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REAL TIME COMPUTER TESTER FOR AUTOMATIC VOLTAGE REGULATORS USED IN MARINE GENERATORS

This article briefly introduces the characteristics of ships' electrical power networks, and an existing system is described as an example. A mathematical model of a selected power system, including generators with a drive and its loads, is presented. The algorithm implementing the author's numerical method, named 'the average step voltages method', is described. The chosen numerical method is notable for its stability and high accuracy, even in combination with a large integration step size. Software and hardware applications of the RT AVR tester are also shown. To check the adequacy of the simulations using the implemented model, experimental measurements were carried out. The measurements, including dynamic states, obtained by the computer tester with the AVR system, as well as the physical model with the AVR system, are summarized. Possibilities for usage in the marine industry in the future are also outlined.

KEYWORDS: synchronous generator, mathematical model, numerical method, real time

1. BRIEF INTRODUCTION TO SHIPS' ELECTRICAL POWER NETWORKS

The main electric energy sources on ships are three-phase synchronous brushless generators driven by diesel engines and adapted for parallel operation. Such systems are the simplest and most effective in terms of the required investment outlays and the reliable solution of the ship's electric plant [1, 2].

A ship's electric power network is usually a three-phase, three-wire, alternating-current network insulated from the ship's hull structure [2]. In medium voltage systems, an indirect earthing system (neutral point of generator grounded to ships hull by impedance) may be used.

The ship electric power network is fed from a voltage source of impedance on the order of 1/10 Ohm [1]. The network's impedance consists of the impedance of generators, transformers, cables and consumers. Its value is changeable over a

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wide range, mainly due to the switching on and switching off of generators and consumers that often have comparable power in relation to the available power, changing-over in the network etc. The ship's electric power network is a flexible ('soft') one. It is characterized by large changes of voltage and frequency, resulting from the comparable powers of the ship electric power plant and of switched-on consumers, such as thrusters, pumps and compressors [1].

Environmental factors are a separate group of factors that cause changes of voltage and frequency in the shipboard electric power networks. Electric and electronic devices operating in a marine environment are exposed to the influence of extreme external conditions such as high and low air temperature, salt mist, water wetting, high air humidity, vibrations, impacts and ship oscillations (rolling, pitching, etc.) [1].

In addition to ordinary energy consumers, there are also critical loads vital for the safety of navigation and the safety of ongoing offshore industrial processes. Any unexpected issues with those pose a risk to human life and may cause marine pollution and high-cost equipment damage.

Because of their significance to ensuring a continuous power supply of appropriate quality, automatic voltage regulators (AVRs) take an important part in that process by controlling the excitation current and proper reactive power distribution between running generators. A disproportional power distribution between generators working in parallel can cause an apparent overload of the ship's electric power plant and, consequently, the switching-off of less important consumers (trip of nonessential loads) or the even decay of supply (blackout) in the ship's electric power network [1].

The frequency and commonness of problems with the generators excitation circuits that the author has encountered and experienced during his professional sea service on over twenty different vessels lead to the research subject presented in this article.

2. DESCRIPTION OF AN EXAMPLE SYSTEM

Prior to use in a marine environment, any new equipment should be tested under safe inland conditions. The convenient way of implementing and verifying a new tester is to use the power station laboratory at the Department of Marine Electrical Engineering – Faculty of Electrical Engineering of Gdynia Maritime University. The laboratory plant reproduces a ships power plant with generators, loads, a main switchboard, electrical apparatus, measuring instruments, a power management system, non-essential load trip, etc. The most important components are:

- a marine main switchboard (RG103A),

- three synchronous generators of type GCf84a/4, 27 kVA each, manufactured by ELMOR and driven by DC machines controlled by 6 pulse thyristor rectifiers (emulating the characteristics of 4-stroke diesel engines),
- active and passive electrical loads [3].

A simplified block diagram of the laboratory power network is shown in the Fig. 1. In the drawing, only a marine network configuration has been presented (single or parallel operation of generators on common busbars and loads). However, it is worth mentioning that the laboratory allows one to perform tests in two other configurations: island network (simultaneous and independent operation of each generator on separated loads) and inland network (synchronization and cooperation with an existing supply network).

The voltage of generator no.1 can be optionally controlled by an analogue voltage regulator (TUR, manufactured by EFA) or a modern digital voltage regulator (DECS200, manufactured by BASLER ELECTRIC). One of machines can be used as a generator or, after switching off its drive and by-passing reverse power protection, it can be used as a synchronous motor (by manual adjusting of field current, we can use it for inductive or capacitive load).

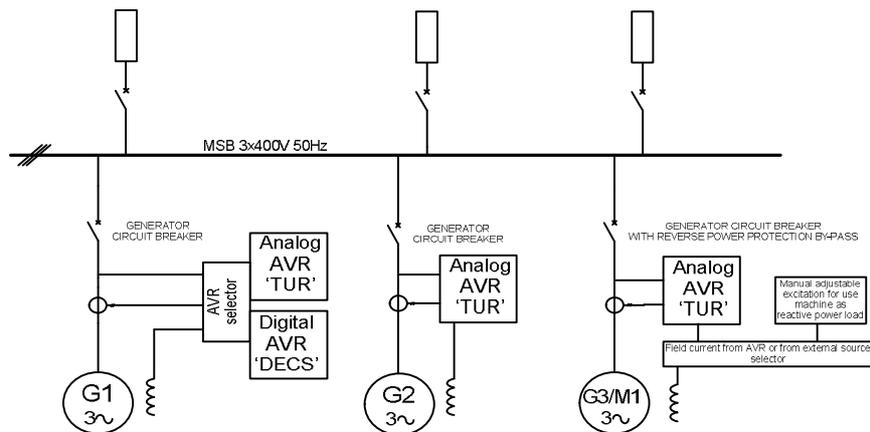


Fig. 1. Simplified block diagram of the laboratory power network

Generator excitation can be controlled by a Digital AVR DECS 200, which is a microprocessor-based excitation control system that contains all of the functionalities for limiting, controlling and protecting the generator from operating outside of the machine's capability. It incorporates a pulse width modulated power stage, which improves the system's performance in non-linear load applications [4].

Of the two types of voltage regulators available in the laboratory, the digital one was selected due to following factors: 1) currently, digital equipment is commonly used onboard vessels, 2) the digital voltage regulator has separate

terminals for measurement and power supply (it is not necessary to emulate high power signals) and 3) it uses standard signals (i.e., 4-20mA, 1A CT, RS 232) [3].

The power part of the presented laboratory system was chosen for implementation in the mathematical model.

3. THE MAIN PRINCIPLES OF POWER SYSTEM MATHEMATICAL MODELING

For the creation of a mathematical model of the power part of an electrical power generation system, the numerical one-step method of average voltages on the integration step is used [5]. According to this method, the equation for an electrical branch containing a source of e.m.f., inductance, capacitance and resistance, is written as:

$$\frac{I}{\Delta t} \int_{t_0}^{t_0 + \Delta t} (u + e - u_R - u_C - u_L) dt = 0, \quad (1)$$

where: u , e , u_R , u_C , u_L are – the instantaneous values of the applied voltage, e.m.f., voltages on resistance, ideal capacitor and inductance; t_0 is – the time value at the beginning of integration step; Δt is – the integration step value.

In accordance with (1) the equation for the electrical branch has been obtained [5], in which unknowns are the current of the branch at the end of integration step i_1 , and the average on the step value of the applied voltage U :

$$U + E - u_{R0} - u_{C0} + \left(\frac{R}{m+1} + \frac{\Delta t}{C} \cdot \frac{2 - (m+1)(m+2)}{2(m+1)(m+2)} + \frac{L_0}{\Delta t} \right) i_0 -$$

$$- \sum_{k=1}^{m-1} \left(\frac{R \Delta t^k}{(k+1)!} \cdot \frac{m-k}{m+1} + \frac{\Delta t^{k+1}}{C(k+2)!} \cdot \frac{(m+1)(m+2) - (k+1)(k+2)}{(m+1)(m+2)} \right) \frac{d^{(k)} i_0}{dt^{(k)}} -$$

$$- \left(\frac{R}{m+1} + \frac{\Delta t}{C(m+1)(m+2)} + \frac{L_1}{\Delta t} \right) i_1 = 0, \quad (2)$$

where: i_0 is – the branch current at the beginning of integration step; u_{R0} , u_{C0} are – the values of voltages on the resistance and capacitor at the beginning of the integration step; L_0 , L_1 are – the branch inductance at the beginning and at the end of the integration step; m is – the order of polynomial by which the current

is described on the integration step (the order of method); $U = \frac{I}{\Delta t} \int_{t_0}^{t_0 + \Delta t} u dt$ – the

average on the step value of the applied voltage.

As an example, in the case of the 2nd-order ($m = 2$) method used for the RL-branch with e.m.f, the next equation can be obtained from (3):

$$U + E - u_{R0} + \left(\frac{R}{3} + \frac{L0}{\Delta t} \right) i_0 - \frac{R\Delta t}{6} \frac{di_0}{dt} - \left(\frac{R}{3} + \frac{L1}{\Delta t} \right) i_1 = 0 \quad (3)$$

The mathematical model of the system is formed from the models of the typical elements that are represented as electric multipoles and are described by the external vector equation:

$$\vec{i}_e + G_{se} \frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \vec{v}_e dt + \vec{C}_{se} = 0 \quad (4)$$

where: \vec{v}_e – the vector of potential of the multipole's external poles; \vec{i}_e – the vector of currents of the multipole's external branches; G_{se} , \vec{C}_{se} – the matrix of coefficients and the vector of the absolute values.

The equation (4) is formed based on equation (2).

To form the models of electro-technical systems, the external branches of electrical multipoles are interconnected in the system's nodes. The relation between potentials of the multipole's external poles and potentials of the independent nodes of system, in accordance with [7], is described by equation:

$$\frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \vec{v}_e dt = \Pi^T \frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \vec{v}_c dt \quad (5)$$

where: Π is– the incidence matrix, that determines the manner of connecting the element's external branches to the independent system's nodes.

The averages on integration step values of potentials of the independent system's nodes $\frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \vec{v}_c dt$ are obtained from the vector algebraic equation:

$$G_{sc} \frac{1}{\Delta t} \int_{t_0}^{t_0 + \Delta t} \vec{v}_c dt + \vec{C}_{sc} = 0, \quad (6)$$

The coefficients of the equation (6) are defined based on the coefficients of the external vector equations (4) for all elements that form the system and their incidence matrices, from the formulas (7):

$$G_{sc} = \sum_{j=1}^L \Pi_j G_{sej} \Pi_j^T, \quad \vec{C}_{sc} = \sum_{j=1}^L \Pi_j \vec{C}_{sej} \quad (7)$$

where: L is – the number of elements in the system.

The algorithm of mathematical modeling is as follows. The coefficients of equation (6) are calculated based on the coefficients of the external vector equations (4) for all elements and their incidence matrices. From the equation (6) the average on the integration step values of potentials of the independent nodes of system are obtained. For every element from equation (5) the average on the integration step values of external pole potentials are obtained, and the currents of the external branches at the end of integration step are calculated from equation (4). Variables that describe electrical multipoles and are not the currents of external branches (if there are any) are determined from the internal equations of electrical multipoles.

In the case of the use of second and higher order of the method of average on the integration step voltages, it is necessary to obtain information about the derivatives of the branch currents. For calculation these derivatives, the principles of the theories of electro-technical systems mathematical modeling described in [6] have been used.

The mathematical model of synchronous machine is formed in accordance with the described approach in phase coordinates and includes the non-linearity of the magnetic circuits' characteristic, the influence of the rotor's damper system, and also gives an opportunity to research asymmetrical working regimes.

4. TECHNICAL IMPLEMENTATION OF THE COMPUTER TESTER

4.1. Software

For the development of the computer model the authorial object-oriented method [7] and the corresponding program complex (using C++) were used. According to this method the model of every element of the system is represented as an object in accordance with the principles of object-oriented design. A computer model is formed by the combination of the corresponding objects.

The software of the computer tester was developed with the use of C++ Builder in Windows. The main interface is shown in Fig. 2. In the computer model, there is a generator with its drive, active and passive loads, and other synchronous machines with manually adjusted excitation voltages. The control and power parts of the AVR are not included in the model. The program takes and sends data to and from the physical object by analog input/output cards.

The model allows one to load the generator with active or passive load and to connect another synchronous machine, G2, which can operate as a motor or generator.

When the program is running, there is a possibility of changing the system configuration (by opening or closing circuit breakers) as well as of changing particular load values or the G2 machine excitation. It is also possible to perform various types of short circuits: single-phase, double-phase and triple-phase short circuits.

An important feature of the developed computer model is the ability to cooperate in real-time mode with a physical object – the marine AVR. For this purpose, the calculated time in the model is constantly synchronized with real time. For the high performance time counting function, *QueryPerformanceCounter* is used in the model.

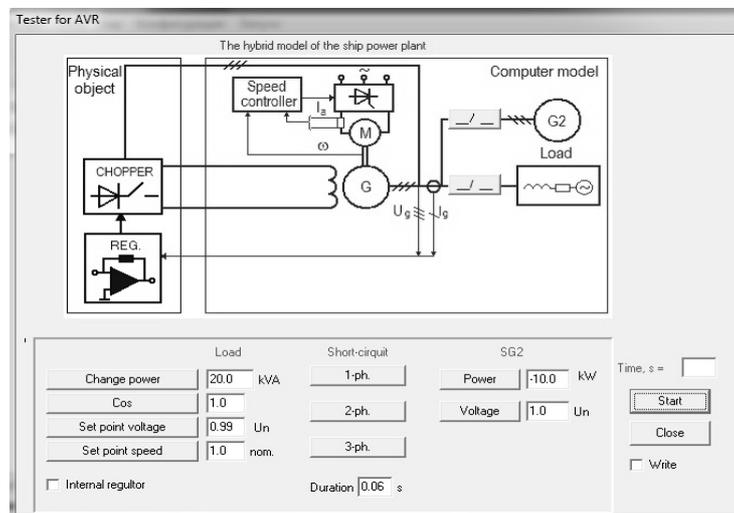


Fig. 2. Computer tester interface

4.2. Hardware

The application works on a PC, equipped with I/O cards manufactured by ADVANTECH: PCI-1727 and PCI-1712. One of the cards leads out the calculated generator values of current and voltage. These signals go to the AVR as voltage and current-sensing inputs. The other card measures the excitation current from the AVR output (converted down and separated by the LEM current transducer) and forwards it into the application. To make the implemented model cooperative with the real AVR, it is necessary to apply signal conditioning and to ensure galvanic separation. Therefore, APEX DC amplifiers are used: WN-21 for voltage and WP-05 for current. The block diagram of the hardware used is shown in Fig. 3.

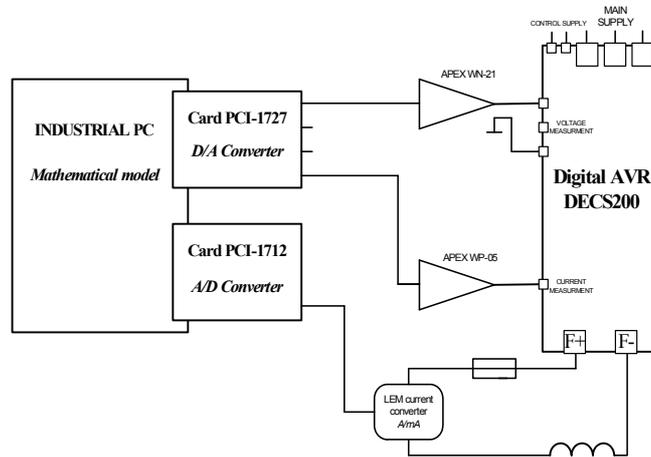


Fig. 3. AVR tester hardware

5. THE RESULTS OF RESEARCH

The research results for the main working regimes of the power station system are shown in Figs. 4-11 as the time dependencies of variables. On these figures, the results of the computer simulation with the help of the developed computer tester (a) are shown in comparison with the results of the experiment (b), which were obtained on the physical model (laboratory plant).

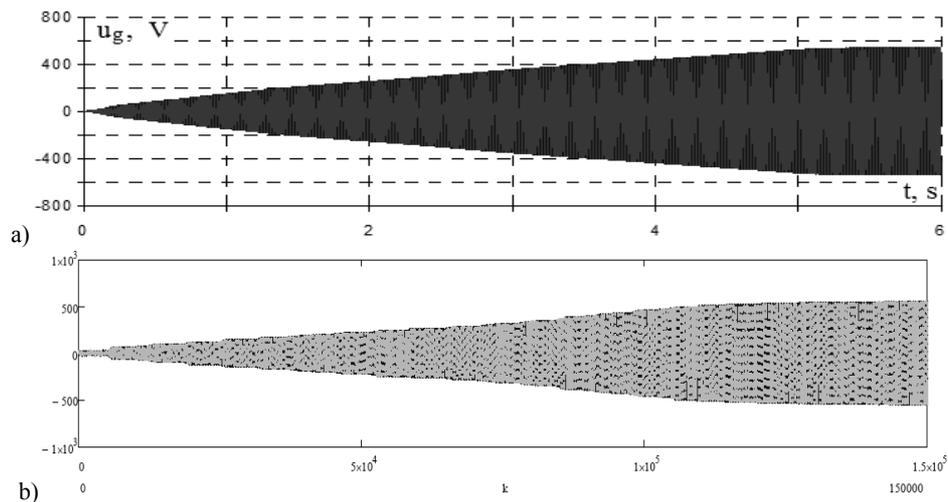


Fig. 4. Generator's output voltage (instantaneous values) during the initial excitation :
a – computer simulation, b – experiment (150000 point = 6 s)

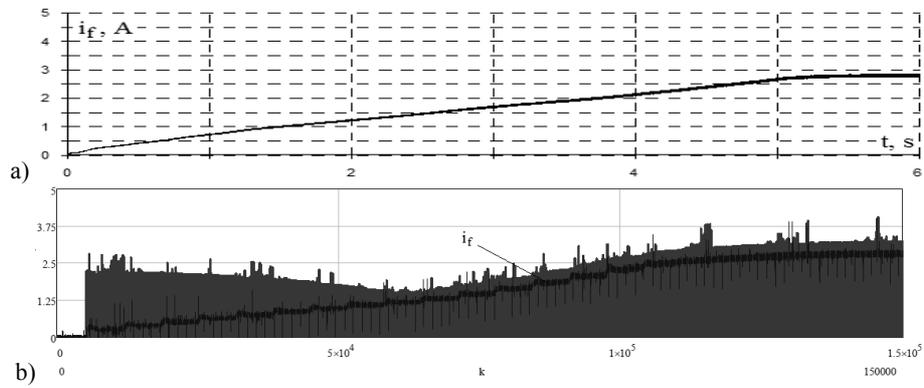


Fig. 5. Generator's excite current during the initial excitation: a – computer simulation, b – experiment (150000 point = 6 s).

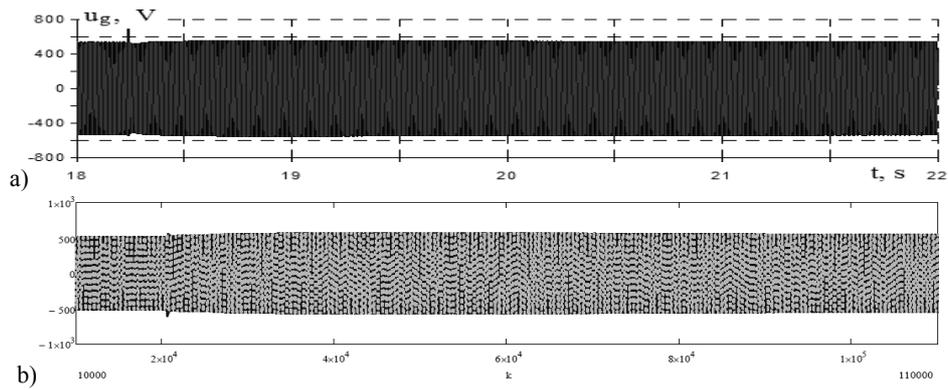


Fig. 6. Generator's output voltage (instantaneous values) during the load dropping: a – computer simulation, b – experiment (100000 point = 4 s)

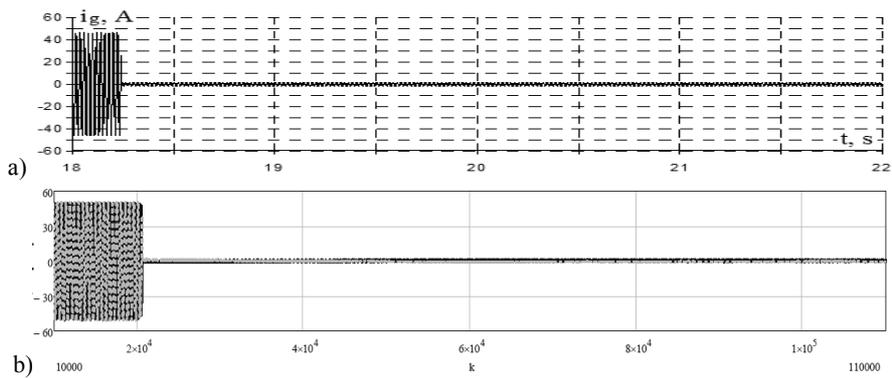


Fig. 7. Generator's stator current (instantaneous values) during the load dropping: a – computer simulation, b – experiment (100000 point = 4 s)

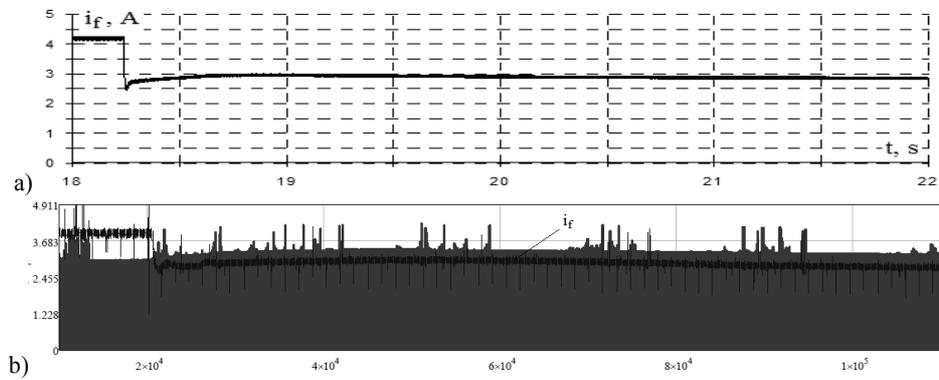


Fig. 8. Generator's excite current during the load dropping: a – computer simulation, b – experiment (100000 point = 4 s)

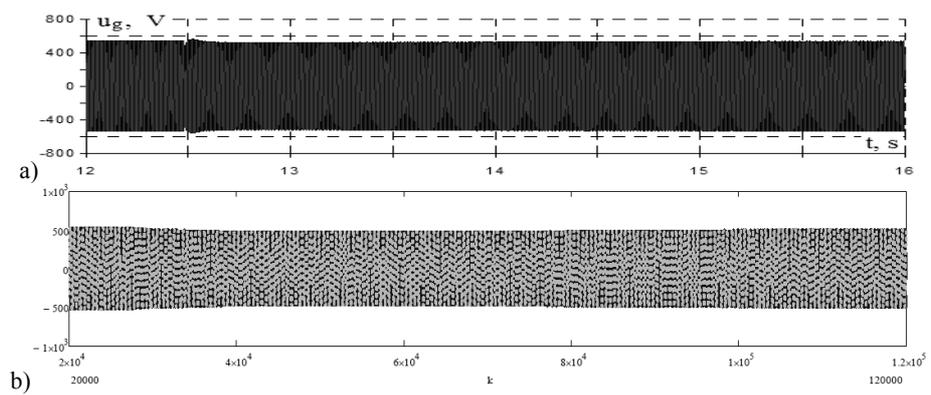


Fig. 9. Generator's output voltage (instantaneous values) during the load-on: a – computer simulation, b – experiment (100000 point = 4 s)

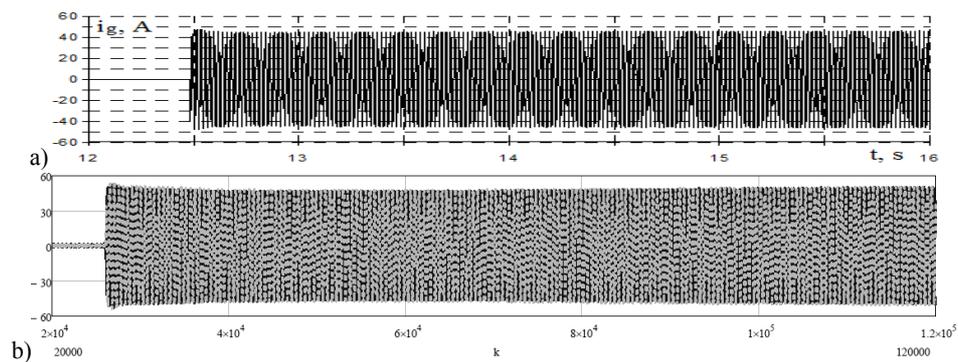


Fig. 10. Generator's stator current (instantaneous values) during the load-on: a – computer simulation, b – experiment (100000 point = 4 s)

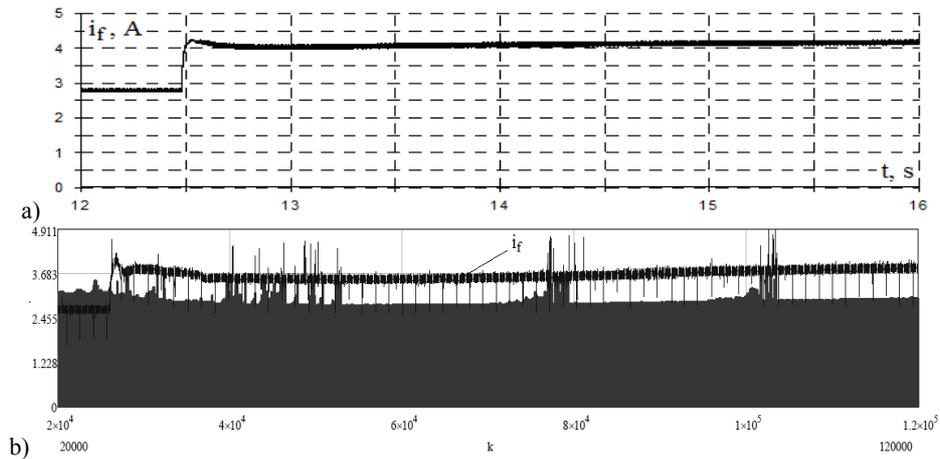


Fig. 11. Generator's excite current during the load-on: a – computer simulation, b – experiment (100000 point = 4 s)

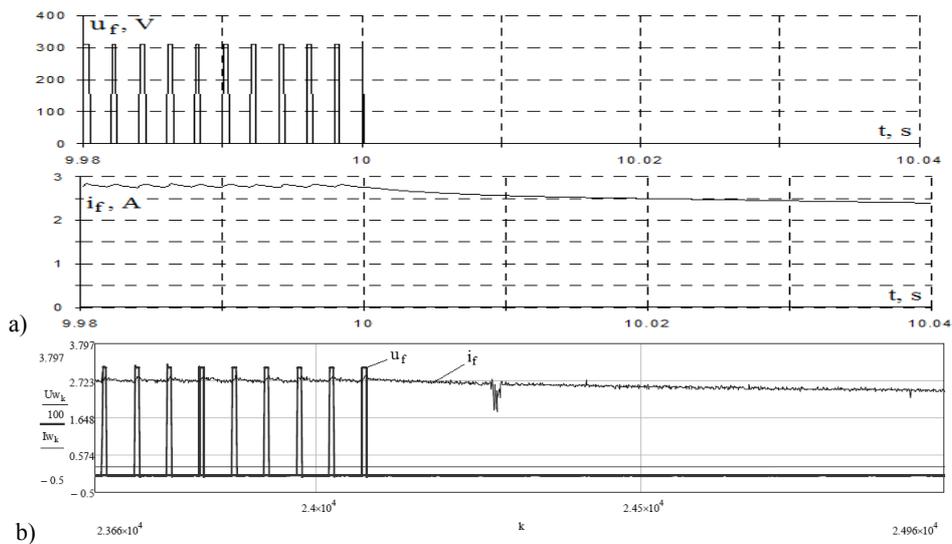


Fig. 12. Excite voltage u_f and current i_f in steady state regimes and after loss of excitation: a – computer simulation, b – experiment (100 point = 4 ms)

The comparison of computer simulation results and experimentally-obtained oscillograms demonstrates the high degree of coincidence in the level of instantaneous values. In particular, the maximum deviation is near 9%, and the average deviation is near 6%.

6. CONCLUSIONS

Diagnostics and settings tests of marine AVRs are reachable by using the developed tester (an application with the implemented real time model and signal conditioning equipment). The mathematical model of the synchronous generator presented in the article is the principal component of the tester and constitutes the most complex part of the network system model. The authorial numerical method provides stability and resistance to numerical method errors in long-duration operation. It allows fast solving of the mathematical model and enables real-time cooperation with a physical object (marine AVR). The adequacy of the computer model is confirmed by the comparison of simulation results to the results of the physical experiment in the laboratory plant.

After improving the tester and verifying its operation at sea, it could become useful for designing and implementing of new regulators, fault finding during the exploitation stage, periodic inspections (i.e., during shipyard overhauls), and finally personnel training and education.

LITERATURE

- [1] Mindykowski J., Assessment of Electric Power Quality in Ships Systems Fitted with Converter Subsystems, Polish Academy of Sciences, Shipbuilding & Shipping, Gdańsk 2003 (in English).
- [2] Wyzkowski S., Elektrotechnika Okrętowa, Wydawnictwo Morskie, Gdańsk 1991 (in Polish).
- [3] Bastian B., Plachtyna O., Mathematical Model of Synchronous Generator for Diagnostics and Settings Tests of Marine AVRS, Electrical Machines-Transaction Journal, no 4 part 2, KOMEL, Katowice 2013 (in English).
- [4] Instruction Manual for Digital Excitation Control System DECS200, Highland Illinois 2007 (in English).
- [5] Plakhtyna O.G. "The digital one-step method for simulated of electrical circuits and it use in electromechanical tasks", Visnyk NTU "HPI", NR 30, 2008, pp. 223-225. (in Ukrainian).
- [6] Plakhtyna O.G. The mathematical modeling of the electrotechnical systems with semiconductor converters. Lviv, 1986. (in Russian).
- [7] Kutsyk A.S. "The object-oriented method for analysis of electromechanical systems", Technical electrodynamics, NR 2, 2006, pp. 57–63. (in Ukrainian).

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