Method of Switching on and Off a Power Transformer with a Capacitor Bank in an Electrothermal Installation

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Abstract. The article is devoted to issues related to increasing the energy efficiency of industrial electrothermal installations, both in starting and stationary operating modes due to the use of capacitors and thyristor starters with special control. The results of a significant reduction in the duration of the transient process, elimination of surges and asymmetry of starting currents and voltage drawdowns are presented. The results of full compensation of the reactive power of the network in the steady-state mode are also presented. It is shown that the starting currents do not exceed their steady-state values and that the shutdown of the electrothermal installation is performed without the occurrence of an arc and switching losses at the contacts of the switches. Researches of an electrothermal installation with a capacity of 750 kV·A and a voltage of 380 / 80 V are made on the model in the Matlab environment.

1. Introduction

Currently, industrial enterprises widely use electrothermal installations of medium and high power, which are designed for heating metals and are used in mechanical engineering and metallurgy [1-15]. Electrical technologies are used in hardening of parts for lifting and transport equipment, in the production of parts made of special hard-to-deform alloys for underwater and aircraft vehicles.

The experience of existing electrothermal installations shows that switching on and off of electrical equipment is carried out using electrical switching devices, which create a negative impact on the network, the electrical equipment of the installation itself and on switching equipment [16-18]. These include an increase in additional losses, a decrease in the quality of electricity, and a shorter service life of electrical equipment.

An analysis of the patent-licensing situation and an analytical study of the literature on the creation of electrothermal installations allowed us to identify their common disadvantages – low energy efficiency and unsatisfactory dynamic properties.

These disadvantages are caused by the lack of regulated switching equipment and a method for controlling electromagnetic processes. They are also due to the lack of means of compensating for reactive power.
2. The purpose of the work
The purpose of this work is to improve the energy efficiency and dynamic properties of an electrothermal installation. To achieve this goal, it is proposed:

1. Turn on the battery of cosine capacitors at the input of the power (furnace) transformer.
2. To connect the furnace transformer and the battery of cosine capacitors to the network, use thyristor switches with natural switching.
3. Apply a special control algorithm for a power (furnace) transformer.
4. Apply a special control algorithm for a battery of cosine capacitors.
5. To develop a method for controlling the switching on and off of an electrothermal installation, combining control algorithms for a power (furnace) transformer and a battery of cosine capacitors with a new sequence of operations performed.
6. Perform numerical experiments in the MATLAB environment for an electrothermal installation with the developed device and a new control method.

3. Device development
The functional diagram of the electrothermal installation with the proposed device is shown in Figure 1. It shows the following elements.

Three-phase network (Va, Vb, Vc), power transmission line (PTL), automatic switch (AS), the first thyristor starter (TS-1) with thyristor switches TS-1 and TS-2, power (furnace) transformer (PT), load (ZL), the second thyristor starter TS-2 with thyristor switches TS-3 and TS-4, capacitor banks (CB), control pulse generator (CPG) with synchronizing inputs (SI), start-timer button (S-T), controlling input 1 and four outputs 2, 3, 4, 5, designed to connect the corresponding thyristor switches to the control circuits.

![Functional diagram of an electrothermal installation with the proposed device](image-url)

**Figure 1.** Functional diagram of an electrothermal installation with the proposed device.

The device elements are connected as follows. Between the three-phase automatic switch AS and the primary winding of the power transformer PT, the capacitor banks CB, the TS-1 and TS-2 thyristor starters, as well as the control pulse generator CPG are connected.

The first thyristor starter TS-1 contains two thyristor switches TS-1 and TS-2 with natural switching, included in the phases "A" and "C" and the bus for direct connection of the phase "B". It
connects the primary winding of the power transformer PT to the output of the three-phase automatic switch AS, to which the synchronizing input of the SI pulse generator of the control CPG with thyristor switches TS-1 and TS-2 is also connected.

The second thyristor starter TS-2 contains two thyristor switches TS-3 and TS-4 with natural switching, included in the phases "A" and "C" and the bus for direct connection of the phase "B". It connects a battery of capacitors CB to the output of a three-phase automatic automatic switch AS, to which the synchronizing input of the CI pulse generator of the control CPG with thyristor switches TS-3 and TS-4 is also connected. The first 1 and second 2 outputs of the control pulse generator CPG are connected to the control circuits of the TS-2 and TS-1 thyristor switches related to phases "C" and "A" of the first thyristor starter TS-1, and the third 3 and fourth 4 outputs are connected to the control circuits of the TS-4 and TS-3 thyristor switches related to phases "C" and "A" of the second TS-2 thyristor starter.

4. The principle of operation of the proposed device

The device, according to the proposed technical solution, works and performs known and newly introduced actions in a certain sequence [19]. The essence of the proposed technical solution is explained by the following description.

When the electrothermal installation is turned on, the actions of the device are performed in the following sequence.

**The first action of the device.** Prepare the power electronic unit and the control unit for operation. To do this, at an arbitrary time, a three-phase automatic switch AS is applied to the thyristors and the pulse generator of the control CPG (pre-switching on the installation).

**The second action of the device.** At the moment of transition through zero of the phase voltage of phase "A", the control pulse generator of the generates a control pulse CPG at the first output 1 for the thyristor switch TS-2 of phase "C" and after its inclusion, a line voltage is applied to the transformer between phases "B" and "C".

**The third action of the device.** At the moment of transition through zero of the line voltage between phases "B" and "C", the control pulse generator of the simultaneously generates control pulses CPG at the second 2 output for the thyristor switch TS-1 of phase "A" in the circuit of the power transformer PT and at the third 3 output for the thyristor switch TS-4 of phase "C" in the circuit of the capacitor bank CB and after switching on the thyristor switch TS-1 of phase "A", a three-phase voltage is applied to the transformer with the formation of a symmetrical three-phase system of currents and their entry into the steady-state mode in the for one half-period, and after switching on the thyristor switch TS-4 phase "C", a line voltage is applied to the battery of capacitors CB between the phases "B" and "C".

**The fourth action of the device.** After applying the line voltage between phases "B" and "C" to the BC capacitor bank, the control pulse generator of the generates a control pulse CPG at the fourth 4 output for the thyristor switch TS-3 of phase "A" and after it is turned on, a three-phase voltage is applied to the capacitor bank CB after one half-period with the formation of a symmetrical three-phase system of currents and their entry into a steady state for one half-period.

The electrothermal installation is also switched off in four steps, but in reverse order, while the first two of them are performed by themselves due to natural processes in the circuit.

Switching off the single-operation thyristors of the first and second thyristor starters TS-1 and TS-2 occurs naturally after removing the control pulses from the thyristors. Both the transformer PT and the capacitor bank CB will first turn off one of the phases "A" or "C", the current through the thyristor switch of which will pass through zero earlier, and then two phases will turn off when the total current for them passes through zero. After switching off the thyristors of the first TS-1 and the second TS-2 thyristor starters, the de-energized automatic switch AS is turned off.

In the description of the principle of operation of the device 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 the phase voltage of phase "A"
passes through zero. This is not the only option, others are also possible. For example, when switching three inputs of the device at the output of the mains switch in the clockwise or counterclockwise direction and while maintaining the direct order of the phases, the device will also successfully perform the known and newly introduced operations of the method and the sequence of actions of the device, starting respectively from the moment of transition through zero of the phase voltage of phase "B" or phase "C".

5. Development of a block-modular model of an electrothermal installation

To research dynamic and stationary processes in the MATLAB environment, the authors developed models of an electrothermal installation [20]. It is shown in Figure 2a. The model consists of a three-phase network (Ua, Ub and Uc), a power transmission line (PTL), a block automatic switch (AS), modules of the first (TS-1) and second (TS-2) thyristor switches with a synchronized (SI) and phased with the network control pulse generator (CPG) unit, a button start-timer (S-T), a power transformer (PT), capacitor banks (CB), active-inductive load (ZL), current and voltage measuring sensors, as well as other auxiliary elements.

The CPG unit is synchronized with the network and is designed to change the conductive state of the TS-1 and TS-2 modules when performing the operations of switching on and off the electrothermal installation. Figure 2b shows the power module of the thyristor switches in an expanded form. As can be seen from Figure 2b, phase "B" is connected directly, and phases "A" and "C" are connected through thyristor starters TS-1 and TS-2 consisting of thyristor switches TS-1 and TS-2.

Figure 2. Block-modular model of an electrothermal installation with the proposed device.
Let’s consider the results of modeling and studying dynamic processes using the above-described special method of switching on and off an electrothermal installation. The waveforms of electromagnetic processes when the electrothermal installation is turned on and off are shown in Figure 3. The following designations are introduced on the waveforms: $U_A$ and $U_{BC}$ – phase and line voltages of the network; $A$, $B$ and $C$ – phase currents, respectively, related to the power transformer, the battery of cosine capacitors and the network.

![Figure 3. Oscillograms of currents and voltages when switching on and off the electrical equipment of an electrothermal installation.](image)

From the obtained results of the study, it can be seen that the switching on and off of an electrothermal installation with a new device is carried out without a negative impact on the network and electrical equipment (power (furnace) transformer, capacitor bank and electrical apparatus).

The scope of application of the proposed device is electrothermal installations of medium and high power.

6. Conclusion
According to the results of the study of stationary and dynamic processes of an electrothermal installation, the following conclusions can be drawn.

The inclusion of an electrothermal installation does not cause surges and asymmetry of currents, and voltage drawdown in the network, does not create dynamic shocks to the power (furnace) transformer and capacitor banks, almost immediately enters the steady-state mode with full compensation of reactive power.

The installation is switched off without the occurrence of an electric arc on the contacts of the automatic switch and without switching losses.

The method of controlling the device preserves the quality of electricity in the network, increases the energy performance of the installation, reduces the heating time of the workpiece and electricity consumption.

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