1
General Background

1·1. Introduction

Modern civilization depends heavily on the consumption of electrical energy for industrial, commercial, agricultural, domestic and social purposes. Electrical power is generated in large thermal, hydro, nuclear power stations. The energy is transferred from these generating systems to distant distribution networks *via* the transmission systems. The modern electrical power system is in the form of a large interconnected 3 phase AC network. The generating stations, transmission and distribution systems are interconnected to form a 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 electrical power supply undertaking aims at the following:

— Supply of required amount of power to all the consumers over the entire geographical area at all times continuously.

— Maximum possible coverage of geographical area.

— Maximum security of supply and minimum fault duration.

— Supply of electrical power within targetted limits of frequency (49 Hz – 51 Hz).

— Supply of electrical power within specified limits of voltage (*e.g.* variation within ±5%), with specified waveform.

— Supply of energy at lowest cost.

Transmission systems form a very important part of the Network for fulfilling the above mentioned tasks. 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 substations, transmission lines and intermediate substations, associated controls, protection, auxiliaries etc.*

Transmission systems 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 substations. Important considerations include power transfer and distance.

Transmission systems are planned along with the Generation Planning. The planning deals with the requirements of new transmission lines and substations.

1·2. Trends in Transmission Voltages

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.

The *Electrical Power System (Network)* is formed by a 3 phase, 50 Hz, AC System with several AC voltage levels for generation, transmission, distribution and utilisation. Choice of transmission voltage depends on power and distance. AC power transformers are installed in various transmission and distribution substations and near load points to step-up or step down AC Voltages to required levels. The entire AC Network operates synchronously at common prevailing frequency (50 Hz, ± 3%). 3 Phase AC System has a tendency to operate naturally in synchronism and the operation and control is very easy. Power transfer through an AC transmission link is given by

$$Pac = \frac{|V_1| \cdot |V_2|}{X} \sin \delta \qquad \text{... Watts/ph.}$$

where $|V_1|$ is sending-end voltage magnitude, $|V_2|$ is receiving – voltage magnitude, δ is power angle between V_1 and V_2 phasors, X is the series reactance. We will consider high power transmission links, long transmission links and system interconnections only. We note that power transfer P_{ac} is proportional to square of voltage $|V|$. In an AC Network AC Power transfer through a particular AC line *cannot be controlled easily, quickly and accurately*. The sin δ causes transient stability limit which is almost 50% of steady state limit. Reactive power flow causes additional ($I^2 Rt$) transmission losses and voltage regulation problems. For long lines and for higher power transfer, higher transmission voltages are necessary. (220 kV, 400 kV, 750 kV AC).

AC voltage above 220 kV are called *Extra High Voltage AC (EHV AC)*. The transmission network is formed by 3 phase EHV AC and HV AC transmission lines and substations.

For very long, high power transmission lines (> 800 km ; > 1000 MW), for System Interconnections between two or more independently controlled AC Networks (Regional Grids) and for long submarine cables. *High Voltage Direct Current Transmission (HVDC)* links are preferred due to technical and economic superiority over equivalent EHV AC transmission links for same power/distance.

Nominal Power transfer through an HVDC Link is given by :

$$P_{dc} = U_d \, . \, I_d = [(U_{d1} - U_{d2}) / R] \, U_d \qquad \text{...Watts/pole}$$

where, U_d is nominal DC Voltage. I_d is DC current, R is line resistance. R is small, reactance X is absent, hence a small change in $(U_{d1} - U_{d2})$ gives a large change in P_{dc}. *The HVDC power transfer can be controlled quickly and accurately by thyristor control and tap changer control.* There are no problems of reactive power flow, voltage fluctuations and high transmission losses. However HVDC voltages cannot be easily stepped up or stepped down. HVDC requires costly and complex substations, high technology, complex controls.

The Modern Transmission Network continues to be of 3 phase 50 Hz, AC System with a few specific HVDC links integrated with the 3 phase AC Network. HVDC links are considered only for specific projects such as :

— A few long high power, point to point, 2 terminal HVDC Transmission Systems. (*e.g.* ± 500 kV, 1500 MW, 820 km, Rihand-Delhi Bipolar 2T HVDC System (UP, India, 1992) : ± 500 MW 1500 MW, 850 km Chandrapur-Padaghe Bipolar 2T HVDC System (Maharashtra, India, 1997)

— Back to Back Interconnecting HVDC Coupling Systems between Regional Grids (*e.g.* Vindhyachal Back-to-Back, 500 MW Link between Western Region and Northern Region, India (1989) ; Chandrapur Back-to-Back, 1000 MW Link between Western Region and Southern Region, India, 1996)

— Multi-terminal HVDC Interconnecting Systems (*e.g.* 5-Terminal Hydro-Quebeck : New England, USA/Canada, 1987-96)

— High Voltage long high power Cable transmission. (*e.g.* UK/France submarine Link, 2000 MW, 65 km)

HVDC Solution is not for general purpose transmission/distribution network.

During 1980's Ultra High Voltage AC (above 760 kV) transmission lines have been introduced for bulk power transfer in USSR, USA, Canada, Western Europe 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 EHV/UHV AC transmission particularly for (1) long distance bulk power transmission; (2) Submarine cable transmission and (3) system interconnection. For these three applications HVDC transmission systems have a distinct superiority over EHV-AC and are being increasingly preferred.

Upto 1980, all the HVDC transmission systems have been with

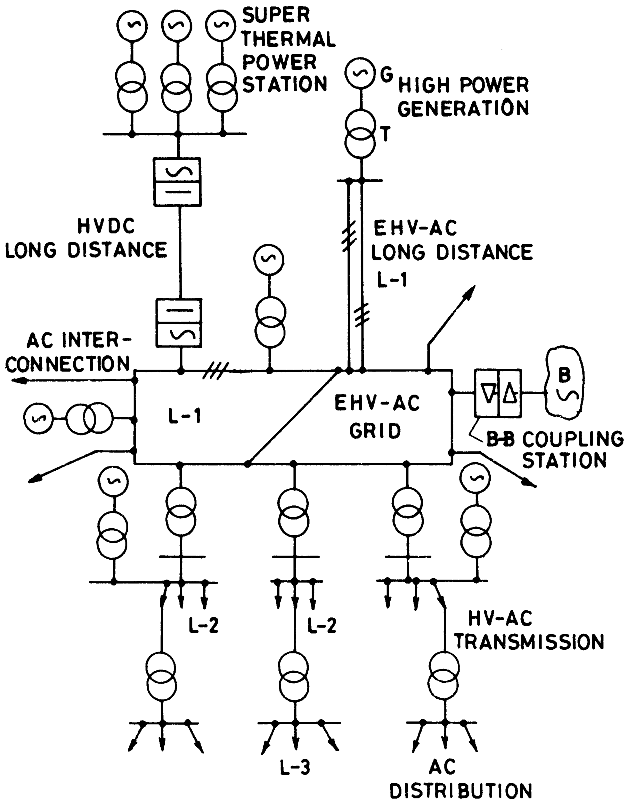


Fig. 1·1. Hierarchical Voltage Levels in transmission network.

point-to-point transmission, without intermediate substations for T-offs. The first multi-terminal HVDC transmission system has been commissioned during 1988. Some large multi-terminal HVDC systems have been executed. HVDC transmission is likely to be preferred for multiterminal interconnecting system as well as for back-to-back coupling stations.

Thus, the choice of transmission systems and rated voltages for a transmission line is made from HV AC (upto 220 kV); EHV AC, (between 400 kV and 760 kV AC); UHV-AC (above 760 kV AC) and HVDC (upto ± 600 kV DC) depending upon technical and economic considerations.

The Network is formed by several HV, EHV (AC) lines with a few HVDC systems (Fig. 1·1).

The following tables gives the reference values of transmission voltages.

Table 1·1
Reference values of Transmission Voltages for 3 Ph AC line

Nominated Rated Voltage kV, rms, Phase to Phase	132,	220,	275,	400,	500,	750,	1000,	1200

Table 1·2
Reference values of Transmission Voltages of Bipolar Overhead HVDC Transmission

Rated Voltage Pole to earth kV, DC.	± 100,	± 200,	± 300,	± 400,	± 500,	± 600

With the increasing requirement of longer lines and higher line loads, the highest transmission voltages have increased over the years (Fig. 1·2).

1·3. Hierarchical Levels of Transmission and Distribution

During 1950's small isolated transmission systems were generally adequate for limited geographical coverage. Such networks were formed by a few radial out-going transmission lines from generating stations.

Modern Transmission systems are interconnected networks and cover a vast geographical area and transmit a large amount of power from various generating stations to the various substations. For systematic power transmission and control; the network is divided into three hierarchical level of transmission and distribution (Ref. Fig. 1·1).

(1) Back-bone or Main Transmission Network (EHV-AC)

(2) Sub-transmission Network (HV-AC)

(3) Distribution Network (MV-AC, LV-AC)

Table 1·3
Functions of Hierarchical Levels in Transmission and Distribution Network

Level Title	*Function*	*Remarks*
1. Back-bone EHV-AC Network. (Main transmission)	—To receive power from generating stations and long bulk power EHV-AC/HVDC transmission lines —To deliver power to Sub transmission system *via* HV transmission lines.	—In meshed or Ring Form. —Interconnected with neighbouring network. —Generally EHV-AC lines (400 kV or 760 kV). r.m.s., ph. to ph. —Generally double circuit for radial lines.
2. Subtransmis-sion Network (underlying below the back-bone network)	—To receive power from the back-bone network and some local power stations —To deliver power distribution system *via* HV transmission lines	—Less meshed —More radial lines —Generally at High voltage AC (220 kV, 132 kV) r.m.s., ph. to ph.
3. Distribution network.	—To receive power from the sub-transmission Network and —To deliver power to consumers	—Medium Voltage AC and Low Voltage AC 33 kV, 22 kV, 11 kV, 3·3 kV 415 V, ph. to ph.

The EHV-AC Network receives power from large power stations. *Back-bone transmission Network* is of EHV-AC lines. It is in a ring form (mesh). The long bulk power transmission lines between distant super thermal power stations and this network are either EHV/AC or HVDC. Super thermal power stations and super hydro power stations are generally located far away from load centres.

The division between the Main and Secondary Transmission is not very rigid. Their functions and coverage overlap.

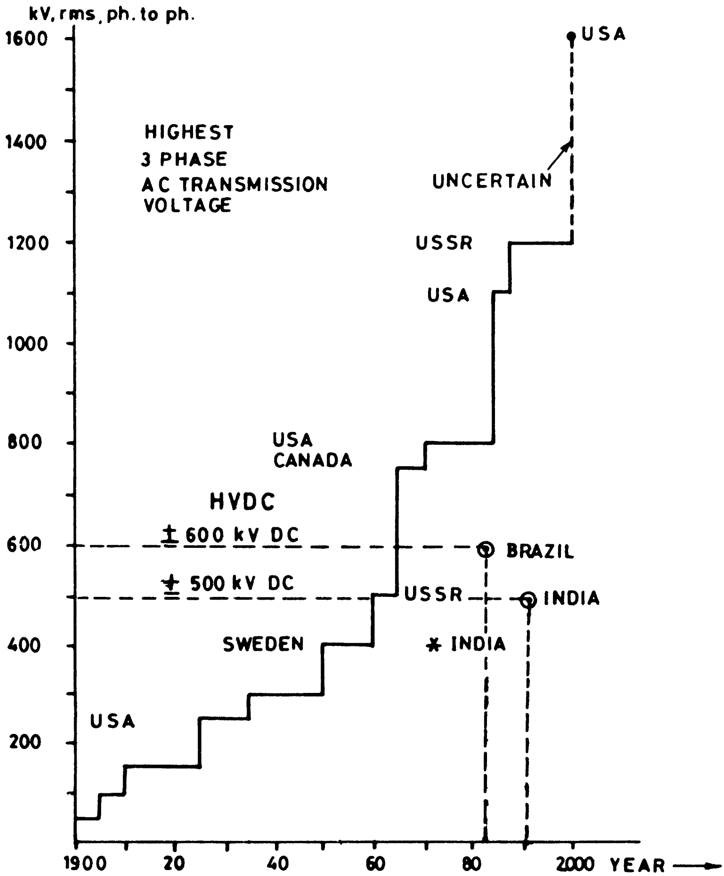


Fig. 1·2. Trend of increasing highest transmission voltages in the world.

Interconnections between neighbouring Networks between neighbouring independently controlled AC Networks are by one of the following :

— Overhead HV/EHV AC lines or
— Overhead HVDC lines, or
— Underground/Underwater HVDC cable
— Back-to-back HVDC Coupling stations
— Multi-terminal HVDC interconnecting system.

1·4. Tasks of Transmission Systems

The tasks associated with transmission systems include :

- Transmission of electric power at specified voltage and frequency.
- Control of flow of power with respect to magnitude and direction.
- Ensuring steady state stability and transient stability of the transmission link and associated AC Networks.
- Control of flow of reactive power.
- Voltage control at sending-end and receiving-end of transmission lines.
- Assistance in frequency control by rapid exchange of power.
- Network segregation (Islanding) in the event of a major fault.
- Security of supply by feeding at various points, providing adequate line capacity, facility for alternate transmission paths.
- Data transmission *via* Power line carrier communication channel (PLCC) for the purpose of telemetry, telecontrol and network automation.
- Minimise transmission losses by selecting shorter transmission paths.
- Adequate protection, minimum faults and minimum fault-duration. Pinpointing location of fault, causes and subsequent improvements.

For convenience the transmission lines, substations, distribution circuits and generating stations are identified separately. However the Network is homogeneous. The function of these parts overlap. Each part has a significant influence on the others.

1·5. The Choice of a Transmission System

A transmission system includes : the terminal substations, intermediate substations, transmission lines and associated controls and auxiliaries etc.

The choice of the voltage is made from HVAC, EHV-AC, HVDC on the basis of the following economical and technical considerations.

Economic Considerations

- Capital cost of transmission systems :
  * Cost of line conductors, towers, insulators, installation land/right of way.
  * Capital cost of substations, intermediate substations,

compensating substations, conversion substations, substation equipment like transformers, switchgear; substation area, buildings.

— Cost of energy losses, maintenance.
— Needs of future expansion and associated cost.
— Economic aspects related with availability, reliability.
— Economic strategy for Energy Transmission.

Technical Considerations

— Length of the transmission line and total power to be transferred
— Control over Power Transfer, magnitude, rate of change.
— Existing network and long term plans.
— Choice of voltage considering power flow.
— Stability considerations related with power flow and frequency disturbances.
— Reliability and security of power flow. Availability of transmission link.
— Reactive power compensation and voltage control.
— Switching requirement.
— Right of way for transmission lines.
— Radial or Mesh.
— 2T or 3T or MT.
— Type of line : Overhead/underground/submarine cables.
— Network configuration, parallel lines, T-offs, multi-terminals etc.

1·6. Application of EHV-AC Transmission

EHV-AC lines have the following inherent merits :

— Voltage can be stepped-up or stepped-down in transformer substations to have economical transmission voltage.
— Lines can be tapped easily, extended easily.
— Parallel lines can be easily added.
— Control of Power flow in the Network is simple and natural.
— Power flow in a particular line cannot be controlled easily and quickly.
— Equipments are simple and reliable without need of high-tech.
— Operation is simple and adopts naturally to the synchronously operating AC systems.
— Generation and distribution is by AC.

EHV-AC or HV-AC transmission links may be used for one of the three following functions :

1. Backbone transmission network.
2. System interconnection.
3. Connection between distant generating centres (energy parks) and the AC network.
4. Subtransmission network.

However for (2) and (3) above, the HVDC forms a strong alternative to EHV-AC. In case of interconnection, HVDC has technical superiority. In case of long distance bulk power transmission, HVDC has economical superiority. For the backbone EHV-AC network and subtransmission network, AC transmission has unquestionable superiority.

1·7. Configuration of an EHV-AC Transmission Link

Fig. 1·3 gives the typical configuration of a very long EHV/UHV three phase AC transmission system.

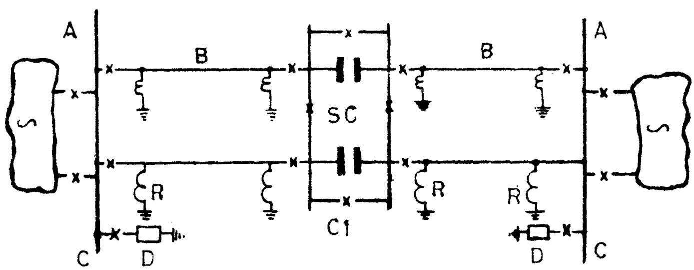


Fig. 1·3. Schematic diagram of an EHV-AC transmission line.

A AC Substations at terminals connected to AC networks
B Transmission line, three phase AC, double circuit
C Busbars in substations
C_1 Intermediate substation
R Shunt reactor
D Shunt compensation or Static VAr Source (SVS)
SC Series capacitors
X Circuit-breaker.

The complete transmission system has the following parts :

— AC system at terminals
— AC terminal substations.
— AC transmission lines, at least two parallel three phase AC circuits per path.
— One or more intermediate substations
— Static VAr system (SVS) incorporating thyristor controlled shunt reactance and shunt capacitance.
— Shunt reactors.

A long AC transmission link needs at least two parallel three phase transmission circuits to ensure reliability and stability during a fault on any one phase of the three phase lines.

A long AC transmission link has one or more intermediate substations for installing series capacitors, shunt reactors, switching and protection equipment. Generally an intermediate substation is required at an interval of 250 to 300 km.

The long AC transmission line takes lagging reactive power (kVAr) during heavy loads and leading reactive power (kVAr) during low load resulting in low receiving voltage during heavy loads and high receiving end voltage during low loads. However, substation bus voltage should be held within specified limits (about ± 10% about rated voltage). Hence Static VAr Sources (SVS) or conventional shunt reactors and shunt capacitors are necessary as terminal substations for controlling Volt-Ampere Reactive (VAr) and voltage.

1·8. Special Features and Technical Consideration for EHV-AC Lines

The significant aspects about EHV-AC transmission systems include the following :

1. The most important requirement of an EHV-AC transmission line is power transfer ability based on transient stability limit.

$$Pac = \frac{|V_1| \cdot |V_2|}{X} \sin \delta$$

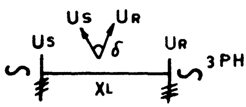
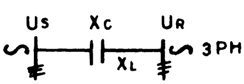
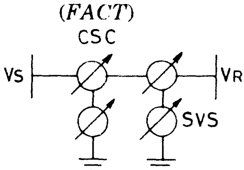
   at $\delta = 30°$, $\sin \delta = 0{\cdot}5$. Hence AC line can transfer only 50% of its steady state power limit.

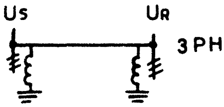
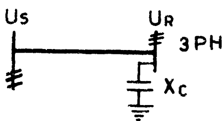
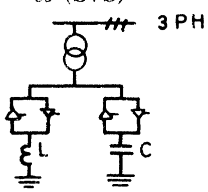
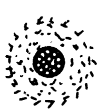
2. EHV-AC line needs compensation of reactive power. This is provided by SVS ; shunt reactors, Shunt capacitors, etc. installed in sub-stations. Intermediate substations are necessary at interval of 250 km to 400 km.
3. Power transfer ability of EHV lines may be increased by using series capacitors or adding a parallel line. For high power lines several parallel circuits may be necessary.
4. The line design is based on limits of corona, radio interference, TV interference, electrical field at ground level, etc.
5. For EHV-AC lines the voltage stress at conductor surface should be kept below critical voltage. For achieving this, the use of bundled conductors is essential. Bundle conductors reduce the corona losses, Radio Interference, TV Interference.
6. Switching surges occur during opening and closing of unloaded lines. Line insulation is designed on the basis of switching overvoltages. Appropriate circuit-breakers and compensation is necessary to limit switching surges. Insulation co-ordination is achieved with the use of suitable surge arresters.
7. EHV-AC lines and Network have high short-circuit levels and associated protection problems. HVDC interconnection limits the short-circuit levels of both the AC networks.

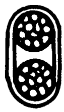
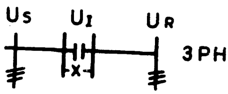
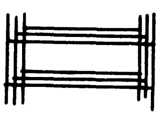
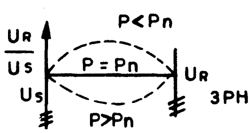
8. EHV-AC lines experience power swings during system disturbances, switching and faults. Protection of EHV-AC lines is designed to block during low power swings.
9. EHV-AC lines transmit bulk power. Outage of a line causes stability problems in the network. Hence alternative transmission paths should be planned along with the protection system design. For each radial line, at least two three phase circuits are necessary.
10. In large interconnected networks, the effect of a major fault in one of the networks can result in cascade tripping and a large scale blackout. To prevent this the Network Segregation is carried out. HVDC interconnection eliminates the problem of cascade tripping.

Table 1·4

Engineering Aspect of EHV-AC Transmission

Aspect	*Significance*	*Remarks*
1. *Power transfer ability, Transient stability limit.*  $P = \frac{U_S U_R}{X_L} \times \sin\delta$ Fig. 1·4·1	— The maximum power transfer from sending end to receiving end is limited by the power transfer ability of the line. — Choice of voltage is decided by the required power transfer distance. — Choice of number of parallel lines depends on required power transfer. — $P_{max} = \frac{\lvert U_S \rvert \cdot \lvert U_R \rvert}{2X}$ Occurs at $\delta = 30°$, $\sin\delta = 0{\cdot}5$	— Power transfer ability (Ps) of an EHV-AC line is limited by transient stability limit. — Higher voltage gives higher Ps. — Series reactance of line reduces the power transfer ability. — AC line cannot be loaded upto thermal limit of conductors due to the transient stability limit.
2. *Series Capacitors*  $P = \frac{U_S U_R}{X_L - X_C} \sin\delta$ Fig. 1·4·2	— Series capacitors may be provided with long EHV-AC Lines for increasing the power transfer ability. — The power transfer ability is increased by reducing series reactance. — Line losses one reduced.	— Series capacitor are installed in either. (1) Sending-end and receiving end substation. or (2) Intermediate substation.
3. *Flexible AC Transmission (FACT)*  Fig. 1·4·3	— AC Transmission with controlled SVS and SC at regular intervals.	— For medium high power lines, with power control.

Aspect	*Significance*	*Remarks*
4. *Shunt Compensation by Shunt Reactors.*  Fig. 1·4·4	— During low loads the shunt capacitive reactance of transmission line is predominant. The voltage at receiving end rises. — Shunt reactors are necessary for compensating the capacitive VArs of the line and thereby regulating voltage within desired limits.	— Shunt reactors are installed in sending end substation, receiving-end substation and intermediate substations. — For very long lines shunt reactors are installed at an interval of about 250 km in intermediate substations.
5. *Shunt Compensation by Shunt capacitors*  Fig. 1·4·5	— During heavy lagging power factor loads, the line series reactance causes voltage drop. The receiving end voltage drops. Shunt capacitors at receiving end are switched in for compensating reactive power absorbed by a lagging loads.	— Shunt compensation by static shunt capacitors is provided at distribution level and secondary transmission level.
6. *Static VAr Sources (SVS)*  Fig. 1·4·6	— Need of shunt compensation varies rapidly with varying load. During low loads, shunt reactors are necessary and during heavy loads, shunt capacitors are necessary. These requirements are fulfilled by Static VAR sources (Static Voltampere Sources) connected in substations. — SVS gives rapid stepless control of voltages and reactive power flow (± Q)	— SVS has capacitor, reactor branches. The current in these branches is controlled by thyristors. — During low loads, current through reactor increased. — During high loads current through capacitive branch increased.
7. *Corona*  Fig. 1·4·7	— During bad weather when the surface voltage gradient of a conductor exceeds the dielectric strength of air, ionization occurs and corona discharge takes place at sharp points. — Corona causes power loss, audible noise, Radio interference, Television interference. — Conductor design, hardware design is based on corona inception.	— Choice of conductor is based on consideration of (1) fair weather noise level (2) foul weather level. — Occasional corona loss of short durations occuring during foul weather is accepted for economical design of conductor.

Aspect	*Significance*	*Remarks*
8. *Bundled conductors*  Fig. 1·4·8	— Used universally for rated voltages above 220 kV for reducing corona loss, *RI, TVI.* — Two or more sub-conductors per phase are suspended with spacers at regular interval.	— Bundled conductors give reduced line reactance, corona loss — Diameter of conductor per phase increased
9. *Intermediate substations*  Fig. 1·4·9	— EHV-AC and UHV-AC lines require intermediate substations at an interval of 250 for installing shunt compensation equipment, and T-offs.	— Intermediate substations increases the capital cost of EHV-AC lines.
10. *Number of circuits*  Fig. 1·4·10	— For long radial lines at least two three phase circuits are essential. — Stability of Transmission path must be considered.	— The number of circuits required is calculated from present and future load requirement and power transfer ability per circuit.
11. *Surge Impedance loading (Pn)*  Fig. 1·4·11	— When the receiving end is loaded with resistive load equal to $\sqrt{L/C}$ the line is said to have unit surge impedance load (Zs) or Natural load. — Surge Impedance Load gives guideline for load capability of line.	— Long lines can be loaded upto less than 1 Pn. — Medium lines can be loaded upto 1 Pn. — Short lines can be loaded above 1 Pn.

1·9. Choice of Voltage for EHV-AC Transmission Lines

The choice of transmission voltage basically depends on :

1. Distance of transmission (V = app 1 kV per km)
2. Power to be transmitted ($P \alpha V^2$)
3. Existing network voltages, available technology, etc.

The voltage is selected on the basis of technical and economic considerations.

To transfer more power, higher transmission voltage is necessary. *Power transfer limit is proportional to the square of rated* *voltage*. For the same powers the line losses reduce with higher rated voltage due to reduction in current. With higher voltage, conductor cross section requirements are reduced. Thereby conductor cost reduced. But the cost of insulation, tower, compensation equipment etc. increased with voltage.

Extra high voltage (400 kV, 750 kV) are necessary for transfer of large blocks of power over longer distances.

For every transmission project, the economic studies are carried out and cost of power transmission (Rs./k Whr) is estimated for various power transfer. Different curves are drawn. From these curves the choice can be identified. (Fig. 1·5).

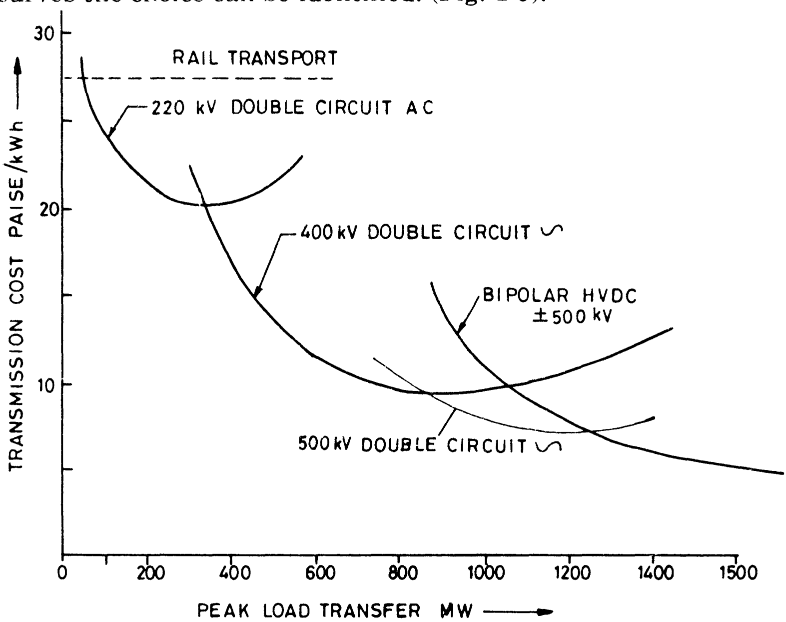


Fig. 1·5. Comparison of Transmission cost.

For higher power and longer distance, higher transmission voltage is essential from stability considerations.

1·10. Standard Rated Voltage of EHV-AC and HVDC

Standard rated voltages for AC transmission and HVDC transmission are given in Table 1·5 and 1·6. The choice is made from these. For choice of a new line, the nearest existing system voltage is preferred.

New transmission voltage level is introduced after detailed survey, technical studies, economic studies and acceptance of feasibility reports. Transmission systems are planned along with the Generation Planning.

Table 1·5
Standard Voltage (IEC) for 3 Ph. AC Overhead lines

Description	*HV*	*EHV-AC*	*UHV-AC*
Rated voltage (Nominal) kV, rms. ph. to ph.	132 220	345 400 500	750 1000 1150
Highest voltage kV, rms. ph. to ph.	145 245	362 420 525	765 1050 1200

Table 1·6
Reference values for HVDC overhead lines

Description	*Rated voltage, kV DC**					
Bipolar voltage pole to ground	± 100	± 250	± 300	± 400	± 500	± 600
Voltage between two poles	200	500	600	800	1000	1200

* 'Pole' refers to conducting path having same polarity with respect to earth. In bipolar line, one pole is positive and other pole is negative. Pole to pole voltage is twice pole to ground voltage. *e.g.* ± 500 kV = 1000 kV pole to pole.

1·12. Number of EHV-AC Line Circuits and Intermediate Substation

A single EHV-AC line circuit has a certain power handling capacity based on surge impedance loading and compensation say 1 Pn.

A flash-over on any one phase of a three phase line trips the total three phase line. Hence an additional parallel three phase line is always provided to maintain continuity of power flow and transmission stability.

Thus a long three phase EHV-AC line is always a double circuit line. Intermediate substations are required at an interval of 250 to 400 km for providing compensation of reactive power. If bulk power Pb is to be transferred by EHV-AC lines over a distance of say 900 km the minimum number of line-circuit will be

$$n = \frac{Pb \times 2}{Pn}$$

where n = Number of three phase circuits
Pb = Total power to be transferred
Pn = Natural load of one line
2 = Factor for double circuit.

Number of line conductors per circuit is 3 and for n circuits is $3n$.

Number of AC line conductors = 3*n*

$$= \frac{Pb \times 6}{Pn}$$

Number of intermediate substations (*Ns*) would be

Ns = (Length in km/300 – 1).

For bulk power long distance transmission, EHV-AC line, requires 6 to 24 Number of conductors. (Each conductor is in the form of a bundle conductor). HVDC line generally requires only two conductors (Ref. Table 1·7).

Table 1·7

EHV-AC Lines for different powers and lengths

Length km	*Power MW*	*Number of 3 Ph. AC lines n*	*At rated voltage kV*	*Number of line conductors 3n*
250	1000	2 × (2)	400	12
500	1000	2 × (2)	400	12
800	1000	3 × (2)	400	18
1000	1000	4 × (2)	400	24
1000	1000	2 × (2)	750	12
1000	2500	4 × (2)	400	24
1000	2500	2 × (2)	750	12
1000	3000	2 × (2)	750	12

— HVDC requires a single bipolar line up to app. 3000 MW over very long distance.

— EHV-AC line requires a double circuit line for each transmission path.

1·13. Definitions Related with EHV-AC Transmission Systems

Power system. A system comprising installations of generators, transformers switchgear, lines etc. for generation, transmission, conversion, distribution of electrical energy.

Network. An individual electrical system in which the conductors and apparatus are connected. The network includes the conductors and associated apparatus.

Radial Network. The network consisting of radial circuits.

Meshed Network. The network consisting of ring circuits with connections of sources and loads to the ring.

Interconnection. Connection by one or more lines or coupling-stations between two or more AC-systems.

Feed point. A point in which the network receiver power.

Supply point. A point at which the consumer receives power.

Electrical Line. A generic term for a set of conductors, insulators and accessories used for transmission and distribution.

Feeder. A line which supplies power without being tapped.

Branch. A line tapped off from a more important line.

Single circuit line. An overhead line having one circuit (generally three phase).

Double circuit line. An overhead line comprising of two separate circuits of the same network, and installed on same support.

Bundle conductors (Multiple conductors). A number of solid or stranded conductors held apart by spacer and connected in parallel.

— Double conductors or twin conductors has two solid or stranded conductors, for each phase/pole.

— Triple conductor has three conductors, for each phase/pole

— Quadruple conductors has four conductors, for each phase/pole

Load on transmission line. The electrical power conveyed at any instant, MW.

EHV-AC. Extra high voltage alternating current (system) (usually 275 kV and above).

UHV-AC. Ultra high voltage alternating current (system) (usually 1000 kV and above).

1·14. Applications of HVDC Transmission System

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 systems are preferred.

— Long distance high power transmission by overhead lines.

— Medium and long high power submarine or underground cables.

— System interconnection by means of overhead lines or underground/submarine cables or back to back HVDC coupling stations.

— Multi-Terminal HVDC System for interconnecting three or more 3 phase AC systems.

— Frequency conversion (60 Hz — 50 Hz ; 50 Hz — 25 Hz)

— Incoming lines in megacities.

An HVDC link has an AC system at each end. The AC power is converted by thyristor-convertor valves into DC power. The energy is transmitted in HVDC form to the other end. At the other end the DC power is inverted in thyristor-convertor valves and fed into the receiving system. Fig. 1·6 illustrates a typical bipolar HVDC link.

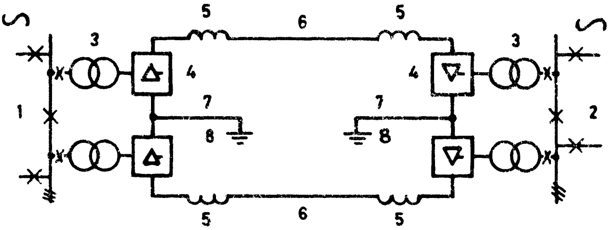


Fig. 1·6. Schematic diagram of an HVDC Transmission System.

1, 2. AC systems at terminals, terminal AC substations
3. Convertor transformers
4. Thyristor valves of convertor
5. Smoothing reactor (HVDC)
6. HVDC transmission line (Bipolar)
7. Electrode line
8. Earth electrodes.

An 2-Terminal HVDC transmission system has an HVDC convertor substation at each end and an HVDC transmission line in between. In case of back-to-back coupling station, the rectifier and inverter are at the same place and there is no HVDC line. A back-to-back HVDC station provides an asynchronous tie between two adjacent AC Networks.

1·15. Choice of HVDC Transmission System

HVDC system are selected as an alternative to extra high voltage AC transmission systems for any one or more of the following reasons : (Table 1·8 gives summary).

1. **Long, high power transmission.** For long distance high power transmission lines HVDC transmission systems are preferred due to their economic advantage and exact, fast and easy control of power flow from generating station to load centre. Though HDVC system needs costly terminal substations, the line cost is lower than that of equivalent AC line. Power flow can be controlled. Line losses are low.

The per km cost of HVDC line is lesser than that of an equivalent 3 phase double circuit AC line. For equal power transfer, the number of conductors for 3 phase AC line is 6 to 24 as against only 2 numbers required for Bipolar HVDC line. HVDC line does not need intermediate substation for compensation, whereas for EHV-AC line intermediate substation is required at an interval of 300 km. HVDC becomes favourable above 800 km, 1000 MW, when cost of EHV-line/substation exceeds that of equivalent HVDC line/substation. (Ref. Sec. 1·20).

2. **System Interconnections.** For Interconnection (Tie-lines) between two AC systems, HVDC transmission links are being increasingly preferred.

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.

AC interconnection provides synchronous link, Frequency disturbances are transferred quickly to other terminal. HVDC provides asynchronous tie. Frequency disturbance are not transferred from one end to other.

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 of connected AC Networks can be greatly improved.

HVDC interconnection can provide a weak tie (of lesser capacity) between a strong and a weak AC Networks. 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 Networks to maintain transient stability. AC interconnector have limitations (Ref. Table 1·13). HVDC interconnections are without such limitations.

More and more HVDC interconnections are being added on the power map of the world, and of India.

3. **Back-to-back asynchronous tie sub-stations.** In back-to-back HVDC coupling stations the interconnection is by a converter-substation without any transmission line. The HVDC inverter and rectifier are installed in the same station. Such a tie-link gives an asynchronous interconnection between two adjacent independently controlled AC networks. The back-to-back coupling stations are installed at a suitable locations where two networks meet geographically. The exchange of power can be controlled effectively without transferring frequency disturbances.

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 system. Power flow from each connected AC Network can be controlled suitably. Large power can be transferred. Overall stability can be improved. At present only a few such schemes are in operation. More and more multiterminal HVDC schemes are expected.

5. **Cable Transmission.** HVDC is preferred for underground or submarine-cable transmission over long distance at high voltage. The submarine cables are necessary to transfer power across oceans,

lakes 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 an AC cable cannot be used to transfer load current due to thermal limit. HVDC cables have no continuous charging currents and can transfer bulk power over long distances.

At present 40 HVDC links have been installed in the world and by the year 2000, about 50 links are expected with a total transfer capacity of 50,000 MW. The choice between 400 kV a.c. 760 kV a.c., 1200 kV a.c. and HVDC transmission alternatives are made on the basis of technical and economic studies for each particular line and associated a.c. systems. Alternating current continuous to be used for generation, transmission, distribution and utilization of electrical energy.

Table 1·8

1·15. **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 ±600 kV, 2200 MW	**Lower total cost of HVDC Link. Better control on power flow.** — Less number of line conductors. — No need of intermediate substations. — Simpler and economical tower. — Line cost per km lower — Higher substation cost — Break-even above about 800 km, 1000 MW.	— Normal mode Bipolar. — Two terminals — Can be operated in monopolar mode. — Power flow control rapid, accurate
2. **System Interconnection** — Overhead line — Underground or submarine cable — Back-to-back station without cable/line. — MTDC System	**Technical Superiority** — Provides asynchronous ties. — Power flow can be quickly controlled. — Improved stability — Fault levels remain unchanged. — Strong AC Network can be connected to week AC network. — Frequency conversion possible (50 Hz/60 Hz) — Right-of-way is of lesser width.	— Usually two terminals. — Overhead lines simpler ; may be monopolar or bipolar — Coupling stations have no transmission line. — Multi terminal HVDC inter-connection introduced recently (1987).
Submarine cables *e.g.* ± 100 kV, 500 MW ± 400 kV, 2000 MW	**Technical .superiority of HVDC link** — No continuous changing current. — No limit of power or distance.	— Two terminals — Recently bipolar

1·16. Terms and Definitions Related with HVDC Transmission

HVDC. High Voltage direct current (system)

HVDC transmission system. An HVDC system which transfers energy in the form of high voltage direct current.

Two terminal HVDC system. An HVDC transmission system consisting of two transmission substations and connecting DC transmission line.

Multiterminal HVDC system (MTDC system). An HVDC transmission system consisting of more than two transmission substations and interconnecting DC transmission lines.

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 substation.*

HVDC transmission line. A part of HVDC transmission system consisting of overhead lines and or underground cables connected to HVDC transmission substations at terminals.

HVDC Terminal Substation. A part of an HVDC system which consists of one or more convertor units installed in a single location together with buildings, reactors, filters, reactive power supply, control, monitoring protective measuring and auxiliary equipment, AC yard, DC yard, Valve Hall, etc.

HVDC system pole. (abbreviated to 'pole') A part of an HVDC system consisting of all the equipment in the HVDC substations and interconnecting transmission lines (if any) which during normal operating condition exibit a common direct polarity with respect to earth (Associated convertor transformers are included).

Substation pole. The part of an HVDC system pole which is connected within a substation.

HVDC transmission line pole. A part of an HVDC transmission line which belongs to the same HVDC system pole.

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

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

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

Convertor unit. An operative unit comprising one or more convertor bridges together with one of 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 6-pulse convertor bridges in series, with a phase displacement of 30°, then the convertor unit is called a 12 pulse unit.

Valve. A completed 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 convertor connection.

Rectifier operation (Rectification). The mode of operation of a convertor or a convertor substation when the energy is transferred from AC side to DC side. The delay angle (α) is kept less than 96° elec.

Inverter operation. The mode of operation of a convertor or a convertor substation when energy is transferred from DC side to AC side. Delay angle is kept above 90° elec.

1·17. Types of HVDC Systems : Bipolar, Monopolar, Back-to-back

The type of an HVDC Transmission system is identified on the basis of the arrangement of the pole and earth return (Fig. 1·7). Modern HVDC systems have thyristor convertors. A convertor AC to DC or DC to AC.

The word 'pole' refers to the path of direct current which has same polarity with respect to the earth. The total pole includes substation pole and transmission line pole.

The types of HVDC systems include the following :

1. **A bipolar 2-T HVDC transmission system.** This has two poles, one positive and the other negative with respect to the earth. This type is used for all high power point-to-point transmission systems.

During fault on one pole, the Bipolar system is changed to Monopolar Mode.

2. **A monopolar HVDC transmission system.** This has one pole and earth return.

3. **A homopolar HVDC transmission system.** This has two poles of same polarity and return earth. Such a system is not used any more.

4. **A back-to-back HVDC coupling system.** This has no DC transmission line. Rectification and Inversion is done in the same substation by a back-to-back convertor.

5. **Multi-Terminal HVDC System.** It has three or more terminal substations.

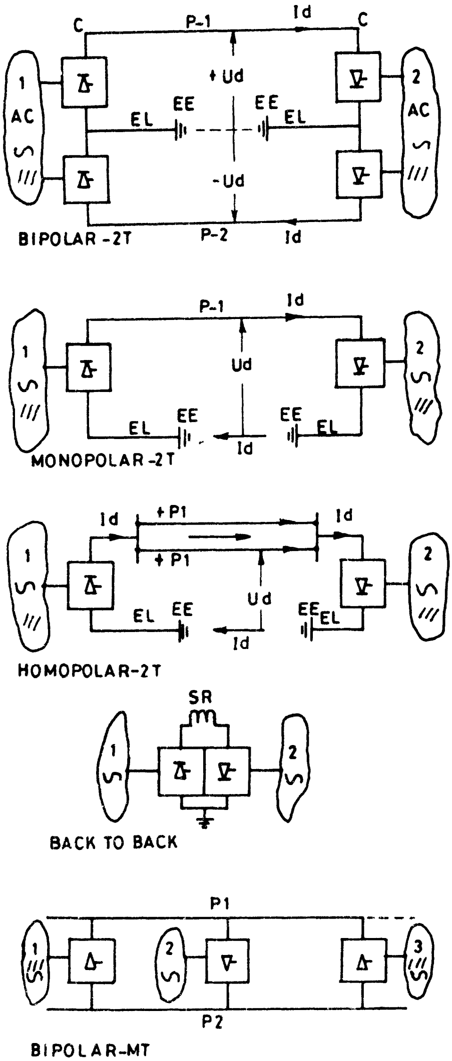


Fig. 1·7. Types of HVDC Systems.

Table 1·9
Example of Monopolar HVDC Systems

Year *Name*	*1966* *Sardinia*	*1965* *Konti-Skan*
Configuration	Monopolar, earth return	Monopolar earth return
Power MW	200	250
Direct voltage kV	200	250
Convertors per Station	2	2
Number of pulses	6	6
Transmission	Two parallel cables and return earth 116 km	One cables and return earth 87 km
Main reason for HVDC	Sea-crossing, frequency control	Sea-crossing sea return.

1·17·1. Monopolar HVDC system

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 are 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 substation pole and transmission pole.

Monopolar system is used for operation of first stage of Bipolar system.

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 projects. The earth path offers a cheaper, low resistance, low-loss conductor which effectively contributes to the economy of the system.

The rating of a Monopolar HVDC transmission system is equal to half of corresponding bipolar system rating and is therefore not economically competitive with EHV-AC Scheme. For long submarine cables longer than 25 km and having power rating of about 250 MW 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.

1·17·2. Homopolar-HVDC System

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.

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

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

1·17·3. Bipolar 2-Terminal HVDC Transmission

This is most widely used for overhead long distance HVDC systems, for point-to-point power transfer.

The HVDC substation and HVDC line has two poles, one positive and the other negative with respect to earth. The mid points 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 operation.

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 tower 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. Typical rating is ± 500 kV, 1500 MW, 800 km.

The normal bipolar HVDC system is composed of two separate monopolar systems 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 continue to carry up to half of bipolar power immediately.

1·17·4. Earth electrodes in a Bipolar System

The mid-point of Convertors (Called neutral point or the earth point) in each station is earthed with a suitable switching arrangement. This earthing is not the same as station earthing. This electrode earthing is through electrode earth installed 5 to 20 km from the HVDC substation. 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 substation and the earth electrode.

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

The earth electrode is installed away from the substation earth to avoid the galvanic corrossion of the substation earthing system, underground pipes, burried cables, structures.

Electrode Line is either a cable or an overhead line.

Table 1·11

Example of Bipolar HVDC Systems

Year *Name*	*1987* *Itaipu scheme* *Brazil*	*1990* *Rihand-Delhi** *Scheme India*
Configuration	Two Bipole Circuits	Single Bipole circuits
Power	2 × 6000 MW	1500 MW
Direct Bipole Voltages, earth circuit	± 600 kV	± 500 kV
Voltage of pole to earth DC	1200 kV	1000 kV
Number of convertors per station	2 × 2	2
Transmission	Overhead	Overhead
Main reason for HVDC	Long distance Frequency conversion 60/50 Hz	Long distance High power, economic choice ; power to Delhi

Cabora Bassa (Africa). The Cabora Bussa-Apollo scheme, the first long-distance HVDC system using thyristor valves, carries 1920 MW of electricity over 1400 km from the Cabora Bassa hydro power station (Mozambique) to the Apollo substation near Johannesburg (South Africa). The three-stage scheme with a nominal voltage of +/– 533 kV was complete in 1979.

Table 1·12

Typical Ratings and Main Specification of a Bipolar HVDC Transmission System*

Operating voltage of AC yard	400 kV A.C.
Operating voltage of D.C. yard	± 500 kV D.C.
Number of Convertor Transformers : each 300 MVA : 3 winding 1 ph.	6
Number of quadruple valves	6
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

...Contd.

* Rihand-Delhi Bipole HVDC Link.

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	820 km
Power Rating of Transmission line	1500 MW
Total MVAr of AC Filters in 2 stations	2000 MVAr
Number of PLCC Repeater Stations	2

*One such substation at each end of the transmission line. IPS-International Pipe Standard.

1·17·5. HVDC Coupling System.

(Back-to-back HVDC Convertor Station)

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

The back-to-back HVDC schemes are rated 500 MW to 1500 MW. The DC voltage and DC current of thyristors can be suitably selected for economical valve design *e.g.* 400 MW back-to-back station can have thyristor convertor ± 200 kV with the voltage between ± DC connection equal to 400 kV and current 1000 A.

The configuration of a back-to-back HVDC coupling system is illustrated in Fig. 1·8. 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 inverter to provided a reference earth on DC side.

As the earthing is only for reference, it does not carry any direct current and there are no problems of galvanic corrossion of substation earth and underground pipes, structures etc.

The requirement of AC filters, shunt compensation is similar to that of a bipolar HVDC system.

The Rectifier and Inverter valves are usually installed in a single valve room. The convertor transformers are installed on either sides of the valve room (Hall) and the DC bushings are taken inside the valve hall for connecting to the valves. AC switchyards and AC filters occupy a much larger area than the valve hall.

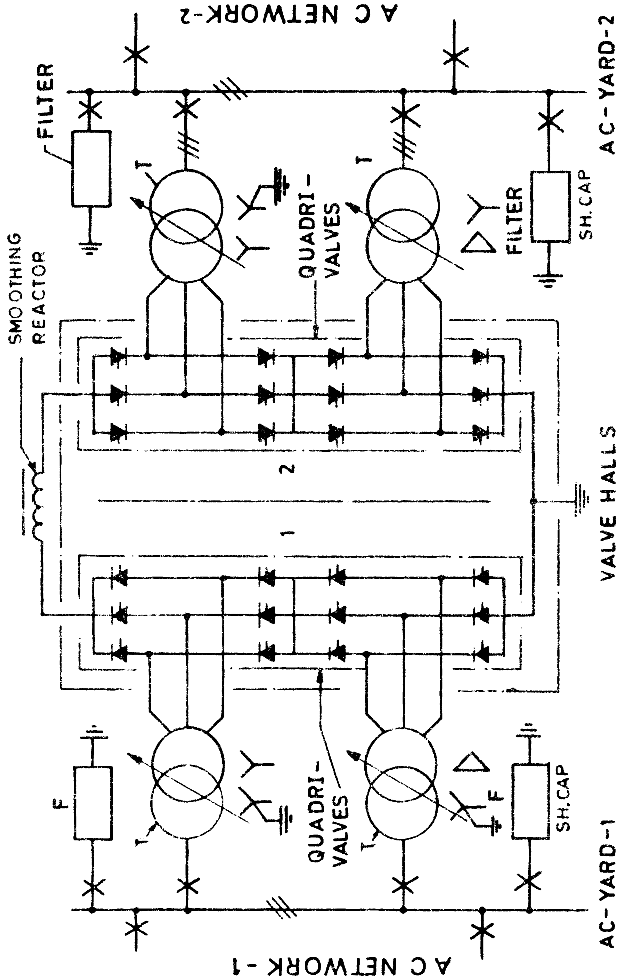


Fig. 1·8. Configuration of a back-to-back HVDC substation.

Multi-Terminal HVDC System (MTDC)

A Multi Terminal HVDC System interconnects 3 or more independently controlled AC Networks. Each of the terminal substation has 12-pulse AC/DC Converters. The three or more terminals are connected by HVDC Interconnecting Transmission Line. The surplus AC Networks export power and deficit AC Networks import power. The overall stability of each connected AC Networks is improved, power can be exchanged quickly/accurately and in required direction, transmission losses are reduced, overall black-out is eliminated. The first 5-Terminal MTDC System in the world has been commissioned in USA-Canada during 1995. MTDC Systems are envisaged in India by year 2010. The MTDC Systems are of high cost and require complex controls and perfect techno-economic understanding between regional grids about power sharing.

Table 1·14

Example of a Multi-Terminal HVDC System

Name	*Hydro-Quebec (Canada)* : *New England (USA)*
Execution of Project	1988-1996 (First MTDC in World)
Bipolar Voltage	± 450 kV DC
Number of Terminals	5
Radisson	2250 MW, 315 kV AC
Nicolet	2100 MW, 230 kV AC
Discantons	690 MW, 230 kV AC
Comerford	690 MW, 230 kV AC
Sandypond	1800 MW, 245 kV AC
Reason for HVDC	Better control over Exchange, Stability, Security. No black-outs, Economy in Energy Exchange and reduced transmission losses.

Table 1·13

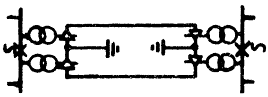
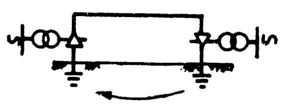
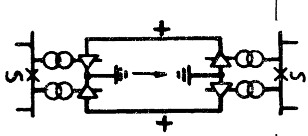
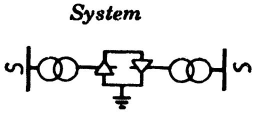
Example of Back-to-back Coupling Stations

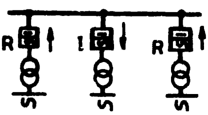
Name	Vindhachal Back-to-back HVDC Station
Purpose	Interconnection between Northern Region and Northern Region, India.
Location	Vindhachal : Border of MP and UP, 200 km from Varanasi.
Year of Commissioning	1987
Rated DC Voltage	70 kV
Rated DC Current	3600 A Continuous
	3760 A Overload for 2 hours
	4320 A Overload for 5 sec.
Thyristor Valve	Bridges 2 Nos. 250 MW each
Rated Power	2 × 250 MW = 500 MW
AC System Voltages	400 kV on each side
AC System frequency	50 Hz

The *Vindhyachal Back-to-back HVDC Station is the first HVDC system in India.* It has two 250 MW converter blocks. Each block consists of rectifier and inverter installed in the same valve hall. Power can be transferred from Northern Region (UP) to Western Region (MP) or *vice-versa*. The main purpose of HVDC interconnection exchange of power in any direction through a bi-directional link, accurately, easily and quickly.

Table 1·14

Types of HVDC Transmission Systems

Types	*Configuration*	*Remarks*
1. *Bipolar System*  Fig. 1·9·1	— Two poles, one positive with respect to earth and other negative. — Pole includes substation pole and transmission line pole. — The midpoint of Bipoles in each terminal is earthed *via* an electrode line and an earth electrode. — Earth electrodes located about 5 to 25 km away from terminals.	— Normal mode of operation : Bipolar, with power flow through line conductors and negligible current through earth. — During fault on a pole the mode is changed to Monopolar with reduced power flow through one pole and return earth.
2. *Monopolar System*  Fig. 1·9·2	— On pole and return earth. — Earthing of poles *via* electrode line and earth electrode — Earth electrode located away from terminal substation — The pole is normally negative with respect to earth.	— Power rating almost half of the rating of bipolar system. — Used for HVDC submarine cables. — Recent HVDC projects are all bipolar and earlier monopolar systems are being extended to bipolar.
3. *Homopolar System*  Fig. 1·9·3	— Two poles of same polarity and return earth.	— This system was used earlier for combination of cable and overhead transmission.
4. *Back-to-back HVDC coupling System*  Fig. 1·9·4	— Usually Bipolar without return earth. — Reference earth provided for protection, controls, measurements. — Convertor and inverter located in the same substation.	— Provides asynchronous tie between two independently controlled AC Networks. — Improves system stability. — Power transfer can be in either direction de-

Types	*Configuration*	*Remarks*
	— No HVDC transmission line. — Two AC systems linked by a single HVDC Back-to-back coupling station.	pending upon control characteristics. — Power exchange can be rapidly varied. — Very popular method of interconnection between adjacent AC Networks.
5. *Multi-terminal HVDC System*  Fig. 1·9·5	— Three or more terminal substations. — Bipolar. — Some terminals feed power in HVDC bus, some receive power from HVDC bus.	— Recently introduced (1986). — Provides interconnection between the three or more AC Networks. — Exchange between AC Networks can be controlled accurately, rapidly. — System stability of AC Networks can be improved.

Multi terminal HVDC system provides effective means for the interconnection between three or more AC Networks. The exchange of power between the connected Networks can be precisely and rapidly controlled. The stability limit of each connected AC Network can be improved.

1·18. Limitations of HVDC Transmission Systems

(1) HVDC is generally used only for point-to-point transmission. Generally HVDC transmission system does not have parallel lines, T-offs, mesh network etc. These limitations are due to following :

—HVDC system does not have step-up and step-down transformers.

—HVDC system does not have suitable HVDC circuit breakers.

(2) HVDC Transmission cannot be used economically for main transmission, subtransmission, distribution. It is used only for specific long distance/cable/interconnection projects.

(3) Cost of HVDC terminal substations is very high. There are several additional equipments, auxiliaries.

(4) Operation of HVDC transmission required continuous firing of thyristor valves. Controls of HVDC are complex. Several additional abnormal conditions are possible on DC side and in controls.

(5) HVDC substation require additional harmonic filters and shunt capacitors.

(6) HVDC substation has additional losses is convertor transformers and valves. These losses are continuous. Elaborate cooling system is necessary to dessipate the heat.

1·19. Configuration and Parts of 2-Terminal HVDC System

An HVDC Transmission system has the following essential parts :

— AC Network and HVDC substation at each terminal.

— Interconnecting HVDC line(s).

— Electrode line(s) and Earth electrodes.

The HVDC side has one or two poles. A 'pole' has same polarity with respect to earth. The pole includes substation pole and line pole.

A two terminal HVDC transmission system has only two terminal substations and two earth electrodes.

A multi-terminal HVDC transmission system will have three or more terminal substations and equal number of earth electrodes, all located at different locations.

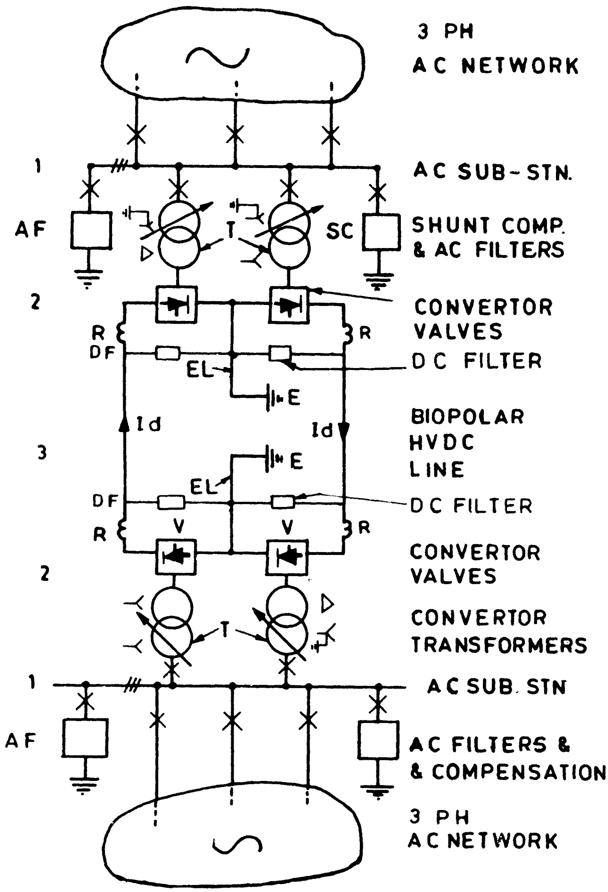


Fig. 1·10. Configuration of a Bipolar 2T-HVDC System (MRTB not shown).

The neutral points of convertors in each terminal are earthed *via* a separate electrode line and a remote earth electrode. The earth electrode is located 5 to 25 km away from the HVDC terminal substation for preventing galvanic corrossion of the earth mat of HVDC terminal substation due to earth return current of HVDC transmission.

Refer Fig. 1·10 (*a*) illustrating the configuration of a Bipolar HVDC transmission link with the following parts :

(1) AC substations at terminals (EHV-AC)

(2) Convertors at each end

(3) HVDC transmission line.

E — Electrode for earthing mid points of convertors.
EL — Electrode lines (5 to 20 km length each)
DF — DC harmonic filters
F — Filters for AC harmonics, shunt capacitors, DC filters.
R — Smoothing reactors (DC)
T — Convertor transformers
V — Convertor valves
SC — Shunt capacitors.

The AC substation (1) has 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.

Convertor transformers (*T*) are connected between convertor valves and the AC bus. 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 or 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*) is necessary for convertor operation and for smoothing the DC current. Smoothing reactor is generally oil cooled.

Fig. 1·10 (*b*) illustrates details of Smoothing Reactor, DC Filter and AC Filter, connections in a bipolar terminal substation.

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

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

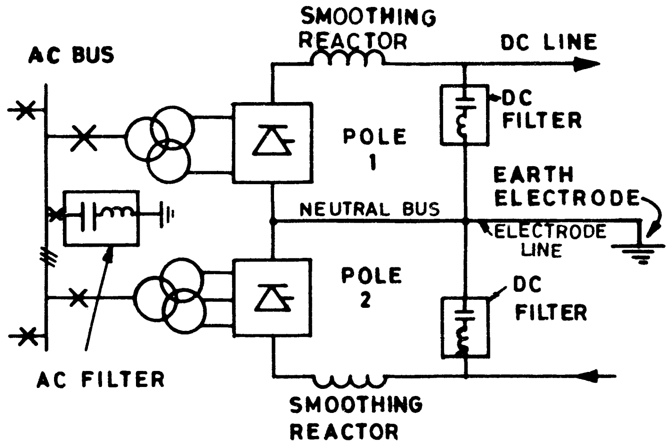


Fig. 1·11. Smoothing reactor AC harmonic filter and DC harmonic filters with an HVDC convertor.

AC Harmonic Filters (AF) cover a large area 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* (*C*) is provided by shunt capacitors. They supply reactive power needed for convertor operation. In some schemes, AC Filter capacitor provide shunt compensation also.

Reactive Power (*Q*) is absorbed by the converters. AC Filter capacitors supply reactive power to AC Bus.

The thyristors in convertor-valves are triggered by firing pulses to gates. The current through the DC valves and DC line is controlled by adjusting the delay angle (α) of firing the thyristors. The *Ud/Id* characteristics of the rectifier and inverter meet at a common point which decides the power flow through the HVDC link.

Each HVDC terminal substation has control system which controls the voltage, current, power through the DC line.

1·19. 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 station to distant load centre located in industrial towns and mega cities.

By HVDC, bulk power of any magnitude can be brought to load centres over distances of 2000 km or more, simply and efficiently by using a single bipolar link without any intermediate substation or parallel line.

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

Thermal power plants can be grouped in 'energy parks' in coal belts far away from the load centres and thereby the environment can be preserved.

Power Rating of long Bipole HVDC Transmission system. Power rating of bipolar HVDC line *Pdc* is given by

$$Pdc = Udc\,Idc \ldots MW \quad \ldots(1{\cdot}1)$$

Udc = DC voltage, kV between pole-lines

= 2 × (± Rated Bipole Voltage)

Idc = Current in conductors, KA

Pdc = Power transfer through line, MW

Idc is decided by normal current rating of thyristor value. Valves range between 0·5 kA and 4 kA. *Udc* is decided by rated voltage of a convertor pole. Values of *Udc* 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 1·15 gives typical ratings of present HVDC Bipolar links for long distance lines.

Table 1·15

Power transfer ability 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	1440	1620	1800	2160

Note. Basic for the above table

Pdc = $Udc \times Idc$ .... MW

Udc = Voltage between conductors kV

Idc = Line current, kA assumed 1·8 kA

1·8 kA = Rating of thyristor valve

* = with 3.6 kA rated valve, these values will be doubled, with same voltage rating.

1·20. Economic Comparison of Long-distance High Power HVDC Transmission System with EHV-AC System

The total capital cost of a transmission system is equal to the sum of capital cost of substations plus capital cost of the lines. The cost also includes cost of land, buildings, losses etc.

Capital cost of substations is higher in case of HVDC. Line cost is variable and per km line cost of HVDC line is lesser than AC line.

Total capital cost of Transmission system

= Cost of substation + cost of line

= Cost of substations + per km cost of line × length of line, km.

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 is considerably less than equivalent AC line. The DC circuit requires only two conductors as against minimum three for a 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.

HVDC bipolar line needs only two line conductors. For an equivalent 3 phase EHV-AC line, the number of line conductors could be 6, 12, 18, 24 (Ref. Table 1·7). For longer lengths the number increases.

EHV-AC lines need intermediate substations at an interval of 300 km. HVDC line does not need any intermediate substation.

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

HVDC has a clear economical advantage over AC line as soon as the benefit of lower line cost is more than the higher substations 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.

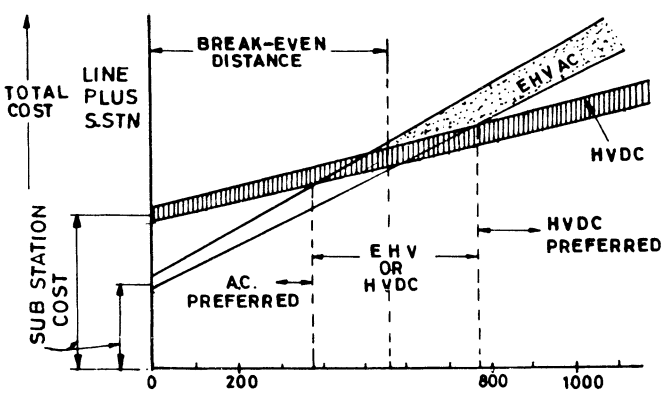


Fig. 1·12. Economic comparison of long distance high power HVDC transmission and EHV-AC transmission.

Fig. 1·9 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 economic studies for each project.

1·21. HVDC Cable Transmission

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

(1) Underground transmission from a distant substation to an indoor substation feeding a large city or from a hydro plant to an open outdoor substation.

(2) Under water 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 a remote on-shore substation.

The EHV-AC cables take continuous alternating charging currents. These charging 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 transfer ability 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 stress are permitted. Hence HVDC cables are more compact and of lesser cost.

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

Table 1·16

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 :

Table 1·17

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.

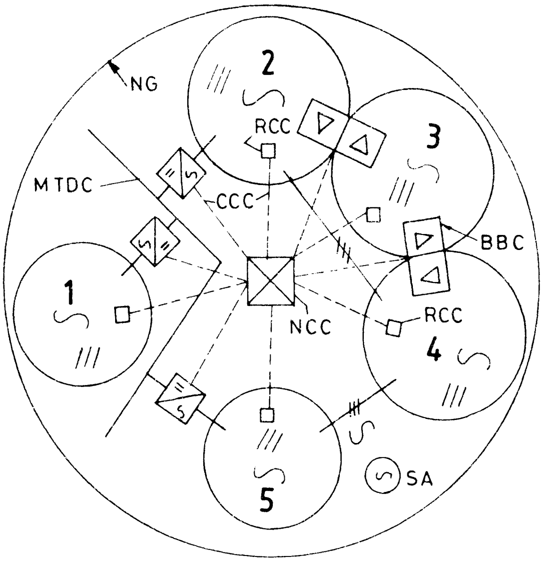


Fig. 1·13. Concept of Interconnected Power System.

NG National Grid
RG 1, 2, 3...5 Regional Grids
SA Stand-Alone power system (not connected to *NG*)
BBC Back-to-Back HVDC Coupling Station
NCC National Control Centre
RCC Regional Control Centre
CCC Carrier Communication Channels
2T Two Terminal HVDC System
MTDC Multi-Terminal HVDC System interconnecting 1, 2, 5.

1·22. Interconnected Network and Role of Interconnecting Transmission Lines

The geographical area is covered by two or more independantly controlled AC Networks. Each AC Network has a load control entre, generating stations, transmission and distribution system, and consumers. The frequency control the network is achieved by matching the generation with the load. The Network operates at a certain prevailing frequency which is maintained within targetted limit (49 Hz – 51 Hz). The Regional Load Centre decides generation in the region and the amount of import/export with the neighbouring Network.

Neighbouring independantly controlled AC Networks are interconnected by system interconnections. System interconnection is either by EHV-AC/HV-AC or HVDC. The basic function of an interconnector is to transfer energy from surplus zone to deficit zone.

When neighbouring AC Networks are connected by and AC interconnection they start operate synchronously at the same frequency. AC interconnection is called synchronous tie.

When neighbouring AC Networks are interconnected by HVDC interconnection, they can continue to have their independant load frequency control.(Asynchronous tie)

System interconnection has following major advantages.

— Lesser overall installed capacity to meet the peak load demand. Lesser spinning reserves.

— Overall economic generation by optimum use of high capacity economical generating plants.

— Better use of energy reserves such as hydro, thermal, nuclear.

— Better system support to week network.

— Better system support to network having emergency due to outage of a plant or a line.

— Stronger grid with stable frequency.

EHV-AC interconnection :

— It is simple.

— Power flow adapts naturally to the needs and prevailing surplus/deficit between interconnected networks.

— Voltages and connections can be made suitably by using transformer connection.

The limitations of EHV-AC interconnections include :

— It is synchronous tie. Frequency disturbance in one zone is quickly transferred to the other.

— Power swings in one network affect the other network.

A weak tie link gets tripped due to such power swings.

— Large interconnected networks suffer from cascade tripping and overall black-outs in the event of major faults in any of the network.

— Direction of power flow cannot be easily changed in AC interconnections.

— Power flow through AC Interconnection cannot be changed easily.

HVDC interconnections :

— It is an asynchronous tie. Frequency disturbance from one AC Network is not transferred to the other.

— Direction and magnitude of power flow can be changed quickly and accurately by controlling the characteristics of rectifier/ inverter.

- Power swings and frequency disturbances in connected AC Network can be quickly dampened by modulating the power flow through the HVDC interconnection.
- HVDC link can be used for interconnecting systems having different frequencies.
- HVDC link can be used for interconnection between two networks separated by sea or lake by using submarine cables.

HVDC interconnections are technically superior to EHV-AC interconnections and are now being preferred increasingly in the following forms :

- Back-to-back HVDC coupling stations.
- Multi-terminal HVDC asynchronous interconnection between three or more networks.
- Interconnections by submarine cables.
- Interconnection by bipolar overhead lines between two independantly controlled AC Networks.

1·23. 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 substation (HVDC coupling system) interconnects two AC systems meeting in common geographical area. Such substations do not have a transmission line. The convertors are connected back-to-back in a common coupling substation connecting two AC systems.

Merits of HVDC System 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 prescribed set level.

2. **Improved stability**

The amount of power transferred by an HVDC link, and its direction, can be controlled reliably 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 adjucent transmission lines. Disturbance is one AC Network is quickly dampened 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 substation buses and each substation equipment should be made suitable for the required fault level. The fault levels in large AC network having AC interconnections tend to become extremely high resulting in uneconomical equipment designs. With HVDC interconnection, the fault levels of each AC Network remain unchanged.

4. **Precise Exchange**

HVDC power flow can be controlled. EHV AC power flow control is slow and difficult. The increase in power flow in AC network is by increase in generated power in power plants. The power flows through various lines as per line impedances and loads. This is called load flow in AC Network. Power flow in a particular AC line cannot be easily controlled. The control over power flow through AC line is slow and of limited range.

HVDC point to point transmission link is suitable for transmitting power over long distance to particular Load Centre (*e.g.* Bombay, Delhi). The power transfer is *point to point* and can be controlled easily, precisely, quickly (subject to available generated MW). For example, power generated in South East UP coal belt is about 15000 MW. This flows to UP via 400 kV AC Network. The 1500 MW power flows through point to point Rihand Delhi HVDC link to load centre Delhi. The power through this link can be changed at a rate of 30 MW/min.

5. **Energy Conservation by Reduced Transmission Losses**

As HVDC line does non conduct reactive power, the transmission losses are less. Commulative energy conservation is significant. The investments in HVDC system are therefore justified.

Table 1·18
Comparison of Characteristic for systems interconnections

S.No.	*Characteristic*	*HVDC Link*	*EHV-AC Link*	*Criterion for preference*
1.	Power transfer ability	High	Lower, limited by power angle and X	HVDC link for higher power
2.	Control of power flow	Fast, accurate, bi-directional	Slow, difficult,	HVDC preferred
3.	Frequency disturbance	Reduced	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 interconnection	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.	Multi-Terminal	Very expensive	Very economical	EHV-AC preferred
10.	Reactive power flow through line	Not possible	Occurs	HVDC preferred
11.	Cascade tripping of AC systems, Blackout	Avoided	Likely	HVDC preferred
12.	Frequency conversion (50 Hz to 60 Hz)	Possible	Not possible	HVDC preferred
13.	Back to back conversion coupling	Possible	Not possible	HVDC preferred
14.	Spinning reserves of AC network	Reduced	Not much reduced	HVDC preferred
15.	Transient stability limit	Very high, upto thermal limit of equipment	Less than half of thermal limit of line conductor	HVDC preferred

HVDC links technically superior and are preferred for interconnection between two individually controlled AC systems. Recently Multi-Terminal HVDC Interconnecting Systems have been successfully introduced.

1·24. 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 subtransmission network.

(2) **Bulk power long distance transmission lines.** HVDC proves economical above breakeven point. Number of lines are less. No need of intermediate substations 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 is 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 application.

(8) **Intermediate substations.** EHV-AC transmission needs intermediate substations at an interval of 300 km for compensation. HVDC line does not need intermediate compensating substation.

(9) **Asynchronous tie.** System having different prevailing frequencies or different rated frequencies can be interconnected. HVDC link provides asynchronous tie. Frequency disturbance does not get transferred large blackouts are avoided.

(10) **Better control.** Power flow through HVDC tie line can be controlled more rapidly and accurately than that of EHV-AC interconnector. HVDC-Power flow can be increased at a rate of 30 MW per minute. This is not possible with EHV-AC line.

(11) **Corona loss and radio interference.** For the same power transfer and same distance, the corona losses and radio interference of DC systems is less than that of AC systems, as the required d.c. insulation level is lower than corresponding a.c. insulation.

(12) **Power Transfer and Reactive Power.** The main difference between EHV-AC and HVDC transmission systems is in control of Real Power flow (Fig. 1·14 and 1·15) and Reactive Power Flow.

For AC line ;

$$Pac = \frac{|V_1| \cdot |V_2|}{X} \sin \delta \qquad \text{...W/ph.}$$

The AC line can be loaded upto transient stability limit which occurs at $\delta = 30°$ and is given by

$$Pac\text{ - max} = \frac{1}{2} \cdot \frac{|V_1| \cdot |V_2|}{X} \qquad \text{...W/ph.}$$

AC line power cannot be changed easily, quickly and accurately as $|V_1|$ and $|V_2|$ should be kept around rated voltage levels and angle δ cannot be changed easily/quickly.

Secondly, the series reactance and shunt reactance of AC line result in *reactive power flow*, voltage regulation problems and additional transmission losses due to reactive component of current.

Power flow through HVDC link is given by

$$Pdc = \frac{(Ud_1 - Ud_2)}{R} \cdot Ud \qquad \text{...W/pole}$$

By varying $(Ud_1 - Ud_2)$ by means of thyristor converter control and tap-changer control; the power flow *Pdc* can be changed quickly, accurately and easily (subject to readiness of generation and load.)

Secondly, HVDC transmission line does not have series reactance and shunt reactance; reactive power flow. Hence voltage regulation problems and stability problems, transmission losses etc. due to the flow of reactive power flow are absent in HVDC transmission systems. Transmission losses are low.

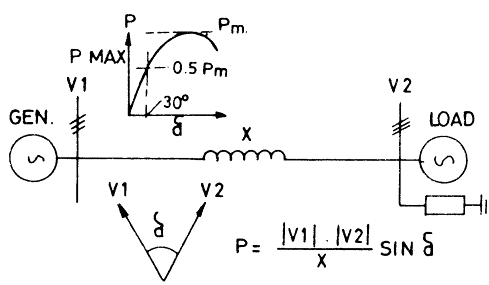


Fig. 1·14 A. Power transfer through AC line
[Power flow *Pac* is limited by sin δ and X]

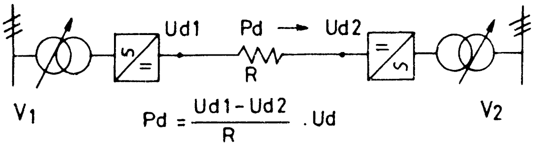


Fig. 1·14B. Power flow through HVDC Link
[Power *Pdc* can be changed quickly, accurately]

(13) **Skin effect.** This is absent in d.c. current. Hence current density is uniformly distributed across the cross-section of the conductor.

(14) **Charging current.** Continuous line charging currents are absent in HVDC lines. Reactive Power (MVAr) does not flow continuously. Hence transmission losses are low.

(15) **Tower size.** The phase-to-phase clearance, phase to ground clearances and tower size is smaller for d.c. transmission as compared to equivalent AC transmission for same power and distance. Tower is simpler, easy to install and cheaper.

(16) **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 converters.

(17) **Earth return.** HVDC transmission can utilize earth return and therefore does not need a double circuit. EHV-AC always needs a double circuit.

(18) **Reactive power compensation.** HVDC line does not need intermediate reactive power compensation like EHV-AC line.

(19) **Flexibility of operation.** Bipolar line may be operated in a monopolar mode by earth as a return path when the other pole develops a permanent fault.

(20) **Staging facility.** DC valves may be connected in series and parallel to get desired DC voltage and current. Multiterminal schemes are now possible.

(21) **Short-circuit level.** In AC transmission, additional parallel lines 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 DC transmission, the fault level of each system remains unchanged.

(22) **Rapid power transfer.** The control of convertor valves permit rapid changes in magnitude and direction of power flow. Limitation is imposed by power generation and AC system conditions.

Table 1·19
Comparison of long distance point-to-point overhead transmission systems

S.No.	*Characteristics*	*HVDC Link*	*EHV-AC Link*	*Remarks*
1.	Capital cost	— Line cost lower — Substation cost higher — Number of circuit one — Intermediate substation not required	— Line cost higher — Substation cost lower — Number of circuits more, conductors more — Intermediate substation required	HVDC lines becomes economical above 800 MW choice based on economics.
2.	Power transfer, stability Limit	— No limit due to power angle (δ)	— Limit imposed by power angle and inductance X_L	Single Bipolar HVDC link adequate upto 3000 MW.
3.	Voltage control	— Easier as reactive power does not flow	— 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 substation.
4.	Power flow control	— Power flow can be controlled quickly, accurately	— Power flow cannot be easily controlled	HVDC preferred for point-to-point transmission.
5.	Corona and radio interference	— DC voltage does not have $\sqrt{2}$ factor for r.ms. to peak — Corona losses and Radio interference less for same conductor to ground rated voltage	— AC voltage has factor $\sqrt{2}$ for r.ms. to peak	Bundle conductors used for both
6.	Skin effect	— Absent	— Present	
7.	Earth return	— Possible Bipolar with Monopolar	— Not possible	
8.	Reliability and availability	— One bipolar line sufficient	— Two AC circuits necessary in place of one Bipolar	
9.	Line losses	— Low as reactive power does not flow	— Higher due to reactive power flow	HVDC station has substation losses
10.	Control system	— Difficult, costly	— Simpler. cheaper	AC preferable
11.	Power line carrier communication	— Essential	— Preferred	HVDC control needs PLCC

(23) **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 present continuously. 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.

(24) **Voltage regulation.** In HVDC systems, the line can be operated with constant current regulation or constant voltage regulation by suitable adaptation of grid control of rectifiers and inverters. Voltage can be varied over a wide range by tap-changer control.

1·25. Prospects of EHV-AC and HVDC Transmission in the World and in India

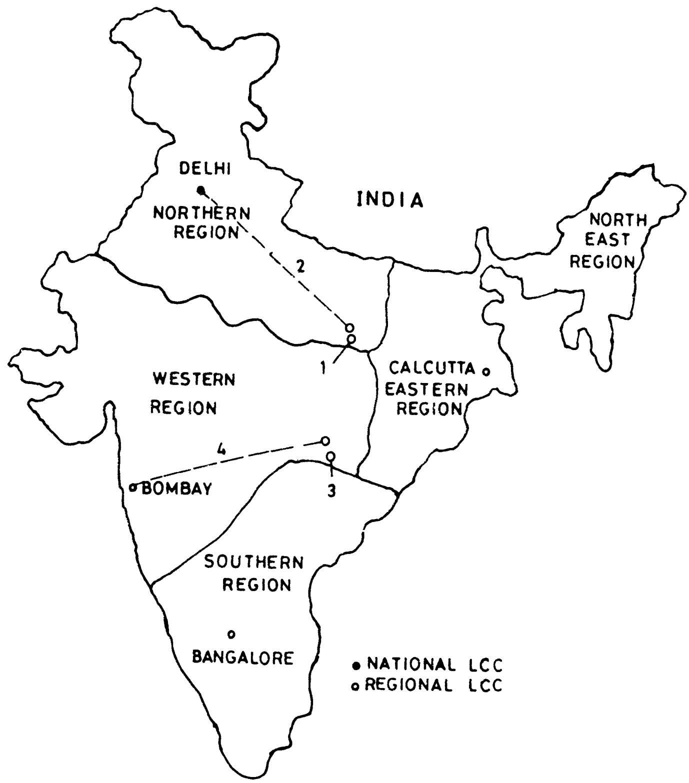


Fig. 1·15. Power map of India showing Regional Grids and HVDC Systems.

1. Vindhyachal back-to-back 2. Rihand-Delhi
2. Chandrapur BBCS 4. Chandrapur-Padaghe

The power requirement in every country goes up with a doubling period of 7 to 12 years. The requirements of bulk power transmission lines, and interconnecting transmission lines, back-bone network and subtransmission network are increasing in terms of

— Voltage rating

Table 1·20
HVDC Systems in India

Name of Scheme	Year	From	–	To	Distance	Rating
Vindhachal Back-to-back	1989	Western Region		Northern Region	0 km Interconnection	500 MW
Rihand-Delhi HVDC System	1992	Rihand (UP)		Dadri (Delhi)	820 km Bipolar	1500 MW ± 500 kV
National Experimental HVDC System APSEB/MPSE	1992 1997	Barsur (MP)		Lower Sileru (AP)	220 km Stage 1 Stage 2	– 100 kV/ 100 MW + 100 kV/ 200 MW
Chandrapur Back-to-back MSEB	1997	Western Region		Southern Region	0 km Interconnection	1000 MW
Chandrapur-Padaghe HVDC System MSEB	1997	Chandrapur		Padaghe (Bombay)	830 km	1500 MW ± 500 kV

* Other Neighbouring Regional Grids will have HVDC Couplings by 2015. MTDC HVDC is not yet planned. Prospects of 760 kV AC Transmission schemes with the aid of former USSR are uncertain

— Power transfer rating

— Lengths of lines.

Highest voltage of EHV/UHV AC transmission are increasing all over the world (Fig. 1·2).

With the successful development of thyristor for HVDC applications, the HVDC schemes have become economically and technically viable. HVDC transmission schemes are now being preferred for long bulk power transmission lines, underground/submarine cables and system interconnections, and also for multiterminal HDVC interconnecting systems (1987).

In the world about 35 projects were executed upto 1995. By the year 2000 more than 50 HVDC projects are likely to be commissioned with total power transmission of 50,000 MW.

The back-bone AC network in India is of 400 kV AC lines. The first 400 kV AC line was introduced in India around 1974 and the 400 kV AC lines are now well established in several parts of India. 760 kV AC lines are likely to be introduced by the year 2005.

At present three HVDC links are in operation in India (1995). By the year 2000 AD about five back-to-back tie links and three long high power bipolar lines are likely to be commissioned.

The National Grid in India will be controlled from National Load Control Centre near Delhi. There will be five Regional Grids (Northern, Western, Southern, Eastern and North Eastern). Each will be controlled by respective Regional Load Control Centre. Tie lines between these regional grids will be either AC or HVDC dpending upon the economic and technical requirements for the particular tie link. At present the majority of the links are of 220 kV AC or 400 kV AC lines. Fig. 1·11 gives the geographical coverage of regional grids in India.

The Vindhyachal back-to-back HVDC station interconnects Western grid with Northern grid. Likewise other back-to-back schemes are envisaged between various regional/state grids.

1·26. Transmission Planning

Transmission Planning is a part of Energy Planning and is carried out along with the Generation Planning. The transmission planning is based on long-range load growth pattern, generation forecasts and determines the growth pattern of transmission network. Transmission planning depends on the system design.

The input data required for transmission planning includes :

— Existing generation, loads and transmission network.

— Short-term generation planning and load growth.

— Long term generation planning and load growth.

The transmission planning includes the study of transmission network expansion with reference to :

— Planning of new transmission circuits between generating stations and the back-bone AC network.
— Planning of system interconnecting transmission links.
— Planning of back-bone network expansion.
— Planning of sub-transmission lines.
— Planning of substations, transformers and equipment.
— Planning of National Network, Regional Network and respective load control centres.

Table 1·20

Transmission Planning

Basic Questions	*Inputs*	*Remarks*
1. Configuration of Transmission, system. Which new circuits ? Which new tie-lines ? Which new substations ?	— Existing network data — Locations and magnitude of all future generating stations — Locations and magnitudes of all future load centres. — Annual study of generation growth and load growth. — Short and long range plans of generation and load.	— Existing network used as starting point. — Long range planning — Short-term planning of transmission — Alternative expansion plans of transmission — Matching transmission growth with load growth and generation growth.
2. What voltage levels ?	— Length and power of transmission line. — Economical voltage level. — Power handling capacity required per circuit. — Existing voltage levels.	— Voltage levels are standardised for 1. Backbone transmission network 2. Primary transmission 3. Secondary transmission 4. Special cases such as very long lines
3. EHV-AC or HVDC ?	— System studies and requirements — Economic studies.	— EHV-AC used for back-bone net work primary transmission : — HVDC used for long high power lines and interconnections
4. Technique for Compensation. Reactive power Planning.	— Load flow studies — Dynamic stability studies	— SVS used at various substations buses.
5. Which inter connections	— Overall policy	— Interconnections are

	— Geographical locations of adjacent independently controlled AC Networks. — Load cycles of networks and available capacity for interchange — Agreement between the organisations.	either EHV-AC/HVDC/HVDC back-to-back. — Interconnections are planned on the basis of long range transmission plants.
6. What should be location of sub-stations	— Location selected on the basis of locations of load centers, generating stations, transmission routes.	— Types : — Outdoor open terminal — Indoor SF_6 insulated GIS — HVDC — Indoor metal clad for medium voltages.
7. What should be the communication channel	— Telephones — Power-line carrier — Radio link.	— PLCC preferred
8. What should be controlled strategy.	— Fully automatic unmanned — Semi-automatic... only control supervisors.	— SCADA preferred

1·27. Power Line Carrier Communication (PLCC)

High frequency carrier signals are transmitted through transmission line conductors. These are used for data transmission, supervisory control, protection etc. In HVDC transmission systems, carrier signals are used for power flow control, protection and monitoring. The entire Supervisory Control and Data Aquisition System (SCADA) requires reliable PLCC System.

1·28. Scope of Subject

EHV AC and HVDC Transmission Engineering is a part of Energy and Power System Engineering. The work related with this subject covers a wide range of activities such as

— Transmission planning, energy supply strategy

— Design of Transmission lines and substations

— Control of voltage, current, power.

— Specifications of new transmission line, towers, conductors

— Analysis of Engineering aspects of EHV AC transmission lines

— Analysis of Engineering aspects of HVDC AC transmission lines

— Interaction between Transmission Systems and AC Networks Reactive power flow and associated equipment for its control.

— Project specifications, tendering, planning.

— Project execution : civil works, erection, testing, commissioning.

— Operation and maintenance.

EHV AC and HVDC transmission systems are very important part of the Energy Transportation System. This book covers the basic principles and practical aspects.

SUMMARY

For high power transfer over long distances (> 800 km) and for system interconnection HVDC is an alternative to EHV AC. 400 kV AC Transmission Network is well established in India and a few long 760 kV lines have been planned. Long 2 Terminal Bipolar ± 500 kV HVDC Transmission link have been established between Rihand (UP) and Delhi and Chandrapur Padaghe (Maharashtra). A 500 MW Back-to-Back HVDC Substations has been established at Vindhachal between Western Region and Northern Region and a 1000 MW Back-to-Back at Chandrapur (Maharashtra). HVDC is superior to AC as power flow can be controlled quickly and accurately with low transmission losses. The network consists Back-bone AC Network of EHV AC lines, a few Back-to-back HVDC interconnections and a few point-to-point HVDC links.

QUESTIONS

1. State the merits of HVDC as compared to EHV AC for (1) Long High Power Lines (2) Interconnection.

2. Sketch a schematic of an EHV AC Transmission link and explain the need for intermediate substations.

3. Sketch a schematic of a 2-Terminal Bipolar HVDC Transmission and explain the need for Earth Electrode and Electrode Line.

4. Explain the difference in power flow through an AC Link and an HVDC Link. Explain how HVDC power can be easily and quickly changed.

5. State the prospects of HVDC Transmission Systems in India (Long 2T and Back-to-Back). Why Back-to-Back HVDC Coupling Stations are being preferred to AC Interconnections.

6. State the objective of Interconnecting Regional Grids to form a National Grid. What are the merits of Back-to-Back HVDC Interconnection over the conventional AC Interconnection ?

7. Which type of transmission system would you recommend for following (7·1 to 7·5) under transmission planning for year 2000 – 2015 ? Give most important considerations for your choice. Choice is to be made from :

(A) 3 phase AC System (B) Bipolar 2 T HVDC System

(C) MT HVDC System (D) Flexible AC Transmission System

(E) HVDC Coupling Stations (F) HVDC Submarine Cables

(G) Bipolar 2 T HVDC System (H) Any other

7·1. National Grid of India with Interconnection between Western Region, Northern Region and Southern Region and North Eastern Region, Eastern Region.

7·2. Interconnection between Shrilanka and India.

7·3. Supply to Andaman Nicobar Islands from Main Land National Grid.

7·4. 20,000 MW Hydro-Electric power pool in Himalayan Region to National Grid over 3000 km.

7·5. 100 MW Ocean Thermal Power Plants in high sea to Madras.

8. Derive an expression for Power Flow Pd through an HVDC link in terms of Udc_1 at sending end, Udc_2 at receiving end, line resistance (R) (neglect delay angle and overlap angle). Explain how the power flow can be changed. Compare the equation with Power Flow equation in an AC transmission line with V_1 ; V_2 and reactance X.

9. How much total reactive power compensation is required for 2 substations of a Bipolar 1500 MW HVDC link operating at full load.

10. Compare AC Interconnection with HVDC Interconnection.

11. Draw graphs of economic comparison indicating Rail Transport (coal) 400 kV AC Transmission, Bipolar HVDC Transmission.

12. Draw graph of Economic break even of long Bipolar HVDC Transmission over double circuit EHV AC Transmission.

13. Explain the steps in Transmission Planning.

14. Why are intermediate substations necessary with EHV AC Transmission System ? What are Static VAr Sources ?

15. What is Flexible AC Transmission system ? Why is it required ?