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SIMULATION OF DYNAMIC PROCESSES IN THE AUTONOMOUS ELECTRICAL POWER SYSTEM AT ASYNCHRONOUS MODE ONE OF SYNCHRONOUS GENERATORS

Annotation. The dynamic processes in the autonomous power system which arise at the transition of one of the parallel operating generators in asynchronous mode as a result of excitation winding power loss are investigated in this research. To create the mathematical models of processes in synchronous generators are used the well known Park-Gorev equations. The problem of simulation of dynamic processes in the power system of containership MSC Japan were solved, the time dependences of stator currents, active and reactive powers of synchronous generators are obtained. The measures to eliminate undesirable consequences of considered emergency situation are proposed.

Keywords: asynchronous mode, autonomous power system, synchronous generator, simulation, dynamic process.

Introduction. The synchronous generators (SG) are the main source of the electric power in autonomous electrical power systems (AEPS). One of emergency mode of parallel operation generators as a part of AEPS is transition one of them to an asynchronous mode. Information about the physical values, characterizing the dynamic processes at SG transition to the asynchronous mode is necessary to diagnose the AEPS emergency state and performing the necessary actions to eliminate it.

Asynchronous mode of SG occurs in case of power loss of excitation winding as a result of any fault in the excitation system or a short circuit in the power network. The transition of SG in asynchronous mode causes the fluctuations of the active and reactive power, at which the stator current is in several times higher than nominal one, whereby at the prolonged asynchronous mode an increased heating of the stator and rotor occurs, that may result in emergency situation. Therefore, the investigation of dynamic processes in AEPS at the transition one of the generators in asynchronous mode has significant theoretical and practical importance.

The main part. The mathematical and computer models of dynamic processes in the autonomous electrical power system in asynchronous mode of operation one of synchronous generators are the subject of research.

Features of an asynchronous operating mode of SG as a part of land electrical power system, its characteristics, the emergence reason, ways of identification are considered in [1,2]. Works [3,4] are devoted to the operation features of ship electrical power systems (SEPS), including automated ones and their elements. In [5] the reasons of danger of the SG asynchronous mode are considered. Works [6,7] are devoted to creation of the computer models, allowing to investigate the transition processes in SEPS with parallel working generators. Despite rather large number of the works devoted to consideration of an asynchronous operating mode of SG as a part of land, including thermal, electrical power systems, the problem of recognition and prevention of the mentioned mode in autonomous, including ship, electrical power systems, is still far from the full decision. Therefore the problem of modeling of dynamic processes in SEPS at loss of one of SG from synchronism taking into account a configuration of concrete SEPS is actual.

The purpose of the peaper is research of the dynamic processes arising at an asynchronous operating mode of one of synchronous generators as a part of ship electrical power system.

The asynchronous mode in SEPS is one of the most difficult emergency operation in which damage of the equipment, violation of power supply of consumers and undesirable development of emergency process with possible serious consequences for electrical power objects is possible [8].

Process of SG transition to the asynchronous mode happens in the following sequence: at disappearance or considerable reduction of current in a excitation winding of the generator the excitation magnetic flux and corresponding to it the synchronous electromagnetic torque on a generator shaft decrease. At some value of excitation current, the value of the synchronous electromagnetic moment becomes less than the rotating moment of the diesel and the generator, continuing to remain in the power network, drops out of synchronism. For maintenance of a magnetic field the generator starts to consum the magnetizing current from the network. Owing to violation of balance between the rotating moment of the diesel and the electromagnetic (braking) torque of the generator, the frequency of the unit rotation starts to increase. The increase of unit frequency rotation leads to the followinf phenomenon: the rotor of the generator rotates quicker, than a magnetic field of the stator, and in rotor contours there are alternating currents having slip frequency s_f. Interaction of the currents, induced in a rotor contours, with the main stream of the stator, creates the asynchronous electromagnetic moment on a generator shaft, braking a rotor [3].

Mathematical modeling of the dynamic processes, arising at the parallel operation of synchronous generators as a part of SEPS, is carried out on the basis equations of Park-Gorev (EPG) of the following look [7]:

$$\begin{cases} p\psi_d = u_d + (1+s)\cdot\psi_q - R_s \cdot i_d \\ p\psi_q = u_q + (1+s)\cdot\psi_d - R_s \cdot i_q \\ p\psi_f = u_f - R_f \cdot i_f \\ p\psi_{\ddot{A}d} = -R_{\ddot{A}d} \cdot i_{\ddot{A}d} \\ p\psi_{\ddot{A}q} = -R_{\ddot{A}q} \cdot i_{\ddot{A}q} \\ ps = \left[M_{\ddot{A}\grave{E}\c{C}} - (i_d \cdot \psi_q - i_q \cdot \psi_d) \right] / T_j \\ p\theta = s \end{cases} \qquad (1)$$

where u_d and u_q – stator voltage; $(i_d \cdot \psi_q - i_q \cdot \psi_d) = M_{C\Gamma}$ – the electromagnetic torque of the synchronous generator, creating resistance to rotation; T_j – mechanical time constant of "SG + driving engine"; $\psi_q, \psi_d, \psi_f, \psi_{\ddot{A}d}, \psi_{\ddot{A}q}$ – windings flux linkages of model SG, which are defined by equations:

$$\begin{cases} \psi_d = x_d i_d + x_{ad} i_f + x_{ad} i_{\ddot{A}d}, \\ \psi_q = x_q i_q + x_{aq} i_{\ddot{A}q}, \\ \psi_f = x_d i_d + x_f i_f + x_{ad} i_{\ddot{A}d}, \\ \psi_{\ddot{A}d} = x_{ad} i_d + x_{ad} i_f + x_{\ddot{A}d} i_{\ddot{A}d}, \\ \psi_{\ddot{A}q} = x_{aq} i_q + x_{\ddot{A}q} i_{\ddot{A}q}, \end{cases} \qquad (2)$$

where x_{ad} – mutual induction resistance of SG on a longitudinal axis d;
x_{aq} - mutual induction resistance of SG on a cross axis q;
x_s – dispersion inductive resistance of the stator windings;

x_f – dispersion inductive resistance of the excitation winding;
$x_{Дd}$, $x_{Дq}$– dispersion inductive resistance of the damping windings on axes d and q;
R_s, R_f, $R_{Дd}$, $R_{Дq}$ – active resistances of SG windings.

Full inductive resistances of windings are equal to the sum of inductive resistances of mutual induction and inductive resistance of dispersion:

$$x_d = x_{ad} + x_s,\ x_q = x_{aq} + x_s,\ x_f = x_{ad} + x_{\sigma f},$$
$$x_{Äd} = x_{ad} + x_{\sigma Äd},\ x_{Äq} = x_{aq} + x_{\sigma Äq}. \qquad (3)$$

If as a result of EPG solution, for example, currents i_d and i_q, are obtained, then the curerent i_A of a phase A of the physical generator will be defined by the next eqution

$$i_A = i_d \cos(\gamma_0 + \omega_c t) - i_q \sin(\gamma_0 + \omega_c t), \qquad (4)$$

where ω_c – current frequency in power network; t – physical time;
γ_0 – initial angle (when t=0) between axes d and q.

The rotating diesel torque $M_{ДИЗ}$ in the system (1) has to be expressed in relative units:

$$\grave{I}_{\ddot{a}\grave{e}\c{c}} = \frac{\grave{I}_{\ddot{a}\grave{e}\c{c}.\hat{o}\,\grave{e}\c{c}}}{\grave{I}_{\tilde{n}\tilde{a}.\acute{i}\,\hat{i}\,\grave{i}}} \qquad (5)$$

From system (2) the windings currents are expressed through the flux linkages by formulas:

$$\begin{cases} i_d = \dfrac{x_f x_{yd} - x_{ad}^2}{D_d}\psi_d - \dfrac{x_{ad}x_{\sigma Äd}}{D_d}\psi_f - \dfrac{x_{ad}x_{\sigma f}}{D_d}\psi_{Äd}, \\ i_q = \dfrac{x_{Äq}}{D_q}\psi_q - \dfrac{x_{aq}}{D_q}\psi_{Äq}, \\ i_f = \dfrac{x_d x_{Äd} - x_{ad}^2}{D_d}\psi_f - \dfrac{x_{ad}x_{\sigma Äd}}{D_d}\psi_d - \dfrac{x_{ad}x_s}{D_d}\psi_{Äd}, \\ i_{Äd} = \dfrac{x_f x_d - x_{ad}^2}{D_d}\psi_{Äd} - \dfrac{x_{ad}x_{\sigma}}{D_d}\psi_d - \dfrac{x_{ad}x_s}{D_d}\psi_f, \\ i_{Äq} = \dfrac{x_q}{D_q}\psi_{Äq} - \dfrac{x_{aq}}{D_q}\psi_q, \end{cases} \qquad (6)$$

where $D_d = x_d x_f x_{Äd} + 2x_{ad}^3 - x_{ad}^2(x_d + x_f + x_{Äd})$, $D_q = x_q x_{Äq} + x_{aq}^2$.

At processes in SG modeling according to EPG (1) as the variables of integration the flux linkages $\psi_q, \psi_d, \psi_f, \psi_{Дd}, \psi_{Дq}$ are used. Therefore in (1) all currents have to be changed according to (6). At the EPG solving, the values of flux linkages $\psi_q, \psi_d, \psi_f, \psi_{Äd}, \psi_{Äq}$ will be obtained. Recalculation of the flux linkages into the currents is carried out on formulas (6).

For research of an asynchronous operating mode one of parallel working generators as a part of SEPS it is necessary to reduce the Park-Gorev equations of one generator to another one [1,3]. Rotors of parallel operating SG have no among themselves a rigid connection, rotate with different frequencies and hold various positions in space, therefore axes d_1-q_1, d_2-q_2 are incoincident. There are angles between d-q axes of parallel working SG, which we will designate as δ. For combination EPG of parallel working SG in one equations system it is necessary to add them with the communication equations which are the functions of angles δ. The model of the leading SG1 generator is the system of EPG (1) and equations of flux linkages definition (2) in which the following change of indexes is made: d → 1d and q → 1q . The stator currents and voltages in model have designations: $i_{1d}, i_{1q}, u_{1d}, u_{1q}$. The components of the power network voltage u_{Cd} and u_{Cq} are accepted as the equal components u_{1d} and u_{1q} of SG1 voltage. Under this voltage there are load consumers of power plant and at known load the components i_{Hd}, i_{Hq} of its current are determined, which are attached to axes d_1-q_1 of SG1 (Fig.1).

The model of the conducted SG2 generator is the system of EPG (1) and eqations of flux linkages (2) determination in which the following change of indexes is made: q → 2q and d → 2d. The stator currents and voltages in the model are marked as $i_{2d}, i_{2q}, u_{2d}, u_{2q}$. SG2 is connected to the tires of the main switchboard (MS), that is common with SG1, and participates in creation of current in load which we designate as complex value $\dot{I}_{2H}$. SG1 also creates the current in load, which we will designate as complex value $\dot{I}_{1H}$. Total complex load current $\dot{I}_H$ is the sum of the specified currents: $\dot{I}_H = \dot{I}_{1H} + \dot{I}_{2H}$. It is possible to summarize the complex currents with the assumption that electric phases of the summand currents are counted rather common coordinate axes. For this purpose it is necessary to enter the blocks of currents i_{2d} and i_{2q} reduction, calculated on the SG2 model in axes d_2-q_2, to equivalent currents in axes d_1-q_1.

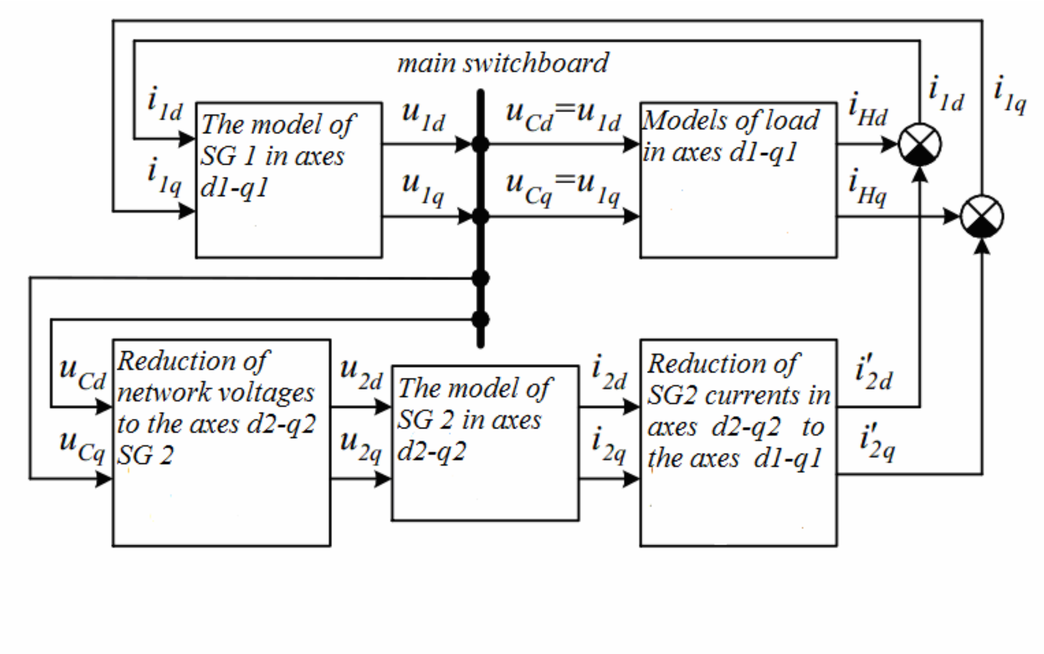

Fig. 1. The block diagram of SEPS with parallel operating SG

To derivate the reduction formulas we consider the generalized current vector $\dot{I}_2$ from paires of axes d_1-q_1 and d_2-q_2 (Fig.2). Projections $\dot{I}_2$ to the axes d_2-q_2 are currents i_{2d} and i_{2q}, which are the valid currents, calculated from the SG2 model in axes d_2-q_2. Projections $\dot{I}_2$ to the axes d_1-q_1 are currents i_{21d} and i_{21q}, which are fictitious currents. The $\dot{I}_2$ current vector is common for the pairs of currents i_{2d} – i_{2q} and i_{21d} – i_{21q}. Therefore, the pair of currents i_{2d} – i_{2q} are changed by the pair of currents i_{21d} – i_{21q}.

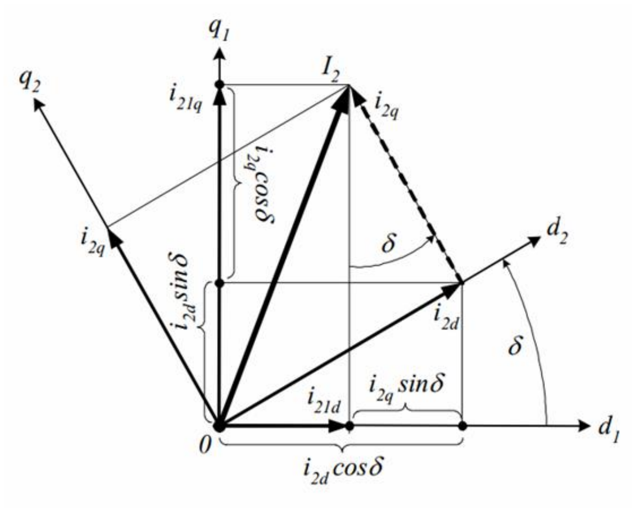

Fig. 2. The vector diagram of SG2 currents reduction to SG1 ones

Rotors of parallel operating generators are rotate nonsynchronously, therefore, there are angle δ between axes d_1-q_1 and d_2-q_2. At the values of slidings s_1 and s_2, founded from the SG1 and SG2 models, the angle δ can be find from the equation:

$$\delta = \int (s_2 - s_1) dt. \qquad (7)$$

At computer modeling instead of (7) the equivalent differential equation in a normal form is used:

$$\frac{d\delta}{dt} = s_2 - s_1. \; (8)$$

The formulas of SG2 current reduction, defined in axes d_2-q_2, in the currents in axes d_1-q_1 follow from the constructions given on Fig. 2:

$$\begin{cases} i_{21d} = i_{2d}\cos\delta - i_{2q}\sin\delta \\ i_{21q} = i_{2d}\sin\delta + i_{2q}\cos\delta \end{cases} \quad \text{or} \quad \begin{vmatrix} i_{21d} \\ i_{21q} \end{vmatrix} = \begin{vmatrix} \cos\delta - \sin\delta \\ \sin\delta + \cos\delta \end{vmatrix} \cdot \begin{vmatrix} i_{2d} \\ i_{2q} \end{vmatrix} \qquad (9)$$

For reduction of currents i_{21d} and i_{21q}, founded from the SG2 model in relative units, to the currents in relative units of the SG1 model it is necessary to take into account the reduction coefficient of SG rated full power, which equals:

$$K_S = \frac{S_{\text{Í Î Ì .ÑÃ1}}}{S_{\text{Í Î Ì .ÑÃ2}}}. \qquad (10)$$

The currents of the conducted SG2, reduced to SG1, are determined by formulas:

$$\begin{cases} i'_{2d} = K_S \cdot i_{21d}, \\ i'_{2q} = K_S \cdot i_{21q}. \end{cases} \qquad (11)$$

Then SG1 current components can be found in the load current:

$$i_{1d} = i_{Hd} - i'_{2d}, i_{1q} = i_{Hq} - i'_{2q}. \qquad (12)$$

These currents are input of SG1 model. Similar to currents, it is necessary to reduce the voltages u_{Cd} and u_{Cq}, which are calculated in axes d_1-q_1, to the voltages u_{2d} and u_{2q} in axes d_2-q_2, in which SG2 is modeled:

$$\begin{vmatrix} u_{2d} \\ u_{2q} \end{vmatrix} = \begin{vmatrix} \cos\delta - \sin\delta \\ \sin\delta + \cos\delta \end{vmatrix} \cdot \begin{vmatrix} u_{Cd} \\ u_{Cq} \end{vmatrix}. \qquad (13)$$

Voltages u_{2d} and u_{2q} are input of the SG2 model and are used in EPG, describing this generator.

For numerical realization of the mathematical models (1), (2), (12), (13) and models of responsible ship's electric power consumers by the means of visually oriented toolbox Simulink of MATLAB (version R2012b), the computer model of containership MSC Japan SEPS is developed (Fig. 3). Subsystem "Load" models operation of induction motor drives of the most responsible ship consumers. Computer modeling of dynamic processes is carried out in the loaded SEPS therefore for adequate representation of the real phenomena the preliminary initialization of models of the electrical machines which are a part of the developed model is carried out. In the process of computer modeling loss of power of SG2 excitation winding in a timepoint of 3 seconds and its resumption in a timepoint 6 s was imitated. As a result of the carried out imitating modeling oscillograms of relative values of active and reactive powers of synchronous generators (Fig. 4 – Fig. 7) and the current components of stators on longitudinal and cross axes are obtained.

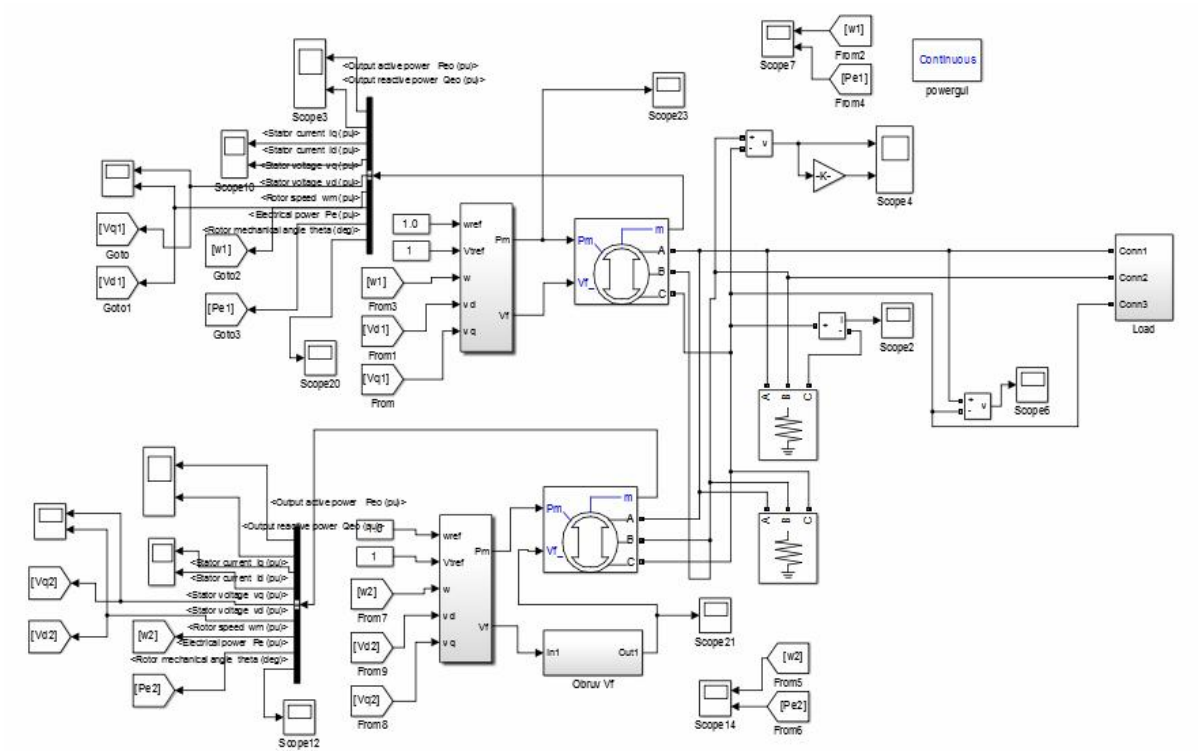

Fig. 3. Computer model for research of dynamic processes in transition one of parallel operating SG in the asynchronous mode

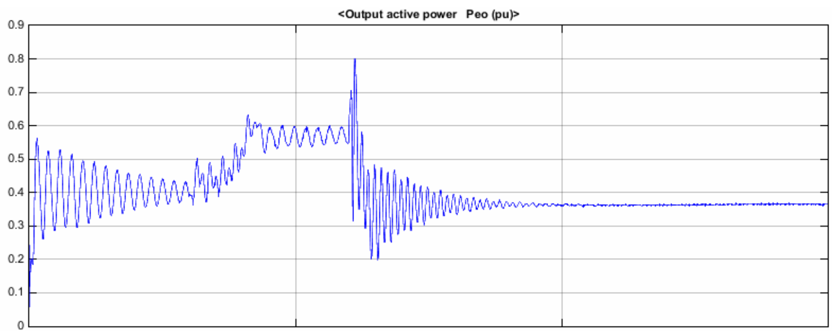

Fig. 4. The time dependence of the SG1 active power

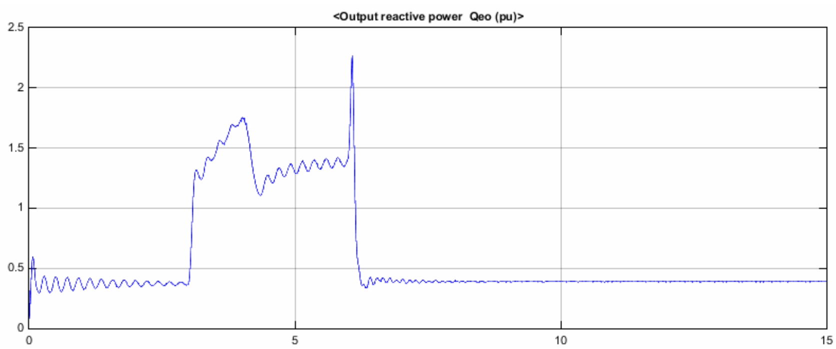

Fig. 5. The time dependence of the SG1 reactive power

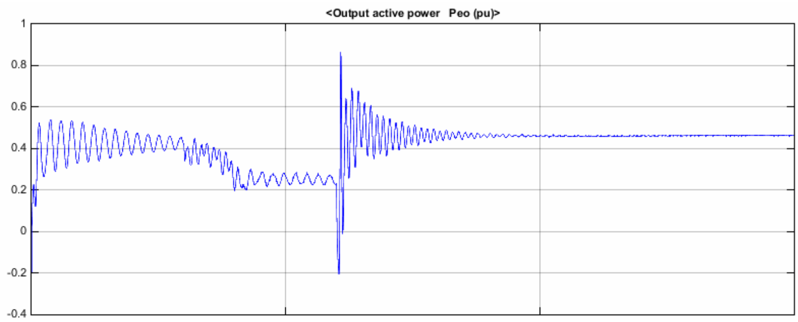

Fig. 6. The time dependence of the SG2 active power

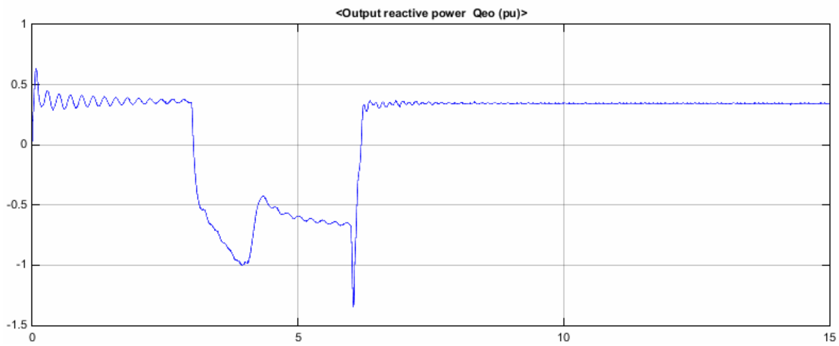

Fig. 7. The time dependence of the SG2 reactive power

Conclusion. The obtained results of computer modeling of dynamic processes in SEPS allow to propose the technical solutions directed on identification of the asynchronous mode of parallel working SG as a part of SEPS and elimination of consequences of this mode by connection of alternative power supplies that, in turn, will allow to increase the operational reliability of SEPS. Prospects of further researches consist in research of operational reliability of autonomous electrical power systems of different purposes.

REFERENCES

1. Электрическая часть станций и подстанций / Под. ред. А.А. Васильева. – М.: Энергия, 1980. – 608 с.

2. Мелешкин Г.А. Устойчивость энергосистем. Книга 1 / Г.А. Мелешкин, Г.В. Меркурьев. – СПБ, 2006. – 289с.

3. Краснов В.В. Основы теории и расчета судовых электроэнергетических систем: Моделирование для исследования специальных режимов / В.В. Краснов, П.А. Мещанинов, А.П. Мещанинов. – Л.: Судостроение, 1989. – 328 с.

4. Эксплуатация электроэнергетических систем морских судов: Справочник / О.П. Хайдуков, А.Н. Дмитриев, Г.Н. Запорожцев. – М.: Транспорт, 1988. – 223 с.

5. Эксплуатация генераторов и синхронных компенсаторов [Электронный ресурс]. – Режим доступа: www.motor-remont.ru/books....

6. Толстов А.А. Параллельная работа синхронных генераторов с возможностью регулирования коэффициента мощности / А.А. Толстов, В.В. Лещенко, Е.С. Логвиненко // Судовые энергетические установки. – Одесса, 2008. – Вып.22. – С. 54–66.

7. Геллер Б.Л. Моделирование параллельной работы судовых синхронных генераторов в пакете VisSim / Б.Л. Геллер, Н.В. Сулименко // Известия Калининградского государственного технического университета. – 2010. – № 18. – С. 160–166.

8. Совалов С.А. Противоаварийное управление в энергосистемах / С.А. Совалов, В.А. Семенов. – М.: Энергоатомиздат, 1988. – 416 с.

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