The Principle of Construction of Capacitive Reactive Power Compensators with Three-Stage Regulation

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Abstract. It is proposed to reduce the number of electrical and electronic devices by 1.5 times in three-stage capacitor installations by changing the connections in the power circuit and using a special control method. The new principle of construction of reactive power compensators will allow, with minimal changes and additions to existing installations, to reduce the costs of their production and the cost of finished products. The existing installations contain three blocks of the same type of capacitors, each of which is equipped with an electrical and electronic device and resistors for their discharge. It is proposed to connect two of these three blocks in parallel without changing the design of the products, using a common electronic device for connecting and disconnecting the resulting block of capacitors with double capacity and a common electrical device in the capacitor discharge circuit of this block. A model is presented in the Matlab environment for the study of dynamic and stationary processes of three-stage reactive power regulation in a new scheme of a capacitor plant. Numerical experiments have shown that when the installation is switched on and off, as well as when switching from one stage of reactive power regulation to another, the proposed device does not create bursts of starting currents. After starting, it almost immediately enters the steady-state operation mode and when switching stages, it also immediately passes from one level of the steady-state values of such to another level of their steady-state values. The installation is switched off without switching losses and without arcing on the mechanical contacts, since thyristor switches with natural switching are switched off first, and then the de-energized mains switch.

1. Introduction
To unload electric networks from reactive power, reduce electricity losses and equalize the voltage of consumers, capacitor installations are used [1-12]. The power of the installed capacitor blocks is selected taking into account the schedule of electrical loads. Taking into account the changes in the load schedule, there is a need for step-by-step regulation of reactive power. To date, three-stage regulation of reactive power by capacitor installations is widely used, in which the number of stages of...
reactive power regulation is equal to the number of capacitor blocks having the same parameters [13-18].

Switching on and off of the condenser unit is performed by a mains switch, and switching on and off of the capacitor banks between the stages of reactive power regulation is carried out using thyristor switches.

The disadvantage of the existing principle of constructing capacitor installations with a three-stage method of regulating reactive power is the use of a large number of switching devices, which is associated with an increase in the cost of their production.

This work is devoted to the elimination of this disadvantage, in which a new scheme of a capacitor plant with a special method of three-stage regulation of reactive power is proposed.

2. The purpose of the work and its achievement

The purpose of this work is to reduce the number of switching devices for three-stage regulation of reactive power by a capacitor plant by changing the power circuit and introducing new operations into the control method with a modified sequence between existing and newly introduced operations.

As a result of achieving this goal, the number of electrical and electronic devices has been reduced by 1.5 times [19].

This is achieved by the fact that the capacity of the second block of capacitors is twice as large as that of the first, while the second stage of reactive power regulation is turned on when the first block of capacitors is turned off, and the third stage is turned on by connecting the first block of capacitors in parallel to the second block of capacitors.

In Figure 1 shows a functional diagram of a capacitor plant with a new method of three-stage regulation of reactive power. The diagram (Figure 1) contains a three-phase network (Va, Vb, Vc), a power transmission line (PTL), a network switch (NS), an active-inductive load (ZL), the first block of capacitors (CB-1) with a resistive block (RB-1) of the discharge of capacitors of the first block, the first thyristor starter (TS-1) with thyristor switches TS-1, TS-2, the second block of capacitors (CB-2) with a resistive block (RB-2) the discharge of the capacitors of the second block, the second thyristor starter (TS-2) with thyristor switches TS-3, TS-4 and the control pulse generator (CPG). The control input of the CPG is connected to the control signal Uc, and its six outputs 1 - 6 are connected to the control circuits of the corresponding thyristor switches and to the keys of the resistive capacitor discharge blocks.

![Figure 1. Functional diagram of a new capacitor plant with three-stage reactive power regulation.](image-url)
3. The principle of operation of the proposed method and device

The essence of the proposed method of three-stage regulation of reactive power in the new scheme of a capacitor plant is the sequence of execution of 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 any time, the mains switch supplies voltage to the thyristor starters TS-1, TS-2 and the control pulse generator with direct connection of one phase of the capacitor banks CB-1 and CB-2, for example, phase "B", to the network.

**The second operation of the method.** It consists in turning on the first stage. It is performed by connecting the first block of the capacitor bank to the network by means of the first thyristor starter when the second block of the capacitor bank is turned off. First, they turn on one thyristor key, for example, for phase "C", the switch TS-2, 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.

**The third operation of the method.** It consists in turning on the second stage. It is performed by connecting the second block of the capacitor bank to the network with the second thyristor starter and disconnecting the first block of the capacitor bank with the first thyristor starter. The first thyristor starter is switched off 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 to the network, the second block of the capacitor bank with a second thyristor starter first turns on one thyristor key, for example, for phase "C" key, at the moment of transition through zero of the line voltage between phases "B" and "C" of the network, and then turns 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 5 and 6 of the control pulse generator.

**The fourth operation of the method.** It consists in the inclusion of the third stage. It is performed by connecting the first block of the capacitor bank to the network by means of the first thyristor starter when the second block of the capacitor bank is connected to the network. This operation of the method is performed according to the algorithm similar to its second operation.

Switching off the three stages of reactive power regulation and the capacitor plant as a whole is also performed in four 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 the proposed capacitor plant with three-stage reactive power regulation

The purpose of the simulation:

1. Checking the functioning of a three-stage reactive power control by a capacitor installation made in the form of two sets of capacitor blocks with switching devices;

2. Research of physical processes with a new method of three-stage regulation of reactive power.

To study the proposed scheme of the capacitor plant, a model was developed in the MATLAB environment [20]. It is shown in Figure 2.
The model consists of a three-phase network (UA, UB and UC), a power transmission line (PTL), a network switch block (NS), the first (CB-1) and second (CB-2) capacitor block, modules of the first (TS-1) and second (TS-2) thyristor switches with a synchronized and phased control pulse generator unit (CPG), active-inductive load (ZL), current and voltage measuring sensors and other auxiliary elements.

The simulation results are represented by the waveforms shown in Figure 3. The following symbols are introduced on the oscillograms Figure 3a and 3b: \( u^*_{A} \) and \( u^*_{BC} \) are synchronizing signals proportional to the phase \( u_A \) and linear \( U_{BC} \) network voltages, respectively; \( U_A \) - the phase voltage of the network; \( i_A, i_B \) and \( i_C \) - phase network currents; \( i_{AC}, i_{CB} \) and \( i_{CB} \) - phase currents of the capacitor bank; T-1, T-2 and T-3 - are the intervals of operation of the first, second and third stages, respectively. The oscillograms (Figures 3a and 3b) illustrate the voltages and currents of the network, capacitor banks and active-inductive load with three-stage regulation of reactive power. In Figure 3a, at the time interval T-1, the first block of capacitors CB-1 (the first stage of regulation) is connected to the network. At the end of the time interval T-1 and the beginning of the time interval T-2, the load increases and the second block of capacitors CB-2 is put into operation, and the first block CB-1 is switched off (the second stage of regulation). The second block of capacitors CB-2 operates at the time interval T-2. At the beginning of the time interval T-3, the first block of capacitors CB-1 is connected to the second block of capacitors CB-2 by thyristors TS-1 (the third stage of regulation).

The oscillogram (Figure 3b) also illustrate the operations of the three-stage reactive power regulation method in the new circuit of the capacitor plant, but in the reverse sequence (T-3 ÷ T-1), that is, at the time interval T-3, the load reaches the maximum value and therefore both blocks of capacitors (CB-1 and CB-2) are in operation (the third stage of regulation). At the beginning of the time interval T-2, the load decreases and the CPG removes control pulses from the TS-1 thyristor block to turn off the CB-1 capacitors, and only the capacitors of the CB-2 block remain in operation at this time interval (the second stage of regulation). At the end of the time interval T-2 and the beginning of the interval T-1, the CPG supplies control pulses to the TS-1 thyristors and simultaneously removes control pulses from the TS-2 thyristors to switch from the CB-2 block to the CB-1 block, transferring the installation to the first stage of regulation.

Figure 2. Block-modular model of the proposed capacitor plant with three-stage reactive power regulation.
From the oscillograms with the three-stage regulation of reactive power by the new circuit of the capacitor plant, it can be seen that when the first stage is turned on and the transition from one stage of reactive power regulation to another, the currents do not exceed their steady-state values. Switching off the installation is performed without the occurrence of an arc on the contacts of the network switch NS 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 perfect one, can replace known control methods in devices with direct reactive power compensation.

5. Conclusion
According to the results of the researches of a new scheme of a capacitor plant with a three-stage regulation of reactive power and a reduced number of electrical and electronic devices by 1.5 times, the following conclusions can be drawn.

The use of three-stage reactive power regulation in the new scheme of the capacitor plant does not create surges of inrush currents when the plant is turned on and off, as well as when performing the operation of a special method of reactive power regulation.

In the process of switching from one stage to another, the currents consumed from the network almost immediately switch from one steady-state value to another. In addition, switching off the capacitor blocks during the transition from one stage of reactive power regulation to another is performed by natural switching of thyristors, without creating switching losses.

When disconnecting the condenser unit from the mains, due to the same natural properties, it allows you to turn off the mains automatic machine in a de-energized state, which means without the occurrence of an electric arc on its contacts.

6. References
[1] Panfilov D I and Elgebaly A E 2016 Modified Thyristor Controlled Reactors for Static VAR Compensators 2016 IEEE 6th International Conference on Power and Energy (PECON 2016) (Melaka, Malaysia)
[2] Panfilov D I, Elgebaly A E and Astashev M G 2017 Topologies of thyristor controlled reactor with reduced current harmonic content for static var compensators 17th EEEIC conference (Milan, Italy)
[3] Panfilov D I, Elgebaly A E and Astashev M G 2017 Design and Optimization of New Thyristors Controlled Reactors with Zero Harmonic Content 18th International Conference of Young Specialists on Micro Nanotechnologies and Electron Devices
[4] Panfilov D I, Elgebaly A E and Astashev M G 2017 Thyristors Controlled Reactors for Reactive Power Control with Zero Harmonics Content 17th IEEE International Conference on Smart Technologies IEEE EUROCON (Ohrid, Macedonia)
[5] Panfilov D I, Elgebaly A E and Astashev M G 2017 Design and evaluation of control system for static VAR compensators with thyristors switched reactors IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON) (Riga, Latvia)

[6] Panfilov D I, Elgebaly A E and Astashev M G 2016 Design and Assessment of Static VAR Compensator on Railways Power Grid Operation under Normal and Contingencies Conditions 16th EEEIC conference (Florence, Italy)

[7] Klimash V S 2002 The booster devices for compensation of voltage deviations and reactive energy, amplitude, and pulse phase control Monograph (Vladivostok: Dalnauka) p 141

[8] Solodukha Ya Yu 1981 Status and prospects of introduction of static reactive power compensators into electric drive (generalization of domestic and foreign experience) Reactive power in networks with non-sinusoidal currents and static devices to compensate Informelectro (Moscow)

[9] Panfilov D I and Elgebaly A E 2016 Modified Thyristor Controlled Reactors for Static VAR Compensators 2016 IEEE 6th International Conference on Power and Energy (PECON 2016) (Melaka, Malaysia)

[10] Dionise T J and Morello S 2014 Comprehensive Analysis to Specify a Static Var Compensator for an Electric Arc Furnace Upgrade IEEE IAS Annual Meeting Conference Record

[11] Dionise T J 2012 Assessing the Performance of a Static Var Compensator for an Electric Arc Furnace IEEE Industry Applications Society Annual Meeting (Las Vegas, NV)

[12] Kawamura A 1983 An Optimal Control Method Applied for the Compensation of the Fundamental VAR Fluctuations in the Arc Furnace IEEE Transactions of Industry Applications vol 1A-19 iss 3 pp 414-423 doi: 10.1109/TIA.1983.4504217

[13] Kabyshev A V 2012 Reactive power compensation in electrical installations of industrial enterprises: a textbook Tomsk Polytechnic University Tomsk: TPU Publishing House p 185

[14] Klimash V S and Tarakanov V I 2015 Methods of switching on three-phase electrical equipment and their implementation Electrotechnical complexes and control systems (Voronezh) 2

[15] Klimash V S, Tarakanov V I and Getopanov A Yu 2016 Patent 2577769 RF, IPC H02J 3/18 (2006.01) The method of switching on the capacitors 2015109785/07

[16] Pospelov G E, Sych N M and Fedin V T 1983 Compensating and regulating devices in electrical systems Pospelov St. Petersburg: Energoatomizdat p 112

[17] Akagi H, Kanazawa Y and Nabae A 1983 Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits IPEC 83 Int. Power Electronics Conf. (Tokyo, Japan) pp 1375 – 1386

[18] Edson H W, Richard M S, Mauricio A 1993 New Concepts of Instantaneous Active and Reactive Power in Electrical Systems With Generic Loads IEEE Transactions on Power Delivery Vol 8

[19] Klimash V S, Tabarov B D, Nimafov R R and Antonov E G 2021 Patent no. 2749606 RF, IPC H02J 3/18 (2006.01) A method of three-stage regulation of reactive power by a condenser installation

[20] Klimash V S and Tabarov B D 2021 A block-modular model for studying the physical processes of an electrothermal installation with reactive power compensation Certificate on the State registration of computer program no 2021614296