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.

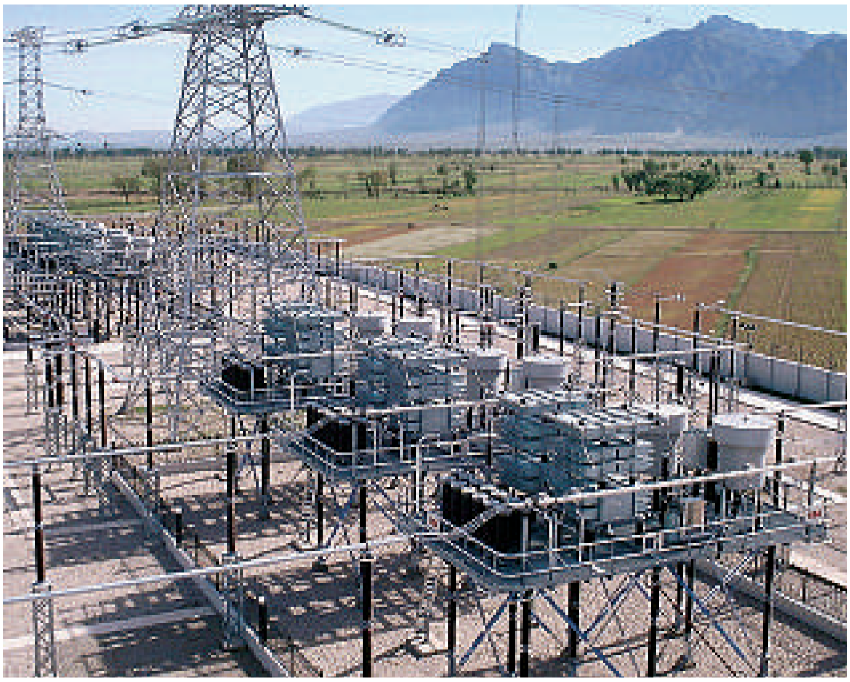
FACTS (Flexible AC Transmission Systems), such as SVC, SVC Light®, TCSC and others, are just such solutions. They take advantage of major technical progress made in the last decade and represent the state of the art for many and various needs. One typical application would be to increase the capacity 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, is

1 The Dafang 500-kV series capacitors



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 **1**. 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

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[1] SVC Light is a product name for an IGBT-based static synchronous compensator from ABB.

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.

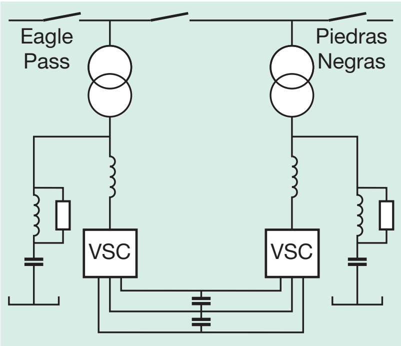
Eagle Pass also has a 138-kV transmission line that ties into Piedras Negras substation (operated by Commission Federal Electricas, CFE) on the Mexican side. This is used mainly in emergencies to transfer load between power systems, but such transfers involve interrupting the power as the CFE and AEP 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.

2 Single-line diagram of back-to-back tie at Eagle Pass



As commutation is driven by its internal circuits, a VSC does not rely on the connected AC system for its operaion. 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. Both sides of the tie can also be energized from ‘across the border’, without any switching that could involve interruptions of supply to consumers.

The back-to-back installation

A simplified one-line diagram of the BtB tie in Eagle Pass is shown in 2.

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 3.

BtB operating modes

The two VSCs of the BtB can be configured for a wide range of different

3 **Eagle Pass back-to-back tie**

Foreground: 138-kV equipment and harmonic filters. Middle: modular buildings housing converters, controls and auxiliaries. Back: cooling towers for water-cooled IGBT converters

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 BtB. 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

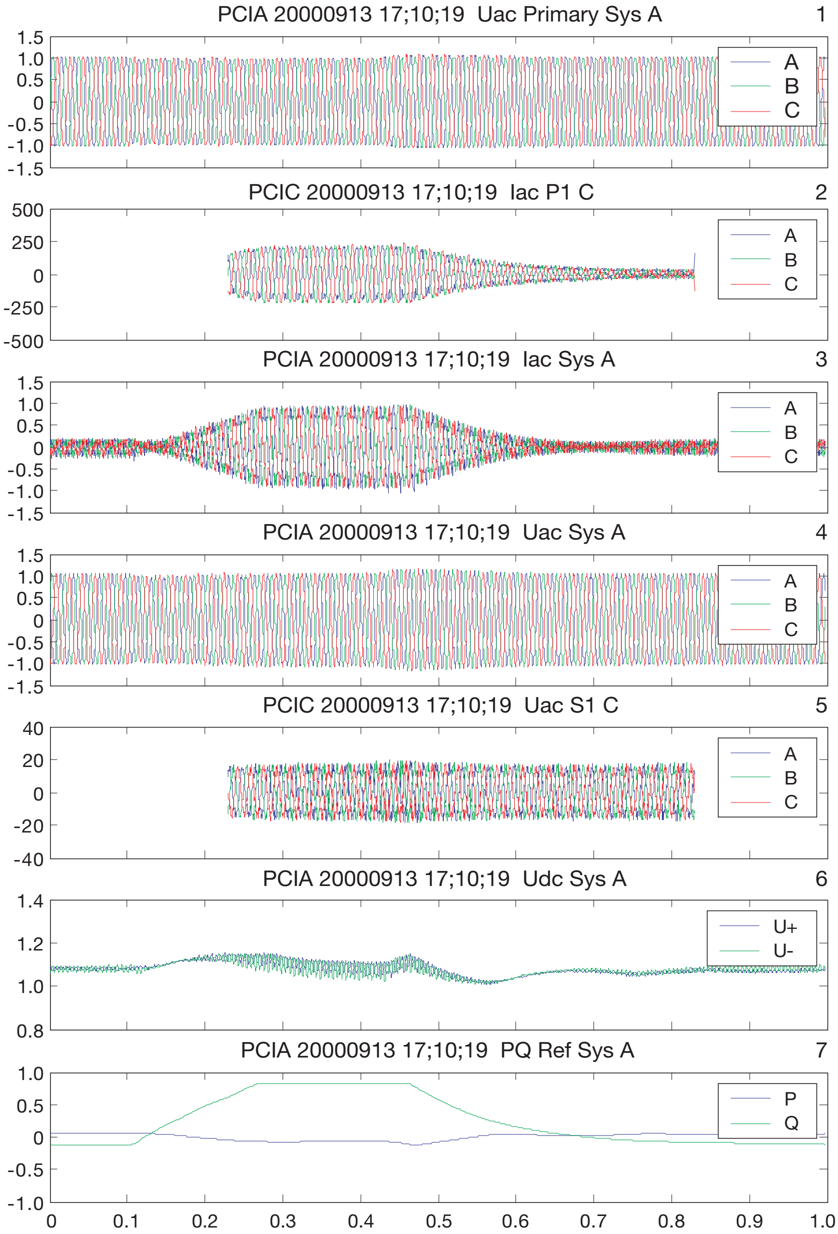
The recording reproduced in 4 illustrates well the highly dynamic performance of the BtB Light installation at Eagle Pass. Plots 1–7 show how the BtB responded to lightning conditions in a remote area that caused a voltage dip in the AEP network. During the fault, the BtB current (capacitive) was increased 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 × 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 5.

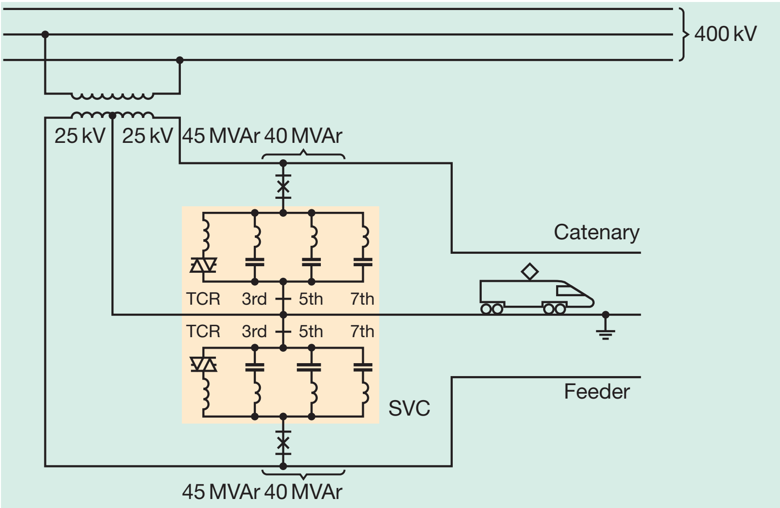
SVCs for the three traction feeding points

A major feature of this power system is the static VAr compensator (SVC) sup-



4 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



5 Power feeding system for the Channel Tunnel rail link between England and France. Singlewell substation with two single-phase static var compensators, each rated 25 kV, –5/+40 MVAr

port, the primary purpose of which 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 traction load of up to 120 MW is connected between two phases. Without compensation, this would result in an approximately 2 % negative phase sequence voltage. To counteract the unbalanced load, a *load balancer* (an asymmetrically controlled SVC) has been installed in the Sellindge substation 6. This has a three-phase connection to the grid.

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 7. 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_{LB}), as shown in 8. This current balances exactly the negative-phase sequence current from the load ($I_{\text{-LOAD}}$ in 7).

The load balancer in the Sellindge substation 9 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

6 Dynamic load balancer, Sellindge substation

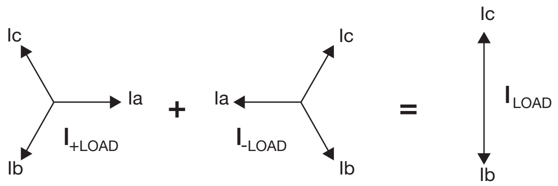
phases need to be as independent of each other as possible.

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.

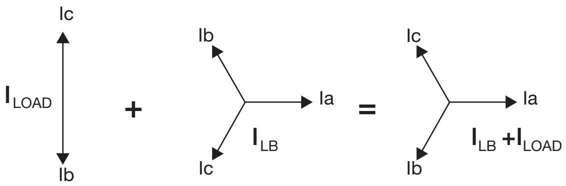
Two independent control systems act on the three-phase system, while the thyristor firing and logic circuits act directly on each interphase. The control systems are strictly segregated, as are the valve-firing logic circuits and the overall protection system. If an interphase fails, the control system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

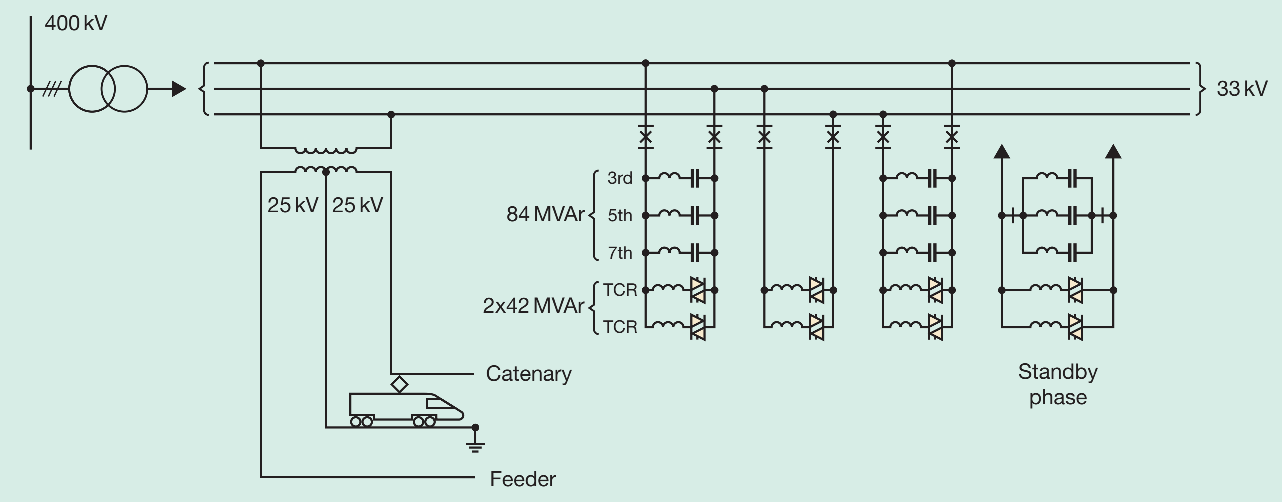
7 Phase-sequence components of the load current



8 Load current balancing



9 Circuit of dynamic load balancer in Sellindge substation (33 kV, –80/+170 MVAr)



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.

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[1] **R. Grünbaum, M. Noroozian, B. Thorvaldsson:** FACTS – powerful systems for flexible power transmission. ABB Review 5/1999, 4–17.