Power Compensators Based on Magnetically Controlled Shunt Reactors in Electric Networks with a Voltage between 110 kV and 500 kV

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***Abstract*-- It is shown that application of adjustable sources of reactive power based on magnetically controlled shunt reactors and capacitor banks in 110-500 kV grids allows to substantially lower the damage from power supply interruption, to reduce the need of electrical grids construction by maximizing power transmission capacity of existing lines, to improve the quality of power supply to end users, and it is a practical development of FACTS technology.**

***Index Terms*-- reactive power, sources of reactive power, controllable magnetic reactors, reactive power compensation.**

I. INTRODUCTION

THE world's power engineering industry associates the progress in operation of power systems with the implementation of FACTS technology, which ensures the most efficient use of power transmission lines and electrical equipment [1-4]. A major part of this technology is the use of automated adjustable sources of reactive power. For this purpose Static Var Compensators (SVC), thyristor-controlled compensators (STATCOM) and asynchronized synchronous compensators have been developed for many years. At the same time, for more than 10 years automated adjustable sources of reactive power with magnetically controlled shunt reactors (MCSR) and capacitor banks (CB), or SRP, have been actively implemented in power grids of Russia and the C.I.S. Such SRP are almost identical to SVC in terms of their functionality and have a number of technological, economical, and operational advantages and, in fact, are the simplest units and the natural first step to implement FACTS technology [1]-[3].

II. GENERAL

Insufficient reactive power compensation in power grids results in a higher reactive component in the power flow and, consequently, in a lower voltage and lower electrical system stability. This has been confirmed by the analysis of major recent failures, which has shown that the main reason of such failures is low usage rate of reactive power compensation devices in power systems. Therefore, the issue of reactive power compensation in power grids has become one of the key measures for ensuring reliable operation for power systems in the Russian Federation [3],[4].

Power transmission from generator to consumer is a complicated multi-stage power conversion physical process that requires various ways of maintaining electric and magnetic fields and thus requires both active and reactive power components. The reactive power generation does not require energy itself but its transmission over electrical grid requires extra cost to generate active power to cover losses. In addition, reactive power transmission from generators to consumers results in an extra load on the electrical grid elements and lowers their throughput. Therefore, increased yield of reactive power by generators in order to deliver it to consumers is not feasible [2]-[4].

Reactive power compensation at consumer end is one of the most effective means of rational power use. [2]-[5].

At present capacitor banks are extensively used by utilities, and especially by industry, due to their relatively low cost and simple maintenance. The CB power can be changed step-wise by changing the number of CB in operation. However, step-wise regulation has a number of drawbacks. For instance, when transmission line throughput needs to be increased to achieve static and dynamic stability and reduce losses both in grid and equipment, controllable reactive power compensation is a superior option. Additionally, in power systems of 110 kV or above, voltage stabilization often requires controllable compensation devices, which generate as well as consume reactive power. SVC and SC can be used to resolve such issues at 110 kV and higher substations. One of the disadvantages of SVC and SC is their rated voltage limitation – up to 35 kV, i.e. a step-down transformer is required to connect them to 110 – 500 kV grid. Compensation devices that can be connected directly to the grid without any intermediate transformer, which increases active and reactive power losses, have a number of advantages which improve efficiency of voltage regulation. Such compensation units

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include step-wise switched CB and continuously controlled reactor, connected in parallel [2],[5].

Installation of a controlled reactive power compensation unit at an intermediate point of power transmission line provides a benefit of subdivision of the line into sections and increasing its throughput capacity (subject to an appropriate voltage control). Reactive power consumed by controllable reactors under any operational conditions of the power transmission line is adjusted to the power flow in the line. In this case the line throughput is limited only by its maximum permissible current of the wires. Magnetically controlled shunt reactors (MCR) are very promising for reactive power compensation in long extra-high-voltage power transmission lines. MCRs installed in extended power grids allow to:

- Control and maintain voltage or other operating parameters without high-voltage circuit breakers;
- Reduce active power losses in power grids and improve their operational reliability due to a dramatically lower tripping rate of on-load tap changers of transformers;
- Increase static stability limit;
- Improve damping in the system;
- Limit the use of synchronous generators as controllable reactive power sources.

III. SRP BASED ON CB AND MCR

Until recent time MCRs have been perceived as having a major inherent drawback - a low fast acting. However, substantial successful experience in MCR operation was accumulated, showing MCR reaction time ranging from tenths of a second to several seconds, depending on customer requirements. There are analytical studies based on the system stability analysis which results have proven that the equivalent time constant can range from 0.01 sec to 20 sec and have no substantial negative effect on system stability [2].

In the recent years SRPs based on CB and MCR have been actively implemented in high voltage power grids 110 - 500 kV. SRP based on CB and MCR with rated power of 25, 32, 63, 100, and 180 MVA have been developed, manufactured, and commercially operated for voltage classes between 110 kV and 500 kV (see Fig. 1).

Successful experience has shown that when an MCR is used in SRP, it provides load-based charging power compensation in power transmission lines, reduced power losses in lines and substation equipment, voltage stabilization, higher throughput and reliability of high voltage power grids. Operational experience has proven their high reliability. Therefore, SRPs based on CB and MCR are approved by the Technical Policy of FGC UES (the Federal Grid Company of Russia) as one of the most promising and recommended devices.

The first SPR based on MCR and CB was installed in 1999 at Kudymkar substation, when RTU 25000/110, the first magnetically controlled reactor, was installed in parallel with CB of 42 MVAr. Three RTU 25000/110-based high voltage SRP with a 46-Mvar CB were installed at TomskNeft substations in the years of 2004 and 2005 and have proven to be highly efficient and reliable.

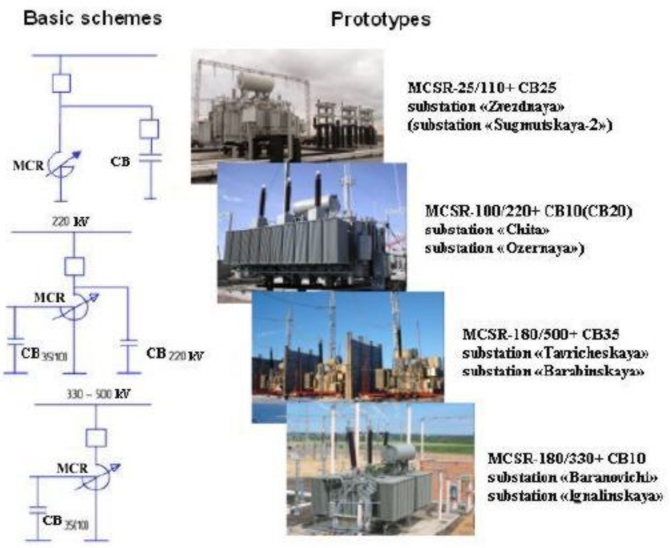


Fig. 1. MCR-based reactive power sources with rated voltage 110, 220, 330 and 500 kV

These high-voltage SRP prototypes required manual CB control. Their electrical schemes were applicable to voltage class of up to 110 kV. But the successful experience in operation of these units has formed a basis for development of new MCR-based high-voltage reversible reactive power sources for 110-500 kV. About two dozens of MCRs are currently successfully operated in the Russian Federation and C.I.S. countries: eight SRP with MCR of 25 MVAr 110 kV; one SRP with MCR of 63 MVAr 110 kV; four SRP with MCR of 100 MVAr 220 kV; three SRP with MCR of 180 MVAr 330 kV; and three SRP with MCR of 180 MVAr 500 kV. A number of other CB and MCR-based SRP are expected to be commissioned in the nearest future and the number of SRP in operation will double.

Experts of the Moscow Power Engineering Institute (Technical University), JSC «NIIPT» (Research Institute for Power Transmission by High Voltage Direct Current), and LLC «ESCO» participate in the development of high voltage stabilization systems (SRP) based on magnetically controlled shunt reactors (MCR) and capacitor banks (CB) and in their installation in power grids 110 - 500 kV [7, 9, 10] (in particular, pursuant to Orders No. 18 of January 19, 2007 and No. 75 of February 13, 2007 issued by JSC RAO UES Russia).

IV. SRP STRUCTURE AND PRINCIPLE OF OPERATION

Fig. 2 shows the SRP single-line diagram which includes a static capacitor bank and a magnetically controlled shunt reactor. The following settings are made in the SRP automated control system (ACS): voltage regulation setting, minimum reactor current, maximum reactor current, and a time delay Δt between two adjacent trippings of capacitor banks (between switching on/off of CB switches). The time interval is usually 1-10 minutes and depends on the SRP and power grid parameters. The magnetically controlled reactor is connected to the network via circuit breakers [5],[9].

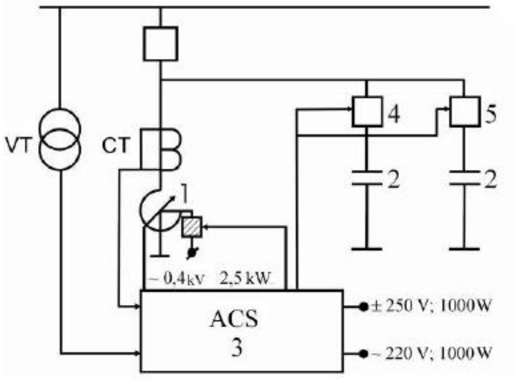


Fig. 2. SRP circuit diagram (1 – MCR; 2 – CB; 3 – ACS (SRP); 4 – switch; VT – voltage transformer; CT – current transformer)

If the load in the grid is low or absent (for example, during off-peak night loads), then there is a redundancy of reactive power in the grid due to charging power of the transmission lines. It results in high levels of voltage in the grid nodes, which is detected by voltage transformers (VT); so the ACS gives an order to increase the reactor magnetizing current. As a result, the reactor current increases (up to the maximum value, when appropriate), and the SRP switches to the reactive power consumption mode. The ACS keeps track of voltage variations due to load changes in the electrical grid and adjusts the voltage to the reference value by continuously changing the reactor magnetizing current.

When the grid load increases, a shortage in the reactive power occurs. The ACS system reacts to the voltage drop, checks the reactor current (if it is less than the minimal allowed value), and gives a command to switch on a capacitor bank and, thus, turns the SRP to the reactive power generation mode. Continuous regulation of voltage and reactive power is ensured by the reactor [5],[9].

If the load on the transmission line keeps increasing then again it results in the new conditions where the voltage decreases below specified value, and the reactor current falls below the minimum permissible value. The ACS gives a command to switch on the second capacitor bank.

When the load decreases in the line a surplus reactive power occurs and the voltage increases. At that moment SRP shall return from the reactive power generation mode to the reactive power consumption mode. Therefore, ACS gives commands to increase the reactor current and to switch off the capacitor banks.

Special requirements are established for SRP in "emergency" modes: during maintenance and after emergency outages. In general, SRP power (i.e. rated CB and MCR power) is determined using these modes and winter peak load and summer off-peak load modes. When SRP are optimally placed in the power grid and if CB and MCR parameters are selected properly, then a normal power supply is provided for consumers in all grid modes.

SRP installation ensures higher electrical grid throughput under maximum permissible operating current and voltage conditions and automatic voltage stabilization in the grid node according to the voltage setting in normal (an example is shown in fig. 3), maintenance, emergency, and post-emergency modes.

The SRP installation ensures not only a higher transmission line throughput but also much lower power losses. It is easy to demonstrate the efficiency of controllable reactive power compensation by using an example of a 110 kV, 25-kilometer long power transmission line with 240 mm^2 conductors (with a specific resistance and reactance R = 0.13 Ohm/km and X = 0.4 Ohm/km).

If the load is $P + jQ = 60$ MW + $j25$ MVAR (tgφ = 0.417) at the receiving end, then, depending on degree of reactive power compensation and on voltage level at the receiving end of the line, the active power losses during power transmission change as follows:

- In the nominal mode (assumed as initial) ($U_{load} = 110$ kV, $\underline{S} = 60 + j25$),

$$\Delta P = 0.378 \text{ MW}.$$

- If the voltage increases up to 120 kV at the receiving end of the line but the power consumption remains the same, then power losses decrease down to

$$\Delta P = 0.318 \text{ MW}.$$

- If the there is a full reactive power compensation of the load at the receiving end of the line and if the voltage increases up to 120 kV, then power losses are:

$$\Delta P = 0.271 \text{ MW}.$$

Thus, the relative loss reduction can be as much as 0.107 MW or 28.3%. If the peak load period lasts for 5,000 hours, then as much as 1,415 MW*h of electric energy can be saved due to the operation optimization related to controllable reactive power compensation.

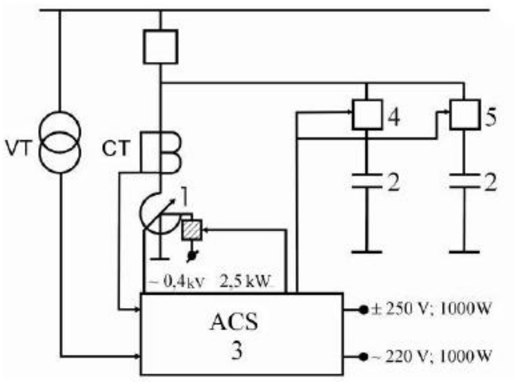
Presented below is an example of recommendation for future SRP applications in the 110 kV distribution network of the oil and gas rich Tyumen region.

On TyumenEnergo`s instructions, power consumption has been analyzed for the peak period in winter 2006 and for the off-peak period in summer 2007 for 286 substations, 11 power networks and six consumers. It allowed to determine the total required value of reactive power compensation (both generation and consumption) and relevant choice criteria, and to develop technical requirements for such high voltage controllable reactive power sources as SRP-110/50/25 and SRP-110/25/25. Sample specifications were provided; a concept program has been developed to install reactive power compensation units in 110/35/6 kV TyumenEnergo power grid to ensure maximum effect for entire system.

The following conclusions have been made from research performed using specialized software:

When the 110 kV grid is operated at the load between 50 and 70 percent of the specified value, a significant amount of substations has low operating voltage (down to minimum permissible values); it is caused by a high reactive power (tgφ is 0.4 or higher) and by "weak" lines (over 30 percent of 110 kV substations have short-circuit currents lower than 5 kA).

Installation of continuously controlled reactive power compensation units in the grid, especially at 110 kV substations with short-circuit currents lower than 5 kA, allows to automatically adjust voltage at load nodes according to the voltage setting in normal, maintenance and post-emergency modes (FACTS technology).



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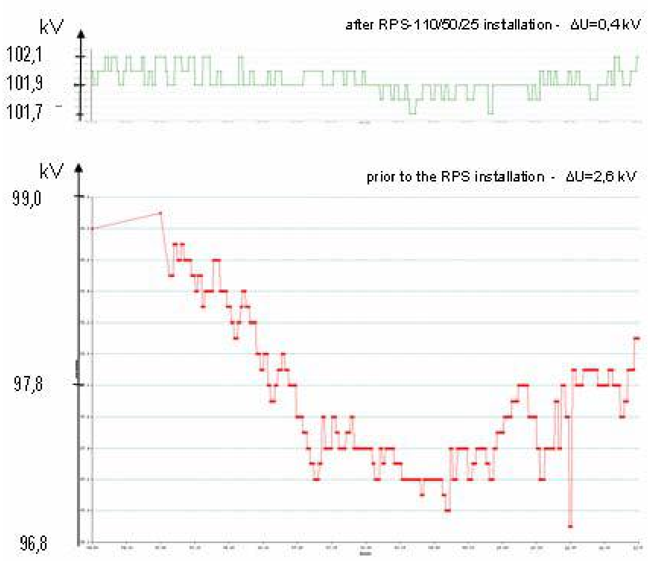

Fig. 3. Fragments of daily voltage diagrams (between 04:00 a.m. and noon) for 110 kV busbars at the Tavricheskaya substation, TyumenEnergo power system. The top diagram: after SRP-110/50/25 installation (MCR 25 MVA and CB 50 MVAR); peak-to-peak voltage: ΔU= 0.4 kV for an average voltage of 101.9 kV. The bottom diagram: prior to the SRP installation; daily peak-to-peak voltage: ΔU=2.6 kV for an average voltage of 97.5 kV (ΔU=2.6 kV at this fragment).

Voltage stabilization and reactive power compensation measures taken in the power grid (for a total of approximately 5 GVAr) will allow to increase the grid throughput as much as 1.3 times while reducing specific losses by 20-30%.

Similar recommendations were also developed for other power systems and grids (Far-Eastern Interregional Distribution Network Company, FGC, KEGOC, etc.). Based on research conducted for these companies the resulting benefits are as follows:

- Automatic voltage stabilization in power networks 110 - 500 kV according to the voltage setting in normal, maintenance, and post-emergency operation modes;
- Exclusion of switching equipment from voltage adjustment processes in normal operation modes;
- Up to 50% increase in throughput of existing lines;
- Up to 30% decrease in specific losses.

V. CONCLUSION

Widespread application of MCR and CB-based SRP in power lines with voltage of 110 kV or higher will allow to significantly reduce the damage from power supply interruptions and to reduce the need for new power transmission line construction due to most efficient use of throughput of existing lines. Total power of SRP in a grid shall be at least 100 percent of maximum consumption of power for 110 - 500 kV grids.

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VII. BIOGRAPHIES

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His field of interests included researches of operating modes and stability of united power grid in long electricity transmission with device FACTS.

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