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Development of the system of preemptive control over excitation of a synchronous generator to reduce voltage dips when starting-up asynchronous motors

***Abstract**. The necessity of preliminary estimation of the value of voltage dip arising at starting-up of asynchronous motor commensurate in power with operating diesel-generator sets as part of the ship electric power system is justified. The model of ship electric power system with a modified in real-time mode configuration is developed. The process of direct starting-up of asynchronous motor is simulated, and the values of voltage dips for various values of voltage and time of excitation boost of the synchronous generator are determined. It is established that there are optimum values of the magnitude and time of boosting of excitation voltage of the synchronous generator, where voltage dip in the network is minimal. The obtained results enable assessing in the process of monitoring and management of ship electric power system of the possible consequences of direct starting-up of asynchronous motor on the network voltage under current conditions, and based on them deciding on whether to connect the additional diesel generator to the network or disconnect the least essential consumers of electricity from the network to provide generated capacity reserve.*

Streszczenie.** Zbadano możliwości zapadu napięcia w systemie okrętowtm generatora współpracującego z silnikiem diesla. Symulowano generator asynchroniczny podłączony do sieci dla różnych warunków startu. Określono optymalna wartość napięcia wspomagającego zapewniającą minimalne zapady napięcia. **System wyprzedzający sterowania wzbudzeniem generatora synchronicznego umożliwiający zredukowanie zapadów napięcia podczas startu silnika asynchronicznego

Keywords: voltage dip, preemptive control, excitation boost, ship electric power station, power quality.
Słowa kluczowe: elektryczna sieć okrętowa, zapady napięcia, generator synchroniczny.

Introduction

One of indicators of quality of electric power in ship electric power systems are characteristics of voltage dips. The quality of electric power has a great influence on the course of technological processes: operation of electric motors of various mechanisms, microprocessor facilities, automated control systems of the production process and telecommunication systems in the event of significant voltage dips may be disturbed for a while. One of the reasons for occurrence of voltage dips is a change in loading of the ship electric power system (SEPS), among which the most significant effect is provided by asynchronous motors (AM). Since starting current of asynchronous squirrel-cage motor is inductive (power factor at starting up is 0.15 – 0.20) and exceeds the rated current by 5-7 times, it effects the synchronous generator performing demagnetizing action, which at high power of the motor is not always compensated by magnetizing force created by excitation winding of the synchronous generator. In order to reduce starting currents and, consequently, to reduce voltage fluctuations, special methods of starting of AM may be used. Such methods include starting with reactive and active resistance in stator circuit, starting with autotransformer, with star-delta transition of windings of the motor stator using a soft starter. It is also possible to connect AM to the network after providing a sufficient power reserve in the network by connecting additional diesel generator to the network or disconnecting the least essential consumers of electric power. Since the first variant of reduction of starting currents requires for special switching equipment and performance of additional installation work, the peculiarities of application of the second variant are considered in this paper.

The use of software (SW) as a top-level subsystem of the automated control system for SEPS allows at each moment to determine the structure of the power plant and load per each of the diesel generator sets (DGS) operating in parallel. This enables estimation of the magnitude of voltage dip after its connection to the network before switching on of asynchronous motor commensurate in power to operating generator sets. If based on the data received the value of voltage dip appears unacceptably high, the decision is made on whether it is necessary to include additional DGS for parallel operation to provide generated power reserve.

The objective of this paper consists in development of the structural scheme of system of preemptive control over excitation of the synchronous generator in order to reduce voltage dips during direct starting up of asynchronous motor, and also, based on simulation studies, in estimation of voltage dip value and determining of the optimum values of voltage and time for boosting of excitation of the synchronous generator, where minimum voltage dip is observed.

For achievement of this objective, it is necessary:

1. To analyse publications, where the latest findings of researches in the field of electric power industry are presented, in particular, the problem of appearance of voltage dips that arise at the direct starting of asynchronous motors is considered in order to determine how to reduce them. To justify the need for a preliminary estimate of the magnitude of voltage dip occurring when directly starting asynchronous motor commensurate in power to operating diesel generator sets. To assess possibility of using the system of preemptive control over excitation of the synchronous generator in order to reduce the magnitude of voltage dips during direct starting-up of asynchronous motors.

2. To develop structural scheme of the system of preemptive control over excitation of the synchronous generator. To develop the simplified model of ship electric power system to study the preemptive control system and to determine the perspectives of its use in real ship electric power systems as a means of information support of operator's actions.

3. To simulate the process of direct starting-up of asynchronous motor. Based on simulation, to determine the optimum values of magnitude and time for boosting of excitation voltage of the synchronous generator, where minimum voltage dip is observed.

Analysis of publications on research topic

The direct starting-up of asynchronous motor in ship electric power system has a number of negative consequences for both asynchronous motor [1, 2] and for other consumers. The direct starting-up of asynchronous motor has a particularly strong effect on voltage dips in ship's network [3]. If the value and duration of the voltage dip caused by starting-up of AM are higher than values stipulated by settings of the protection systems, this may lead to activation of the protection systems and de-energization of the power plant [4], since such situation may be erroneously identified as a short circuit.

The detailed study of the process of direct starting-up of asynchronous motor based on simulation was carried out in [5], but the results obtained in [5] refer to the mode of starting-up of unloaded asynchronous motor. At the same time, the issues of effect of the direct starting-up of asynchronous motor on the electric power source are also not considered. Under conditions of ship electric power systems with limited generated power, direct starting-up of engine will lead to a significant voltage dip. This will negatively affect consumers connected to the network. On ships and drilling platforms, asynchronous motors are used as part of pumps. Their power is often commensurate to power of generators. For reduction of voltage dips when directly starting-up asynchronous motor, special soft starter systems are used.

Power-up sensor of starting-up of asynchronous motor allows selection of starting mode, which is the most suitable in certain conditions of engine operation. In paper [6], a power-up sensor for soft starters of asynchronous motors is considered. It is noted that according to technical requirements the starting process should not exceed 12 seconds. During starting-up of asynchronous motor, a linear increase in starting voltage occurs according to the law generated by regulator. However, the author considered the case of a constancy of supply voltage, and did not consider the influence of starting-up process on the characteristics of mains voltage.

In paper [7], a comparative analysis of transient processes in asynchronous machine under various initial conditions of a soft start is made. However, issues relating to starting-up boundary conditions are not considered, when starting-up time is minimal, and engine power and load are maximal. The studies related to the process of starting-up of asynchronous motors are often conducted under idealized conditions, without considering the influence of other asynchronous motors operating in the network, transformers, and cables.

In paper [8], the problem of propagation of voltage dips over the network is considered taking into account the presence of transformers, and namely, the means of connection of their windings. In this case, short circuit is considered as a source of voltage dips. However, voltage dips may occur when starting-up powerful asynchronous motors. In this case, the magnitude of dip and its duration are determined by the power, type, and size of load of asynchronous motor. As shown in [9], voltage analysis at starting-up of engine allows detection of the presence of short circuit in rotor, which is very important for timely detection and elimination of this problem. Such a system, together with additional system of estimation of the magnitude of voltage dip at starting-up of AM, can be used to ensure reliable functioning of the entire power system. The method of calculation proposed in paper [10] enables selection of the required law of control over the process of starting-up of AM, where in rotor and stator circuits thyristors and resistors are used. This way of starting-up leads to fluctuations in engine speed and electromagnetic torque. However, the author does not also address the issues related to the effect of starting-up of engine on the magnitude of voltage dips in network, but only diminution of the parameters of asynchronous machine during starting-up is considered. Therefore, the issue of investigation of the influence of AM starting-up on voltage characteristics of the network and of search for methods of reduction of voltage dips remains urgent.

The case of isolated synchronous generator and effect of direct starting-up of asynchronous motor on the magnitude of voltage dip is considered in [11]. The author proposes to use commutated capacitors for reduction of the magnitude and duration of voltage dips, but this does not take into account the influence of other motors and generators, which may be connected to the network. In addition, installation of switched capacitors on each engine is associated with high economic costs and increase in weight and dimension parameters of the entire system. One of the ways to prevent propagation of voltage dips across network is to localize them [12, 13]. It is assumed that voltage dip is caused by a short circuit and is an emergency. After the fault location is detected, the damaged network segment is disconnected, and problem is localized. However, if voltage dip is caused by direct starting-up of asynchronous motor, in this case exactly turning off the segment of network where asynchronous motor is located will lead to emergency situation. In particular, voltage dips occurring at the same time will lead to significant financial losses and disturb operation of various equipments connected to the network [5]. For ship electric power systems, these are navigation equipment, computers, microprocessor automation systems, communication systems. In order to reduce voltage dips, active compensators such as dynamic voltage restorers (DVRs) [14] are used. Such compensators are of high cost, and soft starters for asynchronous motors are also used with them. Flexible AC transmission systems are now successfully used to reduce financial losses due to voltage sags [15]. Matlab Simulink may successfully apply for simulation of different topologies of electric power systems [16].

It is shown in [12, 13, 17, 18] that determination of the voltage dip source may be performed by various methods according to such criteria as magnitude of energy, resistance, voltage, or current. The methods proposed in [17, 18] use information on current to determine the source of dip. Simulation results confirm accuracy and correctness of the method. However, this method applied to the regional network, and network capacity was assumed to be infinitely large (considerably exceeding the load power). Starting-up of AM does not result in such significant voltage dips in such network as in ship's network.

Along with the considered ways of reduction of voltage dips on the part of asynchronous motor, as well as of localization of sources of such dips, other control methods may be used. In particular, the method of preemptive control over excitation of the synchronous generator is promising. At present, microprocessor systems are used to control excitation of the synchronous generator, where algorithms of digital signals processing are applied [19, 20]. Also, fuzzy PID controllers [21] are successfully employed, which change their parameters depending on the external conditions to provide the given quality of generator excitation control. Ship electric power system is a composed multi-unit system. Under such conditions synchronous generators operate dynamically, as consumers are constantly switching. As shown in [22], the use of adaptive controllers for stabilization of power supplied by generators and, consequently, the entire power system, is expedient. However, there is no preemptive control circuit in all of the above excitation control systems. Introduction of additional feedback will allow boosting of excitation of generator in advance, thereby reducing the voltage dip that occurs during starting-up of asynchronous motor. Simulation of the preemptive control over 259 MVA synchronous generators as part of the nuclear power plant was considered in [23]. But in this model, current feedback is introduced, and preemptive control is performed after perturbation influence appears. Also, analytical method of calculation proposed in this paper is associated with a large number of calculations. The main task of the predictive controller considered in [23] consists in reduction of electromagnetic torque fluctuations, and not in reduction of voltage dips. As noted in [24], electric power systems are multidimensional and multichannel systems. There are many uncertainties that do not make it possible to fully use analytical methods for studying such systems. Simulation, as a research tool, with simplified models of elements included in the system, may be successfully applied to solve the problems of analysis of the processes in electric power systems. When controlling excitation of the synchronous generators, it is not possible to take into account all such uncertainties. Therefore, as shown in [22, 25], adaptive controllers may be successfully applied for control with a given quality. In this case, magnitude of voltage amplitude must be limited.

Synthesis of synchronous generator excitation control system

It is shown in [26] that current load of the power plant may be represented as one equivalent active-inductive load. It is also necessary to take into account the use of automatic voltage controllers for synchronous generators excitation control and automatic frequency controllers for controlling of drive motor shaft speed. Then, differential equations system describing the transient process in the power plant during connection of asynchronous motor will be of the tenth order. In paper [25], linearized equations describing the system (in operating form for increments in the system of coordinates d-q) are given:

– for synchronous generator circuits:

$$(1)\quad \begin{cases} z_d I_d + pM_d I_f + pM_d I_D + \omega_0 L_q I_q + \omega_0 M_q I_Q = -u_d \\ z_q I_q + pM_q I_Q - \omega_0 L_d I_d - \omega_0 M_d I_f - \omega_0 M_d I_D = -u_q \\ z_f I_f + pM_d I_d + pM_d I_D = u_f,\ z_D I_D + pM_d I_d + pM_d I_f = 0 \\ z_Q I_Q + pM_q I_q = 0 \end{cases}$$

where I_d and I_q – generator stator currents; I_D and I_Q – damping grid currents; I_f – excitation currents; operating resistance of generator circuits z_d, z_q, z_f, z_d and z_Q are calculated as:

$$(2)\quad \begin{aligned} z_d &= pL_d + r_S, \\ z_q &= pL_q + r_S, \\ z_f &= pL_f + r_f, \\ z_D &= pL_D + r_D, \\ z_Q &= pL_Q + r_Q, \end{aligned}$$

where L_d and L_q – stator inductance; r_S – active stator resistance; L_D and r_D, L_Q and r_Q are inductances and active resistances of damping windings;

– for load circuits:

$$(3)\quad \begin{cases} z_1 I_{d1} + \omega_0 L_1 I_{q1} = u_d \\ z_1 I_{q1} - \omega_0 L_1 I_{d1} = u_q \\ z_1 = pL_1 + r_1 \end{cases}$$

where I_{d1} and I_{q1} – load currents; L_1 – load inductance; r_1 – load resistance;

– for AM circuits:

$$(4)\quad \begin{cases} z_a I_{d2} + pMI_{D2} + \omega_0 L_a I_{q2} + \omega_0 L_a I_{Q2} = u_d + p^{-1} u_d^0 \\ z_a I_{q2} + pMI_{Q2} - \omega_0 L_a I_{d2} - \omega_0 L_a I_{D2} = u_q + p^{-1} u_q^0 \\ z_R I_{D2} + pMI_{d2} + \omega_0 M I_{q2} + \omega_0 L_R I_{Q2} = 0 \\ z_R I_{Q2} + pMI_{q2} - \omega_0 M I_{d2} - \omega_0 L_R I_{D2} = 0 \\ z_a = pL_a + r_a, \quad z_R = pL_R + r_R \end{cases}$$

where I_{d2} and I_{q2}, I_{D2} and I_{Q2} – currents of asynchronous motor stator and rotor; "0" index denotes the values of magnitudes at the initial moment of time; L_a and r_a – inductance and active resistance of stator; L_R and r_R – inductance and active resistance of rotor;

– for connection of load currents (I_{d1} and I_{q1}), asynchronous motor (I_{d2} and I_{q2}) and generator (I_d and I_q), the following equations system is used:

$$(5)\quad \begin{cases} I_d = I_{d1} + I_{d2} \\ I_q = I_{q1} + I_{q2} \end{cases}$$

Voltage dip calculation requires for solution of differential equations system obtained by combining of (1), (3) – (5) systems and assumes the use of numerical calculation methods that are well implemented in Matlab Simulink and Scilab Scicos software complexes. These packages have interfaces for interacting with external applications written in C programming language, and allow description of the structure of power plant as a graphic block diagram.

Figure 1 represents the structural scheme of the system of preemptive control over synchronous generator excitation in the presence of perturbation influence.

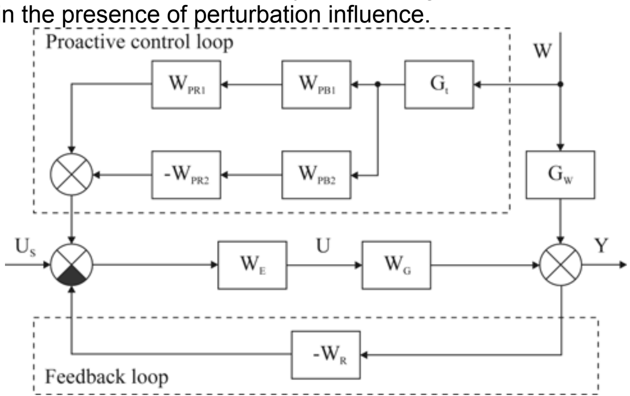

Fig. 1. Flow diagram of the system of preemptive control over synchronous generator excitation by perturbation influence and reference value

The following notations are used in Figure 1: U_s – voltage reference value, W_E – generator excitation system, U – signal adjusted for excitation winding of generator, W_G – synchronous generator, Y – output signal, $-W_R$ – voltage and current compound controller, $-U_R$ – controller signal. Feed forward consists of the following units: $PB1$ and $PB2$ – time relays triggered by signal from perturbation sensor G_t, W_{DG} and $-W_{PR_2}$ – preemptive controllers. Asynchronous motor is an initiator of perturbation W at switching on moment and is indicated with G_W.

Perturbation $W(s)$ affects the process in accordance with the transfer function $G_w(s)$, i.e. there is a dynamic relationship between perturbation and system output:

$$(6)\quad Y(s) = G_w(s) \cdot W(s)$$

The idea of pre-emption is to adjust control signal based on sensor readings $G_t(s)$ and preemptive controllers W_{DG} and $-W_{PR_2}$. The influence of perturbation on the process is neutralized in output parameter Y by means of these controllers generating the signal as a function of perturbation itself:

$$-G_t(s)\cdot\left(W_{PR1}(s)-W_{PR2}(s)\right)\cdot W_E(s)\cdot W_G(s)\cdot W(s)$$
$$+G_W(s)\cdot W(s)=0$$

Let's make substitution, for the sake of simplicity:

(7) $$W_{PR}(s)=\left(W_{PR1}(s)-W_{PR2}(s)\right)$$

By solving equation (7) with respect to $W_{PR}(s)$, we obtain the equation of ideal preemptive controller:

(8) $$W_{PR}(s)=\frac{G_W(s)}{G_t(s)\cdot W_E(s)\cdot W_G(s)}$$

Proceeding from flow diagram in Figure 1, control signal U to excitation winding will consist of three components: voltage reference value signal, preemptive signal for measuring of perturbation and feedback signal.

(9) $$U(s)=U_c(s)-W_R(s)\cdot Y(s)-W_{PR}(s)\cdot G_t(s)\cdot W(s)$$

Let's write equation of system transfer function, and for the sake of convenience omit the s argument:

$$\left(U_c-W_R\cdot Y-W_{PR}\cdot G_t\cdot W\right)\cdot W_E\cdot W_G+G_W\cdot W=Y$$

by grouping the terms, we receive:

$$W_E\cdot W_G\cdot U_c+\left(-W_{PR}\cdot G_t\cdot W_E\cdot W_G+G_W\right)\cdot W=$$
$$\left(1+W_E\cdot W_G\cdot W_R\right)\cdot Y$$

For transformations simplifying, some replacements are performed:

$$W_B=\left(-W_{PR}\cdot G_t\cdot W_E\cdot W_G+G_W\right)\cdot W,$$
$$k1=W_E\cdot W_G,$$
$$k2=\left(1+W_E\cdot W_G\cdot W_R\right)$$

After substitution of coefficients and necessary transformations, we receive:

$$\frac{Y}{U_c}=\frac{k1}{k2}\cdot\left(1-\frac{W_B}{k1\cdot U_c}\right)$$

The transfer function of the entire preemptive control system looks as follows:

$$W_c(s)=\frac{Y(s)}{U_c(s)}=\frac{W_E(s)\cdot W_G(s)}{1+W_E(s)\cdot W_G(s)\cdot W_R(s)}\cdot$$
$$\left(1-\frac{\left(-W_{PR}(s)\cdot G_t(s)\cdot W_E(s)\cdot W_G(s)+G_W(s)\right)\cdot W(s)}{W_E(s)\cdot W_G(s)\cdot U_c(s)}\right)$$

In case of ideal pre-emption which completely compensates perturbation in equation (5), the second term is zero, and feedback system is as follows:

(12) $$W_c(s)=\frac{Y(s)}{U_c(s)}=\frac{W_E(s)\cdot W_G(s)}{1+W_E(s)\cdot W_G(s)\cdot W_R(s)}$$

The signal is $W(s)$ shortened and no longer included in the transfer function. Therefore, perturbation will not have any effect on the output value.

Simulation of preemptive control system operation

In order to manage configuration of the simplified model of ship electric power system, the appropriate unit is also needed, which will manage automation facilities and circuit breakers conditions. For minimization of simulation time, its functions may include monitoring of the change in voltage derivative value after connection of asynchronous motor, and, when it transits into the positive values range, after the simulation process stops. Then, if necessary to calculate the expected voltage dip when asynchronous motor of the given power is switched on, it is possible to call out the model with arguments that determine conditions of generator circuit breakers, current active-inductive load of the power plant and power of the connected asynchronous motor, and by return value – by voltage dip value.

Figure 2 shows a simplified model of ship electric power system for determining of voltage dip value at the direct starting-up of asynchronous motor. This model may be used to determine the expected voltage dip when asynchronous motor of the given power is connected to ship network operated by a given number of diesel generators. The model includes diesel generator with automated frequency and voltage controller, a load equivalent in power to parallel-powered consumers at a given time and asynchronous motor. Technical characteristics of the synchronous generator used in the model are represented in Table 1.

Table 1. Parameters of the synchronous generator

Type	MCK102-4
Voltage, V	400
Power, kW	150
Rotational speed, rpm	1500
Coefficient of efficiency, %	90.2
Active resistance, Ohm	
stator phases	0.02
rotor phases	0.0972
Time constants, s	
T'_{d0}	1.69
T'_d	0.158
T_a	0.014
T''_d	0.0076
Inductive resistance, p.u.	
x_σ	0.0763
x_d	1.92
x_q	0.98
x'_d	0.186
x''_d	0.124
x_0	0.131
x_0	0.0215

All units and loads may control connection to the ship network. Since this model is proposed to be used for power plant management in real-time mode, after asynchronous motor is connected, the sign of voltage derivative of the ship network is calculated. When it reaches zero (or the first positive) value, a time point with a minimum voltage value will be obtained, after which voltage dip value is determined, and simulation process is terminated. Interaction of software with the model (creation and initialization of the variables of Matlab workspace required for simulation – loads and conditions of generator switches of each of DGSs, power of the connected asynchronous motor, simulation, calculation of dip and return of the received value to the program) is performed using the Matlab Engine interface.

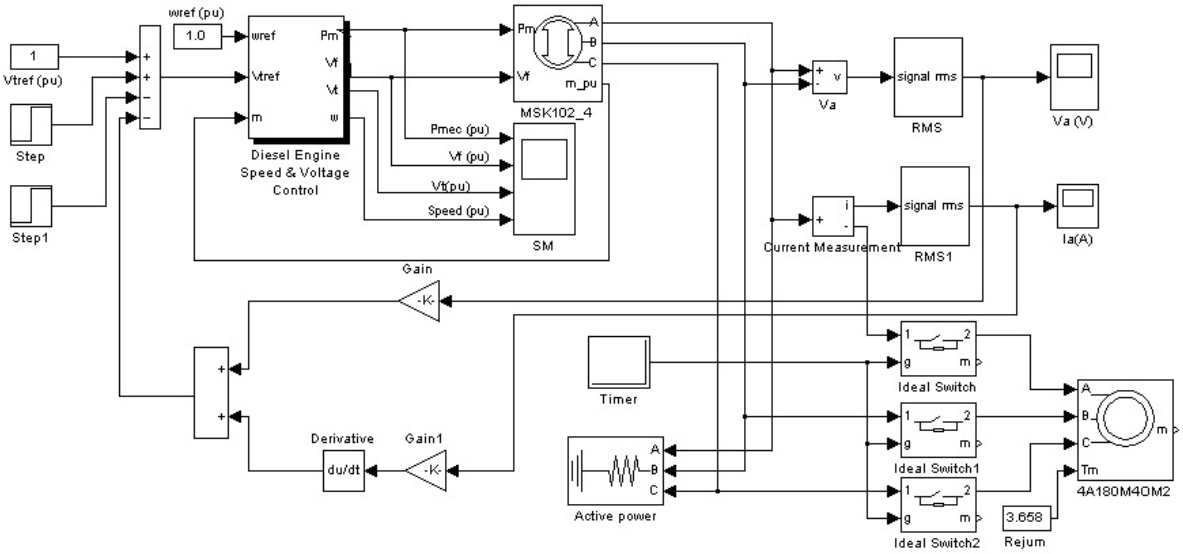

Fig. 2. Matlab-model of diesel generator set with preemptive control of the synchronous generator voltage

The simplified model of ship electric power system shown in Figure 2 can be described analytically using the method developed and described by the author in [27]. The system of preemptive control over excitation of the synchronous generator as part of SEPS, which is used to reduce voltage dips when starting up powerful asynchronous motors, can be optimized by the method considered in [28].

Figure 3 represents experimental dependences of voltage dips magnitude at various values of magnitude of the synchronous generator excitation voltage boost, and also for the different lead time values.

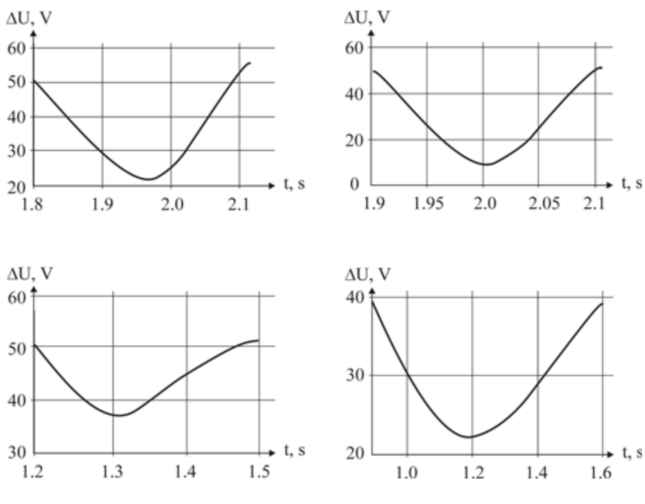

Fig. 3. Dependences of voltage dips on the magnitude and lead time when starting-up 30 kW asynchronous motor: a – 5 V boost value; b – 10 V; c – 15 V; d – 20 V

According to [24], the transient process in excitation winding, after actuation of the controller, is characterized by equation:

(13) $$U_{в} = i_{в} \cdot r_{в} + L_{в} \cdot \frac{\partial i_{в}}{\partial t}$$

For determining of the current in excitation winding, the variables must be separated:

(14) $$\partial t = \frac{L_{в} \cdot \partial i_{в}}{U_{в} - r_{в} \cdot i_{в}}$$

Since drawing of integral from the second member of equation (13) is rather time-consuming, substitution may be used:

(15) $$U_{в} - r_{в} \cdot i_{в} = y$$

Consequently, the equation is received:

(16) $$\partial t = -\frac{L_{в}}{r_{в}} \cdot \frac{\partial y}{y}$$

Such expression on the right of equation (16) is easily integrable, and primitive function is known to all. After integrating the left and right sides we receive:

(17) $$\ln(y) = -\frac{r_{в}}{L_{в}} \cdot t$$

After substitution of (15) into expression (17) and, after having performed necessary transformations, we receive the excitation current-time dependence:

(18) $$i_{в} = \frac{U_{в} - e^{-\frac{r_{в}}{L_{в}} t}}{r_{в}}$$

Equation (18) shows that excitation current is a function of time, and is directly proportional to the change in excitation voltage.

Results and analysis

Analysis of the graphs represented in Figure 3 shows that there is an optimal set of values for magnitude of the synchronous generator excitation voltage boost and lead time. In this case, the obtained values are different for different powers of asynchronous motors. The use of preemptive control system in a ship electric power system implies a stage associated with determining of the optimal values of magnitude of excitation voltage boost and lead time by way of simulation. For this purpose, operator of the power station or automated control system adjusts the parameters of the model and simulates the process of the direct starting-up of asynchronous motor. Simultaneously, maximum value of voltage dip is measured on bus-bars of the main switchboard. Further, values obtained following simulation are transferred to the real system of preemptive control over excitation of the synchronous generator. When a command is received to start asynchronous motor, excitation voltage is boosted, and after the specified time interval, a command is given to connect asynchronous motor.

Conclusion

The paper considers the problem of reduction of voltage dips in ship electric power system, which arises when directly starting-up of asynchronous motors commensurate in power to diesel generator sets. The necessity of preliminary estimation of the value of voltage dip occurring when asynchronous motor is directly started is substantiated. Knowledge of the magnitude of possible voltage dip resulting from the connection of asynchronous motor to the network will prevent activation of the protective equipment and occurrence of emergency situations, which may result in de-energization of the entire electric power system. It is shown that in order to reduce the magnitude of voltage dips during direct starting-up of asynchronous motors, the system for preemptive control over excitation of the synchronous generator may be used.

The structural scheme of the system of preemptive control over excitation of the synchronous generator and simplified model of the ship electric power system are developed for investigation of preemptive control system. Based on simulation, optimum values of magnitude and time for boosting of excitation voltage of the synchronous generator, where minimum voltage dip is observed, were determined. The solution proposed in this paper will enable assessing in the process of monitoring and management of ship electric power system of the possible consequences of direct starting-up of asynchronous motor under current conditions, and based on them deciding on whether to connect the additional diesel generator to the network or disconnect the least essential consumers of electricity from the network to provide generated capacity reserve.

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