FACTS – powerful systems for flexible power transmission

The fast-changing energy market has brought the operators of high-voltage transmission systems a combination of fresh opportunities and new challenges. The latter stem mainly from the strong increase in inter-utility power transfers, the effects of deregulation, and economic and ecological constraints on the building of new transmission facilities. Today's AC power transmission networks are not designed for easy voltage and power flow control in a deregulated market, and steady-state control problems as well as dynamic stability problems are the result. The development of Flexible AC Transmission Systems, or FACTS, based on high-power electronics, offers a powerful new means of meeting the challenges.

Demand for electrical energy continues to grow steadily, and is particularly strong in those countries on the threshold of industrialization. For various reasons, electricity grid upgrades, and especially the construction of new transmission lines, cannot keep pace with the growing power plant capacity and energy demand. Finding suitable right-of-ways is particularly difficult in the industrialized countries, and gaining the necessary approval is more time-consuming than ever. In addition, power line construction ties up investment capital that could be used for other projects.

Due to this situation, operators are looking for ways to utilize the existing power lines more efficiently. Two areas require special attention. In the first place, there is a need to improve the transient and steady state stability of long lines. This is because some power lines cannot be loaded to anywhere near their natural load rating – let alone the thermal limit rating – due to relatively low stability limits. Action taken in support of stability during and after line faults can improve system reliability just as much as by adding one or more lines. Secondly, the load flow needs to be improved in closely intermeshed networks as the 'natural' load flow resulting from the load conditions and existing line impedances is not necessarily the load flow that will minimize the transmission losses.

Another aspect is flexibility: a deregulated energy market requires flexible power system operation to ensure that the electricity supply contracts can be fulfilled.

Rolf Grünbaum
Mojtaba Noroozian
Björn Thorvaldsson
ABB Power Systems

Flexible AC Transmission Systems (FACTS) have all the capability grid operators need to meet the challenges presented by the fast-changing energy market.

Power transfer limits

Power flow over a transmission system is limited by one or more of the following network characteristics:

- Stability limits
- Thermal limits
- Voltage limits
- Loop flows

Technically, limitations on power transfer can always be removed by adding new transmission and/or generation capacity. FACTS are designed to remove such limitations and meet operators' goals without having to undertake major system additions. Given the nature of power electronics equipment, FACTS solutions will be justified wherever the application requires one or more of the following attributes:

- Rapid response
- Frequent variation in output
- Smoothly adjustable output

Flexible AC Transmission Systems (FACTS)

The term 'FACTS' covers all of the power electronics based systems used in AC power transmission.

The main systems are:

- Static var compensator (SVC)
- Fixed and thyristor-controlled series capacitor (TCSC)
- Phase-shifting transformer (PST) and assisted PST (APST)
- Synchronous static compensator (STATCOM)
- Synchronous static series compensator (SSSC)
- Universal power flow controller (UPFC)

Static var compensator (SVC)

Over the years static var compensators of many different designs have been built. Nevertheless, the majority of them have similar controllable elements. The most common ones are:

- Thyristor-controlled reactor (TCR)
- Thyristor-switched capacitor (TSC)
- Thyristor-switched reactor (TSR)
- Mechanically switched capacitor (MSC)

Principle of operation

In the case of the TCR a fixed reactor, typically an air-core type, is connected in series with a bidirectional thyristor valve. The fundamental frequency current is varied by phase control of the thyristor valve. A TSC comprises a capacitor in series with a bidirectional thyristor valve and a damping reactor. The function of the thyristor switch is to connect or disconnect the capacitor for an integral number of half-cycles of the applied voltage. The capacitor is not phase-controlled, being simply on or off. The reactor in the TSC circuit serves to limit current under abnormal conditions as well as to tune the circuit to a desired frequency.

The impedances of the reactors and capacitors and of the power transformer define the operating range of the SVC. The corresponding *V–I* diagram has two different operating regions. Inside the control range, voltage is controllable with an accuracy set by the slope. Outside the control range the characteristic is that of a capacitive reactance for low voltages, and that of a constant current for high voltages. The low-voltage performance can easily be improved by adding an extra TSC bank (for use under low-voltage conditions only).

The TSR is a TCR without phase control of the current, being switched in or out like a TSC. The advantage of this device over the TCR is that no harmonic currents are generated.

A deregulated energy market requires flexible power system operation to ensure that supply contracts can be fulfilled.

(Photo: PRISMA)

The MSC is a tuned branch comprising a capacitor bank and a reactor. It is designed to be switched no more than a few times a day as the switching is performed by circuit-breakers. The purpose of the MSC is to meet steady-state reactive power demand.

SVC configurations

Controlled reactive power compensation is usually achieved in electric power systems by means of the SVC configurations shown in **1**.

SVC applications

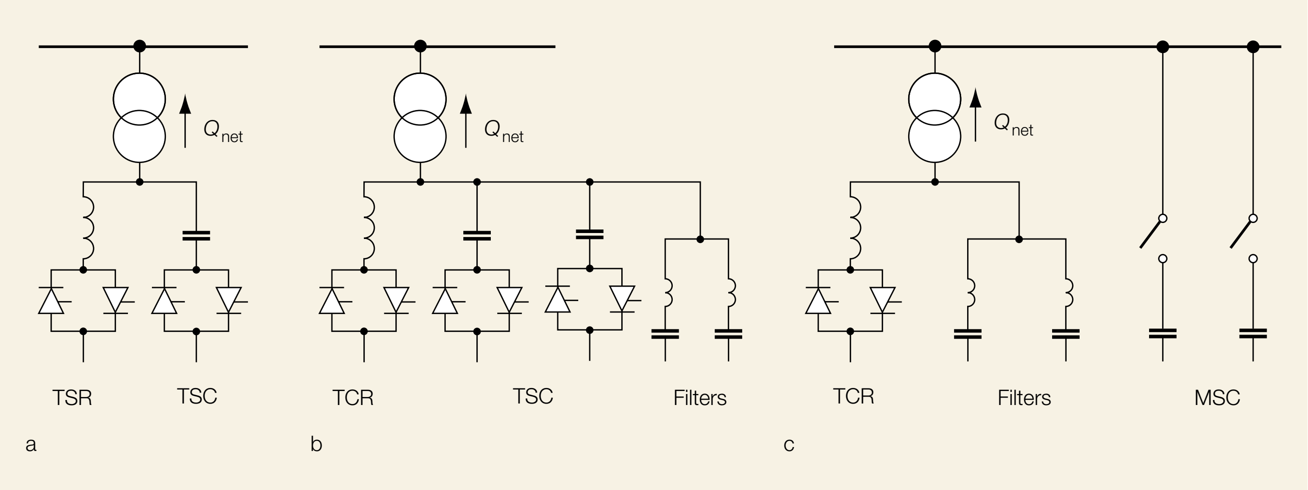
SVCs are installed to perform the following functions:

- Dynamic voltage stabilization: increased power transfer capability, reduced voltage variation
- Synchronous stability improvements: increased transient stability, improved power system damping
- Dynamic load balancing
- Steady-state voltage support

Typically, SVCs are rated such that they are able to vary the system voltage by at least ±5 %. This means that the dynamic operating range is normally about 10 % to 20 % of the short-circuit power at the point of common connection (PCC). Three different locations are suitable for the SVC. One is close to major load centers, such as large urban areas, another is in critical substations, normally in remote grid locations, and the third is at the infeeds to large industrial or traction loads.

Location 1: Major load centers

The usual reason for installing SVCs in load centers is to mitigate the effect of grid disturbances on sensitive loads. The dis-



SVC configurations used to control reactive power compensation in electric power systems **1**

a *TSR-TSC configuration*
b *TCR-TSC configuration*
c *TCR-MSC configuration*

Q_{net} *Net reactive power flow to network*

turbances may be short circuits and/or loss of important power lines. Load centers can be either at the end of a radial network or in a meshed system. The characteristic common to both locations is that the loads are located far away from large-scale power stations. An example of an installation in a meshed network is the SVC at Sylling, near the city of Oslo in southern Norway. This plant is rated at ±160 MVAr and is connected to the 420-kV system at a substation south-west of the city **2**.

If a short circuit occurs in the network, the SVC detects the resulting voltage depression on the 420-kV system and changes its impedance to quickly restore the voltage in the city. As a result of the fault the generators in the system also start to increase their reactive power output to restore the voltage at the machine locations. The SVC makes sure that this is done smoothly, with the result that the short circuit is not noticed in the city. During fault clearing an overvoltage often occurs as a result of the exciter action. The SVC counteracts this surge. Due to the SVC action during and after the fault, the voltage change is virtually unnoticeable at the load sites in the city. Thus, it can be said that the SVC isolates the city from the effect of the remote system fault. A curve taken from a field test shows the principle of operation as described above **3**.

SVCs also play a role in the daily regulation of the voltage, which would vary with the load pattern if corrective action were not taken. The compensator makes sure that customers never notice such variation. When the load increases, the voltage at sub-transmission and distribution levels will decrease. Automatic tap-changing, involving a large number of power transformers, counteracts this drop

420-kV SVC installation at Sylling, Norway **2**

in voltage. As a result of the tap-changing, the voltage at the HV system level decreases further (a tap-changer never solves the problem caused by a voltage drop, it only moves it to a higher system voltage level). The reactive power output of the SVC subsequently increases in order to prevent the voltage reduction. There are now two possibilities: either the SVC is large enough to handle this daily load variation and still have spare capacity for important dynamic tasks, or, if it is not, the dispatch center connects capacitor banks at the system level when the SVC output exceeds a certain value in order to restore dynamic SVC capacity.

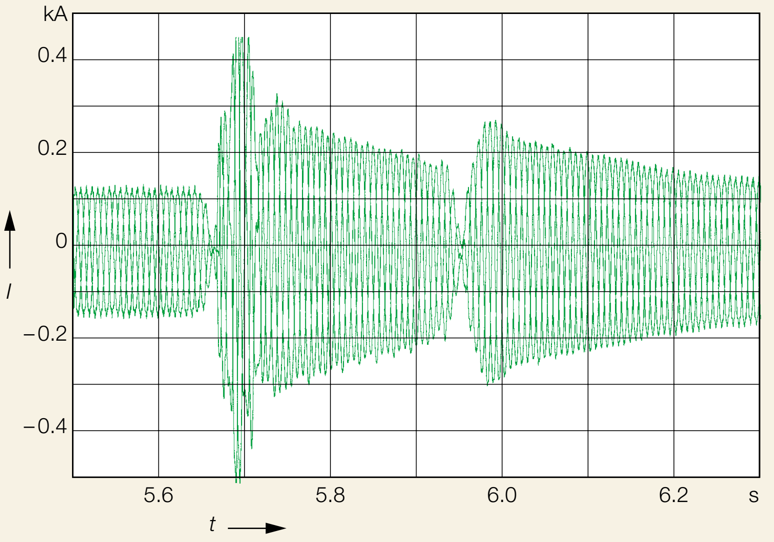
Probably the most important mission for an SVC is to counteract possible voltage collapses, eg during peak load conditions, when many load areas are vulnerable. This applies to load areas at a relatively long distance from the generation plants, where voltage support can be found. With increasing load the voltage in the areas starts to sink. If a major power line trips during a peak load period, the risk of collapse is evident. This risk is efficiently counteracted by rapidly injecting substantial amounts of reactive power into the load area. The dispatch center must always operate the system such that it will survive one single contingency. Without SVCs more power line capacity (higher short-circuit power) or local generation would be necessary to fulfil this requirement.

Location 2: Critical substations

Another typical SVC location is on critical buses in the grid. These SVCs are normally installed to prevent low voltages during active power swings and to avoid excessive temporary over- or undervoltages in the event of major power lines or generating stations being lost. Another important task is continuous voltage support during the daily load cycle without having to have very large capacitor banks energized and thereby risk a troublesome voltage situation occurring during and especially after clearing of severe network faults. Damping of power oscillations is another task performed by SVCs. Providing the SVC is suitably located in the network it can contribute to substantial damping of power swings. This SVC application becomes more and more important as utilities increase the load on lines to levels well above the surge impedance loading (SIL). In fact, there are companies running their lines at two or three times the SIL. In such cases reactive power support has to be given a high priority.

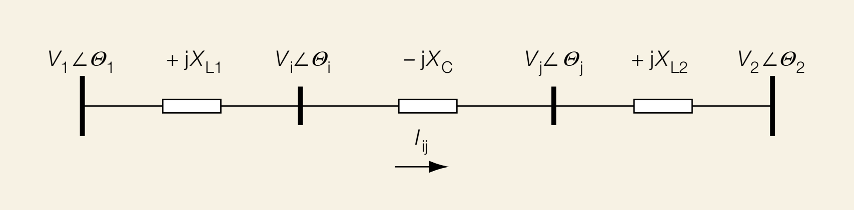
Location 3:
Large industrial/traction loads

SVCs are also located at the supply point of major industries or other types of commercial loads. For example, they act as compensators in steelworks, making sure that other customers connected to the grid do not experience a deterioration in power quality on account of the arc furnaces. Denoted industrial SVCs, these compensators are beyond the scope of this article. However, there is one interesting type of compensator which is intended for dedicated loads but is still a utility SVC. This is the load-balancing SVC used in substations to which modern 50-Hz traction systems are connected. A railway system requires infeed of power every 50 km. Traction system loads are single phase and are fed directly by transformers connected between two phases in the power grid. A typical load in such a substation is 50 MVA. As this load is taken between two phases an imbalance in the power system occurs. It is generally not easy to find points in the power grid with sufficiently high short-circuit power to tolerate the unsymmetrical load at all the locations where substations are required. The unbalance causes problems for other customers connected to the grid, who will suffer from poor power quality. SVCs have the ability to make the network see these loads as being perfectly balanced.



Sylling SVC current during remote three-phase system fault (field test) **3**

I SVC current
t Time



A series-compensated transmission system **4**

I_{ij}	*Current between buses i and j*	$V_{i,j}$	*Voltage magnitude, buses i and j*
$\Theta_{1,2}$	*Voltage angle, buses 1 and 2*	X_C	*Series capacitor reactance*
$\Theta_{i,j}$	*Voltage angle, buses i and j*	$X_{L1,L2}$	*Line segment reactances*
$V_{1,2}$	*Voltage magnitude, buse 1 and 2*		

Series compensation

Series capacitors have been used successfully for many years to enhance the stability and load capability of HV transmission networks. They work by inserting capacitive voltage to compensate for the inductive voltage drop in the line, ie they reduce the effective reactance of the transmission line **4**.

Principle of operation

The voltage inserted by a series capacitor is proportional to and in quadrature with the line current. Thus, the reactive power generated by the capacitor is proportional to the square of the current. A series capacitor therefore has a self-regulating action. When the system loading increases, the reactive power generated by the series capacitor also increases.

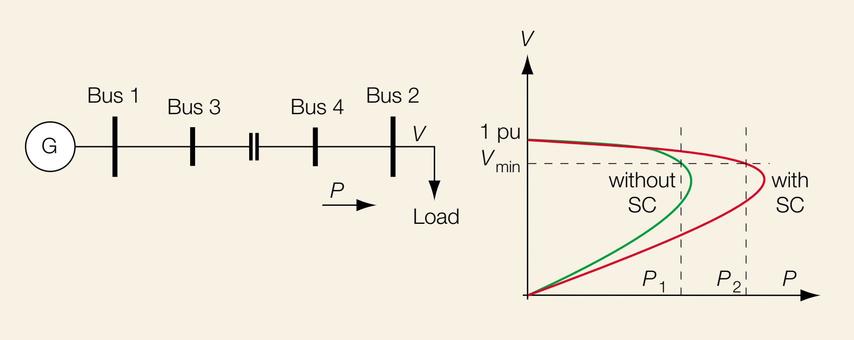
Impact of series compensation on power systems

Steady-state voltage regulation and prevention of voltage collapse

A series capacitor is able to compensate for the voltage drop in a transmission line due to the series inductance. At low loads, the system voltage drop is smaller and the series compensation voltage is lower. When loading increases and the voltage drop becomes larger, the contribution by the series compensator increases and the system voltage is regulated accordingly. Series compensation also expands the region of voltage stability by reducing the line reactance, thereby helping to prevent voltage collapse. **5** shows that the voltage stability limit increases from P_1 to the higher level P_2.

Voltage profile for a simple power system **5**

P	*Power*	*SC*	*Series capacitor*
V	*Voltage*		



Improvement in transient rotor angle stability

In the single-machine, infinite-bus system in **6** the equal-area criterion is used to show how a series capacitor effectively improves transient stability. Under steady-state conditions $P_e = P_m$ and the generator angle is δ_0. If a three-phase fault occurs at a point near the machine the electrical output of the generator decreases to zero. At the time the fault is cleared the angle will have increased to δ_C. The system remains stable providing A_{dec} is greater than A_{acc}. **6** shows that the stability margin is substantially increased by installing a series capacitor, causing the P–δ curve to shift upwards.

Power flow control

Series compensation can be used in power systems for power flow control in the steady state. In the case of transmission lines with sufficient thermal capacity, compensation can therefore relieve possible overloading of other, parallel lines.

Series compensation schemes

Transmission line compensation can be achieved through fixed series capacitors or, offering more versatility, controllable series capacitors. Outlines of typical series compensation schemes are shown in **7**.

Thyristor-controlled series capacitor (TCSC)

Principle of operation

TCSC configurations comprise controlled reactors in parallel with sections of a capacitor bank. This combination allows smooth control of the fundamental frequency capacitive reactance over a wide range. The capacitor bank for each phase is mounted on a platform to ensure full insulation to ground. The valve contains a string of series-connected high-power thyristors. The inductor is of the air-core type. A metal-oxide varistor (MOV) is connected across the capacitor to prevent overvoltages.

The characteristic of the TCSC main circuit depends on the relative reactances of the capacitor bank $X_C = -\frac{1}{\omega_n C}$, and the thyristor branch, $X_V = \omega_n L$, where ω_n is the fundamental angular speed, C is the capacitance of the capacitor bank, and L is the inductance of the parallel reactor.

The TCSC can operate in several different modes with varying values of apparent reactance, X_{app}. In this context, X_{app} is defined simply as the imaginary part of the quotient given below, in which the phasors represent the fundamental value of the capacitor voltage, $\vec{U}_{C1}$, and the line current, $\vec{I}_{L1}$, at rated frequency:

$$X_{app} = \mathrm{Im}\left\{\frac{\vec{U}_{C1}}{\vec{I}_{L1}}\right\}$$

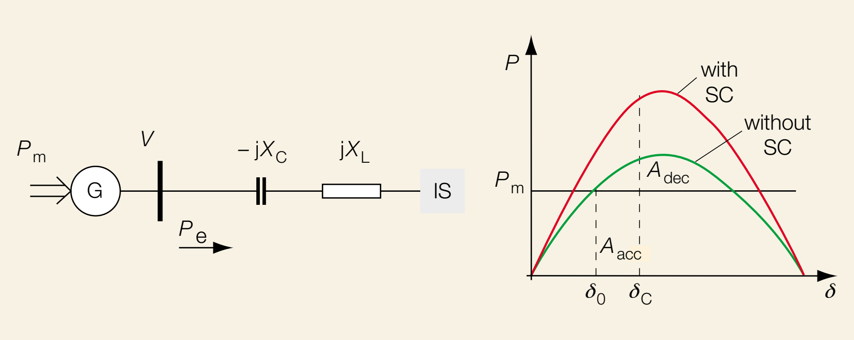
It is also practical to define a boost factor, K_B, as the quotient of the apparent and physical reactance, X_C, of the TCSC:

$$K_B = \frac{X_{app}}{X_C}$$

Blocking mode

When the thyristor valve is not triggered and the thyristors remain non-conducting the TCSC will operate in blocking mode. Line current passes through the capacitor bank only. The capacitor voltage phasor, $\vec{U}_C$, is given in terms of the line current phasor, $\vec{I}_L$, according to the formula:

$$\vec{U}_C = jX_C\vec{I}_L \qquad X_C < 0$$



Enhancing the transient stability margin by means of a series capacitor **6**

A_{acc}	*Accelerating energy*	P_m	*Mechanical power to generator*
A_{dec}	*Retarding energy*	X_C	*Series capacitor reactance*
δ	*Generator angle*	X_L	*Line reactance*
δ_0	*Pre-fault generator angle*		
δ_C	*Angle at fault-clearing*	IS	*Infinite source*
P_e	*Electrical power from generator*	SC	*Series capacitor*

In this mode the TCSC performs in the same way as a fixed series capacitor with a boost factor equal to one.

Bypass mode

If the thyristor valve is triggered continuously it will remain conducting all the time and the TCSC will behave like a parallel connection of the series capacitor bank and the inductor of the thyristor valve branch.

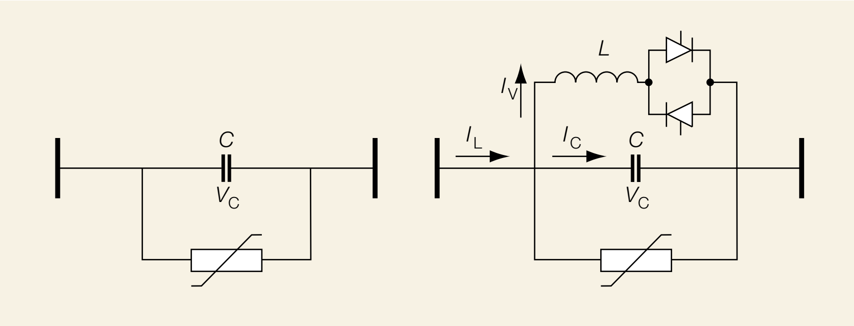
In this mode the capacitor voltage at a given line current is much lower than in the blocking mode. The bypass mode is therefore used to reduce the capacitor stress during faults.

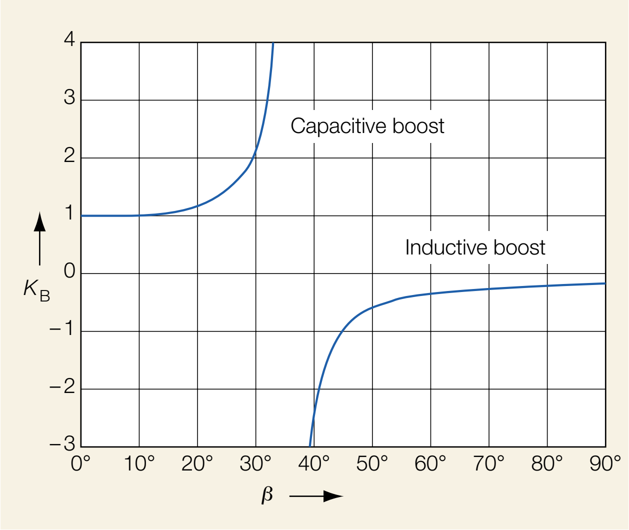
Capacitive boost mode

If a trigger pulse is supplied to the thyristor with forward voltage just before the capacitor voltage crosses the zero line, a capacitor discharge current pulse will circulate through the parallel inductive branch. The discharge current pulse is added to the line current through the capacitor bank and causes a capacitor voltage which is added to the voltage caused by the line current **8**. The capacitor peak voltage will

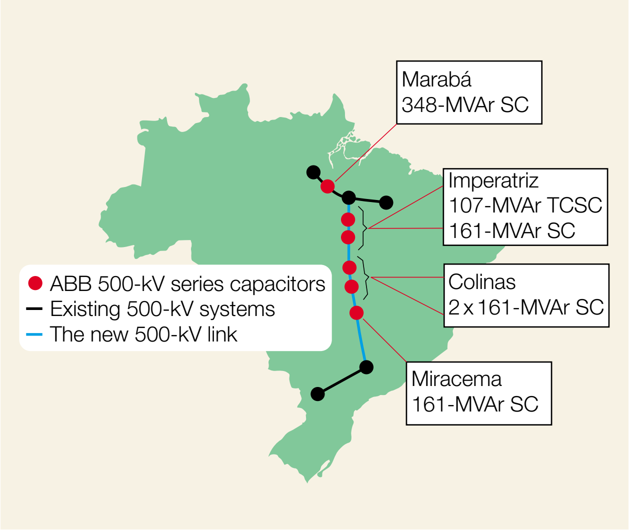
Two typical series compensation schemes with a fixed series capacitor and TCSC **7**

C	*Series capacitor*	I_V	*Valve current*
L	*Parallel inductor*	I_L	*Line current*
I_C	*Capacitor current*	V_C	*Capacitor voltage*





Boost factor, K_B, versus conduction angle, β, for a TCSC **8**



Brazil's North-South Interconnection. ABB supplied six 500-kV series capacitors, five fixed (SC) and one thyristor-controlled (TCSC), for this project. **9**

thus be increased in proportion to the charge passing through the thyristor branch. The fundamental voltage also increases almost in proportion to the charge.

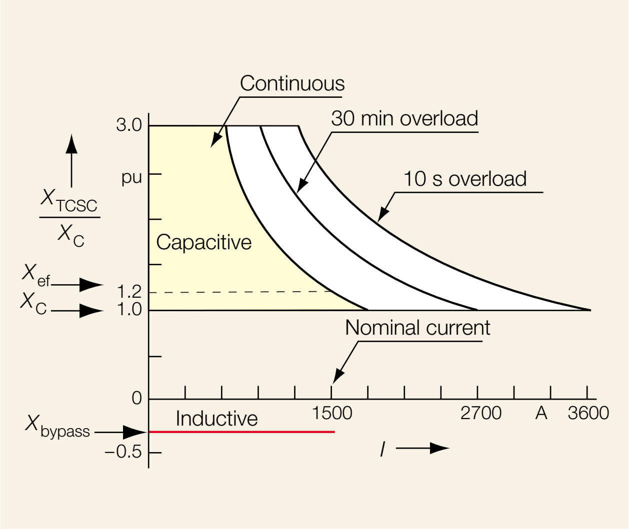
The TCSC has the means to control the angle of conduction, β, as well as to synchronize the triggering of the thyristors with the line current.

Application of TCSC for damping electromechanical oscillations

The basic power flow equation shows that modulating the voltage and reactance influences the flow of active power through

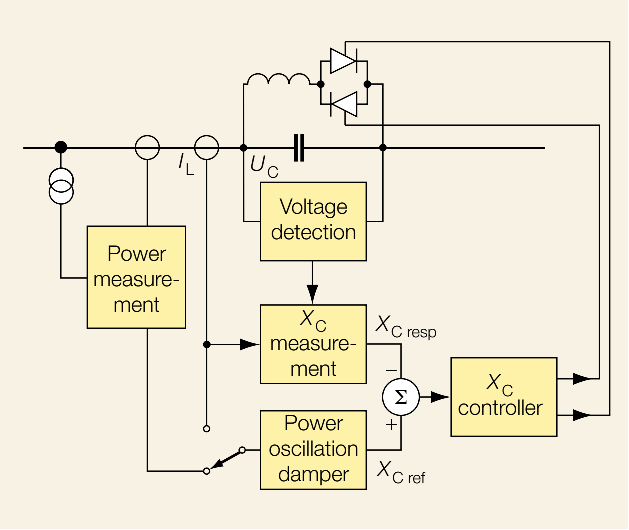
Impedance-current characteristic of the TCSC installed in the Imperatriz substation of Brazil's North-South Interconnection. **10**

I	*Line current*
X_{TCSC}	*TCSC reactance*
X_{ef}	*Nominal boost level*
X_C	*Unity boost level*
X_{bypass}	*Boost level at TCSC bypass*



Control scheme of the TCSC in the Imperatriz substation **11**

I_L	*Line current*
U_C	*Capacitor voltage*
X_C	*Boost level*
$X_{C\ resp}$	*Boost response*
$X_{C\ ref}$	*Boost reference*



the transmission line. In principle, a TCSC is capable of fast control of the active power through a transmission line. The possible control of transmittable power points to this device being used to damp electromechanical oscillations in the power system. Features of this damping effect are:

- The effectiveness of the TCSC for controlling power swings increases with higher levels of power transfer.
- The damping effect of a TCSC on an intertie is unaffected by the location of the TCSC.
- The damping effect is insensitive to the load characteristic.
- When a TCSC is designed to damp inter-area modes, it does not excite any local modes.

View of the Imperatriz TCSC **12**

Brazil: North-South Interconnection

A current example of AC interconnection of separate power systems within a country's borders is found in Brazil. There are two main power systems in the country which were previously not interconnected – the North System and the South System. They transmit mainly hydropower, carrying more than 95 % of the nation's total generated electrical energy. After the feasibility of interconnecting the two systems had been studied, it was decided to build the transmission corridor. AC and DC schemes were assessed before the decision was taken in favour of the AC option. This consists of a single 500-kV compact circuit (to be doubled at a later stage), more than 1,000 km long and series-compensated at several locations along the line. It has been in operation since the beginning of 1999 **9**.

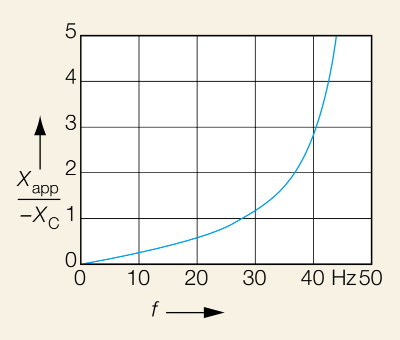
The AC option is highly attractive as it makes inexpensive hydropower available to a rapidly growing federal economy and for the future development of a vast area with great economical potential. Several hydropower plants are expected to be built along this route and connected to the 500-kV AC grid in the next two decades.

ABB supplied a total of six 500-kV series capacitors for the project, five fixed and one thyristor-controlled. In all, series capacitors rated at about 1,100 MVAr have been supplied.

The TCSC is located at the Imperatriz substation at the northern end of the interconnection. Its task is to damp low-frequency, inter-area power oscillations between the power systems on either side of the interconnection. These oscillations (0.2 Hz) would otherwise constitute a hazard to power system stability.

Ideal apparent reactance of TCSC operating in synchronous voltage reversal mode (nominal frequency: 50 Hz) **13**

X_C Physical capacitor reactance
X_{app} Apparent reactance
f Frequency

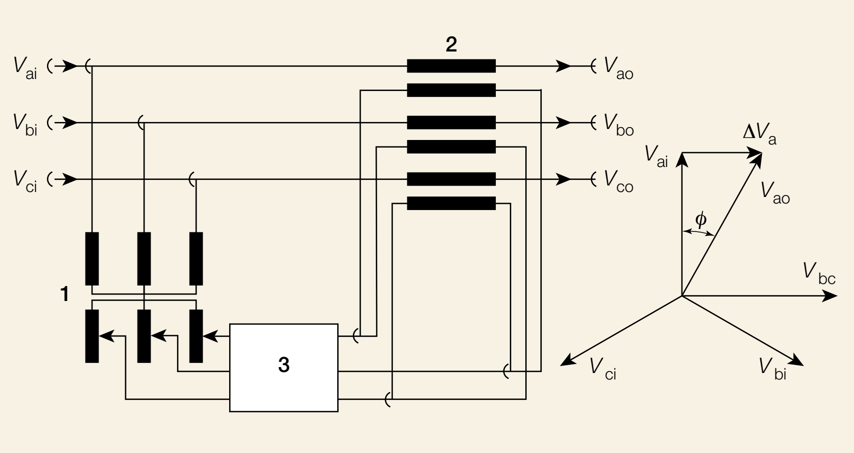


Imperatriz TCSC

The characteristics of the Imperatriz TCSC are shown in **10**. The boost level is a key factor, being a measure of the amount by which the reactance of the series capacitor can be artificially augmented in order to counteract system power oscillations. The boost level can be varied continuously between 1 and 3, which is equivalent to a range of 5 % to 15 % of the line compensation. At rated line current, the nominal boost level has been set to 1.20. The control scheme is shown in **11**.

The thyristor valve is mounted at platform level **12**. It is water-cooled and utilizes indirect light-triggered thyristors.

The valve is rated at 1,500 A continuous current and 3,000 A for 10 seconds. Furthermore, as the valve has to provide back-up protection for the TCSC in extreme situations, where the main ZnO overvoltage protection reaches its rated thermal limit, it needs to be able to with-



A phase shifter with quadrature voltage injection **14**

1 *Magnetizing transformer*
2 *Series transformer*
3 *Switching network*

ϕ *Phase shift*

V_a	*Voltage across series transformer*
$V_{ai, bi, ci}$	*Line to ground voltages*
$V_{ao, bo, co}$	*Line to ground voltages*

stand fault currents of up to 40 kA (peak) for about 60 ms, which is the time it takes for the bypass breaker to close and begin carrying the fault current.

Mitigating subsynchronous resonance with TCSCs

Introducing series compensation improves the transmission system behaviour in terms of the voltage stability and angular stability. However, an electrical resonance could be introduced into the system at the same time. Experience has shown that under certain circumstances such an electrical resonance could interact with mechanical torsional resonances in the turbine-generator shaft systems in thermal generating plants. This phenomenon is a form of subsynchronous resonance (SSR). Today, the SSR problem is well understood and is taken into account when designing series compensation equipment. Sometimes, SSR conditions may limit the degree of compensation needed for better power system performance. The use of TCSCs will overcome such restrictions.

Apparent impedance of TCSCs

The conditions for SSR depend on the network impedance as viewed by the synchronous machine at the sub- and supersynchronous frequencies corresponding to its torsional resonance frequency, ω_m.

The reactance of a fixed series capacitor varies inversely with the frequency, and once its reactance at rated frequency has been selected this determines its reactance at all frequencies. However, this is not the case for the TCSC as its boost depends on control actions that may change the triggering of the thyristors for each half-cycle of the line current.

The apparent impedance, Z_{app}, of the TCSC can then be defined as the complex quotient:

$$Z_{app}(\omega_m) = R_{app}(\omega_m) + jX_{app}(\omega_m) = \frac{\Delta \vec{U}_C}{\Delta \vec{I}_L}$$

It should be noted that the apparent impedance is a property of the TCSC main circuit and its control system. In general, the apparent impedance for a specific TCSC in a specific network must be determined by simulation or measurement. Reports on different control schemes show that in subsynchronous frequency ranges the apparent impedance is of the resistive-inductive type. A simplified calculation, assuming instantaneous, equidistant capacitor voltage reversals at twice the rated frequency and neglecting losses, reveals the apparent impedance of the TCSC to be:

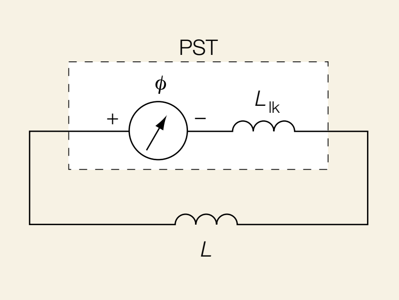
$$X_{app}(\omega_m) = -X_C \frac{\omega_n}{\omega_m} \frac{1 - \cos\left(\frac{\omega_m}{\omega_n}\frac{\pi}{2}\right)}{\cos\left(\frac{\omega_m}{\omega_n}\frac{\pi}{2}\right)}$$

The function is positive in the whole subsynchronous frequency range, showing that the apparent reactance is inductive **13**. At frequencies close to the rated frequency, control of the apparent impedance will force it to become capacitive. An actual case of SSR mitigation is given in [6].

Topology of an assisted phase-shifting transformer (APST) **15**

ϕ	*Phase shift*
L	*Parallel inductance*
L_{lk}	*PST inductance*

PST *Phase-shifting transformer*



Phase-shifting transformer (PST)

Phase angle regulating transformers (phase shifters) are used to control the flow of electric power over transmission lines. Both the magnitude and the direction of the power flow can be controlled by varying the phase shift across the series transformer **14**.

Principle of operation

The phase shift is obtained by extracting the line-to-ground voltage of one phase and injecting a portion of it in series with another phase. This is accomplished by using two transformers: the regulating (or magnetizing) transformer, which is connected in shunt, and the series transformer **14**. The star-star and star-delta connections used are such that the series voltage being injected is in quadrature with the line-to-ground voltage.

A portion of the line voltage is selected by the switching network and inserted in series with the line voltage. The added voltage is in quadrature with the line voltage since, eg, the added voltage on phase ‘a’ is proportional to V_{bc}.

The angle of a phase shifter is normally adjusted by on-load tap-changing (LTC) devices. The series voltage can be varied by the LTC in steps determined by the taps on the regulating winding. Progress in the field of high-power electronics has made it possible for thyristors to be used in the switching network.

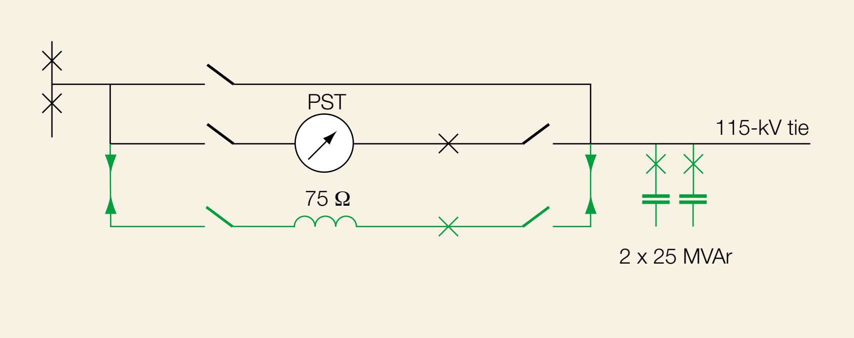
Assisted phase-shifting transformer (APST)

The topology of an APST is shown in **15**. The nature of the reactive element in parallel with the PST depends on the quadrant in which the PST is called upon to operate. The two branches function in unison, enabling the APST to force higher power transfer through a circuit than is obtained with the PST alone. The susceptance of the reactive element is chosen many times smaller than that of the PST. Hence, the behaviour of the APST is mainly dictated by the PST, meaning that the controllability of the PST is preserved in the APST.

NYPA-VELCO Interconnection

In the USA, the New York Power Authority (NYPA) system is interconnected with the Vermont Electric Company (VELCO) system via a 115-kV tieline. This critical link is necessary to ensure reliable local service and provide bulk power transfer between the two systems. To optimize operation, a PST with a nominal rating of 115 kV, 175 MVA, located at Plattsburgh, NY, is used to control the tie. During the summer months this PST constitutes the thermally limiting piece of equipment in the interconnection, restricting pre-contingency loading during this time to 105 MW.

It was seen to be in the common inter-



Single-line diagram of the Plattsburgh APST used to control the 115-kV NYPA-VELCO Interconnection in the USA **16**

Black *Existing equipment* Green *Added equipment*

The Plattsburgh APST **17**

ests of NYPA and VELCO to increase the permissible summer transfers over the tieline. The APST solution was considered the most attractive as it met all the system objectives. Placing a high-impedance inductor in parallel with the existing PST would reduce flow through it while essentially maintaining full controllability of the tie 16. In addition, shunt capacitor banks were required for local supply of the reactive power consumed by the inductor.

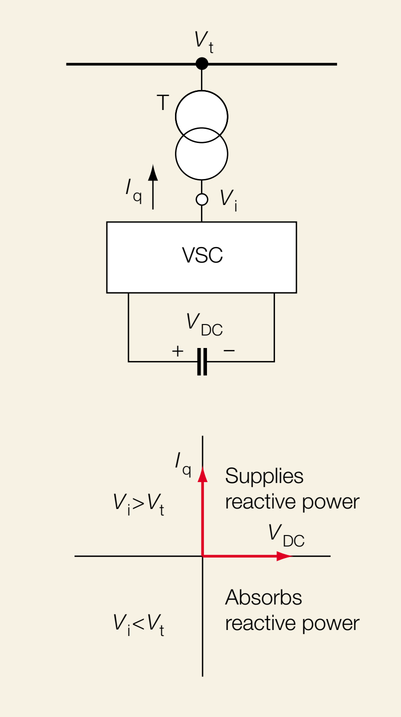
The Plattsburgh APST was commissioned in June 1998 17. With it in operation, the permissible summer transfer over the tieline in question has been increased by 35 MW to 140 MW, an increase of 33 %. It has been assessed that the cost of the APST is only about half of the cost of replacing the existing PST by a new unit appropriately rated for the higher summer transfer [7].

Static synchronous compensator (STATCOM)

The static compensator is based on a solid-state synchronous voltage source in analogy with a synchronous machine generating a balanced set of (three) sinusoidal voltages at the fundamental frequency with controllable amplitude and phase angle. This device, however, has no inertia.

Principle of operation

A static compensator consists of a voltage source converter, a coupling transformer and controls. In this application the DC energy source device can be replaced by a DC capacitor, so that the steady-state power exchange between the static compensator and the AC system can only be reactive, as illustrated in 18. I_q is the converter output current, perpendicular to the converter voltage V_i. The magnitude of the converter voltage, and thus the reactive output of the converter, is controllable. If V_i is greater than the terminal voltage, V_t, the static compensator will supply reactive power to the AC system. If V_i is smaller than V_t, the static compensator absorbs reactive power.



Static compensator, comprising VSC, coupling transformer T, and control 18

I_q *Converter output current*
V_i *Converter voltage*
V_t *Terminal voltage*

Voltage source converter (VSC)

A basic three-phase circuit configuration of a three-level voltage source converter is shown in 19. It consists of twelve self-commutated semiconductor switches, each of which is shunted by a reverse parallel connected diode, and six diode branches connected between the midpoint of the capacitor and the midpoint of each pair of switches. By connecting the DC source sequentially to the output terminals the inverter can produce a set of three quasi-square voltage forms of a given frequency.

The frequency, amplitude and phase of the AC voltage can be varied by suitable control. Thus, the voltage source converter can be considered as a controllable voltage source.

The valves in a voltage source converter act as switches. The phase potentials with respect to the capacitor midpoint can have three distinct values:

1. $V = + V_{dc}$
2. $V = 0$
3. $V = – V_{dc}$

This scheme is called a three-level voltage source converter.

It should be noted that for each phase leg only one of the two switches can be on at a given time; otherwise the DC link would experience a short circuit. The output voltage can be controlled both in terms of its phase and amplitude. The fundamental frequency of the AC voltage is linked to the DC voltage thus:

$$V_{a,b,c} = K_u V_{dc}$$

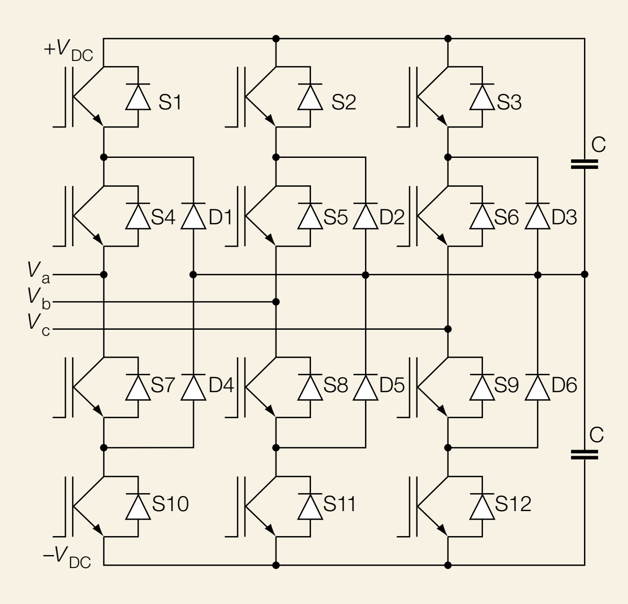
The linking factor, K_u, is controlled by the switching pattern of the valve. This approach is generally called pulse-width modulation (PWM). 20 shows an example of two line-to-converter neutral voltages and the resulting line-to-line voltage waveforms in PWM operation.

By utilizing pulse width modulation it is possible to vary the value of K_u. This ratio, called the modulation index, can be varied between zero and a maximum value.

Applications

The functions performed by STATCOMs are:

- Dynamic voltage stabilization: increased power transfer capability, reduced voltage variations

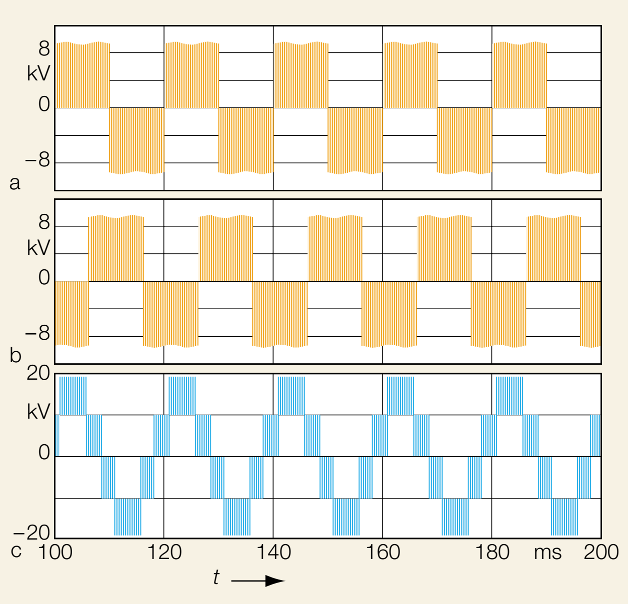


Basic three-level voltage source converter 19

S1–12 *IGBT stacks*

D1–6 *Diode stacks*

C *DC capacitor*



Converter terminal voltage waveforms with pulse-width modulation 20

a, b *Line-to-midpoint voltage*

c *Line-to-line voltage*

- Synchronous stability improvements: increased transient stability, improved power system damping, damping of SSR
- Dynamic load balancing
- Power quality improvement
- Steady-state voltage support

SVC Light

SVC Light is a product name for an IGBT-based STATCOM from ABB [8]. SVC Light technology is based on the principle that the plant topology should be simple, with a minimum of conventional apparatus. The conventional equipment is replaced by high-technology devices, such as IGBT valves and high-performance computer systems. Through the use of high-frequency switching PWM (about 2 kHz), it has become possible to use a single converter connected to a standard power transformer via air-core commutating reactors. The main parts of the plant – the IGBT valves, DC capacitors, control system and the valve cooling system – are located inside a container. The outdoor equipment is restricted to heat-exchangers, commutation reactors and the power transformer. At present, a rating of ± 100 MVAr per converter is available. To obtain a wider range, additional fixed capacitors, thyristor-switched capacitors or a multi-converter assembly can be used.

Typical SVC Light installation for utility applications 21

Voltage and current characteristics

The operating area for the new-generation SVC is defined by the maximum voltage that can be set up on the converter terminals and by the maximum converter current. When undervoltage conditions exist a constant current equal to the maximum converter current can be maintained. This shows that the MVAr production decreases linearly with the voltage. Under overvoltage conditions the maximum current can be maintained up to the ceiling for the converter terminal voltage.

Response time

The semiconductor valves in an SVC Light system respond almost instantaneously to a switching command. Therefore, the factor limiting the speed at which the plant responds is determined by the time needed for voltage measurements and control system data processing. If a high-gain controller is used the response time will be less than a quarter of a cycle.

Harmonic interaction with the network

The plant can in most cases be designed completely without harmonic filters. In cases where the requirements on higher-order harmonics are very stringent, a small high-pass link may be necessary. The risk of conditions under which resonance occurs is therefore negligible. Due to this property SVC Light can be easily relocated to other sites when network requirements change.

The high switching frequency used in the SVC Light concept results in an inherent capability for producing voltages at frequencies well above the fundamental frequency. This property can be used for active filtering of harmonics already present in the network. SVC Light then injects harmonic currents into the network with the proper phase and amplitude to counteract the harmonic voltages.

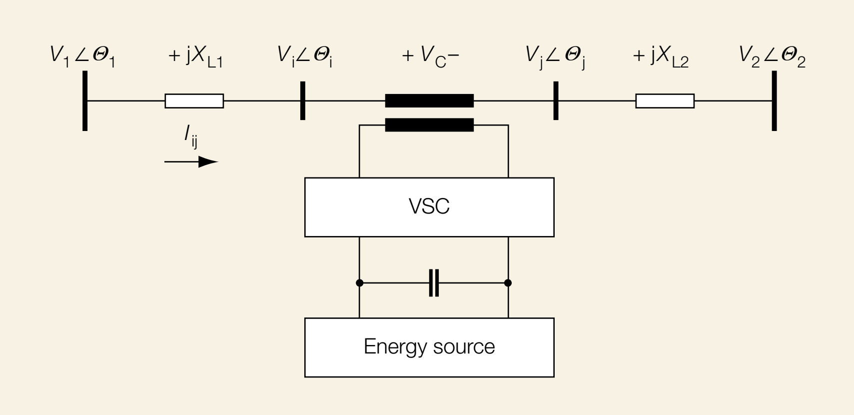
Footprint and layout

A very compact SVC Light system can be built for power utility applications **21**. The area required is no more than about 10 by 20 meters.

The basic configuration of a static synchronous series compensator (SSSC) **22**

$+V_C-$ Voltage across SSSC series transformer

Other notation see Fig. 4



Static synchronous series compensator (SSSC)

A voltage source converter can be used in series in a power transmission system. Such a device is referred to as a static synchronous series compensator.

Principle of operation

22 shows a voltage source converter connected in series with a transmission line via a transformer. A source of energy is needed to provide the DC voltage across the capacitor and make up for the losses of the VSC.

In principle, an SSSC is capable of interchanging active and reactive power with the power system. However, if only reactive power compensation is intended, the size of the energy source could be quite small. The injected voltage can be controlled in terms of magnitude and phase if there is a sufficiently large energy source. With reactive power compensation, only the magnitude of the voltage is controllable since the vector of the inserted voltage is perpendicular to the line current. In this case the series injected voltage can either lead or lag the line current by 90 degrees. This means that the SSSC can be smoothly controlled at any value leading or lagging within the operating range of the VSC. Thus, an SSSC can behave in a similar way to a controllable series capacitor and a controllable series reactor. The basic difference is that the voltage injected by an SSSC is not related to the line current and can be independently controlled. This important characteristic means that the SSSC can be used with great effect for both low and high loading.

Applications

The general application of a controllable series capacitor applies also to the SSSC:

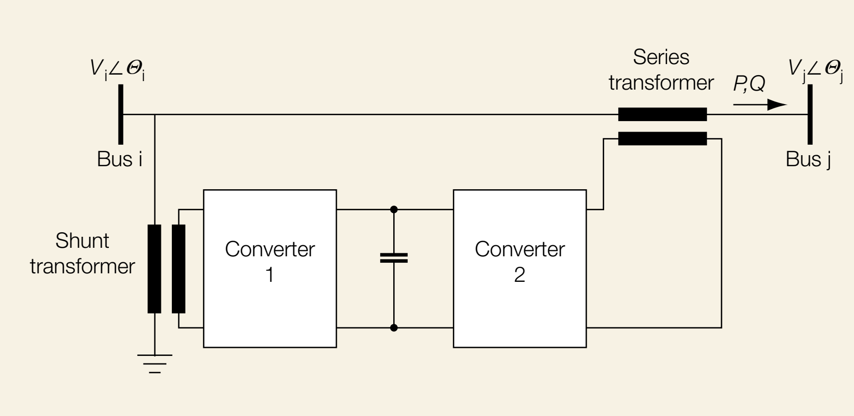
dynamic power flow control and voltage plus angle stability enhancement. The fact that an SSSC can induce both capacitive and inductive voltage on a line widens the operating region of the device. For power flow control, an SSSC can be used both to increase and reduce the flow. In the stability area it offers more potential for damping electromechanical oscillations. However, the inclusion of a high-voltage transformer in the scheme means that, compared with controllable series capacitors, it is at a cost disadvantage. The transformer also reduces the performance of the SSSC due to an extra reactance being introduced. This shortcoming may be overcome in the future by introducing transformerless SSSCs. The scheme also calls for a protective device that bypasses the SSSC in the event of high fault currents on the line.

Unified power flow controller (UPFC)

The unified power flow controller consists of two switching converters operated from a common DC link 23.

Principle of operation

In 23 converter 2 performs the main function of the UPFC by injecting, via a series transformer, an AC voltage with controllable magnitude and phase angle in series with the transmission line. The basic function of converter 1 is to supply or absorb the real power demanded by converter 2 at the common DC link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. Converter 2 supplies or absorbs the required reactive power locally and exchanges the active power as a result of the series injection voltage.



Basic circuit arrangement of the unified power flow controller (UPFC) 23

P Active line power
Q Reactive line power
$V_{i,j}$ Voltage magnitudes, buses i and j
$\Theta_{i,j}$ Voltage angles, buses i and j

Applications

A UPFC can regulate the active and reactive power simultaneously. In general, it has three control variables and can be operated in different modes. The shunt-connected converter regulates the voltage of bus *i* in 23 and the series-connected converter regulates the active and reactive power or active power and the voltage at the series-connected node. In principle, a UPFC is able to perform the functions of the other FACTS devices which have been described, namely voltage support, power flow control and improved stability.

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Authors

Rolf Grünbaum
Mojtaba Noroozian
Björn Thorvaldsson
ABB Power Systems AB
SE-721 64 Västerås
Sweden
Fax: +46 21 18 31 43
E-mail:
rolf.grunbaum@se.abb.com
mojtaba.noroozian@se.abb.com
bjorn.thorvaldsson@se.abb.com