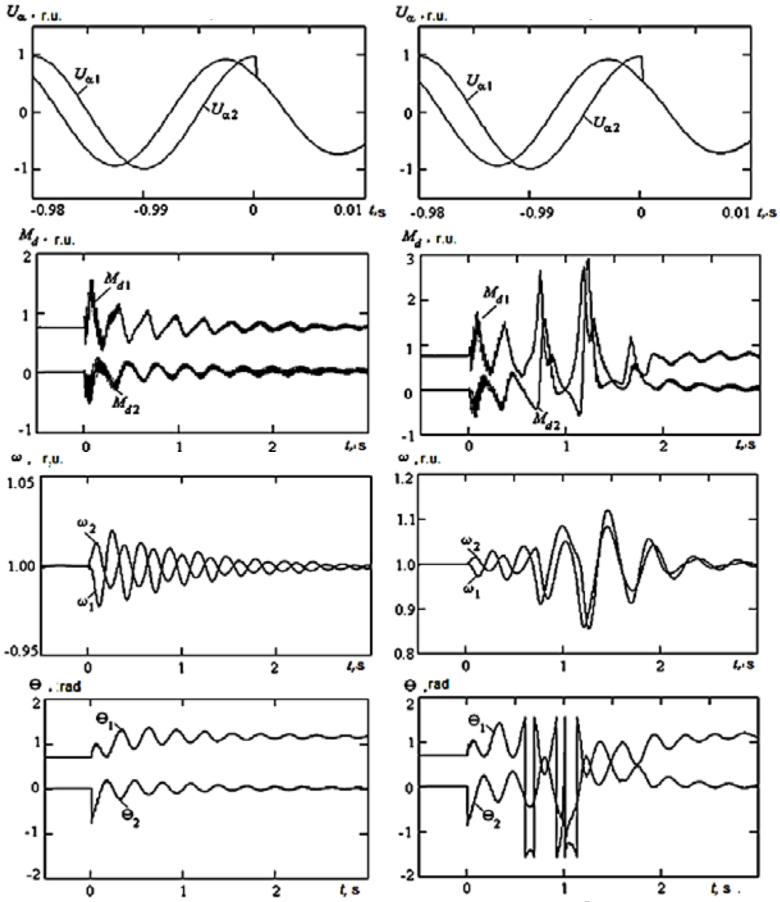


Fig. 3

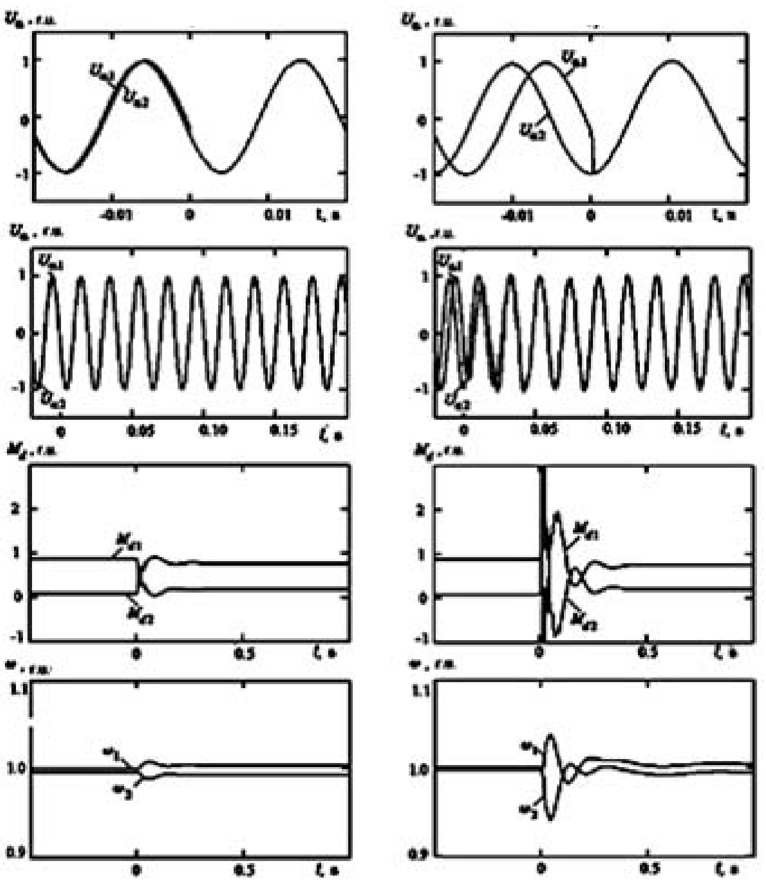
It should be noted that the limitation of the AG overload capacity is proportionally dependent on the magnitude of the capacitance of the excitation capacitors. If the generator is calculated for the nominal, $\cos\phi = 0.8$ then it is possible to directly start an induction motor with power up to 30% of the generator power. If the capacitance of the AG excitation capacitors is not limited, it is possible to start the motor commensurate with the power generator, [1, 8].

Due to the filtering properties of the capacitors, the AG has a sinusoidal shape of the generated voltage curve with a low harmonic content [9], the symmetry of the



a *b*

Fig. 4



a *b*

Fig. 5

three-phase voltage with an uneven load distribution [8].

The SG electromagnetic field vector is rigidly attached to the geometrical axis of the field coil. An increase in the load angle (between the field and the axis of the winding) by more than 180 degrees leads to an emergency mode of loss of synchronism. Especially dangerous is the “swinging rotor” mode of the SG when it is switched on for parallel operation and when the load is redistributed during parallel operation. In this case, loss of synchronism leads to a blackout, [10].

Unlike SG, the technological presence of the slip of the AG rotor relative to the field significantly increases the stability of the system of parallel running generators. At the same time, there are no restrictions on the number of generators operating in one network, which is confirmed by the experience of using AG in wind energy. The mode of turning AG on in parallel is not at all dangerous for generators, and if the phases do not coincide up to 90 degrees, the voltage drop does not exceed 30 %. At the same time, when the phase difference of the switched-on SGs is more than 60 degrees, the voltage drop exceeds 50 %, [1].

Fig. 3 showing the curves of transient synchronization processes: torques, rotational speeds, and the establishment of generator voltages with a phase difference of 90 degrees when switched. The synchronization torques *M1*, *M2* reach 5 nominal values, and the frequencies ω_1, ω_2 deviate by 5...7 %. The attenuation of the oscillations of the moments and frequencies with the inclusion in the parallel of the SG are continued 0.7 s, and for a similar inclusion of the AG, 0.2 s. The dynamic deviations of the modulus of the voltage vector U_m of the SG are + 50...-80 %, the process of voltage establishment lasts 0.35 s. When the AG is switched on, the voltage is deflected by +20...-30 % within 0.2 s.

If a non-excited, rotating with a synchronous frequency, another AG is connected to the AG, then synchronization will occur with a twofold moment, with a frequency deviation of 3 % within 0.2 s, the voltage drop will be 50 % within 0.15 s.

In this work, computer modeling of the AG and the SG operating modes was carried out using the software package developed by the authors for the study of dynamic processes in standard operating modes under the general name ASGEN [1, 8]. Nominal data of the used generators: АИР355М4 AG type with a power of 250 kW, 1490 rpm, 400V, 95.2 % efficiency and SG type 2CH59 / 39-4, 250 kW power, voltage 400 V, 1500 rpm, efficiency 92.2 %, the mechanical time constant of the diesel drive of both generators is 1 second.

Fig. 4, 5 shows the results of computer studies of the processes of turning on asynchronous and synchronous diesel generators for parallel operation at different phase differences and the same rotational speeds [1, 10]. Fig. 4 *a* and *b* show the processes of switching on for parallel operation with close angles of the phase difference of the SG before switching on. In Fig. 4 *a* the SG synchronization process is shown when there is no loss of synchronism. With a slight increase in the angle of the phase difference of the generators (see Fig. 4 *b*), the generator drops out of synchronism. These two processes differ significantly in energy performance. The process in Fig. 4 *b* is unacceptable or emergency, the deviation of its frequency $\Delta\omega$ and the dynamic moments M_d significantly exceed the similar process indicators in Fig. 4 *a*, [10].

A comparison of indicators of the processes of switching on synchronous (Fig. 4) and asynchronous (Fig. 5) diesel generators for parallel operation shows that the dynamic moment of synchronization M_d has a fundamentally different character.

For the AG in the worst case, it is close to the starting moment of the asynchronous machine, is 4 to 7 nominal values, but a short time is valid less than 0.1 seconds. The dynamic moment of synchronization decays in one period and the short duration of the moment does not lead to significant dips in the rotation frequency, as can be seen from Fig. 4, the maximum frequency of dynamic deviation of the rotational speed does not exceed 7 %, which is quite acceptable. When the SG is switched on for parallel operation, there is a range of phase difference values in which the generators fall out of synchronism, while the duration of the transient process and the failure of the rotation frequency sharply increase, see Fig. 4 *b* and *a*. The failure of the rotation speed reaches 15-17 %, and the synchronization process takes 2...5 seconds. The described advantages of AG provide their use as a means of improving the energy efficiency of autonomous electrical installations.

Fig. 6 shows an example of the use of asynchronous generators in a marine electric power plant: MSB, ESB, SB – main, emergency and local switchboard; ME, DE, EDE – main, auxiliary and emergency engine; EGB, AB – utilization and auxiliary boiler; T – turbine; TR – transformer; TC – thyristor converter; Cons – consumers of electricity; EG – emergency diesel generator; CB – block capacitors; AG – asynchronous generator; AM – asynchronous machine.

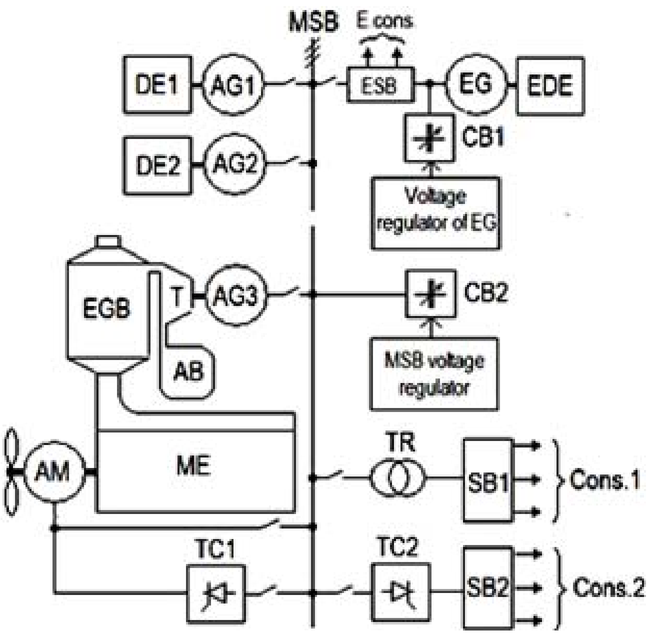


Fig. 6

A significant difference between the proposed control structure of a multi-generator power plant is the method of the voltage regulating the distribution switchboards with one regulator of the capacitance of the exciting capacitors CB. In this case, the AG generating sets are connected to the common buses with their stator windings and receive the necessary excitation current automatically, depending on the active power generated by them. In this way, the problem of reactive power distribution between generators is solved, which for synchronous generators is solved by matching the excitation regulators of each SG with the tuning parameter.

A feature of the proposed circuit is that the stabilization of the AG voltage by the capacitive current CB simultaneously compensates for the reactive power of each consumer of alternating current.

Significantly better overall dimensions of modern capacitors can reduce the installed capacity of synchronous machines. That is, if a capacitor unit is added to the composition of a traditional marine power plant with SG, then the full rated current of generators and automatic machines can be reduced by about 20%.

On ships, to increase the energy efficiency of the main engine, heat recovery from exhaust gases by a waste boiler and a turbo-generator is used, as well as power take-off by a shaft generator, see Fig. 5. In modern ships, a reversible electric machine is installed on the shaft of the main engine, which will act as a generator or electric motor, depending on the operating mode of the main engine. The best solution, in our opinion, is to use an asynchronous short-circuited AM machine, see Fig. 5.

Conclusions. A comparative analysis of the transient processes of the SG electric power plant with the load changes shows that the voltage recovery time in the SG is almost an order of magnitude longer than in the AG. An AG installation with optimal adjustment parameters of the excitation controller makes it practically invariant to load.

Analysis of transient processes of the load switching and switching on parallel operation for SG and AG diesel generator sets confirms the advantage of AG in the speed of the voltage control channel with the same characteristics of the frequency control channel.

The use of capacitor installations for dynamic compensation of reactive power in marine autonomous electric power systems opens up the possibility, firstly, of increasing the speed of the voltage regulation channel for SG by regulating the reactive current of the stator circuit, and secondly, simplifying the implementation of AG, which, as shown by a comparative analysis of the modes of operation with traditional SG, have advantages (constructive, energy, economic) and due to which they can be in the future present the main source of electricity for the vessel.

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ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ СУДНОВИХ ЕЛЕКТРОСТАНЦІЙ ШЛЯХОМ ВИКОРИСТАННЯ АСИНХРОННИХ ГЕНЕРАТОРІВ

Л.В. Вишневський , докт. техн. наук, **М.Й. Муха**, докт. техн. наук, **А.О. Дранкова**, канд. техн. наук

Національний університет «Одеська морська академія»,
вул. Дідріхсона, 8, Одеса, 65029, Україна

У статті розглядається один із способів підвищення енергоефективності суднових автономних електростанцій шляхом використання асинхронних генераторів з конденсаторним збудженням замість традиційних генераторних установок з синхронними генераторами. Проведено порівняльний аналіз перехідних процесів синхронної й асинхронної електроустановок для типових експлуатаційних режимів, який показав переваги асинхронних генераторних установок (конструктивні, енергетичні, економічні), завдяки яким вони можуть стати в майбутньому основними джерелами електроенергії на судні. Наведено графіки відповідних перехідних процесів. Бібл. 10, рис. 6.

Ключові слова: генерація електроенергії, синхронні та асинхронні генератори, порівняльний аналіз енергоефективності.

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ПОВЫШЕНИЕ ЭНЕРГОЭФФЕКТИВНОСТИ СУДОВЫХ ЭЛЕКТРОСТАНЦИЙ ПУТЕМ ИСПОЛЬЗОВАНИЯ АСИНХРОННЫХ ГЕНЕРАТОРОВ

Л.В. Вишневский, докт. техн. наук, **Н.И. Муха,** докт. техн. наук, **А.О. Дранкова,** канд. техн. наук
Национальный университет «Одесская морская академия»,
ул. Дидрихсона, 8, Одесса, 65029, Украина

В статье рассматривается один из способов повышения энергоэффективности судовых автономных электростанций посредством использования асинхронных генераторов с конденсаторным возбуждением вместо традиционных генераторных установок с синхронными генераторами. Проведен сравнительный анализ переходных процессов синхронной и асинхронной электроустановок для типовых эксплуатационных режимов, который показал преимущества асинхронных генераторных установок (конструктивные, энергетические, экономические), благодаря которым они могут стать в будущем основными источниками электроэнергии на судне. Приведены графики соответствующих переходных процессов. Библ. 10, рис. 6.

Ключевые слова: генерация электроэнергии, синхронные и асинхронные генераторы, сравнительный анализ энергоэффективности.

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