A method for Improving the Accuracy of Reactive Power Regulation by a Capacitor Plant

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Abstract. The problem of low accuracy of reactive power regulation by the most common three-component condenser installations in the industry and its impact on the quality of electricity and the efficiency of its consumption and use in industrial power supply systems is considered. To increase the accuracy of reactive power regulation by at least 2.3 times without changing the circuit of the capacitor plant and the number of switching equipment, a new control algorithm is proposed and described in detail. The results of testing a method for regulating reactive power in the Matlab environment based on the proposed algorithm for controlling capacitor blocks with changed parameters are presented. Numerical experiments have shown the possibility of seven-stage regulation, versus three-stage control in known industrial installations. The capacitor unit is switched on by a mains switch and then by thyristor switches without a surge of currents in the capacitors and without an asymmetry of currents in the network. The installation is switched off in the reverse sequence, first by thyristor switches with natural switching, and then by a mains switch without arcing on its contacts.

1. Introduction
Condenser installations are widely used in industrial power supply systems with extended power transmission lines. They unload the electric networks from reactive power, reduce electricity losses and equalize the voltage of consumers [1-12]. The most widely used are three-complete condenser installations with three-stage regulation. Each installation kit includes the same capacitor banks and switching equipment. Depending on the schedule of the technological equipment, multi-stage regulation of reactive power by capacitor installations is also used, in which the number of stages of reactive power regulation is equal to the number of capacitor banks having the same parameters [13-18].
The disadvantage of existing capacitor installations with three-stage regulation (three-complete) is the low accuracy of reactive power compensation, and multi-stage ones – a large number of switching equipment.

To eliminate these shortcomings, an alternative technical solution is proposed. In a three-set capacitor bank, perform capacitor banks with different capacities. The capacity of the second battery is twice as large as the first, and the capacity of the third battery is twice as large as the second. Select the switching devices in accordance with the parameters of the capacitor banks. And, finally, to apply a new algorithm for switching three capacitor banks for seven-stage regulation of reactive power while maintaining the number of switching equipment of a three-complete capacitor plant.

2. The purpose of the work
Improving the accuracy of regulating the reactive power of a three-complete capacitor plant by increasing the control stages from three to seven without changing the number of switching devices.

This goal is achieved by the fact that the capacity of the second capacitor bank is twice as large as that of the first, and the capacity of the third capacitor bank is twice as large as that of the second. In addition, the order of switching capacitor banks and reactive power control stages is as follows [19]. The activation of the second stage of reactive power regulation is performed by switching on the second capacitor bank when the first capacitor bank is disconnected, the activation of the third stage is performed by connecting the first capacitor bank in parallel to the second capacitor bank. The activation of the fourth stage of reactive power regulation is performed by switching on the third capacitor bank when the first and second capacitor banks are disconnected, the activation of the fifth stage is performed by connecting the first capacitor bank in parallel to the third capacitor bank. The sixth stage is switched on by connecting the second capacitor bank in parallel to the third capacitor bank when the first capacitor bank is disconnected, and the seventh stage of reactive power regulation is switched on by connecting the first capacitor bank in parallel to the second and third capacitor banks.

Figure 1 shows the functional diagram of the proposed capacitor plant with a seven-stage reactive power control. It contains a three-phase network (Va, Vb, Vc), a power transmission line (PTL), a network switch (NS), an active-inductive load (Zl), the first capacitor bank (CB-1) with a resistive block (RB-1) of the first battery's capacitor discharge, the first thyristor starter (TS-1) with thyristor switches TS-1 and TS-2, the second capacitor bank (CB-2) with a resistive block (RB-2) discharge of the capacitors of the second battery, the second thyristor starter (TS-2) with thyristor switches TS-3 and TS-4, the third capacitor bank (CB-3) with a resistive block (RB-3) discharge of the capacitors of the third battery, the third thyristor starter (TS-3) with thyristor switches TS-5 and TS-6, a control pulse generator (CPG), the control input of which is supplied with a control voltage Uc, and nine of its outputs 1, 2, 3, 4, 5, 6, 7, 8, 9 designed to connect the corresponding thyristor keys to the control circuits and to the keys of resistive capacitor discharge blocks.

Figure 1. Functional diagram of the proposed three-complete capacitor plant with seven-stage reactive power control.
3. The principle of operation of the proposed three- complete condenser installation
The essence of the proposed method for regulating the reactive power of a capacitor plant is the sequence of performing known and newly introduced operations.

Below are the operations of the method, the description of which with the attached drawings explains its principle of operation.

**The first operation of the method.** It consists in preparing the power unit and the microelectronic control system of the capacitor plant for operation. To do this, at an arbitrary time, the mains switch supplies voltage to the thyristor starters TS-1, TS-2, TS-3 and the control pulse generator CPG with direct connection of one phase of the CB-1, CB-2 and CB-3 capacitor banks, for example, phase "B", to the network.

**The second operation of the method.** It consists in turning on the first stage (time interval T-1). It is performed by connecting the first capacitor bank CB-1 to the network by means of the first thyristor starter TS-1 when the second CB-2 and the third CB-3 capacitor banks are switched off. First, they turn on one thyristor switches, for example, for phase "C", the TS-2 switches, at the moment of transition through zero of the line voltage between phases "B" and "C" of the network, and then turn on another thyristor switches TS-1 at the moment of transition through zero of the phase voltage of phase"A". The thyristor switches TS-1 and TS-2 are switched on by applying control pulses, respectively, from outputs 1 and 2 of the control pulse generator of the CPG.

**The third operation of the method.** It consists in turning on the second stage (time interval T-2). It is performed by connecting the second battery of CB-2 capacitors to the network with the second thyristor starter TS-2 and disconnecting the first battery of CB-1 capacitors with the first thyristor starter TS-1. At the same time, the third batteries of the CB-3 capacitors are turned off. Disconnecting the first thyristor starter TS-1 is performed by removing the control pulses from its thyristor switches TS-1, TS-2 and, respectively, from the outputs 1, 2 of the generator of these pulses. When connecting the second battery of CB-2 capacitors to the network with the second thyristor starter TS-2, first turn on one thyristor switches, for example, for phase "C", the TS-3 switches, at the moment of transition through zero of the line voltage between phases "B" and "C" of the network, and then turn on another thyristor switches TS-4 at the moment of transition through zero of the phase voltage of phase "A". The thyristor switches TS-3 and TS-4 are switched on by applying control pulses, respectively, from outputs 6 and 7 of the control pulse generator of the CPG.

**The fourth operation of the method.** It consists in switching on the third stage (time interval T-3). It is performed by connecting the first battery of CB-1 capacitors to the network by means of the first thyristor starter TS-1 with the second battery of CB-2 capacitors connected to the network. The third battery of the CB-3 capacitors is turned off at the same time. This operation of the method is performed according to the algorithm similar to its second operation.

**The fifth operation of the method.** It consists in turning on the fourth stage (time interval T-4). It is performed by connecting the third CB-3 capacitor bank to the network with the third TS-3 thyristor starter and disconnecting the first CB-1 and the second CB-2 capacitor banks with the first TS-1 and the second TS-2 thyristor starter. Disconnecting the first TS-1 and the second TS-2 thyristor starter is performed by removing the control pulses from their thyristor switches TS-1, TS-2, TS-3, TS-4 and, respectively, from the outputs 1, 2, 6, 7 of the generator of these pulses. When connecting the third battery of CB-3 capacitors to the network with the third thyristor starter TS-3, first turn on one thyristor switches, for example, for phase "C", the TS-5 switches, at the moment of transition through zero of the line voltage between phases "B" and "C" of the network, and then turn on another thyristor switches TS-6 at the moment of transition through zero of the phase voltage of phase "A". The thyristor switches TS-5 and TS-6 are switched on by applying control pulses, respectively, from outputs 8 and 9 of the control pulse generator of the CPG.

**The sixth operation of the method.** It consists in turning on the fifth stage (time interval T-5). It is performed by connecting the first battery of CB-1 capacitors to the network by means of the first thyristor starter TS-1 with the third battery of CB-3 capacitors connected to the network. The second
battery of the CB-2 capacitors is turned off at the same time. This operation of the method is performed according to the algorithm similar to its second operation.

The seventh operation of the method. It consists in turning on the sixth stage (time interval T-6). It is performed by connecting the second battery of CB-2 capacitors to the network by means of the second thyristor starter TS-2 and disconnecting the first battery of CB-1 capacitors by the first thyristor starter TS-1 when the third battery of CB-3 capacitors is connected to the network. This operation of the method is performed according to the algorithm similar to its third operation.

The eighth operation of the method. It consists in turning on the seventh stage (time interval T-7). It is performed by connecting the first CB-1 capacitor bank to the network by means of the first TS-1 thyristor starter with the second CB-2 and the third CB-3 capacitor banks connected to the network. This operation of the method is performed according to the algorithm similar to its second operation.

Switching off the reactive power control stages and, in general, the condenser unit is also performed in eight operations, but in reverse order.

In the formula and in the description of the principle of operation of the method, in accordance with the drawings, the option is considered when the thyristor switches of the first and second starters are switched on in phase "A" and in phase "C" and the device starts from the moment of transition through zero of the line voltage between phases "B" and "C" of the network. This is not the only option, others are also possible. For example, when switching the three inputs of the device in the clockwise or counterclockwise direction at the output of the mains switch and maintaining the direct order of the phases, the device will also successfully perform the known and newly introduced operations and the sequence of operations of the method, starting respectively from the moment of transition through zero of the other two line voltage of the three-phase network.

4. Simulation of a three-complete capacitor plant with seven-stage reactive power regulation
The purpose of the simulation is to test the functioning of a seven-stage reactive power control by a capacitor installation made in the form of three sets of capacitor blocks with switching devices, as well as to study physical processes with a new method of seven-stage reactive power control. To achieve this goal, models of this installation were developed in the MATLAB environment and studies were performed when switching on and off seven stages of reactive power regulation by a capacitor plant and switching from one stage of reactive power regulation to another [20]. The model is shown in Figure 2.

The model contains a three-phase network (Ua, Ub and Uc), a power transmission line (PTL), a network switch unit (NS), the first (CB-1), the second (CB-2) and the third (CB-3) capacitor bank, modules of the first (TS-1), second (TS-2) and third (TS-3) thyristor switches with a synchronized and phased control pulse generation unit (CPG), an active-inductive load (ZL), current measuring sensors and voltage and other auxiliary elements.

![Figure 2. Block-modular model of the proposed capacitor plant with seven-stage reactive power regulation.](image-url)
Figure 3 shows the results of performing operations on the model of the method of seven-stage regulation of the reactive power of a capacitor plant in dynamics.

The following symbols are introduced on the waveforms (Fig. 3):

- $u^*_A$ and $u^*_{BC}$ - synchronizing signals proportional to the phase $i_A$ and linear $u_{BC}$ network voltages, respectively;
- $u_A$ - phase voltage of the network;
- $i_A, i_B$ and $i_C$ - phase currents of the network;
- $i_{kA}, i_{kB}$ и $i_{kC}$ - phase currents of the capacitor bank;
- $i_{A2}$ - phase load currents;
- $T-1, T-2, T-3, T-4, T-5, T-6$ и $T-7$ - the intervals of operation of the first, second, third, fourth, fifth, sixth and seventh stages, respectively.

The given waveforms illustrate the instantaneous (Fig. 3a) and active (Fig. 3b) values of the mains voltages and currents, the capacitor bank and the active-inductive load when connecting seven stages of reactive power compensation of the network.

From the waveforms (Fig. 3) it can be seen that with the seven-stage regulation of reactive power by a three-complete capacitor installation, the currents do not exceed their steady-state values when switching from one stage of reactive power regulation to another. The installation is switched off first by thyristors with natural switching, and then by a de-energized mains switch. This happens without the occurrence of an arc on the contacts and, therefore, without switching losses.

An appropriate field of application of the proposed method is power supply systems with extended power lines. The proposed method, as a more advanced one, has an improved accuracy of reactive power regulation, due to an increase in the control stages without increasing the number of electrical and electronic switching devices in the capacitor plant.

5. Conclusion
The main results of the work performed are as follows.

The model of a three-complete capacitor plant shows the possibility of increasing the number of stages (from three to seven) of switching three-phase capacitor banks with thyristor switches and increasing the accuracy of reactive power regulation.

It is also shown that the connection of three-phase capacitor banks to the network (first two phases are connected, and then the third), by analogy with the process of their natural disconnection by
thyristor switches (first one phase is switched off, and then two), switches the reactive power control stages practically in the steady-state mode of the capacitor plant.

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