BASIC PRINCIPLES OF HVDC
Due to ease of transformation of voltage levels after the invention of the transformers and rugged squirrel cage motors, ALTERNATING CURRENT is universally utilized. Since the loads are AC operated, the generation and transmission also is done in AC. Generators are at remote places and the voltage is around 15-25KV. The voltage is boosted to 220 or 400KV and transmitted to the load centers. To reach the loads like industry and domestic loads, distribution system is built. In this sense AC transmission is advantageous. However, the limitations of AC transmission have caused the power transmitting industries to resort to HVDC systems for some applications. Let us discuss the demerits of AC transmission and the advantages of HVDC transmission.

**PRINCIPLES OF AC TRANSMISSION:**

Let us consider two partial AC networks with two generators G1 and G2 connected through AC transmission line of reactance X. The transmission power P is the difference of the powers P1 and P2 generated respectively between both the generators reduced by the power which is locally consumed and the resultant equation will be

\[ P = \frac{U_1 \times U_2}{X} \sin \theta \]  

\[ \text{Figure (1)} \]
According to the equation (1) the power transmitted between both systems depends upon the product of AC voltages of both systems divided by the line reactance which is almost constant in the practical system multiplied by the sine of the angle (load angle) between both the voltages. The angle $\Theta$ cannot be influenced (in normal AC systems without FACTS) and it depends upon the power balance between the two interconnected systems. Thus excess of power results in acceleration of the system that is leading load angle and deficiency in power results decelerating of the system i.e. lagging angle. This does have undeniable advantage that both systems help each other. But this can lead to undesired displacement of power which can result in overloading of the transmission system. The sensitivity of AC systems to disturbances of the power balance and uncontrollable load flow over the connected AC system are two of the fundamental technical properties make the HVDC transmission attractive.

For long distance AC transmission the demand for reactive power cause major problems and to overcome this intermediate sub-stations are to be provided to compensate the reactive power requirements. To arrive at a cost effective solution HVDC is advantageous in this respect.

With relatively short transmission lines the transfer of short circuit power could cause another problem. The short circuit level in one system part will increase unavoidably due to the increase in number of connected generators. The switchgear apparatus has to cope up with the aggravated short circuit requirements. In this respect, HVDC offers perfect and elegant solution; short circuit power which is basically reactive power cannot be transmitted through a DC circuit.

**CHARACTERISTICS OF HVDC:**

These limitations can be overcome by HVDC system. Figure (2) depicts two AC systems connected through HVDC system. System 1 connected with rectifier and system 2 with Inverter and DC transmission line with resistance $R$. The current flow between the stations is given as per equation (2).

\[
I = \frac{U_{d1} - U_{d2}}{R} \quad \text{..........................(2)}
\]

If the nominal direct voltage is defined as average voltage \((1/2) (U_{d1} + U_{d2})\)

Then the equation for the power transmitted is

\[
P = \frac{(U_{d1}^2 - U_{d2}^2)}{2R} \quad \text{..........................(3)}
\]
U_d = kU_v (\cos \alpha - u_k/2) \hspace{1cm} \text{.....(4)}

Where

\[\alpha = \text{ignition angle / delay angle}\]
\[U_v = \text{valve side transformer voltage}\]
\[u_k = \text{transformer short circuit voltage}\]

**ASYNCHRONOUS CONNECTION:**

In the equation above there are no frequency related terms. This shows that the HVDC system is independent of frequencies or the phase positions of the two AC systems to be linked. Hence, HVDC is the solution to interconnect two AC systems with different frequencies.

**Asynchronous / Back to back links in India:**

In India there are four back to back HVDC links connected between various electrical regions which were operating asynchronously till the year 2006. These links are providing stability to the regions and are being helpful for inter regional power transactions in India. Table below shows the back to back links in India.

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>HVDC LINK</th>
<th>CONNECTING REGIONS</th>
<th>CAPACITY (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vindyachal</td>
<td>WR – NR</td>
<td>2 X 250</td>
</tr>
<tr>
<td>2</td>
<td>Chandrapur</td>
<td>WR – SR</td>
<td>2 X 500</td>
</tr>
<tr>
<td>3</td>
<td>Vizag</td>
<td>ER – SR</td>
<td>2 X 500</td>
</tr>
<tr>
<td>4</td>
<td>Sasaram</td>
<td>ER – NR</td>
<td>500</td>
</tr>
</tbody>
</table>

Figure (2)
LIMITATION OF SHORT CIRCUIT POWER:

Since reactive power cannot be transmitted through the DC link, contribution of one system short circuit power to the other system is eliminated. Hence, second system can be connected by the HVDC link without increasing the short circuit power.

CONTROL OF LOAD FLOW:

Since the direct voltages of both the terminals can be changed using the delay angles it is possible to control the load flow with fast acting microprocessor systems. Thus it is possible to maintain constant flow of energy through the link irrespective of the momentary power balance of the AC system. If necessary, the energy flow can be stopped very quickly or reverse the power flow.

ENHANCEMENT OF STABILITY:

The fast and exact control of power over HVDC link makes it possible to create positive damping of the electromechanical oscillations by modulation of the transmitted power. HVDC can lend support to stabilize the AC network to which it is connected or to a parallel AC network.

LONG DISTANCE TRANSMISSION THROUGH OVER HEAD LINES:

Generally generating stations are located away from the load centers. When bulk power has to be transmitted over long distances HVDC offers the economical solution. Since bulk power is generated by large hydro/thermal plants which are located remotely a DC transmission line is a viable solution. A bipolar DC transmission line requires only two conductors while to transmit the same power (but less distance) over AC transmission requires a double circuit line. The DC transmission line design is relatively simple, less tower weight and reduced right of way. With the growing environmental concern, right of way is an important factor to be considered while building a transmission line.

Long distance HVDC transmission systems in India:

They are mostly Bipolar systems. They are more economical and provide reliability to the system. In India there are three Bipolar HVDC links in operational.

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>HVDC LINK</th>
<th>CONNECTING REGION</th>
<th>CAPACITY (MW)</th>
<th>LINE LENGTH (KM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rihand – Dadri</td>
<td>NR – NR</td>
<td>1500</td>
<td>815</td>
</tr>
<tr>
<td>2</td>
<td>Chandrapur – Padghe</td>
<td>WR – WR</td>
<td>1500</td>
<td>752</td>
</tr>
<tr>
<td>3</td>
<td>Talcher – Kolar</td>
<td>ER – SR</td>
<td>2000</td>
<td>1367</td>
</tr>
</tbody>
</table>
CONVERTER CIRCUITS

The basic module for HVDC converter is the three phase, full wave bridge circuit. This circuit is also known as a Graetz Bridge. The Graetz Bridge has been universally used for HVDC converters as it provides better utilization of the converter transformer and a lower voltage across the valve when not conducting, this voltage is called Peak Inverse Voltage called PIV and is important for selection of the Thyristor.

ANALYSIS OF GRAETZ BRIDGE / SIX PULSE CONVERTER:

The bridge converter is represented by the equivalent circuit in fig. (3) with transformer and source impedance with a loss less inductance. Direct current is assumed to be ripple free and valves as ideal switches with zero resistance when conducting and infinite resistance when not conducting.

![Figure (3)]

Note: Valves are numbered in order of firing.

Let the instantaneous line – to – neutral source voltages be

\[ ea = Em \cos( \omega t + 60^\circ) \]
\[ eb = Em \cos( \omega t - 60^\circ) \]
\[ ec = Em \cos( \omega t - 180^\circ) \] ..............................(5)

Then the line-to-line voltages are

\[ eac = ea - ec = \sqrt{3} Em \cos( \omega t + 30^\circ) \]
\[ \text{eba} = \text{eb-ea} = \sqrt{3} \text{EmCos}(\omega t-90^\circ) \]
\[ \text{ecb} = \text{ec-eb} = \sqrt{3} \text{EmCos}(\omega t+150^\circ) \]  
\[ \text{………………..(6)} \]

**Analysis with negligible source inductance**

1. **With no ignition delay**

   In the figure (4) the cathodes of valves 1,3,5 of the upper row are connected together. Therefore, when phase-to-neutral voltage of phase \(a\) is more positive than the voltage of the other two phases, valve 1 conducts. The common potential of the three valves is then equal to that of the anode of valve one and the since the cathodes of valve 3 and 5 are at higher potential than their anodes, these valves do not conduct. After 120 \(^\circ\) the voltage of phase \(b\) becomes more positive and phase \(a\) becomes less. Valve 3 starts conducting and this turns off valve 1 because the cathode of valve 1 is at higher potential. In the lower row, the anodes of valves 2,4,6 are connected together. Therefore valve 2 conducts when phase \(c\) voltage is more negative than the other two phases. From figure (4) we can observe that each valve conducts for 120 \(^\circ\). When it is conducting the magnitude of valve current is \(I_d\); the valves in the upper row carry positive current and the valve in the lower row carry negative (return) current. Every 60 \(^\circ\) one valve from either positive row or negative row starts conducts. The valve switching sequence is illustrated in figure which shows only the conducting valves during the six distinct periods of a complete cycle.

   The transfer of current from one valve to another in the same row is called *commutation*. In this analysis source inductance is assumed to be zero. Hence current transfer from one row to the other takes place instantaneously. The number of pulsations of output voltage per cycle is *six* and hence this is called *Six pulse bridge* circuits.

   The instantaneous direct voltage \(U_d\) across the bridge is composed of 60 \(^\circ\) segments of the line- to-line voltages. Therefore average direct voltage can be found by integrating the instantaneous values over any 60 \(^\circ\) period.

\[
0 \quad \text{Ud0} = \frac{3}{\Pi} \int_{-60^\circ}^{0} \text{eac} \, d\Theta
\]

Substituting \(\text{eac} = \sqrt{3} \text{EmCos}(\omega t+30^\circ)\)

\[
\text{Vdo} = 1.65 \text{ Em} \quad \text{………………..(7)}
\]

\[
\text{Vdo} = 2.34 \text{ ELN} \quad \text{………………..(8)}
\]

\[
\text{Vdo} = 1.35 \text{ELL} \quad \text{………………..(9)}
\]

Where \(\text{ELL}\) is the line to line voltage and \(\text{Udo}\) is the ideal no load direct voltage.
2. With ignition delay:

The gate control can be used to delay the ignition of the valves. The delay angle is denoted by $\alpha$; it corresponds to time delay of $\alpha/w$ seconds.

With delay of $\alpha$, valve 3 ignites at $\omega t = \alpha$; valve 4 ignites at $\omega t = \alpha + 60^\circ$ and valve 5 ignites at $\omega t = \alpha + 120^\circ$, and so on (refer fig. (5))

With delay angle $\alpha$ the direct voltage $V_d$ is

$$V_d = V_{d0} \cos \alpha \hspace{1cm} \text{(10)}$$
3. Analysis with commutation overlap

Due to the inductance of the ac source and transformer reactance, the phase currents cannot change instantly. Therefore, the transfer of current from one phase to another requires a finite time, called the commutation time or overlap time. The corresponding overlap or commutation angle is denoted by $\mu$.

In normal operation, the overlap angle is less than 60°. With $0^\circ < \mu < 60^\circ$, during commutation three valves conduct simultaneously. However, between commutations only two valves conduct. A new commutation begins every 60° and lasts for an angular period of $\mu$. During commutation the current in the incoming valve increases from 0 to $I_d$ and the current in the outgoing valve decreases from $I_d$ to 0.

Consider the case where commutation from valve 1 to 3 is taking place. The commutation begins when $\omega t = \alpha$ and ends when $\omega t = \alpha + \mu = \delta$ where $\delta$ is the extinction angle.

At the beginning of commutation, $i_1 = I_d$ and $i_3 = 0$

At the end of commutation, $i_1 = 0$ and $i_3 = I_d$

Equivalent circuit during the commutation period is shown in figure (6). From the loop containing valve 1 and 3.
Figure (6)

\[ eb - ea = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt} \]  
\[ \sqrt{3}E_m \sin \omega t = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt} \]  
Since \( i_1 = I_d - i_3 \),

\[ \frac{di_1}{dt} = 0 - \frac{di_3}{dt} \]  
\[ \frac{eb - ea}{dt} = \sqrt{3}E_m \sin \omega t = 2L_c \frac{di_3}{dt} \]  
\[ \frac{di_3}{dt} = \sqrt{3}E_m \sin \omega t \]  
\[ \frac{2 \omega}{L_c} \]

Integrating between the limits \( t \) and \( \alpha/\omega \)

\[ i_3 = \frac{\sqrt{3}E_m}{2 \omega L_c} (\cos \alpha - \cos \omega t) \]  
\[ = I_s2 (\cos \alpha - \cos \omega t) \]
Where \( I_{s2} = \sqrt{3} E_m \frac{E_m}{2\omega L_c} \)

Voltage reduction due to commutation overlap

From equation \( L_c \frac{d}{dt} i_3 = e_b - e_a \)

hence, \( v_a = v_b = e_b - e_a = e_a + e_b \) \( \frac{e}{2} \) ........................(17)
Rectifier Voltage calculation considering the ignition and overlap angles:

\[ U_d = U_d0 \cos \alpha - \Delta U_d \]

Where \( \Delta u = 3\omega L_c = \frac{3}{\pi} X_c \) ……………………(19)

Rc is called the “equivalent commutation resistance” and it accounts for the voltage drop due to commutation overlap.

**Inverter operation:**

Since valves conduct in only one direction, the current in a converter cannot be reversed. A reversal of Ud results in a reversal of power. An alternating voltage must exist on a primary side of the transformer for inverter operation. The direct voltage of the inverter opposes the current as in a dc motor and is called a back voltage. The applied direct voltage from the rectifier forces current through the inverter valves against the back voltage. When \( \alpha \) is greater than 90º inverter operation can be achieved. However, common practice is to use ignition advance angle \( \beta \) and extinction advance angle \( \gamma \) for describing inverter performance.
Converter Angle Definitions

\[ e_{ba} = \text{commutating voltage} \]

\[ I_{S2}(\cos \alpha - \cos \omega t) = \text{current during commutating period} \]

\[ i_1 = \text{current in valve 1} \]

\[ i_3 = \text{current in valve 3} \]
\( \beta = \Pi - \alpha = \text{ignition advance angle} \)
\( \gamma = \Pi - \delta = \text{extinction advance angle} \)
\( \mu = \delta - \alpha = \beta - \gamma = \text{overlap} \)

**Inverter Voltage calculation considering the ignition and overlap angles**

![Diagram showing inverter voltage calculation](image)

\[ \alpha + \mu + \gamma = \pi \quad \text{After evaluation} \Rightarrow \]

\[ U_d = -\left(1.35 \cdot U \cdot \cos \gamma - \frac{3}{\pi} \cdot \omega L \cdot I_d\right) \]

Figure (12)

Since \( \cos \alpha = -\cos \beta \) and \( \cos \delta = -\cos \gamma \)

Equations (16) & (18) may be written in terms of \( \beta \) and \( \gamma \)

\[ \text{Id} = \text{Is2} \cdot (\cos \gamma - \cos \beta) \quad \ldots \quad \text{(20)} \]
\[ \text{Ud} = \text{Udo} \cdot (\cos \gamma - \cos \beta) \quad \ldots \quad \text{(21)} \]
\[ \frac{\text{Ud}}{2} = \text{Udo} \cdot \cos \beta + \text{Rc} \cdot \text{Id} \quad \ldots \quad \text{(22)} \]

Or
\[ \text{Ud} = \text{Udo} \cdot \cos \gamma - \text{Rc} \cdot \text{Id} \quad \ldots \quad \text{(23)} \]

Equivalent circuits for inverter and rectifier can be represented as in figure.

**12 – Pulse bridge converters**

In practice, two bridges are connected in series so as to result in a 12-pulse arrangement to obtain as high a direct voltage as required. The bridges are in series on the DC side and parallel on the AC side. Two banks of transformers one connected Y-Y abs the other Y-D are used to supply each pair of bridges. The three phases voltages supplied at one bridge are displaced by 30° from those supplied at the other bridge. The AC wave
shapes of the two bridges add up so as to produce a wave shape which is more sinusoidal than the current waves for each of the 6-pulse bridges as shown in the figure. With this arrangement fifth and seventh harmonics are effectively eliminated on the AC side. This reduces the cost of the harmonic filters significantly. In addition, the DC voltage ripple reduces; sixth and eighteenth harmonics are eliminated.

Figure (13)
**Operation of HVDC system:**

In a DC transmission, power flows from rectifier to Inverter. Power flow can be controlled by varying the DC voltages, which can be changed by controlling the delay angles. Converter is a common term used in HVDC which can operate either as a rectifier or Inverter for delay angles 0-90° the converter acts as rectifier and delay angles between 90-180 converter acts as inverter. In practice, these ranges are 5°-90° and 90°-160°.

**Rectifier Operation**

**Inverter Operation**

---

**Figure (14)**
HARMONICS IN CONVERTERS:

Converter valves connect cyclically the DC terminal to the AC terminals of a converter circuit. The alternating currents on AC side are therefore composed of sections of currents on DC side. Direct currents are regulated by the converter and therefore the alternating current is also being controlled. The converter acts as a current source. AC side current waveform of the converter is only a rough approximation to a sinusoid. If the commutation reactance were zero, then the waveform would consist of square wave segments. In reality, the inductive reactance of the converter transformers ensures a gradual transfer of current from one phase to the other and so rounds the steps of the resulting current waveform.

The most convenient way of considering this distorted current is to analyze it in terms of harmonics of the fundamental frequency. It can be shown to contain a number of so-called “characteristic harmonics” of relatively high magnitude as well as generally lower magnitudes of all other harmonic orders, the “non-characteristic harmonics”.

Characteristic Harmonics generated by a 12 pulse converter are \((12p\pm1)\) - 11, 13, 23, 25, 35, 37, 47, 49,.....

If these harmonic currents were allowed to flow unmitigated into the AC network, then unacceptable amounts of harmonic voltage and current distortion would occur, possibly causing heating of machines, mal operation of some equipment and telephone interference. AC side Harmonic Filters are used to reduce the distortion to acceptable limits. Because of the phase shift between the applied AC voltage and the converter AC current, due to the firing angle and over-lap effects, an HVDC converter consumes a considerable amount of reactive power – in the range of 50% of the active power transmitted. Normally, it is desirable that this reactive power deficit is compensated within the HVDC station and this is most economically achieved by shunt capacitive compensation in the form of harmonic filters.

The AC side filters therefore fulfill a dual role – mitigation of harmonic distortion and reactive power compensation.

There are many possible design configurations for the AC side harmonic filters and the choice of optimum filter is designed based on the complex studies. There may be single tuned filters, double tuned filters, high pass filter or the combination of both.
Figure (15) – Single Tuned filter

Figure (16) – Double Tuned filter

Figure (17) – High pass filter
MODES OF OPERATION IN BIPOLAR HVDC LINKS:

Bipolar HVDC links can be operated in three modes. Based on the availability of the elements in HVDC they can be operated in

a. Balance bipolar mode
b. Metallic return mode
c. Ground Return mode

These operating modes also make HVDC systems reliable compared to AC systems.

Balanced Bipolar Mode of operation:

When both the poles and both the lines are available and healthy, this mode of operation is possible. Both the poles share equal powers and electrode current will be approximately zero. Full station capacity can be achieved in this mode. This is the normal preferred mode of operation.

Metallic return mode of operation: When any one pole is out of service / faulty and both the lines are healthy, the DC line of the faulty pole is used as the return path for the current and metallic return mode is operated. In this mode 50% of the station power can be achieved. Losses in this mode will be higher than the bipolar mode for the same power transmitted.
Ground Return mode of operation:

When any one DC line is out of service / faulty and the DC line of the corresponding healthy are available, ground return mode of operation is possible. Ground is used as the return path for the current in this mode. In this mode 50% of the station power can be achieved. Losses in this mode will be lesser than the metallic return mode of operation.
# RATINGS OF TALCHER KOLAR HVDC LINK

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rectifier</strong></td>
<td><strong>Talcher, Orissa (Eastern region)</strong></td>
</tr>
<tr>
<td><strong>Inverter</strong></td>
<td><strong>Kolar, Karnataka (Southern region)</strong></td>
</tr>
<tr>
<td><strong>Distance</strong></td>
<td>$\approx 1367$ km</td>
</tr>
<tr>
<td><strong>Rated Power</strong></td>
<td>2000 MW</td>
</tr>
<tr>
<td><strong>Rated DC current</strong></td>
<td>2000A</td>
</tr>
<tr>
<td><strong>Operating Voltage</strong></td>
<td>$\pm 500$ kV DC</td>
</tr>
<tr>
<td><strong>Reduced Voltage</strong></td>
<td>$\pm 400$ kV DC</td>
</tr>
<tr>
<td><strong>Resistance of each DC line</strong></td>
<td>14.2 ohms</td>
</tr>
<tr>
<td><strong>Length of Electrode line</strong></td>
<td>32Km</td>
</tr>
<tr>
<td><strong>Overload</strong></td>
<td></td>
</tr>
<tr>
<td>Two Hour, 50°C</td>
<td>1.1 pu per pole</td>
</tr>
<tr>
<td>Two Hour, 33°C</td>
<td>1.2 pu per pole</td>
</tr>
<tr>
<td>Half an hour, 50/33°C</td>
<td>1.2/1.3 pu per pole</td>
</tr>
<tr>
<td>Five Seconds</td>
<td>1.47 pu per pole</td>
</tr>
<tr>
<td>Going to be upgraded to</td>
<td>2500MW</td>
</tr>
</tbody>
</table>