Chapter 4

HVDC and power electronic systems

G. ó hEidhin

4.1 Introduction

Power electronic devices and systems are becoming an increasingly common feature of power systems. Over the years many power electronic products have been developed and can be used to great effect in the AC transmission and distribution system. Existing examples include:

- high voltage direct current (HVDC) power transmission systems
- static VAr compensators (SVC) – dynamic shunt reactive power compensation
- various forms of motor drive systems based on power electronics, widely used in industry and traction applications
- power supplies – many of these are based on power electronic devices.

Future developments may include:

- 'STATCOM' (GTO based SVC)
- static series compensator – dynamic series compensation of transmission lines
- unified power flow controller (UPFC) – combined dynamic shunt and series compensators
- electronic tap-changer
- phase-shifter (also known as a quad booster) – used to share load between parallel circuits. This is generally a mechanical device but could also be implemented as a power electronic system.

The first item, HVDC, is generally the largest of the various power electronic systems and makes the most dramatic difference to power systems. This is described in some detail. The other power system devices (SVC, STATCOM, series compensation, UPFC) are described more briefly.

4.2 HVDC transmission – a brief overview

Early electricity distribution was by DC. Then the transformer was developed so that AC became the universal choice for generation, transmission, distribution and utilisation. However, during the last 40 years many HVDC systems have been built and operated (and a few even decommissioned!). Have we turned the clock back?

No! Modern HVDC systems are fully integrated into the adjoining AC systems and in some instances are fully embedded in an AC system. HVDC systems offer the following enhancements and capabilities to power systems:

(a) Economic long distance power transfer, e.g. from a remote power source to an urban area. The economy in this instance arises from the fact that a DC transmission line is considerably cheaper to build than the AC power line to carry the same power and if the distance is great enough, this economy more than pays for the HVDC convertor stations at both ends. The break-even distance is approximately 800 km for an overhead line and approximately 50 km for a cable.
(b) Interconnecting independent power systems. HVDC provides an asynchronous link between different AC systems which may continue to operate at different frequencies and/or relative phase angles. HVDC allows the operators to influence reactive power and voltage at each terminal of the link and to control the real power transmitted, regardless of the system voltages, frequencies or relative phase angles. This is in contrast to an AC link over which the real and reactive power flow are entirely dependent on the voltage and phase angles at each end of the link. Additionally the two power systems retain independence of operation while obtaining the benefits of interconnection such as mutual support and shared spinning reserve. Very often such links are of zero length and are called 'back-to-back' schemes.
(c) HVDC power transmission is very controllable and can provide both static and dynamic support for a power system. There is one particular system where the presence of the HVDC system means that the power transfer capacity on the parallel AC interconnections has been increased by 50%.
(d) HVDC can be used to provide tight frequency control of one system.
(e) HVDC systems can damp out oscillations in the attached AC power systems and associated generators.
(f) Unlike an AC interconnection, HVDC transmission causes no increase in the fault level of the attached AC systems.

If the function of an HVDC transmission scheme is to transfer power over a long distance, then it will invariably use a high direct voltage. Most present day schemes use voltages up to ± 500 kV for overhead lines, while cables have been approaching this voltage progressively over the last 20 years. As for AC transmission, high voltage is used to minimise the current in the link to reduce the I^2R losses in the line or cable.

For back-to-back schemes the pressure to use high voltage disappears and the voltage used will be the lowest voltage at which the required power can be transferred, bearing in mind the limitations of the convertor valves. The convertor valves are normally the factor which limits HVDC current rating. Thyristors up to 125 mm diameter are now in general use, enabling direct currents of up to 4000 A to be used.

Therefore, convertor stations can be roughly characterised into two groups:

(i) back-to-back convertors using low direct voltage and high current, typically 20 to 200 kV and 2.5 to 4 kA
(ii) long distance transmission schemes using higher direct voltages and more moderate current, typically 300 to 600 kV and 1 to 2 kA.

The basic configuration of an HVDC link is shown in Figure 4.1. The convertor station designer must assemble all of the required components in such a way as to provide them with the necessary environmental protection, whatever access may be necessary first for construction and later for operation and maintenance, and to provide all the normal supporting services such as auxiliary supplies and cooling. Environmental aspects of an HVDC convertor station, as for a conventional HV substation, include:

- audible noise
- visual impact
- radio interference
- electric and magnetic fields.

In designing the convertor station, the designer must bear in mind the requirements of particular specifications. Specifications for HVDC transmission schemes vary in length from as little as 10 pages to over 1000, so it would be idle to suggest that a discussion of practicable length can take into account all possible variations. Therefore, this chapter is

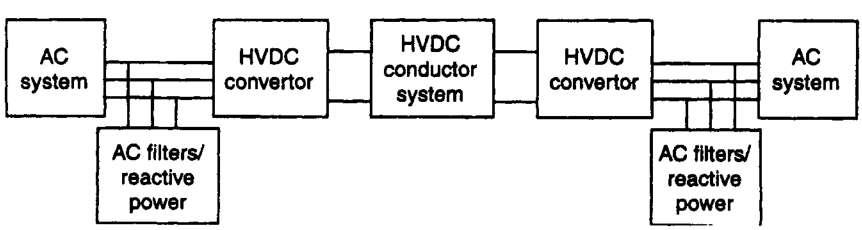

Figure 4.1 HVDC system

only intended to raise the major issues to be considered and not to give a definitive guide to a fixed procedure. More detail is given in References 1–3.

4.3 General principles

Figure 4.2 shows the arrangement of the basic components for a transmission scheme convertor terminal. The function and relationship of these components will be addressed in the following sections.

The HVDC convertor consists of a 12-pulse convertor connected to the AC system through the convertor transformer. Harmonic filters are provided on the AC and DC sides of the convertor as required to limit interference to acceptable levels. A smoothing reactor is provided (except on some back-to-back links) to protect the convertor from externally imposed impulses on the DC line.

4.4 Main components of HVDC links

4.4.1 Thyristor valves

The heart of a convertor station is the thyristor valve which performs the switching function of the convertors. Six identical valves are arranged in

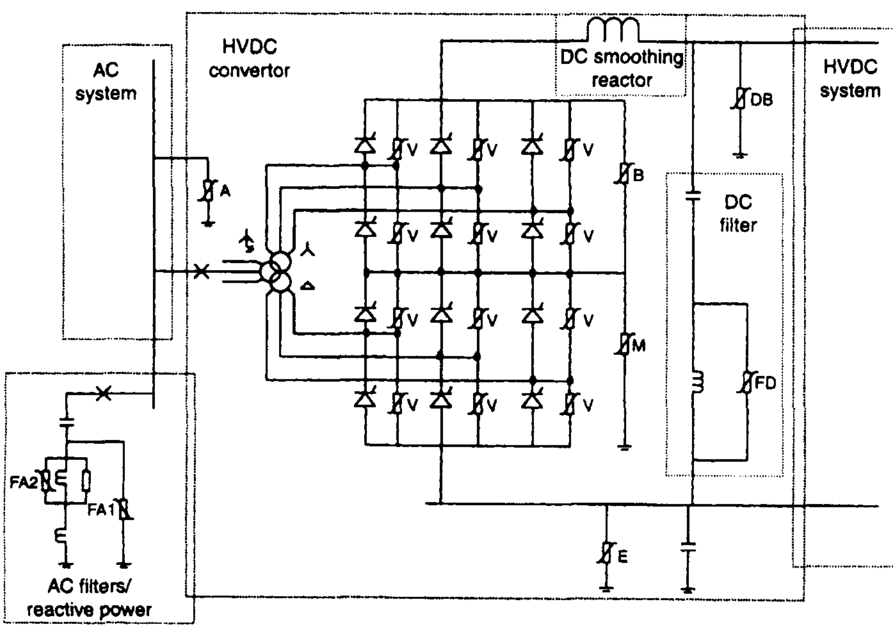

Figure 4.2 Simplified single line diagram of HVDC station

a three-phase bridge so that full range rectification or inversion can be achieved by phase angle control. Such an arrangement is commonly referred to as a six-pulse bridge because it requires six firing pulses per fundamental frequency cycle to operate the valves, so it produces a DC side ripple of six times the AC system frequency. Two six-pulse bridges in series on the DC side fed with AC voltages 30° phase shifted from each other form the modern 12-pulse bridge. This design has a lower harmonic output than a six-pulse bridge.

Each valve consists of a number of identical and electrically independent series connected levels. Typically the number of levels can range from 10 to more than 100, depending on the scheme being considered. Modern thyristor valves are extremely reliable since thyristor redundancy can be included in each valve. This is achieved by increasing the number of series levels by one or two compared with the minimum required to withstand the applied voltage.

The thyristor is fired by sending a light pulse via an optical fibre to the electronics located at each individual thyristor level. On-valve electronic protection protects the thyristor both in the on-state and the off-state.

All valves are protected against overvoltage by zinc oxide surge arresters connected directly between their terminals (item 'V' on Figure 4.2). Additionally, the thyristors are prevented from reaching excessive voltage in the forward direction by protectively firing them when the voltage exceeds a predetermined level. This is accomplished by special circuits, using breakover diodes.

The ALSTOM design is built up from assemblies embodying two series connected thyristors clamped between high efficiency water cooled heatsinks, which is called a banded pair. The clamping force is applied by means of a Belleville spring washer arrangement, acting via the special glass fibre resin bands. To ensure that the inrush current is kept within the capability of the thyristors, saturable reactors are used. Other components include the damping capacitor and the water cooled damping resistors which are also mounted on the thyristor heatsink. The thyristors can be replaced without disturbing water or main electrical connections, by means of a simple hydraulic tool. Figure 4.3 shows a banded pair elevated for maintenance with the hydraulic tool attached. The thyristors and their associated components are mounted in a rigid frame to form a tier, several of which can be stacked up to make a mechanically stable structure. Thyristor valves of modern water-cooled design occupy only a quarter of the volume of the earlier air-cooled design.

The thyristor valves of a 12-pulse convertor are usually arranged in three separate stacks with the four valves in each stack physically mounted on top of each other. Each valve stack is called a quadrivalve and serves one phase of the AC supply. Figure 4.4 shows the complete valve arrangement for both convertors of the ALSTOM supplied 150 MW McNeill back-to-back scheme in Canada, in which each valve

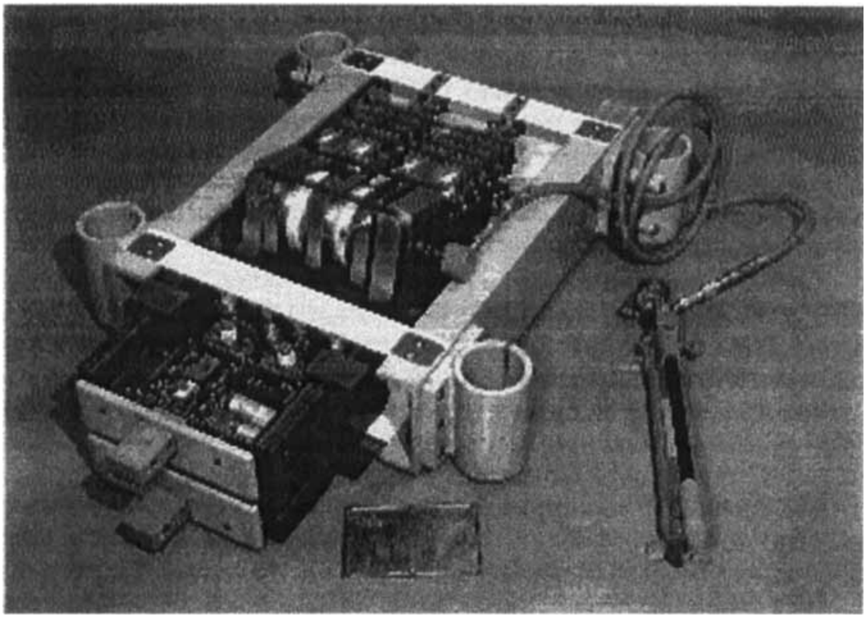

Figure 4.3 Sample banded pair assembly

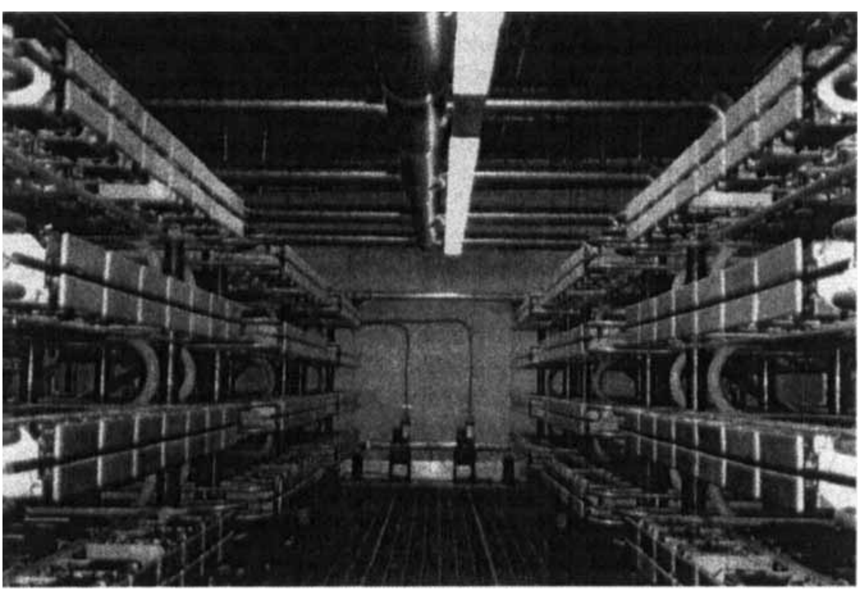

Figure 4.4 View of McNeill valve hall

comprises only one tier of banded pairs. More detail is given in Reference 4. For higher voltage applications further tiers are stacked to form larger valves.

4.4.2 Convertor transformer

The transformer provides the 30° phase displacement between the two six-pulse series connected subconvertors to provide overall 12-pulse performance. This is achieved by having one star-delta and one star-star connected transformer or star and delta secondary windings on the same transformer. The transformer also provides the required valve side AC voltage to give the optimum DC voltage at normal operating conditions. An on-line tap-changer is used to maintain this voltage when the AC voltage varies or (in some cases) when the DC loading conditions change. The transformer also provides the isolation between the DC and the AC systems. The impedance of the transformer together with the AC system impedance limits the fault currents experienced by the convertor valves. The commutating reactance can normally be assumed to be controlled by the transformer impedance only, since AC harmonic filters maintain near sinusoidal voltage at the AC busbar which supports commutation.

The principal purpose of this section is to illustrate the kind of compromises which arise during the design of a convertor. If a design for a given application can be said to be characterised by a single number, that number is probably the commutating reactance, because it influences the design of many major components of a scheme, and also its interface with the AC network. Thus, choosing the most economic reactance is a key decision in convertor design.

The steady state operating conditions of the convertor are governed by the standard convertor equation, relating direct voltage (V_d), direct current (I_d), convertor transformer valve-winding EMF (E_{L-L}) and commutating reactance (X_c) with the firing angle (or extinction angle) to which the convertor is controlled. From Reference 1 the approximate formula is given below (where I_d and X_c are pu):

$$V_d = \frac{3\sqrt{2}}{\pi} E_{L-L} \left(\cos\alpha - \frac{I_d X_c}{2} \right) \tag{4.1}$$

It is evident from this that achieving a given direct voltage will require smaller E_{L-L} if X_c is decreased. However, to demand very small commutating reactance gives rise to high transformer cost. The precise variation is rather specific to the manufacturing technique used and to the voltage rating of the individual windings, so generalisations are approximate. However, values of X_c smaller than about 15% tend to cause transformer capital cost to rise.

Similarly, the required E_{L-L} will be minimised if α at a rectifier (or γ at an inverter) is minimised. The balance to be achieved here is between minimising the steady state ratings of the equipment, and allowing sufficient margin to permit the minor voltage variations routinely encountered on an operating power system to be absorbed without interfering with power flow. Usually, this is translated into a requirement to accommodate a voltage variation of defined amplitude without encountering control system limits. (In specifications, this is sometimes written as 'without mode change'). Typically, a compromise will be implemented in which the convertor remains within its linear range of operation during AC network voltage variations of around 3%. This commonly leads to the adoption of minimum continuous operating angles of 15° for α and 20° for γ.

Frequently, the minimum values for α and γ only occur when operating at full load, since specifications often require the reactive power exchanged with the AC network at low power transfer to be restricted, and this restriction is often partly obtained by operating the convertors at the same E_{L-L} at all currents. Thus, during transfer of low current, the α (or γ) is often larger than the minimum permitted value.

Operating the convertors in this way incurs a small amount of additional losses during low power transfer. These losses have to be tolerated by the valve components (not normally a problem), and are often evaluated by customers when bids are assessed.

In the special case of a back-to-back link, both convertors are located in the same convertor station and they can exert reactive power control much more comprehensively than merely by degrading their power factor at low load. The direct voltage can be reduced (and the direct current increased to maintain the real power transfer) in response to the demands of a closed-loop reactive power controller. From Reference 1 the reactive power absorbed by a convertor is approximated by

$$Q = V_d I_d \sqrt{1 - \left(\frac{V_d}{V_{dio}}\right)^2} \tag{4.2}$$

Therefore, providing the convertor valves are designed to withstand the duty, i.e. if the requirement is stipulated in the specification for a scheme, the convertor can operate as an HVDC convertor (at rated direct voltage), as a thyristor-controlled reactor (at zero direct voltage) or at any intermediate operating condition which may be convenient. The only absolute limit is that the total MVA at which the convertor is asked to operate must not be greater than the rating of the main circuit equipment.

It is necessary to remember that the two convertors share the same DC operating conditions; in other words, actions taken to improve operating conditions of one AC network will influence the other, in a generally similar way. Thus, while it is possible to do a great deal to minimise the impact of reactive power unbalance (between the convertors and the AC harmonic filters) for one of the convertors, the behaviour of the other will be similar. Therefore, this feature is best used when one of the AC networks is weak but the other is strong enough to withstand the consequences of favouring the first.

Another aspect of design which is peculiarly relevant to back-to-back HVDC links is the effect of transformer reactance on valve fault current. The current which flows in the event of a convertor fault is simply $(V/X_L)K$. V is the power frequency EMF behind the effective AC network source impedance, X_L is the total inductance between the valves and that EMF and K is the constant which quantifies the fault currents peculiar to convertors. Typically, X_L is dominated by the convertor transformer reactance. Modern power thyristors as used for HVDC have little difficulty in carrying the fault currents which arise from transmission applications, because the direct current is rarely much more than 2.5 kA, and economic transformer designs usually produce aggregate values for X_L of 18% on transformer rating or so, yielding typical peak fault currents of around 30 kA. However, valve fault current becomes a much more serious consideration for back-to-back links, because they operate at low voltage. This means that not only is the direct current somewhat larger, but also that it is simpler and cheaper to build convertor transformers of much lower reactance than a high reactance transformer. This was overcome at the McNeill convertor station by designing convertor transformers having an additional winding, to which the AC harmonic filters are connected, shown in Figure 4.5. The fault current to which valves may be

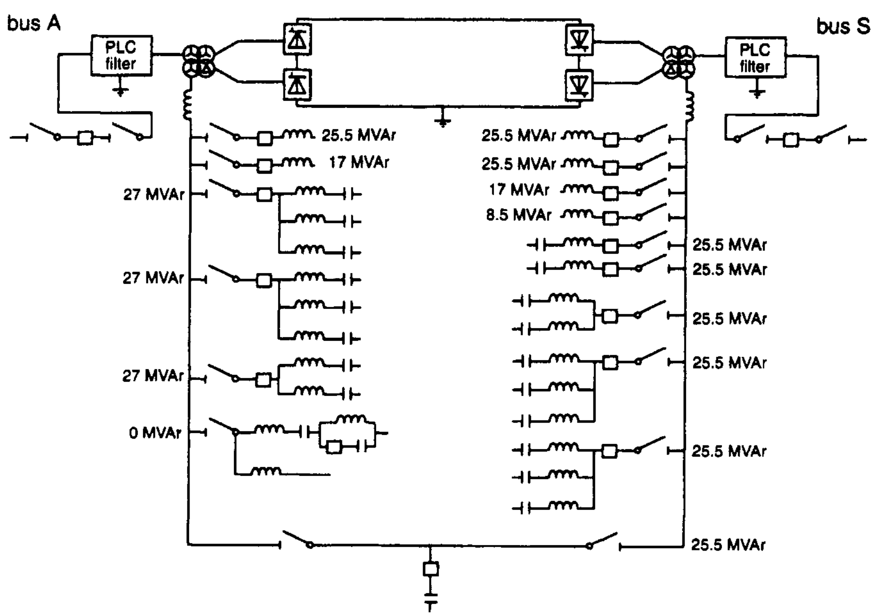

Figure 4.5 Single line diagram of McNeill HVDC station

subjected is limited by the comparatively large line-winding to valve-winding reactance, while commutation reactance was smaller, being approximately the reactance between the valve-winding and the AC harmonic filters.

Low commutating reactance causes some increase in the harmonic output from a convertor. When the AC harmonic filter resides on an additional winding the effects of this can often be offset by making the reactance between the filter winding and the line-winding act as part of the AC harmonic filter. This was done for the McNeill convertor station.

Most of the discussion above concerns the fundamental frequency behaviour of the convertor equipment, which determines much of its cost. However, the convertor transformer must also tolerate the harmonics arising from convertor operation. The difference here arises not merely from the generalised mathematical description of the difference between the fundamental frequency component and the total RMS current. (For an HVDC convertor, the ratio between these two quantities is $3{:}\pi$.) The harmonic content has a greater significance to the transformer designer than is apparent from this ratio because the harmonic currents cause greater heating than do fundamental frequency currents. The transformer design must take into account the anticipated spectrum of harmonic currents, attributing the correct amplitude to each, so that the cumulative heating effect can be estimated.

Convertor transformers are invariably provided with on-load tap-changers. Their purpose is to enable the operating conditions imposed on the DC plant to be substantially independent of the AC network conditions. Therefore, the first requirement of such a tap-changer is that it should be capable of compensating for the working voltage range of the AC network. This is typically ± 5% (especially on higher voltage networks, say above 200 kV) but is often ± 10%. The tap-changer must also be able to compensate for any tolerance which the commutating reactance of the finished transformer may exhibit, and it must be provided with a control system which embodies a large enough deadband to avoid hunting. Sometimes there are special circumstances to be taken into account. For example, some purchasers require the capability to operate at reduced direct voltage during unfavourable weather, and require some extension of the tap-changer range to make this possible without encountering the large change in reactive power balance which would follow from achieving it by means of firing angle alone. Thus, convertor transformers rarely have tap-changer ranges less than 20%, and sometimes they exceed 30%.

The convertor transformers can be provided as single-phase or three-phase units. They can be provided as two-winding, three-winding or even four-winding units (as shown in Figure 4.5). The choice of transformer configuration is dictated by transport limits as well as availability considerations. The advantage of using single-phase transformers is that spares can be provided more cheaply, although each three-phase bank becomes more expensive.

4.4.3 Control equipment

The convertor control and protection equipment is an area in which the component count is so great that it is necessary to categorise the equipment and to incorporate protective features in the design to obtain correct system performance.

Some of the control equipment influences the behaviour of only a single thyristor level. Since the thyristor valves incorporate redundancy, it is generally unnecessary to incorporate further redundancy in such control equipment.

In cases where it is possible to define what constitutes 'safe' action, it is often possible to incorporate duplication. Thus, many protective features are provided with redundancy in the sense that at least two protective functions react to each main circuit event. This is often adequate to secure the safety of the main circuit hardware, but it may be calculated that this leads to an unacceptably large number of spurious interruptions to transmission. In such cases duplication is insufficient and higher levels of redundancy such as triplication may then be incorporated, together with a 'voting' system whose function is to ensure that only the signal presented by a majority of the channels is implemented.

Figure 4.6 is a block diagram showing an example of the different levels of redundancy which may be applied to different functions of the control system. Typically, this will be reinforced by supplying power to each function from at least two independent sources in such a way that failure of one source does not influence the ability of the other to continue to supply the equipment.

Operator interfaces take many forms, but the presentation of information on VDUs (and other forms of display screen) controlled by keyboards or other convenient devices such as tracker balls is increasing rapidly for most applications. This is convenient for the convertor station designer since it is usually not difficult to provide facilities at a remote location, such as a regional dispatching centre, which are identical with those provided in the convertor station itself. Inevitably the local facilities will be heavily utilised during commissioning of the equipment, but the present trend is that once the equipment is in service, direct control of its behaviour from the dispatch centre is becoming the norm.

4.4.4 AC filters and reactive power control

AC filters are provided for two basic reasons:

(i) to minimise the harmonic interference caused to the AC system by

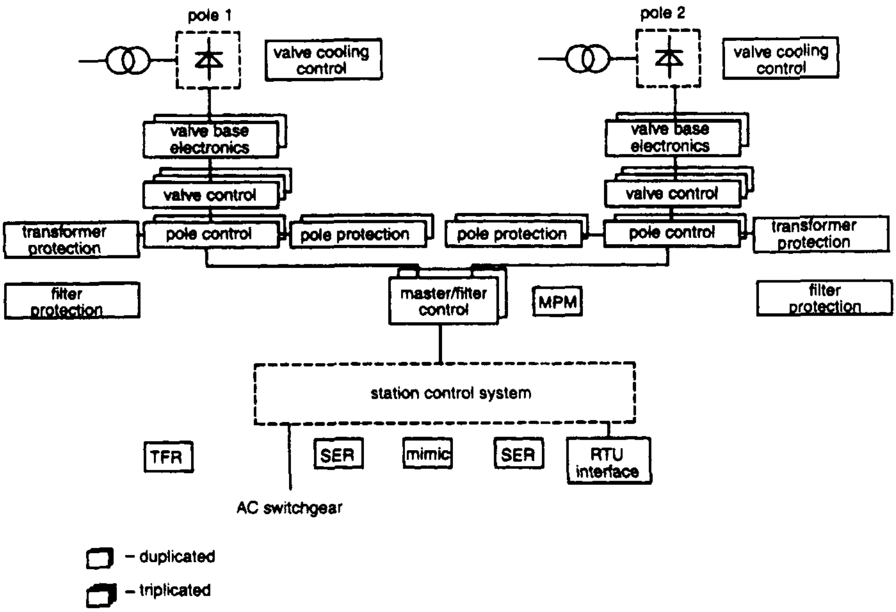

Figure 4.6 Control system block diagram

the HVDC convertor – this includes waveform distortion and telephone interference effects

(ii) to assist in the reactive power control duties of the HVDC link.

This latter requirement is becoming increasingly significant as HVDC links are being increasingly applied to weaker and weaker AC networks which require them to provide reactive power control.

The harmonic performance is generally achieved using a variety of passive filter types (tuned/damped filters, single or multifrequency). In the future there is also the prospect of using power electronics to improve the performance of filters either directly to null the current injected from the convertors or to retune conventional filters.

The filter characteristics and the number of filter groups provided at a convertor station may be influenced by the reliability required of the scheme. Duplication of specialised filter types can be used to ensure that scheme reliability targets are met. Alternatively, the provision of a single general purpose type of filter may be more cost effective, despite giving slightly inferior performance, since reliability can be achieved with fewer switched groups. The 2000 MW England/France link uses two different types of filters in each of the four filter groups.

The voltage excursion produced on the AC busbar when sections of AC harmonic filter/shunt capacitance are energised and de-energised is also important. These being routine events, they may occur several times per day. Typical specifications limit the permitted voltage excursion to about 3%, equivalent to a 100 MVAr capacitor bank connected to an AC network of short-circuit capacity 3300 MVA. A cheaper filter design is normally possible if a larger filter bank size could be employed.

The operating conditions of a back-to-back HVDC convertor can be adjusted easily to minimise the voltage excursion during switching. Subsequent convertor operation can be allowed to relax towards the normal steady state during a time long enough to permit tap-changers to retain control over the convertor operating conditions. Thus, energising a capacitor bank would be accompanied by a sharp decrease in direct voltage/increase in direct current (to increase the reactive power consumed by the convertor). De-energisation of a capacitor would be anticipated by a gradual decrease in direct voltage/increase in direct current, which would be released to regain their normal values when capacitor switching has taken place.

If the normal default steady state operating conditions of the transmission system give rise to reactive power exchange with the AC network which is unacceptable, it may be necessary to increase the reactive power consumption of the convertors by altering the steady state direct voltage and current. This is particularly likely at low power transfer, when the AC harmonic filters required to control harmonic output may provide much more reactive power than is needed to compensate for normal convertor action. This technique for limiting the consequences of capacitor switching or steady state reactive power surplus is most appropriate when the AC network to which the second convertor is connected is more capable of accepting reactive power unbalance than is the one which is the subject of control action. There is only one DC circuit, so changes in direct voltage and current which may be imposed to improve conditions on one AC busbar also affect the other.

If the HVDC convertor under consideration is one terminal of a long-distance transmission, co-ordination between the two convertors to minimise reactive power swings may be more difficult. In particular, such action may depend on the availability of a telecommunications link of adequate security. Thus, for long distance transmission, the use of the convertors to minimise voltage changes arising from switching shunt capacitive elements may be limited to what can be achieved without influencing the direct voltage or current.

However, it should be remembered that use of the convertors to control reactive power involves operating the convertors at relatively large switching voltages, incurring somewhat increased convertor switching losses and increased stress on the thyristor valves. Thus the use of convertors for controlling reactive power is not free from cost, since these losses are often included in evaluation calculations.

The extent to which the AC harmonic filters should be subdivided is also related to the reliability and availability requirement. Typically, AC harmonic filtering is a service which is shared between two poles. Arrangements should be made to ensure so far as it is possible that no single failure can deprive the transmission of more than one section of AC harmonic filters/shunt capacitor bank.

4.4.5 Smoothing reactor and DC filter

DC filters are necessary only on schemes which have sections of high voltage or neutral overhead line. Neither back-to-back links nor schemes utilising only cable require a DC filter. The main purpose of the DC filters is to reduce the levels of interference induced into open wire telecommunication systems and nearby AC power lines. The filtering of high voltage DC lines is best achieved by connecting the filter between the high voltage line and the neutral at the convertor station. DC filters can be implemented as either passive or active (power electronics assisted) filters.

For most purposes, it is the total loop inductance of the relevant part of the HVDC circuit which is important. The DC reactor is the supplementary component which is added when the sum of all other inductances is insufficient, or when the inductance from other sources is inconveniently distributed.

The DC reactor contributes to the source impedance through which harmonics are injected into the DC conductor system. If the entire DC conductor system is contained within a valve hall, then harmonic interference arising from coupling to it is minimal, and the DC reactor is not important in this respect. The most extreme illustrations of this logic are the McNeill back-to-back convertor station in Alberta (Canada) and the Chandrapur and Visakhapatnam back-to-back convertor stations in India, which do not use DC reactors at all [4,5]. In these particular cases, the inductance of the DC circuit is provided almost exclusively by the convertor transformers, with a small contribution from the thyristor valves.

These examples do not prove that all back-to-back links can be constructed without DC reactors without further consideration. Before concluding that a DC reactor is unnecessary, the control system must be shown to be stable without it, and the control system must also be capable of limiting harmonic interactions between AC networks to an acceptable level. There are few desirable features which a modern HVDC control system cannot provide by way of restricting and/or damping low frequency effects on the power system to which it is connected, but there are limitations on the number of features which can be provided simultaneously, since the number of independent variables is limited to two, namely direct voltage and direct current.

The demands made on HVDC filter circuits are influenced by the inductance of the DC reactor. When passive filter circuits were used exclusively, it was often convenient to use quite large DC reactor inductances, sometimes more than 0.5 H. There are even cases in which it has been convenient to divide the DC reactor into two sections, with an HVDC filter connected between them. Now that advances in power electronics have at last made the application of active HVDC filters economic, this is likely to occur less often.

The DC reactor shields the thyristor valves from rapidly changing overvoltages which may be imposed on an HVDC conductor system. It is necessary to determine the distribution of such voltages between the reactor itself and the rest of the convertor station, in order to calculate the insulation requirements of the reactor. DC reactors are not normally protected by terminal-to-terminal surge arresters in modern convertor stations (unless the station design incorporates two such reactors).

Historically, it was believed that the DC reactor inductance had to be selected to prevent the HVDC conductor system from exhibiting fundamental frequency resonance. Modern control systems, based on various implementations of the phase-locked oscillator principle, have made this restriction obsolete.

The earliest designs of smoothing reactors were oil insulated and oil cooled reactors, but in recent years the development of dry type air cored and air insulated reactors has been such that this type of design now offers a very competitive alternative to the oil filled reactors for some applications. They have the disadvantage that they require a larger area (including magnetic clearance) than the equivalent oil insulated unit, the provision of a HVDC wall bushing, and must be located outdoors, away from the valve hall building.

4.4.6 Switchgear

The AC switchgear is conventional, but its attributes must meet the specific operational requirements of the scheme. For example, the circuit-breaker feeding the convertor transformers needs to be capable of fast fault clearance in two or three cycles to reduce the exposure time of the convertor valves to faults. The breakers feeding the AC harmonic filters have to be capable of frequent load switching of capacitors. In most cases, the AC switchgear is conventional SF_6 free standing outdoor equipment. When space is restricted, such as was the case for the England/France link, indoor compact metal-clad gas insulated switchgear can be installed to minimise the layout area.

Capacitor switching is a particularly onerous duty for circuit-breakers. In capacitive circuits current zero occurs at the instant of peak voltage between the terminals of the capacitor. Since the capacitor takes several minutes to discharge, this voltage is still present one-half period of fundamental frequency later when the voltage applied to the AC network terminals has reversed. Thus, 10 ms after the arc in the switch is extinguished, the voltage between the terminals of the opening switch is 2 pu.

If the disconnection takes place during a disturbance this voltage can be considerably greater. This is the so-called 'double voltage' experience which is applied to switchgear during this duty and introduces the risk of a restrike across the contacts of the circuit-breaker.

For a monopolar DC scheme using sea return, the switchgear on the DC side is extremely simple. Generally disconnectors are provided only to enable the station to be isolated safely from possible incoming surges from the DC overhead line or cable during maintenance outages.

For a bipolar scheme the DC switchgear arrangement may be very extensive and complex to enable maintenance to be carried out on parts of the scheme without the need for a total shutdown. Figure 4.7 shows the switchgear used on one pole of a DC scheme using two series connected 12-pulse groups in each pole. In this case special convertor operating modes or switches capable of commutating currents from and to the convertor valves are necessary if operation with only one 12-pulse group is required. Bypass switches with current transfer capability are required for each group to enable maintenance of one group to be carried out whilst the other remains on-load.

In most cases the switchgear used on the DC side of the convertor comprises modified versions of off-load disconnectors designed for AC applications, since the operation of the DC switchgear can be co-ordinated with the DC link controls to ensure that the switchgear is not operated at times when DC current flows through the switch.

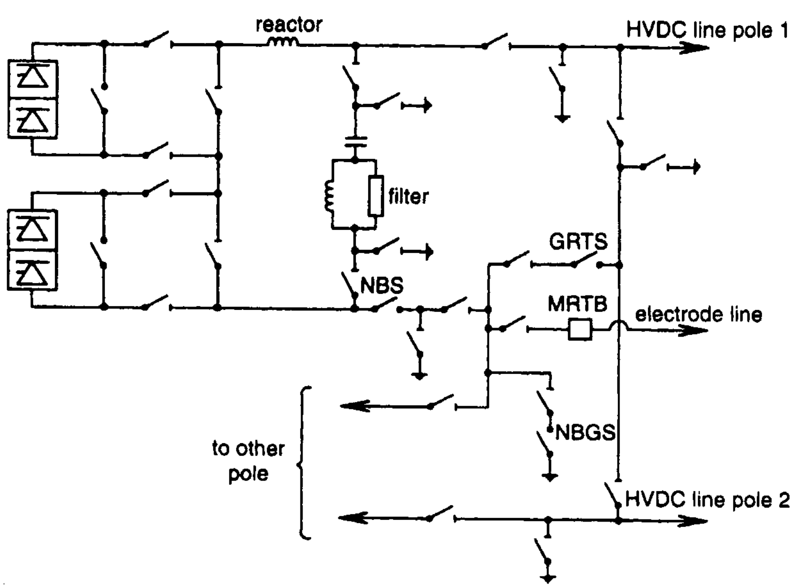

Figure 4.7 Typical DC switchgear arrangement
GRTS = ground return transfer switch; NBGS = neutral bus grounding switch; NBS = neutral bus switch; MRTB = metallic return transfer breaker

However, in special cases such as schemes using parallel connected DC lines, or where permanent use of ground return operation is not permitted, it is possible to provide special DC switchgear capable of transferring DC current to another path.

Figure 4.7 shows the metallic return transfer breaker and the ground return transfer switches, which are necessary when changeover between monopolar earth return and metallic conductor operation is required without an interruption in DC power flow.

If earth electrodes are used, they will normally be located several kilometres from the convertor station. In consequence the neutral connection of the HVDC convertor will exhibit appreciable resistance and (more importantly) inductance. This means that during fault conditions overvoltage may occur and precautions have to be taken to ensure that destructive currents cannot occur either in valves or in surge arresters. To avoid such conditions additional inductors may have to be added.

4.4.7 Surge arresters

Surge arresters using metal oxide nonlinear resistors are used extensively in HVDC schemes for overvoltage protection; see Figure 4.2. In addition to the surge arresters connected directly across each of the thyristor valves (V), arresters are also used across each six pulse group (B,M) to ensure good voltage distribution between the series connected groups. Protection of HVDC equipment connected to the DC line is achieved by a surge arrester connected directly to the DC line termination (DB).

The surge arresters use highly nonlinear zinc oxide resistor blocks. At normal voltage they conduct less than 1 mA, but at a voltage only 60–70% higher they can conduct appreciable current (such as 1 kA). The arresters are built up from a number of series connected blocks mounted in a porcelain housing. They are very simple in construction.

Surge arresters are also used on the AC side. The busbar phase to earth insulation is protected by surge arresters (A) which are placed close to the transformer terminal. Surge arresters are also applied within the AC harmonic filters (FA1, FA2), connected across the reactors or resistors, where the resulting saving in component insulation levels more than compensates for the cost of providing the surge arresters.

One of the tools used for the study of insulation co-ordination is an AC/DC simulator which provides a real time representation of the complete system including the convertor controls. Studies of a large number of different AC and DC system faults can be performed within a relatively short period using this simulator, to identify the conditions which produce the worst overvoltages. Digital computer studies complement the simulator studies and are carried out to establish with greater precision the magnitudes of the worst cases, the co-ordination currents and the energy absorbed in the surge arresters.

4.4.8 Valve cooling

Modern HVDC valves are liquid cooled. The liquid offering the best heat transfer properties is water, but pure water has the disadvantage that it freezes. Where exposure to freezing temperatures is anticipated water glycol mixtures are used. At this level of detail differences emerge between the practices of different suppliers and the requirements of different customers. Water/glycol mixtures may be circulated through the valves themselves or a secondary coolant circuit utilising water/glycol may be used to transfer heat from a primary cooling circuit using fine water. Direct water-glycol cooling is used in the design of the cooling system for the convertor valves in the McNeill back-to-back system because the customer specified that no valve damage should occur when all site services were lost in mid-winter at –50°C.

Because, first, the coolant forms part of the insulation system and second, the resistance of the coolant has to be high to minimise leakage currents, it must be maintained in a very pure condition. Deionisers are provided but the basic design of the cooling system must ensure that the materials used for each individual component provided is satisfactory in terms of compatibility with all the other materials in the system and to survive for the life of the scheme in the environment of the pure demineralised water or water/glycol coolant.

Figure 4.8 shows a flow diagram for a single circuit valve cooling system. A high degree of redundancy is provided in the cooling circuit to ensure that single component failures do not result in a shutdown of the HVDC convertor. For example, the coolant circulation pumps are

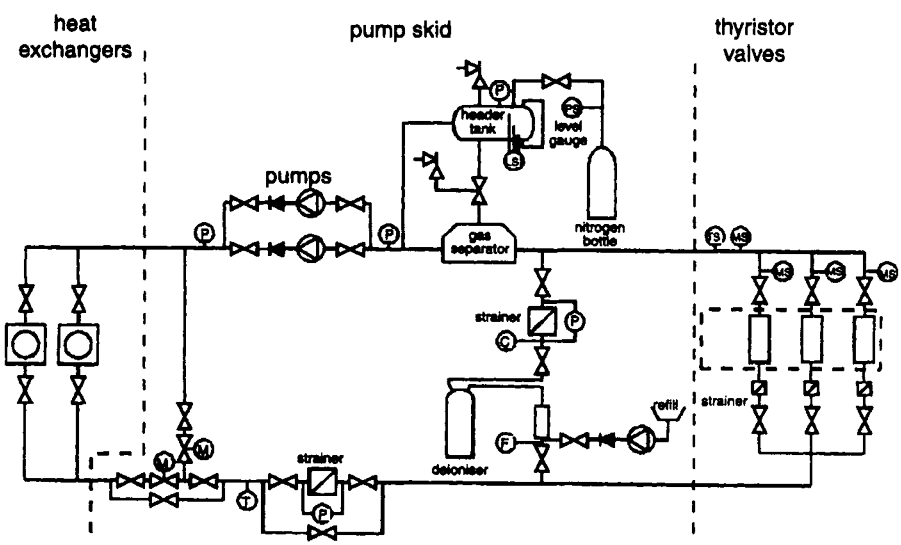

Figure 4.8 Typical cooling plant diagram

duplicated with one on-line pump and one standby pump which will be switched on in the event of a failure of the on-line pump. Similarly, the critical instrumentation is duplicated and redundancy is provided in the air blast coolers, either in the form of redundant fans or one or more complete redundant cooler units.

The majority of the cooling system is provided as a frame-mounted unit, fully assembled and tested. This assembly will include the circulating pumps, control valves, the deioniser and much of the instrumentation. This complete assembly can be transported easily to site for connection to the convertor valves and to the outdoor heat exchanger. This approach reduces the site installation cost, it reduces the commissioning time and gives improved quality control.

4.4.9 Auxiliary supplies

AC auxiliary supplies are normally duplicated (or even triplicated), very often with standby generators as well. The intention is to secure continued power transmission against any single failure, and often to continue to provide some level of power transfer in the event of two unrelated failures. Thus, a power supply arrangement will have two independent sources, each capable of supplying the total load for the whole station via a sectioned distribution busbar. In some schemes where maximum independence between the two poles is required duplicated independent sources are used for each pole; such an arrangement is illustrated in Figure 4.9.

Even if all auxiliary AC power is lost, sufficient energy is stored in batteries to ensure that safe shutdown of the convertor equipment can be accomplished and that the minimum station services including such things as emergency lighting and operation of switchgear continue to be provided with operating power for several hours after AC infeed has ceased.

4.5 Convertor building

The valves and the convertor transformers are brought together in the valve hall. Wherever possible the convertor transformers are arranged along one wall of the valve hall, with their DC side bushings penetrating into the valve hall where the connections to the HVDC valves are made. In parallel with and adjacent to the valves are the surge arresters.

In the case of smaller HVDC schemes (typically only 200 or 300 MW) it is often possible to utilise only a single three-winding convertor transformer for each 12-pulse bridge. The transformer would have two valve windings, connected star and delta, respectively. Such a convertor transformer does not occupy a very long run of valve hall wall and the length

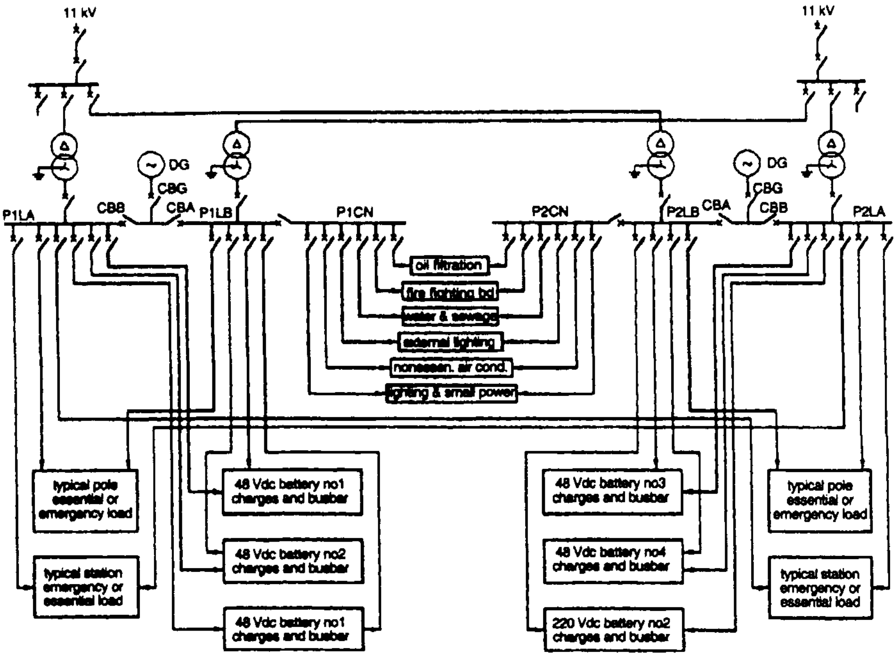

Figure 4.9 AC auxiliary power supply scheme for convertor station

of the valve hall would be determined by the valve arrangement. For larger schemes, such as those intended to transmit 500 MW or more, it will usually prove to be necessary to subdivide the convertor transformer. The simplest subdivision is into two three-phase transformers, one star connected and the other delta connected. However, if transport restrictions are severe it may not be possible to use three-phase transformers. In this case single-phase units having two or three windings are disposed along the wall of the valve hall. This normally determines the length of the valve hall and is a serious economic consideration.

In addition to providing protection from contamination for the convertor transformer valve winding bushings, more extensive contamination protection has been provided on some schemes. For the English terminal of the England/France scheme all the DC equipment, i.e. switchgear, surge arresters, PLC equipment and cable sealing ends, were built inside a protected but not air-conditioned enclosure, formed by enclosing the space between the valve halls of a bipole [6]. The DC reactor bushings also protrude into this enclosure. Experience has shown the benefits of this design since no flashovers on DC associated equipment have occurred on the English terminal during 17 years of operation. Similar practice has been adopted on the Mainland to Cheju Island 300 MW scheme in Korea since severe contamination is possible due to the close proximity of the sea [7]. Environmental protection for the AC filters on the island of Cheju has also been provided by installing the filters inside a building.

Workshops, control equipment, all auxiliary supplies and services, storage space for components and for access platforms to provide maintenance and repair access to the HVDC valves is normally housed in the convertor building itself. Often purchasers wish to accommodate additional facilities such as offices, meeting rooms, hubs for their telecommunications networks, etc. These features are contract-specific and are too variable to be treated usefully in a general review. Figure 4.10 shows a typical layout of the control building and valve halls for an HVDC scheme.

4.6 Economics

Figure 4.11 illustrates the cost breakdown for a typical convertor station. Inevitably, there will be wide variations from this in special circumstances, but it serves to illustrate the basic truth that more than half the cost of a convertor station is represented by the HVDC convertor itself and the convertor transformers. Therefore, it is mainly around these items that the design of the convertor station is optimised.

Figure 4.12 shows the approximate distribution of losses throughout a convertor station. All power transferred passes via the convertor transformers and the convertor valves, and they are the components which generate the greatest losses. Since the losses which result from operating

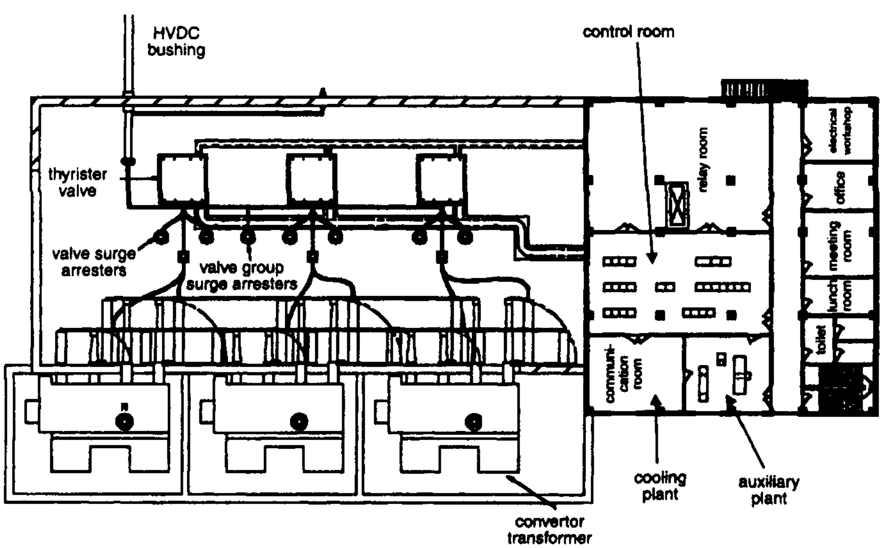

Figure 4.10 Typical layout of the control building and valve hall

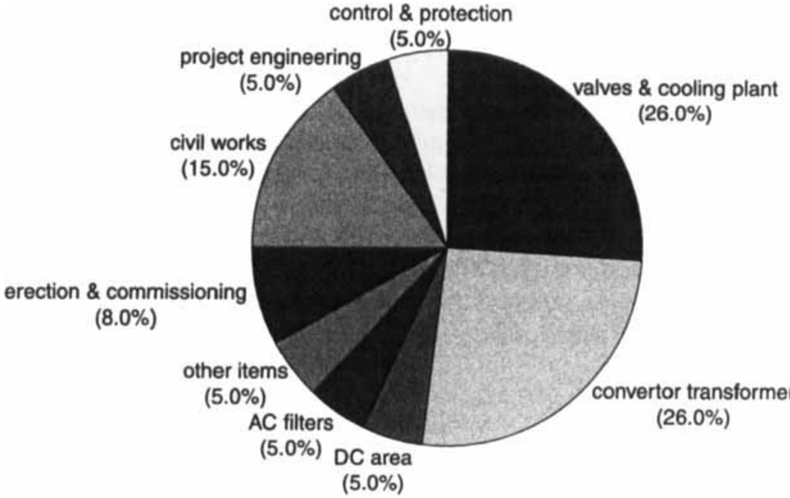

Figure 4.11 Approximate distribution of capital cost of convertor station

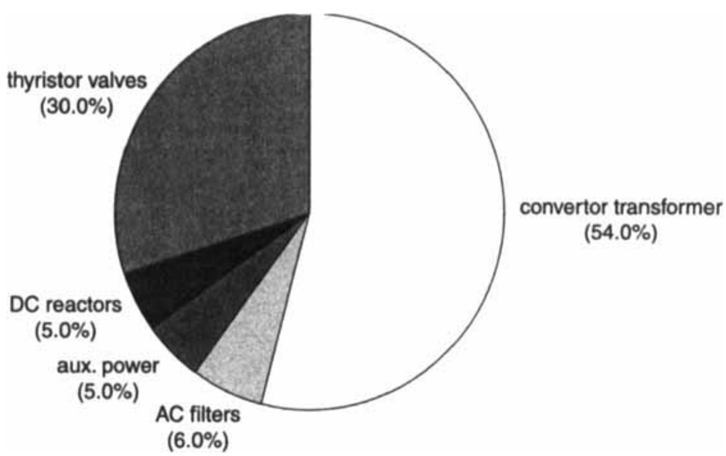

Figure 4.12 Approximate distribution of losses of convertor station

the equipment represent lost revenue, purchasers have a legitimate interest in minimising them, and evaluate them during bid adjudication at rates declared in the specification. Usually, different rates are applied to losses which remain fixed and those which vary with load.

It is essential to take account of the costs attributed to losses by purchasers, since they vary widely, depending on local circumstances. However, certain general trends can be identified. First, the evaluated cost attributed to losses is comparable with the cost of the major plant incurring them. This makes them important, since, for example, the cost of a convertor transformer is commonly several million pounds.

Second, the incremental cost of minimising losses may not vary smoothly. Thus it is often found that there is no advantage in using a smaller thyristor for a transmission scheme required to carry direct current of only, say 1000 A and it is commonplace to find thyristors similar in size to those used for transmitting 3500 A DC being used at much lower currents. (Where available, a higher voltage rating would normally be employed, minimising the number of series-connected levels in each valve.) Third, if evaluation rates are high, it may be advantageous to employ energy-saving techniques, such as operating cooling fans at reduced speed during cold weather. In this case, an evaluation has to be made of the impact of such additional complication on the availability of the equipment. To save auxiliary energy in exchange for losing the ability to transmit power reliably would be a bad trade.

4.7 Power electronic support for AC systems

The basic limits of transmission are well known. The thermal capacity in terms of current in a line is usually far above its normal loading. There is a variety of reasons for this:

(a) At high voltage, conductor size is primarily dictated by corona considerations.
(b) Unequal sharing between parallel lines (both intentionally and accidentally) results in the effective limit being dictated by the line with lowest rating.
(c) Circuits must have sufficient capacity to absorb the consequences of failures in parallel circuits.
(d) The phase angle between the sending end and receiving end voltages is limited by transient stability considerations during fault conditions.
(e) Loop flows (power which is scheduled to pass through a parallel system of lines) effectively reduces the available capacity of a line as the loop flow takes up the thermal and protective margins in a transmission line.

It is possible to add a great deal of controllability to an AC system by embedding an HVDC link.

Sometimes the aims are more modest than those which require an HVDC link embedded in an AC system. In such cases a simpler solution than an embedded HVDC link is to use one of the 'FACTS' (flexible AC transmission systems) type of power electronics-based devices mentioned in Section 1.

4.7.1 Static VAr compensators (SVC)

Traditionally, variable reactive power compensation has been provided by synchronous compensators and saturated reactors. These were used to compensate for the lack of voltage control resulting from transmitting power over long lines. Whilst these performed adequately they are characterised by a lack of flexibility and high capital and maintenance costs.

In recent years static VAr compensators using thyristor switches (Figure 4.13) have been used extensively, particularly in the UK [8,9]. These SVCs generally consist of some combination of thyristor switched capacitors (TSC) and thyristor controlled reactors (TCR). The choice of TCR/TSC/filter combination is largely dictated by loss evaluation, harmonic performance requirement and restrictions in the design of individual components. In some installations, such as at Watertown, South Dakota, USA, the SVC also controls external switched reactors and capacitor banks [10].

A TCR provides continuously variable reactive power absorption and acts to reduce system voltage as the TCR current increases. However this results in the generation of harmonic currents from the TCR which can be controlled by configuring the fixed capacitor as a harmonic filter bank.

TSCs are not phase controlled because the stresses caused by such switching of capacitors are excessive. They act as very precisely switched banks and consequently do not suffer the usual wear and tear from the repetitive switching which is found in circuit-breaker switched capacitors. Indeed SVCs consisting of only TSCs which are used to perform swing damping have been supplied to NGC in the UK and in the Western USA.

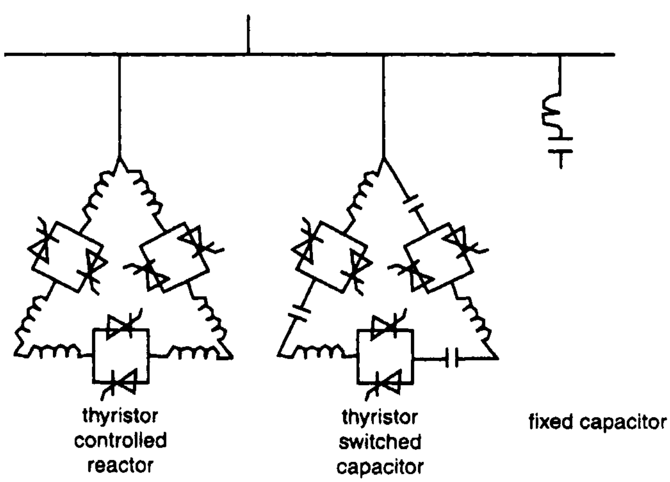

Figure 4.13 Simplified single line diagram of TCR/TSC type SVC

The thyristor valves used for TCRs and TSCs are largely based on the water cooled, air insulated, banded pair construction which is also the basic building block of the HVDC thyristor valve. If a suitable connection voltage is not available (typically 2–25 kV) a stepdown transformer is required to connect the SVC to the power system.

A picture of a typical SVC installation is shown in Figure 4.14.

4.7.2 STATCOM

The STATCOM is an SVC based on the gate turn-off thyristor (GTO) (see Figure 4.15). This device provides phase controlled output – both capacitive and inductive – and can respond very quickly to disturbances. The STATCOM also provides a response superior to that of the SVC at low voltage since its output is proportional to voltage which is less variable than the square of the voltage with which the SVC output is proportional.

The basic concept behind the STATCOM is that of a voltage sourced inverter. The reactive power exchanged with the power system is dictated by the relative magnitude of the inverter voltage (V) and the power system voltage (E). For example, when the inverter voltage (V) exceeds the system voltage (E), then current flows 'from' the convertor to the system and thus generates reactive power in a manner similar to a capacitor. With this design it is possible to change the STATCOM from fully inductive to fully capacitive in a single half-cycle of the power frequency.

A STATCOM is very compact, occupying approximately 40% of the

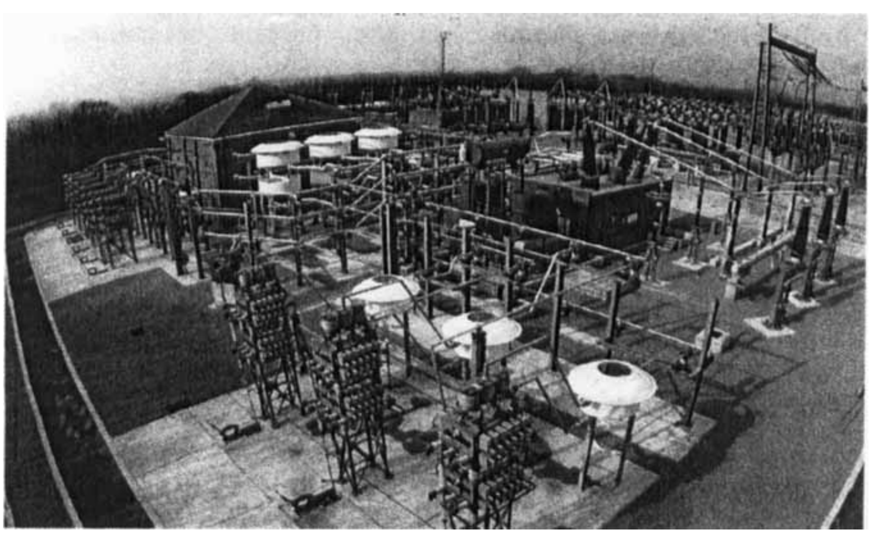

Figure 4.14 View of 225 MVAr SVC

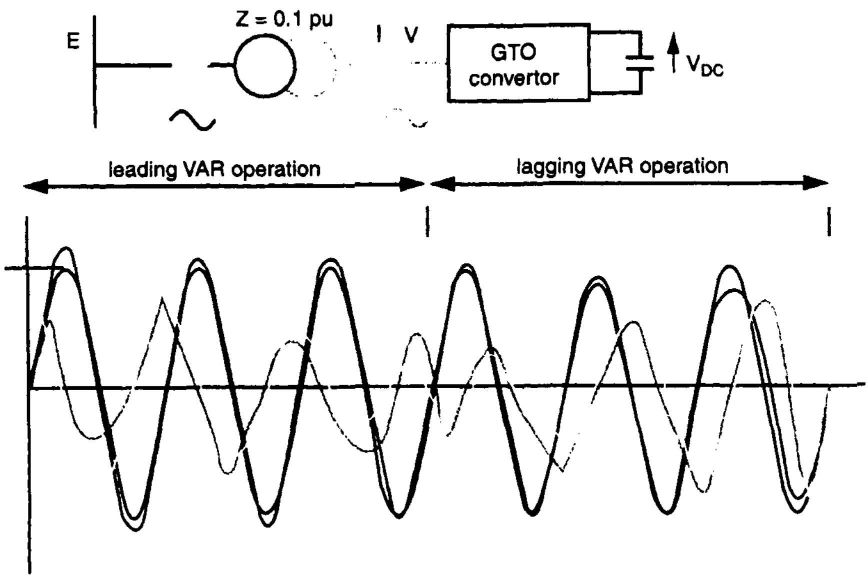

Figure 4.15 Basic theory of STATCOM operation

area of a comparable thyristor SVC. ALSTOM has recently supplied such a device rated at 225 MVAr to NGC in the UK at their 400 kV East Claydon substation [11]. This compensator is also relocatable, which is an important consideration given the changing nature of the electricity network following deregulation.

The STATCOM has a number of other advantages over the thyristor SVC (TCR/TSC):

(a) Using GTOs (with their ability to 'turn off' at other than zero current) the STATCOM can respond much more quickly than a conventional TCR/TSC SVC.
(b) The use of GTOs also allows the STATCOM to act as an active filter and reduce significantly the harmonics it produces compared with a TCR of the same rating.
(c) The STATCOM provides significantly enhanced low voltage reactive output because it is a controlled device rather than a variable impedance. Figure 4.16 shows the extended low voltage operating range of the GTO compared with that of a TCR/TSC type SVC.

4.7.3 Series compensators

Another solution to compensating long lines has been to insert series capacitors. This introduces a new natural frequency and results in

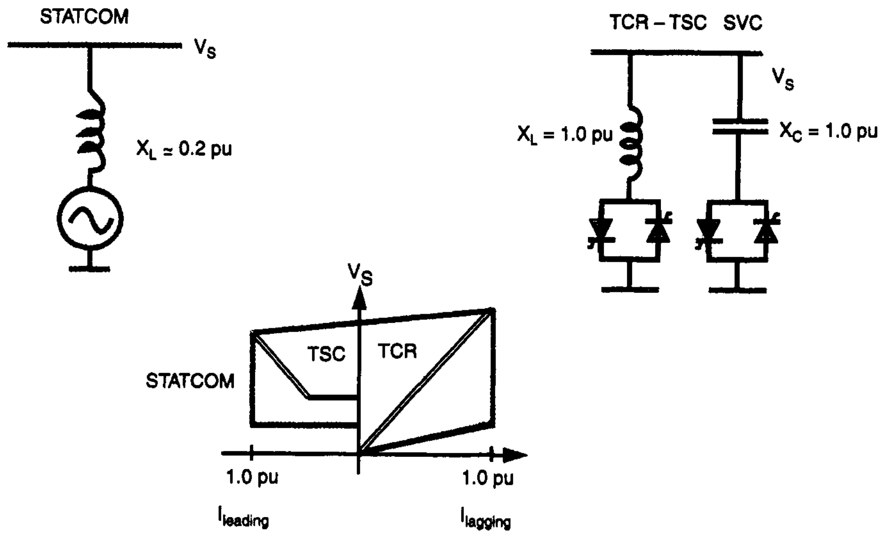

Figure 4.16 Comparison of TCR/TSC type SVC and STATCOM operation

the possibility of resonance with generators and large machines at subsynchronous frequencies. One solution has been to effectively add a TCR in parallel with the series capacitor (Figure 4.17). However this requires an extensive high voltage insulated platform.

A new solution being investigated currently is to apply a voltage-sourced GTO convertor to a series connection (Figure 4.18). This static series compensator presents a voltage source to the transmission line and so removes the subsynchronous threat. It also has the advantage over the thyristor-controlled series capacitor that it only requires a transformer and a conventional building (possibly portable) rather than the high voltage platform.

4.7.4 Unified power flow controller (UPFC)

This combines the STATCOM and the GTO based series compensator in one facility (Figure 4.19). Both transmission angle and voltage come under the influence of this controller, which operates in all four quadrants on the real/reactive power diagram. The UPFC consists of two voltage-sourced convertors – one connected in shunt and one in series to satisfy especially demanding circumstances.

However, the UPFC requires the GTO controlled capacity of the individual static and series compensators, whereas the user may not always require the series and shunt compensation in the same place.

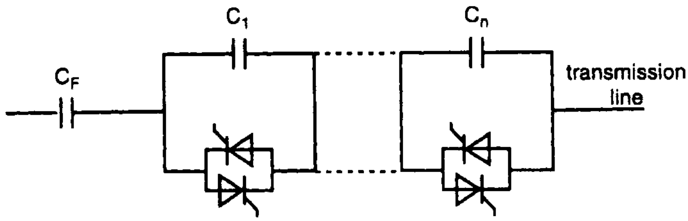

Figure 4.17 Thyristor controlled series capacitor

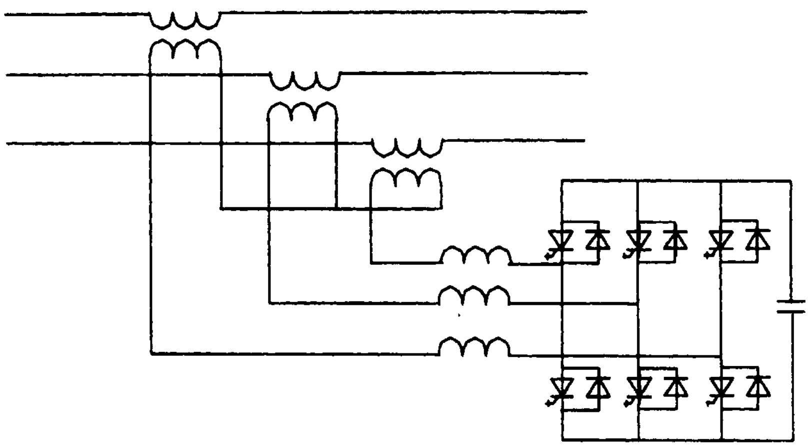

Figure 4.18 Series compensator concept – STATCOM based variant

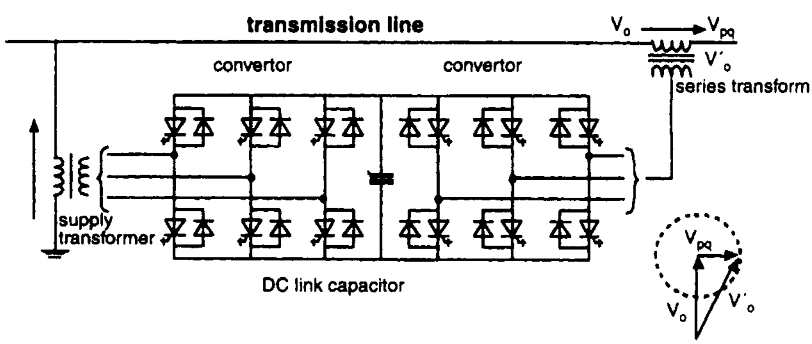

Figure 4.19 Simplified single line diagram of UPFC

4.8 Conclusion

HVDC is in many respects the ultimate power electronics based FACTS device which can act within an existing AC network or even replace parts of it [12]. In evaluating the usefulness of HVDC it is important to remember the controllability which it adds to the power system in addition to its bulk power transfer capabilities. HVDC often provides the best of both worlds – support from a neighbouring network without the problems of synchronous interconnection.

Power electronic based devices enable better utilisation to be achieved of all the principal attributes of the electricity network – generation, transmission and distribution. Where slow acting devices such as tap-changers and circuit-breakers can be used then these are usually most economic. However, if fast or controlled response is required, for example to prevent system collapse, then FACTS power electronic facilities provide a cost effective solution.

In many cases power electronics is the only way to achieve some functions, particularly with HVDC. Otherwise, they can be justified where the application requires one or more of the following attributes: rapid control action; frequent variation of output; smoothly adjustable output; and precise output.

4.9 References

1 KIMBARK, E.W.: 'Direct current transmission' (Wiley Interscience, New York, 1971)
2 ARRILLAGA, J.: 'High voltage direct current transmission' (IEE Power and Energy Series 29, The Institution of Electrical Engineers, London, 1998)
3 UHLMANN, E.: 'Power transmission by direct current' (Springer-Verlag, 1975)
4 BURGESS, R.P. and KOTHARI, R.: 'Design features of the back-to-back HVDC convertor connecting the western and eastern Canadian systems'. IEEE 1989, PES Summer Meeting
5 WHEELER, J.D. and HADDOCK, J.L.: 'Chandrapur back to back HVDC scheme in India'. ICPST Conference, Beijing, China, October 1994
6 GODDARD, S.C., YATES, J.B., URWIN, R.J., LE DU, A., MARECHAL, P. and MICHEL, R.: 'The new 2000MW interconnection between France and the United Kingdom'. CIGRE Paper 14–09
7 THANAWALA, H.L., WHITEHOUSE, R.S., KWON, G.O. and LEE, S.J.: 'Equipment and control features of Haenam-Cheju HVDC link in South Korea'. CIGRE 1994 Session, 28 August – 3 September 1994
8 YOUNG, D.J., HORWILL, C., MUKHOPADHYAY, S.B., HADDOCK, J.L. and GARDNER, D.: 'City versus country – a comparison of two types of standardised SVC for the National Grid in England', AC and DC Transactions, IEE, 1991, p. 248

9 WHITLOCK, I., YOUNG, D. and BAKER, M.: 'Static var compensators for the city – St John's Wood'. Modern Power Systems, June 1994, p. 45

10 HARRINGTON, B.A.: 'Improving system stability'. T & D International 4th quarter 1995, p. 20

11 KNIGHT, R.C., YOUNG, D.J. and TRAINER, D.R.: 'Relocatable GTO-based static var compensators for NGC substations'. CIGRE paper 14–106, Paris 1998

12 BAKER, M.H., *et al.*: 'Economic assessment of HVDC links', CIGRE Working Group 14.20, *Electra*, 2001, **196**, pp. 30–41
[See also CIGRE Study Committee 14 details at http://www.cigre-sc14.org/ and http://www.cigre.org]