1.3 Application of DC transmission

Due to their costs and special nature, most applications of DC transmission generally fall into one of the following three categories.

Underground or underwater cables:

In the case of long cable connections over the breakeven distance of about 40-50 km, DC cable transmission system has a marked advantage over AC cable connections. Examples of this type of applications were the Gotland (1954) and Sardinia (1967) schemes. The recent development of Voltage Source Converters (VSC) and the use of rugged polymer DC cables, with the so-called “HVDC Light” option, are being increasingly considered. An example of this type of application is the 180 MW Direct link connection (2000) in Australia.

Long distance bulk power transmission:

Bulk power transmission over long distances is an application ideally suited for DC transmission and is more economical than ac transmission whenever the breakeven distance is exceeded. Examples of this type of application abound from the earlier Pacific Intertie to the recent links in China and India.

The breakeven distance is being effectively decreased with the reduced costs of new compact converter stations possible due to the recent advances in power electronics.

Stabilization of power flows in integrated power system:

In large interconnected systems, power flow 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 fast controllability of DC power and provide much needed damping and timely overload capability. The planning of DC transmission in such applications requires detailed study to evaluate the benefits. Example is the Chandrapur-Padghe link in India.

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 the AC grid will be replaced by a DC power grid in the future. There are two major reasons for this:

First, the control and protection of MTDC systems is complex and the inability of voltage transformation in dc networks imposes economic penalties.

Second, the advances in power electronics technology have resulted in the improvement of the performance of AC transmissions using FACTS devices, for instance through introduction of static VAR systems, static phase shifters, etc.

Types of HVDC Links

Three types of HVDC Links are considered in HVDC applications which are

Monopolar Link:

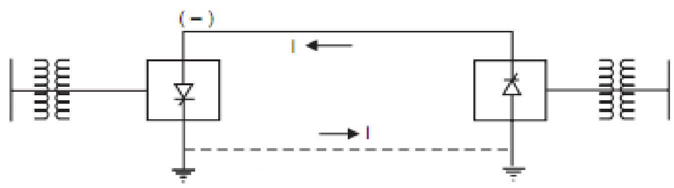


Figure 1.3.1 Monopolar DC link

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-10]

A monopolar link as shown in the above figure has one conductor and uses either ground and/or sea return. A metallic return can also be used where concerns for harmonic interference and/or corrosion exist. In applications with DC cables (i.e., HVDC Light), a cable return is used. Since the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity, a monopolar link is normally operated with negative polarity.

Bipolar Link:

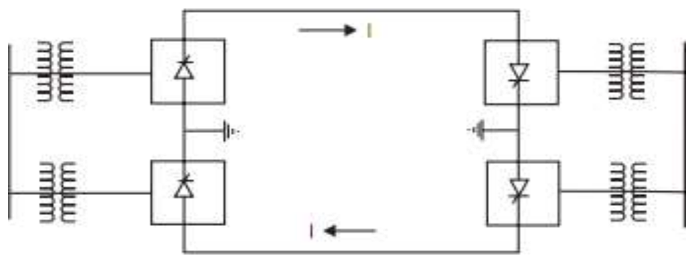


Figure 1.3.2 Bipolar DC link

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-10]

A bipolar link as shown in the above figure has two conductors, one positive and the other negative. Each terminal has two sets of converters of equal rating, in series on the DC side. The junction between the two sets of converters is grounded at one or both ends by the use of a short electrode line. Since both poles operate with equal currents under normal operation, there is zero ground current flowing under these conditions. Monopolar operation can also be used in the first stages of the development of a bipolar link. Alternatively, under faulty converter conditions, one DC line may be temporarily used as a metallic return with the use of suitable switching.

Homopolar Link:

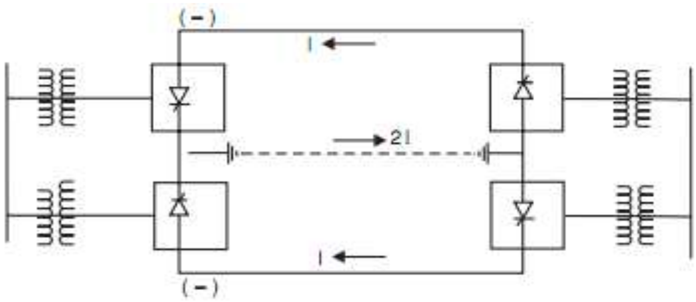


Figure 1.3.3 Homopolar DC link

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-10]

In this type of link as shown in the above figure two conductors having the same polarity (usually negative) can be operated with ground or metallic return.

Due to the undesirability of operating a DC link with ground return, bipolar links are mostly used. A homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages.

1.2 Comparison of AC and DC transmission

The merits of two modes of transmission (AC & DC) should be compared based on the following factors.

1) Economics of transmission
2) Technical Performance
3) Reliability

Economics of Power Transmission:

In DC transmission, inductance and capacitance of the line has no effect on the power transfer capability of the line and the line drop. Also, there is no leakage or charging current of the line under steady conditions.

A DC line requires only 2 conductors whereas AC line requires 3 conductors in 3-phase AC systems. The cost of the terminal equipment is more in DC lines than in AC line. Break-even distance is one at which the cost of the two systems is the same. It is understood from the below figure that a DC line is economical for long distances which are greater than the break-even distance.

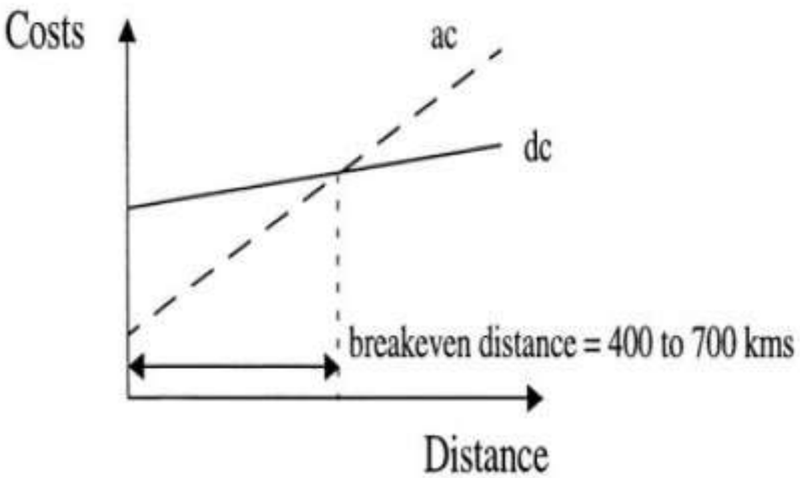


Figure 1.2.1 Relative costs of AC and DC transmission lines vs distance

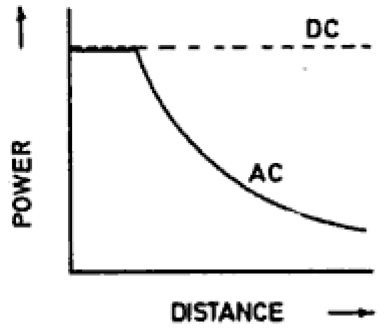
[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-03]

Technical Performance:

Due to its fast controllability, a DC transmission has full control over transmitted power, an ability to enhance transient and dynamic stability in associated AC networks and can limit fault currents in the DC lines. Furthermore, DC transmission overcomes some of the following problems associated with AC transmission.

Stability Limits:

The power transfer in an AC line is dependent on the angle difference between the voltage phasors at the two line ends. For a given power transfer 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 is inversely proportional to transmission distance whereas the power carrying ability of DC lines is unaffected by the distance of transmission.



Power transfer capability vs. distance

Figure 1.2.2 Relative power of AC and DC transmission lines vs distance

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-04]

Voltage Control:

Voltage control in ac lines is complicated by line charging and voltage drops. The voltage profile in an AC line is relatively flat only for a fixed level of power transfer corresponding to its Surge Impedance Loading (SIL). The voltage profile varies with the line loading. For constant voltage at the line ends, the midpoint voltage is reduced for line loadings higher than SIL and increased for loadings less than SIL.

The maintenance of constant voltage at the two ends requires reactive power control as the line loading is increased. The reactive power requirements increase with line length. Although DC converter stations require reactive power related to the power transmitted, the DC line itself does not require any reactive power. The steady-state charging currents in AC cables pose serious problems and make the break-even distance for cable transmission around 50kms.

Line Compensation:

Line compensation is necessary for long distance AC transmission to overcome the problems of line charging and stability limitations. The increase in power transfer and voltage control is possible through the use of shunt inductors, series capacitors, Static

Var Compensators (SVCs) and, lately, the new generation Static Compensators (STATCOMs). In the case of DC lines, such compensation is not needed.

Problems of AC Interconnection:

The interconnection of two power systems through ac ties requires the automatic generation controllers of both systems 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:

The presence of large power oscillations which can lead to frequent tripping,

1. Increase in fault level, and
2. Transmission of disturbances from one system to the other.

The fast controllability of power flow in DC lines eliminates all of the above problems. Furthermore, the asynchronous interconnection of two power systems can only be achieved with the use of DC links.

Ground Impedance:

In AC transmission, the existence of ground (zero sequence) current cannot be permitted in steady-state due to the high magnitude of ground impedance which will not only affect efficient power transfer, but also result in telephonic 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. 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 period, 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

1. High cost of conversion equipment.
2. Inability to use transformers to alter voltage levels.
3. Generation of harmonics.
4. Requirement of reactive power and

5. Complexity of controls.

Over the years, there have been significant advances in DC technology, which have tried to overcome the disadvantages listed above except for (2). These are

1. Increase in the ratings of a thyristor cell that makes up a valve.
2. Modular construction of thyristor valves.
3. Twelve-pulse (and higher) operation of converters.
4. Use of forced commutation.
5. Application of digital electronics and fiber optics in the control of converters.

Reliability:

The reliability of DC transmission systems is good and comparable to that of AC systems. The reliability of DC links has also been very good.

There are two measures of overall system reliability-energy availability and transient reliability.

Energy availability:

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

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.

$$\text{Transient reliability} = \frac{100 \text{ X No. of times HVDC systems performed as designed}}{\text{No. of recordable AC faults}}$$

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.

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

1.1 Introduction

Electric power transmission was originally developed with direct current. The availability of transformers and the development and improvement of induction motors at the beginning of the 20th century, led to the use of AC transmission.

DC Transmission now became practical when long distances were to be covered or where cables were required. Thyristors were applied to DC transmission and solid state valves became a reality.

With the fast development of converters (rectifiers and inverters) at higher voltages and larger currents, DC transmission has become a major factor in the planning of the power transmission. In the beginning all HVDC schemes used mercury arc valves, invariably single phase in construction, in contrast to the low voltage polyphase units used for industrial application. About 1960 control electrodes were added to silicon diodes, giving silicon-controlled-rectifiers (SCRs or Thyristors).

Today, the highest functional DC voltage for DC transmission is +/- 600kV. D.C transmission is now an integral part of the delivery of electricity in many countries throughout the world.

In large interconnected systems, power flow 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 fast controllability of DC power and provide much needed damping and timely overload capability. The planning of DC transmission in such applications requires detailed study to evaluate the benefits. Example is the Chandrapur-Padghe link in India.

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Second, the advances in power electronics technology have resulted in the improvement of the performance of AC transmissions using FACTS devices, for instance through introduction of static VAR systems, static phase shifters, etc.

Need for HVDC Systems

For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be warranted, due to other benefits of direct current links.

HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing exchange of power between incompatible networks.

Brief History

HVDC technology first made its mark in the early under-sea cable interconnections of Gotland (1954) and Sardinia (1967), and then in long distance transmission with the Pacific Intertie (1970) and Nelson River (1973) schemes using mercury-arc valves. A significant milestone occurred in 1972 with the first Back to Back (BB) asynchronous interconnection at Eel River between Quebec and New Brunswick; this installation also marked the introduction of thyristor valves to the technology and replaced the earlier mercury-arc valves.

The first 25 years of HVDC transmission were sustained by converters having mercury arc valves till the mid-1970s. The next 25 years till the year 2000 were sustained by line-commutated converters using thyristor valves. It is predicted that the next 25 years will be dominated by force-commutated converters . Initially, this new force-commutated era has commenced with Capacitor Commutated Converters (CCC) eventually to be replaced by self-commutated converters due to the economic availability of high power switching devices with their superior characteristics.

The first commercially used HVDC link in the world was built in 1954 between the mainland of Sweden and island of Gotland. Since the technique of power transmission by HVDC has been continuously developed.

In India, the first HVDC line in Rihand-Delhi in 1991 i.e. I 500 KV, 800 Mkl, 1000 KM. In Maharashtra in between Chandrapur & Padaghe at 1500 KV & 1000 MV. Global HVDC transmission capacity has increase from 20 MW in 1954 to 17.9 GW in 1984. Now the growth of DC transmission capacity has reached an average of 2500 MW/year.

Table 1.1 List of HVDC Projects in India.

S.No	Project Name	Connecting Region	Commissioned On	Power Rating	AC Voltage	DC Voltage	Mode Of Operation	No. of Poles/ Blocks	Length Of Line
1.	**Rihand-Dadri**	ER-WR	December 1991	1500 MW	400 KV	500 KV	Bipole	2	816 Km
2.	**Talcher-Kolar**	ER-SR	June 2003	2000 MW	400 KV	500 KV	Bipole	2	1369 Km
3.	**Ballia-Bhiwadi**	ER-NR	Pole1: March 2010 Pole 2: March 2011	2500 MW	400 KV	500 KV	Bipole	2	780 Km
4.	**Chandrapur Padge**	CR-WR	1999	1500 MW	400 KV	500 KV	Bipole	2	752 Km
5.	**Mundra-Mohindergarh**	WR-NR	2012	1500 MW	400 KV	500 KV	Bipole	2	986 Km
6.	**Bishwanath-Agra**	NER-ER	2015	6000 MW	400 KV	800 KV	Multi-Terminal	2	1728 Km
7.	**Vidhyanchal**	WR-NR	April 1989	2x250 MW	400 KV	70 KV	Back To Back	2	-
8.	**Chandrapur**	WR-SR	December 1997	2x500 MW	400 KV	205 KV	Back To Back	2	-
9.	**Sasaram**	ER-SR	September 2002	1x500 MW	400 KV	205 KV	Back To Back	2	-
10.	**Gazuwaka**	ER-SR	March 2005	2x500 MW	400 KV	Block 1: 205 KV Block 2: 177 KV	Back To Back	2	-

1.4 Description of DC transmission system

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. A typical converter station with two 12 pulse converter units per pole is shown in figure below. The block diagram of converter station is given above.

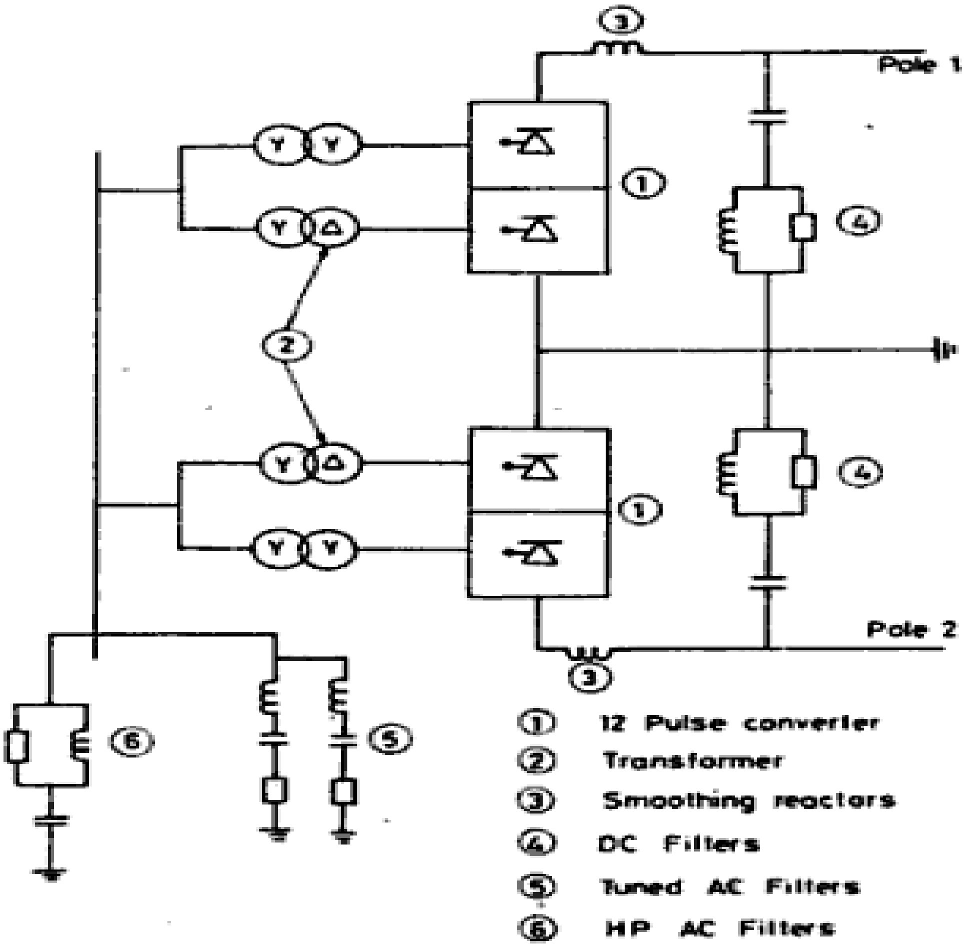

Figure 1.4.1 Schematic diagram of a typical HVDC converter station

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-11]

Converter Unit:

This usually consists of two three phase converter bridges connected in series to form a 12 pulse converter unit as shown in above figure. The total number of valves in such a unit is twelve.

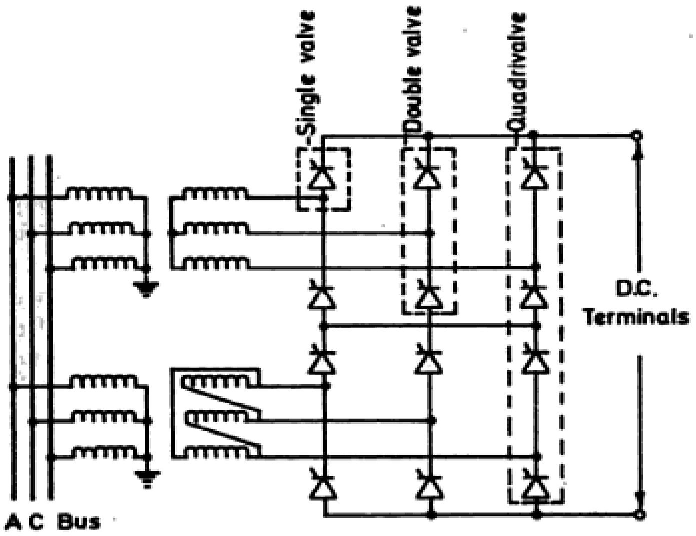

Figure 1.4.2 12-pulse converter station

[Source: "HVDC Power Transmission Systems" by K.P.Padiyar, page-12]

The valves can be packaged as single valve, double valve or quadrivalve arrangements. Each valve is used to switch in segment of an AC voltage waveform. The converter is fed by converter transformers connected in star/star and star/delta arrangements.

The valves are cooled by air, oil, water of freon. Liquid cooling using deionized water is more efficient and results in the reduction of station losses. 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 thyristor in the valve through a fiber optic light guide system.

The valves are protected using snubber circuits, protective firing and gapless surge arrestors.

<u>Converter Transformer:</u>

The converter transformer has three different configurations-

(i) three phase, two winding,

(ii) single phase, three winding and

(iii) single phase, two winding

The valve side windings are connected in parallel with neutral grounded. The leakage reactance of the transformer is chosen to limit the short circuit currents through any valves.

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 due to the DC magnetization of the core due to unsymmetrical firing of valves.

Filters:

There are three types of filters used which are

1. ***AC Filters:***

   These are passive circuits used to provide how 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. But part of the reactive power requirement is provided by AC filters. In addition, shunt capacitors, synchronous condensors and static VAR systems 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:

It is modified AC equipment used to interrupt small DC currents. DC breakers or Metallic Return Transfer Breakers (MRTB) are used, if required for interruption of rated load currents.

In addition to the DC switchgear, AC switchgear and associated equipment for protection and measurement are also part of the converter station.

1.6 HVDC transmission based on VSC

Conventional HVDC transmission employs line-commutated, current-source converters with thyristor valves. These converters require a relatively strong synchronous voltage source in order to commutate. The conversion process demands reactive power from filters, shunt banks, or series capacitors, which are an integral part of the converter station.

Any surplus or deficit in reactive power must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the system or the further away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance.

These VSC-based systems are force-commutated with insulated-gate bipolar transistor (IGBT) valves and solid-dielectric, extruded HVDC cables HVDC transmission and reactive power compensation with VSC technology has certain attributes which can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. This control capability gives total flexibility to place converters anywhere in the ac network since there is no restriction on minimum network short-circuits capacity.

1. **Physical Structure**

The main function of the VSC-HVDC is to transmit constant DC power from the rectifier to the inverter. As shown in Figure.1, it consists of dc-link capacitors C_{dc}, two converters, passive high-pass filters, phase reactors, transformers and dc cable.

2. **Converters**

The converters are VSCs employing IGBT power semiconductors, one operating as a rectifier and the other as an inverter. The two converters are connected either back-to-back or through a dc cable, depending on the application.

3. **Transformers**

Normally, the converters are connected to the ac system via transformers. The most important function of the transformers is to transform the voltage of the ac system to a value suitable to the converter. It can use simple connection (two-winding instead of three to eight-winding transformers used for other schemes). The leakage inductance of the transformers is usually in the range 0.1-0.2p.u.

4. **Phase Reactors**

The phase reactors are used for controlling both the active and the reactive power flow by regulating currents through them. The reactors also function as ac filters to reduce the high frequency harmonic contents of the ac currents which are caused by the switching operation of the VSCs. The reactors are essential for both active and reactive power flow, since these properties are determined by the power frequency voltage across the reactors. The reactors are usually about 0.15p.u. Impedance.

5. **AC Filters**

The ac voltage output contains harmonic components, derived from the switching of the IGBTs. These harmonics have to be taken care of preventing them from being emitted into the ac system and causing malfunctioning of ac system equipment or radio and telecommunication disturbances. High-pass filter branches are installed to take care of these high order harmonics. With VSC converters there is no need to compensate any reactive power consumed by the converter itself and the current harmonics on the ac side are related directly to the PWM frequency. The amount of low-order harmonics in the current is small.

6. **Dc Capacitors**

On the dc side there are two capacitor stacks of the same size. The size of these capacitors depends on the required dc voltage. The objective for the dc capacitor is primarily to provide a low inductive path for the turned-off current and energy storage to be able to control the power flow. The capacitor also reduces the voltage ripple on the dc side.

7. **Dc Cables**

The cable used in VSC-HVDC applications is a new developed type, where the insulation is made of an extruded polymer that is particularly resistant to dc voltage. Polymeric cables are the preferred choice for HVDC, mainly because of their mechanical strength, flexibility, and low weight.

8. IGBT Valves

The insulated gate bipolar transistor (IGBT) valves used in VSC converters are comprised of series-connected IGBT positions. The IGBT is a hybrid device exhibiting the low forward drop of a bipolar transistor as a conducting device. A complete IGBT position consists of an IGBT, an anti parallel diode, a gate unit, a voltage divider, and a water-cooled heat sink. Each gate unit includes gate-driving circuits, surveillance circuits, and optical interface. The gate-driving electronics control the gate voltage and current at turn-on and turn-off, to achieve optimal turn-on and turn-off processes of the IGBT. To be able to switch voltages higher than the rated voltage of one IGBT, many positions are connected in series in each valve similar to thyristors in conventional HVDC valves.

9. AC Grid

Usually a grid model can be developed by using the Thevenin equivalent circuit. However, for simplicity, the grid was modeled as an ideal symmetrical three-phase voltage source.

HVDC Circuit breakers & Operating problems

Circuit breakers will be positioned on DC grids and act when a fault occurs. Breakers would have to fulfill some basic requirements. Current zero crossing should be created to interrupt the current once a fault occurs. At the same time the energy that is stored in the system's inductance should be dissipated and the breaker should withstand the voltage response of the network.

There are two types of HVDC circuit breakers: electromechanical and solid-state. Electromechanical can be grouped into three categories: (1) inverse voltage generating method, (2) divergent current oscillating method, and (3) inverse current injecting method. Only the inverse current injecting method can be used in high voltage and current ratings. In this type of breaker, current zero can be created by superimposing an inverse current (of high frequency) on the input current by dis-charging a capacitor (that was pre- charged) through an inductor. (Explained on next section) The cost of components required for an electromechanical DC circuit breaker would not be significantly higher than that of an AC circuit breaker. Electromechanical HVDC circuit breakers are available up to 500 kV, 5 kA and have a fault-clearing time of the order of 100 ms.

Solid-state circuit breakers are the second type of HVDC breakers. These breakers can interrupt current much faster (which is required in some cases) than electromechanical circuit breakers, having an interruption time of a few milliseconds. They are based on Integrated Gate Commutated Thyristors (IGCT), which compared to IGBT (bipolar thyristors) have lower on-state losses. Current flows through the IGCT and in order to interrupt, the IGCT is turned off. Once that happens, voltage quickly increases until a varistor (that is in parallel to the thyristor) starts to conduct. The varistor is designed to block voltages above the voltage level of the system. The main disadvantages of these types of circuit breakers are the high on-state losses and the capital costs.Typical ratings of solid-state circuit breakers in operation are 4 kV, 2 kA, although in ratings of up to 150 kV, 2 kA were considered.

Electromechanical HVDC circuit breakers:

- The nominal current path is where DC current passes through and the switch is closed during normal operation
- The commutation path consists of a switch and a resonant circuit with an inductor and a capacitor and is used to create the inverse current
- The energy absorption path consists of a switch and a varistor

The commutation path has a series resonance. When interruption is required, current oscillation can occur between the nominal and the commutation path at the natural frequency (1/LC). If the amplitude of the oscillating current is larger than that of the input current then zero crossing occurs and the switch can interrupt the current in the nominal path. Current (Io) will continue to flow and will charge the capacitor.

If the capacitor voltage exceeds a given value, which is chosen to be the voltage capability of the circuit breaker, the energy absorption path will act causing the current to decrease.

This is a basic circuit that would need further implementations to be efficient in high voltages. Reduction in cost and better use of the costly components (varistor, capacitor) will be required. Also, the optimum capacitance value would minimize the breaker's interruption time and improve the whole interruption performance. Furthermore, current oscillations grow when the arc resistance (dU/dt) of the switch on the nominal path is negative. Growing oscillations can lead to faster current interruption. At the same time a large C/L ratio can help maximize the breaker's interruption performance.

Solid State Circuit Breakers:

The second type of circuit breaker we will be analyzing is the solid-state circuit breaker. In the following figure we can see that a solid-state circuit breaker uses gate-commuted thyristors instead of integrated gate-commuted thyristors for semiconductor devices, this is due to the fact that in this topology our immediate concern is lowering the on-state losses.

1.5 Modern Trends in DC Transmission

To overcome the losses and faults in AC transmission, HVDC transmission is preferred. The trends which are being introduced are for the effective development to reduce the cost of the converters and to improve the performance of the transmission system.

Power semiconductors and valves:

The IGBTs or GTOs employed required huge amount of current to turn it ON which was a big problem. GTOs are available at 2500V and 2100A. As the disadvantage of GTOs is the large gate current needed to turn them OFF, so MCT which can be switched OFF by a small current is preferred as valves.

The power rating of thyristors is also increased by better cooling methods. Deionized water cooling has now become a standard and results in reduced losses in cooling.

Converter Control:

The development of micro-computer based converter control equipment has made possible to design systems with completely redundant converter control with automatic transfer between systems in the case of a problem.

The micro-computer based control also has the flexibility to implement adaptive control algorithms or even the use of expert systems for fault diagnosis and protection.

DC Breakers:

Parallel rather than series operation of converters is likely as it allows certain flexibility in the planned growth of a system. The DC breaker ratings are not likely to exceed the full load ratings as the control intervention is expected to limit the fault current.

Conversion of existing AC lines:

There are some operational problems due to electromagnetic induction from AC circuits where an experimental project of converting a single circuit of a double circuit is under process.

Operation with weak AC systems:

The strength of AC systems connected to the terminals of a DC link is measured in terms of Short Circuit Ratio (SCR) which is defined as

$$SCR = \frac{\text{Short circuit level at the converter bus}}{\text{Rated DC Power}}$$

If SCR is less than 3, the AC system is said to be weak. The conventional constant extinction angle control may not be suitable for weak AC systems.

Constant reactive current control or AC voltage control may overcome some of the problems of weak AC systems. The power modulation techniques used to improve dynamic stability of power systems will have to be modified in the presence of weak AC systems.

Six Pulse Converters

The conversion from AC to DC and vice-versa is done in HVDC converter stations by using three phase bridge converters. The configuration of the bridge (also called Graetz circuit) is a six pulse converter and the 12 pulse converter is composed of two bridges in series supplied from two different (three-phase) transformers with voltages differing in phase by 30^o.

1.7 Types and applications of MTDC systems

There are two possible types of MTDC systems

(i) Series

(ii) Parallel

The parallel MTDC systems can be further subdivided into the following categories:

(a) Radial

(b) Mesh

Series MTDC System

This is a natural extension of the two terminal system which is a series connected system. A three-terminal MTDC system is shown in Fig. 9.4. This shows a monopolar arrangement; however, a homopolar arrangement with two conductors is also possible. The system is grounded at only one point which may be conveniently chosen. If the line insulation is adequate, the grounding point can be shifted, based on changes in the operating conditions. Grounding capacitors may also be used to improve insulation coordination and system performance during transients.

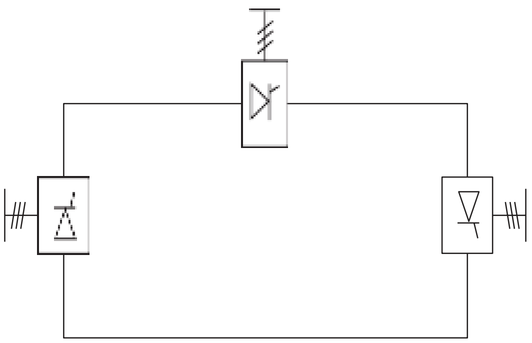

Figure 1.7.1 A series connected MTDC system

[Source: "HVDC Power Transmission Systems" by K.P. Padiyar, page-205]

In a series connected system, the current is set by one converter station and is common for all the stations. The remaining stations operate at constant angle (extinction or delay) or voltage control. In order to minimize the reactive power requirements and the losses in valve damper circuits, the normal operating values of firing angles may be adjusted using tap changer control. At all times, the sum of the voltages across the rectifier stations must be larger than the sum of the voltages across the inverter station. In case of a drop in the voltage at the current controlling rectifier station, the inverter with the larger current reference takes over thecurrent control.

The switching in or out of a bridge is accomplished by deblocking/block and bypass in a manner similar to that in a two terminal system. The clearing of a fault in the DC line is also similar. The power reversal at a station is also done as in a two terminal system, by reversing the DC voltage by converter control.

The power control in a two terminal system is accomplished by adjusting the current while trying to maintain a constant voltage in the system. This is done to minimize the losses. However, in a MTDC series system, central control would be required to adjust the current in response to changing loading conditions. The local control of power would imply adjusting voltage at the converter station using angle and tap controls. Using only one bridge or a 12 pulse unit for the voltage control and operating the remaining bridges at minimum (or maximum) delay angle can reduce the reactive power requirements.

Parallel MTDC System

Here, the operating philosophy of constant voltage AC systems is extended to DC systems. The currents in all the converter stations except one are adjusted according to the power requirement. One of the terminals operates as a voltage setting terminal at constant angle or voltage. An example of 3 terminal radial system is shown below. This shows a monopolar system but bipolar arrangement would be normally used.

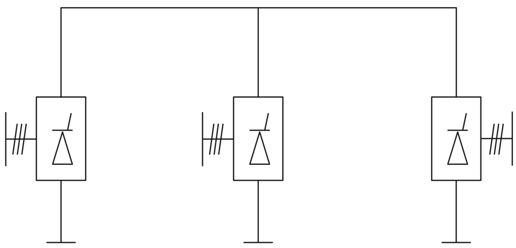

Figure 1.7.2 A parallel connected radial MTDC system

[Source: "HVDC Power Transmission Systems" by K.P. Padiyar, page-206]

A radial system is one in which the disconnection of one segment of transmission would result in interruption of power from one or more converter stations. In a mesh system, the removal of one link would not result in a disruption, provided the remaining links are capable of carrying the required power (with increased losses). Evidently, a mesh system can be more reliable than a radial system. An example of a 4 terminal mesh system is shown in Figure 1.7.3

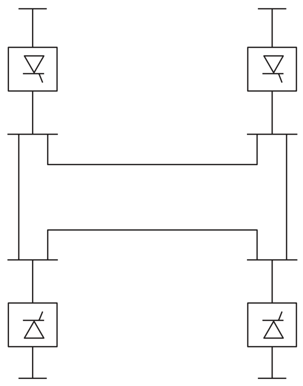

Figure 1.7.3 A parallel connected mesh type MTDC system

[Source: "HVDC Power Transmission Systems" by K.P. Padiyar, page-206]

The power reversal in a parallel MTDC system would involve mechanical switching as the voltage cannot be reversed. Also, loss of a bridge in one converter station would require either the disconnection of a bridge in all the stations or disconnection of the affected station.

Comparison of Series and Parallel MTDC Systems

The advantages and disadvantages of series and parallel MTDC systems are given below:

1. High speed reversal of power is possible in series systems without mechanical switching. This is not possible in parallel systems.
2. The valve voltage rating in a series system is related to the power rating, while the current rating in a parallel connected system is related to power. This would imply that for small power ratings of the tap, series connection may be cheaper even though valves have to be insulated for full voltage to ground. The parallel connection has the advantage of staged development in the converter stations by adding parallel converters as the power requirements increase.
3. There are increased losses in the line and valves in series systems, in comparison to parallel systems. The system operation in series systems can be optimized by

operating the largest inverter at rated voltage.

4. Insulation coordination is a problem in series systems as the voltage along the line varies.
5. The permanent fault in a line section would lead to complete shutdown in a series connected system, while it would lead to only the shutdown of a converter station connected to the line section in a radial MTDC system. With provisions for fast identification and clearing of faults in mesh connected system, there is no disruption of power transfer.
6. The reduction in AC voltages and commutation failures in an inverter can lead to overloading of converters as current is transferred from other terminals in a parallel system. The problem is severe if the rating of the inverter is relatively small. Increased values of smoothing reactor and voltage dependent current limits can reduce the severity. However, the valve ratings would increase, resulting in increased unit costs. A recent study shows that the cost of a 500 MW DC equipment (at ± 500 kV) would be 74% of the cost of a 1000 MW DC equipment. It is concluded that a practical limit to unequal inverter ratings may be 75% : 25%.
7. The control and protection philosophy in a series MTDC system is a natural extension of that in a two terminal system. However, extension to parallel systems is not straightforward. Increased communication requirements and problems in recovery from commutation failures are associated with parallel systems. HVDC breakers of appropriate rating may be required for clearing faults in the DC line or converter stations.

From the relative merits and demerits of series and parallel MTDC systems described above, it may be concluded that series connection is appropriate for taps of rating less than 20% of the major inverter terminal. Parallel connection is more versatile and is expected to be widely used as in AC systems. The first application of a MTDC system is the Sardinia-Corsica-Italy link where an existing link between Sardinia and Italy is tapped at Corsica. This is a 50 MW parallel connected tap with two 100 kV six pulse thyristor bridges connected in series. A series tap was rejected for two reasons (i) the operating current due to frequency control can be as low as 10% of the rated current. This increases the voltage rating of the series tap. (ii) A series tap in inverter operation reduces voltage at the main inverter terminal, requiring increased extinction angles. This is harmful to mercury arc valves as the probability of arc-through increases.

Commutation failure at Corsica can result in overcurrents of 7 p.u. Smoothing reactors of 2.5H are chosen to limit the overcurrents due to disturbances in the AC system.

Quebec-New England link from Radisson in Quebec to Sandy Pond in Massachusetts with a converter at Nicolet became operational in 1992 with two inverters and one rectifier of capacity 2250 MW. While it was planned to integrate an existing two terminal HVDC link (from Des Canton to Comerford) with this system to form a 5 terminal MTDC system, this plan was dropped. Other plans to introduce MTDC system was also shelved. The setback to planning for MTDC was primarily due to the inadequate preparation in the development of control and protection concepts required for reliable system operation.