Digital control by the discrete systems of reactive power compensation in ship electrical power plants

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Abstract. The reactive power required to create the electromagnetic fields of electric motors, transformers and converters worsens the performance of the power system, the total current of the generator, transformers and cable lines must be significantly increased in relation to the required active load current by an amount that proportionately increases the installed capacity of the electrical equipment and the cross section cable connections. Instead of single work with full load, the parallel operation time of generating units with underload is increased to provide excess full power of electric consumers, including their reactive power. Solving the problem of energy saving, reducing the reactive power consumption allows capacitors Reactive Power Compensation Devices (RPCD). Varying the capacitance of the stages of the compensating capacitors, it is possible to fully compensate the reactive current of the actively inductive load of consumers. An analog (continuous) change in the capacitance of high-power capacitors is still an unsolved technical task. In most power plants, the capacity of capacitors varies stepwise, by connecting a different number of capacitor sections. This article is devoted to the investigation of RPCD, consisting of several blocks of compensating capacitors that are switched to the powernet independently of each other by means of high-speed thyristor switches. The change in the capacity of compensating capacitors in RPCD in power plants is accomplished by connecting a certain number of sections of capacitors. In this case, the capacitance value changes stepwise, i.e. discretely according to the adjustable value. The capacitance of each capacitor section, the number of sections of capacitors and the algorithm of their switching to the network are the technical parameters of the discrete system of reactive power compensation. Analysis of these parameters and their optimization is the task of this article.

Keywords: reactive power compensation, compensating capacitors, high-speed thyristor switches, RPCD

1. Introduction

The main consumer of inductive reactive power on ships are asynchronous engines (60 ... 65% of its total consumption), transformers, including welding (20 ... 25%), valve converters, reactors and other consumers.

The inductive load in the process of operation is a source of reactive electricity, which oscillates between the load and the generator, is not connected with the performance of useful work, but is spent on creating electromagnetic fields and creates an additional load on the power lines. Accordingly, all
network power, transmission and distribution equipment must be designed for large loads. In addition, as a result of heavy loads, the lifetime of this equipment can be reduced accordingly. A further factor in increasing costs is the heat transfer due to the increased value of the total current in cables and other switchgears, in transformers and generators.

Reactive power compensation improves the efficiency of generation, transportation, distribution and consumption of electricity. Effective compensation of inductive currents provides resource saving, improving the quality of electricity, [1,2].

The most common devices for reactive power compensation in ship distribution networks are static automated condenser installations. However, static RPCD provides compensation for the average value of reactive power, while rapid transient processes in the energy system are not taken into account. Their use is effective only for work in the established regime of loads of the grid system.

One of the leading electrotechnical firms in Europe Schneider Electric produces RPCD type Varset with capacitors of Varplus2 type with control from the functional modules Varlogic. As the switches that switch capacitors, specially designed contactors are used in the Varlogic modules. At the first moment of switching capacitor C is connected to the network through the resistor R and the reactor L, which allows avoiding dangerous throws of charging currents. Then the power contact of the key closes. However, the lack of synchronization of the moments of switching on the capacitors with the mains voltage leads to transient processes at the commutation moments.

The use of power semiconductor elements as the keys allows the capacitor to be switched in each phase at the time of equal network voltage and capacitor. Schneider Electric Company produces thyristor RPCD type Varset FAST with a key operating time less than 40 ms. Another example of a reactive power controller with contactor switching of capacitors is the MULTICOMP 96 Eco controller from MKS technology. The controller BR7000 of firm EPCOS is also designed for performing similar operations for measuring the electric power parameters and switching capacitor sections. Change of reactive power and set in contactor installations is performed with a certain clock frequency according to the specified control program. The required value of the capacitive current is achieved by connecting and disconnecting the respective stages of the capacitors of the compensation device. Regulatory programs take into account the power of the stages.

All the presented RPCD systems are static and do not provide dynamic (continuous) compensation of reactive power.

A more promising and completely unsolved problem is the use of dynamic reactive power compensation devices in the ship power system.

2. Model of the system

The mathematical model of a ship electric power plant includes differential, algebraic and logical equations describing physical processes in the elements of the system and the connection between aggregates. The model includes accepted assumptions in the mathematical description.

The composition and structure of the mathematical model is determined by the functional scheme of the ship's power plant. Each element of the installation under study corresponds to a specific model. The links between the elements are modeled by introducing common variables and combining the subsystems of the equations of the corresponding parts of the SEPP.

Simulation of a three-phase thyristor-capacitor block consisting of several switched sections requires a separate description of the connection of currents and voltages in each phase separately. An equivalent circuit of one phase of a four-digit thyristor-capacitor block is shown in Fig. 1.
The symmetrical thyristor switch is represented by two parallel-connected resistors with an open state resistance \( R_0 \) and a closed state \( R_z \). When the switch is open \( K_i \) the resistance of the switch will be equal \( R_0 \), and when it is closed - \((R_0 \cdot R_z) \cdot (R_0 + R_z)^{-1} \approx R_0\), as \( R_z >> R_0 \). This representation of the thyristor switch in the mathematical model allows to write the same equations when state is closed and when it is opened, assuming the switch resistance is equal \( R_z \). In the open state \( R_z = R_0 \), in the closed state \( R_z = R_0 \).

The thyristor switch is simulated by software dy changing the resistance of the switch. Each thyristor switch \( K_i \) switches the capacitor \( C_i \) of one of the sections through the safety throttle \( L_i \).

The active-inductive load of the generator is modeled by the serial connection of the active conductivity \( G \) and the circuit \( RL \).

In the mathematical model, stator chains are described for each phase separately. Equations in the Cauchy form that connect the voltages and currents in the equivalent circuit in Fig. 1 has the following form.

\[
U_s = (I_s - I_l - I_{c1} - I_{c2} - I_{c3} - I_{c4}) \cdot (G)^{-1}
\]

\[
\frac{dI_l}{dt} = (U_s - I_lR) \cdot (L)^{-1}
\]

\[
\frac{dI_{c1}}{dt} = (U_s - I_{c1}R_{x1} - U_{c1}) \cdot (L_1)^{-1}
\]

\[
\frac{dI_{c2}}{dt} = (U_s - I_{c2}R_{x2} - U_{c2}) \cdot (L_2)^{-1}
\]

\[
\frac{dI_{c3}}{dt} = (U_s - I_{c3}R_{x3} - U_{c3}) \cdot (L_3)^{-1}
\]

\[
\frac{dI_{c4}}{dt} = (U_s - I_{c4}R_{x4} - U_{c4}) \cdot (L_4)^{-1}
\]

\[
\frac{dU_{c1}}{dt} = I_{c1} \cdot (C_1)^{-1}
\]

\[
\frac{dU_{c2}}{dt} = I_{c2} \cdot (C_2)^{-1}
\]

\[
\frac{dU_{c3}}{dt} = I_{c3} \cdot (C_3)^{-1}
\]

\[
\frac{dU_{c4}}{dt} = I_{c4} \cdot (C_4)^{-1}
\]

Equations of the stator load and compensating condenser sections of one phase of the generator are described by a system of ninth-order differential equations. For three phases, the order of the equations is 27.
Such a number of additional differential equations which describe each capacitor circuit in each phase substantially increases the order of the mathematical model of the electrical installation. Together with the equation of the diesel drive, the synchronous contactless generator, the voltage regulator and the frequency of rotation and the filters of the measured parameters, the order of the system is 38. If the capacitor bank is modeled without inclusion in each phase, the order of the system is 15 orders.[3]

An increase of the order of the system of equations substantially increases time of calculation of the transient process.

Accounting for the features of the operation of thyristor switches when switched on and off is modeled using logic functions. The thyristor is closed when the control signal is removed after the current is reduced to a value less than the thyristor holding current. The thyristor will close when the current through the thyristor is calculated at each integration step and the instant of change of the current sign can be determined when the product of the capacitor currents at the current step \( I_a(t) \) and at the previous step of calculation \( I_a(t-T_p) \), i.e., \( I_a(t-T_p) \cdot I_a(t) < 0 \).

A shock-free thyristor unlocking commuting the capacitor is possible, if the voltage on the thyristor is zero. If the closed thyristor is modeled by a resistor with a large resistance \( R_z \), then the voltage at the anode and the cathode of the thyristor will equal when the current is zero through the resistor \( R_z \). When the voltage across the thyristor is zero, the current through the resistor \( R_z \) will also change sign. Thus, condition for changing the state of the switching thyristor can be determined by the general condition \( I_a(t-T_p) \cdot I_a(t) < 0 \).

![Figure 2 Processes in one phase of a four-digit capacitor unit](image)

The logical condition for changing the resistance of the thyristor switch \( R_k \) will be:

If \( I_a(t-T_p) \cdot I_a(t) < 0 \) and \( I_a(t) < 0 \) then \( R_k = R_o \) or \( R_k = R_z \).

Selection of resistance value of the switch \( R_k = R_o \) or \( R_k = R_z \) is determined by the control device. The condition \( I_a(t) < 0 \) allows to clock the capacitor capacitance change once during the generated voltage period. Synchronization of control during simulation is determined by the phase transition of the phase voltage through zero: If \( U_a(t-T_p) \cdot U_a(t) < 0 \) and \( U_a(t) > 0 \) then \( C_f = f(\Delta U_a P_a) \). The calculated processes of changing currents \( I_a(t) \) and voltages \( U_a(t) \) in each section of capacitors of one phase are shown in Fig. 2.
3. Results and Discussion

3.1. Two-digit RPCD

The reactive energy compensation device with two sections of capacitors, whose capacitance is two times different, is the simplest adjustable system. It is possible to combine only three values of the total capacity: $\Delta C, 2\Delta C$ and $3\Delta C$.

Nevertheless, it allows to ensure sufficient accuracy of compensation of the load angle at the radian level

$$\Delta \phi_{\min} = \arcsin(\sin \phi_n \cdot (2^2 - 1)^{-1}) = \arcsin(\sin \phi_n \cdot 3^{-1}) = 0.2...0.27 \text{ radian.}$$

At the same time, the power factor can be provided not less than

$$\cos \phi_{\min} = \cos(\arcsin(\sin \phi_n \cdot (2^2 - 1)^{-1})) = \cos(\arcsin(\sin \phi_n \cdot 3^{-1})) = 0.96...0.98.$$

The capacitance of the smaller section of the capacitors is equal

$$\Delta C = C \cdot (2^2 - 1)^{-1} = \sin \phi_n \cdot 3^{-1} = 0.2...0.27 \text{ r.u.}$$

Figure 3 shows the transient processes of switching on 50% of the active-inductive load of a synchronous generator with a two-digit regulator. The implementation of a complex control algorithm [4] in a two-digit controller is difficult and does not lead to the desired result. Improvements in the dynamic properties of the voltage stabilization system can not be achieved.

3.2. Three-digit RPCD

The increase in the number of switched sections and the number of control bits to three increases the accuracy of reactive energy compensation by more than 2.2 times. The accuracy of maintaining the load angle near zero is

$$\Delta \phi_{\min} = \arcsin(\sin \phi_n \cdot (2^2 - 1)^{-1}) = \arcsin(\sin \phi_n \cdot 7^{-1}) = 0.09...0.12 \text{ radian,}$$

and the power factor equal to unity with a three-digit regulator is
\[ \Delta \cos \phi_{\text{min}} = 1 - \cos \Delta \phi_{\text{min}} = 1 - \cos(\arcsin(\sin \phi_n \cdot (2^3 - 1)^{-1})) = 1 - \cos(\arcsin(\sin \phi_n \cdot 7^{-1})) = 0.3 \ldots 0.6 \% . \]

Such accuracy of compensation is quite sufficient for ship and other technical electric networks.

Figure 4 Transient processes in a three-digit discrete-pulse compensation system for the reactive energy of a synchronous generator when 50% of the active-inductive load is switched on:

- (a) \( T_0 = T_c \)
- (b) \( T_0 = 5T_c \)

An increasing of the minimum switching capacity of the compensating capacitors worsens the dynamic properties of the synchronous generator voltage stabilization system.

Figure 4 shows the calculated transient processes of switching on 50% of the active-inductive load of a synchronous generator with a three-digit regulator under the U-PI control law [4] with the optimum tuning parameters: \( k_u = 1.5, k_q = 0.05, T_q = 0.003 \) c.

The time-quantization period in Figure 4a was also selected \( T_0 = T_c \) and \( T_0 = 5T_c \) in Figure 4b. With a longer period \( T_0 \), compensation time increases from 0.5 to 0.8 s, the power factor failure remains the same, and the dynamic quality of the generator voltage is somewhat degraded [4,5].

3.3 Four-digit RPCD

The ratio of the capacitance values of the three-phase sections will be chosen proportionally to the weights of the bits of the binary number system: 1: 2: 4: 8. The functional diagram of the control device of the compensating device is shown in Figure 5.
Signals from voltage sensors $\Delta U$ and the reactive energy parameter are fed to analog regulators that form the law of variation of the compensating capacitance $C_1(t)$. Further, the ADC converts it into a binary number $N_c = Q_1Q_2Q_3Q_4$, that controls the corresponding switches $K_1, K_2, K_3, K_4$, connecting the sections of the capacitor block $C_1, C_2, C_3, C_4$. The synchronization device determines the moments of changing the binary number $N_c = Q_1Q_2Q_3Q_4$ accordingly to the period of the generated voltage. The minimum period of discrete switching of capacitors is equal to one period of the generated voltage $T_0 = T_c$. However, it can be increased multiples of the network period $T_0 = K_c T_c$. That is, capacitors can be switched once for one period, for two periods and more periods of the network. Calculate the transient processes in a system with a four-digit compensator under the U-PI control law with optimal adjustment parameters $C_1(t) = k_u \Delta U_m(t) + k_q P_q(t) + T_q \int_0^t P_q(t) dt$.

Figure 6 shows the reactive power compensation processes in the digital system when 50% of the active-inductive load is switched on with the U-PI control law. The time-quantized period is equal to one period of the network $T_0 = T_c$. Adjustment parameters of the controller are: $k_u = 1.5, k_q = 0.05, T_q = 0.003$ s. The detailed simulation of each switched capacitor in each phase and section, taking into account the synchronization of the inclusion and the discreteness associated with a limited number of sections, shows that the splitting of the capacitor block into four three-phase sections allows to achieve the required parameters of the reactive energy compensation system. The accuracy of maintaining the load angle near zero is $\Delta \phi_{\text{min}} = \arcsin(\sin \phi_n \cdot (2^4 - 1)^{-1}) = \arcsin(\sin \phi_n \cdot 15^{-1}) = 0.04...0.05$ radian, and the power factor equal to unity with a four-digit regulator is $\cos \phi_{\text{min}} = \cos(\arcsin(\sin \phi_n \cdot (2^4 - 1)^{-1})) = \cos(\arcsin(\sin \phi_n \cdot 15^{-1})) = 0.1...0.2$ %. The dynamic failure of the power factor does not exceed 0.2, the recovery time is not more than 0.5 s.
Figure 6 Processes in a four-digit discrete-pulse compensation system for reactive power

Figure 7 shows the calculated transients in a four-digit discrete-pulse compensation system for reactive energy when 50% of the active-inductive load is switched on. All processes are constructed with the same settings of the regulators and differ in the time of the time quantization period \( T_0 = 2...10 \cdot T_c \). Comparison of these processes shows that the compensation of the power factor in all cases satisfies the requirements for accuracy and compensation time. Thus, the recovery time of the power factor does not exceed 0.6 s at \( T_0 = 2...10 \cdot T_c \).

Therefore, the main criterion for choosing the discrete period \( T_0 \) for a four-digit discrete-pulse compensation system for reactive energy will be the quality of the transient process along the voltage stabilization channel of the synchronous generator.

Analysis of voltage transient processes in Figures 5, 6 and 7 shows that the best is the recovery process with minimal discrete time \( T_0 = T_c \), Fig. 5 b.
4. Conclusion
The choice of a binary system for capacitor capacitance control is justified by the wide application of the binary system in computer devices. The capacitance values of the capacitor sections of the RPCD are referred to as the weights of the bits of the binary number system: 1, 2, 4, 8 ... The value of the control number will correspond to the value of the compensating capacity, provided that the corresponding bit of the binary number is controlled. From the switching period of capacitors $T_0$ the time of reactive load compensation $t_q$ depends on the dynamic quality of the voltage stabilization system. For discrete level systems, the dependencies of the integral quality index of the voltage transient process $I_{Du}$ from the period of discreteness in time $T_0$ are determined. These dependences for a two-, three- and four-digit compensator of a reactive load are of a different nature. The best processes for a two-digit compensator ($N=2$) will be for $n=7...8$. For a three-digit compensator ($N=3$) the best processes are achieved at $n=2...3$. In the four-digit compensator ($N=4$) the optimal value of the discrete period is equal to the network period, $T_0=T_c$.

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