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 eco-logical 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.

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)

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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.

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 Figure 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 dis-
FACTS

F    A    C    T    S

turbances on sensitive loads. The distur-

bances 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 com-

mon 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 connect-
ed to the 420-kV system at a substation

south-west of the city.

If a short circuit occurs in the network, the
SVC detects the resulting voltage de-pres-
sion on the 420-kV system and changes its
impedance to quickly restore the voltage in
the city. As a result of the fault the gener-
ators 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 re-
sult that the short circuit is not noticed in
the city. During fault clearing an overvoltage
often occurs as a result of the exciter ac-
tion. 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.

SVCs also play a role in the daily regula-
tion 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 varia-
tion. When the load increases, the voltage
at sub-transmission and distribution levels
will decrease. Automatic tap-changing, in-
volving a large number of power transfor-

c V warnings used to control reactive power compensation in electric power systems

\( Q_{\text{net}} \)

\( \text{Net reactive power flow to network} \)

a  TSR-TSC configuration

b  TCR-TSC configuration

c  TCR-MSC configuration

420-kV SVC installation at Sylling, Norway

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

420-kV SVC installation at Sylling, Norway
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, e.g., 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 fulfill 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 instead 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.
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, i.e., they reduce the effective reactance of the transmission line.

**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. Figure 4 shows that the voltage stability limit increases from $P_1$ to the higher level $P_2$.

**Improvement in transient rotor angle stability**
In the single-machine, infinite-bus system, 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 $\delta_0$. 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 $\delta_C$. The system remains stable providing $A_{dec}$ is greater than $A_{acc}$. Figure 5 shows that the stability margin is substantially increased by installing a series capacitor, causing the $P-\delta$ 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 Figure 6.

**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, \( X_C \), and the thyristor branch, \( X_L \), where \( \omega_n \) 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, \( \tilde{U}_C \), and the line current, \( \tilde{I}_L \), at rated frequency:

\[
X_{app} = \text{Im} \left( \frac{\tilde{U}_C}{\tilde{I}_L} \right)
\]

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, \( \tilde{U}_C \), is given in terms of the line current phasor, \( \tilde{I}_L \), according to the formula:

\[
\tilde{U}_C = jX_C \tilde{I}_L, \; X_C < 0
\]
Boost factor, $K_B$, versus conduction angle, $\beta$, for a TCSC

The TCSC has the means to control the angle of conduction, $\beta$, 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 influence the oscillations.

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

| $I$ | Line current |
| $X_{TCSC}$ | TCSC reactance |
| $X_d$ | Nominal boost level |
| $X_C$ | Unity boost level |
| $X_{bypass}$ | Boost level at TCSC bypass |

Control scheme of the TCSC in the Imperatriz substation

- $I_L$: Line current
- $U_C$: Capacitor voltage
- $X_C$: Boost level
- $X_C_{\text{resp}}$: Boost response
- $X_C_{\text{ref}}$: Boost reference

Boost factor, $K_B$, versus conduction angle, $\beta$, Brazil's North-South Interconnection. ABB supplied six 500-kV series capacitors, five fixed (SC) and one thyristor-controlled (TCSC), for this project.

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Application of TCSC for damping electromechanical oscillations

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ences the flow of active power through 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 intert isi not affected by the location of the TCSC.
- The damping effect is insensitive to the load characteristic.
- When a TCSC is designed to damp interarea modes, it does not excite any local modes.

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.

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.

Imperatriz TCSC

The characteristics of the Imperatriz TCSC are shown in the figure. 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 the diagram.

The thyristor valve is mounted at platform level. 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 backup protection for the TCSC in extreme situations, where the main ZnO overvoltage protection reaches its rated thermal limit, it
needs to be able to withstand 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, $\omega_m$.

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:

$$Z_{app}(\omega_n) = R_{app}(\omega_n) + jX_{app}(\omega_n) = \frac{\Delta V_a}{\Delta I_a}.$$  

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:

$$X_{app}(\omega_n) = \frac{X_C}{\omega_m^2 - \omega_n^2}.$$  

The function is positive in the whole subsynchronous frequency range, showing that the apparent reactance is inductive. 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].

**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.

**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. The star-star and star-delta conne-
tions 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, e.g., 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.

**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 Fig. 1. $I_q$ 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.

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:

$$V_{abc} = K_u V_{dc}$$

The linking factor, $K_u$, is controlled by the switching pattern of the valve. This approach is generally called pulse-width modulation (PWM).

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
- 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.

Voltage and current characteristics

The operating area for the new-generation SVC is defined by the maximum voltage that

![Typical SVC Light installation for utility applications](image)
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.

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

References

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Improving the performance of electrical grids

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The electricity supply industry is undergoing rapid evolution, driven by deregulation and privatization. Years of underinvestment in the transmission grid in many markets has turned attention to increasing the utilization of existing transmission lines, cross-border cooperation and the issue of power quality. This has dramatically increased interest in new and classical solutions.

FACTS (Flexible AC Transmission Systems), such as SVC, SVC Light®, TCSC and others, are just such solutions. They take advantage of major technical progress made in the last decade and represent the state of the art for many and various needs. One typical application would be to increase the capacity of any given transmission line, but in this article we will describe some special cases with unique requirements and how they have been met.

If prestige projects were ever needed to demonstrate FACTS’ credentials as an improver of T&D performance, none could serve better than the Dafang 500-kV series capacitors helping to safeguard Beijing’s power supply, the Eagle Pass back-to-back tie straddling the US/Mexican border, or the Channel Tunnel rail link. These, in their different ways, show why FACTS is arousing so much interest in the electrical supply industry today.

Dafang: series capacitors safeguard the Beijing area power supply

Power demand in the area served by the North China Power Network, with 140 million people and including Beijing,
The Dafang 500-kV series capacitors are growing at a steady pace and installing new plant is not easy. An attractive alternative is to insert series capacitors in the existing transmission corridor to provide series compensation. ABB was contracted to do this, and recently installed two series capacitors (each rated 372 MVAR, 500 kV) in the middle of each line of a 300-km twin-circuit corridor between Datong and Fangshan. They came on stream in June, 2001, a mere nine months after the contract was awarded.

A series capacitor acts to decrease the transfer reactance of the power line at power frequency (50 Hz) and supplies reactive power to the circuit at the same time. The benefits of this are:

- **Increased angular stability.** There must always be a certain difference between the voltage phase angles at either end of the power line to enable transmission. This increases with power and the series capacitor keeps the angular difference within safe limits, ie it ensures that the angular difference does not increase so much that it could jeopardize the angular stability.
- **Improved voltage stability of the corridor.**
- **Optimized power sharing between parallel circuits.** Without series capacitors, the line with the least power transmission capacity would saturate first and no additional power could be fed into the system, despite the fact that the other line still has capacity to spare. The series capacitors redistribute power between the lines for better overall utilization of the system.

The series capacitors are fully integrated in the power system and benefit from its control, protection and supervisory capability. They are fully insulated to ground.

The main protective devices used are ZnO varistors and circuit-breakers. The first is to limit the voltage across the capacitor and is supplemented by a forced-triggered spark gap to handle excess current during a fault sequence. The circuit-breakers connect and disconnect the series capacitors as required. They are also needed to extinguish the spark gap, as it is not self-extinguishing.

The capacitors are rated for operation during normal, steady-state grid conditions as well as for severe system contingencies, such as loss of one of the two parallel 500-kV lines. In such a case, the capacitor of the line remaining in service must be able to take the full load of both lines for a certain amount of time. This was, in fact, one of the reasons for installing the series capacitors in the first place – to ensure the safe import of power to the Beijing area even with a line down.

**Eagle Pass Back-to-Back (BtB) Light**

SVC Light technology\(^1\) has successfully solved power quality problems in several projects undertaken by ABB. Being based on a common platform of voltage source converters (VSC), SVC...
Light also provides solutions for power conditioning applications in transmission systems. The Eagle Pass tie is a good example of a project in which the VSC platform is configured as back-to-back HVDC, although functionally with priority given to voltage support with the dual SVC Light systems.

Most important in this respect is the fact that installation of active power transfer capability, using HVDC Light across a certain distance or in a back-to-back configuration, will provide both bidirectional active power and dynamic reactive power support simultaneously. Thus, strong voltage support is readily available along with the steady-state power transfer.

The Eagle Pass substation (operated by American Electric Power, AEP) is located in a remote part of Texas, on the Mexican border, and is connected to the Texas transmission system through two 138-kV transmission lines. The nearest significant generating station is located 145 km away and provides very little voltage support to the Eagle Pass area.

Eagle Pass also has a 138-kV transmission line that ties into Piedras Negras substation (operated by Commission Federal Electricas, CFE) on the Mexican side. This is used mainly in emergencies to transfer load between power systems, but such transfers involve interrupting the power as the CFE and AEP systems are asynchronous (despite both being 60 Hz). To overcome this disadvantage, and also solve problems arising from increasing demand, a better solution was sought.

The solution: voltage source converters
Load flow studies demonstrated that the installation of a 36-MVAR voltage source converter directly at the Eagle Pass substation would provide years of respite. Installation of a VSC is ideal for weak systems as the alternative, reactive support provided by shunt capacitors, decreases rapidly when the voltage is reduced. Extending the scenario, two VSCs connected back-to-back would not only supply the necessary reactive power but also allow active power transfer between the two power systems. A BtB scheme would enable the 138-kV line between Eagle Pass and Piedras Negras to be energized all the time and allow the instantaneous transfer of active power from either system.

Having the capability to control dynamically and simultaneously both active and reactive power is unprecedented for VSC-based BtB interconnections. This feature is an inherent characteristic of the VSC. As commutation is driven by its internal circuits, a VSC does not rely on the connected AC system for its operation. Full control flexibility is achieved by using pulse width modulation (PWM) to control the IGBT-based bridges. Furthermore, PWM provides unrestricted control of both positive- and negative-sequence voltages. This ensures reliable operation of the BtB tie even when the connected AC systems are unbalanced. In addition, the tie can energize, supply and support an isolated load. In the case of Eagle Pass, this will allow the uninterrupted supply of power to local loads even if connections to one of the surrounding networks were tripped.

The back-to-back installation
A simplified one-line diagram of the BtB tie in Eagle Pass is shown in .

The BtB scheme consists of two 36-MVA VSCs coupled to a common DC capacitor bus. The VSCs are of the NPC (neutral point clamped) type, also known as three-level converters. Each VSC is connected to a three-phase set of phase reactors, each of which is connected to a conventional step-up transformer on its respective side of the BtB. The layout of the BtB installation is shown in .

BtB operating modes
The two VSCs of the BtB can be configured for a wide range of different
functions. At Eagle Pass, the main BtB operating configurations are as follows:

- Voltage control
- Active power control
- Independent operation of the two VSCs
- Contingency operation of the BtB

**Voltage control**

In this mode, both the AEP and CFE systems are capable of independent voltage control. The BtB provides the required reactive power support on both sides to maintain a pre-set voltage. Active power can be transferred from either side while a constant system voltage is maintained on both. Any active power transfers that are scheduled are automatically and instantaneously lowered, if required, by the control system to supply the reactive power needed to maintain a constant voltage.

**Active power control**

In this mode, active power can be transferred between the AEP and CFE systems. Power transfer is allowed when the voltage is within a dead-band. If the voltage lies outside it, the BtB automatically reverts to voltage control mode. The active power flow is then automatically and instantaneously lowered by the BtB to provide the required reactive power support. The dead-band is designed so that local capacitor switching or changes in remote generation which cause slight voltage swings do not cause the BtB to switch to the voltage control mode.

**Independent operation of the two VSCs**

Should maintenance be required on one side of the BtB, the other side is still able to provide voltage control to either side of the tie. This is done by opening the DC bus, splitting it into two halves. As the DC link is open, no active power can be transferred between the two sides of the BbB. Each VSC will then be capable of providing up to ±36 MVar of reactive support to either side.

**Contingency operation of the BtB**

If one of the 138-kV lines into the Eagle Pass substation is lost, the remaining 138-kV line can only support 50 MW of load at the substation. Should this occur, the voltage falls below 0.98 pu and the BtB switches to the voltage control mode. Active power is reduced automatically and instantaneously to make sure the 50-MW load level at the substation (AEP load plus the export to CFE) is not violated. The BtB supplies the required reactive support to maintain a 1-pu voltage. Load flow studies have
shown that the transmission line contingency on the AEP side will have little impact on the power transfers from AEP to CFE.

**Dynamic performance**
The recording reproduced in [1] illustrates well the highly dynamic performance of the BtB Light installation at Eagle Pass. Plots 1–7 show how the BtB responded to lightning conditions in a remote area that caused a voltage dip in the AEP network. During the fault, the BtB current (capacitive) was increased to almost 1 pu to support the bus voltage at Eagle Pass.

**Channel Tunnel rail link**
When the high-speed electrified railway line between London and the Channel Tunnel to France is finished in 2007 it will be possible to travel between London and Paris in just over two hours, at a maximum speed of 300 km/h. The railway power system is designed for loads which are high (power ratings in the range of 10 MW) and which fluctuate (rapid acceleration and retardation). The traction feeding system that was chosen is a modern 50-Hz, 2 x 25-kV supply incorporating an autotransformer scheme to keep the voltage drop along the traction lines low. Power step-down from the grid is direct, via transformers connected between two phases.

**SVCs for the three traction feeding points**
A major feature of this power system is the static VAr compensator (SVC) sup-

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1. Remote fault case
   1: AEP 138-kV voltages
   2: AEP step-down transformer secondary currents, in amps
   3: AEP phase reactor currents
   4: AEP 17.9-kV voltages
   5: AEP 17.9-kV phase-to-ground voltages, in kV
   6: DC voltages
   7: AEP converter, active (P) and reactive power (Q) reference
The primary purpose of the SVCs is to balance the unsymmetrical load and to support the railway voltage in the case of a feeder station trip – when two sections have to be fed from one station.

The second purpose of the SVCs is to maintain unity power factor during normal operation. This ensures a low tariff for the active power.

Thirdly, the SVCs mitigate harmonic pollution by filtering out the harmonics from the traction load. This is important as strict limits apply to the traction system’s contribution to the harmonic level at the supergrid connection points.

The SVCs for voltage support only are connected on the traction side of the interconnecting power transformers. The supergrid transformers for the traction supply have two series-connected medium-voltage windings, each with its midpoint grounded. This results in two voltages, 180 degrees apart, between the winding terminals and ground. The SVCs are connected across these windings; consequently, there are identical single-phase SVCs connected feeder to ground and catenary to ground.

The load balancer transfers active power between the phases in order to create a balanced load (as seen by the supergrid). A brief explanation of how the load balancing works is given in the following.

Load current
When the load is connected between two phases (B & C) only, the traction current can be expressed by two phase vectors, one representing the positive sequence and the other the negative sequence \( I_{LB} \). The summation of the two vectors is the resulting current (current in phase A is zero and currents in phase B and C are of equal magnitude, but phase opposed). Note that the vector amplitudes are not truly representative.

To compensate the negative sequence and thus balance the current to be generated by the power systems, the load balancer generates a (pure) negative-phase sequence current, \( I_{LOAD} \), as shown in \( \text{Fig. 7} \). This current balances exactly the negative-phase sequence current from the load (\( I_{LOAD} \) in \( \text{Fig. 7} \)).

The load balancer in the Sellindge substation is optimized to handle a load connected between the C and A phases. Load balancing theory says that, to balance a purely active load, a capacitor has to be connected between phases A and B and a reactor between phases B and C. The traction load also has a reactive part, which likewise has to be balanced. In this substation, not only the asymmetry is compensated but also the power factor. This is achieved by inserting a capacitor between phases C and A.

Redundancy
High availability is required, so all critical components are redundant: A complete fourth redundant phase has been added in the main circuit. All the
phases need to be as independent of each other as possible.

These requirements have resulted in a unique plant layout and design for the control and protection. There are four fully independent ‘interphases’ (an assembly of components connected between two phases). Each interphase features an independent set of filters, reactors, thyristor valves, thyristor firing logic circuits, measuring transformers, relay protection devices and cooling system. Each of the connections to the substation busbars has a circuit-breaker and disconnector inserted in it. Filters can be connected to or disconnected from the fourth interphase to turn it into either an inductive or a capacitive branch.

Two independent control systems act on the three-phase system, while the thyristor firing and logic circuits act directly on each interphase. The control systems are strictly segregated, as are the valve-firing logic circuits and the overall protection system. If an interphase fails, the control system trips it and automatically substitutes the standby unit.

The thyristor valves make use of a new type of thyristor – a bidirectional device with two antiparallel thyristors on a common silicon wafer. This halves the number of units needed in the valves. The thyristor is a 5-inch device with a current-handling capability of about 2000 A(rms).

\[ I_{a} + I_{b} + I_{c} = I_{LOAD} \]

\[ I_{a} + I_{b} = I_{LB} + I_{LOAD} \]
Summary and outlook

The importance of improving grid performance is growing for economical as well as environmental reasons. FACTS devices have established themselves as the currently most suitable solutions for increasing transmission line utilization.

The Dafang project is a classic example of a transmission capacity upgrade providing much-needed power to a fast-growing area, in this case the region around Beijing. The project was completed in the extremely short time of nine months and brings existing, remotely generated power to an area where it is urgently needed.

The case of Eagle Pass shows the possibilities offered by new technologies able to combine advanced FACTS properties with network interconnection capability. The latest developments in semiconductor and control technology have made this possible. Thanks to this back-to-back tie, existing transmission facilities can be utilized to a much greater extent than before.

Finally, the Channel Tunnel rail link illustrates well the flexibility of FACTS devices by showing how they can also be used to solve the problems created by new, sophisticated types of load. The unbalance caused by new traction loads, for example, can be mitigated, and downgrading of the electricity supply for other users avoided, by means of the described solid-state solutions.

These examples show that FACTS devices will be used on a much wider scale in the future as grid performance becomes an even more important factor. Having better grid controllability will allow utilities to reduce investment in the transmission lines themselves. ABB is currently exploring ways in which FACTS devices can be combined with real-time information and information technologies in order to move them even closer to their physical limits.

References

The spectacular dune landscapes of Namibia are a key factor in the country's booming tourist industry and a valuable source of revenue for the nation. Another, even more important pillar of the Namibian economy is the power-hungry mining industry. To cope with growing energy demand in these two sectors and to ensure a reliable power supply for the country as a whole, NamPower, Namibia’s national electricity utility, has installed a new 400-kV AC transmission system linking its grid system with the Eskom grid in South Africa. Voltage stability problems, which the new line would have aggravated, have been resolved by installing a static var compensator from ABB.
While construction of the new line has brought reliable power to Namibia, it was not without problems of its own. The line’s length of 890 km, for instance, aggravated certain problems – mainly voltage instability and near 50-Hz resonance – that already existed in the NamPower system.

An ABB static var compensator (SVC) rated from 250 MVAR inductive to 80 MVAR capacitive has been installed to solve these problems. The turnkey project was concluded with the successful commissioning of the SVC in NamPower’s Auas 400-kV substation, just 18 months after the contract was signed.

The case for a new 400-kV grid

Power consumption in Namibia is concentrated in Windhoek and in the northern region, where most of the mining and mineral industry is located. Until recently, the NamPower grid consisted of a radial network, with bulk power supplied by the Ruacana hydro-station in the north via a 520-km 330-kV transmission circuit, linked by an 890-km 400-kV interconnection to Eskom’s system in the south.

This network was often loaded to its stability limits during low-load periods when Ruacana was not providing power. The system is also unique for its long 220-kV and 330-kV lines and the fact that the loads are small in comparison with the generation sources – two features that further aggravated the stability problems in low-load conditions.

To solve these problems, the utility decided to build a 400-kV grid. The final phase of construction – a 400-kV interconnection between Auas and Kokerboom – was completed in 2000. This single-circuit 400-kV AC transmission line strengthens the NamPower system by connecting it to Eskom’s system in...
the south. However, with a length of 890 km it is also very long, in fact one of the longest lines of its kind in the world. This and the network’s tree-like configuration, coupled with remote generation and the very long radial lines operated at high voltage, results in the charging capacitance being high. The effect of this is to shift the existing parallel resonance closer to 50 Hz, making the network more voltage-sensitive during system transients, for example when the 400-kV line is energized or during recovery after a line fault clearance. Each of these phenomena manifests itself as an extremely high and sustained overvoltage.

**Resonance and overvoltages**

The NamPower network has a first natural parallel resonance frequency well below 100 Hz, namely in the 55–70 Hz range (curves 1 and 2 in ).

The effect of adding the new 400-kV line section (Aries-Kokerboom-Auas) and its four 100-MVar shunt terminal reactors has been to shift the system’s first resonance into the 60–75 Hz frequency range (curves 3 and 4). (The reduction in system impedance at 50 Hz is due to the new 400-kV line, and an indication of how the system has been strengthened.)

Curves 5 and 6 in show the network impedance as seen at the Auas 400-kV bus the instant the 400-kV line is energized from the northern section (from the Auas side) and before the circuit-breaker on the Kokerboom side is closed.

The impact of the resonance problem in the NamPower system is best illustrated by simulating the condition at Auas substation, represented by curve 6. The voltage situation is shown in , in which the line circuit-breaker at Auas is closed at time $t = 1.0$ s and it is assumed that the breaker at Kokerboom is synchronized at $t = 1.2$ s. Due to the large charging capacitance of the line the voltage first dips, then overshoots.

The extremely high overvoltages appearing at Auas, with a peak value in excess of 1.7 pu and a sustained transient overvoltage (TOV) of more than 1.5 pu, attest to the severity of the problem. It is clear that as soon as 50-Hz resonance is triggered very high dynamic overvoltages appear with large time constants under certain system load and generation conditions.

Preliminary studies indicated that overvoltages would appear that would make the NamPower system inoperable unless very fast, effective and reliable countermeasures are taken.

Several solutions were considered as an answer to the resonance problem, including fixed and switched reactors, before deciding to install a FACTS device in the Auas substation. Preference was given to conventional, proven SVC technology [1].

**SVC design features**

The Auas SVC has a dynamic range of 330 MVar (250 MVar inductive to 80 MVar capacitive) and is installed primarily to control the system voltage, in particular the extreme (up to 1.7 pu) overvoltages expected as a result of the near 50-Hz resonance. An uncommon feature of the project is that the SVC is installed in a system with very long lines, little local generation and fault levels lower than 300 MVA.

The SVC that is installed is of a new type, developed by ABB for power applications. Its unique control principle has since been patented. The inductive power of 250 MVar is provided by three thyristor-controlled reactors (TCRs), a fourth, continuously energized TCR being always on standby . Two identical double-tuned filters, each rated at 40 MVar, take care of harmonics and supply capacitive reactive power during steady-state operation.

Studies showed that overvoltages could make the NamPower system inoperable unless very fast, effective and reliable countermeasures are taken.

High availability is essential for the Auas SVC. If, for any reason, it should have to be taken out of service, the 400-kV transmission system could not be oper-
ated without risking dangerous overvoltages. As a result, an availability figure of 99.7% was specified, and this strongly influenced the design, quality, functionality and layout of its components and subsystems as well as of the SVC scheme as a whole.

Operating range
The Auas SVC provides resonance control over its entire operating range, which extends well beyond its continuous range. Controlled operation is possible all the way up to 1.5 pu primary voltage – a necessary feature for controlling the resonance condition. Besides providing resonance control, the SVC also controls the positive-sequence voltage (symmetrical voltage control) at the point of connection.

Single-phase transformers
Four single-phase transformers, including one spare, are installed. Due to the high overvoltage demands made on them during resonance these transformers have been designed with a lower flux density than standard units; they should be the last transformers in the NamPower system to go into saturation.

TCR reactor and valve
Each TCR branch consists of two air-core reactors connected on each side of a thyristor valve. The reactors have special exterior surfaces to protect them from the effect of sand storms and sun in the harsh desert environment.

A secondary voltage of 15 kV was chosen as an optimum value for both the thyristor valve and busbar design. The thyristor valves consist of single-phase stacks of antiparallel-connected thyristors (16 thyristors, two of which are redundant, in each valve). Snubber circuits (series-connected resistors and capacitors) limit overvoltages at turnoff. The thyristors are fired electrically using energy taken directly from the snubber circuit.

An overvoltage protection device limits the voltage that can appear across the valve, being triggered by control units that sense the instantaneous voltage across each thyristor level.

Redundant TCR branch
Three TCR units rated at 110 MVar have been installed to cope with the NamPower network’s sensitivity to reactive power and harmonic current injections. A fourth, identical TCR is kept on hot standby. The SVC control system automatically rotates the current standby TCR unit every 30 hours to ensure equal operating time for all units.
Redundant cooling system

An unusual feature of the Auas SVC is that each TCR valve has its own cooling system, making four in all. Thus, outage time is minimized and availability is increased. A water/glycol cooling media is used to avoid freezing in case of auxiliary power outages during the cold desert nights.

Filter branches

The required capacitive MVar are provided by two 40-MVar filter banks. Each filter is double-tuned to the 3rd/5th harmonics and connected in an ungrounded configuration. The double-tuned design was chosen to ensure sufficient filtering even in the case of one filter becoming defective.

Black-start performance

Since the SVC is vital for operation of the NamPower system, everything has to be done to avoid the SVC breaker tripping, even during a network blackout. In such a case the network could be energized from the Eskom side and the SVC would have to be immediately ready to control a possible resonance condition. To handle this task, the SVC has three separate auxiliary supplies, one of which is fed directly from the SVC secondary bus. The SVC is capable of standby operation with its MACH 2 controller active for several hours without auxiliary power, and automatically goes into resonance control mode as soon as the primary voltage returns.

Worst-case situation: energization from north to south

The worst-case scenario for the SVC and the NamPower system is energization of the 400-kV line from the northern section (Auas substation). This system condition, which initiates the critical 50-Hz resonance, was therefore simulated in a real-time digital simulator with and without the new resonance controller. As shown in the overvoltage that appears at Auas is 1.62 pu with a conventional PI controller. (The two resonance frequencies – 56 Hz and 81 Hz – that can be seen in the result correspond to the system’s first and second pole, respectively.) The new resonance controller has a considerable impact on the system’s behav-
Staged fault test
After the Auas substation had been commissioned, a phase-to-ground fault was used to test various SVC control functions and the interconnection protection scheme. The performance of the SVC is shown in (a). As the results show, the SVC controls the voltage and the resonance controller forces the SVC to become fully inductive in resonance conditions. The fault is initiated at $t = 4.9$ s and is cleared by opening the faulty phase in the Auas-Kokerboom line. A single-phase auto-reclosure is initiated after 1.2 s, starting with the breaker on the Kokerboom side. The overvoltage at Auas is reduced to 1.14 pu.

Easier cross-border power sharing
As a result of installing the ABB SVC, the resonance problems that had previously plagued the Namibian grid are a thing of the past. Southern Africa’s state energy sectors can now be more easily integrated and power more easily shared. And the growing demand for power – the motor driving the region’s economic ambitions – can be more easily met.

References