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Dynamic Compensation of Reactive Power in Ship Power Plants

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ABSTRACT: In this article, the authors analysed the starting modes of the powerful marine electric drives with asynchronous electric motors and capacitor reactive power compensators. The article considers reactive power control in the class of linear-pulse regulators associated with the unstressed switching of the capacitors in the network. The analysis of reactive power parameters sensors which are used in the discrete-pulse control system showed that the most effective sensor is the reactive conductivity sensor, the value of which is defined as the average value during the switching period and the current sensor, where measurements occur in the moments when voltage transition through zero. The technical implementation of the second sensor is quite simple, does not require the execution of division and multiplication operations, i.e. use of controllers.

1 INTRODUCTION

On the sea fleet ships, the use of alternating current in the electric power plant is dominant. The energy efficiency of this power plants depends and provides by using the rational methods of electric energy control. The process of transmitting and converting electric energy into other types of energy is accompanied by periodic exchange and the transition of reactive power between its inductive and capacitive elements. With such energy metabolic processes, energy losses are inevitable [1, 2].

Active-inductive consumers of alternating current require generation of additional reactive power for their operation, the sources of which on ships are usually synchronous generators. However, alternating current capacitors can also be sources of reactive power. Cosine polypropylene capacitors with aluminium-coated plates are an order of magnitude lighter, smaller and cheaper than electric machines. Therefore, their wider use as reactive power compensators will increase the energy efficiency of the ship's power plant. [3-5].

Until now, the industrial reactive power compensation units (RPCU) are operating at a steady-state load power factor, i.e. they are not dynamic. This explains their insufficiently widespread use on ships, where short-term and transient operating modes of mechanisms predominate. The use of capacitor reactive power sources on ships will be justified with the successful scientific and technical development of high-speed (dynamic) systems for measuring the reactive power of consumers and controlling the necessary compensating capacity RPCU [5, 6-8].

The operation modes of ship multi-generator electrical power installations are characterized by sharply variable loads with frequent start-ups of electric drives with the commensurate power of an induction electric motors and generators. As is known, in the starting mode the motor consumes a large reactive current, significantly reducing the overall power factor of the generating network.

Approximately the same power of drive engines and generators aggregates, different slopes of loading characteristics of primary engines and the speed performance of their regulators, the modes of generators parallel operation with different type of driven mechanisms affect a transitional energy processes of a ship autonomous multi-generator power plant. In addition, the commensurate power of generators and load, the need for generators autonomous operation with high-power electrical drives lead to more severe transitional modes with the danger of disconnecting the electric power plant [5,9].

The use of condenser installations of dynamic compensation for reactive power in the ship's autonomous power plants opens the following possibilities: firstly, to solve the problem of reactive power compensation during the starting of the powerful induction motor from the synchronous generator and reduce the total current consumed from the electric grid, and secondly, to increase the speed of the voltage control channel for the synchronous generator by joint regulation of reactive current in its stator circuit. The effectiveness of this increasing energy efficiency method requires the use of a high-speed system for measuring and controlling the consumed reactive power [5,9,10].

2 ANALYSIS OF STARTING AN ASYNCHRONOUS MOTOR FROM THE SYNCHRONOUS DIESEL GENERATOR WITH A REACTIVE POWER COMPENSATION DEVICE

To compensate for the consumed inductive current of the electric motor, we will consider the use of the capacitive current adjustable source of switched capacitors connected in parallel to the asynchronous motor stator windings, Fig. 1 [9].

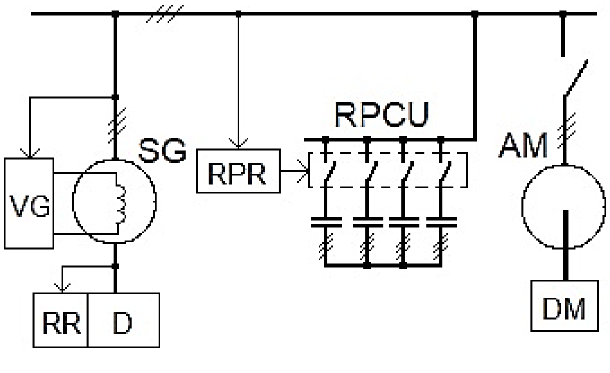

Figure 1. Modelling scheme of starting an asynchronous motor from the synchronous diesel generator with a reactive power compensation device: SG - synchronous generator; D - diesel engine; AM - asynchronous motor; DM - driven mechanism; RPCU – reactive power-controlled compensator; VR, RR, RPR – voltage regulator, rotation regulator of diesel, reactive power regulator

The calculation of the starting processes will be performed on the developed mathematical model of the system. The simulated autonomous power plant contains automatic voltage control systems for the synchronous generator, the rotation frequency control drive engine, the starting asynchronous motor, and a device for reactive power compensating load.

Let us consider two processes: direct starting of an electric motor without compensation (Fig. 2 - Fig. 4) and with compensation of the motor reactive current (Fig. 5 - Fig. 6). The starting electric motor power is 40% of the diesel generator power. Parameters of the simulated asynchronous motor are: R_1=0.02; R_2=0.018; X_1=0.11; X_2=0.073; X_m=3.3

The generator load before asynchronous motor starts was 10% at power factor: cosφ=1. The nominal values of the generator corresponding parameters, as well as the nominal rotation frequency of the starting electric motor, are taken as the basic values of the electrical and electromagnetic quantities in the figures.

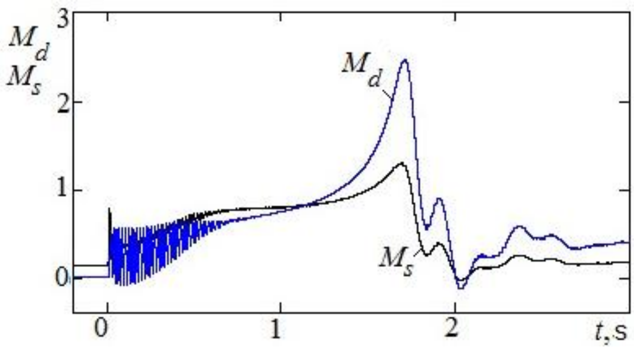

Figure 2. Electromagnetic starting torque M_d of the electric motor and the resistance torque M_s of the driven mechanism

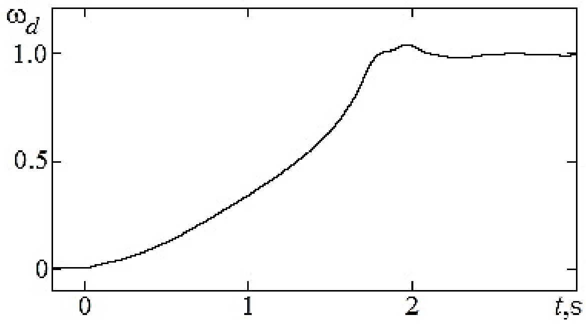

Figure 3. Rotation speed of the starting electric motor ω_d

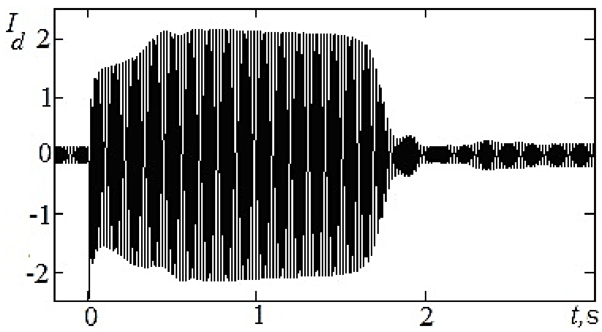

Figure 4. Starting current I_d of an electric motor for direct starting

The regulation of the consumed reactive power in the model is carried out by a controlled reactive power compensator (RPCU) by changing the capacitive current of the connected capacitors, which ensures a close-to-zero angle φ and a practically unitary load power factor cosφ. The current I_g of the generator in the asynchronous motor start mode with reactive power compensation is shown in Fig. 5.

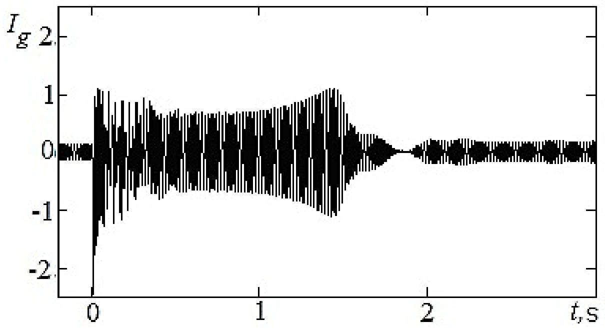

Figure 5. Generator current I_g when starting an electric motor with reactive current compensation

The reactive current of the generating network total load is measured during each current period. The capacitance of the compensating capacitors also changes during each period, its change is shown in Fig. 6.

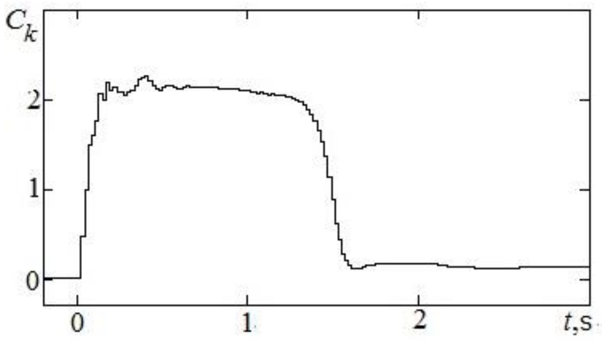

Figure 6. Compensating capacitance C_k changing when starting an electric motor

Comparison of transient processes in Fig. 4 and Fig. 5 shows that with reactive power compensation the maximum starting current of the generator decreases approximately twofold. At the same time, the starting torques, and acceleration time of the asynchronous motor remain practically unchanged.

2.1 *Reactive power control with the unstressed inclusion of the capacitors in the network*

This article discusses technical solutions for the third problem: an analysis of several discrete control laws for three-phase sections of AG excitation capacitors is carried out. The authors of the article consider the further development of the previously described controller [8, 9], which implements the integral discrete-pulse law of voltage stabilization of the AG with capacitor excitation.

In this article, we consider the reactive power control in the class of linear-pulse regulators [9], in which the control is quantized by time, and the control signal amplitude linearly depends on the input signal. Discrete time control is associated with synchronization of the unstressed inclusion moments of capacitors in the network [8-13].

The switching processes in circuits with capacitors contribute to the occurrence of recharge currents, which can be unacceptable for the normal operation of thyristor switches.

If the difference in the voltage of the network and the switched capacitor is more than a few volts ΔU, and the resistance of the open key R_k is not enough, then the charging current I_{RC} may exceed the permissible values of the thyristor current I_{max}. At the beginning of the recharge, the current is equal, $I_{RC}=\Delta U/R_k$, i.e. $I_{RC}>I_{max}$. In RC–circuits, the accumulation rate of the capacitor charge during switching dI_{RC}/dt is determined by the maximum of opening speed the pn-transition of the thyristor switch. The rate of voltage increases in the RC-circuit is determined by constant time $T=RC$:$dU_{RC}/dt=\Delta U/RC$. The maximum values of the pulse current I_{max}, current dI/dt growth rate and the voltage dU/dt growth rate of the thyristors is limited, excesses of which leads to their destruction. Operational restrictions on the parameters of switches elements can be solved by turning on the limiting throttle or synchronizing the moments of inclusion of capacitors in the network, when the voltage on the condenser and the network are equal, ΔU=0. In this case, the charging current of the capacitor is zero.

An example of the synchronous inclusion of the capacitor in the system for regulating the reactive power of the synchronous generator's load is shown in Fig. 7.

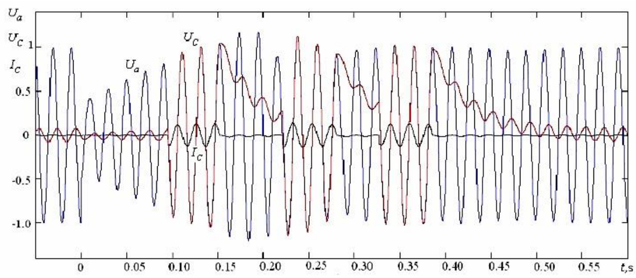

Figure 7. Transition processes during synchronization of the inclusion of the capacitor to the network with equality $\Delta U=U_a-U_b=0$

The opening moments of the switches in Fig.7 coincide with the moments when the difference between the voltages of the network and the capacitor is equal to zero $\Delta U=U_a-U_b=0$. In the open state of the thyristor switch, the voltage on the capacitor U_c coincides with the network voltage U_a, and when turned off, the capacitor is discharged according to an exponential law through a discharge resistor. There are no charging currents, and the value of the capacitor current after opening the switch is determined by the derivative of the network current: $I_c=C\cdot dU_a/dt$.

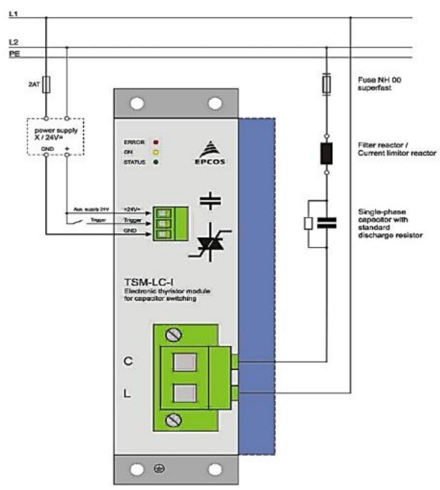

Figure 8. Thyristor switch for shockless capacitor switching from EPCOS [3]

When a powerful load of the ship's network is turned on during the transient process, the voltage decreases significantly. The voltage on the capacitor may not have time to drop to the mains voltage. If at this moment the control circuit should turn on the capacitor, then the synchronization circuit will not allow this to happen and a delay in control will occur. To discharge capacitors during the off state, special discharge resistors are used, which are installed in parallel with the capacitors, Fig. 8 and Fig. 9. These schemes show examples of unstressed synchronization of the inclusion of capacitors to the AC network [8,14].

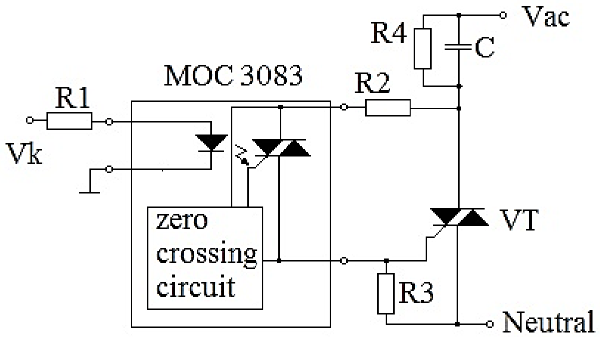

Figure 9. Simistor switch for shockless capacitor switching using a MOC 3083 type simistor with zero crossing circuit

The use of thyristor (simistor) circuit of unstressed inclusion leads to a delay in switching of three phases capacitors by at least 120 electric degrees. When using synchronization of switching with the network, the minimum period of discretion of control in time will be 180 electric degrees or a half-period of the network.

2.2 *Discrete sensors of reactive power parameters*

In this work, we limit ourselves to the consideration of discrete control systems with a period of switching T_0, a multiple of the network, which for a network of 50 Hz is 20 ms. During this time, switching processes end in the scattering chains of the motor load of the shipboard network.

For discrete-pulse reactive power control, there are several options for using information about the adjustable parameter in synchronized moments of time. We can use instant (1), filtered (2) or averaged for the switching period (3) the value of the adjustable parameter. As previously considered [5, 9], such parameters can be reactive conductivity Y, reactive current I_r or reactive power of the load Q.

The simplest implementation is the use of the instantaneous value of the adjustable parameter - the reactive current of the load I_r, because at the time of the transition of phase voltage u_g through zero, the instant value of the phase current is equal to the value of the reactive current, $I_r=i_{l0}$, see Fig. 10. It is enough to measure this value, preserve and use for unstressed control of capacitors at the time of the transition of their currents through zero.

To use the instantaneous value of reactive conductivity Y or reactive power Q for control, the measured value of the reactive current I_r can be divided and multiplied respectively by the voltage amplitude U_m:$Y=I_r/U_m$, $Q=I_r \cdot U_m$. During the management period T_0, it is possible to perform additional operations of filtering and averaging the control signals.

The computing process of multiplication or division involves the use of more complex and expensive controllers. However, the use of synchronized instantaneous load current i_{l0} values allow the use of simple microcontrollers.

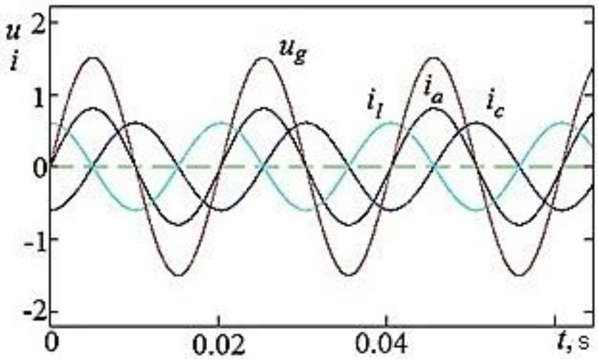

Figure 10. Voltage and load currents in the alternating current circuit with a frequency of 50 Hz

The amplitude values of signals in discrete-pulse systems change only in quantum moments of time. To determine the current value of the reactive current load, the measurement should be made at the moment of the supply voltage transition through zero value, Fig. 11.

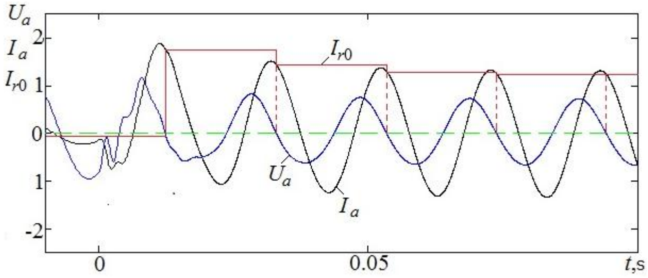

Figure 11. Measurement of the current reactive current value at the beginning of the direct start of the asynchronous electric motor with a capacity of 36 % of the generator power at the time of the phase voltage transition through zero value

If there are sources of nonlinear distortion in the generator load, then the generator voltage and the load current can be filtered with the same frequency properties filters [10-17]. In this paper, we do not consider such a load, so the role of the filters of interference will be performed by the sensors of the average for the period of the measured signal value, Fig. 12:

$$Y_{dat} = \frac{1}{N}\sum_1^N Y_n, \quad I_{dat} = \frac{1}{N}\sum_1^N I_{rn}, \quad Q_{dat} = \frac{1}{N}\sum_1^N Q_n,$$

$$U_{dat} = \frac{1}{N}\sum_1^N U_{mn},$$

where N is the number of measurements of the adjustable parameter during the T_0 period of the discrete-pulse control system of reactive power.

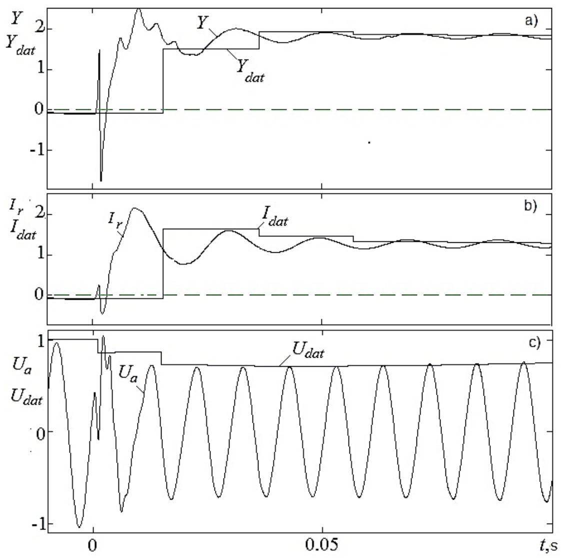

Figure 12. Sensors signals of adjustable parameters - average values for the switching period T_0: a - reactive conductivity sensor signal Y_{dat}; b - reactive current signal I_{dat}; c - voltage sensor signal U_{dat}

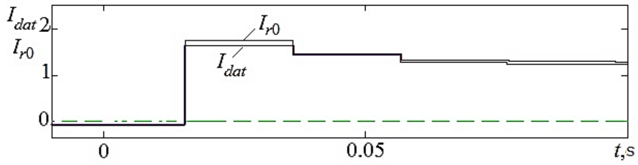

Figure 13. Comparison of reactive current sensors

3 CONCLUSIONS

1. The reactive power dynamic compensation by connecting corresponding capacitors capacitance when starting powerful electrical drives of the ship mechanisms reduces the ship generator current of two times.

2. This method of the reactive power compensation allows to double of the ship power plant capabilities in the start-up modes of powerful asynchronous motors, which in turn will make it possible to increase the power of asynchronous electric motors to 35-40 % compared to the generators power.

3. Analysis of the measuring processes of reactive power parameters in the discrete-pulse control system shows that the most effective are the sensors of the average value of reactive conduction and reactive current.

4. The reactive current sensor can be implemented by using a simple controller, since there is no need to calculate nonlinear functions.

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