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DC POWER TRANSMISSION TECHNOLOGY

1.1 INTRODUCTION

The industrial growth of a nation requires increased consumption of energy, particularly electrical energy. This has led to increase in the generation and transmission facilities to meet the increasing demand. In U.S.A. till the early seventies the demand doubled every ten years. In developing countries, like India, the demand doubles every seven years which requires considerable investment in electric power sector.

The imperatives of supplying energy at reasonable costs coupled with the depleting reserves of non-renewable energy sources has led to the establishment of remote generating stations– predominantly fossil-fuel fired thermal stations at pit head. Environmental considerations also dictate sometimes, siting of power stations at remote locations. Large hydro stations are invariably at distances of hundreds of kilometers from load centres. The need to economize on costly investments in generation reserves, sharing of benefits in utilizing variability in generation mixes and load patterns have given rise to interconnection of neighbouring systems and development of large power grids.

Remote generation and system interconnections lead to a search for efficient power transmission at increasing power levels. The increase in voltage levels is not always feasible. The problems of AC transmission particularly in long distance transmission, has led to the development of DC transmission. However, as generation and utilization of power remain at alternating current, the DC transmission requires conversion at two ends, from AC to DC at the sending end and back to AC at the receiving end. This conversion is done at converter stations – rectifier station at the sending end and inverter station at the receiving end. The converters are static—using high power thyristors connected in series to give the required voltage ratings. The physical process of conversion is such that the same station can switch from rectifier to inverter by simple control action, thus facilitating power reversal.

The HVDC transmission made a modest beginning in 1954 when a 100 kV, 20 MW DC link was established between Swedish mainland and the island of Gotland. Until 1970, the converter stations utilized mercury arc valves for rectification. The successful use of thyristors for power control in industrial drives encouraged its adoption in HVDC converters by development of high power semiconductor devices. The device voltage rating is now in the range of 10 kV, and current rating up to 5 kA (for 125 mm device). The highest transmission voltage reached is ± 600 kV.

The total installed HVDC capacity now exceeds 75000 MW. Several developments and innovations in HVDC technology, over the years, have made it attractive to consider HVDC transmission for a wide range of applications. This can cover a wide spectrum from bulk power transmission of thousands of megawatts over long distances to connecting small distributed electrical generators to a grid.

Deregulation or restructuring in the power sector has encouraged competition and private investments. The power transmission and distribution network is also viewed as a means for trading power among the competing generators and consumers of electrical energy. This introduces increased uncertainty in system operation and poses challenges in maintaining system security. The controllability of power flow in a transmission line becomes an important issue in planning of new lines.

The relative merits of AC and DC transmission are reviewed in the next section.

1.2 COMPARISON OF AC AND DC TRANSMISSION

The relative merits of the two modes of transmission (AC and DC) which need to be considered by a system planner are based on the following factors:

1. economics of transmission
2. technical performance
3. reliability

A major feature of power systems is the continuous expansion necessitated by increasing power demand. This implies that the establishment of a particular line must be considered as a part of an overall long-term system planning.

1.2.1 Economics of Power Transmission

The cost of a transmission line includes the investment and operational costs. The investment includes costs of Right of Way (RoW), transmission towers, conductors, insulators and terminal equipment. The operational costs include mainly the cost of losses.

The characteristics of insulators vary with the type of voltage applied. For simplicity, if it is assumed that the insulator characteristics are similar for AC and DC and depend on the peak level of voltage applied with respect to ground, then it can be shown that for lines designed with the same insulation level, a DC line can carry as much power with two conductors (with positive and negative polarities with respect to ground) as an AC line with 3 conductors of the same size. (Note that $P_{AC} = \frac{3}{\sqrt{2}} V_p I \cos\phi$ and $P_{DC} = 2V_p I, V_p$ is the peak voltage of a conductor with respect to ground, $\cos\phi$ is the power factor and I is the effective current rating of a conductor. Thus, $P_{AC} \simeq P_{DC}$.) This implies that for a given power level, DC line requires less RoW, simpler and cheaper towers and reduced conductor and insulator costs. The power losses are also reduced with DC as there are only two conductors (about 67% of that for AC with same current carrying capacity of conductors). The absence of skin effect with DC is also beneficial in reducing power losses marginally. The dielectric losses in case of power cables is also very less for DC transmission.

The corona effects on DC conductors tend to be less significant than for AC and this also leads to the choice of economic size of conductors with DC transmission. The other factors that influence the line costs are the costs of compensation and terminal equipment. DC lines do not require compensation but the terminal equipment costs are increased due to the presence of converters and filters.

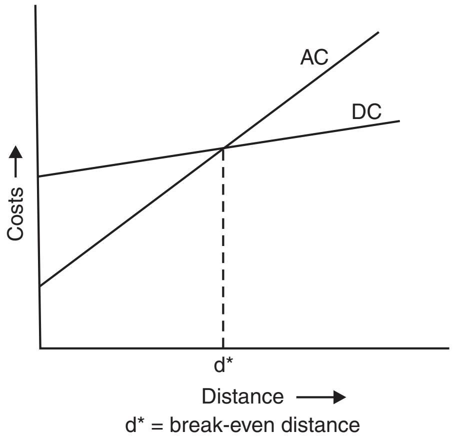


Fig. 1.1: Variation of costs with line length

Figure 1.1 shows the variation of costs of transmission with distance for AC and DC transmission. For distances less than 'break even' distance, AC tends to be economical than DC and costlier for longer distances. The break even distances can vary from 500 to 800 km in overhead lines depending on the per unit line costs.

1.2.2 Technical Performance

The DC transmission has some positive features which are lacking in AC transmission. These are mainly due to the fast controllability of power in DC lines through converter control. The advantages are:

1. full control over power transmitted
2. the ability to enhance transient and small signal stability in associated AC networks
3. fast control to limit fault currents in DC lines. This makes it feasible to avoid DC breakers in two terminal DC links.

In addition, the DC transmission overcomes some of the problems of AC transmission. These are described below:

Stability limits

The power transfer in AC lines is dependent on the angle difference between the voltage phasors at the two ends. For a given power level, this angle increases with distance. The maximum power transfer is limited by the considerations of steady state and transient stability. The power carrying capability of an AC line as a function of distance is shown in Fig. 1.2. The same figure also shows the power carrying capability of DC lines which is unaffected by the distance of transmission and is limited only by the current carrying capacity of the conductors (termed as 'thermal limit').

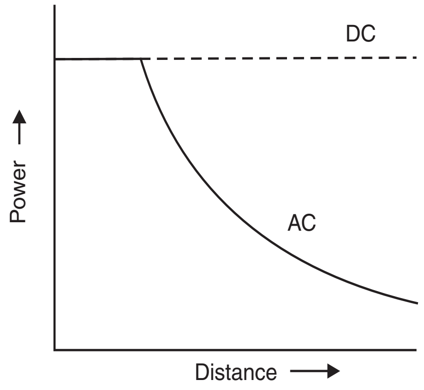


Fig. 1.2: Power transfer capability vs. distance

Voltage control

The voltage control in AC lines is complicated by the line charging and inductive voltage drops. The voltage profile in a AC line is relatively flat only for a fixed level of power transfer corresponding to surge impedance loading (SIL). The voltage profile varies with the line loading. For constant voltage at the line terminals, the midpoint voltage is reduced for line loading higher than SIL and increased for loadings less than SIL. This is shown in Fig. 1.3.

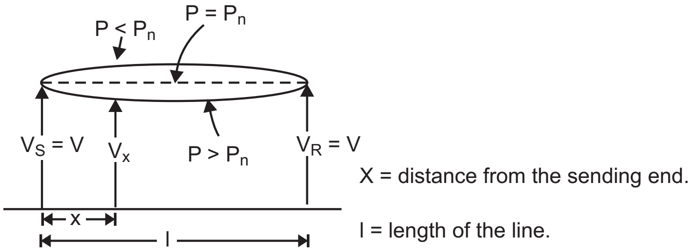


Fig. 1.3: Variation of voltage along the line

The maintenance of constant voltages at the two ends requires reactive power control from inductive to capacitive as the line loading is increased. The reactive power requirements increase with the increase in line lengths. Although DC converter stations with line commutated converters require reactive power related to the line loadings, the line itself does not require reactive power.

The steady-state charging currents in AC lines pose serious problems in cables. This puts the break-even distance for cable transmission around 40 km.

Line compensation

For reasons mentioned earlier, AC lines require shunt and series compensation in long distance transmission, mainly to overcome the problems of line charging and stability limitations. Series capacitors and shunt inductors are used for this purpose. The increase in power transfer and voltage control is also possible through the use of shunt connected Static Var Compensator (SVC).

In AC cable transmission, it is necessary to provide shunt compensation at regular intervals. This is a serious problem in underwater cables.

Problems of AC interconnection

When two power systems are connected through AC ties (synchronous interconnection), the automatic generation control of both systems have to be coordinated using tie-line power and frequency signals. Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to:

(*i*) presence of large power oscillations which can lead to frequent tripping
(*ii*) increase in fault levels
(*iii*) transmission of disturbances from one system to the other.

The controllability of power flow in DC lines eliminates all the above problems. In addition, for asynchronous DC ties, there is no need of coordinated control.

It is obvious that two systems which have different nominal frequencies cannot be interconnected directly with AC ties and require the use of DC links.

Ground impedance

In AC transmission, the existence of ground (zero sequence) currents cannot be permitted in steady-state due to high magnitudes of ground impedance which will not only affect efficient power transfer, but also result in telephone interference. The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return (Monopolar operation). The ground return is objectionable only when buried metallic structures (such as pipes) are present and are subject to corrosion with DC current flow.

It is to be noted that even while operating in the monopolar mode, the AC network feeding the DC converter station operates with balanced voltages and currents. Hence, single pole operation of DC transmission systems is possible for extended periods, while in AC transmission, single phase operation (or any unbalanced operation) is not feasible for more than a second.

Disadvantages of DC transmission

The scope of application of DC transmission is limited by the following factors:

(*a*) the difficulty of breaking DC currents which results in high cost of DC breakers
(*b*) inability to use transformers to change voltage levels
(*c*) high cost of conversion equipment
(*d*) generation of harmonics which require AC and DC filters, adding to the cost of converter stations
(*e*) complexity of control.

Over the years there have been significant advances in DC technology, which have tried to overcome the disadvantages listed above except for (b). These are:

(*a*) development of DC breakers
(*b*) modular construction of thyristor valves
(*c*) increase in the ratings of thyristor cells that make up a valve
(*d*) twelve pulse operation of converters

(*e*) use of metal oxide, gapless arrestors

(*f*) application of digital electronics and fiber optics in control of converters.

Some of the above advances have resulted in improving the reliability and reduction of conversion costs in DC systems. It can be said without exaggeration that complexity of control does not pose a problem and can actually be used to provide reliable and fast control of power transmission not only under normal conditions but also under abnormal conditions such as line and converter faults. This has removed the need for DC current interruption in two terminal links. Even for multiterminal operation, the requirements of current ratings of DC breakers are modest due to effective converter control.

1.2.3 Reliability

The reliability of DC transmission systems is quite good and comparable to that of AC systems. An exhaustive record of existing HVDC links in the world is available from which the reliability statistics can be computed. It must be remembered that the performance of thyristor valves is much more reliable than mercury arc valves and further developments in devices, control and protection have improved the reliability level. For example, the development of direct light triggered thyristors (LTT) can improve reliability because of elimination of high voltage pulse transformers and auxiliary supplies for turning on the devices.

There are two measures of overall system reliability.

Energy availability

This is defined as

$$\text{Energy Availability} = 100\left(1 - \frac{\text{equivalent outage time}}{\text{total time}}\right)\%$$

where equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to outage.

Transient reliability

This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems

$$\text{Transient reliability} = \frac{100 \times \text{No. of times HVDC system performe}}{\text{No. of recordable AC faults}}$$

Recordable AC system faults are those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault. It is assumed that the short-circuit level after the fault is not below the minimum specified for satisfactory converter operation.

The energy availability or transient reliability of existing DC systems with thyristor valves is 95% or more.

The average failure rate of thyristors in a valve is less than 0.6% per operating year. It is common practice to provide redundant thyristors in the series string composing a HVDC valve, so that failed thyristors can be replaced during scheduled maintenance period (once or twice a year). The maintenance of thyristor valves is also much simpler than the earlier mercury arc valves.

Table 1.1: HVDC Outage Statistics

Equipment	MTTF (years)	MTTR (hours)
Thyristor Group	13.7	6.1
Converter Transformer	16.1	1700.0
Smoothing Reactor	76.8	1700.0
DC Filter	19.7	7.9
AC Filter	12.6	9.3
Master Control	25.0	6.9
Pole Control	9.0	8.6
Pole of Transmission Line	1.25/100 km	1.5
DC Line Switch	147.2	7.8

MTTF = Mean time to failure

MTTR = Mean time to repair.

Some of the HVDC outage statistics is given in Table 1.1. In comparing the reliability of various alternatives, it must be kept in mind that bipolar DC line can be as reliable as a double circuit AC line with same power capability. This is because of the fact that failure of one pole does not affect the operation of the other pole (with ground return). If the DC line conductor has adequate overload rating and if the converters on the failed pole can be paralleled with the converters on the healthy pole, the prefault power level can be maintained even with permanent outage of one pole.

1.3 APPLICATION OF DC TRANSMISSION

The detailed comparison of AC and DC transmission in terms of economics and technical performance, leads to the following areas of application for DC transmission:

1. long distance bulk power transmission
2. underground or underwater cables
3. asynchronous interconnection of AC systems operating at different frequencies or where independent control of systems is desired.
4. control and stabilization of power flows in AC ties in an integrated power system.

The first two applications are dictated primarily by the economic advantages of DC transmission, where the concept of break-even distance is important. To be realistic, one must also assign a monetary value for the technical advantages of DC (or penalty costs for the drawbacks of AC). The problem of evaluation of the economic benefits, is further complicated by the various alternatives that may be considered in solving problems of AC transmission—phase shifters, static var systems, series capacitors, single pole switching etc.

The technical superiority of DC transmission dictates its use for asynchronous interconnections, even when the transmission distances are negligible. Actually there are many ‘back to back’ (BTB) DC links in existence where the rectification and inversion are carried out in the same converter station with no DC lines. The advantage of such DC links lies in the reduction of the overall conversion costs and improving the reliability of DC system.

The alternative to DC ties may require strengthening of existing AC network near the boundary of the two systems. This cost can be prohibitive if the capacity of the tie required is moderate compared to the size of the systems interconnected.

In large interconnected systems, power flows in AC ties (particularly under disturbance conditions) can be uncontrolled and lead to overloads and stability problems, thus endangering system security. Strategically placed DC lines can overcome this problem due to the controllability of power. The planning of DC transmission in such applications requires detailed study to evaluate the benefits.

Presently the number of DC lines in a power grid is very small compared to the number of AC lines. This indicates that DC transmission is justified only for specific applications. Although advances in technology and introduction of multi-terminal DC (MTDC) systems are expected to increase the scope of application of DC transmission, it is not anticipated that AC grid will be replaced by DC power grid in future. There are two major reasons for this. Firstly, the control and protection of MTDC systems is very complex and the inability of voltage transformation in DC networks imposes economic penalties. Secondly, the advances in DC technology have resulted in the improvement of the performance of AC transmission, through introduction of FACTS (Flexible AC Transmission System) controllers.

The rate of growth of DC transmission was slow in the beginning. In over 16 years, only 6000 MW of DC systems were installed using mercury arc valves. The introduction of thyristor valves overcame some of the problems of system operation mainly due to the arc backs in mercury arc valves. Since then, the rate of growth of DC transmission capacity has reached an average of 2500 MW/year.

There are more than 92 HVDC projects worldwide with a total capacity exceeding 75000 MW. Initial application of HVDC transmission was for submarine transmission or frequency conversion where HVDC is the unique solution. Subsequently, HVDC has been applied for long distance bulk power transmission and for asynchronous BTB links.

Table 1.2 gives the list of BTB and line projects in India.

Table 1.2: List of BTB and Line Projects in India.

(a) Back to Back (BTB) Links

S. No.	System/Project	Year Commissioned	Supplier	Power Rating (MW)	Voltage (kV)
1.	Vindhyachal	1989	ABB	500	2 x 69.7
2.	Chandrapur–Ramagundam	1997/98	GEC Alsthom	1000	2 x 205
3.	Vizag–I	1999	GEC Alsthom	500	205
4.	Vizag–II	2005	ABB	500	±88
5.	Sasaram	2002	GEC Alsthom	500	205

(b) Line Projects

S. No.	System/ Project	Year Comm-issioned	Supplier	Power Rating (MW)	Voltage (kV)	Line Length (km)
1.	National HVDC Project–Stage–I	1989	BHEL	100	100	196
2.	NHVDC–Stage–II	2000	BHEL	100	200	196
3.	Rihand–Delhi	1991-92	ABB/BHEL	750/1500	± 500	814
4.	Chandrapur–Padghe	1998	ABB	1500	± 500	736
5.	Talcher–Kolar	2003	Siemens	2000	± 500	1400
6.	Balia–Bhiwadi	2009	Siemens	2500	± 500	780

A compilation of the worldwide HVDC projects titled "HVDC Projects List" is available at the website maintained by HVDC and FACTS subcommittee of IEEE/PES Transmission and Distribution committee [22].

1.4 DESCRIPTION OF DC TRANSMISSION SYSTEM

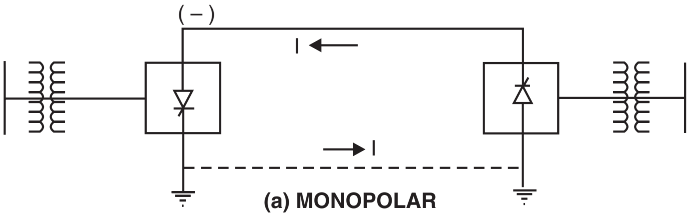
1.4.1 Types of DC Links

The DC links are classified into three types which are defined below:

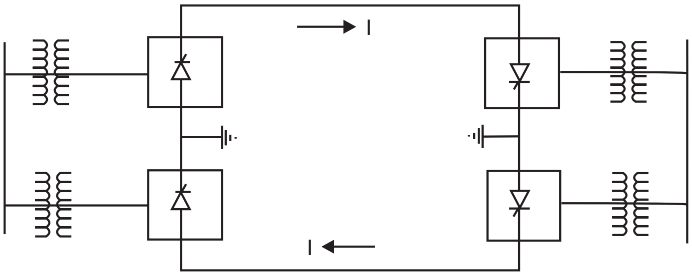
1. Monopolar link (see Fig. 1.4 (a)) has one conductor usually of negative polarity and use ground or sea return. Sometimes metallic return is also used.
2. Bipolar link (see Fig. 1.4 (b)) has two conductors, one positive and the other negative. Each may be a bundled conductor in EHV lines. Each terminal has two sets of converters of identical ratings, connected in series on the DC side. The junction between the two sets of converters is grounded at one or both ends. Normally, both poles operate at equal currents and hence there is zero ground current flowing under these conditions.
3. Homopolar Link (see Fig. 1.4(c)) has two or more conductors all having the same polarity (usually negative) and always operated with ground or metallic return.

Because of the desirability of operating a DC link without ground return, bipolar links are most commonly used. Homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages. Incidentally, the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity.

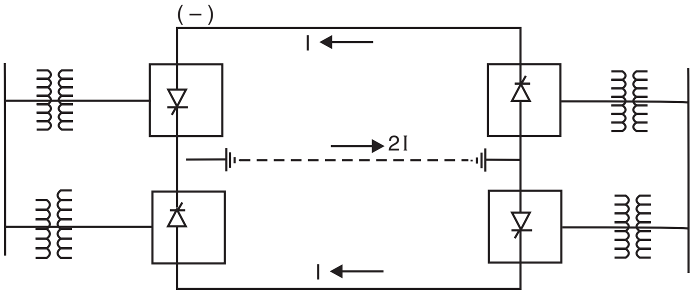
The monopolar operation is used in the first stage of the development of a bipolar line, as the investments on converters can be deferred until the growth of load which requires bipolar operation at double the capacity of a monopolar link.



(a) MONOPOLAR



(b) BIPOLAR



(c) HOMOPOLAR

Fig. 1.4: DC link configurations

1.4.2 Converter Station

The major components of a HVDC transmission system are converter stations where conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed. A point to point transmission requires two converter stations. The role of rectifier and inverter stations can be reversed (resulting in power reversals) by suitable converter control.

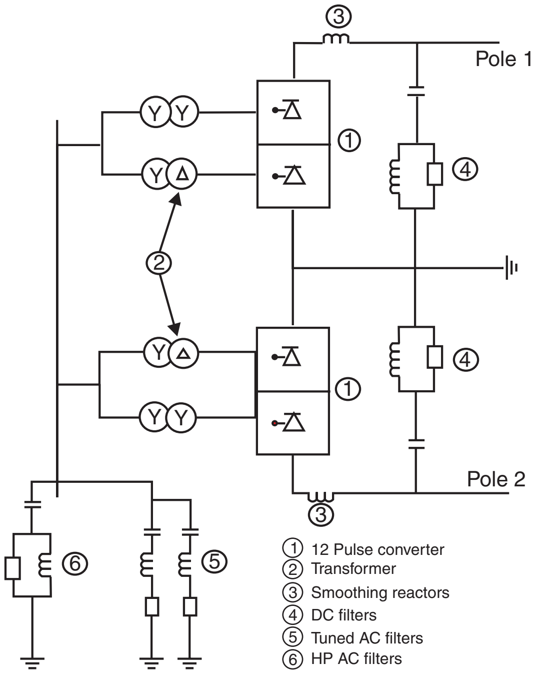


Fig. 1.5: Schematic diagram of a typical HVDC converter station

A typical converter station with one 12 pulse converter unit per pole, is shown in Fig. 1.5. The various components of a converter station are discussed below.

Converter unit

This usually consists of two three phase converter bridges connected in series to form a 12 pulse converter unit as shown in Fig.1.6. The total number of valves in such a unit are twelve. The valves can be packaged as a single valve, double valve or quadrivalve arrangements. Each valve is used to switch in a segment of an AC voltage waveform. The converter is fed by converter transformers connected in star/star and star/delta arrangements.

The valves can be cooled by air, oil, water or freon. Liquid cooling using deionized water is more efficient and results in the reduction of station losses. The ratings of a valve group are limited more by the permissible short circuit currents than steady state load requirements. The design of valves is based on the modular concept where each module contains a limited number of series connected thyristor levels.

Valve firing signals are generated in the converter control at ground potential and are transmitted to each of the thyristor in the valve through a fiber optic light guide system. The light signal received at the thyristor level is converted to an electrical signal using gate drive amplifiers with pulse transformers.

The valves are protected using snubber circuits, protective firing and gapless surge arrestors. Some of the details of the operation, control and protection of thyristor valves are given in Appendix A.

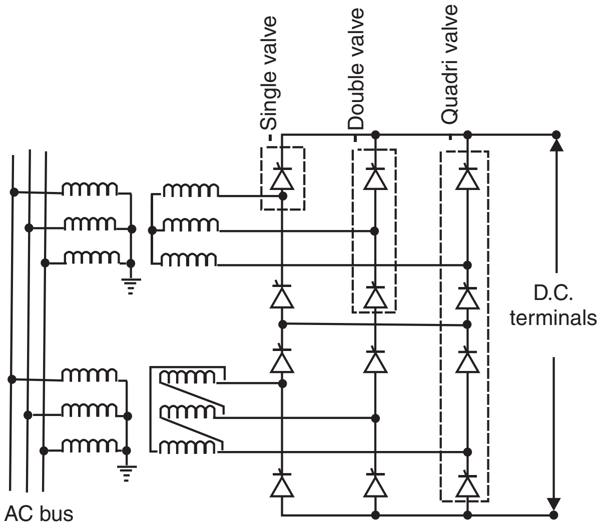


Fig. 1.6: A twelve pulse converter unit

Converter transformer

The converter transformer can have different configurations – (i) three phase, two winding, (ii) single phase, three winding, (iii) single phase two winding. The valve side windings are connected in star and delta with neutral point ungrounded. On the AC side, the transformers are connected in parallel with neutral grounded. The leakage reactance of the transformer is chosen to limit the short circuit currents through any valve.

The converter transformers are designed to withstand DC voltage stresses and increased eddy current losses due to harmonic currents. One problem that can arise is caused by the DC magnetization of the core due to unsymmetric firing of valves.

In back to back links, which are designed for low DC voltage levels, an extended delta configuration can result in identical transformers being used in twelve pulse converter units. This results in the reduction of the spare capacity required. However, the application of extended delta transformers is limited.

Filters

There are three types of filters used:

1. AC filters: These are passive circuits used to provide low impedance, shunt paths for AC harmonic currents. Both tuned and damped filter arrangements are used.
2. DC filters: These are similar to AC filters and are used for the filtering of DC harmonics.
3. High frequency (RF/PLC) filters: These are connected between the converter transformer and the station AC bus to suppress any high frequency currents. Sometimes such filters are provided on high-voltage DC bus connected between the DC filter and DC line and also on the neutral side.

Reactive power source

Converter stations require reactive power supply that is dependent on the active power loading (about 50 to 60% of the active power). This is due to the fact that current drawn by a Line Commutated (current source) Converter (LCC) can only lag the supply voltage. Fortunately, part of this reactive power requirement is provided by AC filters. In addition, shunt (switched) capacitors, synchronous condensers and static var systems (SVC or STATCOM) are used depending on the speed of control desired.

Smoothing reactor

A sufficiently large series reactor is used on DC side to smooth DC current and also for protection. The reactor is designed as a linear reactor and is connected on the line side, neutral side or at intermediate location.

DC switchgear

This is usually a modified AC equipment used to interrupt small DC currents (employed as disconnecting switches). DC breakers or metallic return transfer breakers (MRTB) are used, if required for interruption of rated load currents.

In addition to the equipment described above, AC switchgear and associated equipment for protection and measurement are also part of the converter station. This includes DC current and voltage transducers.

1.5 PLANNING FOR HVDC TRANSMISSION

The system planner must consider DC alternative in transmission expansion. The factors to be considered are: (i) cost, (ii) technical performance, and (iii) reliability.

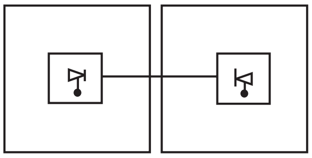
Generally, the last two factors are considered as constraints to be met and the minimum cost option is selected among various alternatives that meet the specifications on technical performance and reliability.

For submarine, cable transmission and interconnecting two systems of different nominal frequencies, the choice of DC is obvious. In other cases, the choice is to be based on detailed techno-economic comparison.

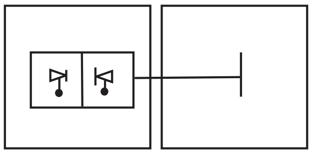
The considerations in the planning for DC depends on the application. Two applications can be considered as representative. These are:

1. Long distance bulk power transmission
2. Interconnection between two adjacent systems.

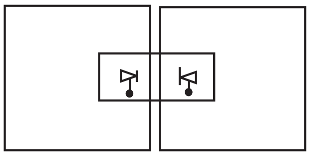
In the first application, the DC and AC alternatives for the same level of system security and reliability are likely to have the same power carrying capability. Thus the cost comparisons would form the basis for the selection of the DC (or AC) alternative, if the requirements regarding technical performance are not critical.



(a) Two terminal DC link



(b) Back to back DC link along with AC feeder



(c) Back to back DC link at border

Fig. 1.7: Different configurations for asynchronous interconnection

In the second application, AC interconnection poses several problems in certain cases. For the same level of system security (and reliability), the capacity of AC interconnection will be much more than that for DC (even ignoring the beneficial aspects of DC power modulation). Thus the choice for DC interconnection will be based on the following considerations.

1. Small fluctuations in the voltage and frequency do not affect the power flow which can be set at any desired value.
2. The system security can be enhanced by fast control of DC power.

Having settled on the DC link for interconnection, there are three possible configurations for interconnection. These are:

1. A two terminal transmission where each terminal is located at a suitable place somewhere within the network and connected by a DC overhead line or cable.
2. A back to back HVDC station (also called HVDC coupling station) located somewhere within one of the network and an AC line from the other network to the common station.
3. A back to back station located close to the border between the two systems. This is a special case of the above.

These are illustrated in Fig. 1.7.

In the choice between the first and the second configuration, it is to be noted that converter costs are less for the common coupling station and the AC line costs are greater than the DC line costs. If the distances involved are less than 200 km, the second configuration is to be preferred. If the short circuit ratio (SCR) is acceptable then the third alternative will be the most economic.

The specifications and design of DC system require an understanding of the various interactions between the DC and AC systems. The interruption (or reduction) of power in a DC link can occur due to:

(*a*) DC line faults

(*b*) AC system faults

The speed of recovery from transient DC line faults is of concern in maintaining the integrity of the overall system. The power flow and stability studies are used in this context. The recovery of DC link from AC system faults is more complex. The depression of AC voltage at the inverter bus can lead to commutation failure and loss of DC power. The DC power is ramped up on the clearing of the fault. Too fast an increase in DC power output can lead to the reduction of AC voltage and failure of commutation (due to corresponding increase in the var demand). An optimum rate of increase in DC power can be determined from stability study. This is influenced by control strategy and system characteristics.

The following aspects also require a detailed study of the system interactions:

1. Var requirements of converter stations and voltage stability
2. Dynamic overvoltages
3. Harmonic generation and design of filters
4. Damping of low frequency and subsynchronous torsional oscillations
5. Carrier frequency interference caused by spiky currents in valves (at the beginning of conduction) due to the discharge of stray capacitances and snubber circuits.

The converter control plays a major role in these interactions and the control strategy should be such as to improve the overall system performance. Digital simulation and HVDC simulators are used for planning and design studies.

Choice of voltage level

For long distance bulk power transmission, the voltage level is chosen to minimize the total costs for a given power level (P). The total costs include investment (C_1) and cost of losses (C_2). The investment costs per unit length are modeled as:

$$C_1 = A_0 + A_1 nV + A_2 nq \tag{1.1}$$

where V is the voltage level with respect to ground

n is the number of conductors

q is the total cross-section of each conductor

A_0, A_1 and A_2 are constants

The cost of losses per unit length is given by

$$C_2 = \frac{\left[n\left(\frac{P}{nV}\right)^2 \rho TLp\right]}{q} \tag{1.2}$$

where

ρ = conductor resistivity

T = total operation time in a year

L = loss load factor