AC POWER TRANSMISSION

Three-phase ac electric power transmission was established at the end of the nineteenth century by such pioneers as Nikola Telsa and Thomas Edison as the most suitable means of connecting bulk power generation to consumer distribution centers. Ac generation and transmission superseded dc because it led to simpler rotating-machine design and could be transformed between different voltage levels, thus enabling the most economic voltage to be chosen for both transmission and distribution networks. In general, the higher ac voltages, up to 1 MV rms, are chosen for the longest and highest power lines, whereas lower voltages, for example, 400 V, 11 kV, 33 kV, and 132 kV, are used for the lower-power distribution networks. Three-phase rather than single-phase ac transmission has been adopted because it makes better use of cable capacity and also allows better generator and motor design. Dc transmission is still used in some special locations, such as long-distance undersea links or for interconnection between nonsynchronized systems where an ac connection would be technically infeasible or extremely expensive. Dc transmission makes more economic use of cable capacity than ac transmission, but the terminal cost of ac–dc conversion equipment is high.

The choice of voltage level for a particular ac transmission link is based on an economic assessment of the alternatives. Higher voltages require more expensive insulation, higher towers, and more expensive switchgear and transformers, but fewer lines are needed than with lower voltages. Environmental considerations mean that the reduced number of lines required can be crucial in many applications. Typically transmission powers above 1000 MW require voltages above 200 kV. Underground cable connections are only used for short transmission links and in particularly environmentally sensitive sites, since they are at least fifteen times more expensive per mile than similarly rated overhead lines.

REAL AND REACTIVE POWER

One major complication with ac transmission is the need to consider all electrical quantities (e.g. current, voltage, and power) as complex or vector quantities. This means that Ohm's law and Kirchhoff's laws when applied to an ac network must be solved using complex algebra. Consequently, the calculation of power flow in an ac network is so involved that nowadays digital computers are invariably used. Before the availability of computers, ac networks were solved using network analyzers, which were basically low-power network models. Despite the theoretical complexities, an "engineering feel" for the power flow problem can be made by treating real power (W) and reactive power (VAr) as independent variables and balancing them across the whole network, even though the real and reactive power flows are very interdependent, as can be seen from the textbook formulations.

In the real power balance the MW generation must equal the MW demand plus losses. In the reactive power balance, shunt- and series-generated capacitive MVAr must balance

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shunt- and series-absorbed inductive MVAr. However, if achieving a reactive power balance involves bulk transfer of MVAr across long lines or transformers, large voltage drops can be involved that can destabilize the network. Thus, it is necessary to prevent major reactive power imbalances in any local area of a transmission network by the use of some form of reactive compensation.

NETWORK SECURITY AND REDUNDANCY

The operation of a transmission network is generally constrained by limitations on one or more specific plant items, even though plant in other parallel transmission lines may have adequate capacity to carry additional amounts of power. This is a consequence of the free flow mode of operation of ac transmission networks, which results in the power flow on individual transmission circuits being determined by the relevant characteristics of the transmission network itself (Kirchhoff's laws). For secure network operation, sufficient transmission margin must be available at all times to accommodate the nearly instantaneous automatic redistribution of power flow that results from a power system disturbance. This margin must be adequate to enable the system to maintain stable operation during and after the disturbance.

In modern society the security of electrical supply is of paramount importance. Occasional local distribution power failures may be acceptable, since they only affect a few consumers. However, major transmission failures can have widespread and catastrophic effects. Techniques for maintaining network security involve the following:

- The adoption of circuit protection equipment that ensures that a system fault clears rapidly and isolates only the line or equipment faulted. All protection is duplicated to guard against protection failure.
- The transmission system is arranged so that it can withstand the loss of any single circuit without overloading any of the remaining lines or causing unacceptable voltage reduction. On-line computer-based security assessment studies are carried out on a routine basis at network control centers to check this condition.
- Sufficient spinning spare generation is operated to ensure that the demand can still be met and system frequency maintained following the loss of any generating unit.
- Automatic load-shedding procedures are arranged to disconnect selected consumers if the frequency falls too low.

The system security requirement is a most significant factor in determining the network configuration. In many countries high-voltage overhead line routes consist of double circuit lines. This provides redundancy and allows lines to be faulted or switched out for maintenance while keeping power flowing along the route. However, a high level of network redundancy together with a highly interconnected network, while providing high system security, also results in low impedances between network nodes and consequently high fault currents. The switchgear must be designed to clear the highest network fault currents rapidly and reliably. The cost of switchgear increases rapidly with increased fault current rating, and it is generally necessary to design and operate a network to keep the fault current below a specified value. Typically a 400 kV network will be designed to a maximum three-phase fault rating of 35,000 MVA in the main network, although switchgear on the periphery of the network may be rated at a lower level. In practice a number of techniques are adopted to limit the fault current while maintaining network reliability:

- The use of series reactors or possibly more advanced fault current limiters in strategic network locations
- Limiting the points of interconnection within a meshed network by the use of overlays or bypass circuitry
- The operational use of on-line security and fault level assessment so that the optimum network switching can be determined

SHUNT COMPENSATION

Equipment

Fixed reactors, capacitors, and synchronous compensators have been used for shunt reactive compensation since ac systems were first installed at the beginning of this century. The first variable compensators were synchronous compensators which were basically three-phase alternators without prime movers; reactive power variation was achieved by varying the excitation current. Time constants of the order of 5 s to 10 s resulted from trying to change the magnetic field of the massive steel rotor. Synchronous compensators are only installed in special cases due to this long response time and high running costs. The earliest static variable compensators were installed in the late 1950s and were based on the saturable reactor principle in which saturation characteristics of iron were used to stabilize the voltage. In order to minimize the massive harmonics generated, Friedlander developed multilimbed reactors with complex harmonic cancellation winding arrangements. The six-limbed twin tripler compensated up to the 11th harmonic, whereas the nine-limbed treble tripler compensated up to the 17th harmonic under balanced load conditions. Saturable reactors up to 150 MVAr have been made. However, these devices, although very rapid in response, are no longer made due to their high costs, high losses, and inflexibility in comparison with modern power-electronics-based compensators.

Reactive compensators involving switched shunt capacitors/reactors and synchronous compensators have been successful in many transmission applications, but they have a relatively slow response time. When it is essential to compensate load fluctuations within a few milliseconds (e.g., in order to reduce flicker or prevent a voltage collapse), then a variable power-electronics-based compensator or *static VAr compensator* (SVC) is usually required. Conventional SVCs using power thyristors have been in use since the early 1960s, and SVC prototype devices based on voltage-sourced converter technology—gate turnoff (GTO)—have been evaluated in power systems worldwide during the last few years. Typical basic connection diagrams for SVCs used in high-voltage applications (>11 kV) are shown in Fig. 1.

The conventional SVC consists basically of a thyristor-controlled reactor (TCR) shunted across the supply, connected in parallel with a fixed or variable high-voltage capacitor bank as shown in Fig 1. Many hundreds of high-voltage TCRs have

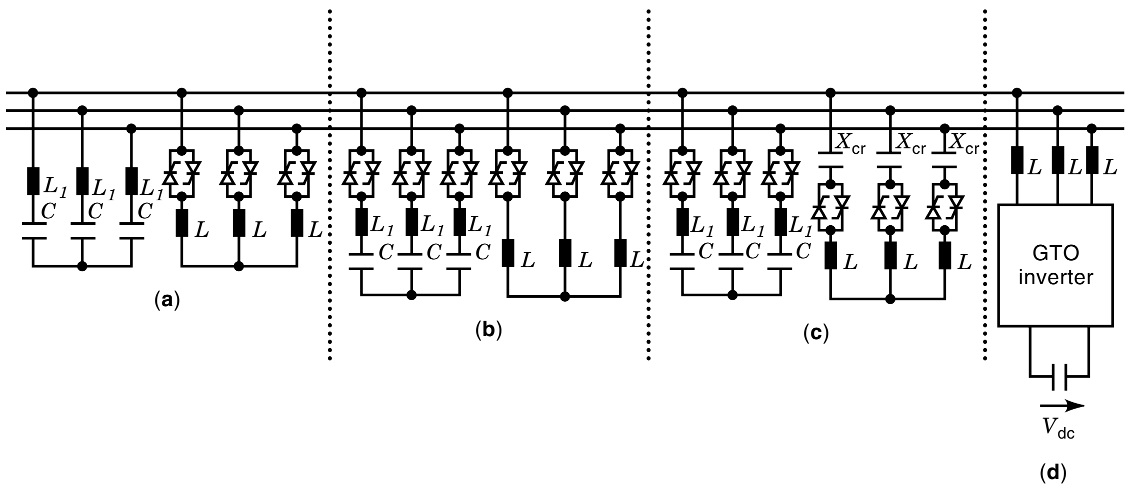

Figure 1. Typical connections for SVC, in high-voltage applications (a) with thyristor-controlled reactors and fixed capacitors, (b) with thyristor-switched capacitors, (c) with series capacitor to give constant voltage characteristic for flicker control, and (d) with 6- or 12-pulse GTO inverter.

been installed worldwide, mainly for reactive and voltage control of transmission systems. SVCs with particular characteristics and control are applied to power systems to solve a variety of system problems, namely:

- To stabilize voltage, particularly at system load locations. Voltage instability is characteristic of demand centers that import heavily via the transmission system and have insufficient dynamic reactive support. Lack of capacitive reactive power support at the receiving end of the transmission system, particularly following a system incident that weakens the network, can lead to voltage collapse. The voltage instability can be aggravated by the action of automatic distribution system transformer tap changers, which aim to maintain consumer voltage—and hence the real and the reactive power demand—regardless of transmission loadings. Static VAr compensators are commonly used to stabilize receiving-end voltages under these circumstances, such as
- To increase the active power transfer capacity of transmission systems
- To balance individual phases of an unbalanced load
- To increase the transient stability margin
- To increase the damping of power system oscillations
- To provide reactive power to ac–dc converters
- To reduce power system voltage flicker caused by disturbing loads

The TCR with six-pulse connections generates significant harmonic distortion. In most cases the capacitive part (capacitor bank) of the SVC will provide harmonic filter facilities. In the case of GTO-based SVCs, ac harmonic filters are needed if harmonic distortion is to be maintained at acceptable levels.

SVCs consisting of thyristor-switched capacitors (TSC) have also been installed in a wide range of system applications and are cheaper than TCRs in most applications due to the reduced equipment required for a particular rating. They have inherently a 1-cycle delay in operation, since the capacitors can only be switched when their terminal voltage matches the instantaneous system voltage. They have therefore been unsuccessful in applications requiring rapid (<1 cycle) closed-loop control, such as arc-furnace flicker compensation, and they also tend to suffer from capacitor failure problems. SVCs employing TSCs, generate no harmonics, but resonance with system and SVC transformer impedances for each combination of capacitor steps can be a problem.

The widespread ability to use computer-based power system simulation tools has enabled rapid development of SVC technology and applications. In the future there are prospects for exciting developments in SVC technology with the introduction of new rapid-turn-on–turnoff power semiconductors [i.e., new GTO designs and MOS-controlled thyristors (MCTs)] and developments in SVC control systems.

Theory

Ideally, the voltage along a transmission circuit would have the same magnitude at every point. This can only be achieved by loading the line *naturally,* setting the power flow P_0 equal to:

$$P_0 = \frac{V^2}{Z_0} \tag{1}$$

where V is the line voltage and Z_0 is the surge impedance given by $Z_0 = \sqrt{l/c}$ where l is the capacitance per unit length and c is the capacitance per unit length. Such a line would have a voltage profile as shown in Fig. 2.

In this situation, only real power is being transmitted across the line SR. This is the benefit of natural loading: there is no requirement to generate extra VArs at either busbar. In reality the natural loading is of little use in the long-distance transmission of power, since it only occurs at one specific load for any given voltage and line combination. In situations where the natural load has been exceeded, there is requirement to generate extra VArs, and where the loading is below the natural load, VArs must be absorbed. Both of these cases are achieved through the use of shunt compensation equip-

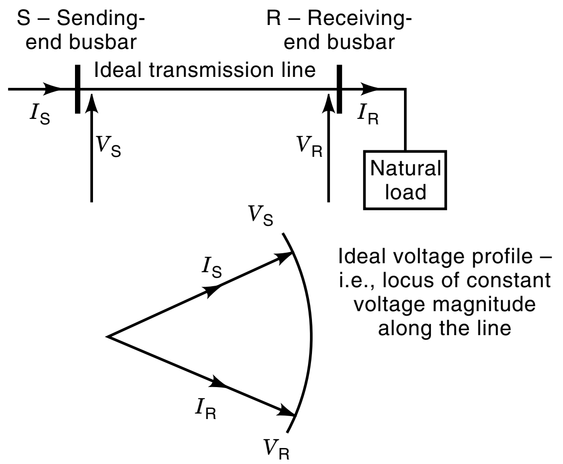

Figure 2. Ideal line loading and voltage profile.

ment. In order to develop a theoretical analysis of shunt compensation, a transmission line consisting of only series reactance will be used for ease of analysis. Figure 3 shows a typical operating state of the transmission line.

It can be seen from Fig. 3 that the voltage magnitude at the midpoint is less than the voltage at the busbars. More importantly, the receiving-end busbar is receiving real power and leading VArs, yet the sending-end busbar is delivering real power and lagging VArs. The difference between the sending- and receiving-end VArs is accounted for by the VArs being absorbed by the transmission line equal to $I_S^2X_L$. In order to compensate the transmission line, that is, try to make it behave more like the naturally loaded case of Fig. 2, it is necessary to either generate more VArs to replace those absorbed by the line, or increase the voltage at the line midpoint to restore it back to the busbar voltage magnitude; in fact, both of these approaches are the same.

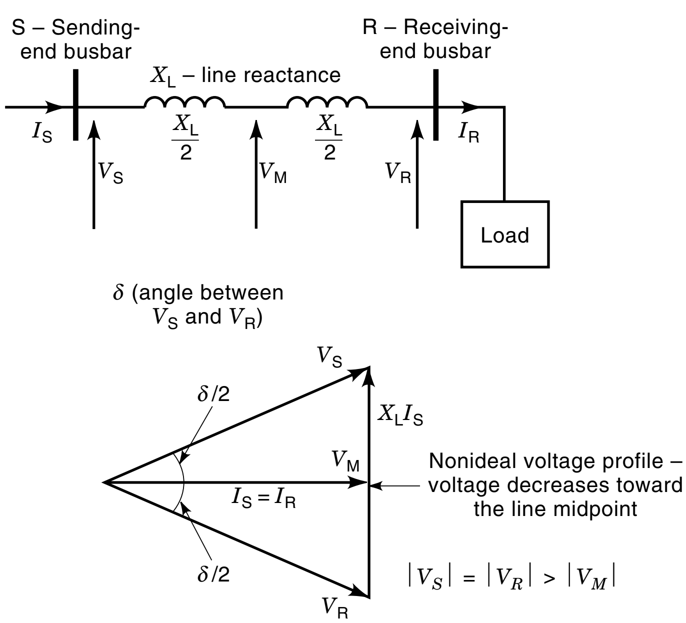

Figure 3. Uncompensated transmission line.

In the case of Fig. 3, the transfer of real power P is given by

$$P = \frac{V_S V_R}{X_L} \sin\delta \tag{2}$$

However, assuming that busbars are always maintained at the same voltage magnitude, V, we have

$$P = \frac{V^2}{X_L} \sin\delta \tag{3}$$

Considering the phasor diagram of Fig. 3, and letting $I = I_S = I_R$, it can be seen that

$$\sin\frac{\delta}{2} = \frac{IX_L/2}{V}, \qquad \text{whence} \quad I = 2\frac{V}{X_L}\sin\frac{\delta}{2} \tag{4}$$

The absorption of VArs by the line, Q_L, is a function of the line current:

$$Q_L = I^2X_L = \frac{4V^2}{X_L}\sin^2\frac{\delta}{2} \tag{5}$$

Using the trigonometrical identity $2\sin^2(\alpha/2) = (1 - \cos\alpha)$, Eq. (5) can be expressed as

$$Q_L = \frac{2V^2}{X_L}(1 - \cos\delta) \tag{6}$$

Thus, Eqs. (3) and (6) describe the real and reactive power requirements of the line as a function of the transmission angle, δ. These relations are plotted in Fig. 4.

The effect of shunt compensation will be examined by considering an ideal shunt compensator situated at the line midpoint. In reality, shunt compensators are applied at the line end substations. However, from the consideration of voltage profile, it is apparent that the compensator is needed at the midpoint, since this is the position of greatest line voltage drop. The general arrangement of the midpoint compensator

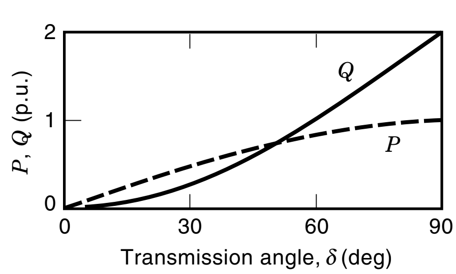

Figure 4. Variation in real and reactive power requirements for uncompensated line.

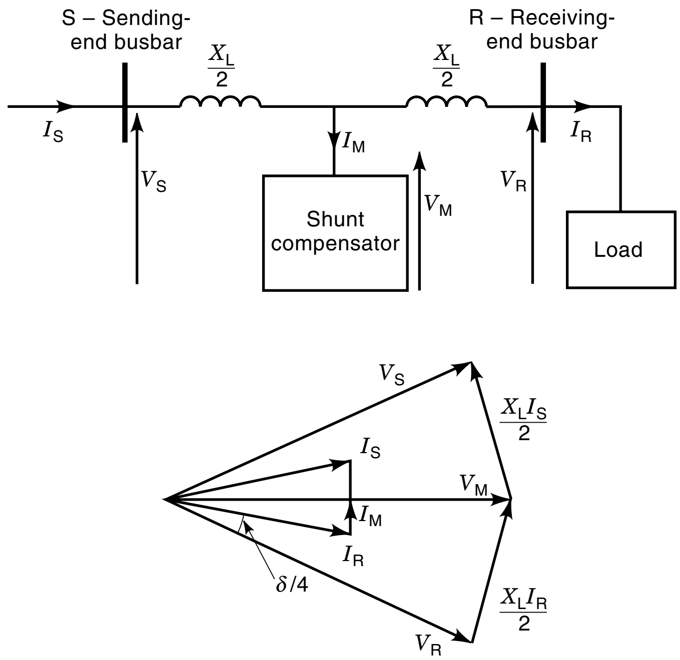

Figure 5. Application of midpoint compensator.

is shown in Fig. 5. The compensator keeps the midpoint voltage V_M at the same magnitude as the busbar voltages, that is, $|V_M| = |V_S| = |V_R|$. This effectively sections the line into two identical halves, each having a total reactance of $X_L/2$, and a transmission angle of $\delta/2$. Thus, the real power characteristic of the line now becomes

$$P = \frac{V^2}{X_L/2}\sin\frac{\delta}{2} = 2\frac{V^2}{X_L}\sin\frac{\delta}{2} \tag{7}$$

and the reactive power characteristic for one half of the line is

$$Q_L = \frac{2V^2}{X_L/2}\left(1 - \cos\frac{\delta}{2}\right) = \frac{4V^2}{X_L}\left(1 - \cos\frac{\delta}{2}\right) \tag{8}$$

From the phasor diagram of Fig. 5, it will be apparent that the compensator generates VArs Q_C that are given by

$$Q_C = -V_M I_M = -VI_M \tag{9}$$

The compensator current, I_M, can be related to the line current from busbar S, I_S, by

$$\sin\frac{\delta}{4} = \frac{I_M/2}{I_S}, \qquad \text{whence} \quad I_M = 2I_S\sin\frac{\delta}{4} \tag{10}$$

I_S may be related to the busbar voltage and line reactance using a similar approach to that used for Eq. (4):

$$\sin\frac{\delta}{4} = \frac{I_S X_L/4}{V}, \qquad \text{whence} \quad I_S = 4\frac{V}{X_L}\sin\frac{\delta}{4} \tag{11}$$

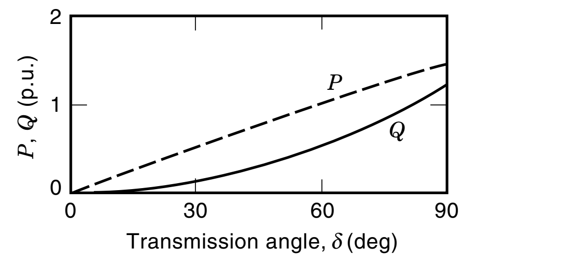

Figure 6. Variation in real and reactive power requirements for compensated line.

Combining Eqs. (9), (10), and (11) gives

$$Q_C = -8\frac{V^2}{X_L}\sin^2\frac{\delta}{4} = -4\frac{V^2}{X_L}2\sin^2\frac{\delta}{4} = -4\frac{V^2}{X_L}\left(1 - \cos\frac{\delta}{2}\right) \tag{12}$$

which is seen to be equal and opposite to the VAr demand for half of the line. The variation in P and Q as a function of δ is shown in Fig. 6, which shows a favorable increase in real power capacity and decrease in the reactive power requirements at the line ends, compared to the uncompensated line case shown in Fig. 4.

The line voltage profiles for the cases of natural loading, noncompensation, and midpoint compensation are shown in Fig. 7.

In Fig. 5, the shunt compensator is generating VArs, which enables it to increase the midpoint voltage; similarly, a shunt compensator absorbing VArs is able to decrease the midpoint voltage.

SERIES COMPENSATION

Equipment

Series capacitors have been used successfully for many years for increasing the transmission capability of long lines by effectively reducing their reactance. The installations tend to be physically large and expensive, since they involve large capacitor banks, totally insulated from line voltage for each phase. Although these fixed capacitor banks have been successful, a search for greater flexibility in power transmission has resulted in the development of the *thyristor-controlled series capacitor* (TCSC).

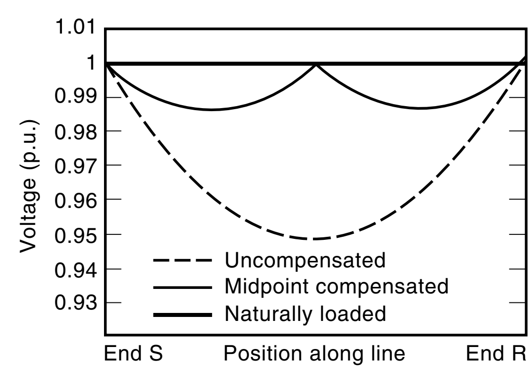

Figure 7. Line voltage profile.

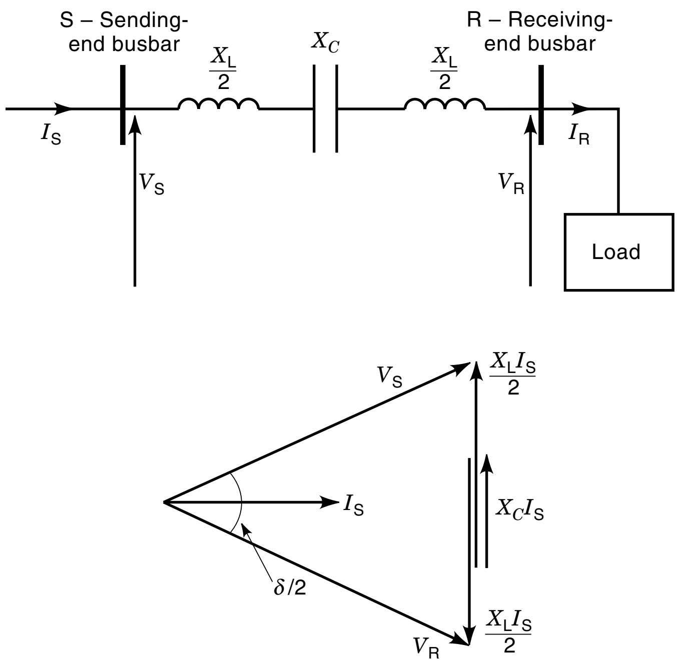

Figure 8. Series-compensated line.

The basic arrangement of the controllable series compensator scheme consists of several capacitors in series with the transmission line, each capable of being bypassed by thyristor valves, and a controller with voltage and current inputs from the line. The control strategy of the series compensator will typically be based upon achieving an objective line power flow in addition to the capability of damping power oscillations.

Three major installations of this general type are under evaluation in the United States, each by a different manufacturer (ABB, Siemens, and GE/EPRI) for transmission reinforcement purposes. All of these employ basic thyristor switching to control the amount of capacitance inserted in series, but the design philosophy differs. As an example, the ABB installation was installed in 1991 at the Kanawha River station in the United States for the American Electric Power Corporation. The TCSC comprises a total capacity of 788 MVar on the 345 kV, 174 km line to Funk. The installation was implemented in the form of three electrically series-connected capacitor segments having a rated current of 2500 A and rated capacities of 131 MVAr, 262 MVAr, and 394 MVAr respectively.

The advantages of introducing thyristor control are:

- Up to 100% of line compensation can now be introduced, since the thyristor control provides stabilization. Non-thyristor-control series compensation is limited to 50% of line reactance to avoid resonance problems.
- Line flows can be adjusted either manually or automatically to meet changing network load patterns, changing energy transfer costs, and planned or unplanned network outages.

Theory

The general arrangement of a series-compensated line is shown in Fig. 8, where the capacitor is placed at the line midpoint, although in practice, capacitors may also be placed at the substations.

In Fig. 8, the overall line reactance has been reduced from X_L to $X_L - X_C$ by the addition of the capacitor. Conventionally, the amount of capacitance added to a line is described by the degree of compensation, s, given by

$$s = \frac{X_C}{X_L}, \qquad \text{whence} \quad 0 \le s \le 1 \tag{13}$$

This allows the real power characteristic to be described as

$$P = \frac{V^2}{X_L - X_C} \sin\delta = \frac{V^2}{X_L(1-s)} \sin\delta \tag{14}$$

The reactive power generated by the capacitor, Q_C, is simply $Q_C = I_S X_C$. The line current can be found from the following expression derived from the phasor diagram of Fig. 8:

$$\sin\frac{\delta}{2} = \frac{I_S X_L/2 - I_S X_C/2}{V} \tag{15}$$

Eliminating I_S from $Q_C = I_S X_C$ using a rearrangement of Eq. 15 gives

$$Q_C = \frac{2V^2}{X_L} \frac{s}{(1-s)^2}(1 - \cos\delta) \tag{16}$$

The variation in P and Q_C as a function of δ is shown in Fig. 9 for the 30%- and 50%-compensated cases. Increasing the degree of compensation, s, gives beneficial increases in the transmitted real power, but high values of reactive power are generated by the capacitor.

PHASE ANGLE COMPENSATION

Equipment

Phase shifters, like series capacitor compensators, allow control of power through the network and power sharing between parallel circuits. Series capacitors are more suitable for long-distance lines, since, unlike phase shifters, they effectively reduce line reactance and hence reduce the reactive-power and

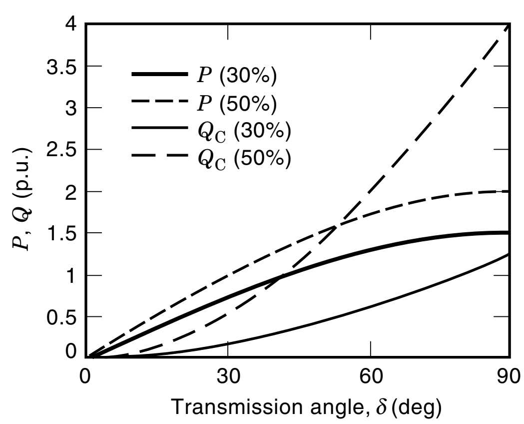

Figure 9. Variation in real power flow, P, and reactive power from capacitor, Q_C, for the series-compensated line.

voltage control problems associated with long-distance transmission. Phase shifters are more suitable for power flow control in compact high-power-density networks such as occur round major UK conurbations, where series compensation is inappropriate due to high cost, environmental impact, and electrical protection problems. To date, only slow-operating mechanically controlled phase shifters have been used, but thyristor-controlled units, due to their much higher operating speeds, will allow control of network power flows with the potential to stabilize postsystem fault conditions.

Theory

The application of a phase shifter to a transmission line is shown in Fig. 10. The phase shifter takes power from the shunt-connected transformer and injects it into the line, using the series-connected transformer. Unlike the shunt compensator and the series capacitor, which are purely reactive power devices, the phase shifter has to handle both real and reactive power. The voltage on the line side of the phase shifter should ideally be equal in magnitude to the busbar voltage. The phase shifter introduces a voltage V_I between the busbar and the line, which has the effect of causing an extra phase shift α to appear between the sending and receiving end busbars. The phase shifter effectively allows the maximum line power flow to occur even if the angle between V_S and V_R exceeds 90°; this is achieved by adjusting V_I, and hence

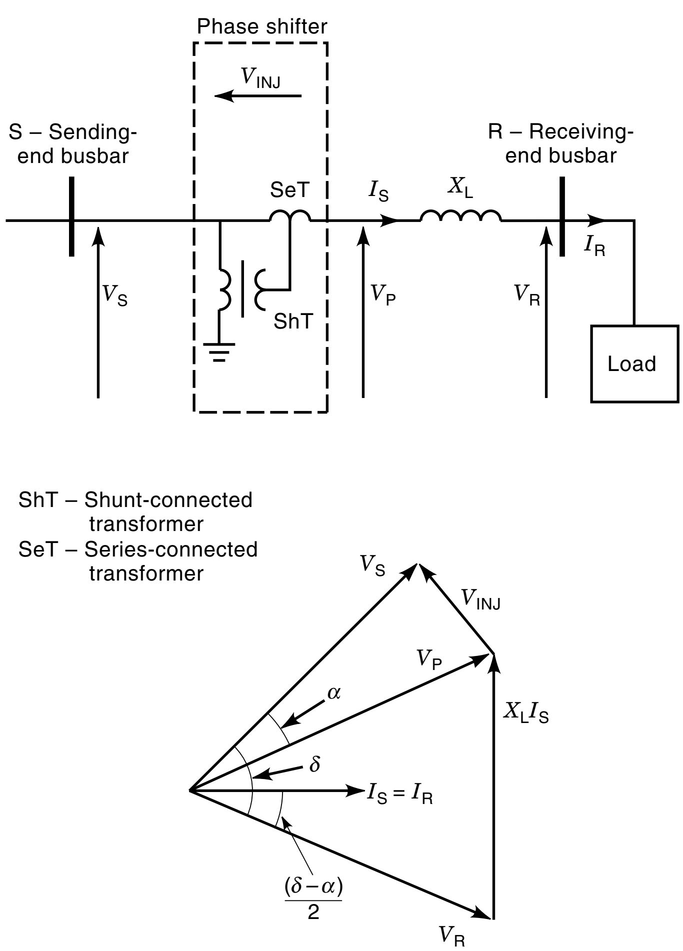

Figure 10. Phase shifter applied to a transmission line.

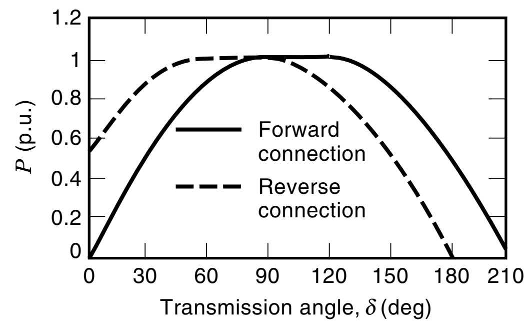

Figure 11. Real power transmission characteristic for the phase shifter (phase shifter is active for $0 \le |\alpha| \le 30°$, forward connection, as shown in Fig. 10).

α, to ensure that the angle between V_P and V_R, $\delta - \alpha$, remains at 90°. Alternatively, the series transformer connection of the phase shifter can be reversed, in which case the line is able to transfer maximum power for values of δ less than 90°. Assuming that the phase shifter is connected as shown in Fig. 10, and that the angle $\delta - \alpha$ is maintained at 90°, the power transfer characteristic is given by

$$
\begin{aligned}
P &= \frac{V^2}{X_L}\sin(\delta-\alpha) = \frac{V^2}{X_L} \quad \text{when} \quad |V_I| > 0 \\
P &= \frac{V^2}{X_L}\sin\delta \quad \text{when} \quad V_I = 0
\end{aligned}
\tag{17}
$$

This characteristic for the two connection cases is shown in Fig. 11.

The apparent power through the phase shifter, S, is given by:

$$S = |V_I|\,|I_S| \tag{18}$$

From Fig. 10, the injected voltage from the phase shifter can be expressed as

$$V_I = 2V\sin\frac{\alpha}{2} \tag{19}$$

and the line current can be derived as

$$I_S = \frac{2V\sin\left(\dfrac{\delta-\alpha}{2}\right)}{X_L} \tag{20}$$

Combining Eqs. 18, 19, and 20 yields

$$S = 4\,\frac{V^2}{X_L}\sin\left(\frac{\delta-\alpha}{2}\right)\sin\frac{\alpha}{2} \tag{21}$$

FLEXIBLE AC TRANSMISSION SYSTEMS

Introduction

FACTS is an acronym for flexible ac transmission systems. The philosophy of FACTS is to use power electronic controllers to control power flows in a transmission network, thereby allowing a transmission line plant to be loaded to its full capability. Power-electronic-controlled devices, such as static VAR compensators, have been used in transmission networks for many years; however, FACTS as a total network control philosophy was only introduced in 1988 by N. Hingorani from the Electric Power Research Institute (EPRI) in the United States.

The significant improvement that FACTS controllers will make on transmission systems arises from their ability to effect high-speed control. Currently, the main control actions in a power system, such as changing transformer taps, switching current, or governing turbine steam pressure, are achieved through the use of mechanical devices, which necessarily impose a limit on the speed at which control action can be made. FACTS controllers are based on solid-state control and so are capable of control actions at far higher speed. The three parameters that control transmission line power flow are line impedance and the magnitude and phase of the line end voltages. Conventional control of these parameters, although adequate during steady-state and slowly changing load conditions, cannot, in general, be achieved fast enough to handle dynamic system conditions. The use of FACTS technology will change this situation. The first generation of FACTS controllers based on current technology comprise thyristor-controlled static VAr compensators, thyristor-controlled series capacitors, and thyristor-controlled phase angle compensation. Future FACTS controllers will include devices using GTOs or more advanced switch-on–switch-off power semiconductors. Such controllers have the potential to be much more compact and operationally flexible.

The use of FACTS devices for controlling power flows in networks independent of transmission plant impedances has benefits other than increasing power line utilization. It is significant that the United States has pioneered FACTS, since private ownership of the electricity supply industry with its power dealing between utilities has a far longer history in the United States than in the United Kingdom. In the United States the desire of the many competing utilities to broaden the markets for production and sale of electric power brought with it the need to be able to deliver the power they sell to another utility that might be anywhere in the network, and required power transmission over circuits of other utilities. This needed some form of transmission access. Their approach, known as the *contract path* procedure, required the two utilities wishing to exchange power to write a contract calling for this power to flow over a prescribed path, which had sufficient capacity and an expected loading low enough so that the additional transfer would not exceed capacity. This approach worked in the early years when there were relatively few utility ties, but has become a great oversimplification with modern networks. A major problem is that only the utilities providing the contract path receive payment, while the transmission facilities of other utilities are used without compensation although their ability to operate economically and reliably could be affected. With FACTS power can be routed over the contract path or prevented from flowing along undesirable alternative paths.

FACTS technology can alleviate both transient and dynamic instability problems. With regard to the former, FACTS devices inherently increase stability margins, thus allowing greater circuit loading before the stability constraint is met. With regard to the latter, the high-speed control action of FACTS devices helps to dampen down power oscillations that would otherwise cause loss of synchronism. In fact there are specialized FACTS devices—for example, the *NGH damper*—designed purely for oscillation damping.

FACTS devices can provide reactive compensation (although some types can even increase reactive power demands), which allow the line to behave as though it were always naturally loaded (i.e., operating so that the transmission line has a reactive power balance). The use of reactive compensation itself is by no means new. However, FACTS provides the advantages, firstly, that the compensation can be continuously varied, as opposed to merely switching reactors in and out, and secondly, that the compensation can be varied at high speed, thus giving stability advantages.

The main benefits of FACTS over conventional solutions are considered to be:

- *Cost.* Due to the high capital cost of transmission plants, cost considerations frequently outweigh all other considerations. Among methods of solving transmission loading problems, FACTS technology is often the most economic.
- *Convenience.* All FACTS devices can be retrofitted to existing ac transmission plants, with varying degrees of ease. In contrast, for example, with high-voltage dc transmission, solutions can be provided without widescale system disruption and within a reasonable time.
- *Environmental Impact.* In order to provide new transmission routes to supply an ever increasing worldwide demand for electrical power, it is necessary to acquire wayleave—the right to convey electrical energy over a given route. It is common for environmental opposition to frustrate attempts to establish new transmission routes. FACTS technology, however, allows greater throughput over existing routes, thus meeting consumer demand without the construction of new transmission lines. However, the environmental impact of the FACTS device itself may be considerable. In particular, series compensation units can be visually obtrusive, with large pieces of transmission equipment placed on top of high-voltage insulated platforms.

Current Technology

Current FACTS technology is based on the use of thyristor devices, which are now available at ratings up to 4 kV and 1000 A per device. A thyristor can be forced into conduction by the application of a small pulse of current to its gate. Once switched on, however, thyristors cannot be similarly forced to stop conducting; instead, natural zero crossings in the line current are used to force thyristors into the off state. Although some FACTS devices rely on thyristors to replace mechanical switches, the application of thyristors to switching inductors and capacitors is an important issue that needs to be considered in detail.

Figure 12 shows the circuit arrangement of a thyristor-controlled reactor. Two back-to-back connected thyristors are needed to allow ac conduction of the circuit; gating pulses are provided by the controller. If gating pulses are provided at current zero crossings, then the circuit of Fig. 12 behaves as if the thyristors were short-circuited; this is shown in the fully conducting case of Fig. 13.

However, if the gating pulse is delayed, then the conduction of the thyristor occurs later in the cycle. Two variables

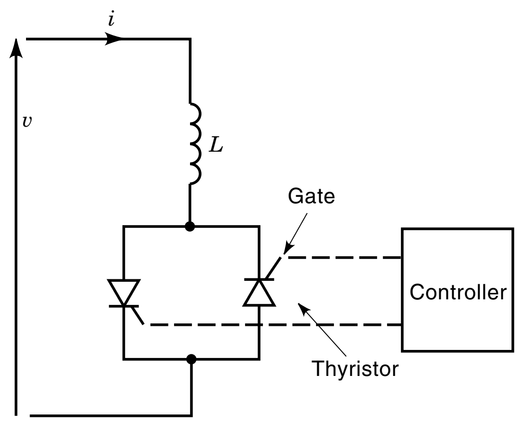

Figure 12. Thyristor-controlled reactor.

are associated with the control of the thyristor conduction: the gating delay angle α, which is measured from the zero crossing of the applied voltage waveform to the point of gating, and the conduction angle σ, which measures the total angular conduction of the thyristor in any one half cycle. Thus, in a fully conducting thyristor-controlled reactor circuit, α will equal 90° and σ will equal 180°. In Fig. 13, the current waveform arising from delayed conduction of the thyristor due to a gating delay angle of 120° is shown; in this case the conduction angle will also be 120°. By varying the gating delay angle in the range 90° to 180°, the conduction angle can be varied from 180° (fully conducting) to 0° (nonconducting).

The ability to electronically control the current in the inductor allows the thyristor-controlled reactor to behave as a variable reactance. Using Fourier analysis to find the fundamental (i.e., power system frequency) component of the current, I_1, in the circuit of Fig. 12 yields the following expression:

$$I_1 = \frac{\sigma - \sin\sigma}{\pi X_L} V \tag{22}$$

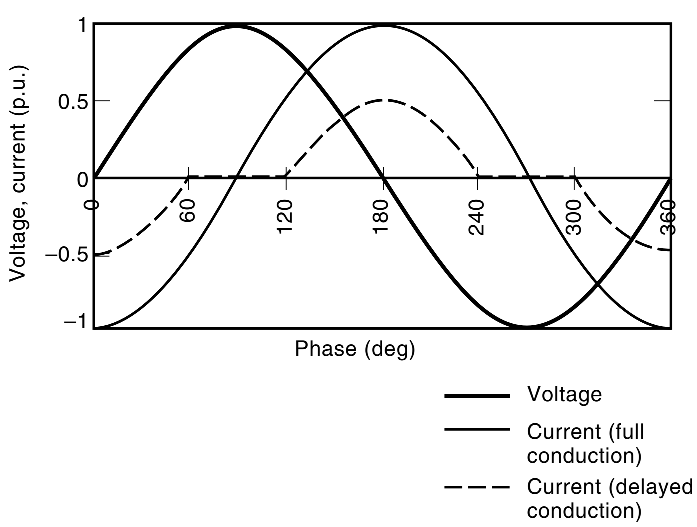

Figure 13. Voltage and current waveforms for thyristor-controlled reactor circuit. (Full conduction: gating delay angle $\alpha = 90°$, conduction angle $\sigma = 180°$. Delayed conduction: gating delay angle $\alpha = 120°$, conduction angle $\sigma = 120°$).

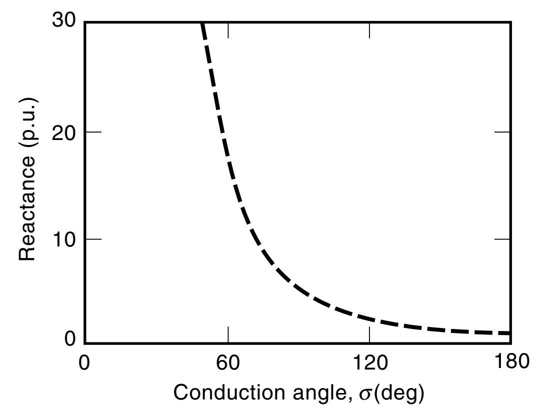

Figure 14. Variation in reactance with conduction angle for thyristor-controlled reactor.

Hence, the variable reactance, as a function of the conduction angle σ, is

$$X(\sigma) = \frac{V}{I_1} = \frac{\pi X_L}{\sigma - \sin\sigma} \tag{23}$$

The variation in $X(\sigma)$ with σ is shown in Fig. 14; increasing the conduction angle increases the reactance.

In the thyristor-controlled reactor circuit, energy storage within the inductor is due to current flow, and hence there is no stored energy in the circuit when the thyristor ceases to conduct, since the current is zero. If a thyristor is used to control a capacitor circuit, as shown in Fig. 15, then substantial stored energy in the capacitor will exist when the thyristor ceases to conduct, since the voltage will be at a maximum. Thus, the capacitor must be reconnected to the source at a point where the capacitor and source voltage are equal. For this reason, no delay in the conduction of the thyristor is permissible, and such a circuit is referred to as a thyristor-switched capacitor. The control circuit of the thyristor-switched capacitor ensures that the thyristor is only gated when supply voltage is at its maximum, and that the polarity is correct.

It should be appreciated that thyristor switching of capacitors can be achieved at a far higher speed than is possible

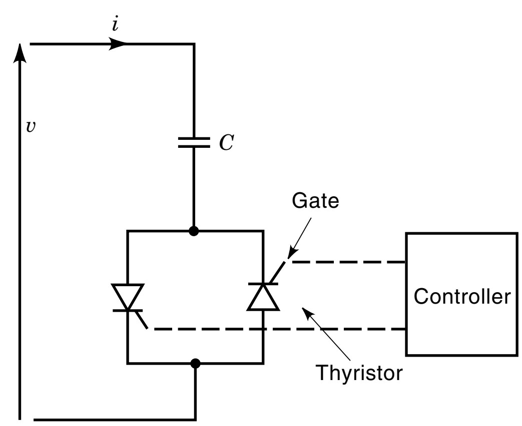

Figure 15. Thyristor-switched capacitor.

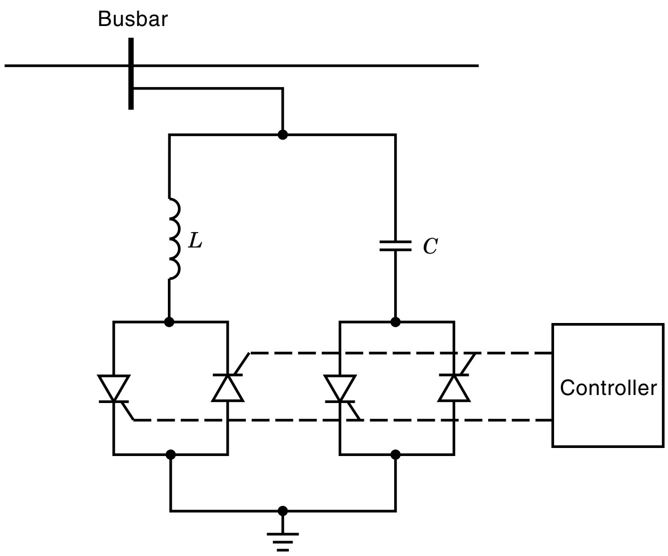

Figure 16. Static VAr compensator.

with mechanical switchgear; it is possible to insert capacitors into a circuit for only one cycle at a time.

Static VAr Compensators. The connection of the thyristor-controlled reactor and the thyristor-switched capacitor can be combined to produce a variable-reactance device that can work in both the capacitive and the inductive area. The general arrangement is shown in Fig. 16.

On high-voltage busbars, the static VAr compensator will be connected via a transformer to reduce the voltage and hence the cost of the equipment. On a three-phase system, the static VAr compensator is connected in delta, rather than the earthed connection shown in the single-phase representation of Fig. 16. Additionally, harmonic-reduction equipment will be needed to filter out harmonics generated by the thyristor-controlled reactor when it operates with conduction angles less than 180°.

The current–voltage characteristic of the static VAr compensator is shown in Fig. 17. This figure shows the ability of the compensator to maintain a constant voltage on the busbar to which it is connected. The characteristic of the compensator has a slight upward slope, which gives a small increase in the busbar voltage when absorbing VArs. This is to ensure that the characteristic meets the system load line at a well-defined point and prevents oscillation of the controller as it attempts to maintain a constant busbar voltage. The effect of the capacitor in the static VAr compensator can be seen from Fig. 17: this moves the "inductor only" characteristic into the capacitative current region. Thus the compensator is able to maintain a constant busbar voltage for both leading and lagging currents. It will be recalled from the theory section relating to shunt compensators that a compensator absorbing VArs will reduce the system voltage, whereas a compensator generating VArs will increase the system voltage. Thus the static VAr compensator is able to act in both regions. In common with all FACTS devices, the static VAr compensator is able to effect high-speed control: the compensator could, in principle, move from its maximum absorption to maximum generation of VArs within one cycle.

Thyristor-Switched Series Capacitor Compensator. The basic outline of a series capacitor compensator is shown in Fig. 18, in which series capacitors are bypassed by thyristor switching units. The controller adjusts the number of capacitors in series with the line to suit local conditions; again this adjustment is made at high speed.

Thyristor-Switched Phase-Angle Control. Figure 19 shows the arrangement of the thyristor-switched phase-angle compensator which is essentially a conventional quadrature booster with the tap changers replaced by thyristors. The thyristors are arranged so as to allow the injected voltage from the series transformer to be added or subtracted from the busbar voltage. The $L:M:N$ shunt transformer allows the controller to set the injected voltage to one of 27 different voltage magnitudes.

Future Technology

The disadvantages of current FACTS devices are mainly due to the inability of conventional thyristors to turn off at any instant except when the current passes through a zero. Thus,

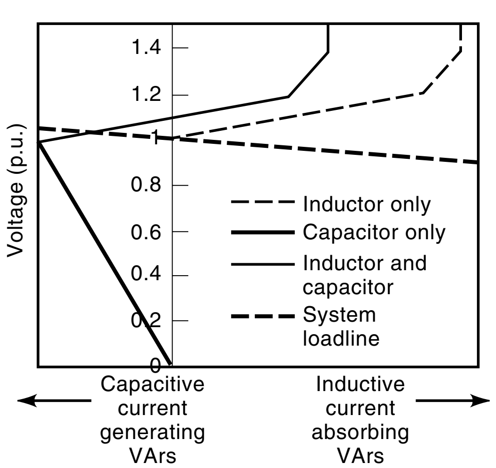

Figure 17. Characteristic of static VAr compensator.

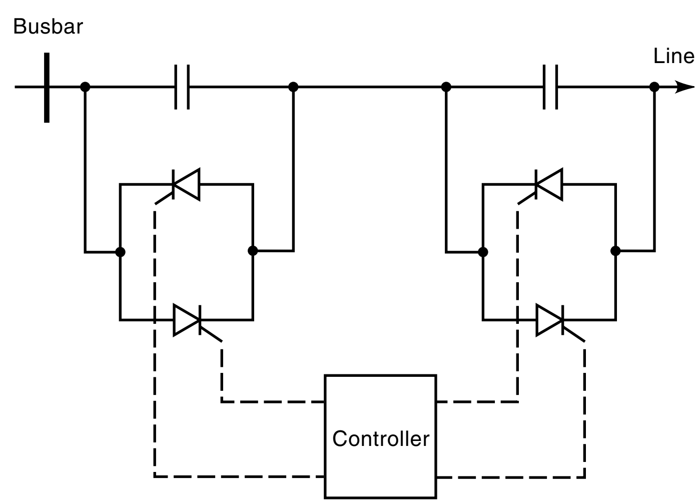

Figure 18. Thyristor-switched series capacitor compensator.

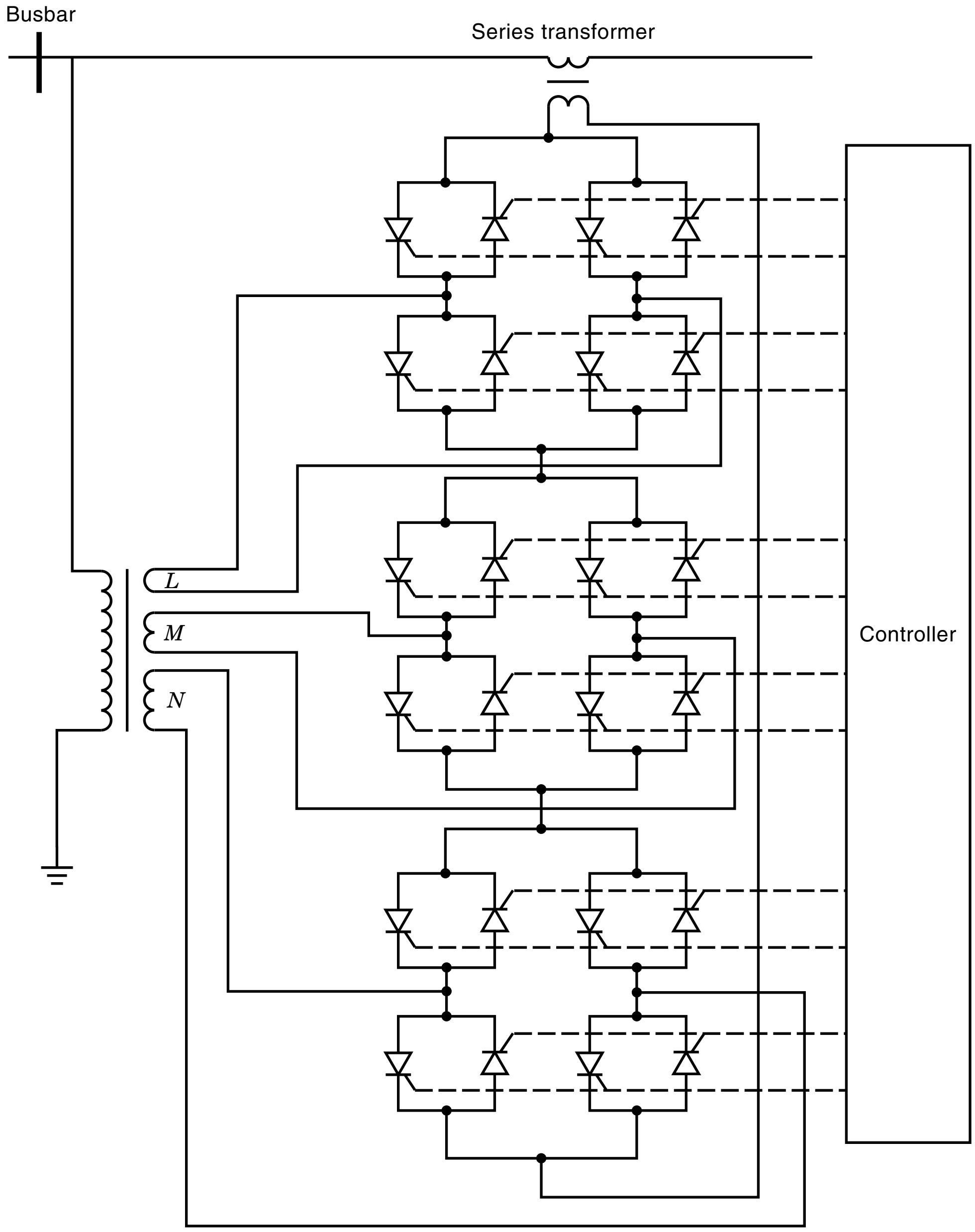

Figure 19. Thyristor-switched phase-angle compensator.

all current FACTS devices rely upon conventional circuit elements as shown here:

FACTS Device	Conventional Circuit Element
Static VAr compensator	Shunt reactor
Thyristor-switched series capacitor	Series capacitor
Thyristor-switched phase angle compensator	Quadrature booster

This table shows that the application of any FACTS device will incur capital costs and substation space roughly the same as with the use of the conventional circuit element. The advantages of using FACTS technology include a reduction in the number of mechanical devices, the ability to effect high-speed control, and the ability to effect variable control (although only the static VAr compensator allows continuously variable control).

The next generation of FACTS devices—advanced FACTS devices—will use thyristors that are able to turn off at any instant and are referred to as turn-on–turn-off devices. There are many different devices that might be developed into commercially viable turn-on–turn-off devices at power distribution/transmission levels. The current main contenders include:

- Gate turnoff thyristors (GTOs)
- High-power bipolar transistors—also known as giant transistors (GTRs)

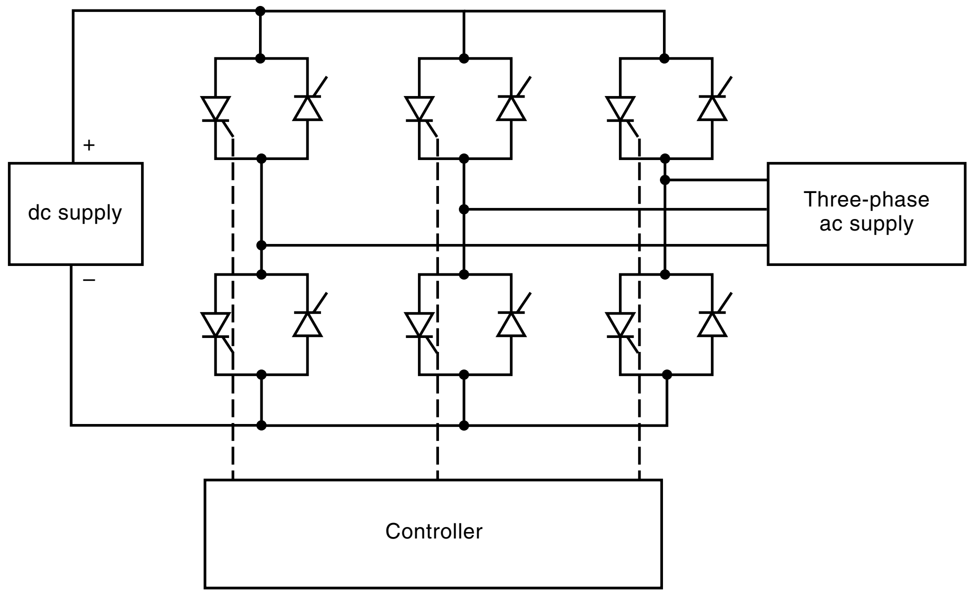

Figure 20. Voltage-sourced converter circuit.

- Static induction thyristors (SITs)
- MOS-controlled thyristors (MCTs)

At present GTOs appear to be the likely device for advanced FACTS applications, and several prototype FACTS devices of that kind have been developed. The difficulty with all turn-on–turnoff devices is the switching loss; future FACTS technology will use GTOs at switching frequencies of several kilohertz rather than the 50/60 Hz switching frequencies used currently with conventional thyristors. Currently, GTOs cannot be produced with switching losses small enough to make advanced FACTS devices economically viable; however, it is only a question of time before this obstacle is overcome.

Voltage-Sourced Converter. The ability to switch distribution/transmission-level loads at high frequencies allows the use of certain switching circuits commonly found in power electronic equipment. The workhorse of advanced FACTS devices will be the voltage-sourced converter circuit shown in Fig. 20.

The voltage-sourced converter is essentially a conventional three-phase rectifying bridge, which connects together a dc and an ac supply, and which has additional controlled GTOs connected across each diode. The rectifying action allows power flow from the ac to the dc side; controlled operation of the GTOs allows power to be transferred from the dc to the ac side. To prevent unwanted harmonics being generated from square-wave-type approximations to sinusoids, the GTOs are switched at high frequency, using a pulse-width modulation (PWM) technique. This allows the generation of a smooth, relatively harmonic-free, sinusoidal voltage at the ac side, which can be varied electronically in phase and amplitude by controlling the turnoff and turn-on instants.

Advanced Static VAr Shunt Compensator. Figure 21 shows the implementation of a static VAr compensator using a voltage-sourced converter circuit. This consists of a voltage-sourced converter circuit connected to a busbar through a step-down transformer. In common with conventional static VAr compensators, the transformer allows the compensator to work at lower voltages, thus reducing cost. However, the leakage reactance of the transformer is also important to the operation of the circuit, since, by increasing or decreasing the compensator voltage, the current through the reactance

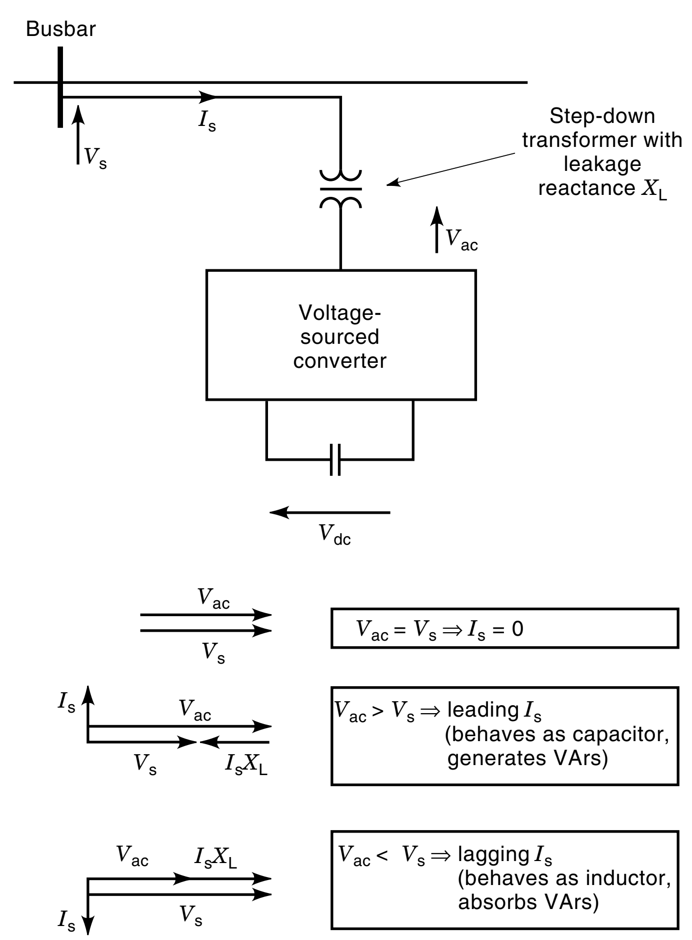

Figure 21. Advanced static VAr shunt compensator.

can be made to lead or lag the busbar voltage, as shown in the phasor diagram of Fig. 21. This mode of operation is similar to that of a synchronous compensator and allows the advanced static VAr compensator to provide either absorbing or generating VAr support. The time constant for changing the generated voltage is almost zero, unlike that for the synchronous compensator, which is dependent on the rotor field time constant of 5 s to 10 s. The compensator characteristic is similar to the characteristic of the conventional static VAr compensator, as shown in Fig. 17. However, since the advanced static VAr compensator does not rely upon the system voltage magnitude for generation of VArs, it is able to provide full VAr support even when the system voltage magnitude reduces substantially, for example, down to 0.1 p.u.

Figure 21 also shows that the dc supply for the compensator is derived from a capacitor. Since the compensator voltage is kept virtually in phase with busbar voltage, there is no interchange of real power between the compensator and the system. However, there is a requirement to overcome the switching losses of the GTOs in the converter; this is achieved by making the busbar voltage slightly lead the compensator voltage, thus allowing a small flow of real power from the system to the compensator. In this way the capacitor voltage can be regulated.

Controllable Series Compensator. By allowing the ac voltage from the voltage-sourced converter to be applied to a transmission line through a series transformer, a controllable series compensator can be derived, as shown in Fig. 22. In this application, the compensator voltage V_{ac} is always 90° out-of-phase with the line current I_s, thus ensuring that no significant real power is generated or absorbed by the compensator except what is needed to keep the capacitor at the correct voltage. If V_{ac} lags I_s, then the device will behave as a capacitor and the overall line reactance will reduce between the busbars. Unlike the thyristor-switched series compensator, the controllable series compensator can continuously vary the degree of compensation, and can even reverse the phase of the voltage and increase the overall line reactance; this feature is useful for dampening power oscillations. Additionally, the controllable series compensator does not exhibit the phenomenon of subsynchronous oscillation—oscillation caused by resonance of the series capacitance with the system reactance—since the compensator voltage can be fixed in magnitude and not vary with the line current as in the case of a genuine capacitor.

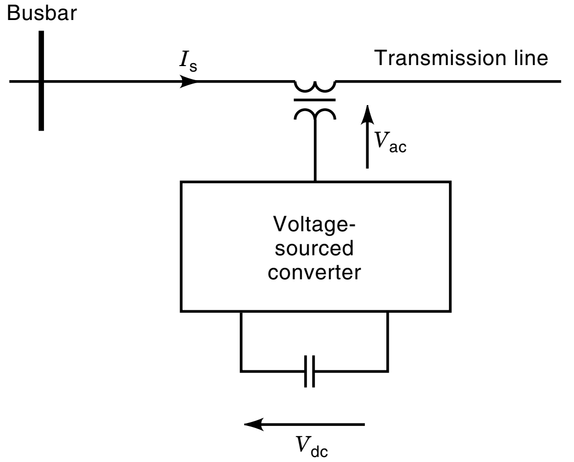

Figure 22. Controllable series compensator.

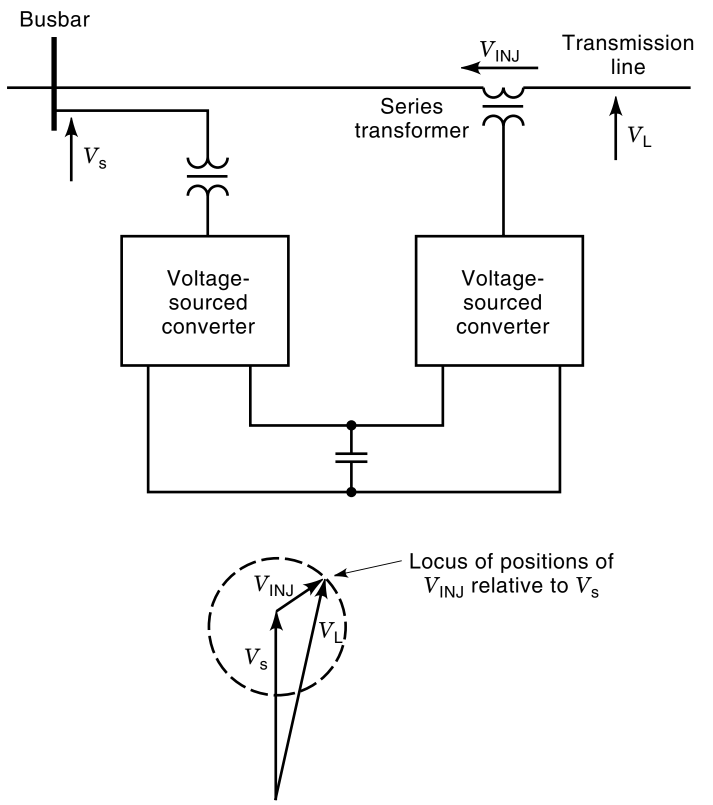

Figure 23. Unified power flow controller.

Unified Power Flow Controller. The final advanced FACTS device arises from the interconnection between an advanced static VAr shunt compensator and a controllable series compensator, as shown in Fig. 23. Since the dc sides of the converters are both interconnected, it is now possible for real, as well as reactive, power to flow through the compensator. This allows the injected voltage V_I to assume any relative phase with respect to the busbar voltage V_s, as shown in the phasor diagram of Fig. 22; the maximum value of V_I will depend upon the compensator rating. The unified power flow controller can thus provide the following methods of compensation:

- Series compensation—by making V_I 90° out of phase with the line current
- Shunt compensation—by making V_I in phase with the busbar voltage V_s, thus raising or lowering line voltage V_L
- Phase angle compensation—by keeping V_s and V_L at constant magnitudes, but using V_I to create a phase angle α between these vectors

Additionally, the compensator is able to provide these modes of operation simultaneously; for example, it is possible to simultaneously provide series line compensation and busbar shunt compensation. It is the flexibility of this controller that gives it the name unified power flow controller.

Note that if the ac connection between the shunt and series transformers is broken, then the device becomes essentially a back-to-back dc converter.

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ACQUEOUS ELECTROLYTES. See ELECTROLYTES.

ACQUISITION, KNOWLEDGE. See KNOWLEDGE ACQUISITION.

ACQUISITION OF KNOWLEDGE. See KNOWLEDGE ACQUISITION.

ACS. See ASYNCHRONOUS SEQUENTIAL LOGIC.

ACTION PLANNING. See PLANNING.