Hardware solutions for connecting static capacitor banks in high voltage electrical networks

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Abstract. This work is dedicated to finding effective hardware solutions for implementing the power part of reactive power compensation units for high voltage electric networks. It shows the possibility of cooperative usage of thyristor and electromechanical key elements for switching static capacitor batteries in high-voltage networks. Based on the suggested hardware solutions main technical and cost characteristics of thyristor capacitor units are determined. The rationality of their use in industrial high-voltage electrical networks of 6-10 kV is concluded. It is shown that the usage of hybrid thyristor capacitor units allows one to reduce the expenses, to provide the required range of accuracy of reactive power regulation, to cut power losses in the network, to guarantee normalized voltage level in the load nodes and to increase the reliability and duration of power equipment life cycle.

1. Introduction

Nowadays it becomes highly important for a country’s successful development to decrease the usage of the resources and to derive benefit from rational use of all types of means to the uttermost. In the face of this challenge, power generating industry is to complete various tasks which includes the following:

- to increase significantly the efficiency in the electric power industry and to reduce the losses in networks;
- to improve the quality and reliability of the electric industry processing by the advanced management of electric networks.

It makes sense to take full advantage of using the Smart Grid concept (creating an “intelligent network” of active and adaptive transferring and dispatching control systems) to address these tasks. Smart Grid includes flexibility, accessibility, reliability, and cost-effectiveness of the electric network management [1-5]. It is well-known that the role of intellectualization of the high-voltage distribution electric networks (6-35 kV) is downplayed at present.

Currently the electric network element (distributing regional power supply networks) is the foundation of the economic progress and welfare of our country. The growth of large cities, the expansion of energy consuming industrial enterprises, an increase in the density of electrical loads pose a new challenge for electric grid companies in reliable and efficient transportation and distribution of electricity.

The electrical power systems of these facilities make up the lion’s share of all distributing networks (with the exception of the ones of 0.4 kV) and stay the closest to direct consumers. However, the process of intellectualization in distributing electric networks of medium voltage (6-35 kV) is left unaddressed. Even though the percent of technological losses of electric energy in distributing electric networks with a voltage of 6-10 kV averages 8-12% of the amount of electricity supplied to the network. The amount of electricity loss is determined by the parameters of the electrical circuit, network design and load conditions.

The calculations for 10 kV networks have shown that energy losses depend significantly on the amount of reactive power transmitted to consumers through the network elements. For example, when the
power factor (\(\tan \phi\)) changes from 0.5 to 0.8, the energy loss increases by about 20%. This task can be easily resolved with the help of intellectualization of distributing electric networks by applying the usage of modern automatic reactive power compensation systems. These devices are highly demanded, and they can significantly increase the level of energy efficiency of distributing electric networks [6].

2. Compensation of reactive power in high-voltage power networks

The above stated was acknowledged by scientific research, including the analysis of large statistical data of the city electric network. We analyzed the performance of "Voronezh Gorelektroset" in this paper. It is the largest territorial grid organization in Voronezh, occupying about 70% of the retail market for electric energy and having a complex technical infrastructure and serving more than 9,500 electricity consumers. The analysis covers two-time ranges of the “Voronezh Gorelectroset”: April - June 2014-2018 and December 2014-2018. For each feeder of eighty-three main power distribution stations, we carried out measurements during 3 months in the spring-summer time period and one month in the winter period.

As a result of studying the obtained measurements database, we established a significant correlation between the system load and the load of the main electricity consumers by power distribution points of the hydroelectric power station. We used the data to calculate diurnal variation of reactive power factor in power distribution stations. The diagrams show diurnal variation of active power (yellow curve), reactive power (blue curve), present power factor (tg\(\phi\) grey curve) and controlled power factor (tg\(\phi\) = 0.35 orange line).

![Figure 1](image1.png)

**Figure 1.** Diurnal variation of active and reactive power in power distribution stations.

Analysis of the diurnal variation of reactive power factor displays that in the course of Smart Grid concept there are good reasons to implement the controlled reactive power compensation for maintaining a high level of energy efficiency. Modern technologies offer several types of hardware solutions for reactive power compensation:

- synchronized electric machine compensators (SC);
- controlled shunt reactors CSR (including those with unregulated sections of capacitors);
- static reactive power compensators (STATCOM);
- controlled thyristor capacitor units (TCU).

All these hardware solutions for the controlled reactive power compensation were carefully analyzed from the theoretical point of view and put into practice [7-10].

Synchronized electric machine compensators (SC) do not always successfully combine their main functions of electric drive and reactive power generation and are not completely reliable and do not have large specific mass-dimensional indicators. Controlled shunt reactors and thyristor groups of power capacitor banks connected by thyristor groups have various modulations (also called SVC - Static VAR Compensator, figure 2), good adjusting characteristics, but have an increased cost due to the use of semiconductor switches [11].

It is worth mentioning that the phase-pulse method of regulating the current in the reactor generates harmonics into the network. This makes it necessary to implement a filter system, providing some
additional obstacles associated with the appearance of higher harmonic and possible resonance, due to the presence of capacities in the SVC installation. Today’s level of development of power conversion technology allows one to use the powerful static devices for the best possible control of electric power facilities at the level of the FACTS technology platform. To perform such a function hardware solution with the ability to consume or return reactive power are required. The devices such as static reactive power compensator (STATCOM) are employed, which are operating on the principles of pulse-width modulation (PWM), with the mandatory installation of a filter between the converter and the network (figure 3). STATCOM devices can also work in the active filtering mode.

![Figure 2. SVC Compensator in RP structure.](image1)

![Figure 3. STATCOM structure.](image2)

With the multifunctionality and adaptability of such devices, their widespread use is restricted by their high cost (mainly because of the need to use either fully controlled thyristors 1-6 in conjunction with 1’-6’ diodes, or complex artificial switching nodes) [12-14].

Controlled thyristor capacitor units (TCU) use thyristors groups to connect the capacitor banks. This allows one to avoid a number of issues that can arise when connecting static capacitors to the network with electromechanical keys. In accordance with the requirements of reactive power regulation during the operation of the power capacitor banks, when regulating the stages, the capacitor banks undergo frequent switching. In this case, large inrush currents arise, significantly (up to 250 times) exceeding the nominal value and significant power surges. This results in the need of using the specially designed high-speed electromagnetic contactors or high-cost vacuum circuit breakers. However, with an average daily connection frequency of more than 10-50, it is advisable to use power capacitor banks hardware solutions. Many circuit design solutions have been developed by now for connecting power capacitors to the network, a great amount of companies have launched the production of TCU.

It should be noticed that, along with sufficient functionality, the disadvantage of such solution is the high cost of high-voltage semiconductor equipment, which increases significantly with an increase in the number of power capacitor banks stages (which is directly related to the quality of reactive power control).

3. Hybrid switching method of power capacitor banks
For high-voltage networks (6, 10, 35 kV), the most reasonable are reactive power compensation installations using a hybrid method of switching power capacitor banks with a network [15, 16]. This method resides in the usage of semiconductor power keys (thyristor, thyristor-diode groups, bidirectional thyristor), shunted by the contactor (figure 4). Power keys 3, 4 perform the function of connecting the power capacitor bank to the network at the most favorable moment (the passing of the phase voltage line through zero). After that, the corresponding signal from the control system is supplied to contactor 2 and it shunts keys 3, 4, and control signals are taken from them. This long-term mode of the TCU work is maintained until the power capacitor bank is turned off. Then a corresponding signal is supplied to turn on power keys 3, 4, and with a slight delay - a signal to turn off the drive of contactor 2. Its shutdown occurs, in fact, in a de-energized (off-the-line) mode (the load current continues to flow through included
power keys 3, 4). Next, a signal from the control system comes for a guaranteed shutdown of the battery during a fraction of a half period of the supply voltage. Thus, mechanical keys 2 operate in an extremely light, low-loaded mode. Therefore, as contactor 2, high-voltage switches (vacuum) and even disconnectors with a high-speed electromagnetic drive can be used.

![Diagram of reactive power compensation unit based on a hybrid connection of power capacitor banks.](image)

**Figure 4.** Structure of reactive power compensation unit based on a hybrid connection of power capacitor banks.

Practising a hybrid method of switching capacitor bank 1, the requirements for power keys 3, 4 can be significantly lowered. Due to the fact that the semiconductor device (thyristor, bidirectional thyristor, diode) can function in overload mode for a short time, it is possible to reduce the value of the installed power of the mode keys by 2-10 times [17]. The volume of reducing of the installed power (and, consequently, the cost) of power keys 3, 4 directly depends on the speed of contactor 2. The faster the bridging of power contacts of all three phases occurs in it, the more significant the reduction in the installed power of keys 3, 4 can be. Moreover, the cost of equipment will be reduced due to the lack of a conventional cooling system for semiconductor devices, which does not required in TCU switching modes.

The proposed hardware solutions for using hybrid TCU have a wide range of variations in the structure and specific design of the power unit of reactive power compensation installation. The best possible implementation scenario of hybrid TCU is selected depending on the specific requirements for regulating the mode of the electric network (range and accuracy of regulation of the RP), its main parameters (voltage level, value of the required RP value, compliance with standard quality parameters of voltage quality standardized by GOST (All-Union State Standard)), limitations on the cost of the main power equipment, and its resource of work.

It can be noted that the implementation of any option will reduce the cost of the installation (by 1 kvar of compensated RP) in comparison with typical units of reactive power compensation using high-voltage contactors and vacuum circuit breakers [18]. Moreover, the more sections the power capacitor bank has, the lower the unit cost of 1 kvar of compensated RP in comparison with similar contactor units of reactive power compensation [19]. This effect is achieved by usage of one common thyristor switching unit for the disconnecter system of individual sections of the QSG3, QSG4 battery. Figure 5 shows a single-line connection diagram for a 2-section power capacitor bank based on a hybrid thyristor switching.

![Single-line connection diagram for a 2-section power capacitor banks based on hybrid TCU.](image)

**Figure 5.** Single-line connection diagram for a 2-section power capacitor banks based on hybrid TCU.
As a rule, contactor units of reactive power compensation have similar structure and parameters. For example, two sectional power capacitor banks with 4 power levels (100 and 200 kvar) was installed at one of the 10 kV power distribution station of Voronezh Hydroelectric Station. Based on the minimum requirements of GOST 13109 to maintain the normalized value of the reactive power coefficient $\phi$ at a level of no higher than 0.35 and the actual load schedule on the connections of this power distribution station, the approximate number of switching sections of the units of reactive power compensation should be about 50 per day. With this switching mode, after 2-3 years of service there is a need to replace high-voltage contactors based on the resource run out. Therefore, the control system of the units of reactive power compensation based on the digital microprocessor controller of the DCRG "LOVATO Electric" series is configured for the number of switching no more than 5-10 times a day. In this mode the vacuum contactors used in the installation are guaranteed to ensure the required quality of RP compensation during the entire period of operation (at least 10 years) [20].

Along with two vacuum contactors of the KVT-10-6,3 / 630D-3 U3 type, the installation contains: 2 KEPl-6,3-ZUZ capacitors, 6 fuses PKT 1CO-VK-6 / 7.2-31,5-50 UZ, 6 reactors RMV-360-60-250, 2 current transformers TOL-10-1-2-0.5 / 10R-50/5 U2, 4 disconnector RVZ-10/400, and a control system.

To implement the hybrid TCU principle based on such an installation, minimal changes in the power part are required (to remove two vacuum contactors and add one QSG5 disconnector and a three-phase power key of thyristor switching, figure 5) and it is necessary to reprogram the microprocessor controller of the control system accordingly (its functionality allows providing the necessary operation algorithm of the power part of a two-stage power capacitor bank).

Given the cost of two high-voltage contactors (87,000 rubles), disconnectors (14,000 rubles) and a three-phase key of thyristor switching (based on either domestic thyristors T471-200 and diodes D371-250, or ABB thyristors of the S5TP series, and diodes 5SDA) approximately 32,000 rubles, we can estimate the cost reduction during the modernization of units of reactive power compensation at 476,000 rubles during its lifetime. At the same time, it is possible to ensure the required range and accuracy of regulation of the RP, reduce the loss of energy efficiency in the network, provide a normalized voltage level in the load node and increase the reliability.

4. Conclusion
1. Nowadays in the light of the increasing losses of electrical power in the networks of 6-35 kV it is necessary to expand the usage of up-to-date energy-saving technologies in the terms of Smart Grid concept.
2. An analysis of the load graphs of a typical city power grid shows the possibility of a significant reduction in electricity losses due to automatic compensation of reactive power on the 10 kV buses of the distribution points of the HPP. After analyzing the diagrams of the load of the city’s electric grid it becomes evident the possibility to cut the electricity losses due to the automatic compensation of reactive power in 10 kV connection of distribution stations of hydroelectric power stations.
3. Existing means of reactive power compensation have insufficient operating life cycle of switching equipment, which does not allow one to provide the required network power factor, according to the criterion of minimum power loss.
4. There are effective hardware solutions of connecting static capacitor batteries to a high voltage network based on thyristor keys.
5. The suggested usage of hybrid thyristor capacitor units in electric networks of 6-10 kV will allow one, at lower costs, to ensure the required range and accuracy of regulation of the RP, reduce the loss of energy efficiency in the network, provide a normalized voltage level in the load node and increase the reliability.

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