UNIT-I

INTRODUCTION TO HVDC

EVOLUTION OF POWER SYSTEMS:

YEAR	HOW COMMERCIAL USE OF ELECTRICITY TOOK PLACE
	The basic discoveries of **GAVLANI, VOLTA, OHM** and **AMPERE** pertained to DC. The first widespread practical application was DC telegraphy by electrochemical batteries and using under- ground return circuits
1870	Commercial use of Electricity when Carbon Arc Lamps were used to illumination of light house and street lighting in series at constant current fed by series wound generators and later carbon filament lamps are used which are operated in parallel at constant voltage supplied current from shunt generators.
1882	First Electric Power System with (steam driven Bipolar DC Generator, Cable, Fuse and Load) by Thomas Alva Edison at Pearl street in New York DC system for 59 customers ,1.5m radius of 110V Underground cable with incandescent lamp load
1884	Electric Motors were developed by Frank Sprague
1886	Limitation of DC became apparent ➢ High losses and voltage drops ➢ Transformation of voltages requirement Development of Transformers and AC Transmission by L. Gaulard and J.D.Gibbs of Paris and France George Westinghouse secured the rights in U.S. William Stanley an associate of Westinghouse developed and tested commercial practical use of Transformers and AC Transmission for 150 lamps at Great Barrington Massachusetts
1888	Nikola Tesla developed Polyphase Systems and had patents of Generators, Motors, Transformers, Transmission lines but these patents were sold to Westinghouse.
1889	First AC Transmission system in North America in Oregon Between Willamette Falls and Portland Single Phase 4KV over 21 Km
1890	Controversial industrial revolution whether the industries need go for DC/AC ➢ Thomas Alva Edison advocated for DC and ➢ Westinghouse advocated for AC
	Earlier Frequencies were used are 25,50,60 and 133Hz European Countries Fixed their values to 60Hz Asian Countries Fixed their values to 50Hz
	Earlier Frequencies were used are 25,50,60 and 133Hz European Countries Fixed their values to 60Hz Asian Countries Fixed their values to 50Hz
1893	First 3-phase line , 2300V , 12km in California . AC was chosen near Niagara falls
1922	165kV
1923	220kV

1935	287kV
1953	330kV
1965	500kV
1966	735kV Hydro Quebec
1969	765kV in USA
1990	1100kV
	Standards are 115 , 138 , 161 , 230KV - HV &
	345 , 500 , 765kV - EHV

VOLTAGE LEVELS:

BASIC ELEMENTS OF ELECTRICAL POWER SYSTEM

YEAR	HOW COMMERCIAL USE OF ELECTRICITY TOOK PLACE
HVDC TRANSMISSION SYSTEMS	
1880-1911	HVDC transmission systems was designed by a French Engineer **Rene Thury** when the AC system is at Infancy. At least 19 Thury systems were installed in Europe by the use of water power most prominent was Mouteirs to Lyons (France) in 1906 57.6KV, 75A, 4.3MW 180Km (4.5Km Underground Cable) ➢ DC series generators were used ➢ Constant Current Control mode of operation ➢ Four water turbines each of 3.6KV 1911- Second plant at La Bridoire rated at 6MW, 150A added in series 1912 –Third located at Bozel 11Km beyond Mouteirs rated at 9MW added raising the total capacity to 193 MW,125KV with 225KM
1920	Transverters (Polyphase transformers commutated by synchronously rotating bus gear) were developed by Two British Engineers W.E Highfield and J.E. Calverly. Functions: ➢ Voltage Transformation ➢ Phase Multiplication ➢ Commutation
1932	Atmospheric arc converters were developed by E.Marx of Braunschweig it is a switching device in which an arc between two water cooled main electrodes
1938	Due to death of Rene Thury all the Thury systems were dismantled
1950	Mercury arc valves were developed
1954	First HVDC Transmission system between Sweden & Gotland Island by Cable

VOLTAGE LEVELS:

MILESTONES OF HVDC:

- Hewitt´s Mercury - Vapour rectifier, which appeared in 1901.
- Experiments with Thyratrons in America and mercury arc valves in Europe before 1940.
- First commercial HVDC transmission, Gotland 1 in Sweden in 1954.
- First solid state semiconductor valves in 1970.
- First microcomputer based control equipment for HVDC in 1979.
- Highest DC transmission voltage (+/- 600 kV) in Itaipú, Brazil, 1984.
- First active DC filters for outstanding filtering performance in 1994.
- First Capacitor Commutated Converter (CCC) in Argentina-Brazil Interconnection, 1998.
- First Voltage Source Converter for transmission in Gotland, Sweden ,1999

COMPARISON OF AC AND D.C TRANSMISSION:

ADVANTAGES OF HVAC

- Voltage transformation.
- Current interruption.
- Easy conversion into mechanical energy to electrical energy and vice-versa.
- Frequency as system-wide control signal.
- Meshed networks.

DISADVANTAGES OF HVAC

- Long distance transmission.
- Difficult to use cables, already at 100km high reactive power consumption.
- Reactive power loss.
- Stability problem.
- Current carrying capacity.
- Skin Effect and Ferranti Effect.
- Power Flow Control.

ADVANTAGES OF HVDC

- More power can be transmitted per conductor per circuit.
- Use of Ground Return Possible.
- Require Less Space compared to AC of the same voltage rating and size.
- Higher Capacity available for cables.
- No skin effect.
- Less Corona and Radio Interference.
- No Stability Problem.
- Asynchronous interconnection possible.
- Lower short circuit fault levels.
- Tie Line Power is easily controlled.
- Cheaper for Bulk Power Transmission.
- Fast Fault Clearing Time.
- No Compensation required for the line.

- **More power can be transmitted per conductor per circuit:**

Let the peak DC voltage $V_m = V_{dc}$

Let the peak AC voltage $V_{ac} = V_m = \sqrt{2}V_{rms}$

For the same insulation Peak DC voltage = Peak AC voltage

$$V_{dc} = \sqrt{2}V_{rms}$$

For the same conductor size, the same current can transmitted with both DC and AC if the skin effect is not considered then

$$I_{dc} = I_{ac}$$

DC power per conductor $P_{dc} = V_{dc}I_{dc}$

AC power per conductor $P_{ac} = V_{ac}I_{ac}\cos\Phi$

The ratio of powers be

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}V_{rms}I_{dc}}{V_{ac}I_{ac}\cos\Phi} = \frac{\sqrt{2}V_{rms}I_{dc}}{V_{rms}I_{dc}\cos\Phi} = \frac{\sqrt{2}}{\cos\Phi}$$

Case - I

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}}{\cos\Phi} = \frac{1.414}{\cos\Phi}$$

$$\frac{P_{dc}}{P_{ac}} = \sqrt{2} \quad \text{Unity Power Factor}$$

$$P_{dc} = \sqrt{2}P_{ac}$$

Case - II

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}}{\cos\Phi} = \frac{1.414}{\cos\Phi}$$

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}}{0.8} = 1.7677$$

$$P_{dc} = 1.7677P_{ac} \quad \text{For 0.8 P.F}$$

From the above expressions we can say that more amount of power can be transferred in DC.

In practice, DC transmission is carried out using 2 conductors (+/-) and AC transmission is carried out using either single circuit or double circuit 3Φ transmission using 3 or 6 conductors. In such a case the above ratio for power must be multiplied by 2/3 or by 4/3.

In general, we are interested in transmitting a given quantity of power at a given insulation level, at a given efficiency of transmission.

Let RDC = Resistance of DC line

RAC = resistance of AC line

AAC= Area of cross-section of the conductor of AC

ADC= Area of cross-section of the conductor of DC

For DC

$$\text{DC Current} = \frac{P}{V_m} = \frac{P}{V_{dc}}$$

$$\text{Power Loss } P_L = \left(\frac{P}{V_{dc}}\right)^2 R_{dc} = \left(\frac{P}{V_{dc}}\right)^2 \frac{\rho l}{A_{dc}}$$

For AC

$$\text{AC Current} = \frac{P}{\cos\phi V_{rms}}$$

$$\text{Power Loss } P_L = \left(\frac{P}{\cos\phi V_{rms}}\right)^2 R_{Ac}$$

$$= \left(\frac{P}{\cos\phi V_{rms}}\right)^2 = \frac{\rho l}{A_{ac}} = \left(\frac{P}{\frac{\cos\phi V_m}{\sqrt{2}}}\right)^2 \frac{\rho l}{A_{ac}}$$

$$= \left(\frac{\sqrt{2}P}{\cos\phi V_m}\right)^2 \frac{\rho l}{A_{ac}} = 2\left[\frac{P}{\cos\phi V_m}\right]^2 \frac{\rho l}{A_{ac}}$$

Equating the losses in DC and AC

$$\left(\frac{P}{V_{dc}}\right)^2 \frac{\rho l}{A_{dc}} = 2\left[\frac{P}{\cos\phi V_m}\right]^2 \frac{\rho l}{A_{ac}}$$

$$\left(\frac{P}{V_m}\right)^2 \frac{\rho l}{A_{dc}} = 2\left[\frac{P}{\cos\phi V_m}\right]^2 \frac{\rho l}{A_{ac}}$$

Ratio of the Area is

$$\frac{A_{dc}}{A_{ac}} = \frac{\cos^2\phi}{2} = \frac{0.5 \text{ at a P.F} = \text{Unity}}{0.32 \text{ at a P.F} = 0.8}$$

By this we can say one-half the amount of copper is required for the same power transmission at unity power factor, and less than one-third is required at the power factor of 0.8 lag

- **USE OF GROUND RETURN POSSIBLE:**
  - In the case of HVDC transmission, ground return (especially submarine crossing) may be used, as in the case of a Monopolar DC link.
  - Also the single circuit bipolar DC link is more reliable, than the corresponding AC link, as in the event of a fault on one conductor; the other conductor can continue to operate at reduced power with ground return.
  - For the same length of transmission, the impedance of the ground path is much less for DC than for the corresponding AC because DC spreads over a much larger width and depth.
  - In fact, in the case of DC the ground path resistance is almost entirely dependant on the earth electrode resistance at the two ends of the line, rather than on the line length. However it must be borne in mind that ground return has the following disadvantages. The ground currents cause electrolytic corrosion of buried metals, interfere with the operation of signaling and ships' compasses, and can cause dangerous step and touch potentials

- **SMALLER TOWER SIZE:**

The DC insulation level for the same power transmission is likely to be lower than the corresponding AC level. Also the DC line will only need two conductors whereas three conductors (if not six to obtain the same reliability) are required for AC Thus both electrical and mechanical considerations dictate a smaller tower.

- **HIGHER CAPACITY AVAILABLE FOR CABLES:**
  - In contrast to the overhead line, in the cable breakdown occurs by puncture and not by external flashover. Mainly due to the absence of ionic motion, the working stress of the DC cable insulation may be 3 to 4 times higher than under AC also, the absence of continuous charging current in a DC cable permits higher active power transfer, especially over long lengths.
  - Charging current of the order of 6 A/km for 132 kV). Critical length at 132 kV ≈ 80 km for AC cable. Beyond the critical length no power can be transmitted without series compensation in AC lines. Thus derating which is required in AC cables, thus does not limit the length of transmission in DC.
  - A comparison made between DC and AC for the transmission of about 1550 MVA is as follows. Six number AC 275 kV cables, in two groups of 3 cables in horizontal formation, require a total trench width of 5.2 m, whereas for two number DC ±500 kV cables with the same capacity require only a trench width of about 0.7 m.

- **NO SKIN EFFECT:**
  - Under AC conditions, the current is not uniformly distributed over the cross section of the conductor.
  - The current density is higher in the outer region (skin effect) and result in under utilization of the conductor cross-section.
  - Skin effect under conditions of smooth DC is completely absent and hence there is a uniform current in the conductor, and the conductor metal is better utilized.

- **LESS CORONA AND RADIO INTERFERENCE:**
  - Since corona loss increases with frequency (in fact it is known to be proportional to f+25), for a given conductor diameter and applied voltage, there is much lower corona loss and hence more importantly less radio interference with DC.
  - Due to this bundle conductors become unnecessary and hence give a substantial saving in line costs. (Tests have also shown that bundle conductors would anyway not offer a significant advantage for DC as the lower reactance effect so beneficial for AC is not applicable for DC.)

- **NO STABILITY PROBLEM:**
  - The DC link is an asynchronous link and hence any AC supplied through converters or DC generation do not have to be synchronized with the link.
  - Hence the length of DC link is not governed by stability. In AC links the phase angle between sending end and receiving end should not exceed 30 at full-load for transient stability (maximum theoretical steady state limit is 90).
  - The phase angle change at the natural load of a line is thus 0.6°per 10 km.

- The maximum permissible length without compensation ≈ 30/0.06 = 500 km.
- With compensation, this length can be doubled to 1000 km**.**

➢ **ASYNCHRONOUS INTERCONNECTION POSSIBLE:**

- With AC links, interconnections between power systems must be synchronous. Thus different frequency systems cannot be interconnected. Such systems can be easily interconnected through HVDC links.
- For different frequency interconnections both convertors can be confined to the same station.
- In addition, different power authorities may need to maintain different tolerances on their supplies, even though nominally of the same frequency. This option is not available with AC With DC there is no such problem.

➢ **LOWER SHORT CIRCUIT FAULT LEVELS:**

- When an AC transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels.
- This problem can be overcome with HVDC as it does not contribute current to the AC short circuit beyond its rated current.
- In fact it is possible to operate a DC link in "parallel" with an AC link to limit the fault level on an expansion.
- In the event of a fault on the DC line, after a momentary transient due to the discharge of the line capacitance, the current is limited by automatic grid control. Also the DC line does not draw excessive current from the AC system.

➢ **TIE LINE POWER IS EASILY CONTROLLED:**

- In the case of an AC tie line, the power cannot be easily controlled between the two systems.
- With DC tie lines, the control is easily accomplished through grid control.
- In fact even the reversal of the power flow is just as easy.

➢ **RELIABILITY:**

- Energy Availability: $= 100 \ \ 1 - \underline{\hspace{6cm}}$ %

Where equivalent Outage Time= Product of the actual Time and the fraction of the system capacity lost due to the outage.

- Transient Reliability: $= \underline{\hspace{12cm}}$

Recordable Faults: Faults which cause the one or more AC Bus phase voltage drop below 90% of the rated Voltage.

Disadvantages of HVDC:

- Expensive convertors.
- Huge Reactive power requirement.
- Generation of harmonics.
- Difficulty of circuit breaking.
- Difficulty of voltage transformation.
- Difficulty of high power generation.
- Point to Point Transmission.
- Limited Over load capacity of converters.

- **EXPENSIVE CONVERTORS:**
  - Expensive Convertor Stations are required at each end of a DC transmission link, whereas only transformer stations are required in an AC link.

- **REACTIVE POWER REQUIREMENT:**
  - DC line does not require any amount of reactive power as there is no Inductance effect .
  - Convertors require huge amount of reactive power, both in rectification as well as in inversion for their energy conversion.
  - At each convertor the reactive power consumed may be as much at 50% of the active power rating of the DC link.
  - The reactive power requirement is partly supplied by the filter capacitance, and partly by Synchronous or Static Condensers that need to be installed for the purpose.

- **GENERATION OF HARMONICS:**
  - Convertors generate a lot of harmonics both on the DC side and on the AC side.
  - Filters are used on the AC side to reduce the amount of harmonics transferred to the AC system.
  - On the DC system, smoothing reactors are used. These components add to the cost of the convertor.

- **DIFFICULTY OF CIRCUIT BREAKING:**
  - Due to the absence of a natural current zero with DC, circuit breaking is difficult.
  - This is not a major problem in single HVDC link systems, as circuit breaking can be accomplished by a very rapid absorbing of the energy back into the AC system. (The blocking action of thyristors is faster than the operation of mechanical circuit breakers).
  - However the lack of HVDC circuit breakers hampers multi-terminal operation.

- **DIFFICULTY OF VOLTAGE TRANSFORMATION:**
  - Power is generally used at low voltage, but for reasons of efficiency must be transmitted at high voltage.
  - The absence of the equivalent of DC transformers makes it necessary for voltage transformation to carried out on the AC side of the system and prevents a purely DC system being used.

- **DIFFICULTY OF HIGH POWER GENERATION:**
  - Due to the problems of commutation with DC machines, voltage, speed and size are limited.
  - Thus comparatively lower power can be generated with DC

- **ABSENCE OF OVERLOAD CAPACITY:**
  - Convertors have very little overload capacity unlike transformers and this overload capacity depends on the rating of the Thyristors individually and also the valves.

ECONOMIC COMPARISON:

% COST FOR HVDC COMMISIONING:

TYPES OF HVDC SYSTEMS:

- MONOPOLAR LINK
- BIPOLAR LINK
- HOMOPOLAR LINK
- MTDC LINK

- **MONOPOLAR LONG-DISTANCE TRANSMISSIONS:**
  - Here one Conductor is used only negative(-ve) and the return path is through ground/Sea return.
  - If the Fault occurs on this line the power transferred is Zero.
  - For reducing corona loss negative is preferred
  - If possible instead of ground return metallic return can also be used even if the cost increases.

- **BIPOLAR LONG-DISTANCE TRANSMISSION:**
  - A bipolar is a combination of two poles in such a way that a common low voltage return path, if available, will only carry a small unbalance current during normal operation.
  - This configuration is used if the required transmission capacity exceeds that of a single pole. It is also used if requirement to higher energy availability or lower load rejection power makes it necessary to split the capacity on two poles.
  - During maintenance or outages of one pole, it is still possible to transmit part of the power. More than 50 % of the transmission capacity can be utilized, limited by the actual overload capacity of the remaining pole.
  - The advantages of a bipolar solution over a solution with two monopoles are reduced cost due to one common or no return path and lower losses. The main disadvantage is that unavailability of the return path with adjacent components will affect both poles.

- **HOMOPOLAR DISTANCE TRANSMISSION:**
  - In this type the conductors are two which are negative and operate with he ground return

SYPNOSIS:

The main areas of the Applications based on Economic & Technical Performances:-

- **Long Distance Transmission.**
- **Underground & submarine Cables.**
- **Asynchronous Connection of two power systems with different frequencies.**
- **Control & Stabilize the power system with power flow control**

PRIMARY OBJECTIVES HVDC APPLICATIONS

- **BULK POWER TRANSMISSION**: Transmit Bulk power from one point to another point over long Distances.
- **BACK TO BACK HVDC SYSTEM**: Here rectification and inversion takes place at the same station with very small DC line or No DC line. This is basically used for control power and stabilize the system and also used for connecting 2 power stations at different frequencies.
- **MODULATION OF EXISTING AC/DC SYSTEM**: Parallel connection of AC/DC links where both AC/DC lines run parallel. It is mainly used to modulate power of AC line

COMPONENTS OF HVDC:

- CONVERTERS.
- CONVERTER TRANSFORMERS.
- SMOOTHING REACTORS
- HARMONIC FILTERS
- OVER HEAD LINES
- REACTIVE POWER SOURCES

- EARTH ELECTRODES
- LOCATION OF EARTH ELECTRODE
- CHOICE OF VOLTAGE

- **CONVERTERS:**
  - Heart of the HVDC System.
  - Each HVDC System has 2 converters one at each end.
  - Convertor at sending end act as Rectifier
  - Convertor at Receiving end act as Inverter.
  - For achieving higher voltages and currents thyristors are connected in parallel and series
    - Higher Voltages – Thyristors in Series.
    - Higher Currents – Thyristors in Parallel.
  - Valve: Thyristors in series and parallel.
  - Bridge Converters are Generally used
  - Current rating of the converters can be increased.

    Thyristors in Parallel
    Valves in Parallel
    Bridges in Parallel
    or Some Combinations of above.
  - Voltage rating of the converters can be increased.

    Thyristors in Series
    Valves in Series
    Bridges in Series
    or Some Combinations of above

REQUIREMENT OF THE VALVE:

- To allow the current flow in one direction (Conduction State) and should not allow the current in other direction (Non Conduction State) i.e the less resistance in one direction and infinite resistance in other direction
- For an ideal switch forward Direction R = 0.
    - Reverse Direction R = ∞.
- To withstand high P.I.V (Peak Inverse Voltage) during the Non-Conduction State.
- To allow a reasonably Short Commutation Margin Angle during the inverter operation.
- Smooth Control of conduction to Non-Conduction Phases

OPERATION MODES:

- Depending on the DC Storage Devices
    - Inductor – CSC (Current Source Converter)
    - Capacitor – VSC (Voltage Source Converter)
- HVDC - CSC
- FACTS – VSC (SVC, STATCOM, Filters)

S.No	Current Source Converters	Voltage Source Converters
1.	Inductor on DC side	Capacitor on DC side
2.	Constant Current	Constant Voltage
3.	High loss	Less loss
4.	Fast accurate method	Slow control (Capacitor – sluggish)
5.	Larger & more Expensive (Reactor large)	Small & less Expensive
6.	More Fault tolerant and more reliable	Less Fault tolerant and Less reliable
7.	Simple cost	expensive cost
8.	Not expandable in series	Easily Expandable

CONVERTER VALVE ASSEMBLY

- **CONVERTER TRANSFORMERS (OLTC):**
  - The converter transformers transform the voltage of the AC bus bar to the required entry voltage of the converter.
  - The 12-pulse converter requires two 3-phase systems which are spaced apart from each other by 30 or 150 electrical degrees. This is achieved by installing a transformer on each network side in the vector groups star – star and star-delta.
  - The transformer is an interface between AC side and DC side the main insulation, The converter transformers are equipped with on-load tap-changers in order to therefore, is stressed by both the AC voltage and the direct voltage potential between valve-side winding and ground provide the correct valve voltage
  - Generally a bridge converter is of 6-Pulse in nature so the transformer can be 3Φ or three 1Φ transformers.
  - But for HVDC a 12 pulse converter is needed so two 6 pulse are connected in series
    - Six 1Φ 2 winding Transformer.
    - Three 1Φ 3 winding Transformer.
    - Two 3Φ Transformer.
  - It is not possible to use the winding close to the yoke as the potential of winding connection is determined by conducting Valve.
  - When some valves are operating they produce harmonics. So these harmonics pass through the transformer so the winding have to be insulated properly.
  - When the valves are in non conduction states they experience PIV and this voltage replicated at the converter transformer so to protect the transformer from this higer voltages they should be properly insulated.
  - As the DC currents flow in the windings of the transformer there is problem of saturation
  - As the leakage flux of a converter transformer contain high harmonics it produces eddy currents, hysteresis loss and hot spots in the transformer tanks.
  - Since under fault the fault current flows through the transformer impedance , so to limit this high current the impedance of the transformer should be high
  - Transformer is of the OLTC (On Load Tap Change)

- **SMOOTHING REACTOR:**
  - Prevention of intermittent current.
  - Limitation of the DC fault currents.
  - Prevention of resonance in the DC circuit.
  - Reducing harmonic currents including limitation of telephone interference

- **PREVENTION OF INTERMITTENT CURRENT:**
  - The intermittent current due to the current ripple can cause high over-voltages in the transformer and the smoothing reactor.
  - The smoothing reactor is used to prevent the current interruption at minimum load.

- **LIMITATION OF THE DC FAULT CURRENT:**
  - The smoothing reactor can reduce the fault current and its rate of rise for commutation failures and DC line faults.
  - This is of primary importance if a long DC cable is used for the transmission. For an overhead line transmission, the current stress in valves is lower than the stress which will occur during valve short circuit

- **PREVENTION OF RESONANCE IN THE DC CIRCUIT:**
  - The smoothing reactor is selected to avoid resonance in the DC circuit at low order harmonic frequencies like 100 or 150 Hz.
  - This is important to avoid the amplification effect for harmonics originating from the AC system, like negative sequence and transformer saturation.

- **REDUCING HARMONIC CURRENTS INCLUDING LIMITATION OF TELEPHONE INTERFERENCE:**
  - Limitation of interference coming from the DC over-head line is an essential function of the DC filter circuits.
  - However, the smoothing reactor also plays an important role to reduce harmonic currents acting as a series impedance.

- **HARMONIC FILTERS:**
  - If the switch is operated there is a harmonic in the system.
  - Generally there are characteristic harmonics and non characteristics harmonics present in the system

    Characteristic harmonics

    AC= np±1: DC=np

    Non-Characteristic harmonics

    DC= np±1: AC=np Where n= integer

    P=Pulse Number
  - Filters provide low impedance path to the ground for one or two particular frequencies
  - They are connected to the converter terminals so that harmonics should not enter AC system and also provide necessary reactive power support for the converter operation.
  - The harmonics which are at greater magnitude are only considered for the filter placements.
  - Filters are used at the bus bar also.
  - filters are required for both at AC side also on the DC side.

- **REACTIVE POWER SOURCES:**
  - Generally consumers does not consume reactive power but to the phase displacement of current drawn by the converters and voltage in the AC system .
  - Reactive power requirement at the converter stations is 50% to 60% of the Real power transferred, which is supplied by the filters , capacitors & synchronous condensers.
  - If the generating station is near to the HVDC generators can also provide necessary reactive power support.
  - Synchronous condensers not only provide reactive power support but also provide AC voltage for Natural Commutation of inverter .
  - These reactive power sources not only should operate in normal condition but also should operate in abnormal conditions as well

- **EARTH ELECTRODE:**
  - Under Emergency condition ground Return Path is used.
  - Earth Resistivity is generally high in the order of 4000 Ω-m.
  - Earth electrode cannot be kept directly on the earth surface.
  - Electrodes are to be buried deep in the ground where the resistivity is (3-10Ω-m) to reduce transient over voltages during line faults and also gives low DC electric potential and potential gradient at the surface of the earth

- **CHOICE OF VOLTAGES:**
  - For example 1000MW, bipolar
    - $P_{DC} = V_{DC} \times I_{DC}$ Monopole
    - $P_{DC} = 2\, V_{DC} \times I_{DC}$ Bipole
  - Conductor sizes depending on the voltages Dog, panther, moose, zebra etc are used.
  - Generally for DC the right of way is less when compared to AC

- **MODERN TRENDS IN HVDC TECHNOLOGY:**
  - Power Semiconductors & Valves.
  - Converter Control.
  - Dc Breakers.
  - Conversion of Existing AC Lines.
  - Operation with weak AC system.
  - Active Dc Filters.
  - Capacitor Commutated Converters (CCC).
  - UHVDC Transmission

- **POWER SEMICONDUCTORS & VALVES:**
  - current Rating (overload Capacity)
  - Direct Light Triggered Thyristors (LTT).
  - Power rating of the devices. By better cooling
  - Each Thyristor 8KV, 40mW gate power.
  - Gate Turn Off thyristor (GTO) - 6KV & 4KA
  - Insulated Gate Bipolar Transistor (IGBT) – ±150KV and 350MVA switching

- **CONVERTER CONTROL:**
  - Microprocessor Based control.
  - Experts in fault detection and Rectification
  - Transducers for measuring Voltages and Currents for protection and control.

- **DC BREAKERS:**
  - High Current Breaking.
  - Development of MTDC**.**

- **CONVERSION OF EXISTING AC LINES:**
  - ROW (Right of Way).
  - Electromagnetic Interference

- **OPERATION WITH WEAK AC SYSTEM:**
  - Short Circuit Ratio **=** ————————————————

    SCR <3- weak AC System
    SCR =3- Moderate AC System
    SCR >3- Strong AC System

More Reactive power is needed to transmit power or else load rejection is done

- **ACTIVE DC FILTERS**:
  - VSC + Passive Filter
  - Characteristic and Non characteristic Harmonics

- **CAPACITOR COMMUTATED CONVERTERS (CCC):**
  - Capacitors in series with Valve Side Windings of the Converter Transformer
  - Forced Commutation.
  - Reactive Power Support

- **UHVDC TRANSMISSION:**
  - ± 800KV HVDC- ± 500KV
  - Power Transmitted 3000MW / 1500Km

HVDC BIPOLAR/ASYNCHRONOUS LINKS IN INDIA

RIHAND-DELHI 2*750 MW	
CHANDRAPUR-PADGE 2* 750 MW	VINDYACHAL (N-W) – 2*250 MW
TALCHER-KOLAR 2*1000 MW	CHANDRAPUR (W-S)– 2*500 MW
SILERU-BARASORE 100 MW	VIZAG (E-S) - 2*500 MW

HVDC IN INDIA BIPOLAR

HVDC LINK	CONNECTING REGION	CAPACITY (MW)	LINE LENGTH (Km)
Rihand – Dadri	North-North	1500	815
Chandrapur - Padghe	West - West	1500	752
Talcher – Kolar	East – South	2500	1367

HVDC IN INDIA BACK TO BACK

HVDC LINK	CONNECTING REGION	CAPACITY (MW)
Vindyachal	North – West	2 x 250
Chandrapur	West – South	2 x 500
Vizag – I	East – South	500
Sasaram	East – North	500
Vizag – II	East – South	500

REFERENCES

- DC CURRENT TRANSMISSION BY EDWARD WILSON KIMBARK. VOLUME - I
- SIEMENS AG ENERGY SECTOR AND TRANSMISSION SECTOR CATALOGUES AND BROCHURES.
- ABB CATALOGUES AND BROCHURES.
- IEEE JOURNAL AND CONFERENCE PAPERS.
- E- RESOURCE.

INTRODUCTION TO FACTS CONCEPTS

TRANSMISSION INTERCONNECTIONS:

- The world's electric power supply systems are widely interconnected, involving connections inside utilities' own territories which extend to inter-utility interconnections and then to inter-regional and international connections.
- This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply.

NEED OF TRANSMISSION INTERCONNECTIONS:

- Transmission network is to pool power plants and load centers in order to minimize the total power generation capacity and fuel cost.
- Adversity of loads, availability of sources, and fuel price in order to supply electricity to the loads at minimum cost with a required reliability.
- If a power delivery system was made up of radial lines from individual local generators without being part of a grid system, many more generation resources would be needed to serve the load with the same reliability, and the cost of electricity would be much higher.

FLOW OF POWER IN AN AC SYSTEM:

- In AC power systems, given the insignificant electrical storage, the electrical generation and load must balance at all times.
- To some extent, the electrical system is self-regulating. If generation is less than load, the voltage and frequency drop, and thereby the load, goes down to equal the generation minus the transmission losses.
- If voltage is propped up with reactive power support, then the load will go up, and consequently frequency will keep dropping, and the system will collapse. Alternately, if there is inadequate reactive power, the system can have voltage collapse.

POWER FLOW IN PARALLEL PATHS

Consider a very simple case of power flow , through two parallel paths (possibly corridors of several lines) from a surplus generation area, shown as an equivalent generator on the left, to a deficit generation area on the right. Without any control, power flow is based on the inverse of the various transmission line impedances

With HVDC, power flows as ordered by the operator, because with HVDC power electronics converters power is electronically controlled. Also, because power is electronically controlled, the HVDC line can be used to its full thermal capacity if adequate converter capacity is provided. Furthermore, an HVDC line, because of its high-speed control, can also help the parallel ac transmission line to maintain stability.

FACTS Controller can control the power flow as required. Maximum power flow can in fact be limited to its rated limit under contingency conditions when this line is expected to carry more power due to the loss of a parallel line.

POWER FLOW IN A MESHED SYSTEM

Suppose the lines AB, BC, and AC have continuous ratings of 1000 MW, 1250 MW, and 2000MW, respectively, and have emergency ratings of twice those numbers for a sufficient length of time to allow rescheduling of power in case of loss of one of these lines. If one of the generators is generating 2000 MW and the other 1000 MW, a total of 3000MW would be delivered to the load center.

For the impedances shown, the three lines would carry 600, 1600, and 1400 MW, respectively, as shown in Figure (a). Such a situation would overload line Be (loaded at 1600 MW for its continuous rating of 1250 MW), and therefore generation would have to be decreased at B, and increased at A, in order to meet the load without overloading line BC. Power, in short, flows in accordance with transmission line series impedances (which are 90% inductive) that bear no direct relationship to transmission ownership, contracts, thermal limits, or transmission losses.

If, however, a capacitor whose reactance is -5 ohms at the synchronous frequency is inserted in one line Figure (b), it reduces the line's impedance from 10 0hm to 5 0hm, so that power flow through the lines AB, BC, and AC will be 250, 1250, and 1750 MW, respectively. It is clear that if the series capacitor is adjustable, then other power-flow levels may be realized in accordance with the ownership, contract, thermal limitations, transmission losses, and a wide range of load and generation schedules.

Although this capacitor could be modular and mechanically switched, the number of operations would be severely limited by wear on the mechanical components because the line loads vary continuously with load conditions, generation schedules, and line outages. Other complications may arise if the series capacitor is mechanically controlled. A series capacitor in a line may lead to sub-synchronous resonance (typically at 10-50 Hz for a 60 Hz system). This resonance occurs when one of the mechanical resonance frequencies of the shaft of a multiple-turbine generator unit coincides with 60 Hz

Similar results may be obtained by increasing the impedance of one of the lines in the same meshed configuration by inserting a 7 ohm reactor (inductor) in series with line AB [Figure (c)]. Again, a series inductor that is partly mechanically and partly thyristor-controlled, it could serve to adjust the steady-state power flows as well as damp unwanted oscillations

- **LOADING CAPABILITY:**
    - THERMAL CAPABILITY
    - DIELECTRIC CAPABILITY
    - STABILITY CAPABILITY
        - TRANSIENT STABILITY
        - DYNAMIC STABILITY
        - STEADY-STATE STABILITY
    - FREQUENCY COLLAPSE
    - VOLTAGE COLLAPSE
    - SUB-SYNCHRONOUS RESONANCE

- **THERMAL CAPABILITY :**
  - Thermal capability of an overhead line is a function of the ambient temperature, wind conditions, condition of the conductor, and ground clearance.
  - It varies perhaps by a factor of 2 to 1 due to the variable environment and the loading history. The nominal rating of a line is generally decided on a conservative basis, envisioning a statistically worst ambient environment case scenario

- **DIELECTRIC CAPABILITY:**
  - From an insulation point of view, many lines are designed very conservatively. For a given nominal voltage rating, it is often possible to increase normal, operation by +10% voltage (i.e., 500 kV-550 kV) or even higher. Care is then needed to ensure that dynamic and transient overvoltages are within limits. On EHV overhead lines switching surges rather than lightining create more serious transient over voltages
  - Switching surges in DC are lower than 1.7 times normal voltage.

- **STABILITY:**
  The ability of system to regain its original state when it is subjected to any disturbances
  - **TRANSIENT STABILITY:** The ability of system to regain its original state when it is subjected to small and large disturbances
  - **DYNAMIC STABILITY:** The ability of system to regain its original state when it is subjected to small and large disturbances with controller action
  - **STEADY-STATE STABILITY**: The ability of system to regain its original state when it is subjected to small and gradual disturbances

- **FREQUENCY COLLAPSE**: If the frequency of the system falls below a preset value then it is Frequency collapse. It can be eliminated by load shedding

- **VOLTAGE COLLAPSE:** If the voltage of the system falls below a preset value then it is voltage collapse. It can be eliminated by injecting excess amount of reactive power in to the system

- **GRID COLLAPSE:** Both voltage and frequency collapse together account for grid collapse

- **SUB-SYNCHRONOUS RESONANCE**: If the mechanical frequency of the turbine and the electrical frequency of the system are equal then this resonance occurs and these frequencies occur below the synchronous speeds if this Resonance occur the consequence is severe which is torsion stress occurs on the shaft which results in shaft breakage.

- **REACTIVE POWER AND VOLTAGE REGULATION**

On Long EHV AC lines and on shorter AC cables the production and consumption of reactive power by the line itself constitutes a serious problem

Consider a line with series inductance L and shunt capacitance C per unit length and operating at a given voltage V and carrying a current I the line produces a reactive power given by $\mathbf{Q_C = \omega CV^2}$ and consumed reactive power $\mathbf{Q_L = \omega LI^2}$**. The net** reactive power in both should be equal

$$Q_C = Q_L$$

$$\omega CV^2 = \omega LI^2.$$

—

— = —

In this case the load impedance has a value Z_S known as the **Surge Impedance loading** of the line. This SIL of the Over head line with single conductor is about 400Ωand with bundled conductors about 300Ω that of the cable 15 to 25Ω

The power carried by the line is = = — which also called Natural Loading. It is independent of distance and depends on voltage

- **POWER FLOW AND DYNAMIC STABILITY CONSIDERATIONS OF A TRANSMISSION INTERCONNECTION:**

  E_1 and E_2 are the magnitudes of the bus voltages with an angle δ between the two. The line is assumed to have inductive impedance X, and the line resistance and capacitance are ignored. As shown in the phasor diagram the driving voltage drop in the line is the phasor difference EL between the two line voltage phasors, E_1 and E_2• The line current magnitude is given by: $I = E_L/X$, and lags E_L by 90

- Active component of the current flow at E_1 is: $I_{P1} = (E_2 \sin \delta)/X$
- Reactive component of the current flow at E_1 is: $I_{ql} = (E_1 - E_2 \cos \delta)/X$
- Thus, active power at the E_1 end: $P_1 = E_{1(}E_2/X)\sin\delta$
- Reactive power at the E_1 end: = $E_1 (E_1 - E_2 \cos \delta)/X$
- Active component of the current flow at E_1 is: $I_{P2} = (E_1 \sin \delta)/X$
- Reactive component of the current flow at E_1 is: $Iq_2 = (E_2 – E_1 \cos \delta)/X$
- Thus, active power at the E_1 end: $P_2 = E_2(E_1/X)\sin\delta$
- Reactive power at the E_2 end: = $E_2 (E_2 – E_1 \cos \delta)/X$
- Naturally Powers are equal

- **RELATIVE IMPORTANCE OF CONTROLLABLE PARAMETERS:**

  - Control of the line impedance X , When the angle is not large, which is often the case, control of X or the angle substantially provides the control of active power.
  - Control of angle which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.
  - Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90 degrees, this means injection of reactive power in series, can provide a powerful means of controlling the line current, and hence the active power when the angle is not large.
  - Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.
  - Combination of the line impedance control with a series Controller and voltage regulation with a shunt Controller can also provide a cost-effective means to control both the Active and Reactive Power Flow between the two systems.

- **FLEXIBILITY OF ELECTRIC POWER TRANSMISSION:**
  - The ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady state and transient margins.

- **FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)**
  - Alternating Current transmission systems incorporating Power Electronic-based and other Static Controllers to enhance controllability and increase Power Transfer Capability.

- **FACTS CONTROLLERS:**
  - A power electronic-based system and other static equipment that provide control of one or more A C transmission system parameters

BASIC TYPES OF FACTS CONTROLLERS:

- SERIES CONTROLLERS
- SHUNT CONTROLLERS
- COMBINED SERIES-SERIES CONTROLLERS
- COMBINED SERIES-SHUNT CONTROLLERS

- **SERIES CONTROLLERS:**
  - The series Controller could be a variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, sub-synchronous and harmonic frequencies (or a combination) to serve the desired need.
  - In principle, all series Controllers inject voltage in series with the line. Even a variable impedance multiplied by the current flow through it, represents an injected series voltage in the line.
  - As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

- **SHUNT CONTROLLERS:**
  - As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these.
  - In principle, all shunt Controllers inject current into the system at the point of connection.
  - Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line.
  - As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power.
  - Any other phase relationship will involve handling of real power as well.

- **COMBINED SERIES-SERIES CONTROLLERS:**
  - This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link.
  - The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "**Unified**" here means that the DC terminals of all Controller converters are all connected together for real power transfer

- **COMBINED SERIES-SHUNT CONTROLLERS:**
  - This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements.
  - In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link

- **SERIES CONNECTED CONTROLLERS:**
  - Static Synchronous Series Compensator (SSSC)
  - Interline Power Flow Controller (IPFC)
  - Thyristor Controlled Series Capacitor (TCSC)
  - Thyristor-Switched Series Capacitor (TSSC)
  - Thyristor-Controlled Series Reactor (TCSR)
  - Thyristor-Switched Series Reactor (TSSR)

- **STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC):**
  - A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power.

- **INTERLINE POWER FLOW CONTROLLER (IPFC):**
  - It is a combination of two or more Static Synchronous Series Compensators which are coupled via a Common DC link to facilitate bi-directional flow of real power between the AC terminals of the SSSC's, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines.
  - The IPFC structure may also include a STATCOM, coupled to the IFFC's common DC link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSC's.

- **THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC):**
  - A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor- controlled reactor in order to provide a smoothly variable series capacitive reactance.

- **THYRISTOR-SWITCHED SERIES CAPACITOR (TSSC):**
  - A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance.

- **THYRISTOR-CONTROLLED SERIES REACTOR (TCSR):**
  - An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.

- **THYRISTOR-SWITCHED SERIES REACTOR (TSSR):**
  - An inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance.

- **SHUNT CONNECTED CONTROLLERS:**
  - STATIC SYNCHRONOUS COMPENSATOR (STATCOM)
  - STATIC SYNCHRONOUS GENERATOR (SSG)
  - BATTERY ENERGY STORAGE SYSTEM (BESS)
  - SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)
  - STATIC VAR COMPENSATOR (SVC)
  - THYRISTOR CONTROLLED REACTOR (TCR)
  - THYRISTOR SWITCHED REACTOR(TSR)
  - THYRISTOR SWITCHED CAPACITOR (TSC)
  - STATIC VAR GENERATOR OR ABSORBER (SVG)
  - STATIC VAR SYSTEM (SVS)
  - THYRISTOR CONTROLLED BRAKING RESISTOR (TCBR)

- **STATIC SYNCHRONOUS COMPENSATOR (STATCOM)**
  - A Static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

- **STATIC SYNCHRONOUS GENERATOR (SSG):**
  - A static self- commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power.

- **BATTERY ENERGY STORAGE SYSTEM (BESS):**
  - A chemical-based energy storage system using shunt connected, voltage-source converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.

- **SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES):**
  - A Superconducting electromagnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an ac system.

- **Static VAR Compensator (SVC):**
  - A shunt-connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).

- **THYRISTOR CONTROLLED REACTOR (TCR):**
  - A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.
- **THYRISTOR SWITCHED REACTOR(TSR):**
  - A shunt- connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.
- **THYRISTOR SWITCHED CAPACITOR (TSC):**
  - A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.
- **STATIC VAR GENERATOR OR ABSORBER (SVG):**
  - A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power.
  - Generally considered to consist of shunt-connected, thyristor-controlled reactor(s) and/or thyristor-switched capacitors.
- **STATIC VAR SYSTEM (SVS):**
  - A combination of different static and mechanically-switched VAR compensators whose outputs are coordinated.
- **Thyristor Controlled Braking Resistor (TCBR):**
  - A shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance.
- **COMBINED SHUNT AND SERIES CONNECTED CONTROLLERS:**
  - UNIFIED POWER FLOW CONTROLLER (UPFC)
  - THYRISTOR-CONTROLLED PHASE SHIFTING TRANSFORMER (TCPST)
  - INTERPHASE POWER CONTROLLER (IPC)
- **UNIFIED POWER FLOW CONTROLLER (UPFC):**
  - A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common de link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.

- **THYRISTOR- CONTROLLED PHASE SHIFTING TRANSFORMER (TCPST):**
    - A phase-shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle.
- **INTERPHASE POWER CONTROLLER (IPC):**
    - A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches