Flexible alternating current transmission systems (FACTS) devices are used for the dynamic control of voltage, impedance and phase angle of high voltage AC lines. FACTS devices provide strategic benefits for improved transmission system management and operation efficiency through better utilisation of existing transmission assets; increased transmission system reliability and availability; increased grid stability as well as increased quality of supply.

The economical utilisation of transmission system assets is very important for utilities to remain competitive and to survive. A magnetically controlled shunt reactor (MCSR) is a new type of FACTS device which is used for voltage stabilisation and reactive power control in transmission and distribution networks and at the level of industrial consumers. The main competitive advantages of MCSR are:

- A robust design similar to the conventional transformer design
- High operational safety
- Optimal technical and economical characteristics
- Easy maintenance
- Lower price

When equipped with series capacitor banks, MCSRs function as static var compensators (SVC). Unlike a standard SVC which consists of an interconnection transformer, reactors and a thyristor valve, a MCSR is a transformer device, the windings of which act as a SVC reactor while a saturable core acts as a back-to-back thyristor valve. As a result three power elements are replaced by only one.

MCSRs can be connected directly to high voltage (HV) busbars without using a step-up transformer. This additional advantage makes it possible for MCSRs to provide a full regulating range at voltage levels where regulation is needed according to the network’s requirements. The high quality of customised MCSRs designs has been proven by a decade of successful field operations. Even if only one MCSR is installed at a key substation, continuous automatic control and optimum voltage support for several distribution substations in a large network can be provided. Repair and maintenance costs of transformer and switching equipment used for voltage regulation can be significantly reduced.

A magnetically controlled shunt reactor is a three-phase static device operating on the principle of continuous regulation of inductive reactance. MCSRs are designed for automatic voltage stabilisation as well as for compensation and regulation of reactive power flows. The use of MCSRs enables operators to:

- Avoid daily and seasonal voltage oscillations in electric networks
- Improve the quality of electric energy
- Optimise and automate power system operational procedures; rapidly and efficiently respond to changes of electrical parameters by remote control of a MCSR set point from a SCADA/EMS terminal at the relevant dispatch centre.
- Reduce energy losses during transmission and distribution.
- Improve network stability.
- Improve maintenance conditions of electrical equipment by eliminating the number of switchings of non-regulated reactive power compensation devices.
- Increase transfer capability of HV lines and provide secure automatic voltage control when active power flows are close to the thermal or stability limits.
- Avoid voltage collapses after network incidents (e.g. load rejections, generator and line outages, etc.).
- Provide favourable voltage conditions for the operation of power generators.

Based on their advantages and operational experience, MCSRs can be used in power grids including, but not limited to, the following:

- Networks which sustain significant daily or/and seasonal fluctuations in electricity consumption.
- Networks with worn-out switching and transformer equipment, which is regularly used for voltage stabilisation.
- Networks which include long transmission lines prone to frequent changes of loads or power directions.
- Networks distributing electrical energy to consumers which are highly sensitive to voltage oscillations.
- Networks experiencing excess losses of electrical energy.
- Networks having voltage profiles under which power generators can not operate within permissible reactive power ranges.

Principle of operation

A MCSR is a semiconductor switch transformer device, based on the principle of alternate high saturation of each magnetic core. The magnetic system of each phase includes a control winding and a high-voltage winding. Both windings are placed on two solid cores. When a
regulated DC voltage source is connected to the control winding of a DC magnetic bias flux appears in the core. The alternating magnetic flux of the HV-winding overlays with the bias flux produced by the DC voltage source and a resulting magnetic flux moves to the saturation range of the MCSR core. Saturation of the core causes an inductive current flow in the HV-winding. As magnitude of energy in the control system changes, the magnitude of the inductive current in the HV-winding changes respectively.

This increases or reduces the reactive power consumed by the MCSR. The DC voltage source which produces current in the control winding is fed by a compensating winding of the MCSR. Rectification of the compensation winding's AC is provided by a small-power thyristor converter. The magnitude of the inductive current in the HV-winding is regulated according to the difference between the thyristors' operating angle is defined proportionally. This means that the thyristors' operating angle is defined according to the difference between the MCSR voltage set point and the actual voltage of the bus the MCSR is connected to. In order to achieve a quick change of the MCSR loading from one quasi-steady state to another a super-excitation circuit is provided.

MCSRs are designed to allow any required rate of power changes. The optimum balance between the MCSR's operation speed and the rated capacity of a magnetic bias system is defined during MCSR operation. The recommended time of MCSR loading/unloading is within 0.3 to 1 s. Depending upon the client's requirements MCSRs can be adjusted so as to either stabilise voltage level or keep the rate of the consumed reactive power or consumed current at a constant level. Similar to non-regulated reactors, magnetically controlled shunt reactors can be of two types: busbar MCSRs and linear MCSRs. Depending on the type, or upon the client's request, a MCSR design may provide for an additional element to ensure preliminary biasing of the magnetic system and subsequent instantaneous loading up to the nominal capacity directly after switching to the network. Like any transformer device, MCSRs allow continuous overloading up to 120 to 130% of rated current and can also be briefly overloaded up to 200%. MCSRs can, if necessary, operate as standard non-regulated reactors with all their functional capabilities, including arc extinction, during auto reclosing.

**MCSR system structure**

A MCSR system consists of:

- Electromagnetic part of a three-phase or single-phase reactor
- Magnetising system
- Automatic control system

A MCSR can include the following additional elements:

- A reserve phase of a single-phase reactor
- An earthing reactor
- A monitoring system
- Process control signals and protective apparatus monitoring signals
- A fire fighting system

An electromagnetic system is the main power element of any magnetically controlled shunt reactor. This consists of a HV winding which is connected directly to the electric network, a compensation winding and a control winding. In some designs the compensation and control windings are designed as a single winding. The HV winding is used for consumption of reactive power from the network while the control winding is responsible for magnetic biasing of a MCSR core.

The compensation winding feeds a DC voltage source and loops inside the three-aliquot harmonics. An oil transformer with a converter (OTC) is designed to regulate the magnitude of a direct current in the control winding of the electromagnetic system via changing the magnitude of the DC voltage on the terminals of the converter (DC voltage source). The rated capacity of the OTC normally equals to 1 to 2% of the MCSR's rated capacity.

Some MCSRs are equipped with two or three OTCs connected in parallel. This allows operators to increase redundancy of MCSR construction and ensure its stable operation even in case of the failure of the main OTC. Normally all OTCs (except for those used for preliminary magnetic biasing) are connected to the compensation winding. An automatic control unit (ACU) generates control signals to thyristor valves of the converter (DC voltage source). According to such signals the converter changes the magnitude of DC voltage in the magnetic biasing system which results in respective changes of MCSR reactive power loading. The ACU is an electronic device mounted in a standard cabinet. Input power of the control system is less than 1 kW.

**MCSR-based static var compensators**

A MCSR-based static var compensator (SVC) consists of a controlled shunt reactor and series capacitor banks (SCB) connected in parallel. Functionally, it is equivalent to a "classic" thyristor-based var compensator. A controlled shunt reactor functions as a variable inductor, whereas a capacitor bank can include several units to enable the step regulation. The automatic control unit (ACU) ensures reactive power compensation and sends switch-on/off signals to the capacitor bank circuit breakers as shown in Fig. 2. The number and power of capacitor banks are determined in such a way as to minimise circuit breakers (CB) commutations, which, in some instances, prevents the capacitor banks from switching on or off.
Unlike a classic SVC design, compensators based on MCSRs do not contain a HV opposite-parallel thyristor valve for full power. The maximum voltage of currently manufactured thyristor valves does not exceed 35 kV, which necessitates using a step-up transformer to connect a classical SVC to a HV power grid as shown in Fig. 3.

The absence of a step-up transformer in the MCSR-based var compensator as shown in Fig. 4, leads to improved voltage regulation and significant cost reduction. The step-up transformer’s own resistance leads to partial absorption of SVC power, which prevents the use of such power for regulation of the HV level. Thus, there exists a constant disagreement between a SVC target influence and a real effect of regulation at the HV busbar. Besides, the cost of a step-up transformer adds to the overall cost of the SVC, increasing the payback period of the device.

Manufacturers of classic SVCs can sometimes, as in Fig. 5, connect them directly to the grid through an autotransformer’s tertiary winding. This does not require using a step-up transformer, but still has its disadvantages. The SVC connection to the autotransformer’s tertiary winding leads to its additional reactive power load, and as a consequence, to decreasing transformer transfer capacity. Moreover, the greater the autotransformer power flow, the greater the voltage loss will be in it. In order to keep the voltage within prescribed limits, a SVC has to generate more reactive power, thus decreasing the autotransformer’s transfer capacity. Finally, it can result in autotransformer overload and reduction of its power transfer capacity. In addition, when regulating voltage in the autotransformer tertiary winding, reactive power from the source is being redistributed towards both HV and MV windings of the autotransformer.

Therefore the control range of the SVC connected to the autotransformer’s tertiary winding can not be fully employed. The use of MCSR-based static var compensators allows more flexibility in reactive power compensation and power loss reduction as shown in Fig. 6. It is not required that all elements of the SVC should be connected to a single point of an electric grid. In certain cases a MCSR and a capacitor bank can be connected to busbars of different operating voltages at the same substation. Normally, the MCSR is connected to HV substation busbars for compensation of excess reactive power in the HV power grid. It can also maintain consistent voltage levels during daily voltage variations. Capacitor banks are connected to LV busbars in order to provide consumers with quality power. Thus, MCSRs meet the system requirements for power transfer reliability of HV backbone transmission lines, and capacitor banks ensure proper operation conditions for consumers. On the condition that the load of consumers connected to LV busbars does not vary the scheme described here helps to reduce the cross-flow through the substation transformer to zero, which results in considerable electric power loss reduction.

Overall, the advantages of MCSR-based static var compensators are as follows:

- High operational safety
- No need for powerful harmonic filters
- No need for additional maintenance staff training
- No need for water cooling of powerful thyristor valves
- Service conditions similar to those of conventional transformer equipment

MCSR as a solution for full-scale voltage stabilisation in transmission networks

Since 1991 the power system of Belarus has experienced a sharp decrease in active power load demand. Excessive amounts of reactive power which previously served to ensure long distance active power transfers appeared in the 750 – 330 kV transmission network. Surpluses of reactive power caused significant voltage buildup at each voltage level of the power system. The regulating range of all reactive power compensating devices was exhausted. Uneconomical and unsafe measures were taken daily to prevent violations of voltage in the range of minimum load periods. The most popular among them were: tripping some 330 kV lines to decrease charging capacity of the network, large-scale disconnection of consumers’ series capacitor banks, operation of synchronous generators in the mode of consumption of reactive power.

These measures led to significant increases in electric energy losses and caused violations of procedures for safe power transmission and supply. A comprehensive solution for existing voltage problems in the power system had to be found. An extensive feasibility study was carried out to define measures to normalise the voltage profile. Finally, it was decided to install four shunt reactors (one non-controlled shunt reactor and three MCSRs) with a rated capacity of 180 Mvar and rated voltage of 330 kV. The feasibility study proved that due to high levels of current energy losses the payback period of the installed MCSRs was less than five years.

MCSR operation on long distance high voltage transits

The Ormsk power system includes a long 500 kV transmission line connecting the Russian power system with that of Kazakhstan. Synchronous operations of these systems depend on the reliability of the interconnected 500 kV lines. The Ormsk network performance depends on reversible power cross-flows, which results in voltage variations at 500 kV busbars at the Tavricheskaya substation of up to 40 kV per day. After the Kazakh and Russian systems were resynchronised in July 2000 the safety of the power supply was increased but voltage oscillations increased as well. Prior to the MCSR being installed, high voltages and excess losses of electric energy were common faults in the Ormsk system. Voltage oscillations directly depended on the magnitude of active power flow on the 500 kV transmission line. As the magnitude of active power flow decreased voltages on the 500 kV network reached boundary values or even violated upper voltage limits.

In December 2005 a 180 Mvar/500 kV MCSR was installed in the Ormsk power system at the Tavricheskaya substation. The device solved the problems of early wear in electrical equipment and circuit breakers in the Ormsk power system. The MCSR maintained voltages in the network at safe and optimum levels irrespective of the magnitude of active power flow and load demand profile.

Conclusion

The MCSR responds almost instantaneously to short circuits and has all the functional characteristics of a non-regulated shunt reactor including arc-quenching during auto reclosing. For some operational conditions the MCSR keeps voltages at substation busbars close to the highest permissible rates ensuring maximum transfer capacity of the HV transmission line.

Contact Neelesh Pema,
Afritek, Tel 011 316-7512,
neelesh.pema@afriteksa.co.za