1

Introduction

1.1 The Conventional Power Grid

The power sources in conventional power systems must operate at exactly the same frequency and in perfect synchronism. Each generator controls the magnitude of its terminal voltage by the excitation current and the phase angle of this voltage by means of the mechanical torque developed by the turbine. The generators are designed to produce relatively low voltages, and thus the generated power undergoes a number of voltage transformations, from low to high voltage (for efficient power transmission) and from high to medium and low voltage (for economic and safe power distribution). These changes are implemented by power transformers.

Within a national grid, the use of a fully interconnected primary transmission system, to which the new power stations are connected, has traditionally been the generally accepted philosophy behind the development of an efficient power system.

The expansion of the primary transmission system was normally continued until the rated switchgear fault level was exceeded. Beyond that point a new primary transmission system, of higher voltage and fault levels, was created, while the previous one continued expanding into several separate (secondary) systems. Each of these secondary transmission systems in turn supplied a number of distribution (normally radial) feeders. So the conventional power grid has traditionally been grouped into three separate parts, i.e. generation, transmission and distribution, all of them inflexibly tied by the synchronous constraints.

1.1.1 Power Transfer Mechanism

Transformers, generators and transmission lines are predominantly inductive, and most loads have an inductive component as well. The presence of inductance delays the current response of these components to the voltage variation across them, and this effect causes phase shifts between the voltage and current waveforms which affect the efficiency of the power transmission process.

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The instantaneous power (p) associated with a power system component is the product of the instantaneous values of the voltage (v) and current (i) at its terminals ($p = vi$). The integration of the instantaneous power variation over a complete cycle divided by the period of repetition, i.e.

$$(1/T)\int_{t}^{t+T} p dt$$

provides the average or ***active power***. If both the voltage and current vary sinusoidally at the same frequency, in terms of rms (root mean square) voltage (V) and current (I) quantities, the active power is expressed as

$$P = VI\cos(\phi) \tag{1.1}$$

where ϕ is the phase angle between the voltage and the current fundamental frequency waves.

As the rms values are always positive, the product VI (referred to as volt-ampere or apparent power), gives no indication of the active power sign. It is the sign of cos (ϕ) (the ***power factor***) that determines whether the circuit component is generating or absorbing power.

In Figure 1.1, using the voltage as the phase angle reference and resolving the current into in-phase (I_p) and quadrature (I_q) components, the product of V and I_p is clearly the active power, while the product of V and the quadrature component I_q, i.e.

$$Q = VI\sin(\phi) \tag{1.2}$$

is referred to as ***reactive power***.

Reactive power is needed to establish the magnetic and electrostatic fields; it is temporarily stored and then released (i.e. it consists of positive and negative regions within the cycle). In fact the energy associated with the reactive power oscillates between the element and the rest of the circuit (at the rate of two reversals per period). Although the reactive power has a zero average value, it still represents real reciprocating energy that must be present by virtue of the inductance or capacitance of the network.

When ϕ, the phase angle difference in Equation (1.2), is between 0 and π, sin(ϕ) is positive and the circuit element is said to be a consumer of Q; similarly, when ϕ is between π and 2π, sin(ϕ) is negative and the element is said to be a generator of Q. The convention

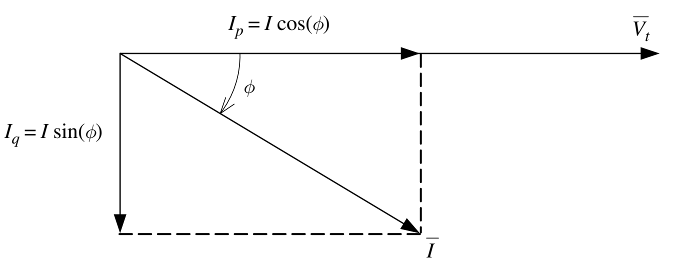

Figure 1.1 In-phase and quadrature current components

used is that when Q is positive the current lags the voltage and when Q is negative the current leads the voltage

Squaring the expressions of P and Q in Equations (1.1) and (1.2) and adding them gives

$$(VI\cos(\phi))^2 + (VI\sin(\phi))^2 = (VI)^2 \tag{1.3}$$

and

$$VI = \sqrt{P^2 + Q^2} \tag{1.4}$$

Equations (1.3) and (1.4) can be represented in a four-quadrant complex diagram, as shown in Figure 1.2, with the axes labelled $\pm P$ and $\pm jQ$.

Power transfer between active sources

Figure 1.3 shows a purely inductive line interconnecting two ideal voltage sources V_1 and V_2 (which can be either generators or nodes of a synchronous system). The phasor diagram in Figure 1.4 represents the operating condition when the voltage at terminal 1 leads that of terminal 2 by an angle δ (referred to as the power angle) and the current at terminal 2 lags its voltage by an angle ϕ (referred to as the power factor angle). Using the voltage of terminal 2 as a phase reference, the following expressions are derived from this diagram:

$$I_2 X\cos(\phi) = V_1\sin(\delta) \tag{1.5}$$

$$I_2 X\sin(\phi) = V_1\cos(\delta) - V_2 \tag{1.6}$$

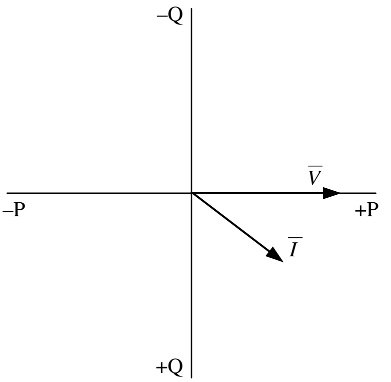

Figure 1.2 Four-quadrant diagram with the voltage as reference

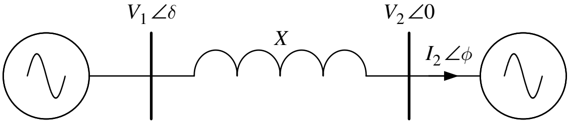

Figure 1.3 Interconnection between two synchronous systems

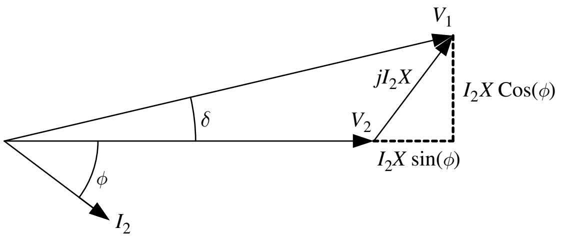

Figure 1.4 Phasor diagram for the interconnection of Figure 1.3

From Equations (1.5) and (1.6) the active and reactive power transfers become

$$P = V_2 I_2 \cos(\phi) = \frac{V_1 V_2 \sin(\delta)}{X} \tag{1.7}$$

$$Q = V_2 I_2 \sin(\phi) = \frac{V_2 (V_1 \sin(\delta) - V_2)}{X} \tag{1.8}$$

Thus to control the P and/or Q transfers it is necessary to vary one or more of the four variables V_1, V_2, δ and X in Equations (1.7) and (1.8). As indicated earlier, the generated voltage phase and magnitude values can be controlled by the turbine governor and generator excitation respectively. However, from the power transmission viewpoint, the generator controls are slow and inefficient: the slow control imposes a power transmission restriction on the steady-state operating point, as the power angle δ in Equation (1.7) has to be kept low in order to preserve transmission stability following large disturbances; also the relatively large requirement of reactive power (Equation (1.8)) will overload unnecessarily the generation and transmission systems.

Power transfer to a consumer load

Consumer loads are connected to radial feeders, normally at the end of the power distribution network. Low power factor loads have a detrimental effect on the load voltage and, therefore, on the power transfer capability. This effect is illustrated with reference to Figure 1.5 on the assumption that the feeder and the primary system behind it are represented by a voltage source (V_s) in series with a total system reactance (X_s). To maintain the active power constant when the power factor reduces (i.e. angle ϕ increases) requires an increase in the load current, i.e. $I'_L > I_L$; this increase causes a higher voltage drop in the system reactance which, in turn, reduces the load voltage (V_L).

Thus to maintain the required power level, either the source voltage must increase or some means of voltage support must be provided locally. For instance, the latter can be achieved by connecting a capacitance in parallel with the load. This will add a quadrature component to the load current and will reduce the overall current in the feeder; this solution is referred to as ***power factor correction***. However, the use of local compensation by means of passive components, although efficient, is neither fast nor continuous and increases the likelihood of low-order harmonic resonance with the system impedance.

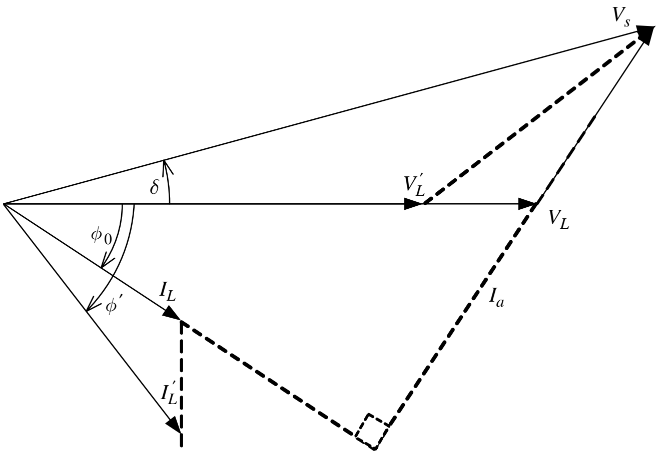

Figure 1.5 Effect of the load power factor on the load voltage

1.2 Towards a More Flexible Power Grid

A variety of technical, economical and environmental reasons affecting the generation, transmission and utilisation of power are forcing a rethink on the conventional power system development philosophy. The dilemma is that, on the one hand, there is growing opposition to the acceptance of new transmission lines and ever increasing primary transmission voltages. On the other hand, there is the realisation that power system interconnections bring undisputable benefits, such as economies of scale, wider choices of generating plant, reductions in reserve capacity, diversity in demand, supply reliability, pooling opportunities, etc.

Clearly an important factor in the solution is the possibility of increasing the power carrying capability of the transmission lines. In this respect conventional AC transmission is severely restricted by the need to keep the two systems interconnected by the line in synchronism following disturbances (i.e. when the phase difference between the terminal voltages increases rapidly), a condition referred to as transient stability. Therefore increases in the steady-state power carrying capability are linked to improvements in the transient stability levels, which in turn require faster controllability. Controllability and flexibility are used in power transmission as synonymous terms; in other words, greater flexibility implies greater and faster controllability. The latter has been made possible by the development of power semiconductors (discussed in Chapter 2) and their application to the control of power apparatus and systems, commonly referred to as power electronics.

1.2.1 Power Electronics Control

The advent of power electronics technology has been the catalyst for the provision of greater grid flexibility. A power electronics controller can be broadly described as a matrix of static switches connecting a number of input nodes to a number (not necessarily the same) of output nodes and the power flow may be in either direction. The circuits behind these nodes may be either DC or AC and predominantly inductive or capacitive.

The application of power electronics in power transmission systems has led to the development of two complementary technologies, referred to as HVDC (High-Voltage Direct Current) [1–5] and FACTS (Flexible AC Transmission System) [6–7]. However, only the latter has so far used the term flexibile, which is often interpreted as an exclusive characteristic of this technology. This book widens the flexibility concept by discussing HVDC technology under the umbrella of flexible power transmission.

Both HVDC and FACTS make extensive use of AC–DC static power conversion; the basic characteristics of this process are discussed in the next section.

Static power conversion

Within the power electronics discipline, the designation AC–DC static power conversion is used for the processes of rectification and inversion, which provide the basis for fast power controllability. As well as improving controllability, these two processes, when applied to DC transmission, also remove the synchronous constraints. The first consideration in the process of static power conversion is how to achieve instantaneous matching of the AC and DC voltage levels, given the limited number of phases and switching devices that are economically viable. The following circuit restrictions are imposed on a static power converter by the characteristics of the external circuit and of the switching components:

1. If one set of nodes (input or output) of the matrix of switches is inductive, the other set must be capacitive so as not to create a loop consisting of voltage sources (or capacitors and voltage sources) when the switches are closed or a cut set consisting of current sources when the switches are opened.

2. The combination of open and closed switches should not open-circuit an inductor (except at zero current) or short-circuit a capacitor (except at zero voltage).

For stable conversion some impedance must, therefore, be added to the switching circuit of Figure 1.6(a) to absorb the continuous voltage mismatch that inevitably exists between the two sides. If the impedance is exclusively located on the AC side (as shown in Figure 1.6(b)), the switching devices transfer the instantaneous direct voltage level to the AC side and, thus, the circuit configuration is basically a voltage source converter (referred to as VSC), with the possibility of altering the DC current by controlling the turn-on and turn-off instants of the switching devices.

If, instead, a large smoothing reactor is placed on the DC side (as shown in Figure 1.6(c)), pulses of constant DC flow through the switching devices into the AC side. Then, a basically current source converter results (referred to as CSC), again with the possibility of adjusting the direct voltage by appropriate switching control. CSC is the more practical alternative when using thyristor switches without turn-off controllability.

Another classification relates to the source of the commutation process between the converter valves. When the source is the AC system voltage the converter is said to be line-commutated (LCC). LCC relies on the natural current zeros created by the external circuit for the transfer of current from switch to switch. CSC-LCC is the only

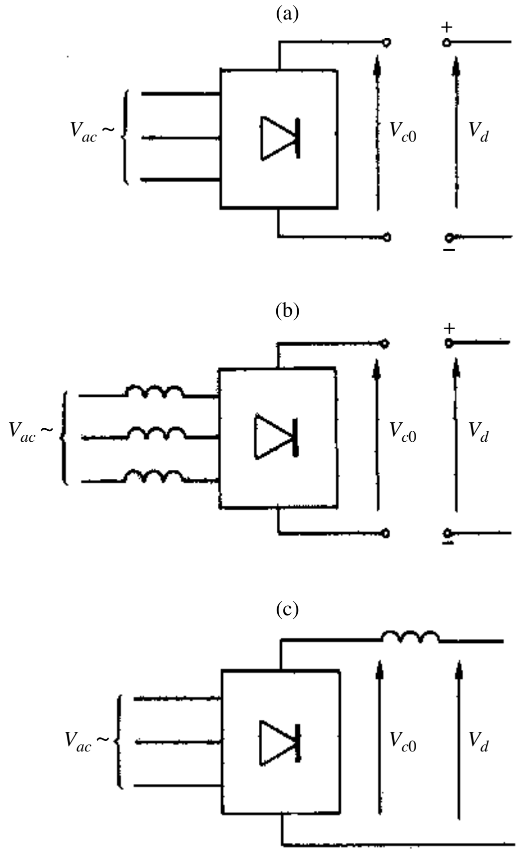

Figure 1.6 AC–DC voltage matching: (a) unmatched circuit; (b) circuit for voltage conversion; (c) circuit for current conversion

practical alternative when using thyristor switches without turn-off capability. This is still the most common solution for DC transmission, even though it is the least flexible, and is discussed in Chapter 3.

The alternative is self-commutation (a process described in Chapter 4), which is achieved independently from the external circuit components by the use of advanced switching devices with turn-off capability and, thus, provides greater flexibility.

Static power converters are also classified by the principle, and related configurations, used to produce the output waveforms. The most flexible alternative, in this respect, is the use of a simple (normally two-level) converter configuration and a complex sub-cycle waveform control. This subject, discussed in Chapter 5, uses a high-frequency carrier signal to modulate the required waveform and is, thus, referred to as pulse width modulation (PWM).

The second principle in the self-commutating category is the derivation of a stepped (multi-pulse or multi-level) waveform using only fundamental frequency switching. This concept, discussed in Chapters 6 and 7, is more efficient but less flexible than PWM, and it involves a greater number of components.

The main technical requirements of static converters for high-power applications are:

1. The provision of high-voltage valves with balanced voltages across the series-connected individual switches during the off-state and in the dynamic regions.
2. The ability to achieve high-quality output waveforms.
3. Limitation of the *dv/dt* rate across the switches and other converter components to simplify insulation coordination and reduce RF interference.
4. The ability to achieve high efficiency by reducing on-state and switching losses.
5. Simplification of the topology to reduce component costs.
6. Flexibility in terms of active and reactive power controllability.

1.3 HVDC Transmission

The original motivation for the development of DC technology was transmission efficiency, as the power loss of a DC line is lower than that of a corresponding AC line of the same power rating. However, this required the use of HVDC and, therefore, the development of conversion switches capable of withstanding high voltages

The invention of the high-voltage mercury valve half a century ago paved the way for the development of HVDC transmission. By 1954, the first commercial DC link came successfully into operation and was soon followed by several other schemes orders of magnitude larger. The success of the new technology immediately triggered research and development into an alternative solid-state valve, which by the mid-1960s had already displaced the use of mercury arc valves in new schemes. The early history and technical development of the HVDC technology are described in [8].

Substantial progress made in the ratings and reliability of thyristor valves has increased the competitiveness of HVDC schemes. DC transmission has lower transmission losses and cost than equivalent AC lines, but requires terminal equipment which adds to the cost and power losses. Thus traditionally, the DC option has been found economically viable only when the distance involved is long and the amount of energy to be transferred large. However, there are other factors that must be taken into consideration in the selection of an HVDC interconnection. An important factor in the economic comparison between AC and DC interconnections is to determine whether synchronisation of the previously separate systems is feasible and economical.

Issues affecting the feasibility of the interconnection include:

- whether the cable (in the case of a submarine interconnection) exceeds its capacity to carry its own charging current (for sea cable interconnections with distances over 50 km, DC is the only practical solution);
- whether the link is capable of maintaining synchronism of the two systems under all but extreme operating conditions;

- whether it is practical to arrange generation and frequency control in the joint system on a common basis;
- whether the synchronous interconnection exceeds the fault levels of the interconnected systems.

All the above issues can be avoided when using the DC alternative, which offers the following advantages:

- lack of technical limitations on the length of a submarine cable;
- the interconnected systems do not need to operate in synchronism;
- no increase in the short-circuit capacity is imposed on the AC systems switchgear
- any power transfer can be set independently of impedance, phase angle, frequency and voltage;
- the receiving end of the link operates like a generator, i.e. it can supply power according to any prespecified criteria (load flow, frequency control, voltage regulation, etc.);
- the interconnection can be used as a fast system's generation reserve to be able to provide power immediately;
- the DC link can be operated to improve the stability of one or both AC systems by modulating the power in response to the power swing.

HVDC links are built for a variety of purposes and the specific factors to be taken into account in their economic evaluation will depend on the purpose of the link. As well as identifying the main economic risks and uncertainties, the assessment must take into account the environmental and institutional changes bringing competition to the electricity supply.

Very often the projected links are intended to deliver firm energy from remote sources to a loading centre, in which cases the economic evaluation will be mainly concerned with the cost of generation and transmission.

The main purpose of recently emerging merchant plants (or IPPs, for Independent Power Producers) will be to calculate the cost of energy delivered to the proposed market.

In schemes developed for a one-way flow of energy an important extra consideration will be the variability of the price of energy purchased and sold. Some schemes are justified in terms of the seasonal variations in the interconnected systems. In such cases the economic analysis will be based on the impact of the interconnection on total costs in both systems.

HVDC interconnections are also considered for mutual support, such as reserve sharing, generation capacity savings, etc. In these cases the economic evaluation must also take into account the impact of the interconnection on the total capital and operating costs of the two systems to be connected.

The place of conventional and modern HVDC in power systems can be found in [9] and [10] respectively. The reliability of HVDC schemes, expressed in the permissible number of forced outages (and therefore the unavailability of the system), is published by CIGRE every two years [11]. The economic assessment of HVDC transmission has been the subject of a recent CIGRE Working Group document [12] and the procedure to calculate HVDC losses has been established by the IEC [13].

1.3.1 Thyristor-Based CSC Transmission

The thyristor, or silicon-controlled rectifier (SCR), has been the only solid-state switch used in the process of HVDC conversion, prior to the availability of high-power turn-off switching devices. The thyristor converter is still the most cost-effective solution for large-power and long-distance power transmission.

With reference to the complex diagram of Figure 1.2, converter operation in the two lower quadrants permits bidirectional transfer of active power but only absorption of reactive power. The DC current flow is unidirectional, but the DC voltage can be reversed. This mode of operation is achieved purely by thyristor turn-on control.

Since the static conversion process provides rectification and inversion, its use in power transmission permits the interconnection of synchronous and asynchronous systems. The elimination of the synchronous restrictions permits a better utilisation of the transmission systems. In half a century of existence the static converter terminals used in DC technology have gone from tens to thousands of megawatts, with present individual SCR ratings of over 8 kV and 4 kA. In fact the modular design of series SCR structures permits the use of valves of any power and voltage rating; this is an important factor because bipoles with only one converter group per pole appear to be more reliable than bipoles with two converter groups per pole (probably because the more items of equipment, the more there is to go wrong). However, the converter size may, of course, be limited by the interface transformer.

SCR-based conversion provides active power controllability (i.e. rectification and inversion) at the expense of large and varying demand of reactive power. Both the rectification and inversion processes consume reactive power, because the commutation is performed by the voltage source and the leakage reactance of the converter transformer generally dominates the commutation circuit. Therefore, the fundamental component of the current always lags that of the voltage. Moreover, for inverter operation, as the commutation overlap is not known at the instant of firing, an extinction angle of the order of 15° must be allowed to prevent commutation failure and this increases further the consumption of reactive power, which will be of the order of between 50 and 60 % of the active power in normal operation. As the reactive power consumption varies with load, the filters and extra capacitors must be switched by means of circuit breakers to match the converter reactive power requirement. If the commutation circuit inductance is compensated by means of series capacitance, unity power factor is possible; this is the purpose of the so-called CCC (Capacitor-Commutated Converter or Conversion), a configuration described in Chapters 3 and 9.

A minimum short-circuit level is needed for stable operation of LCC, because an active power change requires a corresponding change in reactive power, which causes voltage fluctuations. Moreover, AC system voltage drops cause further reactive power consumption which may lead to a voltage instability. To avoid this instability the short-circuit ratio (or SCR), defined as the ratio between the AC system short-circuit power and the rating of the converter, is rarely below two.

The reversal of power flow requires a polarity change of the DC system voltage. This is not a problem in two-terminal DC transmission systems, but complicates the operation of multi-terminal DC schemes, which would need the use of mechanical switches to achieve individual terminal power reversals.

Despite their limited controllability, static LCCs of high reliability are now used extensively in the power transmission field, either as long-distance interconnections or back-to-back asynchronous links. The conventional thyristor-based LCC technology is at present superior to self-commutating VSC transmission in terms of capital cost, power losses and reliability for large-scale HVDC transmission.

Over 75 GW of installed capacity is already in existence and more capacity is added every year, despite its inherent reactive power restriction. Present schemes include both overhead and cable point-to-point schemes as well as zero-distance (back-to-back) interconnections.

Chapters 8 and 9 describe the present state and future developments of LCC-CSC transmission and Chapter 11 discusses the potential application of thyristor-type self-commutating multi-level alternatives.

1.3.2 VSC Transmission Based on the Integrated Gate Bipolar Transistor (IGBT)

The flexibility of the transmission system can be greatly improved by the use of VSC-based four-quadrant static power conversion, the subject of Chapter 10. VSC transmission permits the flow of active power, as well as the provision of reactive power, in either direction at each end of the link. It is particularly effective when combined with cable transmission, because in this case the lack of polarity reversal greatly simplifies the cable design. However, their power rating is restricted to about 300 MW, although larger ratings are under development, due to the voltage limitations in the presently used PWM technology.

Self-commutated VSC does not need an AC system voltage source for the commutations and therefore can operate stably with any (even zero) SCRs. VSC can be controlled to generate or absorb reactive power independently from the active power flow. The maximum active power that can be exchanged with the AC system is limited only by the reactance of the AC system viewed from the VSC terminals. VSC, whether the PWM or multi-level control concept is used, reduces substantially the generation of harmonics; therefore the need for filters is eliminated or their size reduced to absorb only the higher harmonics. The low rating of passive filtering required by VSC also eliminates the problem of overvoltages following converter disconnection. As it is possible to change the current flow direction, fast power reversal can be achieved at each terminal of a multi-terminal DC scheme without the need for switching operations.

The following applications have been identified for VSC transmission [14]:

1. The supply of power to isolated areas without generating sources, as it avoids the need to install expensive synchronous compensators. In this application the inverter end controls the frequency and the voltage of the receiving system.

2. The interconnection of two or more synchronous or asynchronous AC systems, where each converter end controls its own AC voltage and all, except one of them, their DC power contribution, while the remaining converter controls the DC voltage.

3. To bring power from an offshore wind farm to an onshore substation. At the sending end, the control of frequency, voltage and power can be coordinated with the generators, which can be induction machines, as well as with the turbine pitch controller and the wind velocity.

   The variable speed of the wind turbine using static converters allows a reduction in mechanical load and much greater control of the output. This can also be achieved by a doubly fed induction generator (DFIG). Variable speed turbines can then be used by injecting a variable voltage into the rotor of the induction generator via slip rings at the slip frequency. In this case a low-voltage DC link using two AC–DC IGBT-based VSCs injects the rotor voltage. The converter rating required for the variable speed range is of the order of 25 % of that of the generator. When running at super-synchronous speed the DFIG wind turbine will deliver power from the rotor through the converters to the network, while at sub-synchronous speed the DFIG rotor will absorb power.

   However, distributed generation systems based on the direct connection of induction generators may often be impractical because of the fault-level increase, and in such cases a DC link interface can be a more effective solution.

4. The direct connection of generators to DC links [15] avoids the need for generator transformers and AC filters and reduces considerably the switchgear requirements. Voltage control can be exercised entirely by the generator excitation and, thus, converter transformer tap-changers are not needed. While no use has been made to date in conventional power stations, the idea is now being used to transmit DC power from synchronous generators in oil rigs and is equally applicable to wind generation. Also, with the use of flexible static power conversion, which eliminates the need for the supply of reactive power, the unit connection concept can be extended to non-synchronous generators.

1.3.3 Multi-terminal HVDC

The extension of CSC technology to multi-terminal HVDC has been discussed for over four decades [16, 17], the interest peaking in the 1980s, by both academic researchers and the power industry. However, only one fully multi-terminal scheme was constructed for commercial operation [18]. Its object was to convert the Hydro-Quebec–New England link (commissioned in 1986) into a five-terminal scheme with the addition of three further terminals. However, the original two-terminal link (between Des Cantons and Comerford) was never integrated into the multi-terminal DC network because of anticipated performance problems. No other (higher than three) multi-terminal scheme has been considered since then based on CSC technology. When at the planning stage a third terminal extension is to be made in the future, this is equivalent to reducing the transmission distance, and makes the DC solution less competitive.

Normally the power rating of a proposed third-terminal tap is relatively small compared with the main transmission link and, therefore, the high transmission voltages of the bipolar interconnection will require expensive converter equipment for a parallel-connected third terminal. To try and reduce the cost, consideration has been given to the use of series, rather than parallel, tapping of the additional terminal. There have been many contributions on the series tapping concept to show that it is technically feasible, but none has been built so far.

The transistor-based VSC technology is better suited to multi-terminal HVDC transmission. However, due to present limitations on the transmission voltage, the multi-terminal applications being discussed relate to medium-voltage DC grids interconnecting different alternative energy sources (such as wind farms, solar panels, etc.) with local loads and the distribution system. This topic will be discussed in Chapter 10.

1.3.4 The Flexibility Concept Applied to HVDC

The term flexibility has been defined with reference to AC transmission and it implies the use of power electronics control. In this respect the conventional thyristor-based option described in Section 1.3.1 is already a flexible system. However, this option is severely restricted by the switching characteristics of the SCR, or thyristor, and requires considerable support at the terminals for stable operation. The recent incorporation of advanced switching devices permitting self-commutation (described in Section 1.3.2) has greatly increased the degrees of freedom of HVDC transmission and, therefore, its flexibility. The new HVDC converters are capable of controlling their terminal voltage and power conditions independently from the AC system parameters. In a fully flexible DC system, the fundamental component of the converter output voltage can be controlled in magnitude and phase, and its harmonic content practically eliminated.

HVDC is also being introduced in distribution systems, especially in the presence of distributed generation, to decouple the voltage and frequency of the various energy renewable and non-renewable generating sources from the nominally fixed values of the conventional grids. In this respect it is an interesting matter to discuss the appropriateness of the term HVDC for use in distribution systems. A recent CIGRE document [19] has considered the use of the acronym FDS (Flexible Distribution System) for a distribution system that employs power electronics controllers to make the distribution of electricity more reliable, controllable and efficient. The advantage of the term FDS is that it includes FACTS and HVDC. However, the Working Group finally adopted the more conservative approach and decided to continue using the presently accepted terminology, i.e. FACTS-D and HVDC.

The question of whether the acronym HVDC needs to be further extended to differentiate between transmission and distribution has not been discussed. In this book we have decided to consider the whole subject under the umbrella of HVDC transmission. The reasons for the decision are the lack of clear boundaries (in terms of voltage or power levels) between conventional transmission and distribution systems and the changing nature of distribution systems, including the use of dispersed generation, which is often installed to supply power to the network. HVDC transmission is sufficiently general to cover all present and future HVDC applications, even multi-terminal ones, and should provide a more permanent term.

1.4 Relative Power Carrying Capability of AC and DC Transmission Lines

(1) For a given insulation length, the ratio of continuous-working withstand voltages is

$$k = \frac{\text{DC withstand voltage}}{\text{(rms) AC withstand voltage}} \tag{1.9}$$

If an overhead line is passing through a reasonably clean area, k may be as high as $\sqrt{2}$, corresponding to the peak value of rms alternating voltage. The DC advantage is even greater for cable transmission, where k is at least two.

(2) A transmission line has to be insulated for overvoltages expected during faults, switching operations, etc. To meet such requirement the AC lines need levels of insulation corresponding to an AC voltage of 2.5 to 3 times the normal rated voltage, i.e.

$$k_1 = \frac{\text{AC insulation level}}{\text{rated AC voltage } (\mathbf{E}_p)} = 2.5 \tag{1.10}$$

On the other hand, with suitable converter control the corresponding HVDC transmission ratio, i.e.

$$k_2 = \frac{\text{DC insulation level}}{\text{rated DC voltage } (\mathbf{V}_d)} = 1.7 \tag{1.11}$$

Thus for a DC pole-to-earth voltage $\mathbf{V}_d$ and AC phase-to-earth voltage $\mathbf{E}_p$ the following relation exist:

$$\text{insulation ratio} = \frac{\text{insulation length required for each AC phase}}{\text{insulation length required for each DC pole}} = (k \cdot k_1/k_2)(E_p/V_d) \tag{1.12}$$

(3) The total transmission losses result from the addition of those in the converter and in DC line. For a bulk power transmission of 6 GW, Figure 1.7 compares the losses of several AC and DC voltages for various transmission distances [20]. Beyond a distance of 500 km the line losses dominate the station losses and thus DC solutions become more efficient than their AC counterparts. The comparison shows that for a distance of 1000 km (for which the various options are optimised in this example), the losses in the 800 kV DC option are about 1 % lower than for the 500 kV alternative.

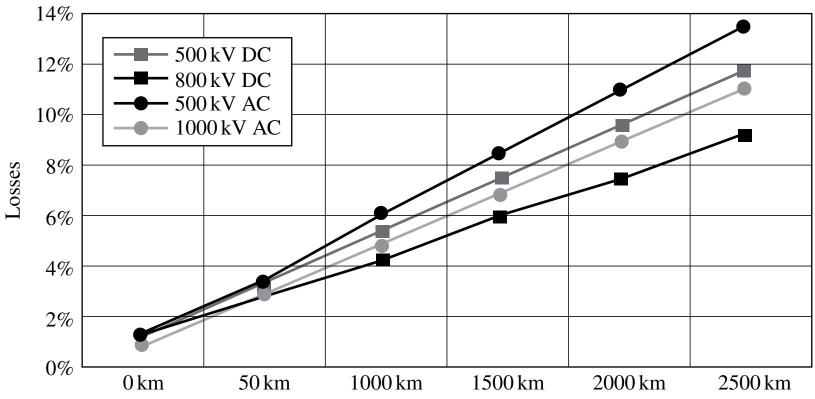

Figure 1.7 Transmission losses over transmission distance for HVAC and HVDC (Zhang, X.P. (2006), 'A grid for tomorrow', *Power Engineer*, October, reproduced by permission of the IET.)

(4) Consider a new DC transmission system to be compared with a three-phase AC system transmitting the same power and having the same percentage losses and using the same size of conductor. The DC system is considered to have two conductors at $\pm\mathbf{V}_d$ to earth.

Power in the AC system:	$3\mathbf{E}_p\mathbf{I}_L$ (assuming that $\cos(\phi) = 1$)
Power in the DC system:	$2\mathbf{I}_d\mathbf{V}_d$
AC losses:	$3\mathbf{I}_L^2\mathbf{R}$
DC losses:	$2\mathbf{I}_d^2\mathbf{R}$

Equating line losses,

$$3\mathbf{I}_L^2\mathbf{R} = 2\mathbf{I}_d^2\mathbf{R} \tag{1.13}$$

or

$$\mathbf{I}_d = (\sqrt{3}/\sqrt{2})\mathbf{I}_L \tag{1.14}$$

Equating powers,

$$3\mathbf{E}_p\mathbf{I}_L = 2\mathbf{I}_d\mathbf{V}_d \tag{1.15}$$

or

$$\mathbf{V}_d = (\sqrt{3}/\sqrt{2})\mathbf{E}_p \tag{1.16}$$

and substituting Equation (1.16) in Equation (1.12),

$$\text{insulation ratio} = (kk_1/k_2)(\sqrt{2}/\sqrt{3}) \tag{1.17}$$

For the values of k, k_1 and k_2 recommended above, the above ratio is equal to 1.2 for overhead lines and 2.4 for cables.

(5) The AC line consists of six conductors, which is equivalent to three bipolar DC circuits, each having two conductors at $\pm\mathbf{V}_d$ to earth, respectively. Thus

$$\text{power transmitted by AC}: \quad \mathbf{P}_a = 6\mathbf{E}_p\mathbf{I}_L \tag{1.18}$$

$$\text{power transmitted by DC}: \quad \mathbf{P}_d = 6\mathbf{V}_d\mathbf{I}_d \tag{1.19}$$

On the basis of equal current and insulation

$$\mathbf{I}_L = \mathbf{I}_d \tag{1.20}$$

$$\mathbf{V}_d = (kk_1/k_2)\mathbf{E}_p \quad \text{(derived from Equation (1.12) set to one)} \tag{1.21}$$

The power ratio is therefore

$$\frac{\mathbf{P}_d}{\mathbf{P}_a} = \frac{\mathbf{V}_d}{\mathbf{E}_p} = (kk_1)/k_2 \tag{1.22}$$

and since the actual losses are the same, the percentage power loss ratio will be the inverse of Equation (1.22). Thus, for the same values of k, k_1 and k_2 used above, the power transmitted by overhead lines can be increased to 147 %, with the percentage line losses reduced to 68 % and corresponding figures for cables of 294 % and 34 %, respectively.

(6) Following on from (5) above, consideration is being given to the conversion of existing AC transmission corridors for use in DC transmission, with the aim of increasing their power carrying capability. In this respect a double three-phase transmission corridor could be used as three parallel DC lines, operating at higher voltage and current levels (the latter determined purely by thermal considerations, as there is no transient stability restriction in the DC case). An interesting recent proposal for a single three-phase line is the use of a modulated control to change periodically the DC power in the three conductors to balance their thermal capability [21]; this solution requires bidirectional current carrying capability in one of the three conductors, and therefore an extra converter in opposition at each end.

1.5 The Impact of Distributed Generation

A great variety of renewable and non-renewable sources are being considered as alternative sources of power generation, closer to the points of utilisation. The most typical examples are co-generation, small hydro, wind farms, fossil-fuelled generators, photovoltaic systems, fuel cells and microturbines. These can operate as separate units or be integrated with the synchronous grid.

In addition to environmental benefits, distributed generation (DG) is also seen as offering important possibilities for improving the quality and security of power supply; it can provide improved reactive power and system voltage control, may avoid losses and user-of-system charges, as well as provide black start capability and the prospect of system islanding.

In the present state of development the proportion of DG installed varies between countries from about 10 to 30 %, and these figures are expected to increase substantially in the future.

There is an increasing tendency for dispersed generators to be connected to the distribution network through static power conversion. This is of course essential with DC sources such as fuel cells and photovoltaics, but even some large designs of wind turbines transmit their power through converters.

In the future the large number of dispersed generators may lead to alternative network designs, including for instance ‘active distribution networks’ where the operation of the dispersed generators is integrated with that of the network.

1.6 The Effect of Electricity Deregulation

An important factor behind the change towards greater flexibility has been the now generally accepted deregulation philosophy, which encourages the development of a competitive market, whereby energy providers and buyers have open access to the transmission services. In this new environment power generation and transmission are unbundled and the control of the grid is in the hands of an independent system operator. For competitive reasons, unbundling seems to discourage the generators from investing in equipment to provide effective reactive power control of the transmission system, and this has serious implications on voltage and power stability.

Thus, without appropriate countermeasures, the reliability and security of the power system should deteriorate. These problems can, of course, be reduced by conventional transmission system reinforcement, but the cost and the difficulty of obtaining new rights of way discourage such an approach.

The transmission network as an active market player

In the present market philosophy for the generation of electricity the network service providers play no part in the location and level of operation of the generating plants. They are therefore ill-equipped to respond with developments suited to the random needs of the market following generator bids. And yet the deregulation benefits can only be fully exploited when the network services become active players in the market, even in competition with the generators. The lack of competition has been an important factor in the gradual deterioration of national grids. Only when the transmission system becomes an active player in the market will there be sufficient incentive for suitable development of the grid.

While the owners of regulated networks receive a fixed revenue on their investment, those of unregulated networks get their income from the market players according to the services provided. The principal source of income in this case is the spot price differential between the terminals of the interconnected system. A further source of income can be the provision of ancillary services. Thus, as well as energy, there are markets developing in power reserve, frequency regulation, black start capability and voltage control.

However, to compete in the power market, the network services should be independently controllable, a condition difficult to meet by conventional synchronous interconnections, particularly when the size of the tie is small relative to the interconnected systems; in such cases the tie will be easily overloaded (and thus disconnected) even by normal operating changes in either of the interconnected systems.

A comparison of system interconnections

The liberalisation of the electricity industry relies on system interconnections to permit the exchange of power among regions or countries and to transport electrical energy more economically and (environmentally) acceptably over long distances to the load centres.

Among the advantages of interconnection are:

- the pooling of generation capability with the opportunity to utilise diverse primary energy resources;
- the creation of larger markets, which enable economies of scale to be realised in the operation of power plants and in accommodating demand growth;
- greater flexibility for the introduction of competition into electricity supply.

Traditionally such advantages have been achieved by the use of additional AC lines between the various subsystems, in order to strengthen the interconnection. However, with the increasing complexity of power systems the reliability of power supply has deteriorated and the number of blackouts in various parts of the world has increased. Thus strengthening the transmission system is essential to the reliability of block power interchanges among interconnected power systems. The probability of blackouts can be substantially decreased with the use of back-to-back HVDC interconnections due to their asynchronous character and greater controllability.

Possible additional bottlenecks inside the AC systems, resulting from the increased transmitted power, can be avoided by the use of long-distance HVDC links integrated into the system to transmit power directly from remote power generation to load centres.

The cost advantage of HVDC transmission in a multi-system environment has been quantified [22] with the help of a benchmark model of an interconnected system. The benchmark model is used in a rigorous power flow study to incorporate an extra 2000 MW transmission between two systems separated by 950 km. The AC reinforcement option required 950 km of double 400 kV and 750 km of single 400 kV lines, as well as their associated switchyards. For the HVDC alternative, two DC converter stations and a point-to-point 950 km, ±500 kV bipolar overhead line were required. When the total investment and the capitalised losses are taken into account, the DC solution was found to be 70 % cheaper.

1.7 Discussion

Both the use of FACTS and HVDC increases the power carrying capability of a transmission line. In this respect, FACTS technology has probably reached its peak with the development of the unified power flow controller (UPFC) [6, 7], where a proportion of the AC power transmission is subjected to AC–DC–AC conversion, though still has to meet all the requirements of the synchronous AC system.

Originally, the boundaries between HVDC and FACTS were determined by the type of transmission waveform (i.e. AC or DC), the solid-state devices used (which in the HVDC case had been restricted to the SCR) and the power rating of the schemes. However, as the rating and acceptability of alternative solid-state devices improve, these boundaries are gradually becoming ‘blurred’. HVDC is beginning to use the more advanced switching devices and the FACTS controllers are increasing their power rating. The general acceptance of FACTS technology has to a large extent changed the attitude towards DC transmission and the industry has become more open to alternative designs.

The asynchronous interconnector (with or without transmission distance) provides a higher degree of flexibility than the UPFC, and in many cases will be the only practical alternative for the interconnection of separate networks, by retaining (albeit increasing) the power controllability, while removing the synchronous constraints (fault-level increases, transient stability, etc.). The asynchronous link provides the perfect isolation between the interconnected parts and can be designed to provide any required level of power quality control (such as harmonic distortion, unbalance, flicker voltage, etc.). The zero-distance (or back-to-back) asynchronous interconnector has been part of HVDC transmission technology from its very beginning.

Increased transmission flexibility comes at a price in terms of either components or energy efficiency. Therefore, the concept of a new standard HVDC converter (the conventional approach) does not necessarily produce cost-effective solutions for all applications. It is thus essential to consider the degree of flexibility required for the particular transmission application (i.e. taking into account power ratings, transmission distances, extent of ancillary services expected, etc.), before deciding on the most appropriate HVDC alternative

Despite its limited controllability, the thyristor-based HVDC technology is still the preferred one for long-distance, large-power transmission. However, with the use of more advanced switching devices, such as the IGBT and IGCT (Integrated Gate Commutated Thyristor), an HVDC interconnection can now be designed to combine any or all the properties of the individual FACTS controllers: it permits maximum power transfer regardless of the AC voltage phase relationship, delivers or absorbs the required reactive power to maintain the specified voltages at the interconnected buses, contains fast emergency controls to avoid large fault current levels, is designed (if required) to control sub-synchronous resonances, etc. Moreover, the DC link permits the connection of asynchronous systems and systems of different frequencies. *A modern DC link can be the ultimate power transmission controller, i.e. the most* ***flexible transmission system****.*

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