5. Explain the co-relation between load-frequency control and economic loading of power stations. How are both of these achieved simultaneously ?

6. Fill in the blanks :

1. For economic loading of generating stations, the ... should be equal.
2. The unit of incremental operating cost of generating cost is ....
3. Incremental operating cost for a particular load is given by ... curves.
4. Loss formula coefficient is expressed as

Ch. 49 Covers interconnected power systems.

Ch. 50 Covers further details about SCADA systems used in todays Power System Operation and Control.

47

HVDC Transmission Systems

47.1. INTRODUCTION CHOICE OF HVDC TRANSMISSION

In India, 400 kV a.c. transmission lines have been introduced during 1970's. 4 HVDC transmission links have been executed (1997). By the year 2000, about six HVDC transmission links are expected to be commissioned in India. HVDC transmission systems are selected as an alternative to extra high voltage a.c. transmission systems for any one or more of the following reasons :

1. **For long distance high power transmission lines.**

2. **For interconnection (Tie-lines) between two or more a.c. systems having their own load frequency control.**

3. **For back-to-back asynchronous-tie sub-stations.** Where two a.c. systems are interconnected by a convertor-sub station without any a.c. transmission line in between. Such a tie-link gives an asynchronous interconnection between two a.c. systems.

4. **For underground or submarine-cable transmission over long distance at high voltage.**

At present 40 HVDC links have been installed in the world and by the year 2000, about 55 links are expected with a total transfer capacity of 70,000 MW. *The choice between 400 kV a.c., 765 kV a.c., 1100 kV a.c. and HVDC transmission alternatives is made on the basis of technical and economic studies for each particular line and associated a.c. systems. Alternating current continues to be used for generation, transmission, distribution and utilization of electrical energy.*

47.2. HVDC TRANSMISSION SYSTEMS

47.2.1. Applications of HVDC Transmission Systems

For generation, transmission, distribution, and utilization of electrical energy, 3-phase AC systems are used universally and have a definite superiority over HVDC.

However in following particular applications, High Voltage, Direct Current Transmission (HVDC) is a strong alternative to EHV-AC transmission and HVDC lines are preferred.

— Long distance high power transmission by overhead lines.

— Medium high power submarine or underground cables.

— System interconnection by means of overhead lines, or underground/submarine cables, or back-to-back HVDC coupling stations, or Multi-Terminal DC systems (MTDC).

— Frequency conversion links (*e.g.* 60 Hz/50Hz)

— Incoming lines in mega-cities.

In HVDC link AC power is converted by thyristor-convertor valves at one end. The energy is transmitted in HVDC form to the other end. At the other end, the DC power is inverted to AC and fed into the receiving AC system. Fig. 47.1 illustrates a typical bipolar HVDC link.

A 2-Terminal HVDC transmission system has a HVDC convertor sub-station at each end and an HVDC transmission line in between. In case of back-to-back coupling station, the convertor and invertor are at the same place and there is no HVDC line. Multi-Terminal HVDC interconnects 3 or more AC systems, by HVDC transmission lines.

47.2.2. Choice of HVDC Transmission System

HVDC system are selected as an alternative to extra high voltage, a.c. transmission systems for any one or more of the following reasons : (Table 47.1 gives the summary).

1. **For long distance high power transmission lines** for economic advantage of HVDC with respect to lesser cost of transmission line, and better control of power flow. Though the HVDC link needs additional conversion substation equipment (convertor transformers and convertor etc.) on each side, for long distance high power transmission, the total cost of a d.c. system becomes lower than that of a.c. system. The break-even point is decided by economic studies for each scheme.

The per km cost of one bipolar single circuit HVDC line is lesser than that of an equivalent 3-phase double circuit AC line. Number of conductors for 3 phase AC line is 6 to 24 as against 2 numbers required for an equivalent bipolar HVDC line. HVDC line does not need intermediate sub-station for compensation, whereas for EHV-AC line such a sub-station is required at an interval of 300 km. HVDC becomes favourable above 800 km, 1000 MW when cost of EHV-line/sub-station exceeds that of equivalent HVDC line/sub-station. (Refer Sec. 47.2.8)

2. **For Interconnection (Tie-lines) between two a.c. systems** having their own load frequency control, HVDC links have several advantages over a.c. links. HVDC links form an asynchronous-tie *i.e.*, the two a.c. systems interconnected by HVDC tie-line need not in synchronism with each other.

HVDC interconnection is superior to EHV-AC interconnection in many respects and is selected due to its technical superiority. With HVDC interconnection, power flow can be controlled, the frequency disturbances are not transferred, short-circuit levels remain unchanged at both ends, transient stability of AC network at both end can be significantly improved.

Power flow through the HVDC line can be quickly modulated reversed, changed to dampen the power swing in connected AC Network. Thereby the system stability can be greatly improved.

HVDC interconnection can provide a weak tie (of lesser capacity) between strong and a weak AC Network. This is difficult with AC interconnection.

Most important task of interconnector is to transfer required amount of power in required direction and to assist the interconnected AC Network to maintain transient stability. AC interconnectors have severe limitations. HVDC interconnections are without such limitations.

HVDC system control can be modified to dampen oscillations in load angle δ. Thereby the stability of both AC systems is improved.

3. **For Back-to-back synchronous tie-stations.** Where two a.c. systems are interconnected by a convertor sub-station without any a.c. transmission line inbetween. Such a tie-link gives an asynchronous interconnection between two adjacent AC systems. The back-to-back coupling stations can be located at any suitable location, where to networks meet geographically and exchange of required amount of power is desired.

4. **Multi-terminal HVDC Interconnection.** This is the new HVDC possibility (1987). Three or more AC networks can be interconnected asynchronously by means of a multi-terminal HVDC network. Power flow from each connected AC Network can be controlled suitably. Large powers can be transferred. Overall stability can be improved. At present only one such scheme is under execution (Hydro Quobec Canada to New England USA). More and more multi-terminal HVDC schemes are likely to be executed.

5. **For underground or submarine cable transmission.** Over medium distance at high voltage. The submarine cables are necessary to transfer power across lakes, oceans, etc. In case of AC cables, the temperature rise due to charging currents forms a limit for loading. For each voltage

rating, there is a limit of length beyond which the cable cannot transfer load current due to this limit. In such cases HVDC cables are essential. HVDC cable has no continuous charging current.

Table 47.1. Criterion of Choice of HVDC.

	Type of link	*Criterion of choice*	*Features*
1.	Long high power transmission by overhead line *e.g.* 1000 km ± 400 kV, 1000 MW ± 500 kV, 1500 MW	*Lower Total cost of HVDC Link.* — Less number of line conductors — No need of intermediate sub-stations.	— Normal mode Bipolar. — Two terminal — Can be operated with reduced rating in monopolar mode.
	± 600 kV, 2200 MW	— Simpler and economical tower. — Line cost per km lower. — Higher sub-station cost. — Break-even above about. 800 km., 1000 MW	Line design and construction simpler.
2.	*System Interconnection by*	*Technical Superiority of HVDC Link.*	— Usually two terminal. Recently multiterminal.
	— Overhead line — Underground or submarine cable	— Provides Asynchronous tie. — Power flow can be quickly controlled	— Overhead line simpler ; may be mono-polar or bipolar.
	— Back-to-back station	— Improved stability — Fault levels remain unchanged	— Submarine cable may be monopolar or bipolar.
	— Multi-Terminal HVDC (MTDC)	— Strong AC Network can be connected to weak AC Network. — Frequency conversion possible.	— Coupling stations have no transmission line.
3.	Underground cables or submarine cables *e.g.* ± 100 kV, 500 MW ± 200 kV, 200 MW 5 km to several hundred km.	— *Technical Superiority of HVDC Line.* — No continuous charging current. — No limit of power or distance.	— Two terminal

47.2.3. Types of HVDC systems and brief description

An HVDC transmission system transmits electrical energy from one/or more AC sub-station(s) to another AC sub-station(s) in the form of Direct Current. *A two-terminal HVDC system* transmits electrical energy is direct current form from one AC sub-station to another AC sub-station.

A multi-terminal HVDC system transmits power in direct current form between three or more AC sub-stations.

In *bioplar HVDC transmission system,* the mid-point of convertors at each HVDC convertor sub-station is earthed and earth return path is usually available.

The word Pole refers to the path of direct current which has the same polarity with respect to the earth. The total pole includes sub-station pole and transmission line pole (Refer Fig. 47.18 b)

Types of HVDC systems (Fig. 47.1)

The types of HVDC systems include the following :

— Two terminal system has two terminal substations.

— Multiterminal system has three or more terminals.

— A bipolar HVDC transmission system has two poles, one positive and the other negative with respect to the earth. Mid-point of convertors is earthed. Bipolar system can be operated in monopolar mode.

— A monopolar HVDC transmission system has one pole and earth return.

— A homopolar HVDC transmission system has two poles of same polarity and return earth.

— A back-to-back HVDC coupling system has no DC transmission line. Rectification and inversion is done in the same sub-station by a back-to-back convertor.

An HVDC transmission system has an AC and HVDC terminal sub-stations and inter connecting DC line(s). The type of an HVDC transmission system is identified on the basis of the arrangement of the pole and earth return. Modern HVDC systems have thyristor convertors. A convertor converts AC to DC or DC to AC.

Monopolar HVDC System (Fig. 47.1.-*b*)

This system has only one pole and the return path is provided by permanent earth or sea. The pole generally has negative polarity with respect to the earth.

In monopolar HVDC system the full power and current is transmitted through a line conductor with earth or sea as a return conductor. The earth electrodes are designed for continuous full current operation and for any overload capacity required in the specific case.

The sea or ground return is permanent and of continuous rating.

Monopolar HVDC systems were used only for low power rated links and mainly for cable transmission. In some cases the monopolar systems installed earlier are converted into bipolar systems by adding additional sub-station pole and transmission pole.

The rated currents of the existing three monopolar transmission installations range from 200 to 1000 A. The earth current flows in one direction only in these links. The earth path offers an inexpensive, low resistance, low-loss conductor which effectively contributes to the economy of the system.

Monopolar HVDC transmission system has only the rating equal to half of corresponding bipolar system rating and is, therefore, not economically competitive with EHV-AC scheme. For submarine cables longer than 25 km and having power rating of about 250 MW. For such cables transmission HV-AC is not technically feasible because of high charging currents with AC cables beyond thermal limit. And bipolar cable is not justified for ratings upto about 500 MW. Recent HVDC cable schemes are bipolar.

Homopolar-HVDC System (Fig. 47.1 *c*). In such a system two transmission poles are of the same polarity and the return is through permanent earth. Such a scheme may be used for the following :

— Two homopolar overhead lines feeding to a common monopolar cable termination.

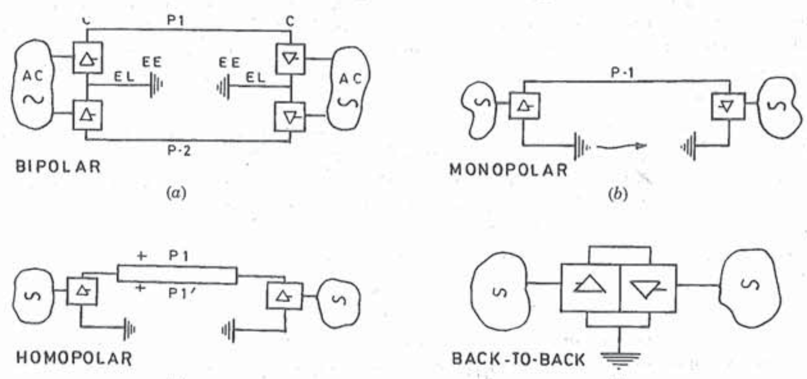


Fig. 47.1. Type of HVDC systems.

— One overhead transmission tower carrying insulator strings supporting two homopolar transmission line conductors.

Applications of homopolar transmission are limited and are not discussed further.

Bipolar HVDC Transmission. (Fig. 47.1 *a*). This is most widely used for overhead long distance HVDC systems and also for Multi-Terminal HVDC systems (MTDC).

The HVDC sub-station and HVDC line has two poles, one positive and the other negative with respect to earth. The midpoints of convertors at each terminal station are earthed *via* electrode line and earth electrode. Power rating of one pole is about half of bipole power rating.

The earth carries only a small out-of-balance current during the normal operations.

During fault or trouble on one of the poles, the bipolar HVDC system is switched over automatically to monopolar mode. Thereby, the service continuity is maintained. After taking corrective action, the system is switched over to normal bipolar operation.

A bipolar HVDC line has two conductors, one of positive polarity with respect to the earthed tower structure and the other of negative polarity. The voltage between poles is twice that of the pole to earth voltage. Therefore, a bipole HVDC system is described as say ± 500 kV.

The normal bipolar HVDC system is composed of two separate monopolar system with a common earth. The two poles can operate independently. Normally they operate with equal currents and, therefore, there is no ground current. In the event of a fault on one of the poles, the other pole can carry upto half of bipolar power.

Earth Electrodes in a Bipolar System. The mid-point of convertors (Called neutral point or the joint) in each station is earthed with a suitable switching arrangement. This earthing is independent of the station earthing. This electrode earthing is through electrode installed 5 to 20 km from the HVDC sub-station. The mid-point of convertor is connected to earth electrode *via* electrode line. The definitions are as follows :

— **Earth electrode.** An array of conducting elements placed in the earth or sea which provide a low resistance path between the DC circuit and the earth and which is capable of carrying continuous current for some extended period.

— **Earth electrode line.** An insulated line between the HVDC sub-station and the earth electrode.

— **Station earth.** An array of conducting elements placed in earth at the sub-station location and which provides connection between the earthed parts of sub-station equipment and the earth.

The earth electrode is installed away from the sub-station earth to avoid the *galvanic corrosion* of the sub-station earthing system, underground pipes, buried cables and structures.

Electrode line is either a cable or an overhead line.

Table 47.2. Examples of Bipolar HVDC Systems

Year	*1987*	*1990*
Name	*Itaipu Brazil*	*Rihand-Delhi India*
Configuration	Two Bipole circuits	Single Bipole Circuit
Power	2×6000 MW	1500 MW
Direct bipole Voltage, each circuit	± 600 kV	± 500 kV
Voltage, pole to pole, DC	1200 kV	1000 kV
No. of convertors/station	2×2	2
Transmission	Overhead	Overhead
Main reason for HVDC	High Power Long distance, Frequency conversion 60/50 Hz.	Long distance, High power.

A bipolar HVDC line has only two line conductors. One called positive pole line conductor and the other is called negative pole line conductor. Earth electrode and electrode line. Besides line conductors, an HVDC transmission system needs *earth electrodes and electrode lines.* The earth electrode is located at a distance of a few tens of km from the HVDC sub-station. The connection between the mid-point or earthed end of the convertor valve and the earth electrode is *via* the electrode line. The electrode line is insulated from the earth. Earth electrode is located away from main sub-station earth to avoid galvanic corrosion of the sub-station earth.

Rectification and Inversion. In an HVDC transmission system or HVDC back-to-back coupling station, alternating current is converted into direct current by means of a combination of convertor-transformers and convertor valves. The conversion from AC to DC is called Rectification or Rectifier operation.

The transmission is in the form of direct current. In bipolar line, there will be two line poles. The earth return carriers negligible current. In monopolar line, the direct current flows through one pole line and return through earth.

At the receiving end of the HVDC transmission line, the direct current is converted to alternating current alternating current by means of convertor valves and convertor transformers. The conversion of DC into AC is called inversion (or inverter operation).

Essential Parts of HVDC Systems. An HVDC transmission system has the following essential parts :

— AC sub-station and HVDC sub-station at each terminal.

— Interconnecting HVDC line(s).

— Electrode lines and earth electrodes.

A two terminal HVDC transmission system has only two terminal sub-stations and two earth electrodes.

A multi-terminal HVDC transmission system has three or more terminal sub-stations and equal number of earth electrodes, all located at different locations.

The HVDC terminal sub-station has following main parts :

— AC Switchyard.

— Convertor Transformers.

— AC Harmonic Filters.

— Valve Hall and Control Building.

— Smoothing Reactors.

— HVDC Yard.

— Electrical and Mechanical Auxiliaries.

Sec. 47.2 (*a*), (*b*) gives details about layout of a bipolar HVDC sub-station.

Table 47.3. Typical Rating and Main Specifications of Bipolar HVDC Transmission System

Operating voltage of A.C. yard	400 kV A.C.
Operating voltage of D.C. yard	± 500 kV D.C.
Rated Power of D.C. line	1500 MW
Number of Converter Transformers : each 300 MVA : 3 winding 1 Phase	6, (each terminal)
Number of quadruple valves	6, (each terminal)
Minimum clearance, phase-to-phase on 400 kV A.C. side	5.75 m
Minimum clearance phase-to-ground on 400 kV A.C. side	3.65 m
Minimum phase-to-phase clearance on 500 kV D.C. side	12 m
Minimum phase-to-ground clearance on 500 kV D.C. side	7 m
Size of Busbars in D.C. yard	10″ IPS
Size of Busbars in A.C. yard	4″ IPS
Type of HVDC transmission	Bipolar
Transmission line voltage	± 500 kV
Transmission line length	1000 km
Power rating of transmission line	1500 MW
Total MVAr of AC Filters	2000 MVAr
Number of PLCC Repeater Stations	2

* One such sub-station at each end of the 1000 km, 1500 MW HVDC transmission line. IPS-International Pipe Standard.

47.2.4. Long Distance, High Power Bipolar HVDC Transmission Systems

Large hydroelectric power stations with low generating costs are generally located far away from load centres. Large thermal power stations are generally built near coal mines. Long distance bulk power transmission lines are required to transfer power from such remote power stations to distant load centres located in industrial towns and megacities.

By HVDC, bulk power of any magnitude can be brought to load centres over distances upto 1000 km, or more, simply and efficiently by using a single bipolar link without any intermediate sub-station or parallel line.

Long distance HVDC transmission between individually controlled power systems allows daily and seasonal balancing of peak load requirements.

Thermal power plants, conventional or nuclear can be grouped in 'energy parks' for away from the load centres and thereby the environment can be preserved.

47.2.5. Power rating of long bipole HVDC transmission system

Power rating of bipolar HVDC line P_{dc} is given by

$$P_{dc} = V_{dc} I_{dc} \dots \text{MW}$$

V_{dc} = D.C. voltage, kV between pole-lines

$= 2 \times (\pm$ Rated Bipole Voltage).

I_{dc} = Current in conductors, kA

P_{dc} = Power transfer through line, MW

I_{dc} is decided by normal current rating of thyristor valve. Valves range between 0.5 KA and 4 KA; V_{dc} is decided by rated voltage of a convertor pole. Values of V_{dc} range between 500 kV for ± 250 kV and 1200 kV for ± 600 kV bipolar HVDC links. By appropriate choice of voltage and current combination, the required power rating of the HVDC link is obtained. Table 47.2 gives typical ratings of present HVDC Bipolar links for long distance lines.

Table 47.4. Power transferability of bipolar HVDC line

Rated Bipolar Voltage kV	± 400	± 450	± 500	± 600
Voltage between pole conductors kV	800	900	1000	1200
Power per circuit, MW (Bipolar)	1440	1620	1800	2160

Note. Basic for the above table : $I_{dc} = 1.8$ kA.

$$P_{dc} = V_{dc} \times I_{dc} \dots \text{MW}$$

V_{dc} = Voltage between pole conductors kV

I_{dc} = Line current, kA (assumed 1.8 kA)

47.2.6. Configuration and description of a Bipolar Scheme

Modern HVDC links are as a rule, bipolar. A bipolar link has two poles. The convertors valves at each terminals are connected in series. The mid-point at each end is grounded. Convertors act for conversion from A.C. to D.C. or from D.C. to A.C. (Rectification and Inversion).

During bipolar operation one pole acts positive and the other pole negative. Only a negligible out of balance current flows through ground path. During fault on any one pole, the power transfer can be continued as a mono-polar operation with ground return. Thus the bipolar d.c. Line is more reliable than a three phase a.c. Line. Three phase line cannot be operated with one phase open for more than one second due to unbalance and disturbance in communication circuits.

Fig. 47.2 (*a*) and (*b*) illustrates the configurations of a HVDC transmission system connected between two AC networks.

Transmission link has the following parts :

— Terminal sub-station at each end.

— Electrode lines and earth electrodes.

— HVDC transmission line poles (one positive and other negative)

Following parts are indicated in Fig. 47.2.(*a*)

E — Electrode for earthing mid-points of convertors.

EL — Electrode lines (5 to 20 km length each) to connect mid-points of convertor to the earth electrode *EL*

F — Filters for AC harmonics.

R — Smoothing reactor (DC)

T — Convertor Transformer

V — Convertor valves. These are installed in Valve Halls.

SC — Shunt Capacitors.

The AC sub-station is generally an EHV-AC sub-station with usual AC switchgear, busbars, CTs, VTs etc. One and a half breaker arrangement is preferred. Surge Arresters in AC yard are co-ordinated with surge arresters in DC yard, valve hall and neighbouring AC yards in the network. More details about the layout have been covered in sec. 47.7 and Fig. 47.18 (*a*) and (*b*).

Convertor transformer. (*T*) are connected between convertor valves (*V*) and the AC bus (*B*). These are specially designed as they have a d.c. voltage component coming from valve side. They are either single phase units, or three phase units with either two winding type of three winding type. *Valves* (*V*) are made-up of series connected thyristors. Valves are connected in bridge formation. Valves transfer power from AC to DC or *vice versa*. Valves are usually water cooled. *Smoothing Reactor* (*R*)

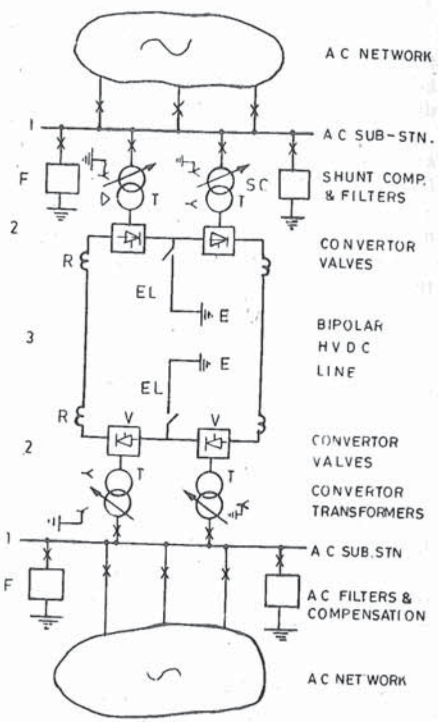
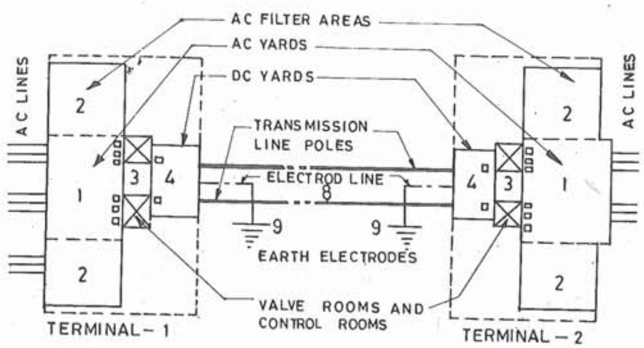


Fig. 47.2 (*a*) Configuration of a Bipolar HVDC system.



1. AC yards 2. AC filter areas 3. Valve hall and control room 4. DC yards
8. Electrode line 9. Earth electrode.

Fig. 47.2 (*b*) Layout of a Bipolar HVDC system and terminal sub-station.

is necessary for convertor operation and for smoothing the DC current smoothing reactor is generally oil cooled.

Electrode line (EL) connects the mid-point of convertors with a distant earth electrode (*E*). The earth electrode is located to 5 to 20 km away from HDVC sub-station so as to prevent galvanic corrosion of station earth-mat.

Operation of thyristor convertor valves (*V*) results in generation of AC harmonics. AC filters (*F*) are connected to the AC bus bars at each end. DC filters are connected between pole bus and neutral bus in DC yard.

AC Harmonic Filters (F) cover a large are near AC yard. These filters are composed of resistor banks, reactors, capacitor banks. They eliminate the AC harmonics arising out of the convertor operation.

Shunt Compensation is provided by shunt capacitors. This is for supplying reactive power needed for convertor operation.

47.2.7. Economic Comparison of Bipolar HDVC Transmission System with EHV-AC System (Fig. 47.3)

The total capital cost of a transmission system is equal to the sum of capital cost of sub-station plus capital cost of the lines. The cost also includes cost of land, buildings, PLCC system, etc.

Capital cost of sub-stations is higher in case of HDVC. Line cost is variable and per km line cost of HVDC line is lesser than AC line.

Total capital cost of transmission system.

$$= \begin{bmatrix} \text{Cost of} \\ \text{sub-stations} \end{bmatrix} + \begin{bmatrix} \text{cost of} \\ \text{line} \end{bmatrix}$$

$$= \begin{bmatrix} \text{Cost of} \\ \text{sub-stations} \end{bmatrix} + \begin{bmatrix} \text{Per km.} \\ \text{cost of line} \end{bmatrix} \times \begin{bmatrix} \text{Length of} \\ \text{line km.} \end{bmatrix}$$

Below certain length of line (800 km) the total capital cost of HVDC link is more than AC link and HVDC link is not preferred due to economical disadvantage (except for interconnections).

The cost of a DC transmission line per km is considerably less than that of equivalent AC line. The DC circuit requires *only two conductors* as against minimum six for a double circuit 3-phase AC line*. A bipolar HVDC line with facility of the convertor mid-point earthing can carry the same power and gives the same reliability as a double circuit 3-phase AC line. The corridor width of HVDC line is only half of that of an equivalent AC line. The cost of tower, insulators and conductors of HVDC line is lesser than that of an equivalent AC line.

The HVDC bipolar line tower is simpler, easy to install and cheaper than EHV-AC tower. Land cost is less due to narrow Right-of-way.

HVDC bipolar line needs only two line conductors. For a equivalent 3-phase EHV-AC lines, the number of line conductors would be 6, 12, 18, 24. For longer lengths the number increases. Against one bipolar HVDC line, two or four 3-phase AC lines are required for long high power transfer.

EHV-AC lines need intermediate sub-stations at an interval of 300 km. HVDC line does not need any intermediate sub-station.

As against the above, HVDC transmission systems need additional convertor sub-stations at each end having convertor transformers, valves, controls, auxiliaries, filters etc. The cost of conversion sub-stations is extra.

HVDC has a clear cut economical advantage over AC line soon as the benefit of lower line cost is more than the higher sub-station cost. In other words, when the transmission distance is beyond the break-even point, HVDC is more economical than equivalent EHV-AC. This advantage becomes still more pronounced with very long distance (above 800 km) for which EHV-AC transmission system requires intermediate switching stations as well as intermediate shunt or series compensation.

* 3-phase AC line requires a double circuit for each transmission path. Thus it requires minimum six conductors per route.

Fig. 47.3 explains the concept of the break-even distance. The break-even distance is different for each project due to variations in local conditions and cost of imported equipment. The choice of AC or DC is based on technical and economical studies for particular project.

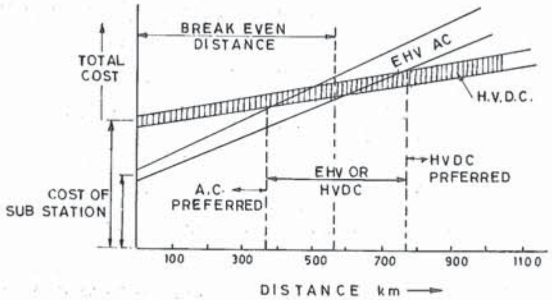


Fig. 47.3. Concept of break-even distance.

[HVDC becomes economically viable only above certain distance and power. This varies with each project].

47.2.8. EHV-AC Versus HVDC.

Table 47.5 gives summary of comparison between EHV-AC and HVDC for long distance high power transmission lines. For point-to-point transmission HVDC is preferred. For multi-terminal mesh network and for intermediate tap-off sub-stations etc. EVH-AC is preferred.

Table 47.5. Comparison of Long Distance Overhead Transmission Systems

Characteristics	*HVDC Link*	*EHV-AC Link*	*Remarks*
1. Capital Cost	— Line cost lower — Sub-station cost higher — Number of circuit one — Intermediate sub-station not required	— Line cost higher — Sub-station cost lower — Number of circuits more conductors more — Intermediate substation required.	HVDC lines becomes economically above 800 MW choice based on economics.
2. Power Transfer	— No limit due to power single — No limit due to X_L.	— Limit imposed by power angle and inductance and X_L	Single HVDC link adequate upto 3000 MW.
3. Voltage Control	— Easier as reactance is not effective	— Difficult for long lines due to shunt capacitance and series reactance. — Compensation of lines is necessary	For very long lines, single HVDC links without intermediate sub-stations.
4. Stability Limit	— No limit imposed by line reactance on power angle. — Power flow can be quickly controlled	— Limit imposed by power angle and reactance X_L	HVDC line can be loaded upto the thermal limit of equipments.
5. Corona and Radio Interference	— DC voltage does not have $\sqrt{2}$ factor for r.m.s. to peak. — Corona losses and radio interference less for same conductor to ground water voltage	— AC voltage has factor $\sqrt{2}$ for r.m.s. to peak.	

Characteristics	*HVDC Link*	*EHV-AC Link*	*Remarks*
6. Skin effect	— Absent because of zero *f*.	— Present	
7. Earth return	— Possible	— Not possible	Only single bipolar HVDC line adequate for most cases.
8. Reliability and availability	— One bipolar line sufficient	Two AC circuit necessary	
9. Line losses	Low (See 12)	Higher (See 12)	HVDC station has sub-station losses.
10. Control system	Difficult, Costly Fast, Accurate control	Simpler, Cheaper limitations of control	For interconnections, HVDC provides advantages due to superior control.
11. Stability of AC Networks	Much higher. HVDC system control is modified to dampen swings in load angle.	Very low. The line reactance X_L brings down power transfer ability.	AC line loaded upto fifty per cent of its thermal rating. DC line upto 90 per cent.
12. Reactive Power flow	— Absent through transmission line	— Flows through the transmission line	AC line has higher line losses due to flow of reactive power
13. Power flow control	— Very rapid (30 MW/min)	— Very slow and difficult	HVDC preferred for tie lines

47.2.9. HVDC Cable Transmission.

High voltage, high power cables are used in the following applications :

1. Underground transmission from a distant sub-station to an indoor sub-station feeding a large city or from a hydro plant to open outdoor sub-station.

2. Underwater transmission through a cable laid on sea-bed or through a lake. Such submarine cables may be for tie-up between two national grids separated by an ocean or between an off-shore gas-turbine generating station and an on-shore sub-station.

The EHV-AC cables take continuous alternating charging currents. These currents become significant for longer lengths of cables and result in dielectric heating. Thereby the thermal limit is reached even without loading the cables. Hence power transferability of long AC cables is very low. The length of AC power cables is, therefore, limited by charging currents and temperature rise.

HVDC submarine cables do not take continuous charging currents. Hence the power transfer is not limited by the thermal effects of the charging currents. Due to lesser temperature rise, higher dielectric stresses are permitted. Hence HVDC cables are more compact and of lesser cost.

Monopolar HVDC links with sea-return are economical. There is no limit on length. Steady charging current of three-phase AC cables are as follows :

Charging kVA for AC cables (continuous)

132 kV	1250 kVA/circuit/km
220 kV	3125 kVA/circuit/km
400 kV	9375 kVA/circuit/km

Due to the above, the a.c. cables have limiting length beyond which shunt compensation would be necessary. These lengths are as follows :

Limiting length of a.c. cables without intermediate shunt compensation.

132 kV	50 km
220 kV	40 km
400 kV	45 km

AC cables can be loaded only upto 0.3 Pn, where Pn is the Natural loading of the cable.

47.2.10. HVDC System Interconnection

By HVDC link, it is possible to interconnect two individually controlled AC systems which operate at different prevailing frequencies. Even AC systems having different rated frequencies can be interconnected by an HVDC interconnection. HVDC interconnection is an asynchronous tie. The exchange of power can be controlled precisely and rapidly.

The AC systems interconnected by HVDC asynchronous tie remain individually controlled despite their interconnection with each other. Each can thus be operated independently from their individual load control centre using their own control principle.

The HVDC interconnecting line may have any length from zero (back-to-back) to several hundred to a few thousand km.

Back-to-back HVDC conversion sub-station (HVDC coupling system) interconnect two AC systems meeting in a common geographical area. Such sub-stations do not have a transmission line. The convertors are connected back-to-back in a common coupling sub-station connecting two AC systems.

Merits of HVDC Systems Interconnection

1. **Stable weak tie between large AC systems.** The linking of large AC systems by means of low-rated AC ties can pose difficulty in controlling the power flow. Even minor events causing a slight change in frequency on one of the AC systems may cause the link to carry power which may easily exceed the permitted limit. As a result, the link gets tripped by tie overload protection of transmission line.

The HVDC link on the other hand, acts as a buffer between the AC systems. It, therefore, prevents fluctuations in one AC system from affecting the other AC system and the transfer of power remains steady at the presecribed set level.

2. **Improved Stability.** The amount of power transferred by an HVDC link, and its direction, can be controlled reliability and rapidly. By introducing control parameters from the AC network (*e.g.* frequency deviations or phase angle of a parallel system etc.) it is possible to improve the stability of the network as a whole, or of adjacent transmission lines. Disturbance in one AC Network is quickly damped by modulating the power flow through the HVDC interconnection.

3. **Limiting the Short-Circuit levels.** The increased generating capacity results in higher short-circuit levels in various sub-station buses and each sub-station equipment should be made suitable for the required fault level. The fault levels in large AC networks having AC interconnection tend to become extremely high resulting in uneconomical equipment design. With HVDC interconnection, the fault levels of each AC Network remain unchanged.

Table 47.6 compares the HVDC and EHV-AC for system interconnection purpuse.

4. Control of direction and magnitude of power flow. HVDC interconnection can given fast, accurate control of power flow magnitude and direction.

Table 47.6. Comparison of Characteristics for Systems Interconnections

	Characteristic	*HVDC Link*	*EHV-AC Link*	*Criterion for Preference*
1.	Power transferability	High practical limit	Lower, limited by power angle and *X*.	HVDC link for higher power
2.	Control of power flow	Fast, accurate, by directional.	Slow, difficult, Direction dependent on frequency	HVDC preferred
3.	Frequency disturbance	Reduced due to asynchronous tie	Transferred from one AC system to other	HVDC preferred
4.	System support	Excellent, power flow through line quickly modulated for damping oscillation	Poor oscillations continue for long duration	HVDC preferred
5.	Transient performance	Excellent	Poor	HVDC preferred
6.	Fault levels	Remain unchanged after interconnection	Get added after interconnetion	HVDC preferred
7.	Power swings	Damped quickly	Continue for long time	HVDC preferred
8.	Submarine cable	No charging currents, high ratings possible	Charging current set a limit on length and power	HVDC preferred
9.	Interconnection	Asynchronous	Synchronous	HVDC preferred
10.	Cascade Tripping of AC systems	Avoided	Likely	HVDC preferred
11.	Frequency conversion (50 to 60 Hz)	Possible	Not possible	HVDC preferred
12.	Back-to-back conversion stations	Possible	Not possible	HVDC preferred
13.	Spinning Reserves of AC Network	Reduced	Not much reduced	HVDC preferred
14.	Transient stability limit	Very high upto thermal limit of equipment	Less than half of thermal limit of line conductors	HVDC preferred

HVDC links technically superior to AC links and are preferred for interconnection between two individually controlled AC systems. HVDC System Control can be modified for (1) Damping of Power Swings (2) Frequency Control of Small Network by larger network.

47.2.11. HVDC Coupling System (Fig. 47.4)

(Back-to-back HVDC Convertor Station)

HVDC coupling system is used for interconnection between two geographically adjacent AC networks for the purpose of frequency conversion or for an asynchronous interconnection. The direction of power flow and amount of flow through the coupling system can be controlled in magnitude and direction irrespective of the conditions in the connected AC networks. A strong AC network can be interconnected to a weak network by back-to-back interconnection.

The back-to-back HVDC schemes are rated about 500 MW. The DC voltage and DC current of thyristors can be suitably selected for economical valve design *e.g.* a 400 MW back-to-back station can have DC voltage 400 kV and current 1000 A.

The configuration of a back-to-back HVDC coupling system is illustrated in Fig. 47.4. The two AC networks are coupled by a back-to-back convertor. The rectifier and inverter are connected to form a DC loop. There is no DC transmission line. A DC smoothing reactor is connected in the DC loop.

Back-to-back coupling stations are generally designed for Bipolar operation only and the return earth is, therefore, not provided. In such cases, the main DC loop is earthed at a single point between the rectifier and the inverter to provide a reference earth on DC side.

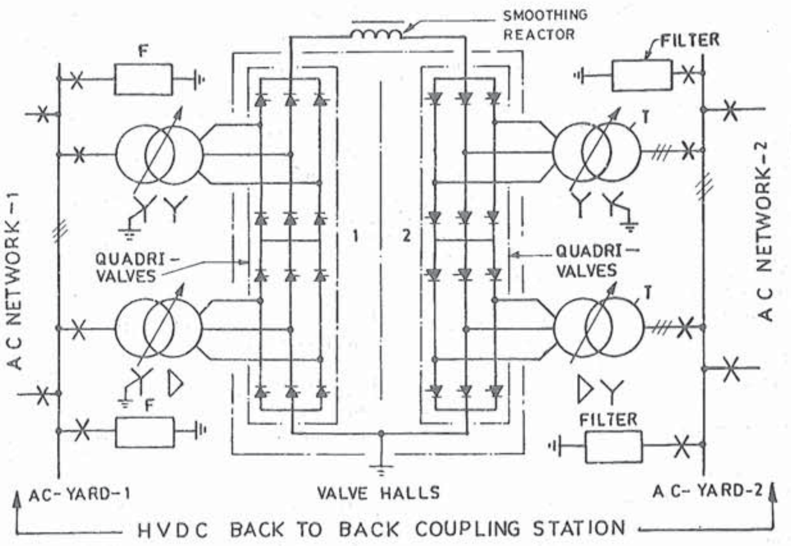


Fig. 47.4. HVDC Back-to-back coupling station.

As the earthing is only for reference, it does carry any direct current and there are no problems of galvanic corrosion of sub-station earth and underground pipes, structures etc.

47.2.12. EHV-AC Versus HVDC Transmission

The various aspects are summarised here.

1. **For Backbone Network.** EHV-AC is superior for forming the mesh. Voltage can be easily stepped up, stepped down. The network has natural tendency to maintain synchronism. Load-frequency control is easy and simple. Network can be tapped at intermediate points to feed underlying submission network.

2. **Bulk power load distance transmission lines.** HVDC proves economical above breakeven distance. Number of lines are less for HVDC. No need of intermediate sub-stations for compensation.

3. **Stability of Transmission System.** HVDC gives asynchronous tie and transient stability does not pose any limit. Line can be loaded upto thermal limit of the line or valves (whichever in lower).

4. **Line Loading.** The permissible loading of an EHV-AC line is limited by transient stability limit and line reactance to almost one-third of thermal rating of conductors. No such limit exists in case of HVDC lines.

5. **Surge Impedance Loading.** Long EHV-AC lines are loaded to less than 0.8 Pn. No such condition is imposed on HVDC line.

6. **Voltage along the line.** Long EHV lines have varying voltage along the line due to absorption of reactive power. This voltage fluctuates with load. Such a problem does not arise in HVDC line. EHV-AC line remains loaded below its thermal limit due to the transient stability limit. Conductors are not utilized fully.

7. **Number of lines.** EHV-AC needs at least two three-phase lines and generally more for higher power. HVDC needs only one bipole line for majority of applications.

8. **Intermediate Sub-stations.** EHV-AC transmission needs intermediate sub-station at an interval of 300 km for compensation. HVDC line does not need intermediate compensating sub-station.

9. **Asynchronous Tie.** System having different prevailing frequencies or different rated frequencies can be interconnected. HVDC link provides asychronous tie. Frequency disturbance does not get transferred, large black-outs are avoided.

10. **Better Control.** Power flow through HVDC tie line can be controlled more rapidly and accurately than that of EHV-AC interconnector.

11. **Corona Loss and Radio Interference.** For the same power transfer and same distance, the corona losses and radio interference of DC system is less than that of AC systems, as the required DC insulation level is lower than corresponding AC insulation.

12. **Skin Effect.** This is absent in d.c. current. Hence current density is uniformly distributed in the cross-section of the conductor.

13. **Charging Current.** Continuous line charging currents are absent in HVDC lines.

14. **Tower Size.** The phase-to-phase clearances, phase to ground clearances and tower size is smaller for DC transmission as compared to equivalent AC transmission for same power and distance. Tower is simpler, easy to installed and cheaper due to absence of central window.

15. **Number of Conductors.** Bipolar HVDC transmission lines require two-pole conductors (instead of several three-phase conductors as in case of AC) to carry DC power. Hence HVDC transmission becomes economical over AC transmission at long distance when the saving in overall conductors cost, losses, towers etc. compensates the additional cost of the terminal apparatus such as rectifiers and convertors.

16. **Earth Return.** HVDC transmission can utilize earth return and, therefore, does not need a double circuit. EHV-AC always needs a double circuit.

17. **Reactive Power Compensation.** HVDC line does not need intermediate reactive power compensation like EHV-AC line.

18. **Flexibility of Operation.** Line may be operated in a monopolar mode by earth as a return path when the other pole develops a permanent fault.

19. **Superior Control.** HVDC system control can be modified for (1) frequency control of AC networks (2) Damping control for improved stability of AC networks.

20. **Short-Circuit Level.** In AC transmission, additional parallel line result in higher fault level at receiving end due to reduced equivalent reactance. When an existing AC system is interconnected with another AC system by AC transmission line, the fault level of both the system increases.

However, when both are interconnected by a D.C. transmission, the fault level of each system remains unchanged.

21. **Rapid Power Transfer.** The control of converter valves permit rapid changes in magnitude and direction of power flow. This increases the limits of transient stability.

22. **Cables.** DC transmission can be through underground or marine cables since charging currents are taken only while energizing the d.c. link and are not effective later. In a.c. systems there is limit on length of cable depending upon rated voltage.

This limit is about 60 km for 145 kV, 40 km for 245 kV and 25 km for 400 kV AC cables.

23. **Voltage Regulation.** In HVDC systems, the line can be operated with constant current regulation or constant voltage regulation by suitable adaptation of phase control of rectifiers and inverters.

24. **Lower Transmission Losses.** Line losses are lesser than equivalent AC transmission losses as the reactive power does not flow through D.C. line.

47.2.13. Limitations of HVDC Transmission

— High cost of terminal apparatus such as a.c. to d.c. rectifiers and d.c. to a.c. inverters, AC and DC filters, controls etc.

— Lack of HVDC circuit-breakers (at present). This limitation has been recently overcome by development of HVDC circuit-breaker system. However HVDC circuit-breaker system comprises several components including the main circuit-breaker, capacitors, reactors etc. and the total cost is likely to be several time that of an a.c. circuit-breaker of equivalent voltage class.

— D.C. voltage cannot be transformed easily. Here it is not used for distribution, sub-transmission, backbone transmission, mesh.

— Complexity and dependance of high technology.

— Several abnormal operating conditions and consequent failures.

The operation of inverter (d.c. to a.c.) requires reactive power at leading power factor. The reactive power can be as high as 50% of real power, *i.e.*, $\frac{\text{kVAR}}{\text{kW}} = 0.5$.

— Thyristor valves are complex and the controls are extremely complex. EHV-AC line has only simple protective systems. EHV-AC lines are, therefore, easy to execute and operate.

— HVDC sub-station has several additional equipment like converter transformers, valves, electrical and mechanical auxiliaries, valve control, pole control etc. Most of these equipment are of specialised high technology class and are imported at high cost.

— HVDC convertor require complex cooling systems.

— HVDC convertor stations require larger number of harmonic filters.

— HVDC is not very suitable for multipoint, multi-terminal networks.

— Losses of valves and convertor transformers are extra in case of HVDC substation. These are continuous and, therefore, nullify lesser line losses of HVDC line.

47.2.14. Terms and Definitions regarding HVDC

1. **HVDC.** High voltage direct current (system) HVDC sub-station and HVDC systems.

2. **HVDC System.** An electrical power system which transfers energy in the form of high-voltage direct current between two or more alternating current buses.

3. **HVDC Transmission system.** An HVDC system which transfers energy in the form of high voltage direct current from one geographical location to the other.

4. **Two terminal HVDC system.** An HVDC transmission system consisting of two transmission sub-stations and connecting transmission line.

5. **Multiterminal HVDC System.** An HVDC transmission system consisting of more than two transmission sub-stations and interconnecting DC transmission lines.

6. **HVDC Coupling system.** An HVDC system which transfers energy between AC buses at the same location. Such a system is generally called as back-to-back HVDC sub-station.

7. **HVDC transmission line.** A part of HVDC transmission system consisting of overhead lines and or underground cables connected to HVDC transmission sub-stations at terminals.

8. **HVDC sub-stations.** A part of an HVDC system which consists of one or more convertor units installed in a single location together with building reactors, filters, reactive power supply control, monitoring, protective measuring and auxiliary equipment.

9. **HVDC system Pole** (abbreviated to 'pole'). A part of an HVDC system consisting of all the equipment in the HVDC sub-station and interconnecting transmission lines (if any) which, during normal operating condition exhibit a common direct polarity with respect to earth.

10. **Sub-station pole.** The part of an HVDC system pole which is connected within a sub-station.

11. **HVDC transmission pole.** A part of an HVDC transmission link which belongs to the same HVDC system pole.

12. **Monopolar HVDC system (Unipolar).** An HVDC system having only one pole and earth return.

13. **Bipolar HVDC system.** An HVDC system with two poles of opposite polarity.

14. **Conversion (in HVDC system).** Transfer of electrical energy from AC to DC or/and *vice versa.*

15. **Converter Unit.** An operative unit comprising one or more converter bridges together with one or more convertor transformers, convertor unit control equipment, essential protective and switching devices and auxiliaries if any for conversion of energy from AC form to DC form or/and *vice versa.*

Note. If a convertor unit comprises two converter bridges with a phase displacement of 30°, then the convertor unit is called a 12 pulse unit.

16. **Valve.** A complete operative controllable array (which has a combination of thyristors and other associated devices) normally conducting only in one direction which may function as a convertor arm or a part thereof in a converter connection.

17. **Rectifier operation** (Rectification). The mode of operation of a converter or a convertor sub-station when the energy is transferred from AC side to DC side.

18. **Inverter operation.** The mode of operation of a converter or a converter sub-station when energy is transferred from DC side to AC side.

19. **Delay Angle** α. The time expressed in electrical degrees from the starting instant of forward current conduction to the zero crossing of communicating voltage.

20. **Extinction Angle** β. The time expressed in electrical degrees from the end of current conduction to the zero crossing of commutating voltage.

CONTROL OF HVDC SYSTEM

47.3. CONTROL OF HVDC LINK

47.3.1. Steady-state Ud/Id characteristic of converters.

The steady state characteristic of a converter for HVDC system is plotted on rectangular co-ordinates with direct current *Id* on *X*-axis and direct voltage *Ud* on *Y*-axis. The *Ud/Id* characteristic of rectifier and inverter are similar but not identical.

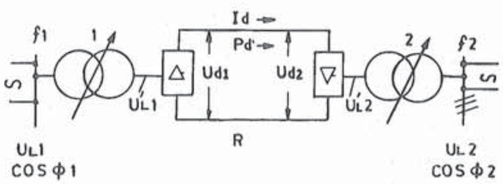
They are similar because it should be possible to interchange the operation of rectifier to inverter and *vice-versa* for achieving reversal power.

They should have difference in voltage level and current level because they should *intersect at a point* (say A) for giving a stable point of operation with definite value of direct current *Id* common to rectifier and inverter (forming a series circuit on DC side). The stable point *A* should lie on the *Ud/Id* characteristics of the rectifier as well as that of the inverter.

Fig. 47.5 illustrates a typical steady-state *Ud/Id* characteristic of a converter (either inverter or rectifier) for an HVDC link. The dark lines give idealized characteristic having two segments.

Let *Ud* = DC Voltage
Id = Direct Current
Ud = AC Voltage
Pd = Direct Power
R = Line Resistance

Subscript 1 for rectifier, 2 for inverter.



1. Horizontal segment *RS* representing constant value of *Ud* as obtained by natural characteristic of a converter.

2. Vertical segment ST representing a constant value of current Id as obtained by constant current controller fitted to the converter control system.

Operating point (say A) should lie on the vertical segment ST so that same current Id flows through rectifier and the inverter.

Actual characteristics has a certain slope and is shown by the dashed segments in Fig. 47.5.

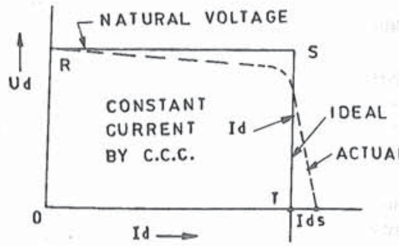


Fig. 47.6. Ud/Id steady state characteristic of a converter

Control functions are so arranged as to shift horizontal segments RS for voltage change and shift the vertical segment ST for current change.

If inverter voltage is changed, the rectifier voltage should also be appropriately changed to satisfy the equation.

$$Ud_1 = Ud_2 + Id \cdot R$$

For shifting the horizontal segment RS upwards or downwards, following means are available :

— Tap changer on line side of converter transfer. By changing the tap position, the turns ratio is changed. Thereby valve side voltage is changed, thereby DC voltage is changed (slow change).

— Change of delay angle α of the convertor (Rapid change).

For shifting the vertical segment ST the setting of constant current controller fitted with the control system of the converter is changed. However since the operating point A is on constant current segment, the direct current will be adjusted to a new valve A with at constant current control of point A. Fig. 47.6.

47.3.2. Intersecting Characteristics of Rectifier and Inverter under Normal operating mode

For stable operation, the operating point should lie on the Ud/Id characteristic of rectifier and inverter simultaneously. To check this, the characteristic are drawn on a common diagram at a point of the HVDC line.

Fig. 47.6 illustrates idealized steady state characteristic of rectifier (1) and inverter (2) drawn on a common diagram, assuming higher DC voltage on rectifier end than that at the inverter end. *This diagram is applicable for the normal operating mode of the HVDC link.*

R_1, S_1, T_1 represents rectifier characteristic (1); R_2, S_2, T_2 , represents the inverter characteristic (2) as seen from rectifier end, *i.e.*, the voltage drop of line is taken into account such that

$$Ud_1 = Ud_2 + Id \cdot R.$$

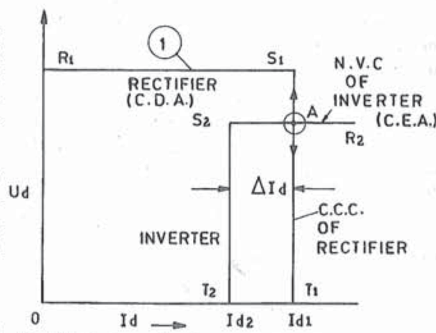


Fig. 47.7. Intersecting characteristics of rectifier (1) and Inverter (2) under normal mode.

The constant current segment of inverter characteristic S_2. T_2 has current margin ΔI with respect to constant current segment of rectifier characteristic S_1, T_1.

The operating point A is obtained where characteristic (1) intersects the characteristic (2).

Point A lies on the constant current segment of characteristic (1) of rectifier and natural voltage characteristic (2) of the inverter.

For this operating point, the current (Id) is determined by the constant current setting of the rectifier (Id_1), *i.e.*. S_1, T_1.

The voltage Ud is determined by the natural voltage characteristic of the inverter, (Ud_2), *i.e.*, (R_2, T_2).

Hence for stable operation with normal steady state operation mode the following conditions apply :

— the direct current is controlled by the rectifier current control set on constant current mode.

— the direct voltage is adjusted at the inverter such that the operating point is on the inverter natural voltage characteristic of the inverter determined by the tap changer and phase angle control of inverter.

Hence under normal operating mode, the rectifier sets the current and the inverter controls DC voltage.

Hence the rectifier is provided with constant current control (with a provision of adjusting current setting) and the inverter has a provision of variation in voltage. The inverter end DC voltage gets adjusted automatically to the value of natural voltage characteristic of inverter corresponding to point A. The rectifier end has higher voltage as given by the $Ud_1 = Ud_2 + Id \cdot R$.

47.3.3. Intersecting Characteristic under steady condition with Current Margin control

Fig. 47.8 shows the characteristic in which the natural voltage segment of inverter ($R_2 S_2$) is above the natural voltage segment of rectifier (R_1, S_1.)

This is not for a normal situation but for contingency arising in the event of fall of rectifier DC voltage due to say a fall in AC side voltage at rectifier-end. Under such eventuality, the operating point A should remain on constant current segment and should be on point of intersection.

To fulfil these conditions, the inverter is also provided with constant current control (segment $S_2 T_2$) with a current margin (ΔId) with respect to current setting of rectifier ($S_1 T_1$).

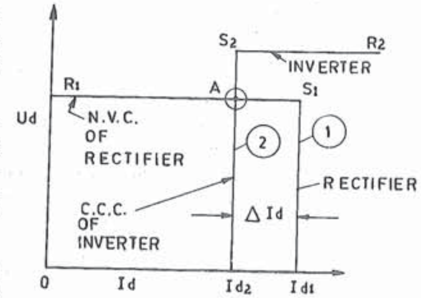


Fig. 47.8. Intersection of characteristics under current margin control.

This control mode is called *current margin control*. In this mode of control, the rectifier-end has a lower DC voltage than the inverter-end. The direct current Id in the link is determined by inverter constant current controller setting (Id_2). The voltage of the inverter is adjusted along the natural voltage characteristic passing through point A.

47.3.4. Power Transmission Characteristic with constant current regulation of Rectifier and constant extinction angle regulation of Inverter.

Figs. 47.6. and 47.7 show the working characteristic of HVDC system having following features :

— Constant current control at rectifier as shown segment $S_1 T_1$ re-presenting Id_1 corresponding to setting of rectifier constant current controller.

— Constant extinction angle (Δ) on inverter with corresponding natural voltage characteristic $R_2 S_2$ representing receiving voltage Ud_2 as seen from say sending end.

This practical working characteristic is generally used for present HVDC schemes.

Rectifier Characteristic. Suppose the constant current controller of rectifier is set at Id_1. The rectifier, line and inverter have to carry the same current Id. The voltage drop in line is $I_d \cdot R$ the Ud_1 should be equal to $Ud_2 + Id_1 \cdot R$. In the rectifier characteristic, account is to be taken to adjust delay angle α such that the natural voltage characteristic represented by segment $R_1 S_1$ is shifted to Ud_1 value corresponding to $Ud_2 + Id_1 \cdot R$.

When inverter AC voltage Ud_2 reduces (say due to fall of AC system voltage Ud_2), the rectifier DC voltage Ud_1 also reduces. Corresponding drop in rectifier voltage is brought about by the control system to maintain Ud_2 constant.

Rectifier voltage reduction is achieved by reducing delay angle α upto minimum limit say 60 below this, further reduction in Ud_1 is achieved by tap changing.

Fast acting tap changer are provided for quick control.

Invertor characteristic. Invertor is operated with α greater than 90°. It is provided with limit of constant minimum extinction angle γ. The line voltage is determined by the inverter voltage control. The inverter side DC voltage is held under control near rated value by appropriate actions on AC side voltage control (shunt compensation, tap changing) and controlling the extinction angle. Fall in AC voltage is corrected by increased shunt compensation of AC bus and appropriate actions at AC networks for voltage control. However the tap-chargers of converter transformers are set such that desired value of Ud_2 is obtained quickly. The current Id is decided by setting Id_1 of rectifier.

47.3.5. Reversal of Power Through an HVDC link : Necessity of Reversal of Power.

Power reversal becomes necessary in following cases :

1. Normal operation of an interconnecting HVDC line in which power flow is scheduled in either forward or reverse direction.
2. Sudden need of power for AC system at sending end due to deficit power generation and drop in frequency.
3. Fault on HVDC line pole during which the line is temporarily de-energized by changing over the rectifier to inverter. After a certain lapse of time attempts are made of re-energize the line by changing the same to rectifier. These operations require ability of each converter to operate as a rectifier or an inverter.
4. During frequency oscillations in AC system, the power flow through DC line is modulated to dampen the oscillations.

Method of Reversal of Power. The converter at each terminal is provided with controls such that their delay angles α can be adjusted at desired value. When delay angle is less than 90° the converter acts as a rectifier.

When α is between 90° and 180°, the converter acts as an inverter. The convertor can be operated as a rectifier or an inverter by setting of its α controller.

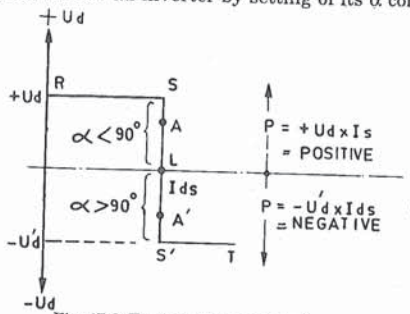


Fig. 47.8. For forward power, α of rectifier is less than 90°.

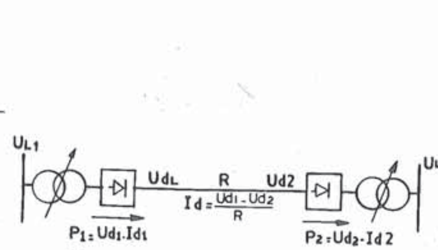


Fig. 47.9. Current Id changed by changing difference ($Ud_1 - Ud_2$).

For *forward power flow,* the convertor at Terminal 1 is operated as rectifier by setting angle $\alpha < 90°$ and convertor at Terminal 2 is operated as an invertor by setting angle α between 90° and 180°.

The effect of change in delay angle α on the average DC power is illustrated in Fig. 47.9.

The direction of power ($P = Ud \cdot Id$) depends on polarity of Ud and direction of Id. Direction of current I_{dc} and instantaneous i in thyristor valves remains unchanged. But polarity of communicating voltage with respect to Id changes with angle.

In Fig. 47.10 (*A*), α is less than 90° and average power during a cycle is positive indicating rectifier operation, *i.e.*. power is transferred from AC system with DC line.

In Fig. 47.10 (*B*), α is equal to 90° and average power per cycle is zero as for one cycle the positive area is equal to negative area of P.

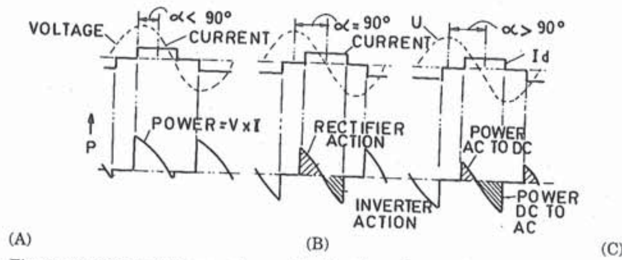


Fig. 47.10. Effect of delay angle α on the direction of power flow through DC link. $\alpha < 90°$ — Rectifier action. $\alpha > 90°$— Inverter action.

In Fig. 47.10 (*C*), α is more than 90° and less than 180°. Average power P during a cycle is negative indicating a reverse power flow (inversion). The power flows from DC line into AC system. Power flow through the HVDC link can be reversed by simultaneous action of reversal at the two terminal stations. The direction of direct current Id through the valves and DC line remains unchanged. The polarity of voltage of the HVDC pole is reversed as shown in Fig. 47.11 (*A*), (*B*), (*C*).

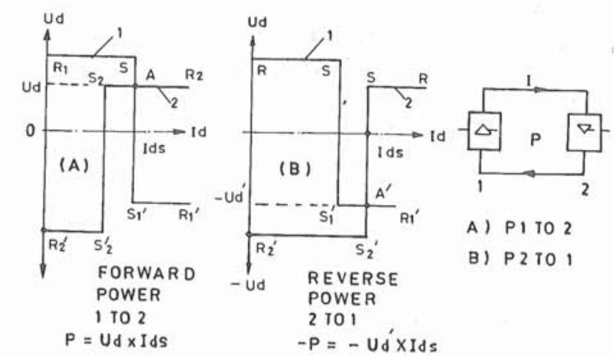
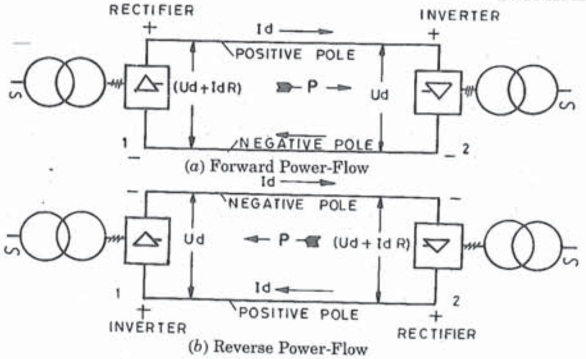


Fig. 47.11 (A). Reversal of power in HVDC link.

Combination Rectifier/Inverter Characteristic. The combined *Ud/Id characteristic* of a convertor indicating rectifier and inverter range is illustrated in Fig. 47.8. The current Id remains in the same direction as indicated by Ids. The direct voltage Ud reverse in polarity as delay angle is changed from $\alpha < 90°$ (Rectifier) to $\alpha > 90°$ (Inverter) as indicated by segments RS (+ Ud) and



(a) Forward Power-Flow

(b) Reverse Power-Flow

Fig. 47.11 (B)

ST (– Ud). For point A on segment S'L, P is positive and for point A' on segment S'L, P is negative (Reverse).

Power Reversal Operating point on Ud/Id characteristic. Fig. 47.11(A) illustrates the point of intersection A between characteristics of convertor 1 and convertor 2 for forward power flow. Point A has + Ud and + Ids giving + P. Power flows from AC system to DC line. This is forward power as seen from terminal 1.

Fig. 47.11 (b) illustrates reversal of power. The point of intersection A' has co-ordinates – Ud and + Ids giving power as (– Ud × Ids) = – P. During reverse power flow, the convertor of terminal 1 operates as an invertor ($\alpha > 90°$) and convertor of terminal 2 operates as a rectifier ($\alpha < 90°$).

47.3.6. Alternatives of HVDC Control

$$P_d = U_d \times I_d \qquad \text{...(47.1)}$$

Power control is achieved by one of the following three alternatives :

1. **Constant U_{dc} and variable I_{dc}.** This method has a disadvantage that during short-circuit on DC lines, short circuit currents reach a very high values. However advantage are low currents for low power and low I^2R losses.

2. **Constant I_{dc} and variable U_{dc}.** This method has disadvantage that I_{dc} is constant irrespective of load. The I^2R losses are also constant and correspond to full load value.

As U_{dc} is variable, U_{dc} has to have a very wide range which is beyond permissible limits of AC system voltage. This method is not used.

3. **Hybrid Method of Controlling Ud and Id appropriately.** This method combines advantages of (1) and (2) above. The method comprises control of Ud_1 and Ud_2 simultaneously so as to control I_d given by the equation.

$$I_d = \frac{Ud_1 - Ud_2}{R} \qquad \text{...(47.2)}$$

where I_d = Direct current, Amp

U_{d_1} = Sending end direct voltage, Volts

Ud_2 = Receiving end direct voltage, Volts.

$$P_{dc} = U_{dc} \cdot I_{dc} \qquad \text{...(47.3)}$$

where $$U_{dc} = \frac{Ud_1 + Ud_2}{2} \qquad \text{...(47.4)}$$

Id is generally controlled by rectifier constant current controller setting.

Ud_2 is generally controlled by inverter natural voltage characteristic corresponding to Ud/Id characteristic of inverter with minimum extinction angle limit setting.

Ud_1 is held at

$$Ud_1 = Ud_2 + Id\,R \qquad \text{...(47.5)}$$

The current in the link would be

$$Id = \frac{Ud_1 - Ud_2}{R} \qquad \text{...(47.6)}$$

Current in rectifier and current in inverter is same (Id).

Voltage at rectifier end Ud_1

Voltage at inverter end Ud_2

Power flow $Pd_1 = Ud_1\,Id$ at (1) ...(47.7)

$P_{dc} = Ud_2\,Id$ at (2) ...(47.8)

Difference P_{dc} (1) – P_{dc} (2) = Line loss = I_d^2R

The control characteristic of rectifier and inverter should intersect as described earlier.

From Eq. (47.5) it is observed that, due to small value of DC line resistance R and absence of reactance X_L *a small change between Ud_1 and Ud_2 can bring about a large change in Id_{dc} and therefore in* P_{dc}. This aspect is used for quick and accurate control of power flow through an HVDC link. Power flow is controlled by changing the difference between sending-end voltage and receiving voltage so as to change value of direct current.

Two means are available for achieving this difference ($Ud_1 - Ud_2$) and thereby changing Pd_1.

— Tap change control — Control of delay angle α.

47.3.6. (a) Tap-changer control : change in tap position of convertor-transformer tap changer

Multi point fast tap-changers are provided at each and for each convertor transformer for controlling DC voltage under steady state.

Assuming constant AC line side voltage U_{L1}, the valve side voltage U_L depends upon the turns ratio (K).

$$K = U_L/U'_L$$

AC bus voltage U_L is held constant by voltage control of AC system. K is changed by means of tap-changer. Tap-changer method is slower and takes 8 to 10 seconds to change one tap. This method is used for slow, steady state variation of DC power.

Tap-changers used for HVDC converter transformers have a very wide range of tappings.

Refer Fig. 47.6 explaining characteristic with changing of Ud. Refer Fig. 47.6 illustrating normal operation of the HVDC link in which operating point A is on natural voltage characteristic of inverter.

The inverter tap-changer is controlled so that the direct voltage Ud_2 at some receiving end is close to desired value obtained by ($Ud_2 = Ud_1 - IdR$), Ud_1 being nearly rated DC voltage tap-changer of inverter raises for lowers Ud_2 raising or lowering turns ratio $k = U_{l2}/U'_{L2}$

Likewise the voltage Ud_1 at rectifier end is held at value.

$$U_{d1} = Ud_2 + Id \cdot R$$

Required Ud_1 is computed and fed as input to tap changer controller of rectifier. The tap position is raised/lowered to obtain desired voltage on valve side of convertor and thereby required Ud_1.

The rectifier tap-changer is controlled so that if α becomes less than 10°, it raises the direct voltage by raising the transformer ratio k. If α becomes more than 20°, the voltage is lowered by reducing transformer ratio k.

The delay angle α of rectifier is held between 10° and 18° under steady state by tap-changer control.

The on-load tap-changer is fitted on AC side of convertor transformer.

For star connection transformer with solidly grounded neutral, the taps and the tap-changer are generally placed on the grounded neutral end of the winding. Though the winding may be of very high voltage at line end (400 kV for example) the maximum voltage to which the tap-changer at neutral end is subjected is equal to voltage between highest tap position and neutral. By placing the taps nearer the neutral end, the voltage rating of the tap-changer can be minimised.

For example for convertor transformers rated 400 kV on AC side on-load tap changers are connected on 400 kV AC side winding located at the neutral end of windings. The neutral is earthed. Number of steps large (say 16) step voltage is 1.25 to 2.0%. A typical tap-changer has a range of $+ 10 \times 1.3\%$ to $- 14 \times 1.3\%$.

The dead band between tap-changing is more than tap step voltage, *i.e.* between ± 1.3 to 2%.

The tap-changing operation is initiated by pressing the push button on the motor drive housing of the tap-changer or by a contactor operated by automatic voltage regulator, in the tap-changer control system. The voltage control relay operates when the line voltage increases or decreases by set amount. When the voltage control relay operates, the motor gear unit of on-load tap-changer gets a command for raise or lower. Depending upon signal, the motor rotates to complete one tap-changing operation to 'Raise' or 'Lower' the tap. To prevent tap-changing operation during transient fluctuations, a time delay relay is provided in a control circuit. The time delay relay can be adjusted upto 60 seconds.

In order to avoid hunting (alternate raise/lower) dead band between taps should be more than tap step and time delay should be provided between two consecutive tap changers.

Tap changers on inverter side convertor transformers should be identical to those on rectifier side.

47.3.6. (*b*) Control of phase angle of thyristor firing (Control of α and γ)

Rapid control of DC voltage is achieved by control of phase angle of firing the thyristor, *i.e.* the delay angle α of rectifiers. This change can be very rapid and accurate (10 to 20 milliseconds) and is used for rapid variation of power flow by changing $(Ud_1 - Ud_2)$.

The tap-changer control is slow as the tap-changing takes about eight seconds per step. The thyristor control is rapid (a few milliseconds). Both the above methods are used at each terminal. The thyristor control is used initially for rapid variation of voltages. This is followed by tap-changer control.

Lower value of delay angle α (of rectifier) gives higher of DC voltage and lower kV Ar demand of AC Bus (Lower shunt capacitors). Hence α should be kept as low as possible at rectifier end. But if α is kept too low (near zero) no margin would be available for increasing the voltage by further reduction of α. Hence in practice angle α at rectifier end is kept between 72° elect, and 18° elect.

Limit of extinction angle γ for inverter. As the delay angle α for inverter is more than 90° elect, it is usually more convenient to define extinction angle γ for the inverter. The inverter requires certain minimum extinction angle γ for safe commutation. Higher γ is better for commutation but causes increase in kVAr demand of inverter.

Hence the inverter is operated with a setting for minimum extinction angle limit γ. In practice the extinction angle of inverter is held between 15° and 18° elect. Larger value gives lower risk of commutation failure and increased kVAr demand.

47.3.6. (*c*) Frequency control of AC Networks by means of HVDC Link

AC Networks connected at each terminal of an HVDC link operate at their respective prevailing frequencies. Each AC Network controls its own frequency by adjusting the total generation to match the total load. All the synchronous machines should run at synchronous speed corresponding to the prevailing frequency f, as given by the equation :

$$N_s = 120\, f/P$$

N_s = Synchronous speed, R.P.M.

f = Frequency, Hz, cycles/sec)

P = Number of poles.

The two AC Networks connected by only an HVDC link operate asynchronously, *i.e.* they are not in synchronism with each other and each operates at its own prevailing frequency. For keeping the frequency within targeted limits (49.5 -50.5 Hz).

The power flow from AC Network (*a*) to AC Network (*b*) through an HVDC link can be controlled quickly and precisely by phase control of rectifier and invertor such that frequency of AC Network (*b*) is controlled by AC Network (*a*).

47.3.6. (*d*) Damping Control of AC Networks by HVDC Link

AC Networks experience violent swings in load angle δ during faults, sudden tripping of generators or loads etc. If swing angle δ is not damped or controlled, the stability of both AC Networks is likely to be lost. By modifying HVDC system control, the swing curve is damped. Swing angle is not allowed to go beyond, permissible limit. The oscillations are damped quickly and systems are made stable. The HVDC power flow magnitude and direction is modulated to damp the oscillation in δ.

Summary of Power Control

Power control of HVDC link is achieved by means of

1. Tap-changer control at rectifier end and inverter end to control Ud_1 and Ud_2. The tap-changer is used for slow variation of Ud_1 and Ud_2 and thereby Pd.

2. By controlling phase angle α (called delay angle α).

Phase angle control is used for rapid variation of α or γ thereby Pd.

U_L on AC side is not varied and held within specified limits.

Power Reversal is achieved by changing of polarity of DC voltage, keeping the direction of current in valves and pole unchanged. For this the delay angle α of rectifier is extended beyond 90° and delay angle α of inverter is advanced to less than 90°.

Power can be quickly changed at a rate of about 30 MW/min.

Operating point A deciding Ud and Id should be on CCC characteristic of rectifier and NVC characteristic of inverter. Same Id flows through both. Id is decided by constant current controller setting of convertor Ud is decided by the natural voltage characteristic of inverter. Operating point is shifted by changing power command at invertor end. This changes Id and thereby Pd.

Frequency control of AC systems is normally achieved by matching generation with load. With HVDC interconnection the flow of power Pd is changed suitably so as to assist frequency control of connected AC systems. In some schemes the frequency control of a weak AC system is governed totally by the power flow through HVDC link.

47.4. CIRCUIT ARRANGEMENTS

Modern HVDC links have thyristorized convertors. A convertor *converts* a.c. into d.c. into a.c. An HVDC link comprises an a.c. sub-station and conversion sub-station at *each end* and a HVDC transmission line in between the two. In case of *back-to-back* HVDC line, there is only a conversion sub-station between two a.c. sub-stations ; there is no d.c. transmission line.

Bipolar Arrangement is used universally for bulk power overhead transmission lines and overhead lines for interconnection. Each pole has one or more 12-pulse convertors. Configuration of one 12-pulse convertor is shown in Fig. 47.12.

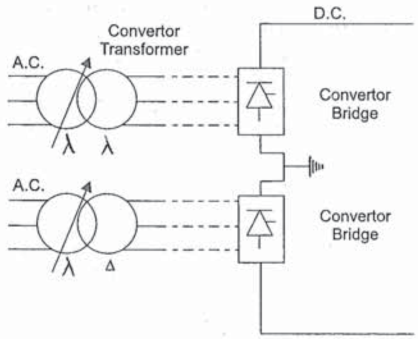


Fig. 47.12. Configuration of one 12-pulse convertor formed by two 6-pulse Convertor Bridges (Fig. 47.14).

47.5. THYRISTOR VALVES FOR HVDC CONVERTOR

The commercial success of HVDC lines is mainly due to successful development of high power, high voltage thyristor valves (1970's). These 'valves' are built-up from :

— Several thyristors connected in series with additional thyristor in parallel for each thyristor for redundancy and higher current rating.

— 'Snubber' (Voltage grading circuit) for equal distribution of voltage across thyristors. The Snubber is made up of following :

— Saturable reactors included in voltage grading circuit to control du/dt and di/dt.

— Surge arrestors connected across thyristors or across phases or both to protect insulation of valves.

— *RC* circuit across each thyristor for voltage grading. Additional *RC* circuit of low time constant across a group of thyristors to improve voltage distribution for fast transients.

— Controlled Avalanche Diodes (*CAD*) across each thyristors to limit peak value of voltage across thyristor.

Cooling System. The valves are cooled by air or SF_6 gas of oil or a combination. The cooling system and insulation are interdependent. The temperature of silicon wafer joint should be held below critical value (90°) to 125°C prevent change in characteristics and damage to thyristors.

A typical arrangement of voltage grading circuit for a thyristor string is shown in Fig. 47.13.

The *valve* comprises a set of thyristors along with associated voltage grading and other components.

A typical *Quadruple valve* comprises four valves placed vertically one above the other to form one limb of the convertor. These are placed in the convertor room.

A typical quadruple valve has 16 modules, each module comprising set of four to twelve thyristors and some reactors. There are totally 64 thyristors and 32 reactors in a quadruple valve.

A typical 12-pulse convertor has four valves connected in series, as shown in Fig. 47.15. *Two* twelve-pulse convertors are connected in series to get a high power convertor (Fig. 47.20).

Optical Control Signals. The thyristors should be triggered in desired sequence and at desired instants. Different kinds of triggering systems have been developed. Most modern method

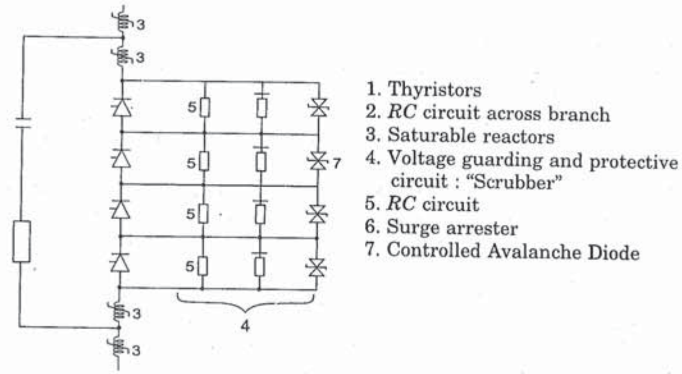


Fig. 47.13. Circuit of a thyristor string in HVDC valve.

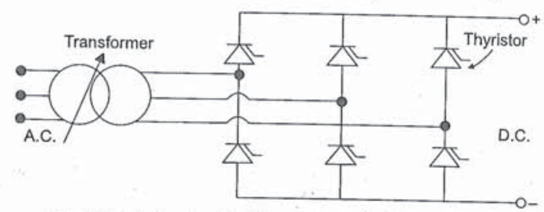


Fig. 47.14. A six pulse thyristor convertor bridge (Graetz bridge).

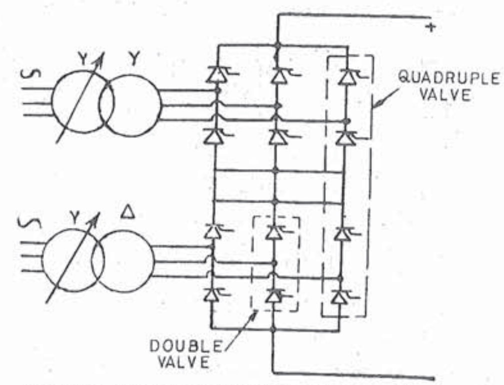


Fig. 47.15. A 12 pulse thyristor convertor formed by connecting two six pulse convertors in series.

is called "optronics" which uses light-guide system. In such a system the electrical pulses are converted into light signal pulses by fibre-optic techniques. The light pulses are transmitted through glass-fibre optical cables upto the individual thyristor. Each thyristor is provided with a small separate thyristor which is triggered by the light pulse. Thereby the main thyristor is triggered. Fibre-optic cables provide insulation as well.

Cooling and Insulation

Following alternatives are used :

— Air for cooling and insulation. (This alternative is used for indoor valves). Fine water cooling for thyristors.

— Special deionised, deoxidised water having high dielectric strength is circulated through plastic pipes and heat sinks of thyristors. Fibre-optic cables are necessary for control of valves as they have insulating property.

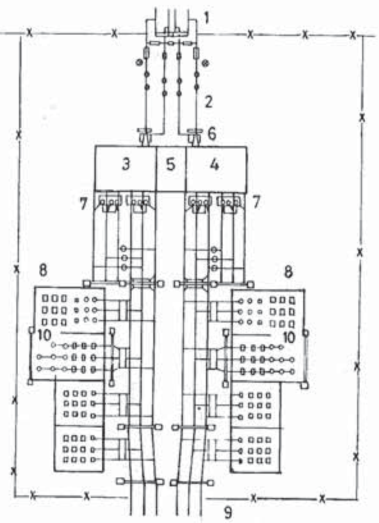
— Oil for insulation and cooling. (This alternative is used for outdoor valves).

The cooling system removes heat due to looses and maintains the temperature of junction within limits. Indoor valves are installed in air-cooled valve rooms.

47.6. REVERSAL OF POWER

Change in direction of power flow of HVDC transmission is usually performed by changing the polarity in the DC voltage.

Rectifier is changed to inverter by advancing angle 90° to beyond 90°. Inverter end is changed to rectifier mode by reducing α to less than 90°.



1. DC line.
2. DC yard.
3, 4. Valve halls.
5. Control room.
6. Smoothing reactors
7. Convertor transformers
8. AC yard
9. AC Lines
10. AC Filter

Fig. 47.16. Layout of HVDC bipolar sub-station.

47.7. TYPICAL LAYOUT OF HVDC CONVERSION OF SUB-STATION

Typical conversion of sub-station comprises the following :

1. A.C. switch yard.
2. Valve hall.
3. Filter area, shunt capacitors.
4. Convertor transformers ; Smoothing reactors.
5. D.C. Switch yard.

A very large portion of area is covered by shunt capacitors and filters. The conversion sub-station layout depend upon the type valve and its design. A typical conversion sub-station has air insulated indoor quadruple valves. These quadruple valves are installed inside air-cooled valve-halls. The convertor transformers and smoothing reactors are installed out-door, very near to the

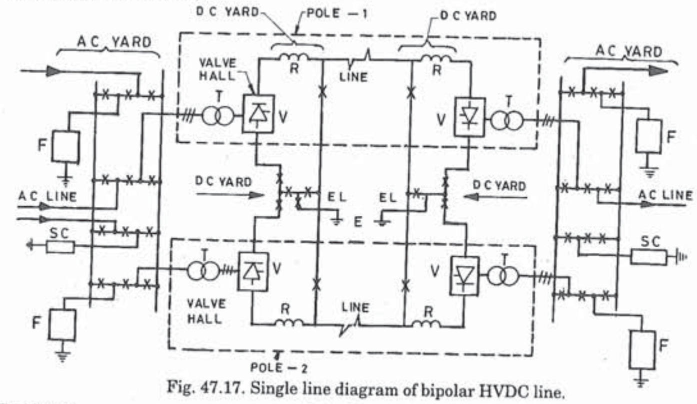


Fig. 47.17. Single line diagram of bipolar HVDC line.

F = Filters
E = Earth electrode
V = Valves (12-pulse Bridge)
R = Smoothing reactor
SC = Shunt-capacitors
EL = Electrode lines
T = Convertor transformer
M = Metallic Return Transfer Breaker

valve halls. The valve side bushing of convertor transformers are installed pointing into the valve side bushing of convertor air-cooling system are installed in the basement below the valve hall. The *valve hall* contains quadruple valves, bushings, reactors connected to the HVDC terminals, surge arrestors. The space for control and auxiliary equipment etc., is provided in the lower part of the building between the two valve halls. The A.C. switch-yard, filter capacitors and shunt capacitors are installed on one side of the valve hall. On the other side of the hall, smoothing reactors, line and neutral bus arrestors, voltage divider, current measuring transductor, disconnecting switches, D.C. circuit, breaker for change over from metallic earth return to ground-earth return etc. are provided.

Requirement of Areas in a bipolar substation are as follow :

— Valve building 10%
— A.C. Filters 30%
— A.C. bus-work and transformer 50%
— D.C. yard 10%

In modern installation, SF_6 GIS may be used for AC and DC switch yard, AC harmonic filters, etc. The area requirement is about 2 m^2/MW which are about 10% of conventional air-insulated switch yard.

47.8. OVER-VOLTAGE SURGE PROTECTION

The convertors are protected by surge arrestors against over-voltage approaching from AC side and DC side. In additional arrestors are also provided for limiting over-voltage surges that may be generated by the convertor itself.

47.9. D.C. SURGE ARRESTORS

For protective convertor equipment from DC side surges have a different design criteria as compared with AC application. The DC arrestors should be suitable for operations in inductive circuit and should be capable of discharging relatively long duration surges. In some cases resealing has to take place without aid of zero passages. To fulfil such requirement and to provide low protective levels a special design of active gap is necessary. ZnO arrestors (metal oxide arrestors) with active gaps are used. These have superior characteristics and high discharge capability.

47.10. LINE PROTECTION SYSTEM

In HVDC transmission system, the grid control of the convertors is used for clearing line faults and subsequent restoring of normal operation. Thus the current control scheme can give very rapid change in line current to reduce full fault current to fraction of rated current within 20 to 40 ms. The reduction of fault current and fault time prevents damage to line conductors, insulators and also deionises the fault zone. This helps in restoring the normal operation rapidly.

47.11. AC HARMONICS

The 3-phase bridge convertor used in HVDC transmission should convert pure sinusoidal AC waveform to pure DC form. But in practice the operation of convertor generates harmonic currents and harmonic voltages on AC side and DC side. These harmonics do not interfere with convertor operation but they flow through AC lines and DC lines and thereby produce the following harmful effects :

— Excessive harmonic currents in syncrhronous machines, power factor capacitors and other equipment.

— Overvoltages at points in the networks.

— Interference with protective gear.

— Interference in adjusting telecommunication lines, radio interference (RI); Television Interference (TI).

These disturbance spread over the AC network and DC line and surrounding residential areas.

In HVDC convertors, following predominant Harmonics are encountered :

AC Harmonics : $H_{ac} = nx + 1$

DC Harmonics : $H_{dc} = nx$

n = Pulse number of convertor. x = Integers 1, 2 ...

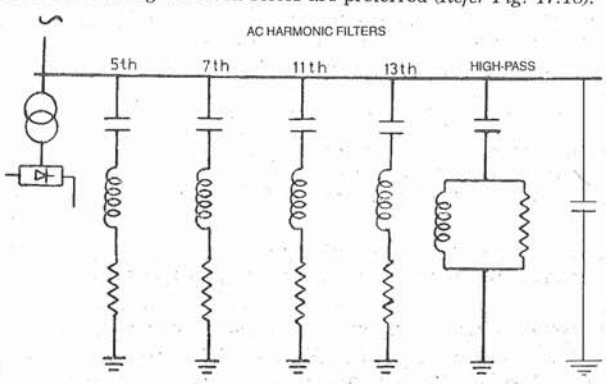
47.12. HARMONIC FILTERS

These are provided on A.C. side for following purposes :

— To reduce harmonic voltages and currents in the A.C. power network to acceptable limits.

— To provide all or a part of reactive consumed by the convertor, the additional reactive power being supplied by shunt capacitor banks.

A.C. shunt filters having R.L.C. in series are preferred *(Refer Fig. 47.18)*.



Single line schematic diagram of AC harmonic filters.
Fig. 47.18. AC Harmonic Filter Circuit.

Convertors generates harmonic voltage and currents at both A.C. and D.C. sides. A convertor of pulse No. 'n' generates harmonics predominantly of the order 'H' as follows :

$$H_{ac} = nx \pm 1 \text{ on a.c. side.}$$

$$H_{dc} = nx \text{ on d.c. side.}$$

where n = number of pulses of rectifier/inverter usually 6 or 12.

x = an integer

H_{ac} = Predominant a.c. harmonic

H_{dc} = Predominant d.c. harmonic.

Table 47.3 gives the list of likely predominant harmonics.

Table 47.3. Predominant Harmonics

Number of Pulses n	*Harmonics on A.C. side* $H_{ac} = nx \pm 1$	*Harmonics on D.C. side*
6	1, 5, 7, 11, 13, 17, 19, 23, 25	0, 6, 12, 18, 24
12	1, 11, 13, 23, 25	0, 12, 24

A.C. Harmonic Filters. Two complete harmonic filters, each comparing tuned band-pass branches for the 11th and 13th harmonics and a high pass branch tune to 24th harmonic are provided in each station for a typical 12 pulse convertor system in Fig. 47.19.

D.C. Harmonic Filters. In bi-polar operation, under ideal conditions, the induced voltages would be negligible and filters are not necessary. However under real operating conditions, assuming certain unbalance (in transformer reactances etc.). The induced voltage level would increases. Therefore, use of high pass d.c. filter turned to 12th harmonic is usually made for a 12 pulse convertor circuit.

47.13. HVDC SIMULATOR

HVDC simulator is a model of HVDC system on which various system conditions and abnormal conditions can be simulated. The simulators are used for analysing dynamic performance of HVDC systems. Before designing an HVDC link and determining the specifications of various equipment, it is necessary to carry out system studies for the proposed HVDC line. These studies are carried out with the help of HVDC simulators. The simulator is a small-scale model of actual HVDC system and comprises the following functional blocks :

— 12 pulse convertors (8)

— Bipolar DC lines (2)

— Synchronous machine models (10)

— Static VAR compensator models (2)

— AC filter bank models for 3rd, 5th, 7th, 11th, 13th and high pass branch.

— A large number of reactor models of AC network representation.

— Complete set of control and protection sub-system of both convertor and pole levels.

Such a simulator can model two bipolar HVDC systems.

Types of studies preformed on HVDC simulator. The performance of a HVDC transmission has a significant influence on the behaviour of complete power system including AC networks to which the convertor stations are connected. On the other hand, this performance is greatly dependent on the control and protection system and their sub-functions. The operation of an HVDC transmission is much more dependent on the control system than that of an A.C. transmission. The control systems should be tested very thoroughly during the development stage and prior to commissioning. A simulator operating in real time is necessary too for this type of testing. In the simulator it is possible to inject different kinds of faults and disturbances in A.C. network and D.C. line and to study the effect of the control and protection system, firing the control design concepts.

Some control circuits like convertor firing control cannot be successfully developed without using real time simulator. The following types of studies are performed in a simulator :

— Development of control and protection systems.
— Main circuit design.
— Requirements on, and improvement of, A.C. network characteristics.
— Dynamic interaction between HVDC convertors and the A.C. systems.
— Transient studies.
— System tests on control equipment for a total project.
— Support for HDVC schemes in operation.

47.14. PROTECTION SYSTEMS IN HVDC SUB-STATION

Table 47.1. Protection chart for HVDC Sub-station

Category	*Protective systems*
1. D.C. side protection	1.1 Convertor protection 1.2 Pole protection 1.3 Bipole protection
2. Convertor transformer protection	2.1 Convertor transformer line side differential protection 2.2 Convertor a.c. bus and transformer differential protection. 2.3 Convertor-transformer differential protection 2.4 Supervision of gas and temperature in the convertor transformer
3. A.C. Filter-bank protection	3.1 Complete a.c. filter-bank and feeders upto a.c. bus are protected by — Overcurrent protection — Differential protection 3.2 Tuned a.c. filter branches are protected by — Unbalance protection — Backup portection — Earth-fault protection — Overload protection
4. Protection of Apparatus (Protective functions distributed to sub-systems demand that convertor be taken out-of service)	4.1 Supervision of smoothing reactor gas and temperature 4.2 Cooling system of valves. 4.3 Power supply to valve control 4.4 Convertor firing control power supply supervision. 4.5 A.C. bus voltage supervision and distributed overcurrent protection.
5. A.C. yard protection	5.1 Power transformer protection (in any) 5.2 Bus differential protection 5.3 Line protection
6. Auxiliary power transformer protection	6.1 Bus overcurrent protection 6.2 Transformer differential protection 6.3 Overcurrent protection and earth-fault protection. 6.4 Supervision of gas and temperature.

47.14.1. Protection of HVDC Transmission System

In HVDC transmission systems, the faults and abnormal conditions can develop in DC line, convertor, DC yard, Auxiliaries etc. The faults on DC side may call for blocking of convertors, de-energizing the DC pole. There are no DC circuit-breakers. DC fault current is reduced to low value by convertor control.

During fault on one pole, only faulty pole is isolated and the other pole continues to transmit. The faulty pole is removed from service by tripping AC circuit-breakers feeding that pole. The entire HVDC system is segregated into two poles.

The protection system in HVDC substation is integrated with the convertor control system. Protective and control action is taken in both terminals of 2 TDC system simultaneously. For this, the microprocessor based protection and control systems in both the terminals are linked by means of Power Line Carrier Communication system or Microwave system.

The present HVDC system are mostly 2-Terminal Bipolar systems without HVDC circuit-breakers. The protection functions of DC line are served by control of thyristor valves. In future, the availability of HVDC circuit-breakers may change the scene and will provide scope for simpler control system and operational flexibility.

The designers of HVDC system feel that there is no need of DC circuit-breakers for clearing faults on DC line side as the control takes care of all faults and abnormal conditions on DC side.

In the HVDC transmission, the function of protective and control systems are integrated. The protective and control functions include sensing (detection) or abnormal operating conditions and faults in the main AC circuit, DC circuit and auxiliaries and to initiate appropriate control action and protective action so as to prevent, minimise the damage to equipments and ensure the service continuity *via* the healthy system. Service continuity of HVDC transmission is very important because of high power through a single transmission link.

During a fault on DC side, there is no provision of tripping HVDC circuit breaker. However, the fault current is reduced rapidly by thyristor control. No tripping is carried out on DC side. Permanent faults in DC side are cleared by tripping AC circuit-breakers associated with the faulty pole.

The entire protection and control sub-system of HVDC system is divided into two poles : Pole 1 and Pole 2 (Fig. 47.17-dashed lines). For any fault in Pole-1 ; the control actions of Pole-1 are initiated automatically to minimise the fault current. If fault continues, pole-1 is tripped by means of AC circuit-breakers in AC yard.

Polewise segregation of HVDC system. The entire substation is divided into 4 parts for protection control and maintenance purpose :

1. Pole-1
2. Pole-2
3. Auxiliaries and Earth Return, common to both poles.

Pole-1 covers zone between AC substation and Pole-1 DC transmission line. In the event of a permanent fault on any of the sub-zones within Pole-1, the total pole-1 is tripped from AC side by tripping AC circuit-breakers behind the convertor transformers of pole-1. (Fig. 13.4-CB-1).

Likewise, for a permanent fault in Pole-2, the entire Pole-2 is tripped from AC side by tripping of AC circuit-breakers of feeding the convertor transformers of Pole-2 (Fig. 13.4-CB-2).

Thus, for a fault in Pole-1 only pole-1 is de-energized and then tripped from AC side. Pole-2 continues to serve.

In principle of one of the poles should be available when the other pole is out of service.

Faults in DC line pole are sensed by protection system in the DC line pole zone. The primary (fast) protection is provided line protection system. The back-up protection with certain time delay is also provided in the line protection system. For a line fault in pole-1, appropriate control actions and protective actions are taken by the control and protective system of pole-1, likewise for pole-2.

Short-circuit (faults) in two-terminal bipolar HVDC line are generally single pole to ground faults due to lightning and flashover across insulators. Such faults are temporary and involve only one pole. Each line pole is covered by a separate line pole protective zone having its own protective and control systems.

The control and protective actions for each DC line pole are integrated with the convertor control of that pole.

The line pole protection has an interface with the convertor pole protection and the operating mode control (change-over from bipolar to monopolar during a line pole fault). During a line pole fault, the operating mode is quickly and automatically changed over to the monopolar operating mode. This is done without interruption in power flow through the healthing DC pole.

De-energizing Line and Re-energizing of DC line. For a fault on DC line pole, by putting both convertors in invertor mode, the line voltage of faulty pole is brought to zero and line current is brought to zero. The fault zone gets de-ionized in about 0.3 sec. After automatic clearing of line fault, the line pole may be re-energized automatically. This is called re-energization of line. The re-energization is carried out in one of the following two alternatives.

1. At normal voltage and with full power before the fault. In such attempt if the fault re-appears, one or two more attempts are made with increased dead time.

2. At reduced voltage and reduced power. This attempt is generally tried during rainy season when the flashover is on wet, dirty insulators the re-energization at reduced voltage may give a success.

The re-energization with reduced voltage is preferred. The direct voltage is not raised in one big step but is raised slowly and upto to the final value. The increase in voltage is under the control of starting control unit so that there is no overshooting of voltages.

The total sequence of occurrence of line fault, de-energization of line pole, re-energizing of line takes approximately 200 ms. If the fault has continued, the complete faulty pole is tripped by means of AC circuit-breakers.

47.15. LINE INSULATION

The requirements of HVDC lines insulation is based on the stresses caused by lightning surges, switching surges and polarity reversal. Insulators of porcelain or toughened glass are used for transmission line. The recommended value for specific creepage distance of HVDC line insulators is between 2.3 cm/kV and 7.0 cm/kV depending upon zones of pollution. (Refer Table below)

Table 47.2. D.C. Specific creepage distance for line insulation.

Zone	*Description*	*Creepage distance cm / kV*
1.	Agricultural area	2.3
2.	Outskirts for industrial complex and a few km from sea	4.0
3.	Industrial area and near sea shores	5.0
4.	In highly polluted areas like dirty insustrial area, some industries, some power stations	7.00

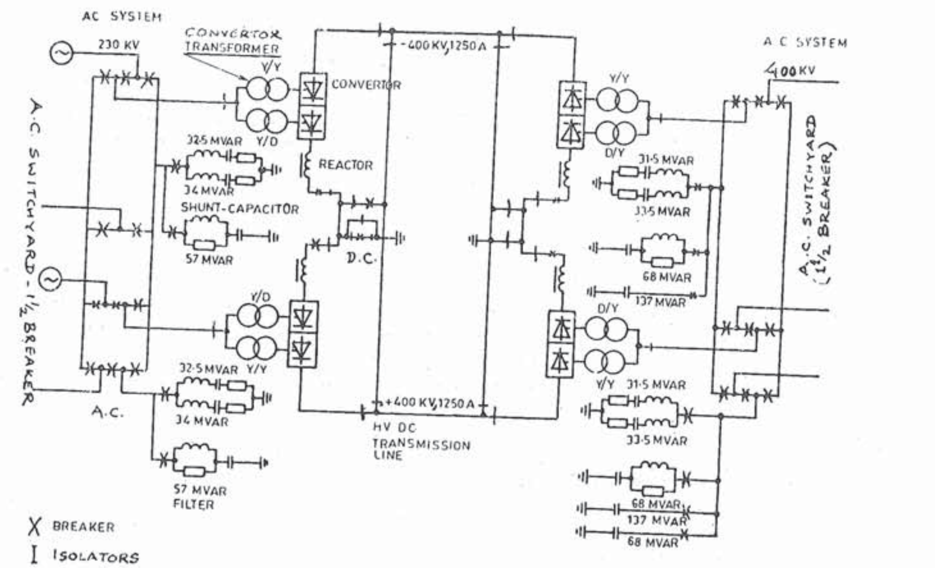
The impulse level of a 400 kV to ground line is about 1400 kV peak.

The creepage distance for indoor HVDC equipment in the range of 1.5 to 2.0 cm/kV of operating voltage.

For HVDC overload lines, bundle conductors with two or more sub conductors are used per pole. The support insulators are of following types :

— Vertical suspension insulator strings.
— V-shaped suspension insulator strings.
— Strain insulator strings.

For straight run of transmission line, V-shaped configuration is preferred as these insulators have a better washing effect during rains. Strain insulators are used at dead-ends, turning points and at regular intervals (for stringing purposes). The insulator units are either of glass or of porcelain. Anti-fog type units are used.



TYPICAL HVDC SYSTEM

Fig. 47.19. *Courtesy* : ASEA, Sweden.

47.16. MAINTENANCE OF HVDC LINKS

The maintenance of HVDC conversion station is similar to that of an A.C. power station. The entire HVDC link is divided into maintenance zones such that one pole continues to operate while the other pole is taken for maintenance. Maintenance is of two types

— Planned Maintenance — Troubleshooting

The substation maintenance zones include

1. Pole I and Pole II
2. AC Filter Areas
3. AC Yard
4. DC Yard
5. Valve Halls
6. Auxiliaries

For purpose of maintenance the operating mode of HVDC system is changed to Monopolar Operation with substation-earth. Other pole and Earth. Return line and Earth Electrode are available for maintenance.

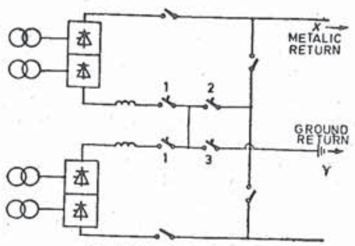
47.17. D.C. BREAKERS AND LOAD SWITCHES

D.C. breakers or load switches are used in three d.c. switching applications, namely :

1. Neutral bus load switch.
2. Load switch for metallic return to ground transfer.
3. Breaker for ground to metallic return transfer.

Fig. 47.20 shows the locations of these units whose design has then adapted to the particular application.

1. The neutral bus switch is normally operated as a dis-connector, that is under no-load conditions. In the unlikely case of a ground (earth) fault on the convertor side of the switch, this must



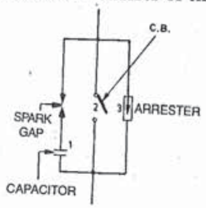
1. Neutral bus switch
2. Switch for metallic to ground. Transfer (Transfer of data from x to r).
3. HVDC Breaker to Ground to Metallic Return Transfer (from y to v).

Fig. 47.20. Switches for neutral bus and return to ground.
Courtesy : ASEA Sweden.

also to commutate the fault current to the electrode line. The fault current corresponds to the difference between the current in the healthy pole and the current in the electrode line. A slightly modified a.c. circuit-breaker with artificial current zero is used here.

2. The switch for metallic return to ground transfer is operated in connection with the normal routine for the change over from single pole metallic return operation to bi-polar operation. After the electrode line has been connected, about 20 per cent of the direct current still remains in the return pole conductor and the switch is needed to commutate this current to the ground return path. The same type of breaker as in point is used also here.

3. The breaker for ground to metallic return transfer is subjected to higher d.c. stresses owing to the higher current and high d.c. recovery voltage. An HVDC breaker is, therefore, used here. As shown in Fig. 47.21 this breaker consists of three principal components.



1. a circuit breaker (SF_6/MOCB/vacuum)
2. a capacitor with a series-connected spark gap and
3. HVDC surge arresters

Fig. 47.21. D.C. Circuit breaker for (3) in Fig. 47.20.

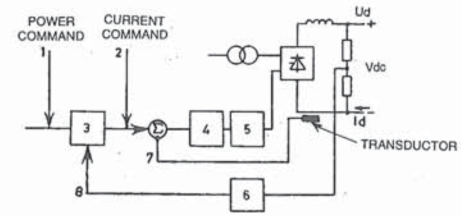
Conventional HVAC and HVDC components are used in this breaker. It shall be capable of commutating the current in the ground return (approx. 80% of the total pole current) to the metallic return conductor. For this application it is, therefore, designed interrupt a maximum direct current of 1500 A and to absorb an energy of 2 MWs.

47.18. CONTROL AND PROTECTIVE EQUIPMENT

The main requirements of a HVDC system is to deliver scheduled amount of power. The power control is obtained by

— Combined voltage and current control by controlling thyristors in the convertor bridge.
— Tap changing of convertor-transformers on a.c. side.

Both the above methods are used. Thyristor control is rapid (few milliseconds), tap-changer control is slower (5 to 10 seconds per step). Both these means of voltage control are applied at each terminal. Thyristor control is used initially for rapid action and this is followed by tap changing for distorting certain quantities. Fig. 47.22 illustrates the control system for power control. The power is measured either on a.c. or d.c. side.



1. Power order
2. Current order
3. Divider (Analogue)
4. Amplifier
5. Trigger pulse system
6. Voltage measuring system
7. Current feedback
8. Direct voltage feedback.

Fig. 47.22. Control system for power control in HVDC.

The voltage is measured on d.c. side by voltage measuring system (6) and is given to analogue divider (3). Thus the power command and measured voltage is used in addition to current control. The main current control is achieved by a closed loop system (7). The transductor measures d.c. currents and feeds it to comparator *via* feed back loop (7). The current command is to compared with feed back current (7) and the error is given as input to amplifier (4). The output of amplifier (4) is given to trigger pulse system (5).

The analogue divider 3 receives power compound P and feedback voltage V_d. The output signal of analogue divider 3 is proportional to $I_d = P/V_d$, this signal is added to current command (2).

Thus the automatic control system is derived from a combination of current control, voltage control and power control.

Increase and decrease of power command (1) is executed manually at the two stations. The communication between the two stations is achieved by microwave communication system.

The following limits are imposed on current control :

1. *Maximum current limit.* This is from 1 to 1.2 times rated current depending upon thermal ratings of valves and ambient temperature.

2. *Minimum current limit.* This is usually 0.1 times rated current.

3. *Voltage dependent current limit.* For lower voltage higher current limit and corresponding power limit is fixed.

Shunt Compensation. (Reactive power equipment). The d.c. line itself does not require reactive power compensation and the voltage drop on the line is purely IR drop. The convertors convert, transformers on both sides drawn reactive power from a.c. side. It varies with amount of power transferred and is 50 to 70% of DC power flow. AC filter capacitors provide compensation of reactive power required for convertor operation.

Reactors

D.C. smoothing reactor with an inductance of 0.4 H to 1 henry is generally located on the low voltage side of the convertors. Air-core reactors on the line side of the convertors limit any steep front surges entering the station from the d.c. side. In addition, air-core reactors are installed in each phase on the a.c. to reduce the rate of the current on firing of the thyristors.

SUMMARY

HVDC transmission is selected as an alternative to EHV transmission for one of the following :

— Bulk power long distance transmission lines for economy, energy conservation, power flow control.
— For interconnecting lines between two or more A.C. system as an asynchronous tie.
— Long distance submarine cables.

In India, HVDC line will be used for bulk power transmission and interconnections. (Back-to-back HVDC substations).

A typical two terminal HVDC link has A.C. sub-station, conversion sub-station at each end and the two such sub-stations are linked by the bipolar transmission line.

In bipolar D.C. transmission system has two poles, one positive with respect to earth and the other negative.

The convertors are made up thyristor valves, 12 pulse convertors are used. The convertor is supplied from convertor transformer. The quadruple valve has 4 valves placed vertically to form a limb. These are installed in valve halls.

The convertor transformer is of special design as D.C. voltage on convertor sides causes additional magnetising currents and voltage stresses.

The rating of a typical long-distance HVDC link are :

(*i*) ± 500 kV (*ii*) 1500 MW (*iii*) 900 kM.

The control of HVDC power flow is by tap changing of convertor transformer and gate control of thyristors valves.

The HVDC lines having point-to-point contact do not need HVDC breaker as the line current can be reduced rapidly in the event of fault by blocking thyristor.

With the development of thyristor valves, the HVDC lines have become commercially viable for long distance high power transmission systems, interconnections, sub-marine cables.

Recently multi-terminal HVDC transmission systems having link between 3 or more AC systems have been commissioned in Italy, USA/Canada.

HVDC Back-to-back coupling stations are being preferred for system interconnections. Several Back-to-back HVDC sub-stations have been commissioned and several new contracts have been signed.

HVDC Projects in India :

1	Vindhyachal Back-to-back(WR-NR)	500 MW (1989)
2	Rihand-Delhi	1500 MW ± 500 kV 820 km, Bipolar (1991)
3	Chandrapur, Padghe	1500 MW, ± 500 kV, 850 km Bipolar 1998
4	Chandrapur Back-to back (WR-SR)	1000 MW (1996)
5	National Experimental HVDC (Barsur-Lower Silera)	± 100 MW, 250 kM (1992)
6	Gujwaka-Jaypur Back-to-Back (SR-ER)	1000 MW, (2000)

Note : WR = Western Region NR = Northern Region
SR = Southern Region ER = Eastern Region

48-A

EHV — AC Transmission Systems and Static VAR Sources

Hierarchical levels in Transmission systems—Characteristics of transmission systems—Design aspects : Electrical, mechanical, structural—Power transferability of AC lines and DC lines—Choice of voltage of AC lines and DC lines—Transient stability limit—Control of power flow—Short circuit levels—Voltage control and reactive power compensation—Insulation co-ordination and surge arrester protection—Conductor design, corona, radio interference— Subsynchronous resonance—Static VAr Sources (SVS).

48.1. GENERAL BACKGROUND OF EHV-AC TRANSMISSION

Modern civilization depends heavily on the consumption of electrical energy for industrial, commercial, agricultural, domestic and other purposes. Electrical power is generated in large thermal, hydro, nuclear power stations. The energy transfer from these generating systems to distant distribution networks is *via* transmission systems. The modern electrical power system is in the form of a large interconnected network. The generating stations, transmission and distribution systems are interconnected by means of 3 phase AC system operating synchronously at the common single frequency of 50 Hz (60 Hz in USA). The total network covers a vast geographical area.

The basic function of a transmission system is to transfer (convey) electrical power from one location to another location or from one network to another network. A transmission system includes terminal sub-stations, transmission lines and intermediate sub-stations.

Transmission system are necessary for (1) bulk power transfer from large group of generating stations upto the main transmission network (2) for the main transmission network (3) for system interconnection and (4) for transfer of power from the main transmission network to the distribution sub-stations.

A transmission system is used either for transfer of power from sending-end to the receiving-end or for system interconnection for exchange of power between independently controlled networks.

The network of transmission and distribution lines is formed by three-phase alternating current system. For longer lines and higher power transfer, higher transmission voltages are necessary, ($P \propto V^2$). Higher voltage gives lesser current, lesser $I^2 R$ line losses, higher power transferability.

As a rule, higher the power rating higher is the requirements of transmission voltage. Longer the lines, higher is the required transmission voltage. In the ending-end sub-station, the voltages are stepping up and then transmitted. At the receiving end the voltage may be appropriately stepped down by using power transformers.

Upto 1970's, the choice was exclusively in favour of high voltage AC (upto 220 kV) and extra high voltage AC (above 220 kV, upto 760 kV, AC).

By 1990's Ultra High Voltage AC (1000 kV, 1100 kV, 1200 kV) transmission lines were introduced for bulk power transfer in USSR, USA, Canada etc.

First commercial High Voltage Direct Current transmission system (HVDC) was introduced during 1953. With the successfully development of high power thyristor valves in early 1970's the HVDC transmission systems have become a technically and commercially viable alternative to